Ultra-Low Temperature Freezers: Opening the Door to Energy Savings in Laboratories

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LEGAL NOTICE

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ABBREVIATIONS AND ACRONYMS

ACH	Air Changes per Hour
ASCB	American Society for Cell Biology
CEEL	Center for Energy Efficient Laboratories
CHW	Chilled Water
CZ	Climate Zone
DX	Direct Expansion
FCU	Fan Coil Unit
FNI	Fisher-Nickel Inc.
FSTC	Food Service Technology Center
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air-Conditioning
IOU	Investor-Owned Utility
LSR	Life Science Research
OA	Outside Air
PI	Principal Investigator
POS	Point of Service
TC	Thermocouple
ULT	Ultra-low Temperature (Freezer)
VAV	Variable Air Volume
VFD	Variable Frequency Drive

EXECUTIVE SUMMARY

Laboratories are one of the next major frontiers in energy efficiency. After data centers, laboratories consume more energy per square foot than any other type of facility. This is due to their energy-intensive equipment, around-the-clock operations, and uniquely demanding HVAC requirements. A recent study conducted by the Center for Energy Efficient Laboratories (CEEL) identified a minimum of 116 million square feet of laboratory space in California in just the academic, life science research, and hospital market sectors. This study also uncovered a substantial, untapped opportunity for energy savings in California's laboratory plug loads, which were found to comprise ~2% of commercial electrical consumption in the state, or up to ~3 billion kWh/year. This report constitutes the critical first step in a widespread multi-year effort to realize savings from laboratory plug load reductions. This effort logically begins by targeting one of the most intensive energy consumers in research, the ultra-low temperature freezer.

A single ultra-low temperature freezer (ULT, -80°C) draws as much energy as an average U.S. household. California is home to at least 58,000 ULT freezers consuming an estimated 400 million kWh/year. This study sought to quantify the potential direct and indirect energy savings associated with energy-efficient ULT freezer technology. Eight different ULT freezer brands from five manufacturers, accounting for over 80% of the total ULT freezer market, were selected for the study. Fifteen ULT freezers, ranging in size from 16-29 ft^3, were evaluated according to the EPA ENERGY STAR® test method, and of those, seven were further tested in a controlled field study that measured energy consumption and temperature performance. Of the ULT freezers tested, ten utilized traditional, standard dual-compressor technology while five were marketed as using new, energy-efficient technology. Additional installed base baseline energy data were gathered for 107 ULT freezers in the field.

Freezer	Refrigerant	Avg kWh/ft^3/Day @ -75°C	Avg kWh/ ft^3/Day @ -80°C (Field Results)	Avg Temp Uniformity (°C) @ -80°C	Avg Temp Stability (°C) @ -80°C
Energy Efficient	Natural and HFC/Natural Blend	0.40	0.34	9.7	5.9
Standard Efficiency	HFC and HFC/Natural Blend	0.73	0.74	8.4	3.9
Installed Base	HFC	N/A	1.1	N/A	N/A

Energy-efficient ULT freezers exhibited temperature performance that was comparable to, and in some cases better than, their standard-efficiency peers, while consuming at least 25%, and in some cases up to 70%, less energy. Even an average new, standard-efficiency ULT freezer was found to consume at least 20% less energy than an average freezer in the existing installed base, which is laden with older, relatively inefficient models. A summary of these findings is above. All data are from the ENERGY STAR test unless otherwise noted.

In addition to quantifying the benefits of energy-efficient freezer technology, the study found that significant energy savings can be achieved through behavioral change. Advocates for energy efficiency in laboratories have suggested that increasing ULT freezer temperature from -80°C to -70°C can reduce energy usage while maintaining performance. This study corroborated that view, finding that such a temperature change reduces energy consumption by an average of 37% for both standard-efficiency and energy-efficient ULT freezers without any discernable effect on temperature stability.

Potential statewide annual electric energy savings, including secondary HVAC energy impacts, associated with improving the efficiency of California's ULT freezer population are shown in the table below. Replacing 10% of the population's older units (5,800 freezers) with energy-efficient models would generate savings of 49 million kWh/year, less a small thermal energy (natural gas) penalty. Approximately 5,800 new freezers are purchased each year in California. If all of these were energy-efficient, as opposed to standard-efficiency, units, the state could save 14 million kWh/year. Adjusting temperature set points for the same number of freezers would also have a large impact, resulting in savings of 26 million kWh/year. In all cases the annual savings would compound in subsequent years, tracking the growth of the installed base of efficient units.

	Direct Savings (kWh/yr)	HVAC Electric Savings (kWh/yr)	Total Electric Savings (kWh/yr)
Savings Over Existing Older Model Freezers	41 million	7.6 million	49 million
Savings Over New Standard Efficiency Freezers	12 million	2.2 million	14 million
Savings From Adjusting Freezer Set Point to -70°C	22 million	4.1 million	26 million

An in-depth market analysis of ULT freezers revealed that the energy-efficient units identified in this study cost an average of $2,000 more than standard-efficiency models. Looking at a specific case study, a comparison between two units of the same size from the same manufacturer showed an energy-efficiency premium of $1,000 for annualized savings of $300. Scientists surveyed for this study indicated that price was the primary driver of ULT freezer purchases, and it was found that institutional rebate programs designed to bridge that price gap have resulted in increased sales of energy-efficient units. Given the significant potential for energy savings, and the historical efficacy of rebates, the CEEL recommends that the IOUs consider incentivizing the purchase of energy-efficient ULT freezers. The CEEL also advocates the implementation of behavior-change programs promoting the adjustment of ULT freezer set points to -70°C from -80°C.

Taken as a whole, this report is intended to provide guidance to the California IOUs, constructive feedback to ULT freezer manufacturers, and comprehensive data to those purchasing ULT freezers or designing laboratory facilities. Should the industry choose to act on the recommendations outlined in this report, California could potentially realize annualized energy reductions of at least 14-49 million kWh in 2017.

INTRODUCTION

Laboratories are one of the next major frontiers in energy efficiency. After data centers, laboratories consume more energy per square foot than any other type of facility, due to energy-intensive equipment, around-the-clock operations, 100% outside air requirements, and high airflow rates. While recent years have seen the emergence of energy reduction plans for laboratory buildings, widespread conversation about laboratory operations and equipment has stalled due to a lack of information on market size and energy consumption, which has been further obscured by the complex relationships between facility managers, manufacturers, procurement departments and end-users. Stakeholders across California, from scientists to vendors, building designers to energy managers, are clamoring for someone to address energy efficiency in laboratory equipment and operations. They recognize that a future in which funding is wisely spent on energy-efficient equipment will see more money funneled into research rather than overhead, and a more equitable sharing of institutional and communal resources. They also acknowledge the potential non-energy benefits of increased overall efficiency, including enhanced safety, improved performance, higher productivity, and reduced environmental impact.

With the support of the California investor-owned utility companies (IOUs), the Center for Energy Efficient Laboratories (CEEL) has taken a significant step toward addressing energy efficiency in laboratories by assessing and quantifying energy consumption from plug loads. A recent study completed by the CEEL[1] identified a minimum of 116 million square feet of laboratory space in California in just the academic, life science research, and hospital market sectors, and found that the research market is growing steadily at an average rate of 5% per year. The study also found that state-wide plug loads from just 13 pieces of commonly used laboratory equipment consume 0.8 – 3.2 TWh/year.

California Lab Equipment Estimates	Equipment Density (units/lab)	Approx. Number (thousand units)	Est. Energy Consumption (GWh/yr)
-80 Freezer	2.9	58	228 – 648
-20 Freezer	3.7	74	126 – 363
Refrigerator	3.7	95	19 – 254
Fume Hood*	3.0	60	661 – 1322
Fluo Micro	1.7	34	6 – 12
Centrifuge	3.8	76	12 – 227
Water Bath	2.6	52	115 – 201
Heat Block	3.0	60	15
PCR Machine	2.2	44	35
Incubator	3.0	60	41 – 524
Shaker	1.2	24	53
Autoclave	0.8	16	26 – 527
Vac Pump	2.1	42	1 – 115
TC Hood	1.7	34	106 – 235

* HVAC electricity consumption due to fume hoods

The CEEL study identified several categories of equipment that present opportunities for energy savings in laboratories, which are summarized in the adjacent table. Of these, only refrigeration has been studied in any depth, and within that category, ultra-low temperature (ULT, -80°C) freezers have garnered the most attention.

The annual statewide energy consumption of ULT freezers exceeds 400 million kWh. Though energy-efficient ULT freezers have been available in the life sciences market for over five years, growth in their adoption has been stunted by the prevalence and institutionalization of older equipment, and a pervasive skepticism of new technology. In addition, the absence of objective, independent, third-party energy testing has made it difficult for end-users to validate manufacturers' promises of greater efficiency and performance.

To provide the needed energy and performance data of new ULT freezer technology, this study sought to evaluate a wide range of ULT freezers on the basis of energy consumption, temperature uniformity, and thermal stability. These tests were conducted in both an ISO 17025 accredited test facility and in the field. The effect of ULT freezers on HVAC system performance was also studied in an effort to understand the overall impact of this technology on whole-building energy consumption. In addition, the study included a comprehensive review of the ULT freezer market, in which data were collected on the size, model, age, location, temperature set point, and purchase price of ULT freezers across California and the greater United States. The data, findings, and recommendations in this report provide the necessary foundation upon which manufacturers, end-users, government agencies, and the IOUs will collaborate to move the market toward the adoption of energy-efficient ULT freezer technology.

