U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

September 2014

Field Demonstration of High-Efficiency Ultra-Low-Temperature Laboratory Freezers

Prepared for Better Buildings Alliance
Building Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Better Buildings
U.S. DEPARTMENT OF ENERGY

By: Rebecca Legett, Navigant Consulting, Inc.

Disclaimer

The work described in this report was funded by the U.S. Department of Energy under Contract No. GS-10F-0200K, Order No. DE-DT0006900.

Acknowledgements

First and foremost, the authors of this report would like to express their gratitude to the demonstration site hosts at University of Colorado at Boulder (CU Boulder) and Michigan State University (MSU). Dr. Kathryn Ramirez-Aguilar and Stuart Neils, at CU Boulder and MSU respectively, provided invaluable support and coordination both in getting the demonstration off the ground and ensuring that it ran smoothly. Without them this project would not have been possible. Many thanks to Dr. Douglas Seals, Dr. Monika Fleshner, and Dr. Michael Stowell at CU Boulder, and Brian Jespersen at MSU, who generously granted permission to monitor the ultra-low freezers in their respective laboratories; and to Molly Russell, Jennifer Shannon Law, and Kelly Grounds, who worked to obtain this permission. Thanks also to all at MSU who arranged for the demonstration to take place, including Lynda Boomer at Infrastructure Planning and Facilities (IPF) and Jennifer Battle in the Office of Sustainability.

We would also like to thank the following people from ultra-low freezer manufacturing companies who provided initial information about their products and in some cases assisted with their procurement or delivery for the study: Neill Lane and Jason Thompson with Stirling Ultracold; Joe LaPorte with Panasonic; and Mary Lisa Sassano and Daniela Marino with Eppendorf-New Brunswick.

We are grateful for the support and review of the U.S. Department of Energy's Better Buildings Alliance, particularly from Amy Jiron, Kristen Taddonio, Jason Koman, Alan Schroeder, Charles Llenza, and Arah Schuur, and Paul Mathew, William Tschudi, and Craig Wray of Lawrence Berkeley National Laboratory.

For more information contact: techdemo@ee.doe.gov

The Better Buildings Alliance is a U.S. Department of Energy effort to promote energy efficiency in U.S. commercial buildings through collaboration with building owners, operators, and managers. Members of the Better Buildings Alliance commit to addressing energy efficiency needs in their buildings by setting energy savings goals, developing innovative energy efficiency resources, and adopting advanced cost-effective technologies and market practices.

Table of Contents

Executive Summary ..... vi -
I. Introduction ..... 1 -
  A. Problem Statement ..... 1 -
  B. Opportunity ..... 2 -
  C. Technical Objectives ..... 2 -
  D. Technology Description ..... 2 -
II. Methodology ..... 7 -
  A. Identifying Candidate Products ..... 7 -
  B. Site Selection and Technology Installation ..... 9 -
  C. Instrumentation Plan ..... 12 -
  D. Data Aggregation and Calculation Methodology ..... 13 -
  E. Interviews ..... 15 -
III. Results ..... 17 -
  A. Energy Savings Results ..... 17 -
  B. Variation Among Comparison ULTs ..... 18 -
  C. Power Factor Impacts ..... 18 -
  D. Internal Temperature v. Set-Point ..... 20 -
  E. Interview Findings ..... 23 -
  F. Economic Analysis ..... 24 -
IV. Summary Findings and Recommendations ..... 26 -
  A. Overall Technology Assessment at Demonstration Facilities ..... 26 -
  B. Recommendations ..... 27 -
V. References ..... 29 -
Appendix A. Unadjusted Results and Observations ..... A-1 -
Appendix B. Regression Analysis Methodology and Results ..... B-11 -
Appendix C. Instrumentation and Data Collection Details ..... C-20 -
Appendix D. Calculating Power Factor ..... D-34 -

List of Tables

Table E-1: ULTs Included in the Demonstration ..... vii -
Table E-2: Energy and Cost Savings ..... x -
Table II.1: Details of Units Chosen for Demonstration ..... 9 -
Table II.2: Technologies Implemented in ULTs Evaluated in Demonstration (Based on Manufacturer - Specifications) ..... 9 -
Table II.3 ULTs Measured at Each Demo Site ..... 10 -
Table II.4: Measurement Periods at Each Site ..... 12 -
Table II.5: Instrumentation Details ..... 13 -
Table II.6: Standardized Operating Conditions ..... 14 -
Table II.7: Space Conditioning Calculation Inputs and Assumptions ..... 15 -
Table II.8: Interview Details ..... 16 -
Table III.1: Energy Savings of Demo Units* ..... 18 -
Table III.2: Power Factor for ULTs in the Demonstration ..... 19 -
Table III.3: Observed Differences between Set-Point and Measured Temperature ..... 21 -
Table III.4: Simple Payback Analysis for Demo ULTs ..... 26 -

Table B-1: Conditions for Calculating Standardized Energy Use .... B-12 -
Table B-2: Regression Variables and Standardized Energy Use: Unit Demo-1........ B-13 -
Table B-3: Regression Variables and Standardized Energy Use: Unit Comp-1........ B-14 -
Table B-4: Regression Variables and Standardized Energy Use: Unit Demo-2........ B-15 -
Table B-5: Regression Variables and Standardized Energy Use: Unit Comp-2........ B-16 -
Table B-6: Regression Variables and Standardized Energy Use: Unit Demo-3........ B-17 -
Table B-7: Regression Variables and Standardized Energy Use: Unit Comp-3........ B-18 -
Table B-8: Regression Variables and Standardized Energy Use: Unit Comp-4........ B-19 -

List of Figures

Figure I.1 Diagram of Cascaded Refrigeration System .... 3 -
Figure I.2: Typical ULT........ 4 -
Figure I.3: Uninsulated (Left) vs. Insulated (Right) Inner Doors .... 5 -
Figure I.4 Diagram of Stirling Refrigeration System .... 6 -
Figure II.1 Graph of Available ULT Energy Data with Selected Models Indicated*........ 8 -
Figure II.2 Schematic of MCDB Laboratory........ 10 -
Figure II.3 Schematic of iPhy Laboratory........ 11 -
Figure II.4 Schematic of MSU Laboratory........ 12 -
Figure III.1 Adjusted Daily Energy Consumption for Demo and Average Comparison ULTs with and without Space - Conditioning Impacts*........ 17 -
Figure III.2: Adjusted Daily Energy Consumption for Comparison ULTs without Space Conditioning Impacts .... 18 -
Figure III.3: Adjusted Electricity Consumption for Demo and Average Comparison ULTs, Accounting for Power - Factor*........ 20 -
Figure III.4: Adjusted Electricity Consumption for Demo and Average Comparison ULTs, Calibrating Set-Point to - Internal Temperature of -80 °C* .... 22 -
Figure III.5: Comparing Internal Temperature of Cascade and Stirling Cycle ULTs........ 23 -
Figure III.6: List Price Data for Demo Models and Other ULTs* .... 25 -
Figure A.1: Daily Energy and Temperature Data: Unit Demo-1 .... A-2 -
Figure A.2: Daily Door Opening Data: Unit Demo-1........ A-2 -
Figure A.3: Daily Energy and Temperature Data: Unit Comp-1 .... A-4 -
Figure A.4: Daily Door Opening Data: Unit Comp-1 .... A-4 -
Figure A.5: Daily Energy and Temperature Data: Unit Demo-2 .... A-5 -
Figure A.6: Daily Door Opening Data: Unit Demo-2........ A-5 -
Figure A.7: Daily Energy and Temperature Data: Unit Comp-2 .... A-6 -
Figure A.8: Daily Door Opening Data: Unit Comp-2 .... A-6 -
Figure A.9: Daily Energy and Temperature Data: Unit Demo-3 .... A-7 -
Figure A.10: Daily Door Opening Data: Unit Demo-3........ A-7 -
Figure A.11: Daily Energy and Temperature Data: Unit Comp-3 .... A-8 -
Figure A.12: Daily Door Opening Data: Unit Comp-3 .... A-8 -
Figure A.13: Daily Energy and Temperature Data: Unit Comp-4 .... A-9 -
Figure A.14: Daily Door Opening Data: Unit Comp-4 .... A-9 -
Figure B.1: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Demo-1 .... B-13 -
Figure B.2: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Comp-1........ B-14 -
Figure B.3: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Demo-2 .... B-15 -
Figure B.4: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Comp-2........ B-16 -
Figure B.5: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Demo-3 .... B-17 -
Figure B.6: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Comp-3........ B-18 -

Figure B.7: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Comp-4 .... B-19 -
Figure C.1: Electrical Diagram for NEMA 5-20 Connector .... C-21 -
Figure C.2: Electrical Diagram for NEMA 6-15 Connector .... C-22 -
Figure C.3: Photograph of Power Meter Inside Electrical Box .... C-23 -
Figure C.4: Pulse Input Adapter and Cable from Power Meter to Logger .... C-24 -
Figure C.5: Front View of Each ULT Showing Approximate Relative Elevation of Internal Thermocouple Placement - .... C-25 -
Figure C.6: Thermocouple Apparatus .... C-26 -
Figure C.7: Photo of Temperature Transmitter .... C-27 -
Figure C.8: Temperature Sensor and Cable from Sensor to Logger .... C-28 -
Figure C.9: Photos of External Temperature Probe Placement .... C-28 -
Figure C.10: Diagram of Data Logger Inputs .... C-29 -
Figure C.11: Instrumentation Schematic for CU Boulder Sites .... C-30 -
Figure C.12: Instrumentation Schematic for Michigan State University Lab .... C-31 -
Figure C.13: Diagram of Logger and Magnet .... C-32 -
Figure C.14: Photograph of Logger and Magnet on ULT .... C-33 -
Figure D.1: Relationship Among Power Variables .... D-34 -
Figure D.2: Comparison of Power Factor for Different Equipment .... D-35 -

Acronyms and Abbreviations

BBA – Better Buildings Alliance
CHP – Combined heat and power
CU Boulder – University of Colorado at Boulder
DOE – U.S. Department of Energy
EIA – U.S. Energy Information Administration
EPA – U.S. Environmental Protection Agency
HVAC – Heating, ventilation, and air conditioning
iPhy – Integrative physiology
LabRATS – Laboratory Resources, Advocates, and Teamwork for Sustainability
MCDB – Molecular, cellular, and developmental biology
MSU – Michigan State University
TC – Thermocouple
UEC – Unit Energy Consumption
ULT – Ultra-low-temperature laboratory freezer

Executive Summary

Ultra-low temperature laboratory freezers (ULTs) are some of the most energy-intensive pieces of equipment in a scientific research laboratory, yet there are several barriers to user acceptance and adoption of high-efficiency ULTs. One significant barrier is a relative lack of information on ULT efficiency to help purchasers make informed decisions with respect to efficient products. Even where such information exists, users of ULTs may experience barriers to purchasing high-efficiency equipment at a cost premium, particularly in situations when the purchaser of the ULT does not pay the electricity cost (e.g., if the facility owner pays this cost), thus the purchaser would not see the energy cost savings from a more efficient product.

Through the U.S. Department of Energy (DOE) Better Buildings Alliance (BBA) program, we conducted a field demonstration to show the energy savings that can be achieved in the field with high-efficiency equipment. The results of the demonstration provide more information to purchasers for whom energy efficiency is a consideration. The findings of the demonstration are also intended to support efforts by the BBA and others to increase the market penetration of high-efficiency ULTs.

We selected three ULT models to evaluate for the demonstration. These models were upright units having storage volumes between 20 and 30 cubic feet—a commonly sold type and size range. We predicted that the selected units would save energy compared to standard models, based on existing manufacturer data (however, we were unable to verify the operating conditions and test protocols that the testers or manufacturers used when previously evaluating the ULTs). We monitored each ULT model at one of three demonstration sites. The demonstration sites included:

- The Molecular, Cellular, and Developmental Biology (MCDB) laboratory at the University of Colorado at Boulder (CU Boulder) in Boulder, Colorado
- The Integrative Physiology (iPhy) laboratory at CU Boulder
- The Pharmacology and Toxicology Department at Michigan State University (MSU) in East Lansing, Michigan.

Alongside each demonstration model, we monitored one or two other ULT models of a similar size and age that were already in the lab, for purposes of comparison. Table E-1 lists the ULTs included in the study.

Table E-1: ULTs Included in the Demonstration

Unit Designator	Description of Unit	Brand/Model Number	Year ULT was Manufactured	Internal Volume (ft^3)*	Demo Location
Demo-1	Demo unit #1	Stirling Ultracold SU780U	2013	28	CU Boulder-MCDB
Demo-2	Demo unit #2	New Brunswick HEF U570	2012	20	CU Boulder - iPhy
Demo-3	Demo unit #3	Panasonic VIP Plus MDF-U76VC	2013	26	MSU
Comp-1	Comparison unit #1	**	2010	23	CU Boulder-MCDB
Comp-2	Comparison unit #2	**	2009	17	CU Boulder - iPhy
Comp-3	Comparison unit #3	**	2013	24	MSU
Comp-4	Comparison unit #4	**	2012	26	MSU

*Rounded to nearest cubic foot. -

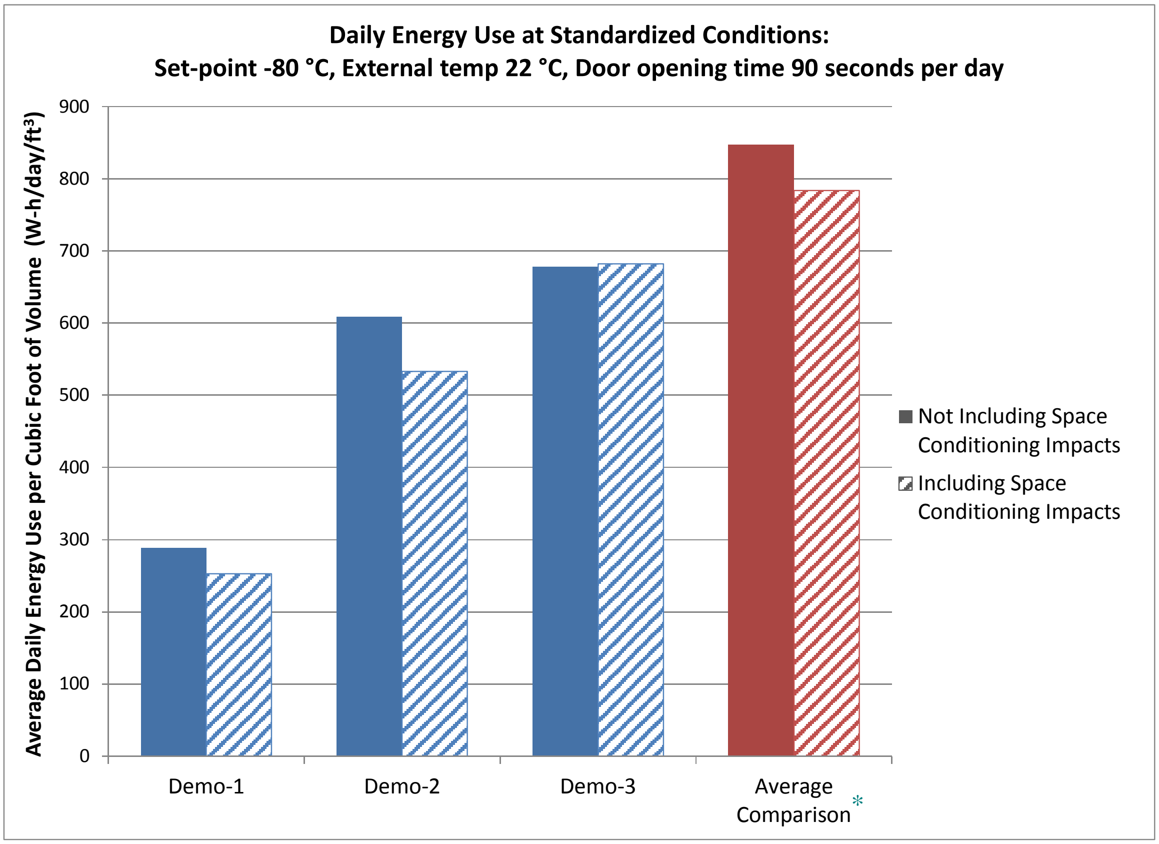
** We did not publish the model number of the comparison ULTs because these ULTs are meant to be representative of the typical ULT on the market, and we did not intend for them to be associated with a particular manufacturer or brand. -

We collected data over a period of approximately 5 months, recording each ULT's energy use, internal temperature at a single point, and temperature outside the ULT at a single point, at 1-minute intervals. We also separately recorded the frequency and duration of door openings. We then aggregated the data on a daily basis and correlated daily energy use with temperature set-point, average daily external temperature, and number of seconds each day that the outer door was opened, to account for variations in field conditions when comparing performance.

Figure E-1 compares the energy consumption of each demo ULT to the average energy consumption of the comparison ULTs measured in the study, after adjusting to a common set of operating conditions.[1] Results are presented with and without secondary space conditioning impacts.[2]

[1] We could not definitively determine whether the set-point was representative of the true average internal temperature of the ULT. In some cases, there were discrepancies between our measured internal temperature and the ULT's set-point.

[2] Secondary impacts are the net change in space-conditioning energy use resulting from heat rejection from the ULT. Heat rejected from a ULT increases the amount of energy needed to cool the space, and reduces the amount of energy required to heat the space. For the ULTs at CU Boulder, accounting for the secondary impacts slightly reduced the total energy use of the ULTs (and, subsequently, the efficiency benefit of the demo ULTs). This was in part due to the relatively long building heating season and relatively short building cooling season associated with the climate in that location. Energy savings will tend to be higher, and payback periods shorter, in warmer climates where the impacts on space-conditioning loads are more significant.



*This represents the average energy use of the four comparison units measured in the study.

Figure E-1: Adjusted daily energy consumption for demo and average comparison ULTs with and without space conditioning impacts

Table E-2 presents the potential energy and cost savings that the demo ULTs may achieve over the average comparison ULT, including an estimated payback period—that is, the time to recoup the difference in first cost between a demo ULT and a comparison ULT.

Table E-2: Energy and Cost Savings

Unit	Percent Energy Savings*	Annualized Energy Savings (MWh)*	Annualized Cost Savings ($)**	Estimated Payback Period (years)†
Demo-1	66%	5.5	$570	2.8
Demo-2	28%	1.8	$180	7.7
Demo-3	20%	1.6	$170	15

*Energy savings are based on comparing each demo ULT to the average of the comparison ULTs, multiplying the energy use per cubic-foot shown in Figure E-1 by the internal volume of each demo ULT. Does not include space conditioning impacts.

**Assuming an electricity price of 10.34 cents per kWh (average U.S. electricity price in January 2014 according to the Energy Information Administration[3]) and rounded to two significant figures.

†Based on a 30 percent discount from the list price for both demo ULTs and comparison ULTs. Actual prices and payback periods may vary due to distributor discounts and utility incentive programs.

The results of the demonstration support the hypothesis that the demo ULTs can achieve energy savings under field conditions, as the demo ULTs saved between 20% and 66% of the energy used by the average comparison ULT on a per-cubic-foot basis. The time to recoup the first cost differential between a demo ULT and a typical ULT of the same size ranged from approximately 3 to 15 years (actual payback periods depend on the ULT model, available discount, and utility rate).

We recommend the following actions to promote the use of high-efficiency ULTs:

For purchasers and purchasing organizations

- *In cases where the facility owner (and not the purchaser) pays for the electricity use of the ULT, work with the facility owner to implement programs that "pay forward" the expected operating cost savings to incentivize the purchaser to choose more efficient products.*
- *Seek out and apply for custom utility rebates to off-set first-cost premiums for high-efficiency equipment.*
- *Demonstrate market demand for high-efficiency equipment by asking for such equipment from their existing vendor and distributor networks, and be willing to use alternate suppliers if current suppliers do not have high-efficiency product offerings. Make clear to suppliers that energy efficiency is a factor in purchasing decisions.*

For manufacturers

- *Continue to develop and promote high-efficiency products, establishing strong relationships with customers to whom energy efficiency is important.*
- *Support existing efforts to promote energy efficient products being undertaken by ENERGY STAR®, the Better Buildings Alliance, the International Institute for Sustainable Labs, and other programs.*

For DOE

- *Promote the use of recently developed standardized rating methods to make it easier for potential purchasers of ULTs to identify high-efficiency products.*
- *Help purchasers overcome first-cost barriers by educating purchasers on life-cycle cost.*

[3] U.S. Energy Information Administration: Electric Power Monthly with Data for January 2014, published March 2014. http://www.eia.gov/electricity/monthly/current_year/march2014.pdf

- - *Publicize government procurement guidelines that require federal agencies and recipients of government-funded research grants to procure energy-efficient products, including ULTs. Encourage the purchase of ENERGY STAR ULTs when available.*

I. Introduction

A. Problem Statement

Ultra-low temperature laboratory freezers (ULTs) can be one of the most energy-intensive pieces of equipment in a laboratory. The average 25-cubic foot ULT uses approximately 20 kWh of energy per day, as much as a small house. Despite the large energy use of this equipment, there are several barriers to adoption of high-efficiency ULTs. ULTs are typically replaced only when they fail, with a similar ULT of the purchaser's choosing. In cases where the facility owner and not the purchaser pays for the electricity use of the ULT, the purchaser has an incentive to minimize first cost without regard to the electricity cost savings that an energy-efficient product can deliver. Finally, few data exist on ULT energy use to help purchasers make informed decisions where energy efficiency is concerned.

Despite these barriers, there is a need for high-efficiency products. Several organizations are already working to promote and publicize improvements in ULT efficiency. The International Institute for Sustainable Laboratories hosts an annual conference, with laboratory equipment as a major focus.[1] Lawrence Berkeley National Laboratory hosts a webpage containing data on energy-efficient laboratory equipment, including ULTs, developed and maintained by Allen Doyle of the University of California at Davis.[2] Other organizations include the Laboratory Resources, Advocates, and Teamwork for Sustainability (LabRATS) program at the University of California at Santa Barbara and the annual StoreSmart sustainable laboratory cold storage challenge.[3,4] The U.S. Department of Energy (DOE) Better Buildings Alliance (BBA) is supporting the deployment of high-efficiency laboratory equipment through its labs team, comprised of major end-users.[5]

In addition to these efforts, DOE and the U.S. Environmental Protection Agency (EPA) are working to cover laboratory-grade refrigerators and freezers, including ULTs, under the ENERGY STAR® program. Recent efforts resulted in the development of a standardized rating method for this equipment, while future efforts will include developing a specification for ENERGY STAR®-qualified products. However, these efforts are meant to provide a uniform method for comparing ULTs; they may not reflect ULT operation under varying conditions of use.

---

[1] International Institute for Sustainable Laboratories: Annual Conference. http://i2sl.org/conference/index.html

[2] Labs for the 21st Century: Energy Efficient Laboratory Wiki. http://labs21.lbl.gov/wiki/equipment/index.php/Energy_Efficient_Laboratory_Equipment_Wiki

[3] UCSB Sustainability: Laboratory Resources, Advocates, and Teamwork for Sustainability (LabRATS). http://www.sustainability.ucsb.edu/labrats/

[4] UC Davis Sustainable 2nd Century: Take Action: Store Smart. http://sustainability.ucdavis.edu/action/conserve_energy/store_smart.html

[5] According to the BBA website, "The BBA is a DOE effort to promote energy efficiency in U.S. commercial buildings through collaboration with building owners, operators, and managers. Members of the Better Buildings Alliance commit to addressing energy efficiency needs in their buildings by setting energy savings goals, developing innovative energy efficiency resources, and adopting advanced cost-effective technologies and market practices. Members bring their powerful insights and industry experience in affiliation with DOE technical experts to develop and demonstrate innovative, cost-effective, and energy-saving technologies and market practices. Together, they catalyze innovation--releasing performance specifications and best practice guidelines for members to deploy." http://www4.eere.energy.gov/alliance/about

Through DOE's BBA program, we conducted a field demonstration of high-efficiency ULT models. The purpose of the demonstration was to showcase the energy savings that can be achieved in the field with high-efficiency equipment and evaluate the effect of varying operating conditions on ULT energy use. The results of the demonstration provide more information to purchasers for whom energy efficiency is a consideration. In cases where the facility owner and not the purchaser pays the electricity cost of operating the ULT, the demonstration results may help the facility owner encourage the purchaser to buy high-efficiency equipment, potentially by offering an incentive commensurate with the expected electricity cost savings during the life of the product. The findings of the demonstration are also intended to support efforts by the BBA and other organizations to increase the market penetration of high-efficiency ULTs.

B. Opportunity

An analysis published by the Energy Information Administration (EIA) in 2013 estimated that the installed base of ULTs is approximately 250,000, consuming approximately 1.6 TWh of on-site energy use per year in the U.S.[6] Replacing just 30 percent of these ULTs with high-efficiency models using, on average, 25 percent less energy, could save about 120 GWh of site energy per year. Assuming an average electricity cost of 10.34 cents per kWh, the potential cost savings are approximately $12.4 million per year.[7]

Because typical ULTs reject a large amount of heat, the secondary impacts on space-conditioning energy; i.e., the heat rejected by ULTs increases space-cooling energy requirements and decreases space-heating energy requirements. This would result in additional benefits of improving ULT energy efficiency by lowering space-conditioning energy in laboratory settings with significant net space-cooling energy requirements.

C. Technical Objectives

The technical objectives of this demonstration were to measure field energy use of selected ULT models, which we expected to represent a "high-efficiency" product, and to compare them to similar models that are meant to represent a "typical" product—i.e., those whose energy use, as reported by the manufacturer and/or measured in previous studies, appears to be close to the energy use of an average ULT. (Characteristics of demonstration and comparison models are discussed in section II.A.) The goal was to evaluate whether the demonstration models used less energy than the comparison models under field conditions to either support or refute the claims that these demo models were significantly more efficient than the average model. Another goal was to collect the ULTs' users' feedback on considerations that would or would not influence them to choose a high-efficiency model, in order to inform estimates of the deployment potential of high-efficiency ULTs.

D. Technology Description

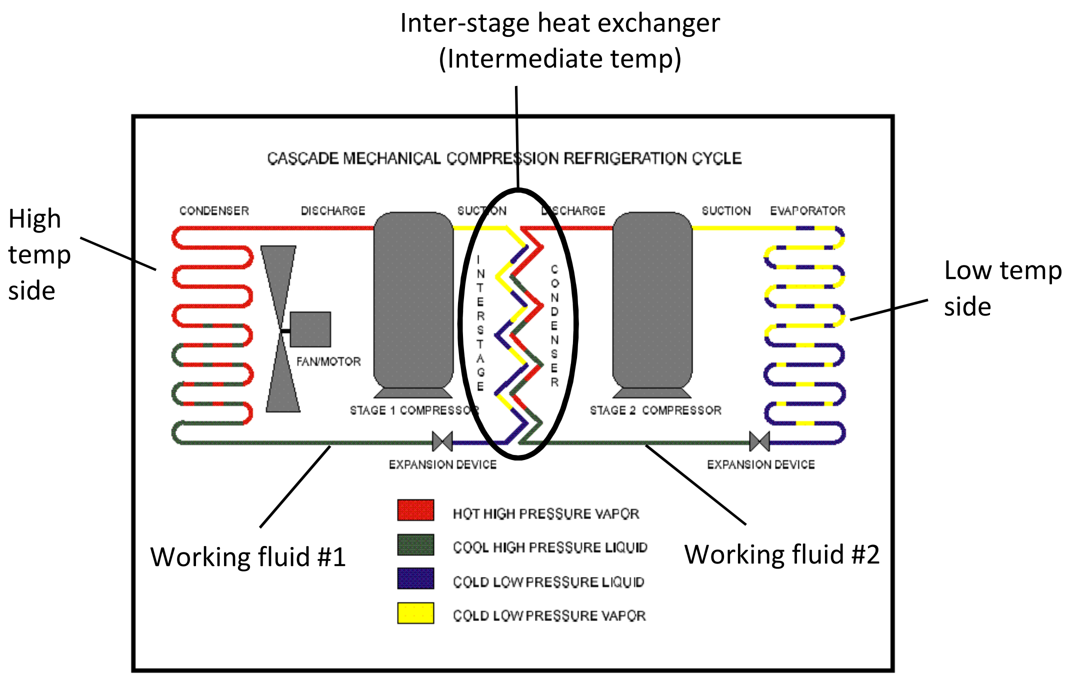
Typical Equipment

---

[6] "Analysis and representation of Miscellaneous Electric Loads in NEMS." Prepared for U.S. Energy Information Administration by Navigant Consulting, Inc. and SAIC, 2013. http://www.eia.gov/analysis/studies/demand/miscelectric/pdf/miscelectric.pdf

[7] U.S. average commercial electricity rate January 2014. Source: U.S. Energy Information Administration: Electric Power Monthly with Data for January 2014, published March 2014. http://www.eia.gov/electricity/monthly/current_year/march2014.pdf

ULTs consist of a well-insulated storage cabinet refrigerated to temperatures of -70 to -80 °C, though some are operated at temperatures up to -60 °C depending on the operator's preference or the ULT's application. The most common ULT refrigeration technology is a cascaded vapor-compression refrigeration system. Cascaded refrigeration systems use two refrigeration loops in series to bring the low-side working fluid to a very low temperature, which cools the storage cabinet. A cascaded system is used because of the very large temperature difference between the interior and the exterior of the ULT: most commonly used refrigerants do not have the physical properties (i.e. relationship between saturation pressure and temperature) necessary to reach both temperature extremes.[8] In a cascaded system, the two loops use different refrigerants with different pressure-temperature properties appropriate to the temperature ranges in which they operate. The high-side loop circulates hot vapor through a condenser to reject heat. The low-side loop circulates a cold liquid-vapor mix through a refrigerant tubing in in contact with the inner walls of the ULT (called a cold-wall evaporator); as the refrigerant evaporates, it absorbs heat from the interior of the ULT. The two loops exchange heat using an inter-stage heat exchanger. Figure I.1 illustrates the mechanism.



Source: ESS, Inc.

Figure I.1 Diagram of Cascaded Refrigeration System

Most ULTs are insulated with several inches of foam-in-place insulation (typically polyurethane) to minimize heat conduction through the walls of the cabinet. Foam-in-place insulation is produced by mixing two chemicals and spraying or injecting them into a hollow cabinet section along with a blowing agent. The chemicals react to

[8] Most ULTs use hydrofluorocarbon (HFC) refrigerants to comply with EPA's ban on chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants. Outside the U.S., hydrocarbon refrigerants are sometimes used, but these have not yet come into wide use in the U.S. due to current EPA restrictions. This situation may change in the near future as EPA issues new refrigerant guidelines.

form a foam with the blowing agent filling the small bubbles inside the foam. The foam material has a high insulating value because the blowing agent has more insulating capability than air. However, the insulative capability of foam-in-place insulation can decrease over time as the blowing agent gas diffuses out of the foam. We attempted to mitigate the effect of this diffusion on the demonstration results by evaluating only relatively new ULTs. All ULTs in the demonstration were less than five years old at the time of measurement.

ULTs also usually have one or two exterior insulated doors, and two or more interior doors closing off sections of the ULT so that cold air does not spill out of the entire ULT when only one shelf needs to be accessed.

Figure I.2 shows a typical ULT with major elements indicated.

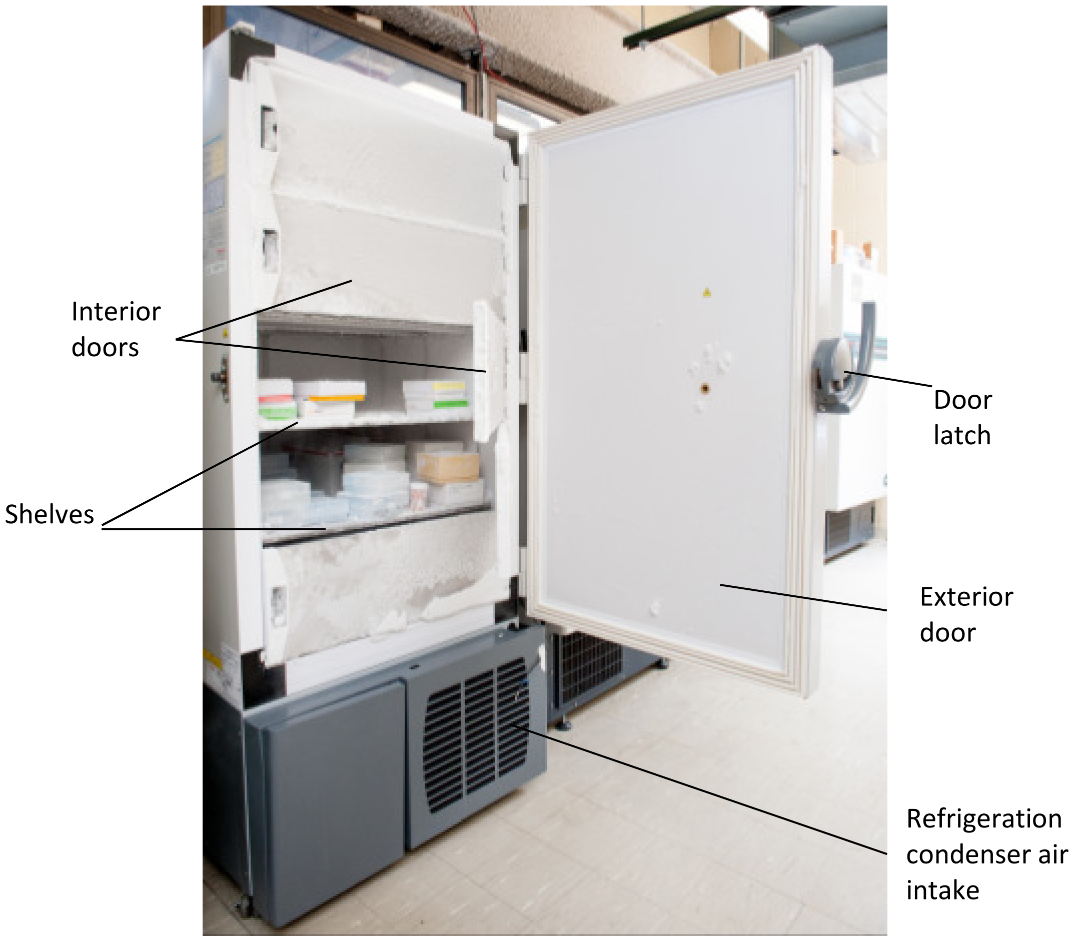


Photo credit: Dave Trumpie

Figure I.2: Typical ULT

High-Efficiency Technologies

Several technologies and designs exist that can improve ULT efficiency. Examples include:

<u>Better insulating capability of exterior cabinet, including use of vacuum insulated panels</u>

Manufacturers can improve the insulating capability of the exterior cabinet by increasing the thickness of insulation or using a more insulative material. Increasing the thickness of the cabinet insulation increases the weight and either increases the footprint or decreases the internal volume of the ULT; thus, many manufacturers have turned to alternate insulative materials, such as vacuum insulated panels. Vacuum insulated panels consist of an air-tight membrane surrounding a porous inner material, which can be evacuated of air while maintaining its shape. A vacuum has a much higher insulating capability than foam insulation, allowing manufacturers to maintain wall thickness comparable to that of a standard ULT but with a much lower rate of heat transfer between the exterior and interior of the ULT. Most ULTs evaluated in this study utilized a vacuum insulated layer in addition to foam insulation, for extra sturdiness and insulating capability.

Insulated interior doors

As noted previously, most ultra-low freezers have one or two exterior insulated doors, and two or more interior doors. The interior doors are typically uninsulated metal and are only useful for preventing air loss. Some ULT models use insulated inner doors to prevent heat conduction in addition to infiltration when the outer door is opened, and also contribute to the insulation of the ULT when the doors are closed. Figure I.3 illustrates uninsulated and insulated doors on the left and right, respectively. (This option's energy-saving potential is affected by how often the outer doors are opened. See Appendix A for door opening data and Appendix B for the relative effect of measured variables, including door openings, on ULT energy use.)

Photo credits: Left – Dennis Schroeder, NREL; Right – Dave Trumpie

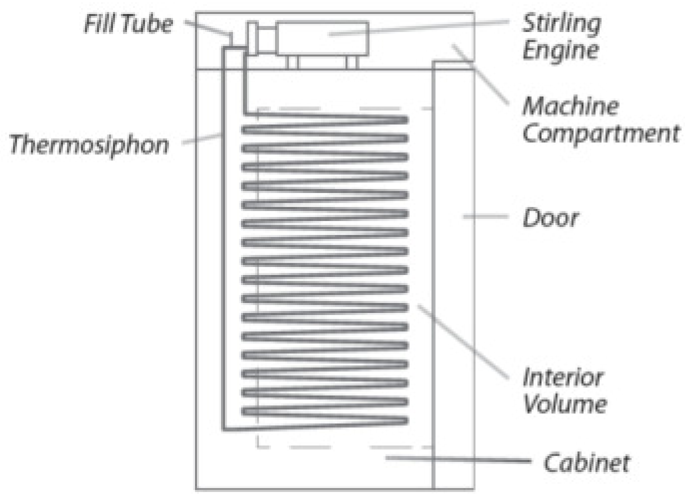
Figure I.3: Uninsulated (Left) vs. Insulated (Right) Inner Doors

Improvements to cascaded refrigeration system design

Air-cooled refrigeration systems require fans to facilitate heat rejection from the refrigerant to the ambient air on the high-temperature side of the refrigeration loop. Fan efficiency can be improved by using high-efficiency motors, such as electronically commutated (brushless direct-current) motors, and improved fan blades that move air more efficiently. Furthermore, some ULTs implement an improved inter-stage heat exchanger to transfer heat more efficiently between the two refrigerant loops.

Alternative Refrigeration Cycles

Although most ULTs implement cascade refrigeration systems, other alternative cycles are available. For example, one manufacturer offers a different technology: a Stirling cooler, which uses a Stirling engine in a reverse cycle. Figure I.4 illustrates the mechanism. Mechanical energy applied to the engine's piston creates a pressure drop in the working fluid, which then absorbs heat from a heat exchanger (called a thermosiphon), thus cooling the ULT. According to the manufacturer, this mechanism saves a significant amount of energy over a standard cascade system. Additional benefits are that there is no current surge when the mechanism starts up, reducing electrical infrastructure requirements; and the mechanism runs continuously, thus eliminating temperature cycling that would otherwise be due to compressors cycling on and off.[9]



Source: Stirling Ultracold

Figure I.4 Diagram of Stirling Refrigeration System

[9] Lane, Neill. 2013. "Ultra-Low Temperature Free-Piston Stirling Engine Freezers." http://www.stirlingultracold.com/lib/sitefiles/whitepaper/10354-GLOBAL-whitepaper-apr13-vF-web.pdf

II. Methodology

The methodology for this field demonstration project consisted of the following steps:

- Identifying candidate products for inclusion in the demo, which we believed represented high-efficiency products on the market
- Choosing candidate sites at which to conduct the demonstration
- Collecting raw, quantitative data about ULT operation (specifically power, current draw, voltage, internal temperature, external temperature, and door openings) using instrumentation
- Aggregating the data in order to be able to draw conclusions about energy savings and compare ULTs to each other
- Collecting qualitative data by interviewing users of the ULTs

A. Identifying Candidate Products

To identify candidate ULT models for the field demonstration, we invited manufacturers of upright ULTs in the size range of 20 to 30 cubic feet— a commonly used type and size range—to suggest models suitable for inclusion in the field demonstration. We also independently collected efficiency data on ULTs currently being sold in the U.S. market. In evaluating suitability of ULT models for the demonstration, we focused on models that seemed to be among the best performers in terms of energy use, based on manufacturer-reported or field-tested energy use data. Figure II.1 shows the available data for upright ULTs between 10 and 35 cubic feet, distinguishing manufacturer data from field data and showing a trend line for energy use. Each of the three models selected for the demonstration represented at least a 25 percent energy savings over the average unit, based on available data.

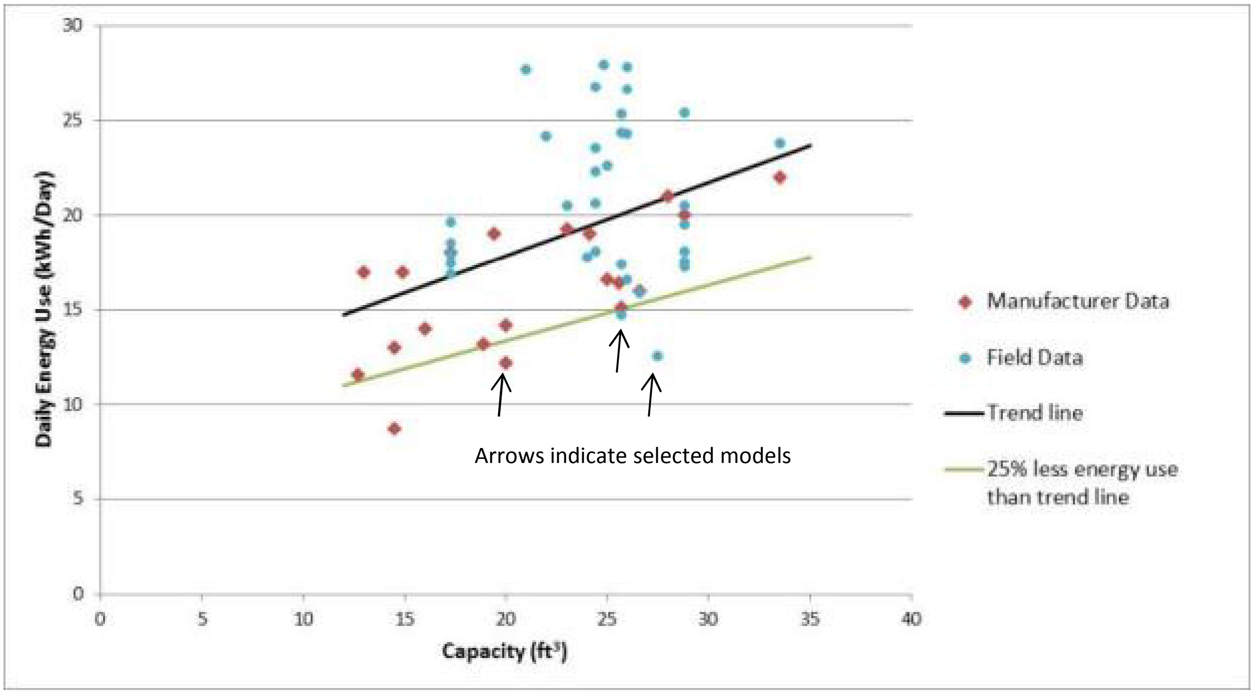


Figure II.1 Graph of Available ULT Energy Data with Selected Models Indicated*

*Sources for the ULT energy data in this figure include manufacturer specification sheets with reported energy use for Thermo Scientific, Dometic, Panasonic, and Eppendorf ULTs; a database of ULT field energy data maintained by Allen Doyle of UC Davis; and field data from a study on ULT energy use conducted at the National Institutes of Health.[10,11] Operating conditions and test protocols were not verified and may vary significantly; the age and condition of the field-measured ULTs may also vary significantly, which could affect the energy efficiency.

Table II.1 contains physical specifications of the ULTs measured in the demonstration at each site. Along with the units selected for the demonstration, we also monitored one or two other ULTs at each site for purposes of comparison. Table II.2 lists the high-efficiency technologies each ULT utilizes, as claimed in the manufacturer literature. The comparison ULTs are included in this table because some of them implemented one or more of the high-efficiency technologies.

[10] Labs for the 21st Century: Energy Efficient Laboratory Wiki. http://labs21.lbl.gov/wiki/equipment/index.php/Category:Ultra_Low

[11] Gumapas, Leo Angelo & Simons, Glenn. "Factors affecting the performance, energy consumption, and carbon footprint for ultra low temperature freezers: case study at the National Institutes of Health." World Review of Science, Technology and Sustainable Development, 2013 Vol.10, No.1/2/3, pp.129-141.

Table II.1: Details of Units Chosen for Demonstration

Unit Designator	Description of Unit	Brand/Model Number	Year ULT was Manufactured	Internal Volume (ft^3)*	# of Outer Doors	# of Inner Doors
Demo-1	Demo unit #1	Stirling Ultracold SU780U	2013	28	1	3
Demo-2	Demo unit #2	New Brunswick HEF U570	2012	20	1	5
Demo-3	Demo unit #3	Panasonic VIP Plus MDF-U76VC	2013	26	1	2
Comp-1	Comparison unit #1	**	2010	23	2	4
Comp-2	Comparison unit #2	**	2009	17	1	4
Comp-3	Comparison unit #3	**	2013	24	1	5
Comp-4	Comparison unit #4	**	2012	26	1	3

*Rounded to nearest cubic foot. -
** We did not publish the model number of the comparison ULTs because these ULTs are meant to be representative of the typical ULT - on the market, and we did not intend for them to be associated with a particular manufacturer or brand. -

Table II.2: Technologies Implemented in ULTs Evaluated in Demonstration (Based on Manufacturer Specifications)

Unit Designator	Vacuum Insulated Panels?	Insulated Interior Doors?	Efficient Inter stage heat exchanger?	High efficiency cond. fans?	Alternative refrigeration cycle?
Demo-1	Y	Y	-	-	Y
Demo-2	Y	Y	-	Y	-
Demo-3	Y	Y	Y	-	-
Comp-1	-	-	-	-	-
Comp-2	-	-	-	-	-
Comp-3	Y	Y	-	-	-
Comp-4	Y	Y	-	-	-

B. Site Selection and Technology Installation

To identify demonstration sites, we invited members of the Better Buildings Alliance, as well as other laboratory organizations, to participate in the study. Of those who expressed interest, we moved forward with three sites based on:

- Possession of, or willingness to purchase at a discount, one of the candidate demonstration models;
- Possession of one or more ULTs similar to, and in the same room as, the demonstration model, to use for comparison; and
- Commitment to participate, as indicated by the signing of a participation agreement.

The three sites participating in the demonstration were:

- The Molecular, Cellular, and Developmental Biology (MCDB) laboratory at the University of Colorado at Boulder (CU Boulder) in Boulder, CO;
- The Integrative Physiology (iPhy) laboratory at CU Boulder; and
- The Pharmacology and Toxicology Department at Michigan State University (MSU) in East Lansing, MI.

Table II.3 indicates which ULTs were monitored at each site.

Table II.3 ULTs Measured at Each Demo Site

Demo Site	Demo ULT Designator	Comparison ULT(s) Designator
CU Boulder – MCDB Lab	Demo-1	Comp-1
CU Boulder – iPhy Lab	Demo-2	Comp-2
MSU – Pharma. & Tox. Dept.	Demo-3	Comp-3 and Comp-4

The following sections describe each demonstration site in detail.

CU Boulder – MCDB Lab

The MCDB lab conducts research on how "living systems operate at the cellular and molecular levels of organization, their assembly and structure, with emphasis on genetic information and regulation."[12] The demo and comparison ULTs were located in a small, climate-controlled room that contained multiple ULTs. Figure II.2 shows the relative location of the ULTs in the room.

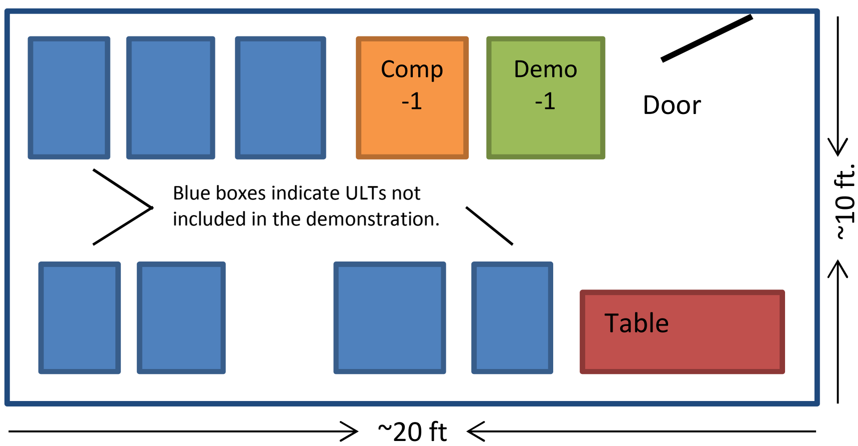


Figure II.2 Schematic of MCDB Laboratory

CU Boulder – iPhy Lab

The Integrative Physiology department studies how "cellular and molecular observations are linked to the health and function of whole organisms."[13] Ultra-low freezers are located along one wall of a large laboratory space. This lab had previously purchased its demo ULT in an effort to reduce their energy use and because its internal configuration was ideal for storing their samples (which were in the form of slides). As a result, this ULT had already been in operation for approximately one year at the time of the demonstration. Figure II.3 shows the relative location of the ULTs in the room.

[12] University of Colorado at Boulder: Molecular, Cellular, and Developmental Biology. http://mcdb.colorado.edu/index.shtml

[13] University of Colorado at Boulder: Integrative Physiology. http://www.colorado.edu/intphys/about/index.html

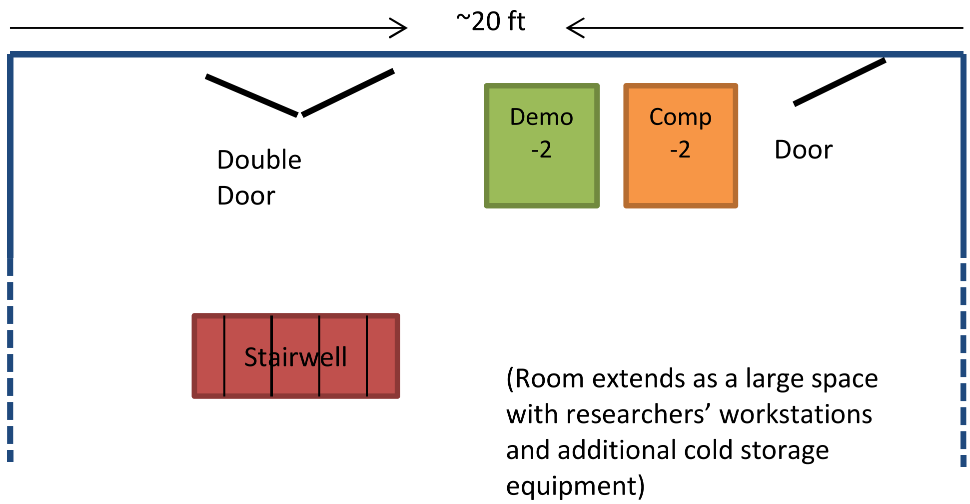


Figure II.3 Schematic of iPhy Laboratory

MSU – Pharmacology and Toxicology Department

The Pharmacology and Toxicology department at Michigan State University conducts biomedical research focusing on "the effects of drugs and chemicals on macromolecules [and] their actions in humans. Researchers use laboratory animals, human and animal cells in culture, and other test systems to examine the cellular, biochemical and molecular processes underlying pharmacologic and toxic responses."[14] Most ultra-low freezers in the laboratory building are located in a large room with an approximately 15-foot ceiling that is served by the building cooling system with an additional dedicated air conditioner for supplemental cooling. The room temperature is recorded as part of the building's energy management system. Figure II.4 shows the relative location of the ULTs in the room.