CHAPTER 1: BACKGROUND

This project constitutes Phase II of a larger effort by the Center for Energy Efficient Laboratories (CEEL) to benefit the Investor-Owned Utilities (IOUs), their customers with laboratories, laboratory equipment manufacturers, and those industry stakeholders involved with laboratory efficiency projects and programs. Founded in 2015 and led by My Green Lab, the CEEL was formed to develop the standards and methods necessary to bring about widespread adoption of energy-efficient practices in scientific research. It is a partnership between My Green Lab, Fisher-Nickel, Inc. (FNI), and kW Engineering.

The $101 billion biomedical industry is the second-largest industry in California, directly employing 270,000 people[2]. This industry is supported by an extensive network of top-tier academic research institutions, which collectively received more than $3.3 billion in NIH funding last year[3]. Hospital research conducted in over 200 hospitals in California also contributes substantially to the state's economic development.

The bioscience market is strong and significant outside California as well. Nationwide, the bioscience industry directly employed 1.62 million people in 2012, and accounted for an additional 5 million jobs. It has grown at a rate seven times faster than the total US private sector since 2001, and its growth continues to outpace most industries[4]. One sector of the US biosciences industry, biopharmaceuticals, generated $789 billion alone in 2013, or 2.9% of total US economic output[5].

Behind these market statistics are scientists working in laboratories. California is home to the largest number of academic research laboratories in the country[6], and San Diego and San Francisco have the highest density of biotech companies outside of Boston[7]. Laboratories can consume 3-5 times more energy per square foot than typical office spaces[8] due to their use of energy-intensive equipment and requirement for high airflow rates using 100% outside air. However, detailed study of laboratory energy consumption has only recently begun in earnest, and the lack of measured data for equipment energy usually leads facility designers to overestimate laboratory plug loads. Space conditioning systems are therefore typically oversized, resulting in large inefficiencies under normal operating conditions.

An analysis of the size, scope, and equipment loads in life science research laboratories across California was conducted in 2015[9]. This report is referenced herein as the CEEL Laboratory Market Assessment. In the ~116 million square feet of lab space in California, just 13 pieces of laboratory equipment, of the 32 studied, were found to collectively consume as much as 3.2 TWh/year. The study also revealed several opportunities for energy conservation in laboratories, including the replacement and/or powering off of refrigeration equipment, autoclaves, incubators, and water baths. ULT freezers were identified as one of the largest energy consumers in the lab, drawing an estimated 400 million kWh/year in the state.

ULT freezers have a long history in the life science research market. The first laboratory freezer was manufactured in 1968 by ScienTemp[10]. Early laboratory freezers achieved temperatures of -20°C to -40°C; ULT freezers, with temperatures generally ranging from -56°C to -86°C, came into the marketplace in the 1970s. Within these temperature ranges, scientists generally chose their own temperature set points. Interestingly, when these freezers were first introduced, they were often set to -70°C, and in fact were referred to as 'minus seventies'. The past two decades have seen temperature set points generally fall to -80°C, and the common name of these freezers adjusted accordingly, from 'minus seventies' to 'minus eighties'.

Achieving such low temperatures was no small feat. Refrigeration systems are designed to remove heat, and the wide temperature range between room temperature and ULT freezer temperature requirements is simply too large for one refrigerant-compressor system to accommodate. The first breakthrough in ULT freezer technology came with the development of the cascade system, which utilizes two individual compressor-refrigerant circuits in which one operates in a high stage configuration and the other in a low stage one. In a cascade system, the low-stage circuit removes heat from the freezer cabinet as the refrigerant absorbs heat and evaporates. After compression of the refrigerant by the low-stage compressor, this heat is transferred to the high-stage via an interstage heat exchanger which acts as the condenser of the low-stage circuit and the evaporator of the high-stage circuit. The condenser coils of the high-stage circuit are exposed to room air. In this way, heat is removed through a two-step process, from the inside of the freezer to the interstage heat exchanger, and from the heat exchanger to the outside. The compressors cycle on and off in response to feedback from a temperature sensor located in the freezer cabinet.

The dual-compressor cascade system continues to be the most widely used technology for ULT freezers. Variations on this technology, including the use of a single compressor with two different refrigerants, are also in use, but the basic principle remains the same. In the United States, most manufacturers use synthetic refrigerants, such as R-508 for the low stage and R-407D for the high stage. Synthetic oil is also used to maintain the integrity of the compressors.

Recent regulations in Europe over high global warming potential refrigerants, like those cited above, and the slow realization that ULT freezers consume large quantities of energy, have begun to drive the market towards new technologies. The first major recent development in ULT freezer technology came in 2010, when Stirling Ultracold built its ULT freezers around a Stirling cooling engine instead of a dual-cascade compressor system. The Stirling freezer uses an electrically driven free-piston engine, which is located at the top of the freezer and employs helium as its working medium. The engine operates at constant frequency and piston stroke amplitude is varied to modulate the cooling capacity in response to demand. Connected to the cold head of the engine is a thermosiphon, a sealed copper tube that wraps around the interior of the freezer cabinet. The thermosiphon contains ethane (R-170) as a refrigerant. Liquid ethane flows via gravity down the length of the tube, where it absorbs heat from the interior of the freezer. As it warms, the ethane transitions from a liquid to a vapor and rises up the tube. At the cold head of the engine, the ethane is condensed back into a liquid. The thermosiphon does not include any mechanical moving parts.

In 2016, Thermo Fisher Scientific released a new ULT freezer technology – the V-drive. In this freezer, the compressors and condenser fans to run at variable speeds in response to varying load demand. When the freezer door is opened, for example, the V-drive is likely to operate in 'high speed' mode in order to maintain internal temperature. Overnight, when the freezer is unlikely to be actively used, the V-drive ramps down into 'low speed' mode. The compressor construction is similar to standard compressors with the inverter drive (converting A/C input to simulated 3 phase variable frequency output) and the motor being the unique difference.

These advancements in ULT freezer technology, including others that have optimized the fans, compressors, and condensers, in combination with the recent adoption of natural hydrocarbon refrigerants, have all been made with energy efficiency in mind. In addition, vacuum-insulated panels and high performance polyurethane insulation have contributed to improved efficiencies. These technologies are employed by several ULT freezer manufacturers, including Eppendorf and Panasonic.

With these innovations, ULT freezers have been a focus of laboratory energy efficiency for nearly a decade. Several field studies have been conducted on the energy consumption of various models of upright ULT freezers. The most recent study, published by the Better Buildings Alliance in 2014[11], documented the energy consumption of four different models of upright ULT freezers at three universities. The study found that the newer freezer models consumed less energy than the older legacy models, and that at least one of the models tested was significantly more efficient than the others. The study further noted that the energy savings associated with the more energy efficient model were at least 9 kWh/day. Additional independent field studies have confirmed that the energy savings opportunities for ULT freezers range from 5-10 kWh/day. Because of this, customized incentive programs have been utilized across California to provide financial incentives for the purchase of energy-efficient ULT freezers. This activity has driven the EPA ENERGY STAR® program to initiate the development of a test method for ULT freezers with the goal of supporting a new product specification for this product category.

With such interest and activity surrounding the promotion of energy-efficient ULT freezers, it is surprising that there has been little effort to evaluate their energy use under the controlled conditions of the ENERGY STAR test method. Room conditions, freezer locations, freezer capacity utilization, and test procedures have all varied widely in the previously-conducted industry studies, making it impossible to compare results and draw uniform conclusions. Moreover, few of the tests have sought to evaluate temperature stability, which is one of the most important, if not the most important, feature of a ULT freezer.

ULT freezers are used in a wide range of life science research laboratories for the same purpose – to maintain the integrity of samples and reagents for long periods of time (usually longer than six months). Biological activity is significantly reduced at the low temperatures maintained by these freezers, allowing for the preservation of samples such as RNA, protein, cell extracts, and tissue[12]. There are an average of approximately three ULT freezers per life science research lab in California[13], with an estimated inventory of 58,000 in the state. However, life science research laboratories are not the only labs or facilities that have ULT freezers – they are found in industrial and chemical labs, manufacturing facilities (particularly in the pharmaceutical industry), and biorepository and blood-banking facilities. In all instances, reliability, thermal stability, and temperature uniformity are critically important. And although academic labs tend to purchase ULT freezers based on vendor datasheets, manufacturing facilities and biorepositories will often independently validate new ULT freezers to ensure that they meet strict internal performance standards.

To properly evaluate new ULT freezer technology, it was thus necessary to perform a comprehensive study of ULT freezer performance and energy consumption in a standard, systematic manner. The EPA ENERGY STAR test method formed the foundation for evaluating ULT freezers under controlled conditions. However, this test method differs from field conditions in several key ways, making it necessary to overlay an evaluation of the temperature and energy performance of ULT freezers as they are used in the field. As a point of comparison, baseline data from traditional, cascade compressor upright ULT freezers were collected alongside data from newer upright ULT freezer models. Whole building energy models were developed in order to understand the interactive effects of ULT freezers on HVAC systems, the results of which should be used to inform the future design of laboratories.

This study also characterized the existing ULT freezer market with respect to freezer model, capacity, age, turnover, and pricing. Energy-efficient freezer designs have been on the market for the last six years, yet these new technologies have not been widely adopted. Understanding the underlying reasons for this lack of market share is an important step in moving the market toward energy-efficient solutions.