[14] Michigan State University: Pharmacology and Toxicology. http://www.phmtox.msu.edu/research/index.html.htm

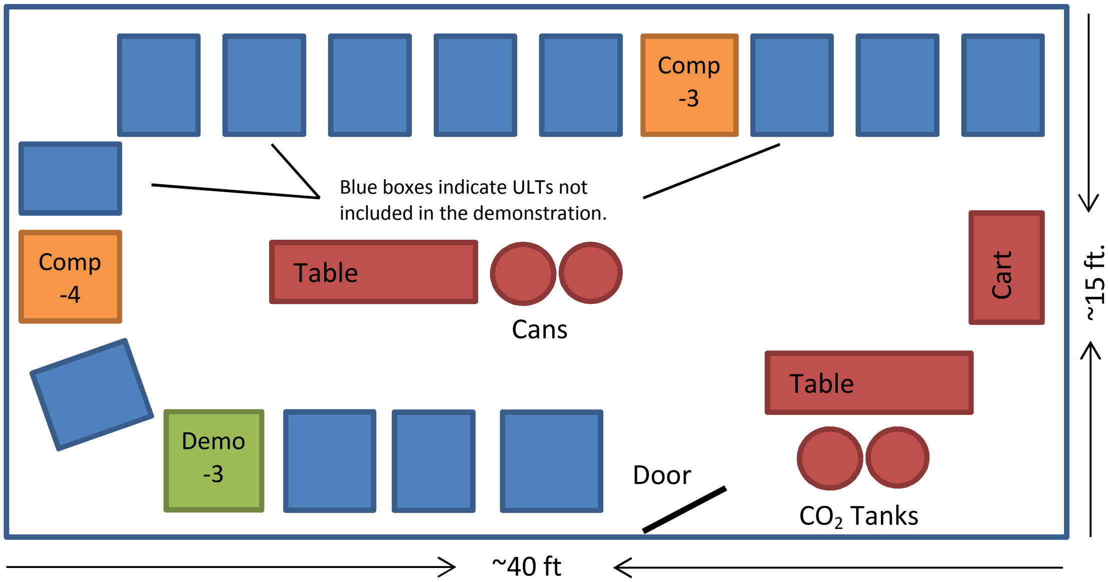


Figure II.4 Schematic of MSU Laboratory

C. Instrumentation Plan

We used instrumentation to measure each ULT's energy use, internal temperature, external temperature surrounding the ULTs, and time and duration of door openings. The instrumentation remained in place over a period of several months, monitoring each ULT's performance during normal use of the lab. Table II.4 shows the measurement periods for each site. (At each site, we monitored both the demonstration and comparison ULTs over the same period of time.)

Table II.4: Measurement Periods at Each Site

Site	Measurement Period	# Days Measured
CU Boulder - MCDB	6/12/13-11/18/13	160
CU Boulder - iPhy	6/18/13-11/18/13	154
MSU	7/12/13-12/10/13	152

Table II.5 contains details of each element of the instrumentation. Appendix C contains further details about the - instrumentation and data collection methodology, including instrumentation photographs and wiring diagrams. -

Table II.5: Instrumentation Details

Quantity Measured	Instrumentation Type	Instrumentation Model	Limit of Error	Measurement Interval
Energy (Real energy, amp hours, and reactive energy)	Veris Compact Power and Energy Meter	T-VER-E50B2	0.5% for real power, 2% for reactive power, and between 0.4% and 0.8% for current depending on the surrounding air temperature	1 minute
Internal Temperature	Type T Thermocouple and Omega Temperature Transmitter	5TC-TT-T-30-72/TX-13	1.0 °C or 1.5% at temperatures below 0 °C, whichever is greater	1 minute
External Temperature	Onset 12-Bit Temperature Smart Sensor	S-TMB-M00x*	0.2 °C from 0° to 50 °C	1 minute
Door openings	HOBO State Data Logger	UX90-001	1 minute per month at 25 °C	Irregular: timestamp (to the nearest second) was recorded when door was opened or closed

* "X" represents the length of the sensor cable in meters. We used various cable lengths as needed.

D. Data Aggregation and Calculation Methodology

Primary Electricity Savings

For the purposes of analysis, we first aggregated the raw data over a daily basis.

- We summed energy data over each day (midnight to 11:59 PM) because the individual energy - measurements represented cumulative energy use during that minute. -
- We averaged temperature data over the course of the day because the individual temperature - measurements represented the temperature at that moment in time. -
- For door openings, we summed the number of door openings and total time of door opening over each day.

Operating conditions and usage patterns were not identical because of different numbers and durations of door openings, different placement within the room potentially affecting the ambient temperature experienced by each ULT, and other factors. To account for these factors, we performed a regression analysis to generate an equation for each ULT expressing the daily energy use in terms of the set-point, external temperature, and total door opening time. We then used the equations to calculate each ULT's expected energy use at a consistent set of operating conditions, thus allowing for fairer comparisons among ULTs. The set of operating conditions we chose for standardization represented typical conditions observed over the course of testing. Table II.6 contains the average operating conditions we used in the calculation methodology.

Table II.6: Standardized Operating Conditions

Quantity	Standard Condition
Setpoint (°C)*	-80
External Temperature (°C)	22
Door opening seconds per day	90

* Although we measured and averaged the ULT's internal temperature, we ultimately decided to conduct the regression analysis based on ULT set-point. Appendix B discusses the rationale for the regression variables we chose.

For a more detailed discussion of the regression analysis and outcome for each ULT, see Appendix B. Appendix B also presents regression results for each ULT in the demo.

Secondary Space Conditioning Impacts

In addition to the electricity use of the ULTs themselves, we estimated the secondary space conditioning impacts of each ULT. Secondary space conditioning impacts are the net change in space conditioning energy use due to reducing or increasing the electricity use (and therefore heat rejection) of the ULT. ULTs emit a substantial amount of waste heat, and during cooling season, this increases the amount of energy needed to cool the space using an air conditioner, chilled water loop, or other cooling source. However, this effect is counterbalanced during heating season, when heat given off by the ULTs offsets the amount of energy required to heat the space. We calculated the energy consumption adjusted for secondary space conditioning impacts using the following equation:

Adjusted UEC =

Percent of year in cooling mode × (UEC + extra air conditioning energy needed during cooling season to reject heat produced by the ULT)

+ Percent of year in heating mode × (UEC – heating energy avoided during heating season due to heat produced by the ULT)

+ Percent of year in neither heating nor cooling mode × UEC

Where: UEC is the unit energy consumption.

The extra air conditioning energy or the avoided heating energy can be calculated by dividing the heat produced by the ULT by the heating or cooling system efficiency (including the efficiency of the distribution system). For any space conditioning provided by fuel, instead of electricity, we used site-to-source energy ratios to put fuel and electricity on an equivalent basis (see notes on Table II.7).

Our estimates were based on information that representatives from each site provided, including descriptions of space-heating and cooling equipment and estimated durations of the heating and cooling seasons. Table II.7 describes the inputs and assumptions we used in calculating the secondary impacts on space-conditioning loads. Information provided by site representatives is noted in the table footnotes; if not otherwise attributed, inputs and assumptions are based on our internal estimates of typical system characteristics.

Table II.7: Space Conditioning Inputs and Assumptions

	Space Heating[a]	Space Cooling
CU Boulder (both sites)		
Description	Hot water heated by gas-fired steam boiler from a central plant[b]	Central water-cooled chillers
Season Duration[c]	68% of year	10% of year
Assumed Efficiency	80% (higher heating value) for central plant, with an additional 10% of distribution losses	0.43 kW per ton, including cooling tower and distribution system losses[d]
MSU		
Description	Hot water heated by gas-fired steam boiler from a central plant	Central water-cooled chillers supplemented by a 5-ton direct expansion unit[e]
Season Duration[f]	50% of year	50% of year
Assumed Efficiency	80% (higher heating value) for central plant, with an additional 10% of distribution losses	0.65 kW per ton, including cooling tower and distribution system losses

Table notes:

[a] Because heating was provided by fuel, we adjusted the heating efficiency to place it on an equivalent basis with electricity consumed at the site. We did this by using source energy, which is the raw fuel required to produce the heat or electricity. We first converted the heating fuel energy to source energy based on the type of fuel, then converted that source energy to the site electricity equivalent using the site-to-source ratio for electricity. Site-to-source energy rations were based on data from the EIA.[15]

[b] At CU Boulder, some heat is provided by combined heat and power (CHP), but we were unable to estimate the CHP plant's efficiency and so did not calculate this separately.

[c] Estimated by a campus mechanical engineer in facilities management.

[d] Estimated by a campus engineer with expertise in HVAC interaction issues.

[e] The site host reported that the supplementary direct expansion unit was operational throughout the year because of the high heat load of the ULTs. We assumed that the direct expansion unit runs for 80 percent of the time.

[f] Estimated by an energy analyst at the university.

E. Interviews

In addition to collecting quantitative data using instrumentation, we also interviewed several personnel from the demonstration sites. Details of the site interviews, including the interviewee, his or her role, and the date of the interview, are listed in Table II.8.

[15] "ENERGY STAR Portfolio Manager Technical Reference: Source Energy." July 2013. (This is the most recent revision of source-site ratios provided by EIA, which are updated every 3-5 years.) https://portfoliomanager.energystar.gov/pdf/reference/Source%20Energy.pdf?e17d-195c

Table II.8: Interview Details

Site	Interviewee (Role at the Site)	Date of Interview
CU Boulder – all labs	HVAC Control Shop Supervisor	6/11/2013
CU Boulder – iPhy	Research Assistant	6/12/2013
CU Boulder – iPhy	Manager of Operations/ Purchasing Manager	6/27/2013
MSU	Core Facilities Manager	8/30/2013

Topics covered in the interviews included, but were not limited to:

- Responsibility and methodology for purchasing ULTs in laboratory, and factors governing choice of new ULT purchase.
- Relative importance of energy efficiency in purchase decisions.
- Common problems experienced by ULTs.
- Details of the ULTs being monitored; specifically, how the ULTs are used, any issues encountered, etc.

III. Results

A. Energy Savings Results

Figure III.1 compares the average daily energy use of each of the three demonstration ULTs to each other and to the average energy use of the comparison ULTs. We adjusted the daily energy use of each ULT to a standard set of operating conditions, as discussed in section II.D, and present the results on a per-cubic foot basis to account for different sizes of ULTs. We present the electrical energy use side-by-side with energy use that incorporates secondary space conditioning impacts (see section II.D for a discussion of the assumptions we used in estimating these space conditioning impacts). We averaged the results from the comparison ULTs to provide a uniform baseline of comparison, as the comparison ULTs are meant to represent a “typical” product. Unadjusted data for all ULTs measured in the demonstration are presented in Appendix A.

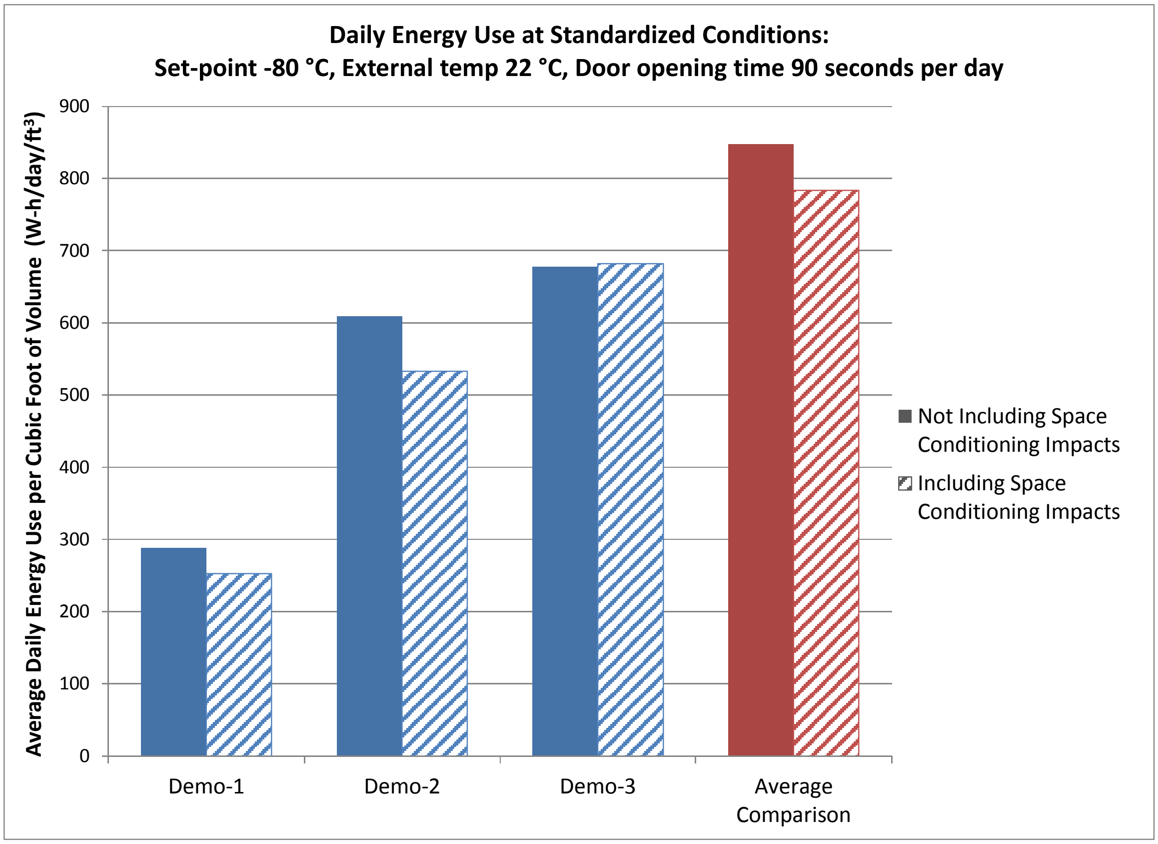


Figure III.1 Adjusted Daily Energy Consumption for Demo and Average Comparison ULTs with and without Space Conditioning Impacts*

*Note: For the ULTs at CU Boulder, accounting for the secondary impacts slightly reduced the energy savings benefit of the demo ULTs. This was in part due to the relatively long building heating season and relatively short building cooling season associated with this climate. In warmer climates, where most of a building’s time is spent in cooling mode and less time in heating mode, one would expect to see a net benefit for high-efficiency ULTs when considering secondary space conditioning impacts.

Table III.1 presents the energy savings that each demonstration ULT exhibited over the average comparison unit on the basis of electricity consumption (i.e., not including space conditioning impacts).

Table III.1: Energy Savings of Demo Units*

	Without Space Conditioning Impacts		With Space Conditioning Impacts	
Unit	Percent Energy Savings	Annualized Energy Savings (MWh)	Percent Energy Savings	Annualized Energy Savings (MWh)
Demo-1	66%	5.5	68%	5.3
Demo-2	28%	1.8	32%	1.8
Demo-3	20%	1.6	13%	1.0

*Energy savings are based on comparing each demo ULT to the average of the comparison ULTs, multiplying the energy use per cubic foot shown in Figure III.1 by the internal volume of each demo ULT.

B. Variation Among Comparison ULTs

Although we aggregated the comparison ULTs for purposes of comparison with the demo ULTs, we observed significant variation on energy use among the comparison ULTs. Figure III.2 compares the daily energy use per cubic foot of the four comparison ULTs, adjusted to the same set of standardized conditions as in Figure III.1.

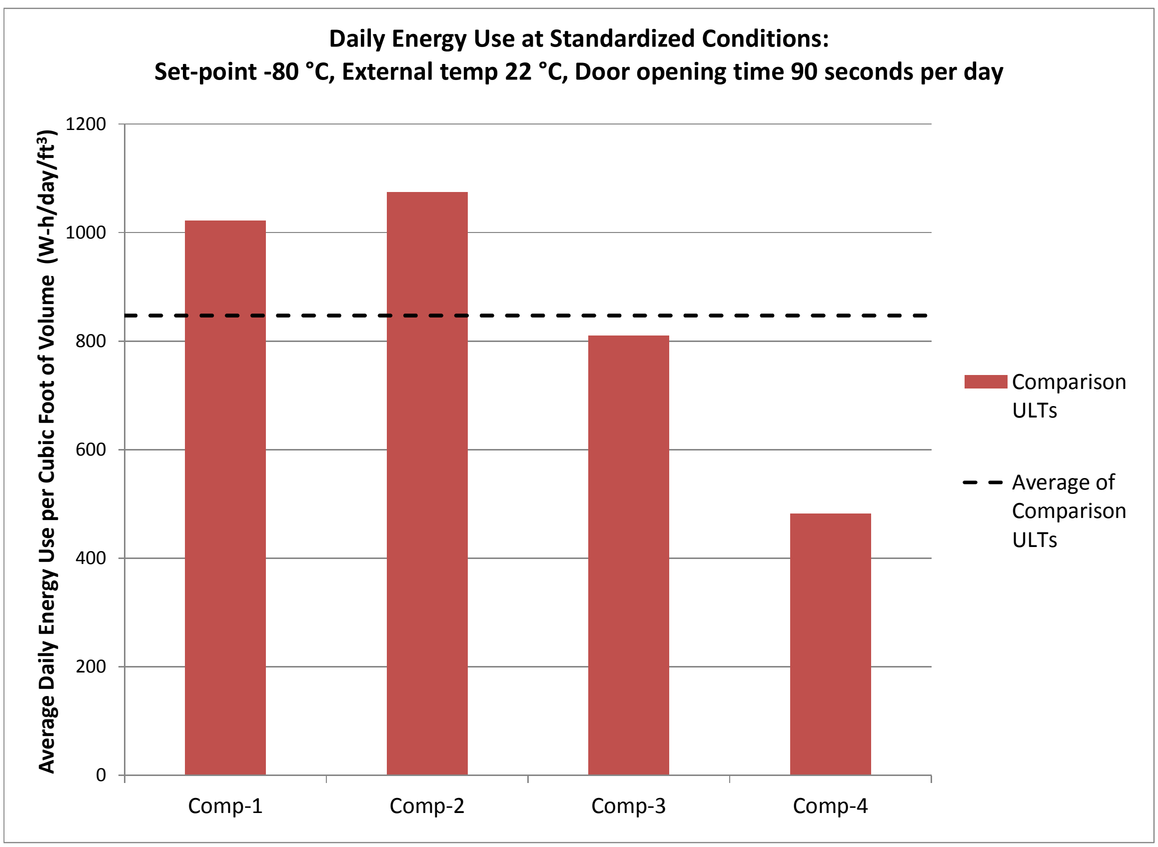


Figure III.2: Adjusted Daily Energy Consumption for Comparison ULTs without Space Conditioning Impacts

C. Power Factor Impacts

Power factor—the relationship between real and apparent energy—can be a significant consideration for equipment that incorporates certain components such as transformers and induction motors. A high power factor (i.e., close to 1) indicates that most of the electrical power supplied by the circuit is being used for real work, while a low power factor (i.e., less than ~0.85) means that much of the total power is being used for inductive current; that is, the electric current produces a magnetic field that is used to operate inductive devices (e.g., compressors).[16] See Appendix D for more details about power factor and how it is calculated.

Because compressors can represent the majority of a ULT's electricity use, power factor is particularly relevant to these products. Typically, utilities only meter the real power when billing customers for electricity. However, they may impose a surcharge that penalizes industrial customers who use low power factor devices.[17] Additionally, electrical circuit capacity is based on the total power. The use of low-power factor devices can cause circuit overloading if the user loads the circuit based on the real (metered) power.

Table III.2 lists the average power factor for each ULT in the demonstration. Figure III.3 compares the demo ULTs to the comparison ULTs in terms of their electricity use, once power factor is accounted for. We found that two of the ULTs exhibited relatively low power factor (the second demo unit and the fourth comparison unit)—a finding that should be of interest to industrial and laboratory customers.

Table III.2: Power Factor for ULTs in the Demonstration

Unit Descriptor	Power Factor
Demo-1	0.96
Demo-2	0.67
Demo-3	0.98
Comp-1	0.99
Comp-2	0.90
Comp-3	0.91
Comp-4	0.60

[16] Capehart, B., Turner, W., and Kennedy, W. Guide to Energy Management: 7th Edition. The Fairmont Press: 2012.
[17] Ibid.

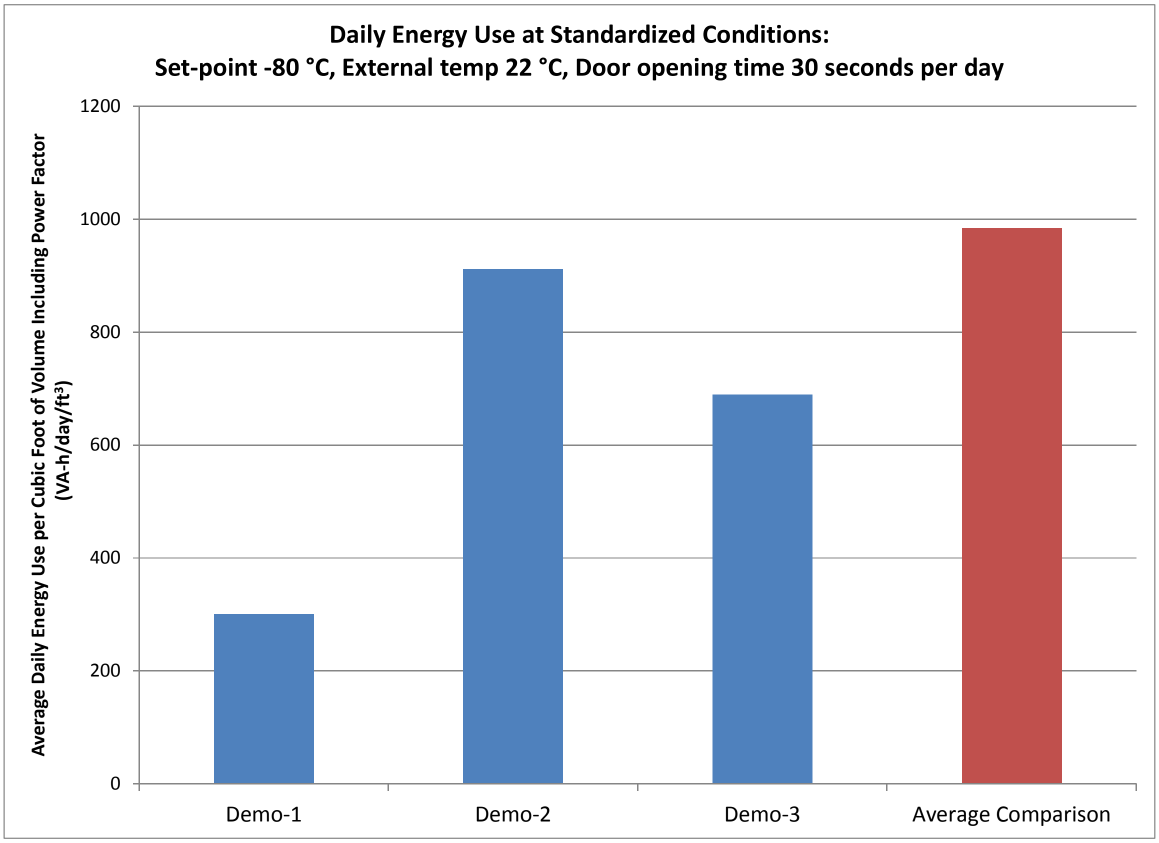


Figure III.3: Adjusted Electricity Consumption for Demo and Average Comparison ULTs, Accounting for Power Factor*

*Not including secondary space conditioning impacts.

D. Internal Temperature v. Set-Point

As discussed in section II.C, we independently measured each unit's internal temperature using a calibrated type-T thermocouple (TC). We observed several cases where the measured temperature differed significantly from the set-point, without a clear cause. Table III.3 shows the average daily temperature difference from the set-point and the maximum daily temperature difference from the set-point for each ULT (excluding days during which the ULT was open for a long period of time; i.e., more than 5 minutes).

Table III.3: Observed Differences between Set-Point and Measured Temperature

Unit	Average Deviation from Set Point (C)*	Maximum Deviation from Set Point (C)*
Demo-1	7.6 (warmer)	15.8 (warmer)
Demo-2	0.2 (warmer)	8.4 (colder)
Demo-3	1.4 (colder)	2.7 (colder)
Comp-1	6.5 (warmer)	13.7 (warmer)
Comp-2	3.5 (colder)	8.4 (colder)
Comp-3	2.1 (warmer)	2.6 (warmer)
Comp-4	Inconclusive**	

*Average and maximum values represent daily averages. "Warmer" indicates the measured temperature was warmer than the set-point, -
while "colder" indicates the measured temperature was colder than the set-point. Data points were excluded if they occurred during a -
day when the set-point was changed, a day when the door was open for more than 5 minutes, or a day on which we believed there to be -
a measurement failure (e.g., if the TC was accidentally displaced into an ambient environment). -
**In this ULT, the TC was displaced for a significant proportion of the measurement period and so we could not draw conclusions about -
measured internal temperature. See unadjusted data in Appendix A, Figure A.13. -

These figures are based on internal temperature measurements taken at one or two locations within each ULT and are not intended to represent a "true" or average internal temperature of the ULT. A determination of a true average internal temperature would require a "map" of temperature measurement devices, which was not feasible in the context of a field study. Due to space constraints, we were not able to place the TC in the same place in each ULT we measured; Figure C.5 in Appendix C illustrates the relative elevation of our TC within each ULT.

Figure III.4 compares the ULTs in the study with the set-point of each ULT adjusted according to the average deviation from the set-point shown in Table III.3, so that the average internal temperature would be expected to equal -80 °C. For example, we calculated ULT Comp-1's energy use at a -86.5 °C set-point, assuming that the average internal temperature is 6.5 °C warmer than the set-point and would therefore be -80 °C at this condition. Likewise, we calculated ULT Demo-3's energy use at a -78.6 °C set-point, assuming that the average internal temperature is 1.4 °C colder than the set-point and would therefore be -80 °C at this condition. The results of this exercise suggest that the differences we observed between set-point and measured temperature do not ultimately change the finding that the demonstration ULTs achieve energy savings over the comparison ULTs.

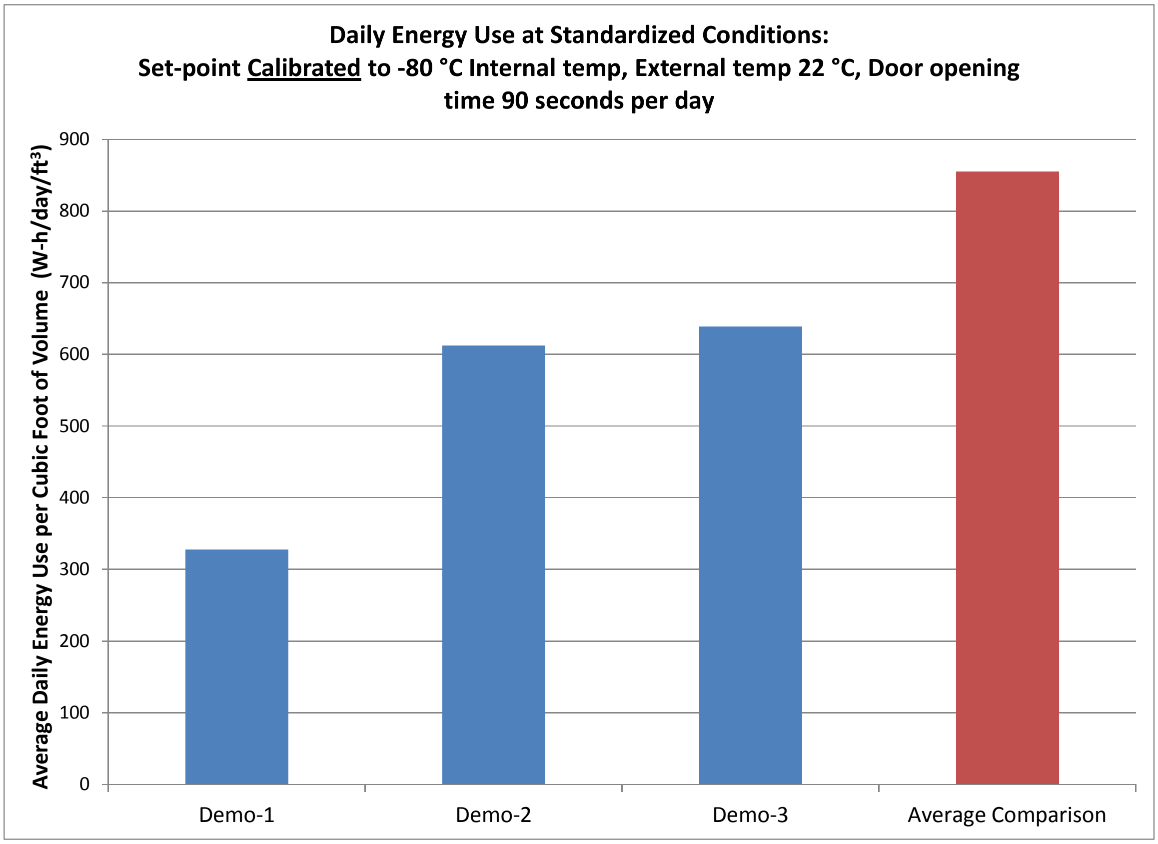


Figure III.4: Adjusted Electricity Consumption for Demo and Average Comparison ULTs, Calibrating Set-Point to Internal Temperature of -80 °C*

*Not including secondary space conditioning impacts.

The average daily data do not reflect changes in internal temperature on a minute-to-minute or hour-to-hour basis. For most of the ULTs in the study, the measured internal temperature cycled up and down slightly over time as the compressors in the cascaded refrigeration system turned on and off to maintain the set-point. One exception was the Demo-1 ULT, which utilized a Stirling cooler that did not cycle. Figure III.5 compares the measured internal temperature for a cascaded-cycle ULT and a Stirling-cycle ULT over the course of a day.

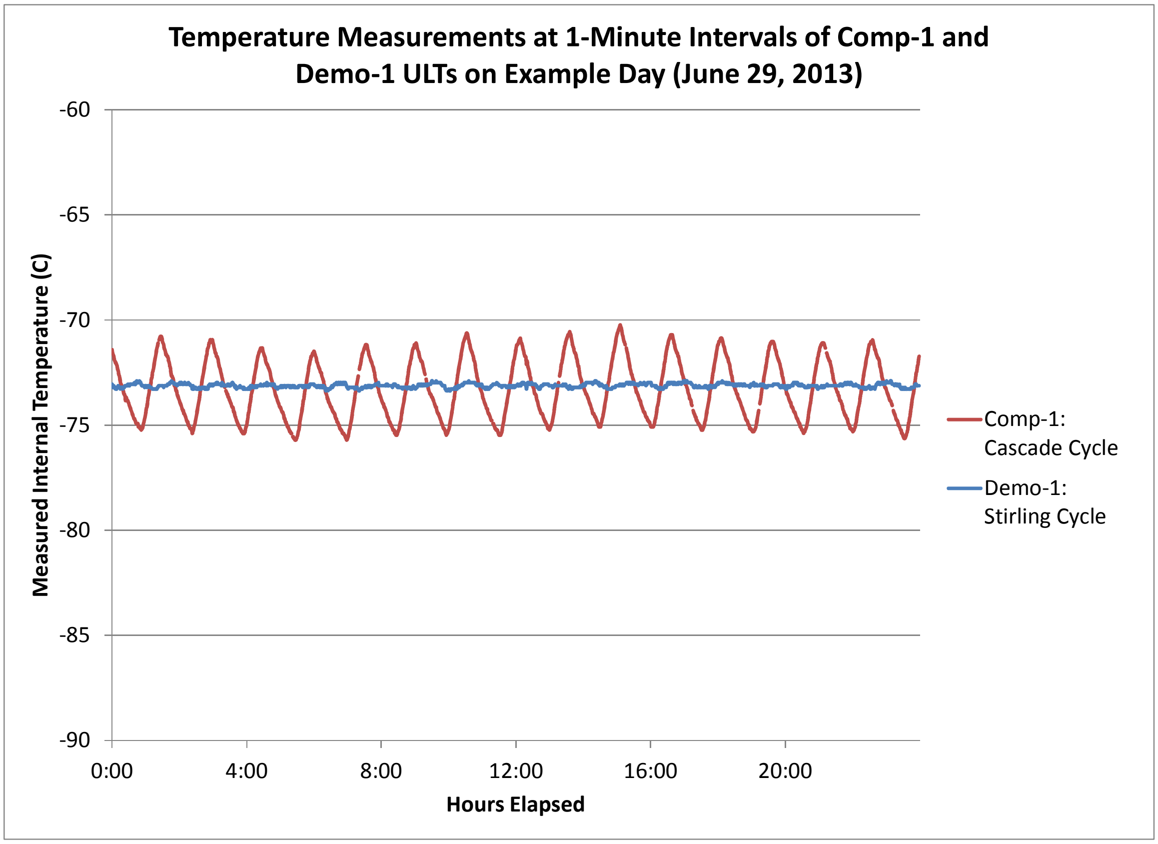


Figure III.5: Comparing Internal Temperature of Cascade and Stirling Cycle ULTs

E. Interview Findings

Interviews held at each site helped shed light on some qualitative factors that could affect market uptake of high-efficiency ULTs, including purchasing methods, operational issues, and feedback on the particular ULTs in the study. Section II.E includes a list of interviewees and their roles.

Interviewees generally noted that energy efficiency was a factor in the lab's ULT purchase decisions, though not the only one or necessarily the most important. One said that most labs would incorporate efficiency into their decision and would potentially pay up to $1,000 more for a high-efficiency ULT. Another said that the purchasing department solicited bids and usually chose the lowest one, but was starting to look at total cost of ownership. Lab-specific needs can also play a role: one interviewee noted that their new demo ULT was more space-efficient due to the unusual size and shape of the racks needed to store their samples. The interviewee added that their research is government-funded and that they would have to follow government procurement guidelines.[18]

[18] 45 CFR 74.44(a)(3)(vi) states that Federal research grant recipients, when soliciting goods and services as part of their research, must show a "Preference, to the extent practicable and economically feasible, for products and services that

Both interviewees who were directly involved in purchasing noted that vendor relationships were very important, with labs preferring to work with certain sales representatives or vendors with whom they had a long history. The implication was that labs would consider choosing a high-efficiency model but may be more comfortable with a vendor or manufacturer representative with whom they had an existing, trusted relationship.

Common ULT problems that interviewees identified were most often related to operational issues and maintenance – factors that could affect both high-efficiency and typical products equally. These problems included dirty air filters, frost buildup, or users leaving the door open, along with electrical issues like power outages. One person involved in maintenance said that electronics are a common failure point, implying that more electronically-complex ULTs may be more prone to failure. Two respondents noted ULT compressors were a common failure point, and since replacing the compressor is a substantial portion of the freezer's cost, the ULT is typically replaced if the compressor fails. Average lifetimes and replacement rates reported by interviewees varied; one noted that ULTs may get replaced after 6 to 8 years if repairs become more expensive than replacement, while another estimated a replacement rate of 10 percent of their ULTs per year, implying an average 10-year lifetime. Respondents said that ULTs can have a lifetime of 20 to 25 years with preventative maintenance and repairs.

Users of the ULTs being studied in the demonstration did not report that they experienced significant problems with the new high-efficiency ULTs. (Although some of the interviews took place towards the beginning of the demonstration, we remained in contact with users at the demonstration sites and asked them to report any problems they encountered with the ULTs.) Some encountered usability issues. For one ULT, users had difficulty engaging the door latch and in one instance this led to the ULT being left ajar for an extended period of time. For another, users were unable to open the door immediately after closing it due to suction created by the rapidly cooling air (most ULTs have an automatic air vent to equalize pressure; this ULT had a manual pressure port intended to eliminate air infiltration when closed). These issues were addressed primarily by educating the users. Two interviewees who had purchased their demo ULTs said that they would consider purchasing that model again. (The third demo ULT was on loan from the manufacturer and the demonstration site operator did not intend to purchase it at the time of this report writing due to its high cost.)

F. Economic Analysis

As discussed in the interview findings, first cost is a significant factor for purchasers of ULTs. Generally, the demo ULTs were more expensive initially than average ULTs with similar qualities (internal volume, configuration, etc.) We conducted a simple payback analysis to compare the first-cost premium of the demo ULTs to their electricity cost savings over time, not including secondary space-conditioning effects (which would have required a full fuel cost analysis due to the different fuels used in space heating) or power factor (which is not always accounted for in utility billing). We obtained list prices for the demo ULTs either directly from manufacturers or from manufacturer and distributor websites. To estimate the price premium associated with the demo ULTs, we first collected list price data for a sample of other ULTs available on the market (including, but not limited to, the

---

conserve natural resources and protect the environment and are energy efficient." However, this provision is neither well known nor consistently enforced.

comparison ULTs measured in the study) from manufacturer and distributor websites. We then plotted the data and developed a linear equation relating list price to volume for this sample of ULTs. In this way, we could compare the demo ULTs to a "typical" ULT of the same volume to avoid biasing the comparison towards smaller or larger ULTs. Figure III.6 shows list prices for the demo and other ULTs, including the trend-line relating list price to volume.

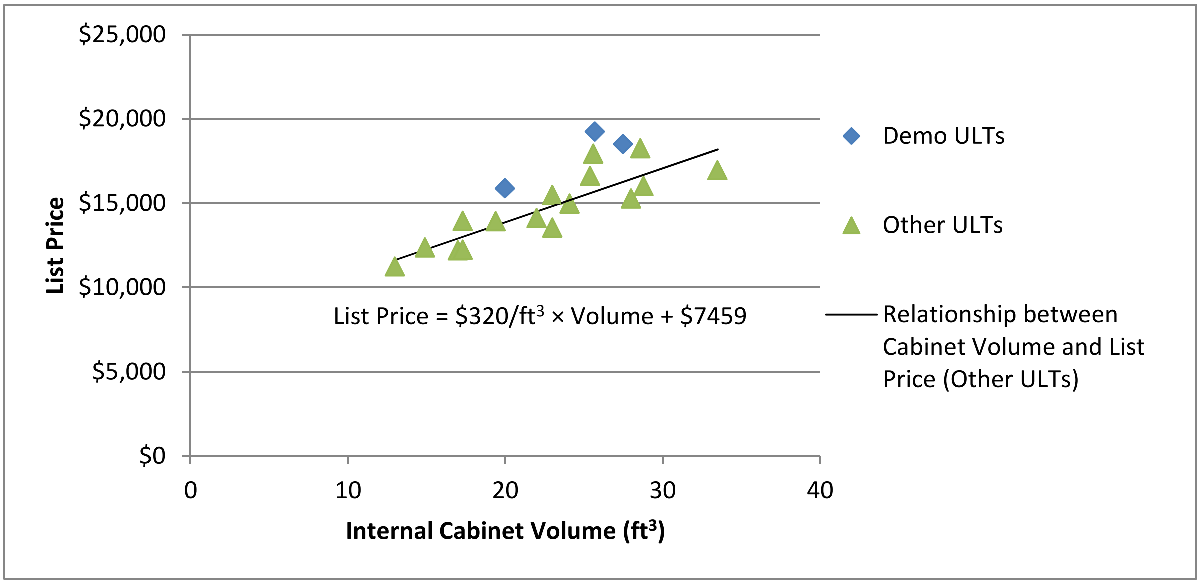


Figure III.6: List Price Data for Demo Models and Other ULTs*

* We obtained list price data from manufacturers and through manufacturer and distributor websites, accessed March 2014. "Other ULTs" includes comparison ULTs in the study as well as other, similar models.

Purchasers and users of ULTs noted in interviews that ULTs are typically sold through distribution networks and distributors often offer discounts, either on the price of the ULT itself or on accessories, such as sample storage racks, or shipping. For this reason, the difference in list price may not be an accurate representation of the actual cost difference between the demo ULTs and other ULTs. Therefore, we included a simple-payback-period analysis for a full-list-price scenario and a scenario in which the demo ULT and another typical ULT of the same volume are each discounted by 30 percent. However, available discounts will vary depending on many factors, so this scenario does not necessarily represent what a given purchaser can expect to pay for a given ULT.

In determining electricity savings of each demo ULT compared to a typical ULT, we applied the daily energy use per cubic foot results in Figure III.1 and multiplied by the volume of the demo ULT. We also considered the effect of electricity prices on the payback period, using EIA data on commercial electricity rates for January 2014, the most recent dataset available at the time of this report.[19] We calculated the simple payback at three different commercial electricity rates: the U.S. average rate and the highest and lowest rates in the 48

[19] U.S. Energy Information Administration: Electric Power Monthly with Data for January 2014, published March 2014. http://www.eia.gov/electricity/monthly/current_year/march2014.pdf

contiguous United States in January 2014. We did not account for other lifetime costs such as maintenance costs, as we did not have any evidence on which to base estimates of these values.

Table III.4 presents the results of the simple payback analysis for each demo ULT under the two first-cost scenarios (list price and discounted) and the three electricity rates. The simple payback period represents the time it would take a user to recoup the first cost difference between a demo ULT and a typical ULT.

Table III.4: Simple Payback Analysis for Demo ULTs

ULT Model	Average Daily Energy Savings of Demo ULT (kWh)[a]	First Cost Premium ($)[b]	Simple Payback Period (years)		
			High Elec. Rate ($0.1637/kWh)[c]	U.S. Average Rate ($0.1034/kWh)	Low Elec. Rate ($0.0726/kWh)
List Price Scenario					
Demo-1	15	$2,200	2.5	3.9	5.5
Demo-2	4.8	$2,000	7.0	11	16
Demo-3	4.4	$3,500	13	21	30
30% Discount Scenario[d]					
Demo-1	15	$1,600	1.8	2.8	4.0
Demo-2	4.8	$1,400	4.9	7.7	11
Demo-3	4.4	$2,500	9.5	15	21

Table notes: -
[a] Calculated by finding the difference in energy use per cubic foot between each demo ULT and the average of the comparison ULTs, as - shown in Figure III.1, and multiplying by the internal volume in cubic feet of the demo ULT. -
[b] Based on list price data for demo ULTs and linear formula for price per cubic foot of other ULTs. Data in Figure III.6. Rounded to nearest $100.
[c] Source: Commercial electricity rates in January 2014, published by EIA.[20] High and low rates represent the highest and lowest state commercial electricity rates in the 48 contiguous United States.
[d] Assumes that the same percent discount would be available on both the demo ULTs and average ULTs.

IV. Summary Findings and Recommendations

A. Overall Technology Assessment at Demonstration Facilities

The results of the demonstration support the hypothesis that the demo ULTs can achieve energy savings under field conditions. Over the course of the study, the demo ULTs used between 20 percent and 66 percent less electricity than the average of the comparison ULTs, on a per-cubic foot basis, and when energy use data were adjusted to the same operating conditions. On an annualized basis, users of the demo ULTs would expect to save between 1.6 and 5.5 MWh over the average comparison ULT, with an associated cost savings of between $170 and $570 per year.[21] (This figure does not include secondary space conditioning impacts, which are expected to vary by location.)

[20] Ibid. -
[21] Assuming an electricity price of $0.1034/kWh, the average US electricity rate in the 12-month period ending January - 2014, according to EIA. -

A simple payback analysis, discussed in section III.F, suggests that users can recoup the first-cost investment in a demo ULT within 10 years, for certain available discounts and electric rates, and assuming that the energy use of the comparison ULTs is representative of a typical ULT on the market. The analysis showed unit Demo-1 recouping its first-cost premium within six years, even under the lowest electricity rate assumption. In interviews, users estimated freezer lifetimes of between six and 25 years, depending on whether the equipment is maintained and repaired as needed (see section III.E for interview details). (Actual payback period depends on circumstances such as first cost differences, maintenance and repair costs, utility incentives, and electricity prices over the life of the ULT.)

Items we were not able to address in this demonstration include long-term reliability, whole-cabinet temperature performance, and evaluation of a wider range of ULTs.

- Reliability: Over the course of the demonstration, we did not observe significant adverse functional differences among the ULTs included in the study, and users of the ULTs did not report any major issues in using either the demo ULTs or comparison ULTs. However, given the relatively short demonstration period, we were not able to draw any conclusions about the long-term reliability of the products.
- Whole-cabinet temperature performance: We compared a single internal temperature measurement point to each ULT's set-point, with results in section III.D. However, we were not able to draw firm conclusions about the temperature performance of the ULTs because gathering the necessary data to conduct a performance study was not feasible within the scope of the project.
- Range of products covered: This report covered a very small sample size of products, with the goal of informing readers of the opportunity presented by high-efficiency ULTs rather than providing definitive figures for ULT energy use. The energy savings observed in this study may not be experienced by all users due to variation among ULTs and operating conditions. Additionally, the demo ULTs covered in this study are not necessarily the only "high-efficiency" ULTs on the market and the comparison ULTs may not represent a truly "typical" ULT.

B. Recommendations

Recommendations for ULT Purchasers and Purchasing Organizations

Many users of ULTs experience barriers to purchasing high-efficiency equipment at a cost premium, when the purchaser of the ULT does not pay the electricity cost and thus would not see the energy cost savings from a more-efficient product. This is often the case for universities, for example, where ULTs are purchased by individual researchers, but energy costs are borne by the university as a whole. Given the results of this demo, which suggest favorable payback periods for high-efficiency products, we recommend that organizations in this situation implement formal programs that provide incentives, commensurate with the expected savings, to encourage the purchase of efficient products. One example is CU Boulder's Green Labs program, where the university "pays forward" the operating cost savings in the form of rebates to researchers who purchase efficient laboratory equipment, based on the expected 3-year electricity cost savings.[22] Additionally, some state and municipal utilities offer custom rebates and incentives for installing energy-saving equipment.[23] If relevant, we recommend that customers apply for utility rebates to offset the first-cost of high-efficiency ULTs.

[22] Discussion with Dr. Kathryn Ramirez-Aguilar, Green Labs Coordinator at CU Boulder. -
[23] For example: http://www.pge.com/en/mybusiness/save/rebates/ief/index.page?WT.mc_id=Vanity_cr -

Interviewees cited the importance of existing vendor relationships as a factor that sometimes prevents purchasers from procuring new, more efficient products. We recommend that purchasers communicate to suppliers that energy efficiency is a factor in purchasing decisions, and demonstrate market demand for high-efficiency equipment by asking for such equipment from their existing vendors and distributors. Customers may also need to develop new vendor relationships to buy more efficient products, as long as warranty terms are acceptable.

Recommendations for Manufacturers

We recommend that manufacturers continue to develop and promote high-efficiency products; however, they should not compromise reliability in order to do so, as reliability is an extremely important factor to ULT users. For new products that customers are unfamiliar with, additional marketing and reliability data may be needed to promote the products. We also recommend that manufacturers help support existing efforts being undertaken by ENERGY STAR®, the Better Buildings Alliance, the International Institute for Sustainable Labs, and other programs.

Recommendations for DOE

DOE is uniquely positioned to aid in deployment of high-efficiency ULTs through the Better Buildings Alliance. Recommendations for promoting adoption of high-efficiency products include:

- Standardization: Promote the use of the standardized rating method that DOE and EPA recently developed through the ENERGY STAR program. When used by manufacturers as the basis for rating their products, the rating method can make it easier for potential purchasers of ULTs to identify high-efficiency products.
- Education: Help purchasers overcome first-cost barriers by educating purchasers on life-cycle cost.
- Guidelines: Publicize government procurement guidelines that require Federal Agencies and recipients of government-funded research grants to procure "products…[that] are energy efficient" where economically feasible, and expand these guidelines to other sources of government funding. Require ENERGY STAR ULTs when available.

V. References

Capehart, B., Turner, W., and Kennedy, W. Guide to Energy Management: 7th Edition. The Fairmont Press: 2012.

Gumapas, Leo Angelo & Simons, Glenn (2013), “Factors affecting the performance, energy consumption, and carbon footprint for ultra low temperature freezers: case study at the National Institutes of Health.” World Review of Science, Technology and Sustainable Development, Vol.10, No.1/2/3, pp.129 – 141.

International Institute for Sustainable Laboratories: Annual Conference. <http://i2sl.org/conference/index.html> Last accessed May 9, 2014.

Labs for the 21st Century: Energy Efficient Laboratory Wiki. <http://labs21.lbl.gov/wiki/equipment/index.php/Energy_Efficient_Laboratory_Equipment_Wiki> Last accessed May 9, 2014.

Lane, Neill (2013). “Ultra-Low Temperature Free-Piston Stirling Engine Freezers.” <http://www.stirlingultracold.com/lib/sitefiles/whitepaper/10354-GLOBAL-whitepaper-apr13-vF-web.pdf> Last accessed May 9, 2014.

Michigan State University: Pharmacology and Toxicology. <http://www.phmtox.msu.edu/research/index.html.htm> Last accessed May 9, 2014.

UC Davis Sustainable 2nd Century: Take Action: Store Smart. <http://sustainability.ucdavis.edu/action/conserve_energy/store_smart.html> Last accessed May 9, 2014.

UCSB Sustainability: Laboratory Resources, Advocates, and Teamwork for Sustainability (LabRATS). <http://www.sustainability.ucsb.edu/labrats/> Last accessed May 9, 2014.

University of Colorado at Boulder: Integrative Physiology. <http://www.colorado.edu/intphys/about/index.html> Last accessed May 9, 2014.

University of Colorado at Boulder: Molecular, Cellular, and Developmental Biology. <http://mcdb.colorado.edu/index.shtml> Last accessed May 9, 2014.

U.S. Department of Energy Office of Energy Efficiency and Renewable Energy: About the Better Buildings Alliance. < http://www4.eere.energy.gov/alliance/about> Last accessed May 9, 2014.

U.S. Energy Information Administration. “Analysis and representation of Miscellaneous Electric Loads in NEMS.” Prepared for U.S. Energy Information Administration by Navigant Consulting, Inc. and SAIC, December 2013. <http://www.eia.gov/analysis/studies/demand/miscelectric/pdf/miscelectric.pdf> Last accessed May 9, 2014.

U.S. Energy Information Administration. “Electric Power Monthly with Data for January 2014.” Published March 2014. <http://www.eia.gov/electricity/monthly/current_year/march2014.pdf> Last accessed May 9, 2014.

U.S. Environmental Protection Agency. “ENERGY STAR Portfolio Manager Technical Reference: Source Energy.” <https://portfoliomanager.energystar.gov/pdf/reference/Source%20Energy.pdf?e17d-195c> Last accessed May 9, 2014.

Appendix A. Unadjusted Results and Observations

The following exhibits summarize unadjusted empirical data for each unit. We collected data for energy use and temperature at one-minute intervals, and collected door opening data each time the door was opened or closed. As discussed in section II.D, we aggregated the raw data so as to report the total energy use, average internal and external temperature, and number and total time of door openings for each ULT over the course of a day (12:00 AM to 11:59 PM). The daily results are shown in the charts below, with temperature and energy use data reported on one graph and the door opening data reported on a subsequent graph. Besides the temperature, energy, and door opening data that we gathered, other data were available at certain sites (e.g., one laboratory had an independent monitoring system that recorded the room temperature). We present and label these data on each graph when they are available. We numbered certain observations on each graph, and discuss each numbered observation below the graph.