Taken together, the results presented in this report are intended to provide guidance to the California IOUs, constructive feedback for ULT freezer manufacturers, and comprehensive data for people purchasing ULT freezers or designing laboratory facilities in the life science research market. Should the industry choose to act on the recommendations outlined in this report, it is conceivable that California could see annualized energy reductions of at least 14-49 million kWh in 2017.

CHAPTER 2: ASSESSMENT OBJECTIVES

The main objectives of this project were to:

- Use the existing EPA ENERGY STAR test method to evaluate upright ULT freezers from a variety of manufacturers under controlled environment and field conditions.
- Evaluate ULT freezer temperature and energy performance under simulated working laboratory conditions at a research facility.
- Model the effects of ULT freezers on HVAC energy use.

- Characterize the ULT freezer market with respect to market size, turnover, and pricing strategies, and evaluate the market changes that might result from program interventions and other external influences.

This project was completed with the intent of providing recommendations to the California IOUs, their customers, and equipment manufacturers regarding strategies for increasing market penetration of energy-efficient ULT freezers. Doing so required confirming that freezers marketed as "energy efficient" actually demonstrate better overall performance. The energy savings of new ULT freezer technology over incumbent technology have therefore been calculated as part of this assessment, and are further used as a basis for framing potential incentive programs.

CHAPTER 3: TECHNOLOGY/PRODUCT EVALUATION

Fifteen upright ULT freezer models of varying storage capacity were evaluated in a standard, independent test facility, and seven of those 15 were further evaluated in the field at a customer site. The test facility evaluated the ULT freezers according to the EPA ENERGY STAR test method; the field evaluation differed in several key ways that resulted in it being a more accurate representation of how the products are used by end-users. The 15 ULT freezers tested utilized both older, dual-compressor technology, as well as newer technology such as the Stirling engine, variable speed compressors, and energy-efficient freezer components. The intention of testing such a wide range of equipment and technologies was to establish the baseline for ULT freezers using older technology, and to compare those to ULT freezers using new technology.

ULT freezer evaluation according to the ENERGY STAR test method was performed at the Food Service Technology Center (FSTC) in San Ramon. This site was chosen owing to the FSTC's decades of experience testing refrigeration equipment. The tests conducted at the FSTC will heretofore be referred to as the controlled environment tests.

The field test was performed at Amgen in Thousand Oaks in a freezer farm. The freezer farm is located in the basement of one of the research buildings, and although the space is nearly full, accommodations were made to allow for this project. The test site criteria were numerous:

- research laboratory facility
- space for up to seven upright ULT freezers
- electrical outlets satisfying the requirements of the freezers
- test site personnel willing and able to open freezer doors at predetermined time points throughout the day
- on-site access for the team

Amgen not only met these criteria but they also have an organizational interest in energy-efficient ULT freezers, making their facility an ideal place to conduct a field test. In addition, this was a co-funded project by the California IOUs, and every effort was made to ensure that each territory contributed to the overall study.

Both the FSTC and Amgen test sites were staffed with personnel familiar with freezer technology. Work at the Amgen test site in particular was aided by several staff members who had previously conducted field tests of ULT freezers in other buildings on the campus. The tests were performed by contractors in addition to staff, including Azzur, a company that specializes in ULT freezer testing and validation, and My Green Lab, a non-profit whose staff has expertise in laboratory equipment operation and use.

In both the controlled environment and field tests ULT freezers were compared on the basis of normalized energy consumption, thermal stability, and temperature uniformity. The ULT freezers studied in the field were subject to further testing; the freezers were validated according to an Amgen-specific validation protocol. Detailed information about how the freezers were assessed can be found in Chapter 4.

In addition to evaluating new ULT freezers, it was also important to establish an energy consumption baseline for these freezers in the field. Therefore several ULT freezer models of varying ages and sizes were metered at laboratory facility locations in the Bay Area. Additional data were collected from facilities across California that had endeavored to meter their freezers on their own. Taken together, these data illustrate the landscape of the existing market, and this should be used as the backdrop against which the data gathered from the new freezers are evaluated.

The Table 1 below summarizes the different methods used to evaluate ULT freezer technology.

TABLE 1: SUMMARY OF ULT FREEZER EVALUATION METHODS

ULT FREEZER RESULTS	TEST METHOD	DATA SOURCE
New ULT Freezers A-O	ENERGY STAR (Controlled Environment Test)	This Study, FSTC
New ULT Freezers A-H	Controlled Field Test	This Study, Amgen
Existing Freezers from University (2)	Field Test	This Study
Existing Freezers from Biotech (5)	Field Test	This Study
Existing Freezers, Additional Data (101)	Various	Other Studies

CHAPTER 4: TECHNICAL APPROACH/TEST METHODOLOGY

ULT freezers evaluated for this study were chosen to be representative of the market. Detailed information on the ULT freezer market can be found in Chapter 5.

CONTROLLED ENVIRONMENT ENERGY STAR TEST OF UPRIGHT ULT FREEZERS

Fifteen upright ULT freezers were brought into the Food Service Technology Center (FSTC) testing facilities for evaluation of their performance characteristics, and to compare energy and temperature metrics in a controlled environment to their operation in a field setting. Freezers were tested in a climate controlled chamber that maintained ambient temperature and humidity according to the specification in the published ENERGY STAR test method. Temperature was regulated by dispersed streams of low velocity air, which were either heated or cooled based on the measured room conditions. Humidity was regulated by intermittent dispersions of steam into the climate chamber, based on humidity measurements. The dry bulb temperature was kept at 75.2°F ± 1.8°F and the wet bulb temperature was kept at 64.4°F ± 1.8°F.

FIGURE 1: CONTROLLED ENVIRONMENT TESTING

FIGURE 2: CONTROLLED ENVIRONMENT TESTING

Units tested had either a 120V or 208V power supply and were connected to a power meter with a minimum resolution of 0.02 Wh.

The tested freezer was monitored for electric energy usage and internal temperature. Electric energy usage was monitored by a calibrated energy meter and freezer temperature was monitored by an array of validated thermocouples. Type K thermocouples (TCs) were arranged within the freezer such that there were 3 TCs arrayed diagonally across three horizontal planes: 3 inches from the top, at the center of the freezer, and 3 inches from the bottom. These TCs were submerged in 5 mL vials filled with a porous foam material and a 50/50 mixture of glycol and distilled water to dampen temperature fluctuations and more accurately represent freezer sample temperature variations (see Figure 4). Freezers with four or more compartments had an additional temperature measurement per compartment not occupied by the three horizontal planes. All TC wires were routed through the designated temperature channels built into the ULT freezer cabinet and were sealed using a factory-provided plug (Figure 5). Prior to testing, all the TC junctions were placed near a calibrated RTD inside the ULT freezer for verification near the desired testing temperatures. All freezer energy and temperature data were collected at an interval of five seconds through a data acquisition system and recorded in a spreadsheet.