Unit Demo-1: Demonstration ULT #1 at CU Boulder – MCDB Lab

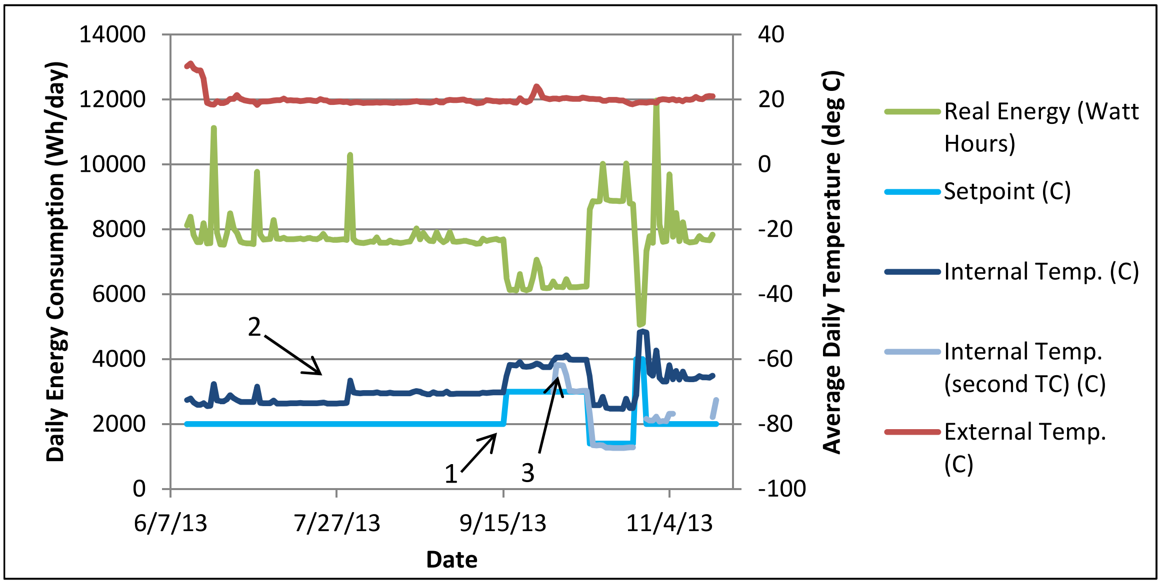


Figure A.1: Daily Energy and Temperature Data: Unit Demo-1

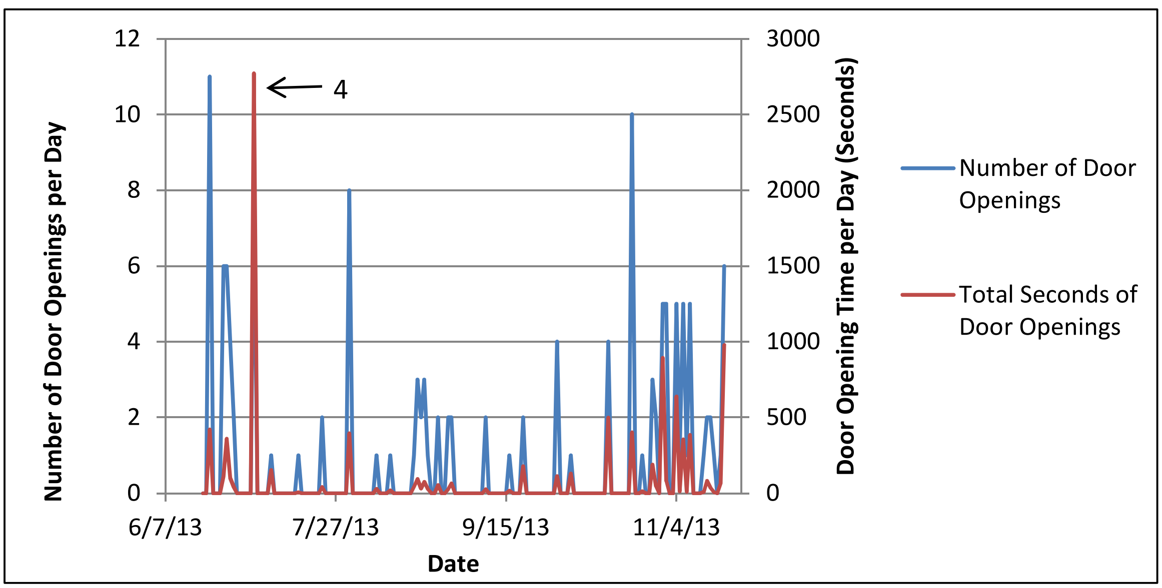


Figure A.2: Daily Door Opening Data: Unit Demo-1

Notes:

1. The user changed the set-point several times throughout the course of measurement to better evaluate the effect of set-point on energy use. Researchers in the lab used this ULT for temporary storage. During times when the ULT was not being used to store samples, the user sometimes changed the set-point to temperatures outside the usual storage range (e.g., -60 °C) to observe the effect on the energy use.
2. The internal temperature measurement for this ULT was consistently warmer than the set-point, and we observed several shifts in measured internal temperature over the course of the demonstration with no corresponding change in set-point.
3. For part of the measurement period, the user placed a second TC (marked as "second TC" in the Figure A.1 legend above) in this ULT. (This second TC was the TC we initially placed in the neighboring "baseline" ULT; see Figure II.2 in section II.B for a schematic of ULT placement in the room.) The user initially placed the second TC

next to the first TC in the top of the ULT for several days—9/30/13 to 10/4/13—to confirm the temperature readings from the original TC. (This ULT had three compartments—in the top, middle, and bottom. See Figure C.5 in Appendix C for a diagram of initial TC placement within each ULT.) In this position, the second TC measured a temperature similar to the first TC. Then, the user moved the second TC to the bottom of the ULT, where it measured a temperature closer to the ULT set-point. For one day towards the end of the measurement period—11/17/13—the user moved the second TC to the middle compartment of the ULT, where it also measured a temperature close to the ULT set-point. These temperature checks suggest that the "warm" zone was confined to the top compartment of the ULT.

4. At one point during the monitoring period, a user did not fully engage the door latch after accessing the ULT and the door remained partially open for an extended amount of time. The site host communicated to the ULT's manufacturer that the latch was difficult to close.

Unit Comp-1: Comparison ULT #1 at CU Boulder – MCDB Lab

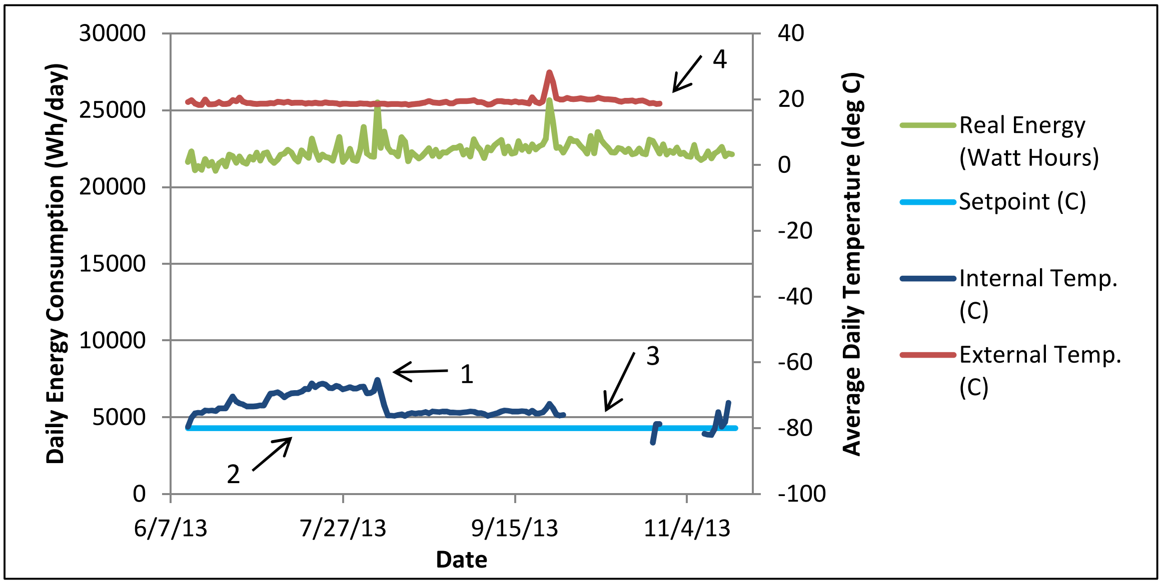


Figure A.3: Daily Energy and Temperature Data: Unit Comp-1

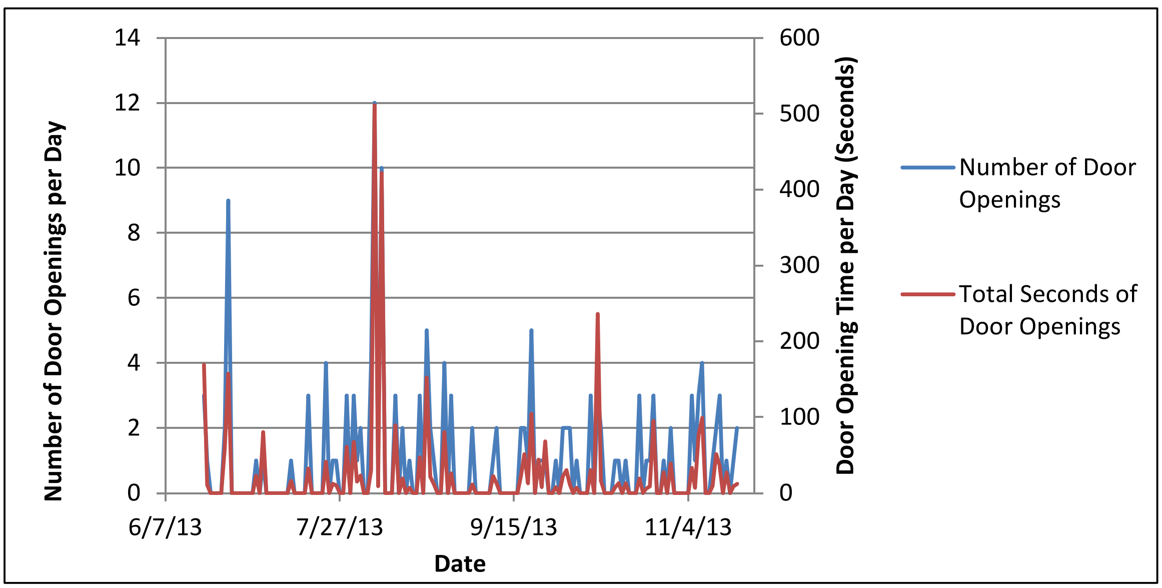


Figure A.4: Daily Door Opening Data: Unit Comp-1

Notes:

1. We do not know the reason for this sudden drop in daily average measured temperature.
2. The user maintained the set-point at -80 °C because the researcher who owned the ULT did not give permission to change the set-point, so we were unable to observe the effect of set-point change on energy use.
3. Gaps in internal temperature data correspond to the periods when we moved the thermocouple from this ULT to the neighboring Demo-1 ULT (see discussion above under Demo-1).
4. The external temperature sensor failed towards the end of the measurement period. We did not replace it because we already had enough data to correlate external temperature with energy use.

Unit Demo-2: Demonstration ULT #2 at CU Boulder – iPhy Lab

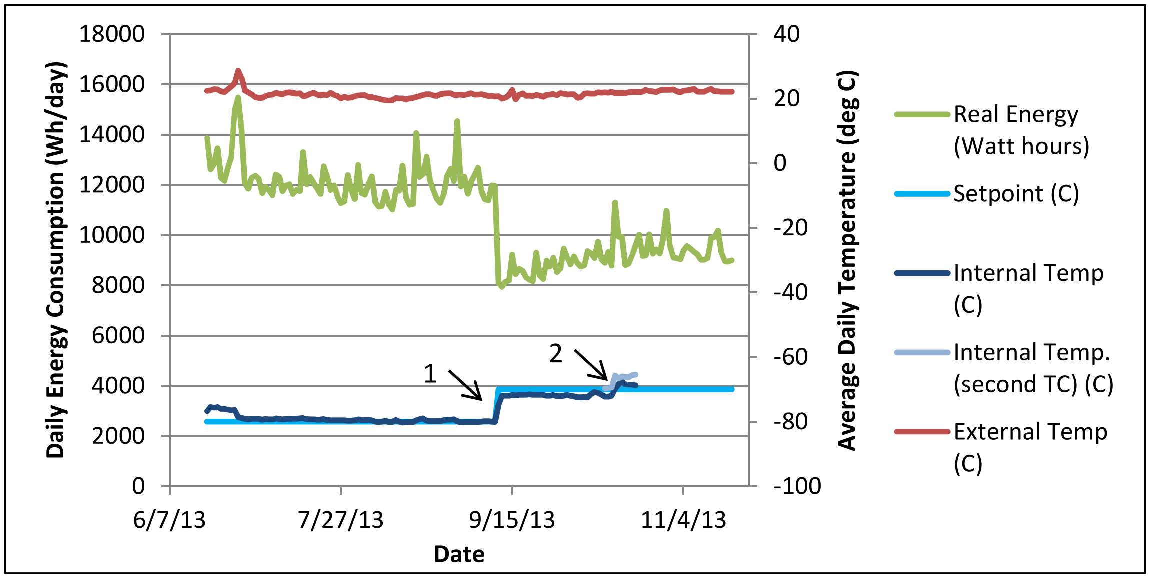


Figure A.5: Daily Energy and Temperature Data: Unit Demo-2

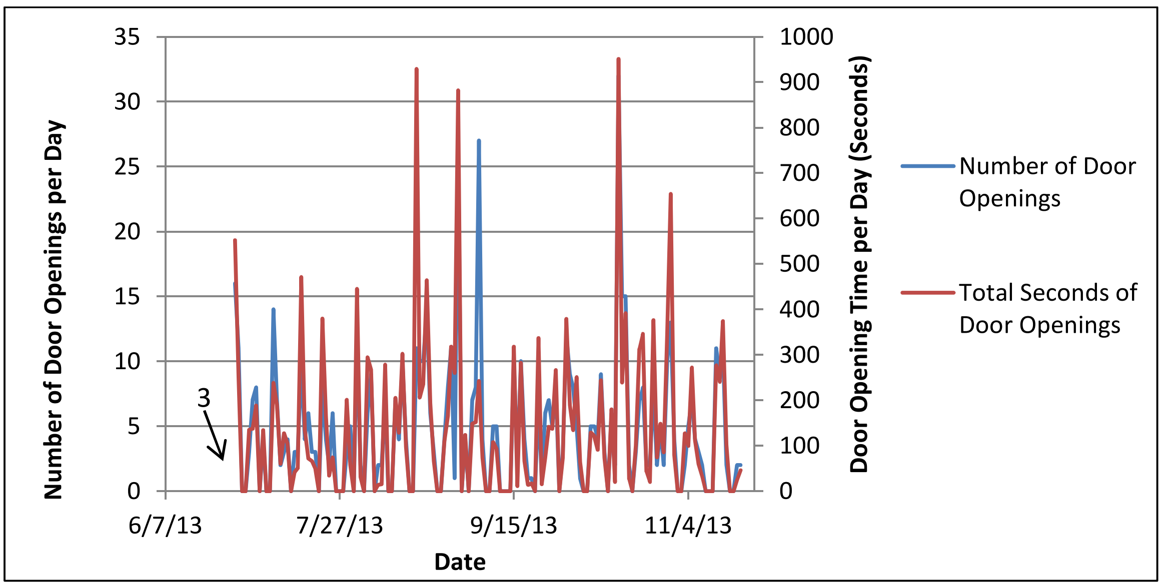


Figure A.6: Daily Door Opening Data: Unit Demo-2

Notes:

1. The user changed the set-point from -80 °C to -70 °C partway through the measurement period to observe the effect of this change on the ULT's energy use.
2. For a short time, the user placed a second TC (marked as "second TC" in the legend) in the ULT. (This second TC was the TC we initially placed in the Comp-2 ULT; see Figure II.3 in section II.B for a schematic of ULT placement in the room.) The user initially placed the second TC next to the first TC in the top of the ULT for several days—10/11/13 to 10/15/13—to confirm the temperature readings from the first TC. Then, the user moved the second TC to the bottom of the ULT for several days—10/16/13 to 10/21/13. The TCs measured similar temperatures in both places.
3. After we initially set up the instrumentation, the door opening logger's adhesive detached from the door, causing the loss of the first two weeks of door-opening data. The user observed this and replaced the sensor.

Unit Comp-2: Comparison ULT #2 at CU Boulder – iPhy Lab

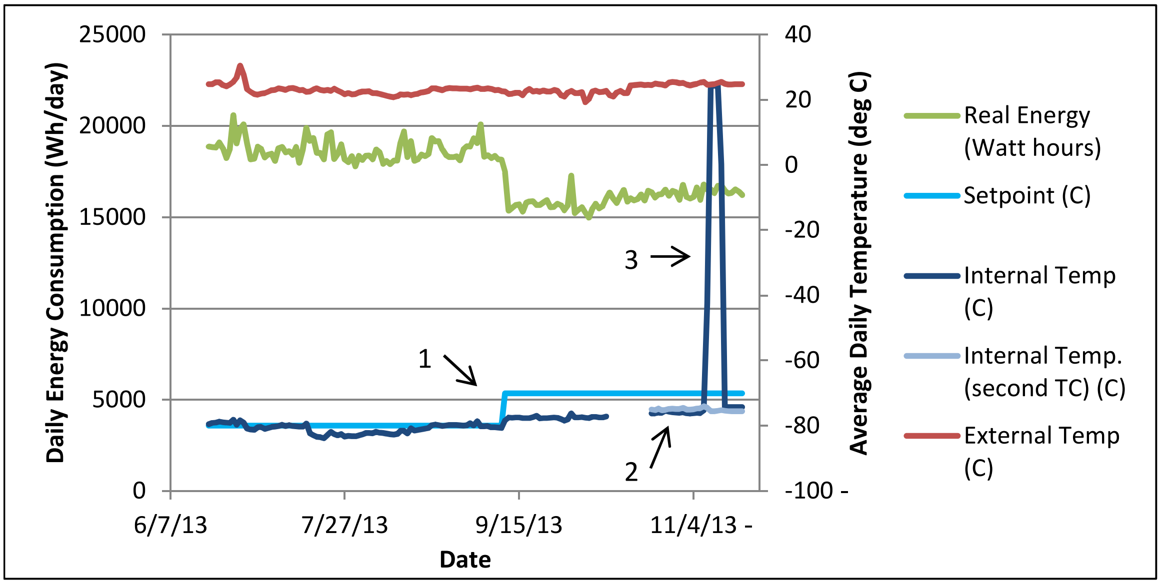


Figure A.7: Daily Energy and Temperature Data: Unit Comp-2

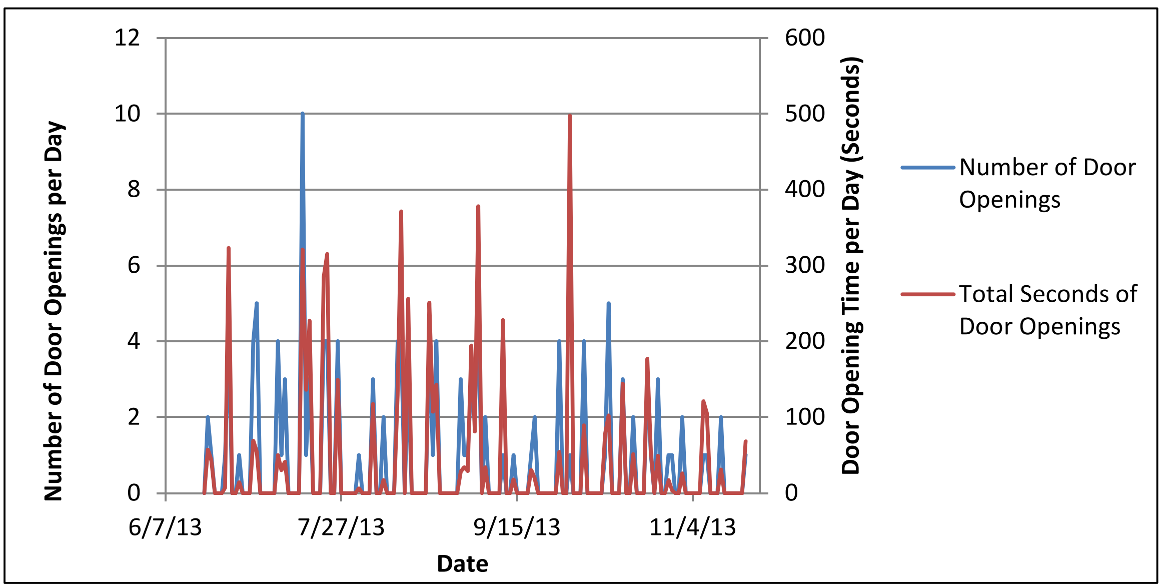


Figure A.8: Daily Door Opening Data: Unit Comp-2

1. The user changed the set-point from -80 °C to -70 °C partway through the measurement period to observe the effect on energy use; however, this did not appear to cause a commensurate change in the measured internal temperature. We do not know why this occurred.
2. From 10/11/13 to 10/21/13, the user had placed the TC from this ULT into the adjacent ULT (the Demo-2 ULT; see Figure A.5 above). On 10/22/13 through the end of the measurement period, the user moved both TCs into this ULT—the TC initially in this ULT in the bottom and the second TC in the top. The TCs measured similar temperatures.
3. The initial TC fell out of the ULT for a short period of time. We noticed this in our real-time review of the data and notified the site host, who repositioned it in the cabinet.

Unit Demo-3: Demonstration ULT #3 at Michigan State University

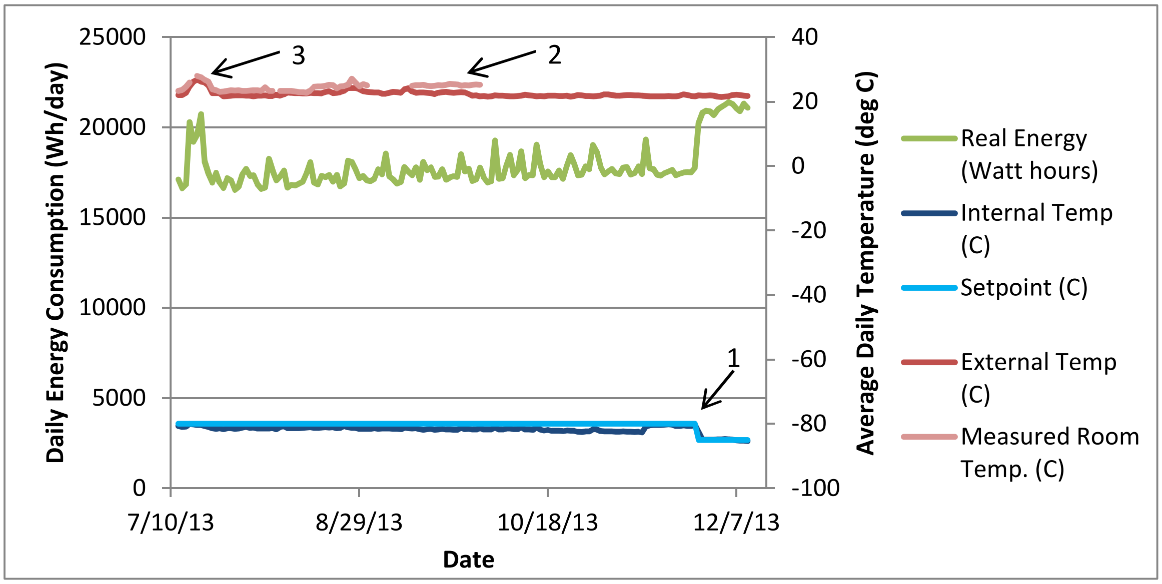


Figure A.9: Daily Energy and Temperature Data: Unit Demo-3

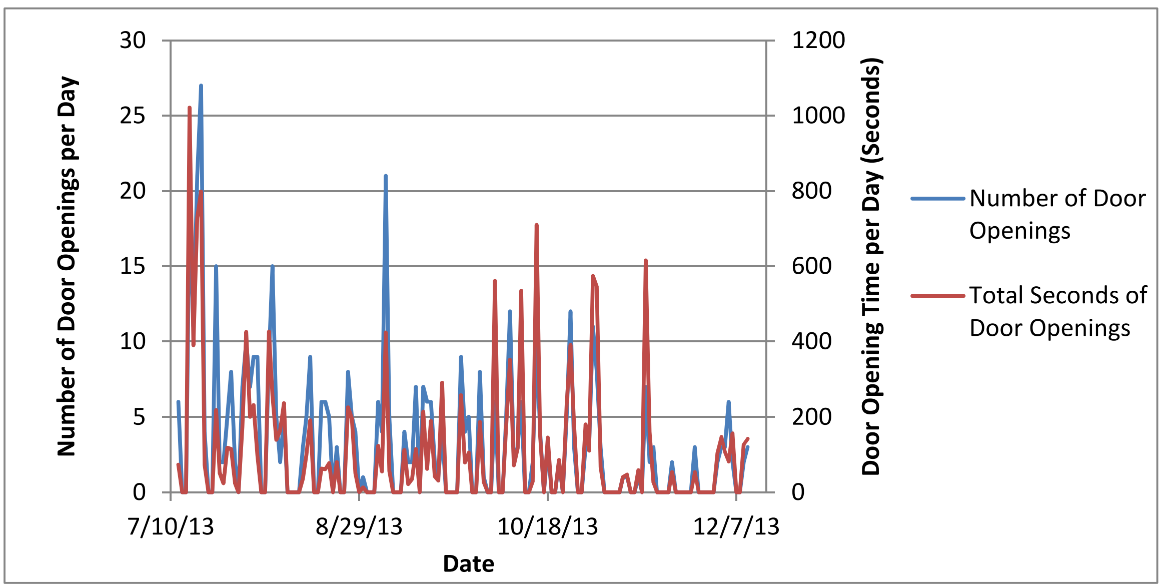


Figure A.10: Daily Door Opening Data: Unit Demo-3

Notes:

1. The user changed the set-point from -80 °C to -85 °C towards the end of the measurement period to observe the effect on energy use.
2. These supplementary data are from a room air-temperature sensor associated with the building energy system, for which the user provided data for part of the measurement period. We present those data as "Measured Room Temp" alongside the measured external temperature data for comparison.
3. The site host reported that the building air conditioning system failed during the time associated with this temperature spike. The impacts on the ULT's energy use (see Real Energy curve) were substantial.

Unit Comp-3: Comparison ULT #3 at Michigan State University

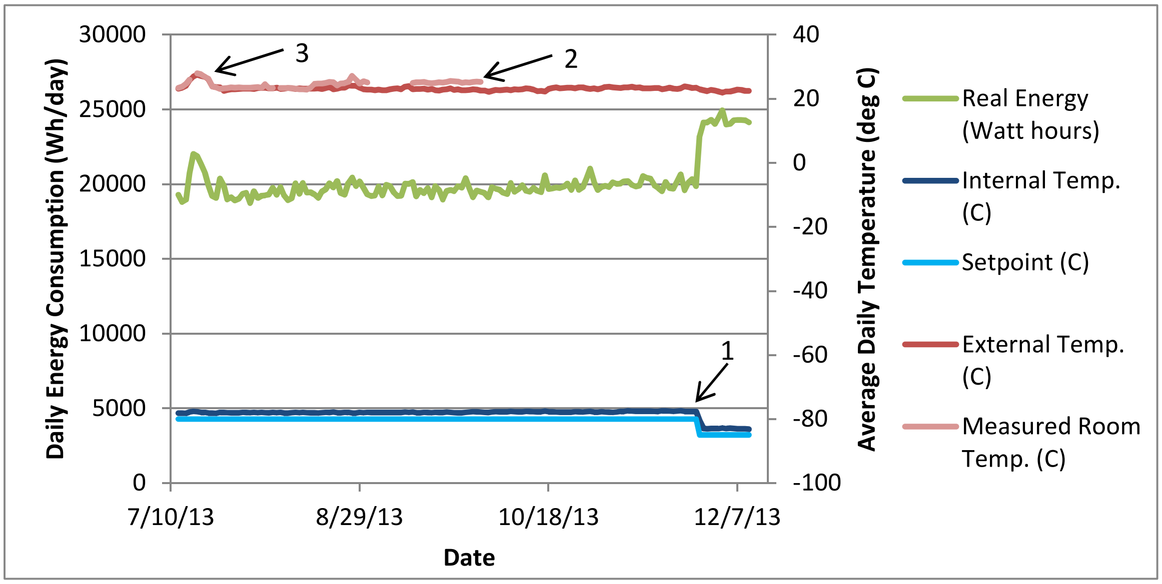


Figure A.11: Daily Energy and Temperature Data: Unit Comp-3

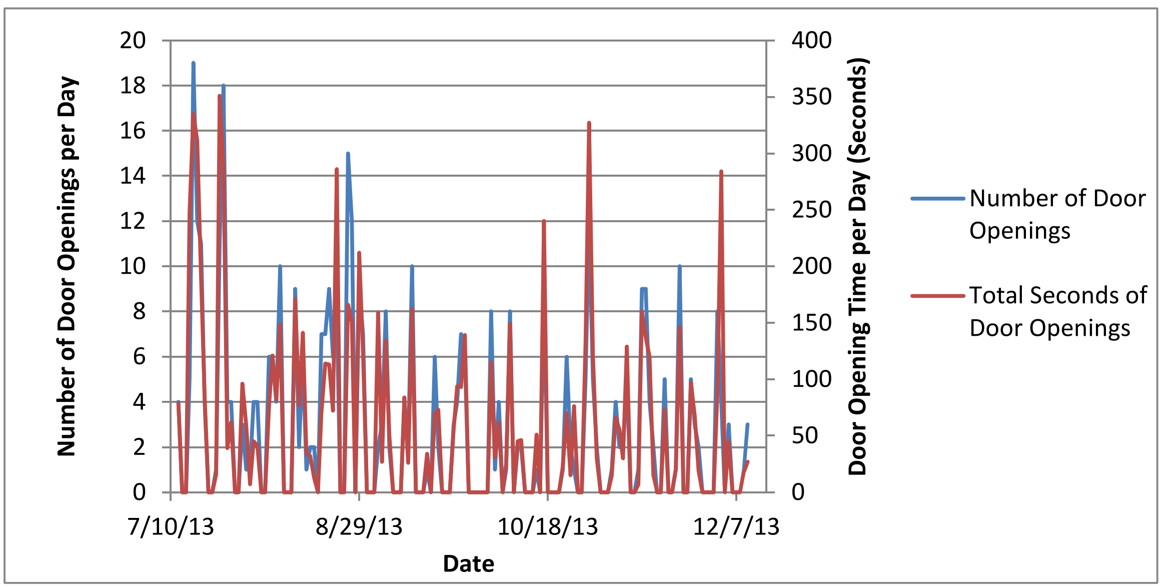


Figure A.12: Daily Door Opening Data: Unit Comp-3

Notes:

1. The user changed the set-point from -80 °C to -85 °C towards the end of the measurement period to observe the effect on energy use.
2. These supplementary data are from a room air-temperature sensor associated with the building energy system, for which the user provided data for part of the measurement period. We present those data as "Measured Room Temp" alongside the measured external temperature data for comparison.
3. The site host reported that the building air conditioning system failed during the time associated with this temperature spike. The impacts on the ULT's energy use (see Real Energy curve) were substantial.

Unit Comp-4: Comparison ULT #4 at Michigan State University

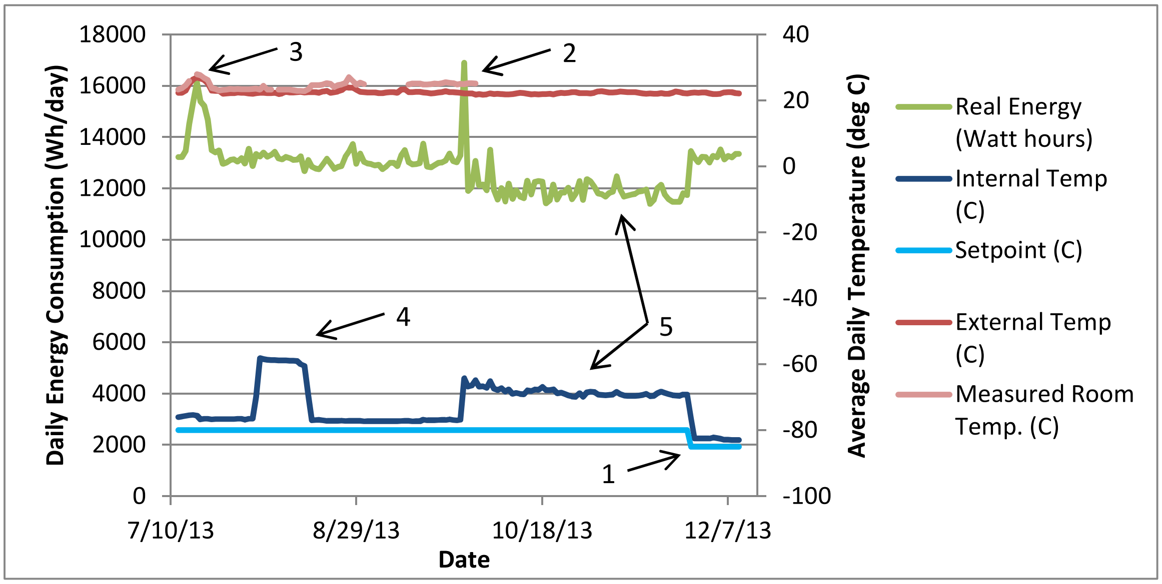


Figure A.13: Daily Energy and Temperature Data: Unit Comp-4

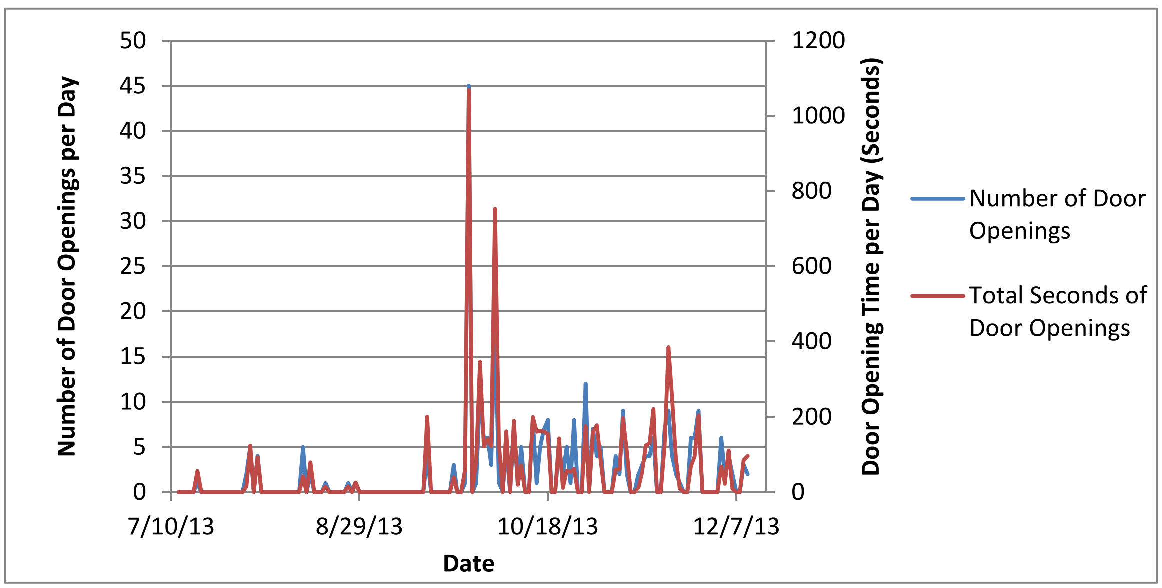


Figure A.14: Daily Door Opening Data: Unit Comp-4

Notes:

1. The user changed the set-point from -80 °C to -85 °C towards the end of the measurement period to observe the effect on energy use.
2. These supplementary data are from a room air-temperature sensor associated with the building energy system, for which the user provided data for part of the measurement period. We present those data as "Measured Room Temp" alongside the measured external temperature data for comparison.
3. The site host reported that the building air conditioning system failed during the time associated with this temperature spike. The impacts on the ULT's energy use (see Real Energy curve) were substantial.
4. On 8/17/13, the site host reported that the cover on the internal temperature sensor was missing (see Appendix C for a description of the temperature sensor setup). The site host did not report whether the sensor

was in its original position or whether it had been dislodged; however, these factors may explain the change in measured temperature for several days prior to this date. Upon replacing the cover and repositioning the probe, temperature measurements returned to the range initially measured.

5. On 11/27/13, the site host reported finding the thermocouple up against the inner door, and moved it back into the shelf space. We observed that for several weeks prior to this date, the temperature that the TC measured was higher than the set-point, which also corresponded to a reduction in the ULT's energy use. We do not know why energy use dropped during this period.

Appendix B. Regression Analysis Methodology and Results

After aggregating the data on a daily basis, as presented in the figures in Appendix A, we conducted a regression analysis to determine the effect of certain variables on the energy use of each ULT. The variables we examined were the ULT's set-point, the measured ambient temperature, and the total time the ULT's outer door was opened each day. We used the results of this analysis to develop equations expressing the expected energy use in terms of these variables, to compare performance of the ULTs at a common set of operating conditions. The following paragraphs discuss the choice of variables.

<u>Internal Temperature or Set-point</u>

We initially planned to correlate the energy use to the measured internal temperature. However, after a review of the data, we determined that set-point would be a more appropriate variable, for several reasons. First, it was unclear whether our measured internal temperature was more representative of average cabinet temperature than the ULT's own internal temperature sensor (which we assumed to be the input to the temperature control to meet the set-point). In some cases, it appears that neither the set-point nor the measured internal temperature provided a true reflection of the average cabinet temperature. For three of the ULTs, we were able to place two temperature sensors in different areas of the ULT for short periods of time, but in one of these cases, the two sensors did not measure consistent temperatures. (See Figure A.1, Figure A.5, and Figure A.7.) Second, the set-point was not dependent on the other variables, while the internal temperature could be affected by door openings. Third, the set-point seemed to be a more salient predictor of the energy use than the measured internal temperature. For example, in Figure A.7, a 10-degree change in the set-point is correlated with an observable drop in energy use, even though the measured internal temperature did not appear to change significantly. In another example, the temperature and energy data in Figure A.13 show a correlation between higher internal temperature and lower energy use, absent a change in set-point. However, the data do not indicate if one is causing the other or whether some other factor is causing both changes. For these reasons, we chose set-point as the regression variable. The relationship between set-point and average internal temperature is certainly of interest and may warrant further study (we believe such study would be more appropriate in a test laboratory setting rather than a field setting); however, as discussed, we could not draw firm conclusions using the data collected in this demonstration.

<u>External Temperature</u>

In the regression analysis, we also correlated the energy use to the ULT's ambient-air temperature (measured at the condenser inlet). We observed in the unadjusted daily data that higher ambient-air temperature is associated with greater energy use (see Figure A.9, Figure A.11, and Figure A.13). Although door openings often caused a temporary drop in the external temperature when viewed at 1-minute intervals due to the placement of the temperature probe below the door, the door openings did not noticeably affect the average daily external temperature. Therefore, we assumed that the average daily external temperature was independent from other variables with respect to its effect on energy use.

<u>Door Openings</u>

As noted in Appendix A, we aggregated on a daily basis both the number of door openings and the total time a door was open. We chose the total time a door was open for the regression analysis. We expected this to correlate somewhat more strongly with energy use (compared to the number of door openings) because it more closely reflects the amount of heat entering the ULT.

Analysis

The outcome of the analysis was an equation in the following form:

Energy Use = A × Set-point + B × External Temperature + C × Door Opening Seconds + Intercept

Where coefficients A, B, C, and the Y-intercept were determined for each ULT by the regression analysis. We assumed that the three variables were not directly related to each other, which we believe is a valid assumption based on the previous paragraphs. Prior to the regression analysis, we removed outlying data that did not reflect normal ULT use, either due to user error (e.g. leaving the door open, as shown in Figure A.2) or instrumentation error (e.g. sensor displacement, as shown in Figure A.7, or sensor failure, as shown in Figure A.3). To fairly compare the ULTs, we chose a set of standardized conditions to apply in the regression equation. The standardized conditions represented average conditions experienced by the ULTs in aggregate, as observed in the demonstration data, and are as follows:

Table B-1: Conditions for Calculating Standardized Energy Use

Condition	Value
Setpoint (°C)	-80
External Temperature (°C)	22
Door opening seconds	90

The following charts and tables show the results of the regression analysis for each ULT in the demo—that is, how each ULT's energy use is predicted to scale with set-point, external temperature, and door opening time, expressed as coefficients A, B, and C in the regression equation, respectively, and the intercept of the equation. We also present the expected energy use at the standardized conditions from Table B-1, and the estimation error associated with each variable in the analysis. The error is a measure of confidence in the results: there is a 95 percent probability that the true result lies within the error bounds.

Following each table, a, chart compares the expected energy use of the ULT at the standardized conditions to the measured energy use, with the estimation error shown as a shaded band. The band represents the range of predicted energy use at the given conditions when we accounted for the statistical error.

The results comparing each ULT at the standardized conditions are shown in section III.A.

Unit Demo-1: Demonstration ULT #1 at CU Boulder – MCDB Lab

Table B-2: Regression Variables and Standardized Energy Use: Unit Demo-1

Coefficient	Variable	Value	Error
Intercept	Constant (Wh)	-3733	1427
A	Setpoint (Wh/°C)	-140	8
B	External Temperature (Wh/°C)	14	58
C	Door opening seconds (Wh/s)	1.48	0.16
Total	Daily Energy Use (Wh)	7851	2060

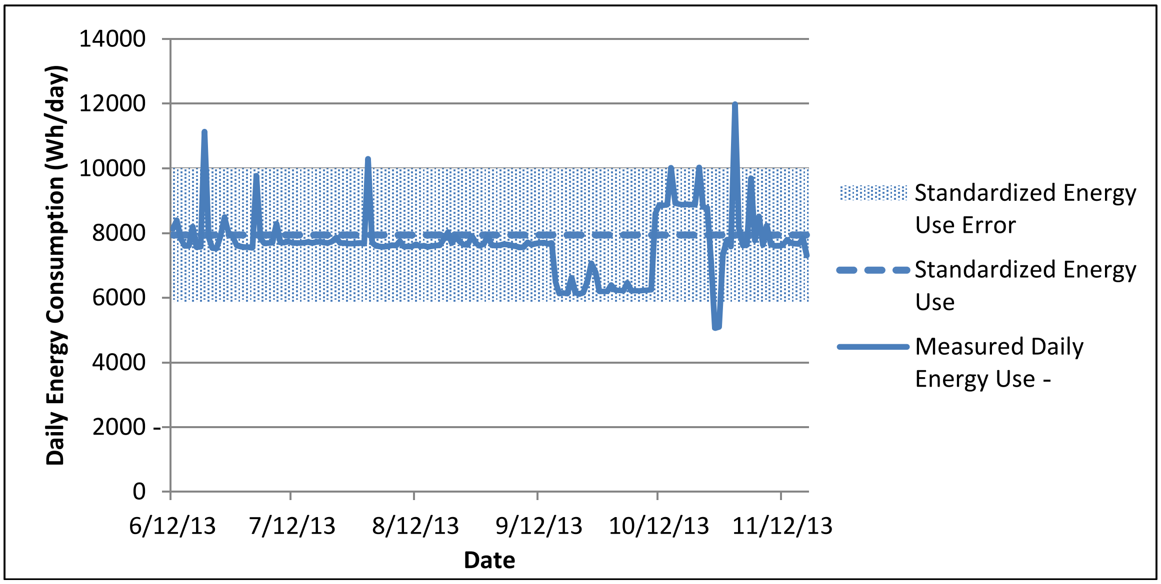


Figure B.1: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Demo-1

Unit Comp-1: Comparison ULT #1 at CU Boulder – MCDB Lab

Table B-3: Regression Variables and Standardized Energy Use: Unit Comp-1

Coefficient	Variable	Value	Error
Intercept	Constant (Wh)	16163	781
A	Setpoint (Wh/°C)	0**	0
B	External Temperature (Wh/°C)	316	41
C	Door opening seconds (Wh/s)	4.29	0.71
Total	Standardized Daily Energy Use (Wh)	23248	1696

*Setpoint was not changed during the evaluation period; therefore, there was no basis on which to correlate set-point with energy use for this ULT.

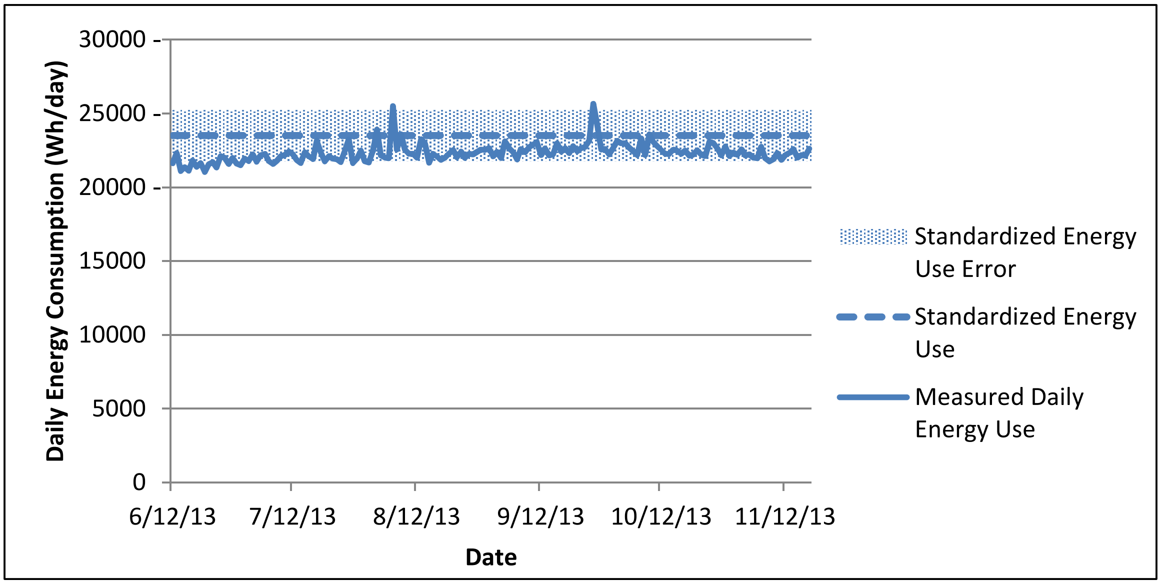


Figure B.2: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Comp-1

Unit Demo-2: Demonstration ULT #2 at CU Boulder – iPhy Lab

Table B-4: Regression Variables and Standardized Energy Use: Unit Demo-2

Coefficient	Variable	Value	Error
Intercept	Constant (Wh)	-19994	571
A	Setpoint (Wh/°C)	-313	4
B	External Temperature (Wh/°C)	311	19
C	Door opening seconds (Wh/s)	2.92	0.11
Total	Standardized Daily Energy Use (Wh)	12006	668

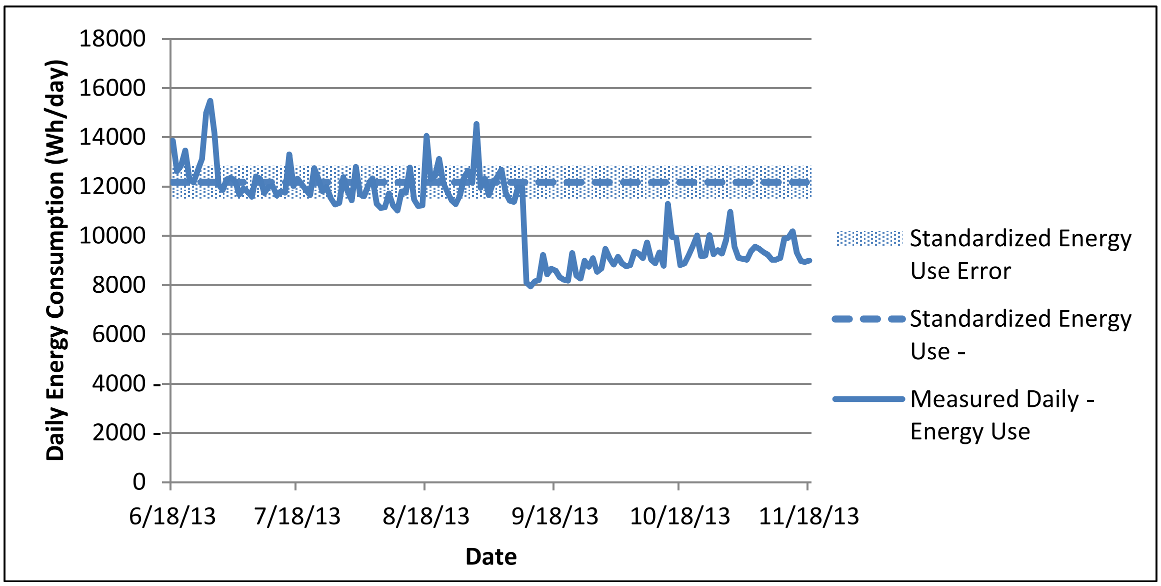


Figure B.3: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Demo-2

Unit Comp-2: Comparison ULT #2 at CU Boulder – iPhy Lab

Table B-5: Regression Variables and Standardized Energy Use: Unit Comp-2

Coefficient	Variable	Value	Error
Intercept	Constant (Wh)	-7905	450
A	Setpoint (Wh/°C)	-267	4
B	External Temperature (Wh/°C)	216	13
C	Door opening seconds (Wh/s)	4.24	0.21
Total	Standardized Daily Energy Use (Wh)	18336	436