FIGURE 3: FREEZER THERMOCOUPLE PLACEMENT LOCATIONS

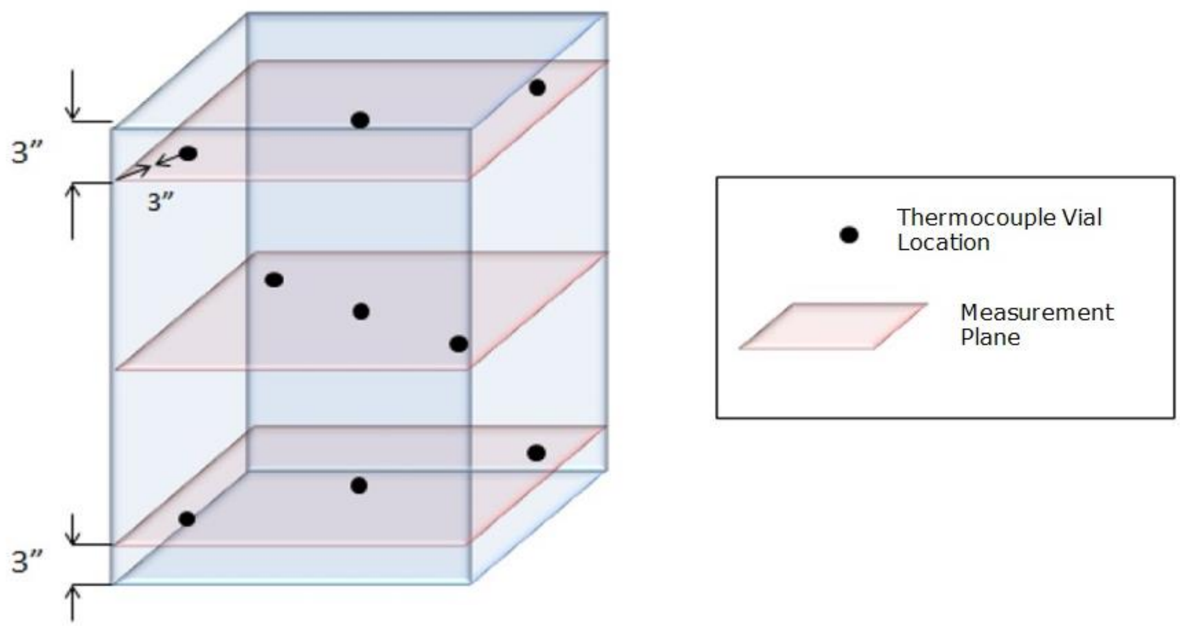


FIGURE 4: GLYCOL SOLUTION FOAM VIALS

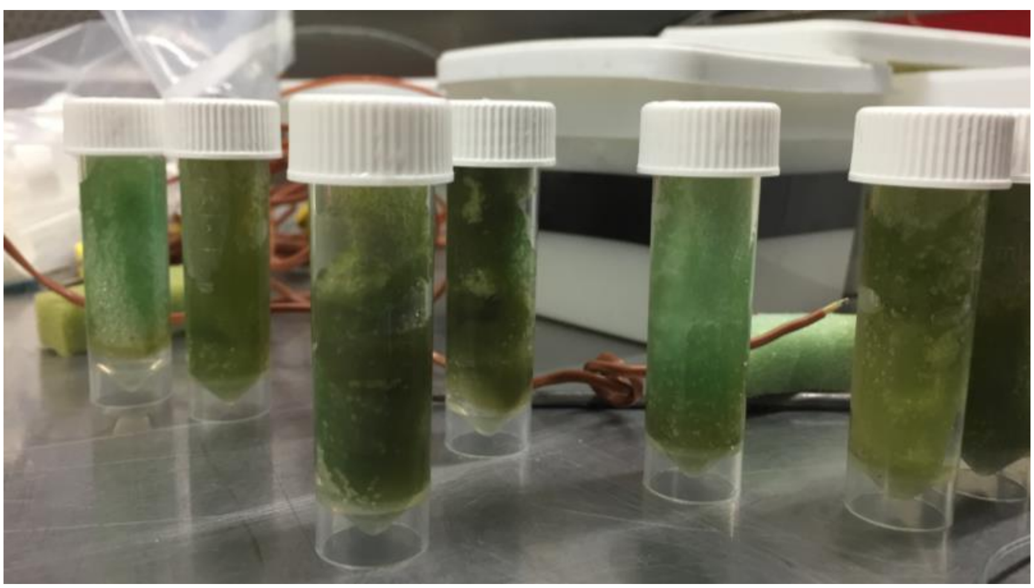


FIGURE 5: THERMOCOUPLE ROUTING

FIGURE 6: THREE COMPARTMENT FREEZER VIAL PLACEMENT

FIGURE 7: FIVE COMPARTMENT FREEZER VIAL PLACEMENT

Humidity was maintained by an electric humidifier placed inside the room with the humid air being dispersed with a low velocity fan. Conditioned air was supplied to the room through large area perforated diffusers at low velocity and exhausted at a flowrate of 700 cfm. The supply and exhaust fan were balanced based on the differential pressure between the inside and outside of the conditioned room with no air currents exceeding 49 fpm. Humidity and temperature gradients were measured with two humidity sensors and TCs located 36 inches from the front of the ULT freezer, at the geometric center of the ULT freezer door, and 6 in above the highest point of the ULT freezer.

The ULT freezers were stabilized for at least 24 hours prior to the beginning of the test. ULT freezers were deemed 'stable' when the internal temperature reached equilibrium and the average temperature during compressor cycles did not exhibit a downward trend. The freezer thermostat was adjusted to maintain an average temperature of -80°C in the placed-vial TCs, as shown in Figures 6 and 7. The door opening test was conducted for a duration of 24 hours. During the first 6 hours, the door was opened every hour for 15 seconds at a time. In total the door remained open for 90 seconds over the 6-hour period. During each opening the main door and the top inner compartment door were opened to an angle of 90 degrees, over a duration of 2 seconds each, with the door remaining fully open for 15 seconds. The steady-state test was conducted for a duration of 24 hours immediately following the last door opening. Both tests were repeated for internal freezer temperature of -70°C.

During TC validation, it was observed that the ULT freezer temperature set point often did not match the average temperature reading of the TCs arranged in the freezer. This is most likely due to the fact that most ULT freezers adjust their temperature based on one or two temperature readings in the vertical center of the freezer.

The controlled environment test setup includes temperature measurements close to the top and the bottom of the freezer, which, due to temperature stratification, is different from a single vertical center reading. Thus, prior to the energy usage testing, ULT temperature set points were adjusted to provide average measured temperatures of -70°C and -80°C, as specified by the test standard. Listed below are the adjusted temperature set points for each freezer.

TABLE 2: ULT TEMPERATURE SET POINTS USED TO OBTAIN DESIRED AVERAGE VIAL TEMPERATURE

ULT FREEZER	SET POINT FOR -70°C AVERAGE VIAL TEMP (°C)	SET POINT FOR -80°C AVERAGE VIAL TEMP (°C)
A	-73.0	-84.0
B	-71.0	-82.0
C	-74.0	-85.0
D	-72.5	-84.5
E	-74.0	-84.0
F	-71.0	-81.0
G	-72.0	-86.0
H	-72.0	-86.0
I	-72.0	-83.0
J	-70.0	-84.0
K	-71.0	-82.5
L	-73.0	-83.0
M	-69.5	-81.5
N	-74.0	-85.0
O	-70.0	-83.5

BASELINE DATA GATHERING

Two field test sites in the Bay Area were selected to gather data on energy consumption of existing upright ULT freezers in laboratories. One site was a university and the other was a biotech incubator.

BASELINE DATA GATHERING AT UNIVERSITY FIELD TEST SITE

Two ULT freezers were evaluated in a university setting. The test site was chosen because the lab was representative of a 'typical' university lab, and because the lab members were particularly interested in energy efficiency. The lab was curious about the energy consumption results, as they planned to use the data to justify the purchase of a new, energy-efficient freezer. Thus they were ideal partners for a baseline energy field study. The freezers were located in a corridor that separated the main lab space from smaller, specialized rooms. All of the labs on that floor housed their ULT freezers in this corridor. The laboratory to which the test ULT freezers belonged could be broadly classified as a biology lab. One of the ULT freezers was ~5 years old and the other was ~30 years old. The two ULT freezers were from different manufacturers.

The two ULT freezers at the university test facility were metered using customized energy meters. Electric meters for field testing were configured at the FSTC. These meters consisted of Continental Control WattNode energy meters and current transducers paired with a HOBO pulse data logger, encased in a protective UL-approved enclosure and attached to the appropriately sized electrical plug. Depending on the electrical requirements, energy meters were wired in Y configuration for 120V or 208V single phase true energy (voltage and amperage) monitoring. The current transducers were sized at 20A for ULT freezer maximum nameplate amperages ranging between 8 and 16A, and at 50A for one 30A ULT freezer. Data loggers were programmed to collect cumulative watt hour measurement readings every 30 seconds and had sufficient battery life to last 3 months without replacement.

Meters were installed for a minimum of two weeks. The freezers were metered sequentially, beginning with the newest.

The ULT freezers were also outfitted with door sensors (Hobo loggers) in order to determine when the doors were opened and for how long (Figure 8). These data were correlated with the energy consumption data.

FIGURE 8: DOOR SENSOR PLACEMENT

The temperature and relative humidity of the equipment corridor was also measured using a Hobo logger. This instrument logged data every 15 minutes.

FIGURE 9: TEMPERATURE AND HUMIDITY GAUGE

All data were downloaded to HOBOware Software upon completion of the field study, and all analysis was performed in Excel.

BASELINE DATA GATHERING AT BIOTECH FIELD TEST SITE

Four upright ULT freezers were evaluated at a biotech incubator. The incubator houses several start-up biotech companies, all of which share the ULT freezers that were metered. This test site was chosen because it was markedly different from the university test site. This facility had purchased five of the same ULT freezer model around the same time, and the freezers were located in the lab itself, not in a hallway corridor. The freezers were in a row against a wall at the back of the lab. The manager of the facility was very supportive of the data gathering, which made this field test site more attractive than other potential candidates.

The four ULT freezers at the biotech test facility were metered using the customized energy meters described above. The meters were provided by the FSTC and installed by My Green Lab personnel. Meters were installed for a minimum of two weeks, and energy data were collected every 30 seconds. To expedite the testing, two freezers were metered at a time.

The ULT freezers were also outfitted with door sensors (Hobo loggers) in order to determine when the doors were opened and for how long. These data were correlated with the energy consumption data.

The temperature and relative humidity of the lab were also measured using a Hobo logger. This instrument logged data every 15 minutes.

All data were downloaded to HOBOware Software upon completion of the field study, and all analysis was performed in Excel.

FIELD TEST OF ULT FREEZERS: EVALUATION OF NEW TECHNOLOGY

New ULT freezers were evaluated in a working research laboratory facility, Amgen in Thousand Oaks. Seven new ULT freezers were shipped to a freezer farm, located in the basement of one of the main research buildings on the campus. The freezer farm was home to over 50 freezers at the start of the field study; space was made to accommodate four new ULT freezers at a time. The field site was chosen for many reasons including the availability of space, on-site staff support, and previous experience with ULT freezer field testing.

FIGURE 10: FIELD TEST FACILITY

FIELD TEST OF ULT FREEZERS: TEST & INSTRUMENTATION PLAN – EVALUATION OF NEW TECHNOLOGY

Of the seven ULT freezers tested at this site, six were shipped after they had completed the controlled environment ENERGY STAR test at the FSTC in San Ramon. The other freezer was shipped directly to the site due to time constraints. The first round of freezer testing began in May 2016, with Freezer A and Freezer B being tested first, followed shortly thereafter by Freezer D and Freezer F. The second round of freezer testing began at the end of June 2016, and during this time both Freezer D and Freezer F were re-evaluated, and Freezer G, Freezer E, and Freezer C were tested for the first time. All freezers were located in the same row, apart from Freezer G, which was located in the row directly across from the others. Freezers in the freezer farm are placed back-to-back, so that two rows of freezers can share one row of outlets.