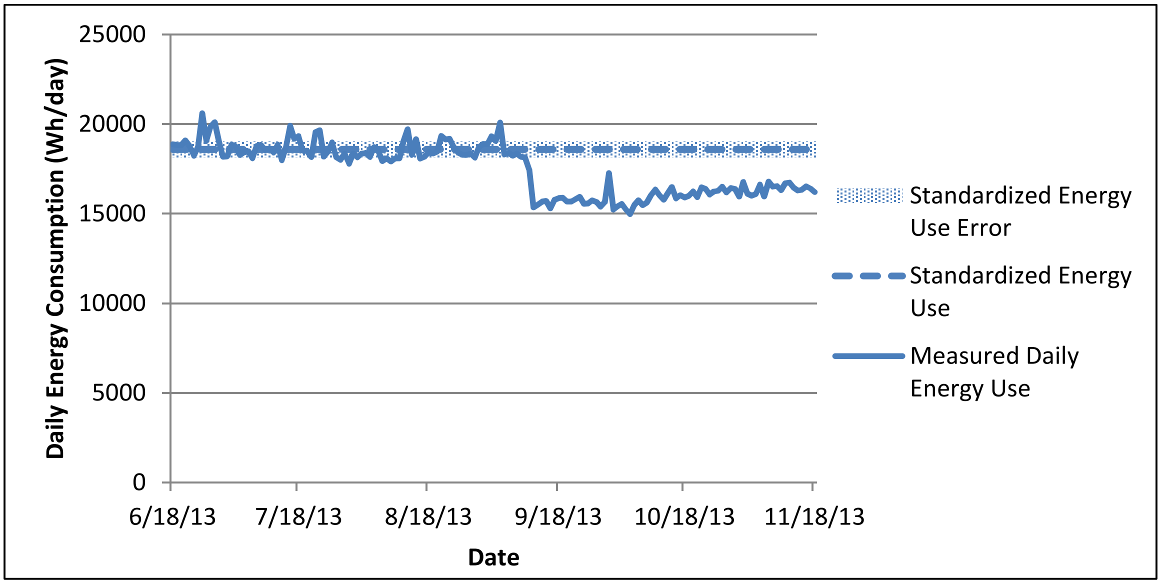


Figure B.4: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Comp-2

Unit Demo-3: Demonstration ULT #3 at Michigan State University

Table B-6: Regression Variables and Standardized Energy Use: Unit Demo-3

Coefficient	Variable	Value	Error
Intercept	Constant (Wh)	-43938	1635
A	Setpoint (Wh/°C)	-737	17
B	External Temperature (Wh/°C)	96	28
C	Door opening seconds (Wh/s)	3.11	0.14
Total	Standardized Daily Energy Use (Wh)	17233	858

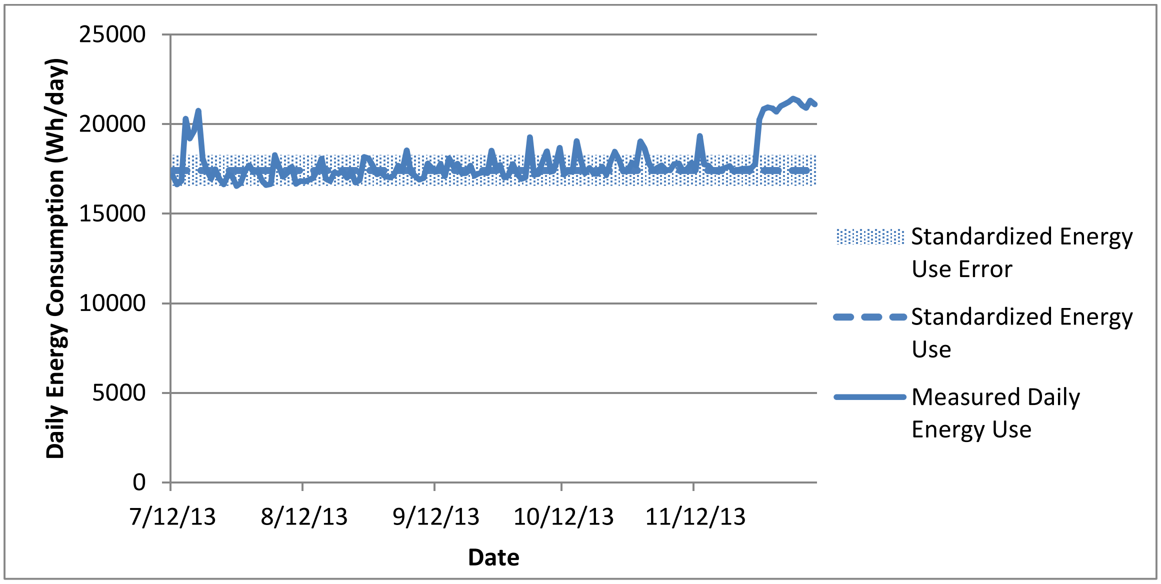


Figure B.5: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Demo-3

Unit Comp-3: Comparison ULT #3 at Michigan State University

Table B-7: Regression Variables and Standardized Energy Use: Unit Comp-3

Coefficient	Variable	Value	Error
Intercept	Constant (Wh)	-62157	1872
A	Setpoint (Wh/°C)	-949	19
B	External Temperature (Wh/°C)	245	34
C	Door opening seconds (Wh/s)	4.01	0.33
Total	Standardized Daily Energy Use (Wh)	19293	1138

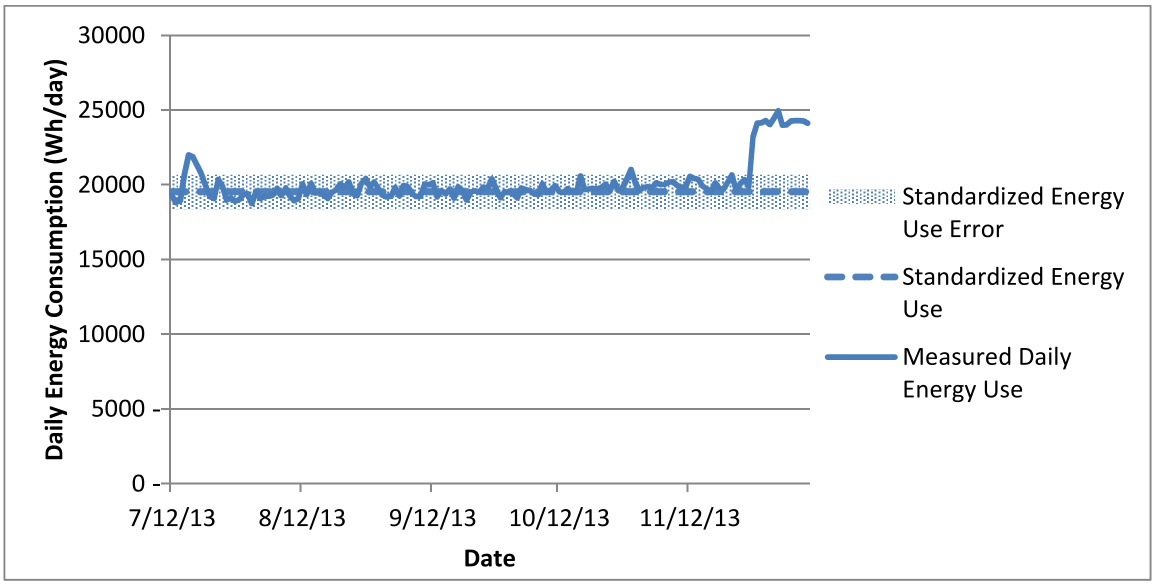


Figure B.6: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Comp-3

Unit Comp-4: Comparison ULT #4 at Michigan State University

Table B-8: Regression Variables and Standardized Energy Use: Unit Comp-4

Coefficient	Variable	Value	Error
Intercept	Constant (Wh)	-16974	3349
A	Setpoint (Wh/°C)	-154	36
B	External Temperature (Wh/°C)	762	64
C	Door opening seconds (Wh/s)	2.23	0.42
Total	Standardized Daily Energy Use (Wh)	12205	1918

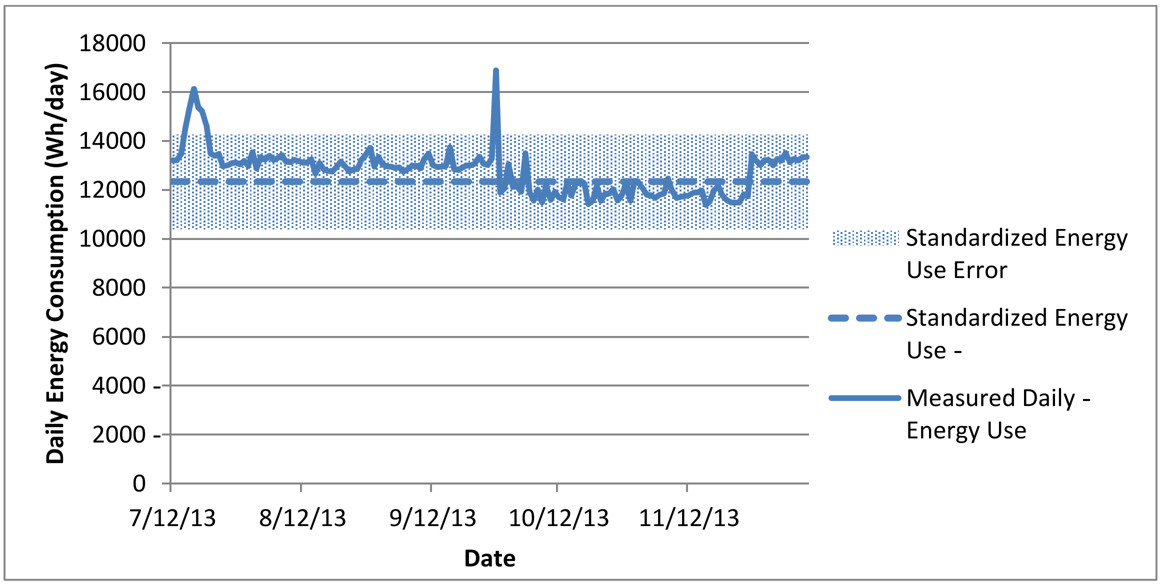


Figure B.7: Unadjusted Measured Daily Energy Use v. Standardized Daily Energy Use: Unit Comp-4

Appendix C. Instrumentation and Data Collection Details

Energy

We measured real energy (watt hours), amp hours, and reactive energy (volt-amp reactive (VAR) hours) for each ULT at one-minute intervals using a Veris T-VER-E50B2 Compact Power and Energy Meter, sold by Onset Computer Corporation (Onset). The measurement accuracy was 0.5% for real power, 2% for reactive power, and between 0.4% and 0.8% for current depending on the surrounding air temperature.[27]

The inputs to the power meter were the current and three-phase voltage (in addition to control power to drive the meter). Because the power supplied to the ULTs was in a 3-wire configuration, the wires had to be isolated from each other to measure the current and voltage. A qualified electrician wired each meter in an electrical box that the ULT could plug into. The wires were isolated inside the box in a touch-safe configuration, and an electrical cord connected the box to the wall outlet. Figure C.1 and Figure C.2 show the wiring diagrams for boxes connected to ULTs with NEMA 5-20 (line-neutral-ground) and NEMA 6-15 (line-line-ground) electrical cords, respectively. Figure C.3 shows a photograph of the setup of the power meter inside the electrical box.

[27] Onset Computer Corporation T-VER-E50B2 Compact Power and Energy Meter: Installation Guide.

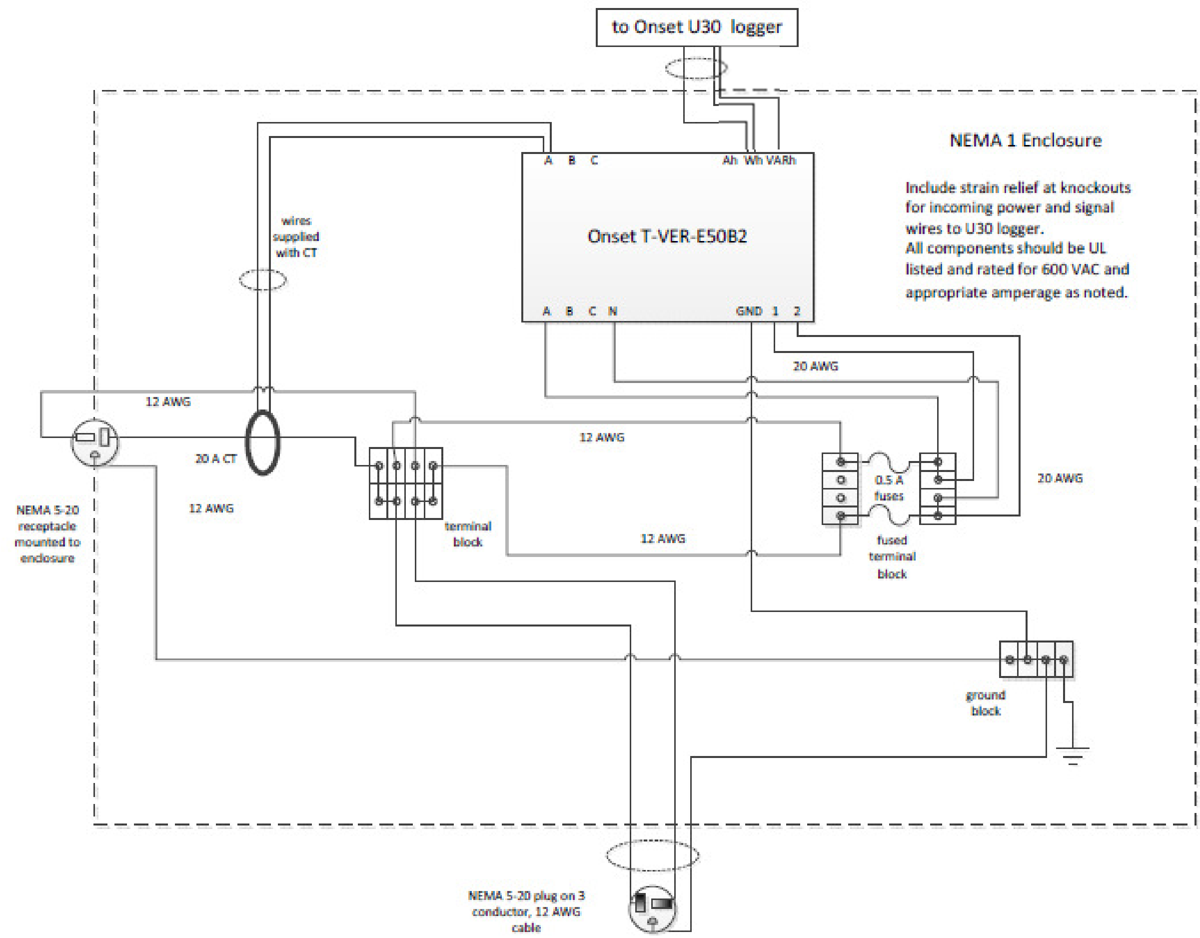


Figure C.1: Electrical Diagram for NEMA 5-20 Connector

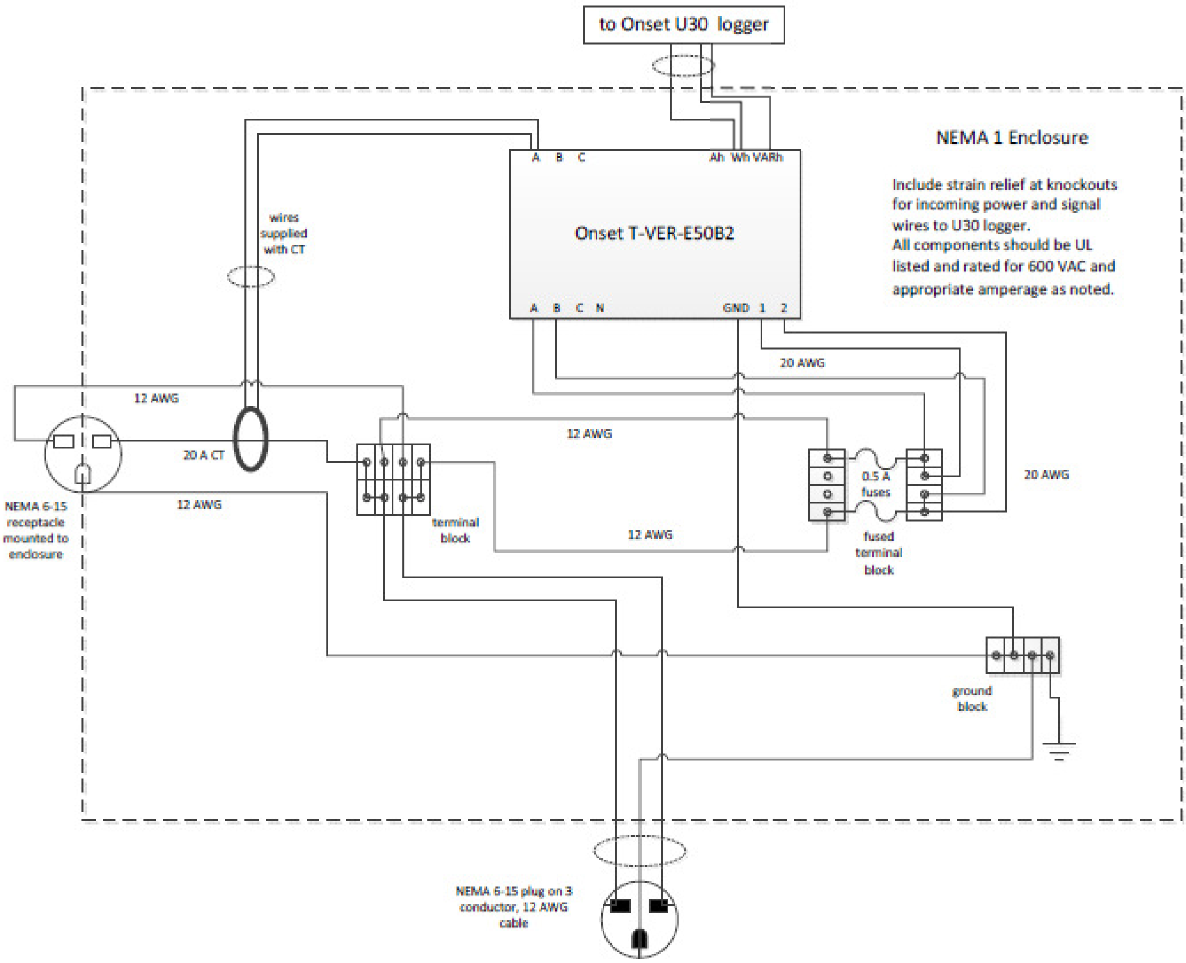


Figure C.2: Electrical Diagram for NEMA 6-15 Connector

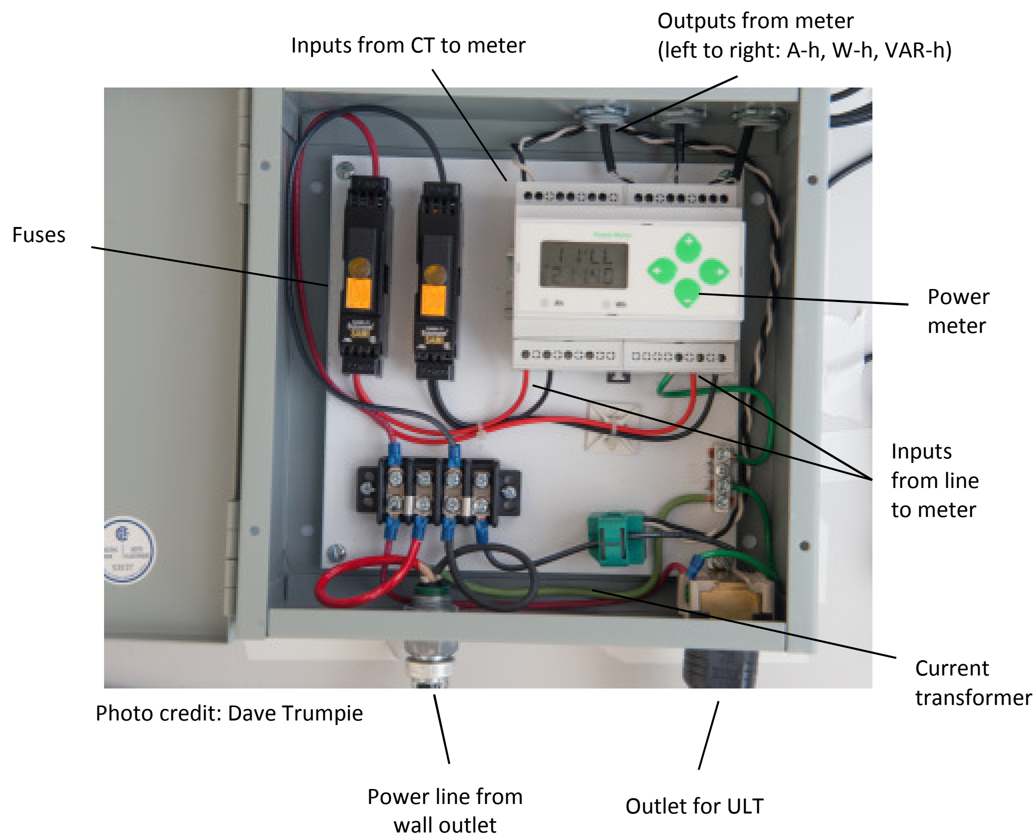


Figure C.3: Photograph of Power Meter Inside Electrical Box

The output of the power meter consisted of three separate signals: for energy, amp hours, and VAR hours. The three signals were transmitted to the data logger using Onset HOBO S-UCC-M00x electronic switch pulse input adapters (the “x” in the model number corresponds to the length of the cable) which adapted the signal to a smart-sensor input to the logger.[28] Figure C.4 shows a picture of a pulse input adapter and cable.

[28] Onset Computer Corporation: Pulse Input Adapters for use with HOBO H21, H22, and U30 Series Data Loggers.

Source: Onset Computer Corporation

Figure C.4: Pulse Input Adapter and Cable from Power Meter to Logger

We measured both real energy and reactive energy to determine the power factor of each ULT. Power factor relates the "real" power that performs useful work (i.e. refrigeration) to the "reactive" power associated with the magnetizing current used to operate inductive devices (i.e., compressors). A high power factor means that most of the electrical power supplied by the circuit is being used for real work. A low power factor, on the other hand, means that most of the total power becomes inductive losses. Appendix D provides a tutorial for calculating power factor given the real and reactive power.

Power factor is important because, while customers are often billed only for the real power used by a device, the electrical circuit containing the device must be sized for, and the utility must provide, the total power. Thus, utilities sometimes impose a separate "power factor" cost that penalizes industrial customers using low power factor devices.[29] Power factor for the ULTs in the demonstration is reported in section III.C.

Internal Temperature

We measured internal temperature at one-minute intervals using Type T thermocouples. The limit of error for the thermocouples was 1.0 °C or 1.5% at temperatures below 0 °C, whichever is greater.[30] Where possible, we placed each internal thermocouple near the top of the ULT, as we assumed this would likely correspond to the highest cabinet temperature. This was not possible for two ULTs due to space constraints (caused by items stored in the ULT); in these cases we placed the internal thermocouple where space was available. Figure C.5 shows the approximate elevation of the thermocouples within each ULT. Each ULT also had a built-in temperature sensor used to maintain the ULT's setpoint, but we did not know the location of the built-in sensor for all ULTs and, in some cases, determining its location would have involved unloading the ULT, which would have disturbed the samples inside. We observed that, in many cases, the temperature measured by the thermocouple was not the same as the displayed set-point temperature. A single-point measurement such as the measured temperature or the set-point temperature is not a reliable indicator of the average cabinet temperature; however, attempting to determine the average cabinet temperature more accurately would have

[29] Capehart, B., Turner, W., and Kennedy, W. Guide to Energy Management: 7th Edition. The Fairmont Press: 2012.
[30] Revised Thermocouple Reference Tables: Type T Reference Tables. NIST Monograph 175 Revised to ITS-90.

required an array of thermocouples, which is impractical in a field test because it would interfere with the normal use of the ULT. In Appendix A, both the measured temperature and set-point temperature are reported for all ULTs on a daily basis.