Per the requirements of the test site, all freezers delivered for this project were subject to validation. Prior to validation, all freezers were calibrated by a licensed company, Al-Tar Services. Freezers were calibrated with NIST traceable standards per Amgen standard operating procedure.

The validation protocol involved testing ULT freezers both empty and full. The empty chamber test lasted a minimum of 24 hours. After the TCs were calibrated, they were placed in the freezer according to the positions outlined below. Kaye data loggers were used to collect data every fifteen minutes until the end of the study. The acceptance criteria required that all TCs maintain an operating range of ≤65°C.

The loaded chamber test also lasted a minimum of 24 hours. The TCs from the empty chamber test were kept in the positions from the empty chamber test. The Kaye data loggers were used to collect data every fifteen minutes until the end of the study. The acceptance criteria required that all TCs maintain an operating range of ≤65°C

In general, a minimum of three TCs were placed diagonally on each shelf. The upper and lower shelves had TCs in each of the four corners and one in the center of the shelf. An example of a five-shelf and four-shelf freezer are shown below in Figures 11 and 12. Details of TC placement for all ULT freezers are given in Appendix A.

FIGURE 11: THERMOCOUPLE PLACEMENT – FREEZER A

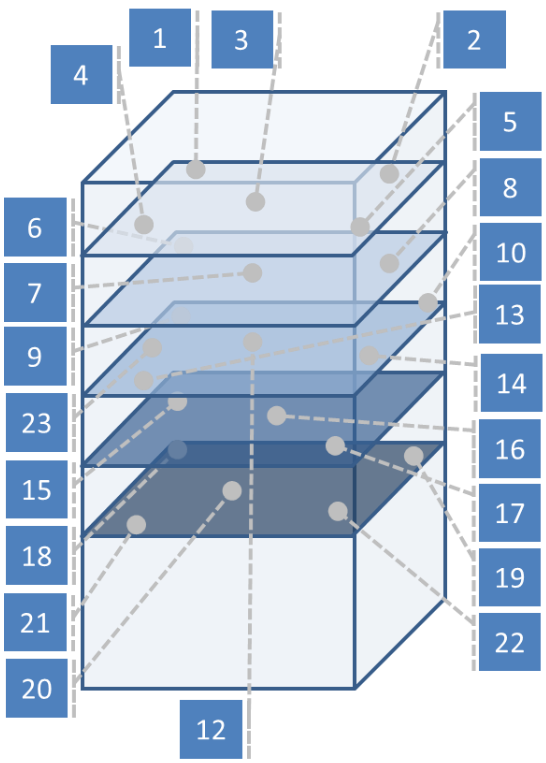
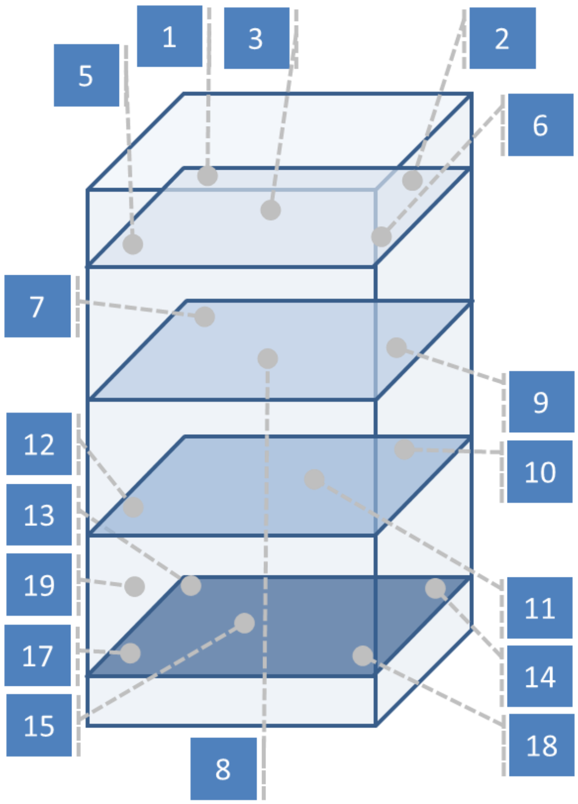


FIGURE 12: THERMOCOUPLE PLACEMENT – FREEZER B



During the validation, energy meters were installed and door sensors were placed on the freezers. The energy meters were custom-made by the FSTC, as described above, and the door sensors were Hobo loggers. Energy data were gathered at 30-second intervals for the duration of the study.

FIGURE 13: THERMOCOUPLE PLACEMENT

Once the freezers had been validated the field study commenced. The meters and TC configurations used for the validation were maintained for the field study, and all equipment had a logging interval of 30 seconds. All freezers were tested at full capacity as described below in Table 3. Water bottles were used to simulate thermal mass when racks and boxes were not provided by the manufacturers.

TABLE 3: ACHIEVING FULL ULT FREEZER CAPACITY

FREEZER	MODE OF REACHING CAPACITY
Freezer A	Top 3 Shelves: Racks & Boxes Bottom 2 Shelves: Water Bottles
Freezer B	Racks & Boxes
Freezer C	Racks & Boxes
Freezer D	Water Bottles
Freezer E	Top 2 Shelves: Racks & Boxes Bottom 2 Shelves: Water Bottles
Freezer F	Racks & Boxes
Freezer G	Racks & Boxes

FIGURE 14: THERMOCOUPLE PLACEMENT IN FULL ULT FREEZER

FIGURE 15: ULT FREEZER FILLED WITH WATER

The field study included opening the freezer doors according to a protocol. This protocol was developed in conjunction with the baseline energy studies described above. Door sensor data from the university and biotech freezers were analyzed. Both exhibited similar frequency and duration patterns, and thus one representative freezer door opening pattern was chosen as the model for the larger field study. The detailed protocol can be found in Appendix E. In brief, the door was opened between 3 and 13 times per day for durations ranging from 10 seconds to 2.5 minutes. Doors openings in the field study differed from door openings done in the controlled environment test facility – in the field study, first the outer door was opened, then at least one inner compartment was opened, and racks/samples were removed to mimic a person looking for a sample. This procedure more closely approximates the actual use of a ULT freezer than the controlled environment ENERGY STAR door opening protocol. ULT freezer doors were opened sequentially, such that Freezer A's door was opened at t1, and Freezer B's door was opened at t1+ [door opening duration]. This method was chosen as it was not possible to open all freezer doors at once for the short durations.

Door openings were performed by four individuals, three of whom were employed at Amgen. All individuals were trained on the protocol and were observed by the project manager to maintain consistency. The door opening protocol was posted on each freezer door, and all who participated in the study were asked to sign off on the door openings that they performed, as well as to make note of any changes to the schedule. In this way door sensor data were corroborated by data logs.

The field study lasted for two weeks for each freezer. During the first week, the door opening protocol was performed at one temperature set point (-80°C or -70°C), and the second week the same protocol was repeated for the other temperature set point. Repeating the test at two different temperature set points provided a consistent comparison to the controlled environment tests conducted in accordance with the ENERGY STAR test method. All field tests commenced on a Friday and ended on a Thursday. The doors were not opened on the weekends.

Data from the Kaye validators were gathered and compiled by Azzur into an Excel spreadsheet. Data from the energy meters and door sensors were downloaded into HOBOware Software and subsequently exported to Excel for analysis. Temperature, energy, and door sensor data were correlated with each other in Excel.

A temperature and humidity sensor was introduced into the field study in July. This sensor captured data every 15 minutes and gathered data in the freezer farm for three weeks.

A comparison between the ENERGY STAR test method and the field test method is shown in the table below.

TABLE 4: COMPARISON BETWEEN ENERGY STAR TEST METHOD AND FIELD TEST METHOD

PARAMETER	ENERGY STAR TEST METHOD	FIELD TEST METHOD
Freezers Tested	15	7
Temperature Settings	-80°C, -70°C	-80°C, -70°C
Door Openings	6 openings, 1x/hour for 15 seconds	various, see Appendix E
Number of Thermocouples	3 per shelf, diagonally placed	5 on top and bottom shelves, 3 per middle shelf
Full/Empty Freezer	Empty	Full
Duration of Test	30 hours at each temperature setting	7 days at each temperature setting

Surveys Used for HVAC Impact Work

Calculation of the HVAC energy impacts associated with ULT freezer energy efficiency requires data on both ULT freezer locations within lab buildings and the HVAC systems serving those space types. While the surveys targeted to scientists (see Market Assessment below) can be used to establish ULT freezer location data, these respondents are not typically sufficiently familiar with HVAC system configurations to answer questions about design and operational parameters. A supplemental study addressing both ULT freezer locations and lab HVAC systems was therefore designed and distributed to facility managers in California. Data were also gathered from a consulting firm's back catalog of lab building energy audits and from facility walkthroughs conducted as part of this study.

Table 5 provides a summary of the survey data used to calculate HVAC energy impacts, along with the total number of responses and total number of freezers in each survey sample. Approximately 15% of all 58,000 ULT freezers in California were involved in the survey work carried out as part of this study.

Details on surveys specific to the HVAC energy impact calculations are provided below.

Facility Manager Survey

This online survey targeted facility managers to obtain information on both ULT freezer locations and typical design and operational parameters of the HVAC systems serving each location type. The survey questions and (anonymized) detailed results are provided in Appendix F.

The survey yielded a total of eight responses over a period of several months.

For one of the facilities, ULT freezer locations were taken from an on-campus equipment inventory and not from facility manager responses to the survey.

Energy Audit Back Catalog Search

This survey examined 30 lab building energy audit reports from one consulting firm's records. Typical lab building sizes, configurations, lab area fractions, HVAC system types, and HVAC control parameters were noted where provided in the audit reports. To maintain client confidentiality, the raw data are not provided in this report.

Facility Walkthroughs

While surveying freezer brands and ages, ULT freezer locations were noted. This sample was used in conjunction with the other location datasets to establish overall average freezer locations. Six facilities were studied in this way.

TABLE 5: SUMMARY OF SURVEY STRATEGIES RELATING TO HVAC IMPACT CALCULATIONS

SOURCE	# RESPONSES	# RESPONSES FROM CA	# ULT FREEZERS	ULT FREEZER LOCATIONS	HVAC SYSTEMS SERVING LABS
Online Survey of Scientists	227	48	885	Yes	-
American Society for Cell Biology Conference	220	65	493	Yes	-
Online Facility Manager	8	8	7,647	Yes	Yes
Energy Audit Back Catalog	30	30	N/A	-	Yes
Facility Walkthroughs	6	6	461	Yes	-

ENERGY MODELING

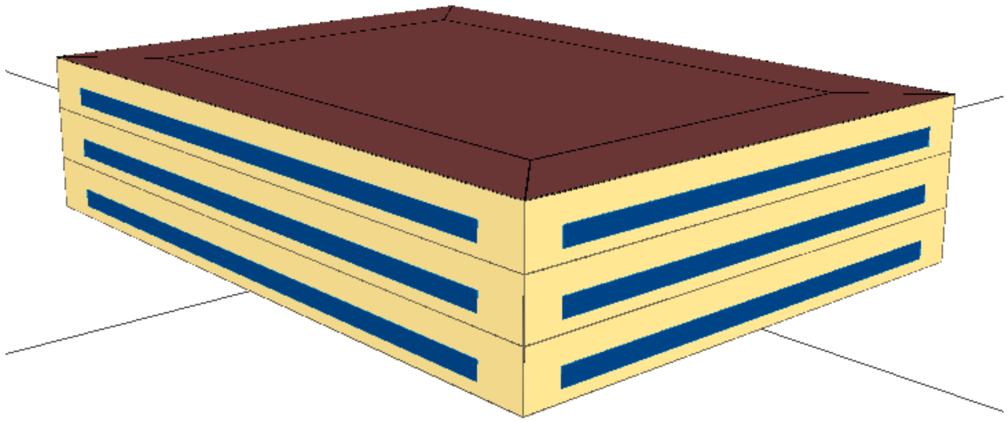
An eQUEST energy model was used to determine the effects of improved ULT freezer efficiency on HVAC energy consumption. The model was used to calculate the HVAC energy impacts per unit of "direct" freezer energy savings.

The model was designed to be analogous to the California Database for Energy Efficient Resources (CA DEER) prototype models for other building types. No laboratory building prototype has previously been developed.[14] This new California Lab Prototype model, the first of its kind, can also be easily extended to applications beyond this study.

Data obtained from the facility manager and audit back catalog surveys were combined with lab building data from the Labs21 Benchmarking Tool database, the CEEL Laboratory Market Assessment, and selected other references, and used to establish inputs for the model that represent typical design and operating parameters of lab buildings in California.

This approach to calculating HVAC energy impacts is significantly more in-depth and well-tuned to lab buildings than the approach used in the DOE Field Demonstration report. In particular, the DOE analysis did not consider the effects of high ventilation rates and year-round reheat in many spaces within lab facilities. The more sophisticated method used here includes typical laboratory HVAC system design and operational parameters, as well as the crucial dependence of HVAC impacts on the type of space in which the ULT freezer is located. Additionally, the lab prototype model can be easily adapted to future studies of HVAC impacts associated with lab energy efficiency upgrades.

FIGURE 16: EXTERIOR GEOMETRY OF THE LAB PROTOTYPE EQUEST MODEL



The eQUEST model (v3.65) was constructed to contain thermal zones representing all four space types identified as common ULT freezer locations. The HVAC systems serving the building were selected to match typical properties from the facility manager survey. Selected critical modeling parameters are shown in the Results section; details are provided in Appendix G of this report.

To model the effect of improved ULT freezer efficiency on HVAC energy consumption, each space in which ULT freezers might commonly be found was assigned an incremental equipment load (in addition to the base equipment loads) representing one ULT freezer. The ULT freezer incremental load was taken to be constant; a spot check of field electrical data from five freezers revealed typical day/night average kW variations below 10% (and all were below 20%). The use of a constant load is also supported by the results of the controlled environment test, which show just a 7% difference in energy consumption between weekdays and weekend days. Further, compressor duty cycling is not expected to produce large oscillations in HVAC system response for two main reasons:

- Where ULT freezers are present in a space, the space typically contains more than one ULT freezer (and additional compressor-based refrigeration equipment). The presence of multiple compression-cycle refrigerators has an averaging effect on load variations.
- Mixing of room air acts to smooth out the impact of rapid load variations on the HVAC system: the air temperature sensed by the room sensor may not respond to load changes for some minutes after the change occurs.

Using eQUEST's parametric run function, the ULT freezer power for each space type was reduced in turn. The resulting overall building savings were then disaggregated into direct ULT freezer kWh savings, electric HVAC energy savings, and natural gas HVAC energy savings. The HVAC energy impacts were then prorated by the direct energy savings; in this way, the model was used to develop an HVAC energy savings metric that can be applied to all ULT freezer energy savings results from the lab and field tests.

Calculations were performed for three representative California climate zones: CZ3 (Oakland), CZ9 (Burbank-Glendale), and CZ15 (Palm Springs).

The HVAC energy impact calculations rely on a number of important assumptions:

- That open lab spaces spend most of the year in reheat mode. This assertion is backed up by data from the facility manager survey (typical minimum ventilation rate of 8 ACH at typical supply air temperature of 60°F) and studies on open lab plug load intensities (often less than 1 W/sf in the biology/biochemistry labs in which ULT freezers are typically found). However, it must be confirmed that ULT freezers, where present, do not drive the typical lab into cooling mode at all times. A conservative estimate follows.
    - For a lab space at 72°F, 8 ACH (1.33 cfm/sf) of 60°F supply air provides 17 Btu/h/sf of cooling, i.e. 5.1 W/sf.
    - Assuming lighting load of 1 W/sf and general plug load of 1.5 W/sf (and no significant envelope loads), the space could accommodate an additional 2.6 W/sf of cooling load without leaving reheat mode.
    - Using the results of the online scientist survey, the median number of ULT freezers (where present) per open (main) lab is two. At 800 W each, this amounts to an average load of 1,600 W per open lab.
    - The median lab area reported by scientists in the CEEL Laboratory Market Assessment report was 1,200 sf. As explained in the report, this is expected to include only open lab spaces because equipment rooms and freezer farms are typically shared spaces not considered to be part of an individual scientist's lab space.
    - With 2.6 W/sf of excess cooling capacity, a 1,200-sf lab space could accommodate approximately four 800-W ULT freezers without leaving reheat mode.
    - It therefore appears reasonable to assume that the presence of ULT freezers does not cause the typical open lab space to operate in cooling mode at all times. The plug load assumptions used in the model are therefore valid.
    - This verification approach cannot easily be applied to equipment rooms, hallways, or freezer farms because these are typically shared spaces and so survey data are not expected to reflect the total number of ULT freezers in any given space of these types.

- That the HVAC system properties described by the facility managers are representative of the locations of the majority of ULT freezers in California. The facility managers were generally from large facilities with multiple buildings and many hundreds of ULT freezers. Anecdotally, some smaller facilities are served by non-100% outside air HVAC systems and/or packaged single zone DX rooftop units; these systems would yield different HVAC energy impacts from those reported here.
    - The CEEL Laboratory Market Assessment report's online scientist survey was not intentionally biased towards employees of large facilities. The survey data from this study were therefore split into responses from small, medium, and large facilities in California to allow an assessment of the fraction of ULT freezers present in "small" institutions. Small institutions were taken to be community colleges, schools with little research activity, and biotech companies with fewer than 50 employees.
    - 16% of the ULT freezers reported (from 21% of survey responses) came from facilities or institutions classified as "small."

  - The HVAC impact results reported here may be inaccurate for some small facilities, but based on the above assessment these are not expected to contain a significant fraction of the ULT freezers in the California market.

- That there is no significant variation in HVAC design and operational system parameters across climate zones within California. Anecdotally, this appears to be the case. Lab system design parameters tend to vary little with location, with the exception of humidity control and exhaust heat recovery (neither of which is a significant factor in most California climates). Additionally, envelope loads are of far reduced significance in lab building HVAC energy consumption than for many other building types. This means that building vintage is of less significance than for many other building types.