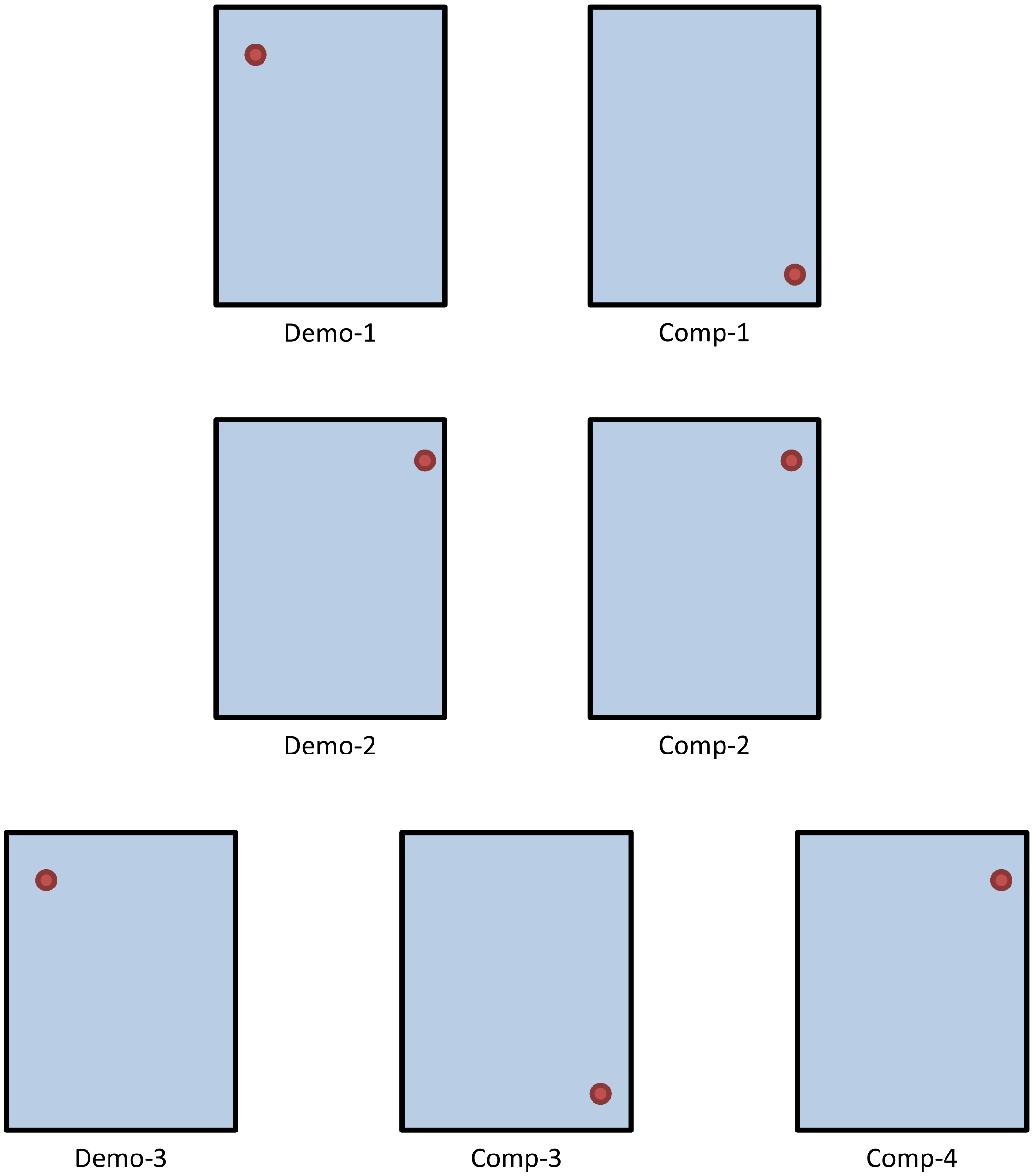


Figure C.5: Front View of Each ULT Showing Approximate Relative Elevation of Internal Thermocouple Placement

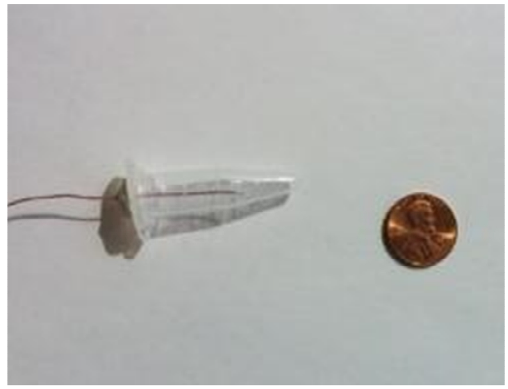
We embedded each thermocouple in a plastic vial and attached each vial to a small cardboard box. The purpose of this was threefold:

1) To protect the tip of the thermocouple from breakage; -
2) To provide thermal mass to simulate the temperature of a typical sample inside the ULT; and -

3) To enhance the visibility of the thermocouple to reduce the likelihood that it would be accidentally damaged or discarded.

Figure C.6 shows how the thermocouples were attached to the box and has an example photo of placement within the ULT.

(1) Bare thermocouple



(2) Thermocouple embedded in vial

(3) Vial attached to box

(4) Box placed in ULT (space permitting)

Photo credits: (1)-(3) Rebecca Legett; (4) Dave Trumpie

Figure C.6: Thermocouple Apparatus

We connected the thermocouples to an Omega TX-13 temperature transmitter, which converted the temperature sensed by each thermocouple junction to a 4 to 20 milli-amp (mA) signal. The transmitter allowed scaling of its output to a fixed range of temperatures (-100 to 100 °C) so that given a mA output, the temperature corresponding to that output could be easily determined. In other words, an output of 4 mA would correspond to a temperature of -100 °C, and an output of 20 mA would correspond to a temperature of 100 °C. For outputs between 4 and 20 mA, the temperature is determined through linear interpolation as recommended by the instrumentation manufacturer.[31]

[31] Omega Engineering, Inc. User's Guide: TX13 Push Button Thermocouple.

We connected the temperature transmitter to the analog input to the data logger using twisted pair cable, also recommended by the manufacturer.

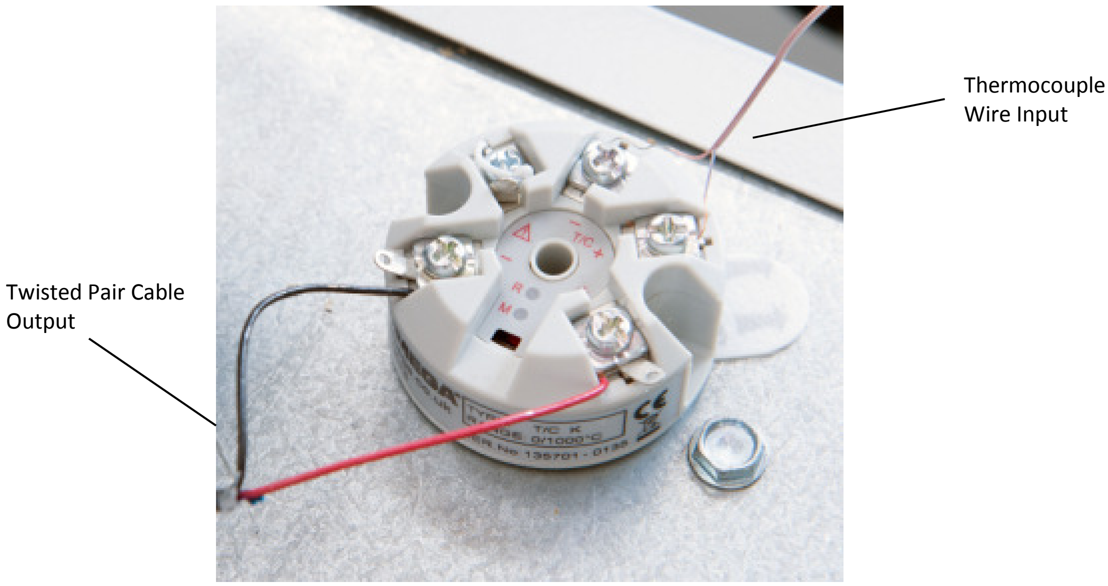


Photo credit: Dave Trumpie

Figure C.7: Photo of Temperature Transmitter

Each thermocouple-transmitter pair was calibrated to -60, -70, and -80 °C by Transcat Calibration & Compliance Services. We chose these calibration temperatures because they encompassed the likely range of temperatures that the thermocouple would be measuring.

<u>External Temperature</u>

We measured external temperature at one-minute intervals using an Onset S-TMB-M00x 12-Bit Temperature Smart Sensor whose probe end we placed at the air inlet to the condenser, just outside of the grille. (The “x” in the model number refers to the length of the sensor cable in meters; we used different lengths in the demonstration as needed.) The manufacturer lists accuracy of the sensor as < +/- 0.2 °C from 0° to 50 °C.[32] Figure C.8 shows a photograph of the external temperature probe and its cable, and Figure C.9 shows example photographs of the external temperature probe attached to the ULT’s air inlet grille.

[32] Onset Computer Corporation: 12-Bit Temperature Smart Sensor Manual.

Photo credit: Onset Computer Corporation

Figure C.8: Temperature Sensor and Cable from Sensor to Logger

Photo credit: Dennis Schroeder, NREL

Photo credit: Dave Trumpie

Figure C.9: Photos of External Temperature Probe Placement

Energy and Temperature Data Logging

We logged energy and temperature data using an Onset HOBO U30 Station with remote communication capabilities, including GSM (Global System for Mobile Communications; in other words, cellular phone network communication), used at the CU Boulder sites; and Wi-fi, used at the MSU site.[33] Each U30 station was capable of receiving input from up to 10 smart sensors and two analog sensors. The power meter output adapters and

[33] Onset Computer Corporation: HOBO U30 Station User's Guide.

the external temperature sensor were smart-sensor inputs with plug-and-play capability. The internal thermocouple was an analog input that required configuration to scale the mA output to the temperature (as discussed in the previous section). Figure C.10 shows a photograph of the data logger with inputs indicated.

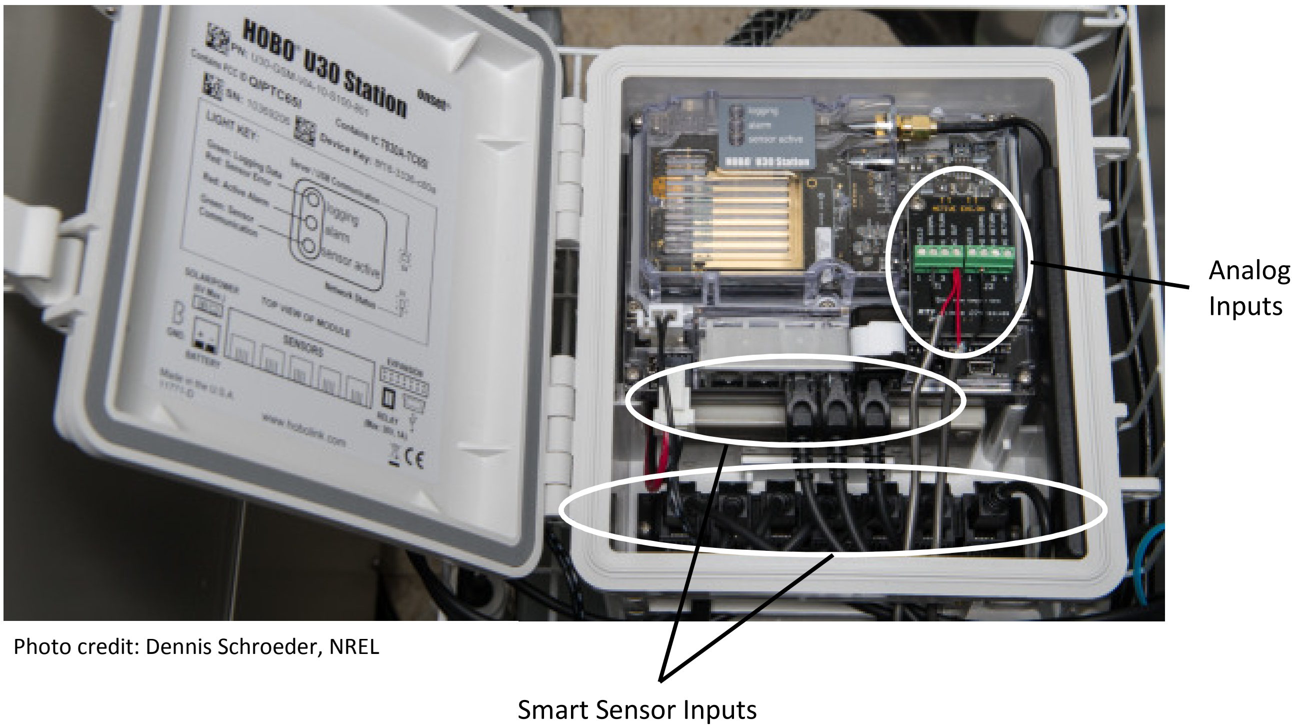


Photo credit: Dennis Schroeder, NREL

Figure C.10: Diagram of Data Logger Inputs

The number of inputs allowed one logger to be used for either two or three ULTs. For the CU Boulder sites, we monitored two ULTs in each room. Figure C.11 shows a schematic diagram of the sensor inputs to the loggers in this configuration.

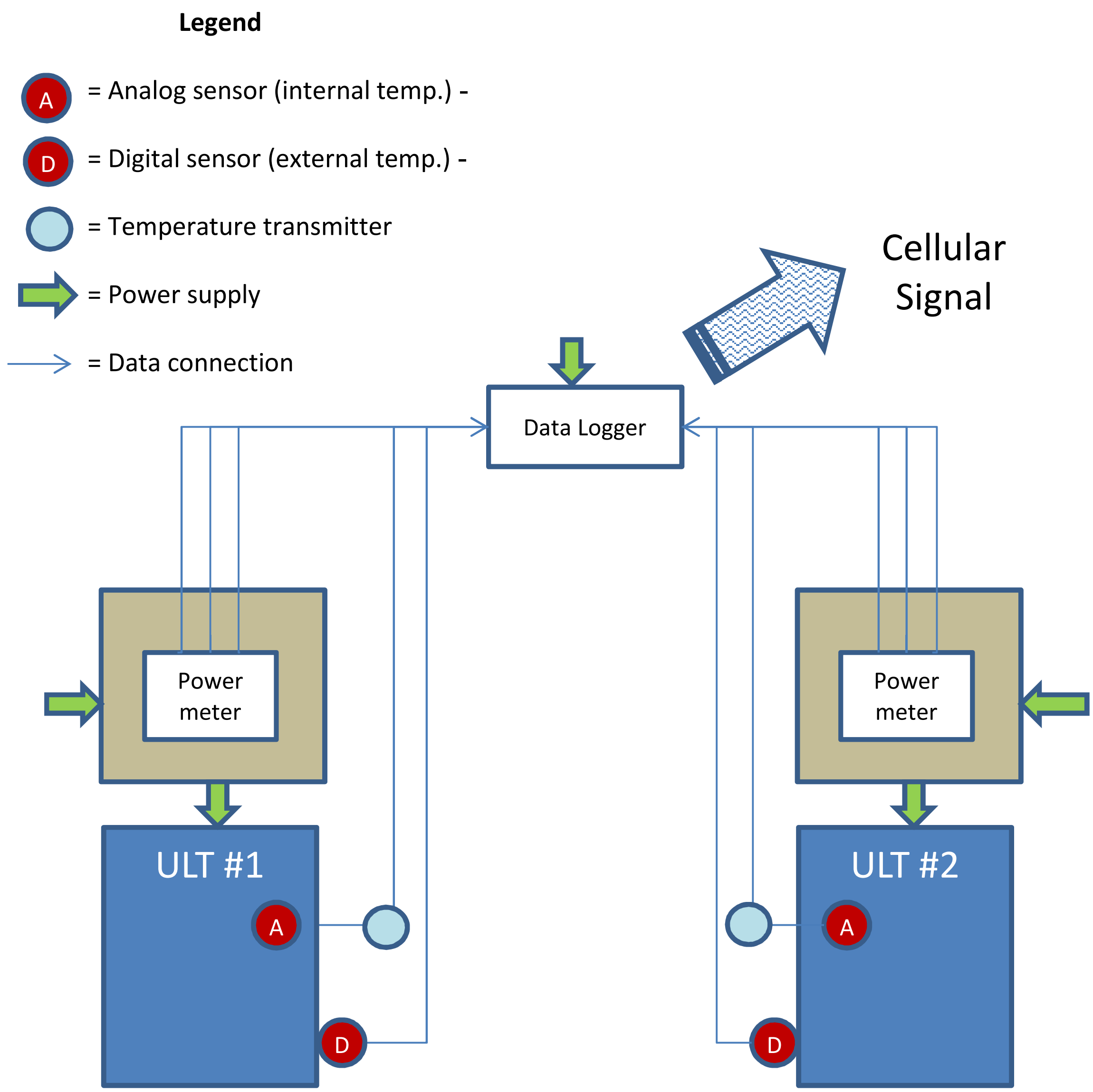


Figure C.11: Instrumentation Schematic for CU Boulder Sites

At the Michigan State University site, there were three ULTs in one room, which were some distance away from each other (see Figure II.4 in section II.B). To avoid running multiple, long-distance wires, we consolidated the smart sensor inputs into a single cable using a cable consolidator. This allowed the signals from multiple sensors to be transmitted through a single cable. Furthermore, there were three total analog sensors in the MSU lab, but only two analog ports on the logger. We converted one of the analog sensors to a digital "smart" signal input using an Onset S-CIA-CM14 12-bit 4-20 mA input adapter.[34] We included a separate 12 VDC power supply to supply power to that analog sensor. Figure C.12 shows a diagram of the instrumentation setup at the Michigan State University site.

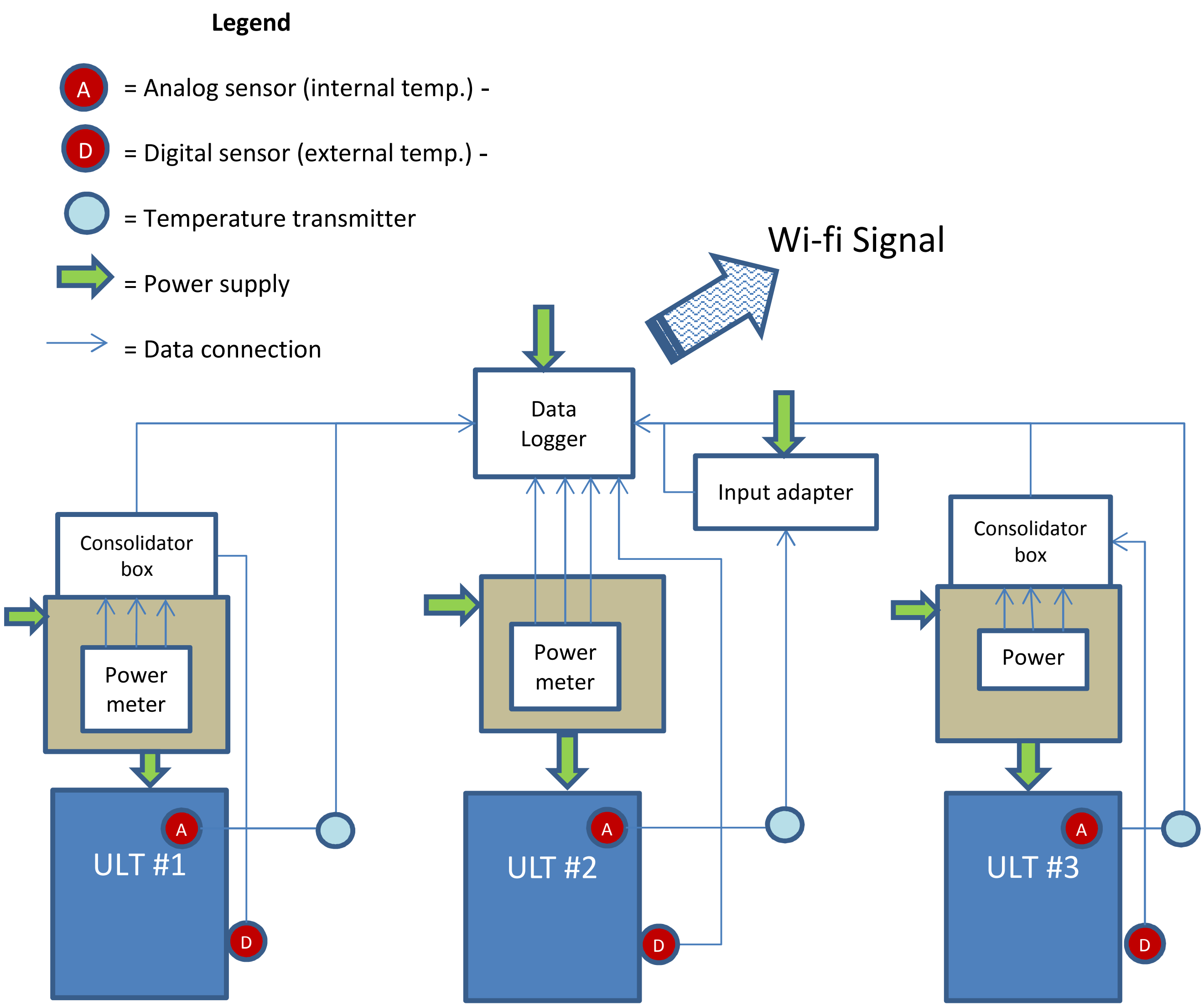


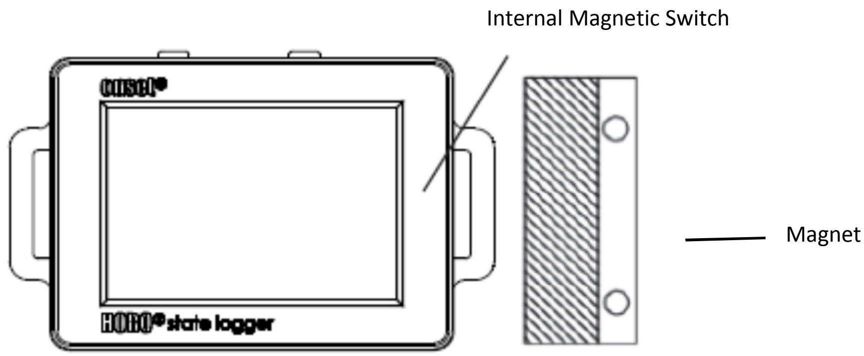
Figure C.12: Instrumentation Schematic for Michigan State University Lab

---

[34] Onset Computer Corporation: 12-Bit 4-20 mA Input Adapter Manual.

Door Openings

We monitored door openings using a stand-alone state logger.[35] The state logger consisted of a logging device on the main body of the ULT with a magnetic switch, and a magnet attached to the outer door. Each time a user opened the door, the magnetic connection would be broken and the logger would record the timestamp. Once the door was closed, the logger would sense the magnetic field and record another timestamp. Figure C.13 shows a schematic diagram of the data logger and magnet, while Figure C.14 shows a photograph of the logger attached to a door. We calculated the duration of each door opening by subtracting each door-open timestamp from its subsequent door-closed timestamp.



Picture credit: Onset Computer Corporation

Figure C.13: Diagram of Logger and Magnet

[35] Onset Computer Corporation: HOBO State Data Logger (UX90-001x) Manual.

Photo credit: Dave Trumpie

Figure C.14: Photograph of Logger and Magnet on ULT

This measurement approach is ideal for intermittent events because it does not require much logging memory (as opposed to, for example, recording the open/closed state every second). On the other hand, the door sensor was not compatible with the one-minute intervals being recorded by the energy and temperature logger and so we could not upload data remotely. Instead, someone visited each site on a periodic basis to collect the door data from the logger. The periodic data retrieval was a precaution to guard against data loss; each of the door loggers had enough memory to collect the door data for the entire measurement period even with a far larger rate of door openings than was observed.

Appendix D. Calculating Power Factor

Power factor is “the ratio of real power being used in a circuit, expressed in watts, to the apparent power drawn from the power line, expressed in volt-amperes.”[36] The real and reactive power values are expressed as vectors at right angles to each other on an electrical phase diagram, while their vector sum is the total (apparent) power. This effect is illustrated in Figure D.1:

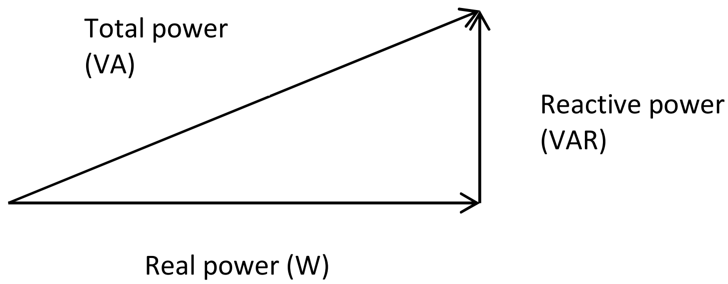


Figure D.1: Relationship Among Power Variables

Power factor can be calculated from the measured energy data using the Pythagorean theorem.

$$(\text{Real power})^2 + (\text{Reactive power})^2 = (\text{Total power})^2$$

$$\text{Power factor} = \frac{\text{Real power}}{\text{Total power -}}$$

$$\text{Power factor} = \frac{\text{Real power -}}{\sqrt{(\text{Real power})^2 + (\text{Reactive power})^2}}$$

“Power” can be replaced with “energy” in the equation in order to use the measured data because the “hours” variable in the energy values cancels out.

$$\text{Power factor} = \frac{\text{Real energy}}{\sqrt{(\text{Real energy})^2 + (\text{Reactive energy})^2}}$$

Figure D.2 compares electrical phase diagrams for equipment with a high power factor and low power factor on the left and right, respectively.

[36] Capehart, B., Turner, W., and Kennedy, W. Guide to Energy Management: 7th Edition. The Fairmont Press: 2012.

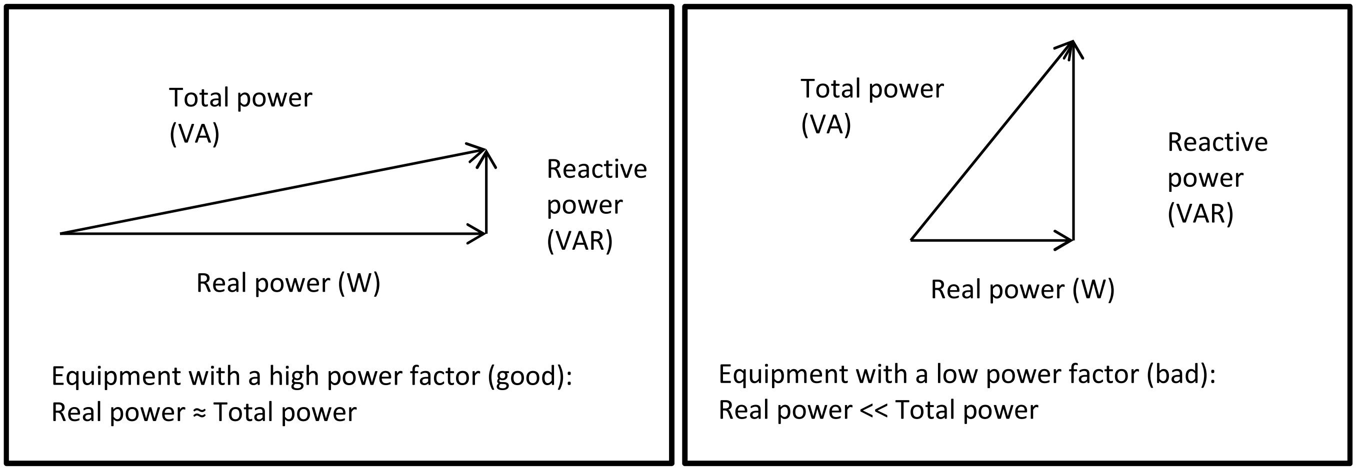


Figure D.2: Comparison of Power Factor for Different Equipment