Note that the HVAC energy impact calculations described in this report are intended to be applied to the replacement of an existing ULT freezer with a more efficient unit, or to the selection of a new high-efficiency ULT freezer over a standard-efficiency model. The results can also be used to calculate the HVAC impact of a change in set point temperature for existing freezers. However, the analysis presented here *cannot* be used to assess the best location within a facility (from a total energy consumption standpoint) for a new freezer. While the new lab building eQUEST model could also be used to inform a discussion on the optimization of freezer locations and HVAC systems, that discussion is beyond the scope of this report.

Market Assessment of ULT Freezers

The market assessment of ULT freezers consisted of three unique approaches. In the first, scientists were surveyed at an international conference, the American Society for Cell Biology, about the brands, sizes, ages, and locations of their ULT freezers (see Appendix J). Scientists were furthermore engaged in conversation about their ULT freezer purchasing habits.

In the second approach, an online survey was developed to assess more detailed information about the ULT freezer market. The complete survey can be found in the Appendix H. This survey was distributed to scientists through a variety of channels, including through My Green Lab's newsletter and website, the Green Labs Planning Group listserv, Stirling Ultracold's marketing group, the International Society for Biological and Environmental Repositories (ISBER)'s newsletter, VWR's marketing channels, the International Institute for Sustainable Laboratories (I^2SL)'s newsletter and website, and through personal connections with scientists across the United States. Scientists who completed the survey were entered into a drawing to win a pair of Sonos speakers as an added incentive for taking the time to respond to the questions.

On-site data were also collected from ten sources across California, half of which were from academic institutions and the other half were from biotech/pharmaceutical companies. No on-site data were collected from hospitals or other institutions. Brand, age, size, and location information were collected either in person by My Green Lab or by a staff member from a participating institution. A total of 3,425 freezers were analyzed from this data set.

Existing baseline energy data from 101 ULT freezers were also analyzed. There data were collected from academic institutions and biotech/pharmaceutical companies, and were analyzed according to freezer brand and age. The data were obtained through solicitations to the Green Labs Planning Group and through existing relationships with many of the participating organizations.

CHAPTER 5: RESULTS

This study is comprised of four distinct sections: (1) the controlled environment ENERGY STAR tests; (2) field tests; (3) HVAC modeling; and (4) a market assessment. As such, the results in this report will be described in four separate sections, with each subsequent section building upon the findings described in the previous ones.

CONTROLLED ENVIRONMENT ENERGY STAR TESTS OF ULT FREEZERS: ENERGY CONSUMPTION RESULTS

The controlled environment testing results yielded the following general characterization chart for the 15 ULT freezers tested. These results span across five different freezer manufacturers and eight different brands of varying ULT freezer sizes.

Table 6: Freezer Descriptions

Freezer	Freezer Volume (ft^3)	Refrigerant Type	kWh/ft^3/Day @ -75°C	Marketed as Energy Efficient?
A	20.1	HFC	0.546	Yes
B	23.0	HFC/Natural Blend	0.587	
C	24.7	HFC	0.770	
D	24.0	HFC	0.745	
E	25.7	HFC	0.925	
F	27.5	Natural	0.321	Yes
G	28.8	Natural	0.364	Yes
H	19.4	Natural	0.468	Yes
I	27.5	Natural	0.286	Yes
J	28.8	HFC/Natural Blend	0.587	
K	16.0	HFC	0.809	
L	25.7	HFC	0.651	
M	18.0	HFC	0.734	
N	18.9	HFC	0.943	
O	26.0	HFC	0.584	

Freezers usually operate at 100% duty cycle in order to pull down the temperature of the freezer from ambient temperature to the set point temperature when they are first plugged in. Once the ULT freezers were stabilized at set point temperature, compressor duty cycles for different freezers tested in the controlled environment study were recorded. Generally speaking, the higher the compressor duty cycle, the less remaining refrigeration capacity there is to perform additional cooling. Larger refrigeration systems require lower compressor duty cycles to perform the same amount of cooling as smaller refrigeration systems. It was found that duty cycles ranged between 31% and 51% at -70°C without door openings and between 53% and 88% at -80°C with door openings. Higher compressor duty cycles thus corresponded to higher cooling demands. The door opening test increased the 24 hour average compressor duty cycle by 6% at -70°C and by 4% at -80°C compared to the energy test with no door openings.

Compressor duty cycle percentage increased by an average of 56% when the set point was lowered from -70°C to -80°C. Freezer M exhibited the lowest duty cycle increase, 32%, from -70°C to -80°C, and Freezer C exhibited the highest duty cycle increase under the same conditions, 87%. Compressors that have a higher duty cycle usually have a shorter lifespan, and therefore increasing ULT freezer set points from -80°C to -70°C could significantly increase ULT freezer lifetimes.

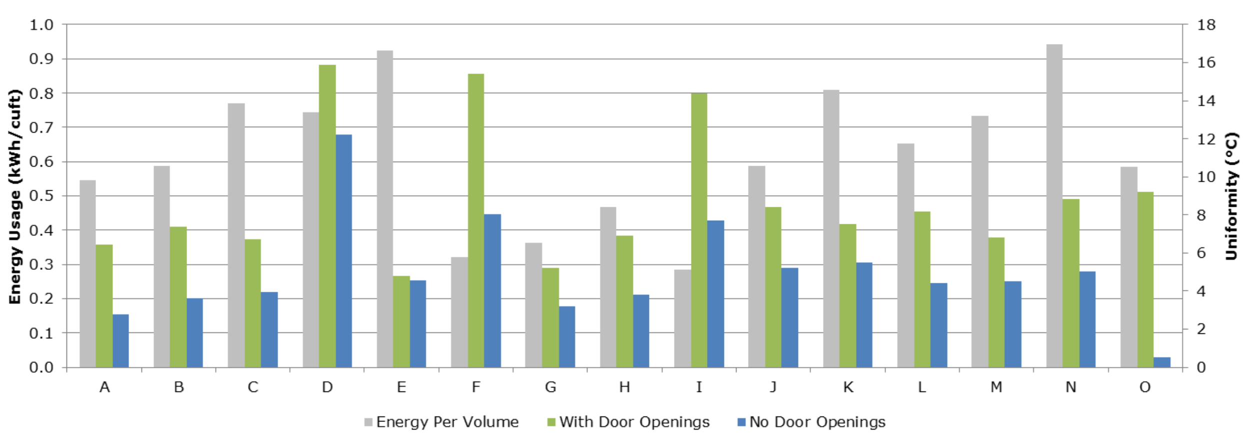
Energy-efficient freezers utilized natural refrigerants and vacuum insulated panels. While energy efficiency is not solely attributable to those two components, the most energy-efficient freezers tested had those attributes. Studies have shown energy efficiency increases of 20% when R290, a natural refrigerant, is used instead of R134, citing the increased heat capacity of natural refrigerants as the reason for this finding[15,16,17]. However, natural refrigerants require the use of a different type of compressor, so it is difficult to attribute the efficiency to the refrigerant only.

Controlled Environment ENERGY STAR Tests of ULT Freezers: Temperature Performance Results

To fully understand the energy efficiency of a ULT freezer, it must be simultaneously judged on performance metrics and energy usage. The three performance metrics analyzed in this report are the freezer's uniformity, stability and peak variance. These metrics were measured across two three-hour periods of time, one beginning with the first door opening and the second beginning three hours after the last door opening. In the graphs below, these will be noted as the "with door openings" and "without door openings" periods respectively.

'Uniformity' measures how much the temperature varies within the space of the freezer. It is defined as the average difference between the highest and lowest simultaneously taken temperature readings, across a given period of time. The uniformity value is a temperature in degrees Celsius. A lower uniformity value represents more uniform temperatures in the ULT freezer; freezers with high uniformity values have less uniform temperatures.

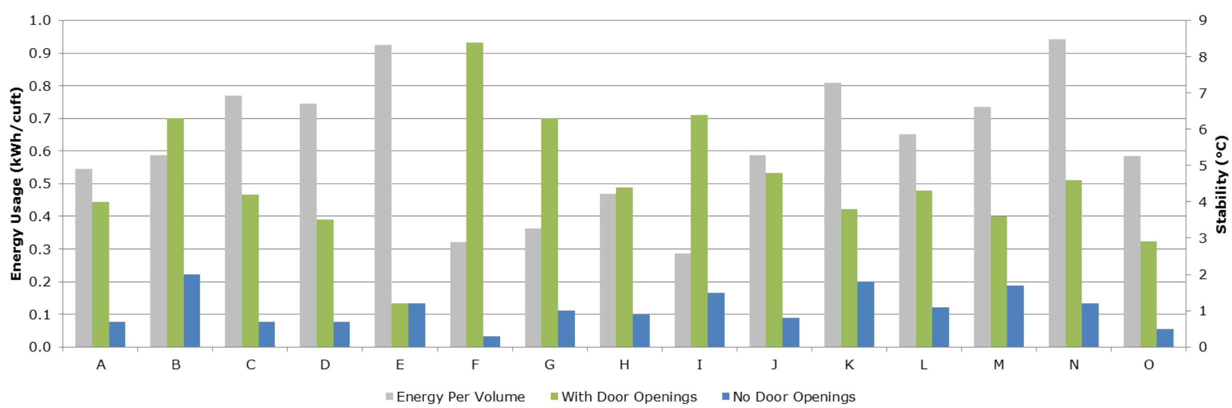
Figure 17: ULT Freezer Uniformity Comparison



It can be seen in the chart above that the majority of freezers have similar uniformity levels regardless of the energy usage rate, ranging between 6-9°C for the active period (with door openings) and 3-5°C for the stable period (no door openings). This implies that the energy-efficient freezers tested have not sacrificed performance in terms of uniformity to achieve high levels of efficiency. This is a promising result that dispels the largest misconception about energy-efficient appliances, namely that the efficiency is achieved by compromising performance. This can be clearly seen as false in a test case, where Freezer G uses 30% less energy than Freezer N yet has ~2°C better uniformity during door openings. The outliers to this trend are Freezers D and F, which both feature significantly less uniform temperature. Freezer D has the fourth-highest energy usage per volume while Freezer F has the lowest. Since three efficient freezers had one of the three best (G) and two of the three worst (F and I) uniformities it can be said that there is no clear correlation between energy usage and temperature uniformity.

'Stability' measures how much the temperature within a freezer fluctuates with time, and is defined as the difference between the highest and lowest recorded temperature at a particular location across a given amount of time. For the tested ULT freezers, the overall stability was determined by averaging the temperature stability at each location across all measured locations.

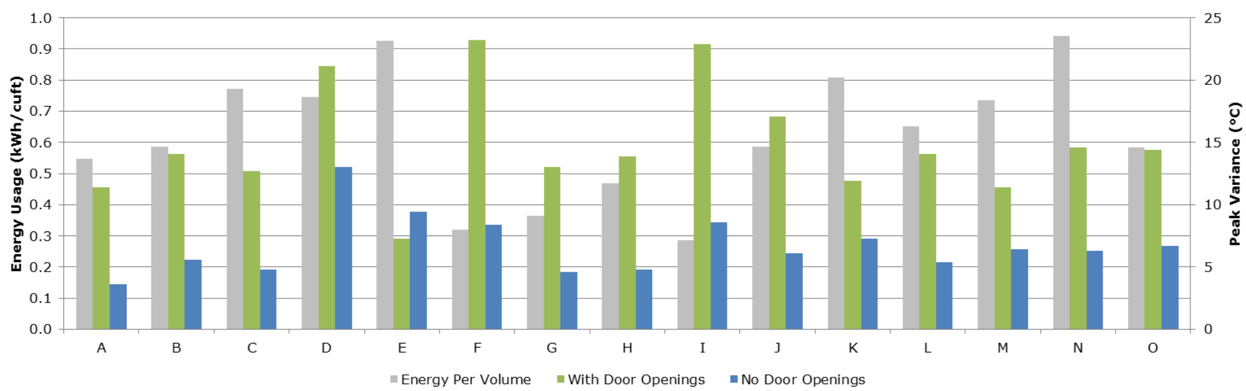
FIGURE 18: ULT FREEZER STABILITY COMPARISON



A fairly consistent range of stability values were observed, with most ULT freezers hovering between 3-5°C for the active usage period and at 2°C or less during the stable period. The outliers are Freezers B, F and G. Freezer F, the freezer with the lowest energy consumption per volume, is the least stable during active usage but the most stable during the stable period. This implies that Freezer F features great stability to complement its energy efficiency, but is slower to recuperate temperature loss after the door has been opened. This could either be an issue of timing, in which the freezer is not activating its active cooling mode soon enough after the door closes, or of cooling capacity, where the freezer is simply not cooling fast enough to regain temperature. A similar issue arises with the second most energy-efficient freezer, Freezer G. This leads to the idea that stability may be more susceptible than uniformity to losses brought on by techniques used to improve energy efficiency. However, the fact that Freezer H, the third most energy-efficient freezer, displayed stability characteristics similar to the other freezers dispels this notion. Similarly, Freezer B displayed even less stability than Freezer G despite being fairly average in energy consumption. This indicates that energy efficiency may not necessarily have a strong correlation to stability, or perhaps any quantifiable correlation at all. Further research into the matter is recommended before drawing any decisive conclusions.

'Peak variance' measures the maximum difference between any two temperatures recorded throughout the monitoring period, regardless of the location or time.

FIGURE 19: ULT FREEZER PEAK VARIANCE COMPARISON



Peak variance is an interesting metric to examine because it combines both stability and uniformity. Peak variance simultaneously considers temperature readings at every location across the entire testing period. The difficulty with extrapolating from this metric is that it provides only a single value rather than incorporating averaging in its analysis, making it more susceptible to outliers. Despite this, testing results show a fairly consistent pattern of peak variances between 10-15°C during the active period and between 4.5-7.5°C during the stable period. Outliers to this trend are Freezer J for the active period and Freezers D and F for both periods. Freezers D and F are the same outliers observed when analyzing uniformity, and the same conclusion can be reasonably drawn about peak variance – that energy usage generally has no significant correlation with peak variance and that the technologies that make a ULT freezer energy efficient does not compromise the peak variance of the unit.

A summary of the findings for uniformity and stability are presented below. Energy-efficient ULT freezers fell within the top, middle, and bottom quartile of temperature uniformity, but they were mostly in the bottom quartile of temperature stability. Of the energy-efficient freezers, Freezer H had the best overall performance, and of the standard-efficiency freezers, Freezer M had the best overall performance.

TABLE 7: ULT FREEZER UNIFORMITY SUMMARY, SORTED BY UNIFORMITY

FREEZER	UNIFORMITY AT -80°C	MARKETED AS ENERGY EFFICIENT?
E	4.0	
G	5.2	Yes
A	6.5	Yes
C	6.7	
M	6.8	
H	6.9	Yes
B	7.4	
K	7.5	
L	8.2	
J	8.4	
N	8.9	
O	9.2	
I	13.5	Yes
F	15.4	Yes
D	15.9	

TABLE 8: ULT FREEZER STABILITY SUMMARY, SORTED BY STABILITY

FREEZER	STABILITY AT -80°C	MARKETED AS ENERGY EFFICIENT?
O	2.9	
D	3.5	
M	3.6	
K	3.8	
A	4.0	Yes
E	4.2	
C	4.2	
L	4.3	
H	4.4	Yes
N	4.6	
J	4.8	
B	6.3	
G	6.3	Yes
I	6.3	Yes
F	8.4	Yes

FREEZER DOOR OPENING TEMPERATURE CHARACTERIZATION

To better understand the underlying temperature controls that result in the aforementioned energy usage figures, the temperature graphs for the 24-hour period tests are shown below for two of the freezers tested. These door opening graphs are more representative of real-world usage of ULT freezers on weekdays in a laboratory, since they feature six door openings spaced apart by one hour each; the other 18 hours have no door openings. The outer and top inner doors were opened for a duration of 15 seconds. Weekend simulations, in which ULT freezer doors were not opened, are also shown below.

FIGURE 20: FREEZER G TC READINGS WITH DOOR OPENINGS AT -80°C

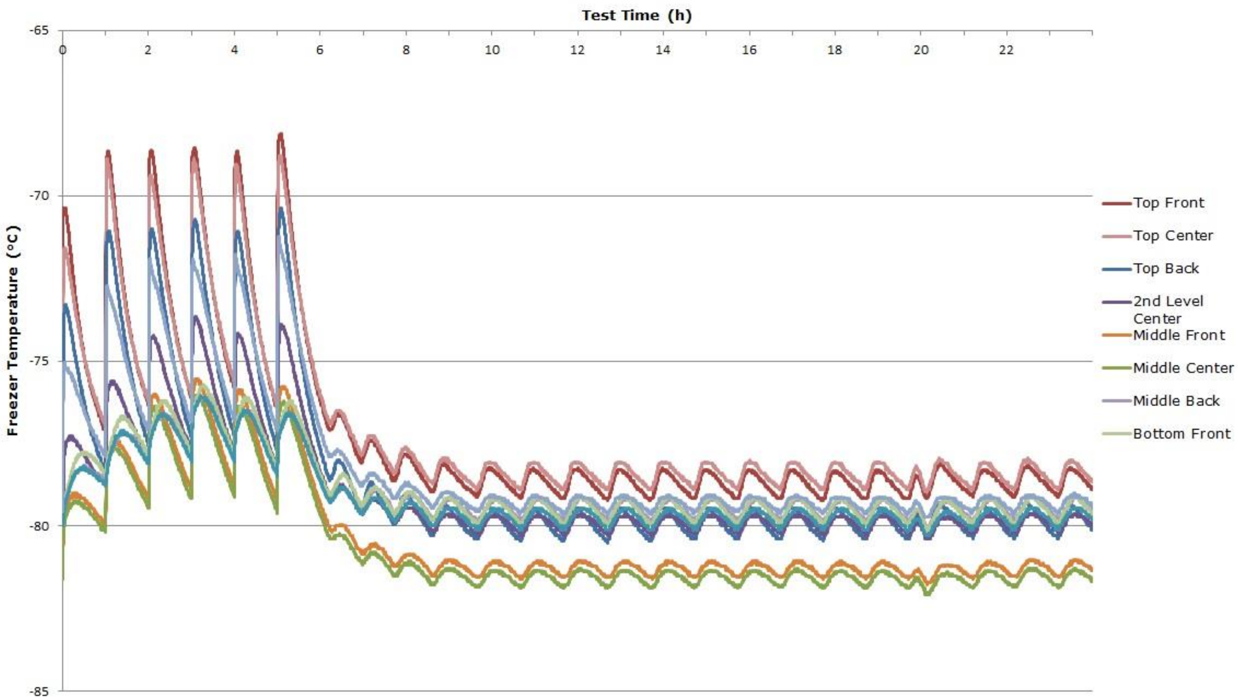


Figure 21: Freezer G TC Readings Without Door Openings at -80°C

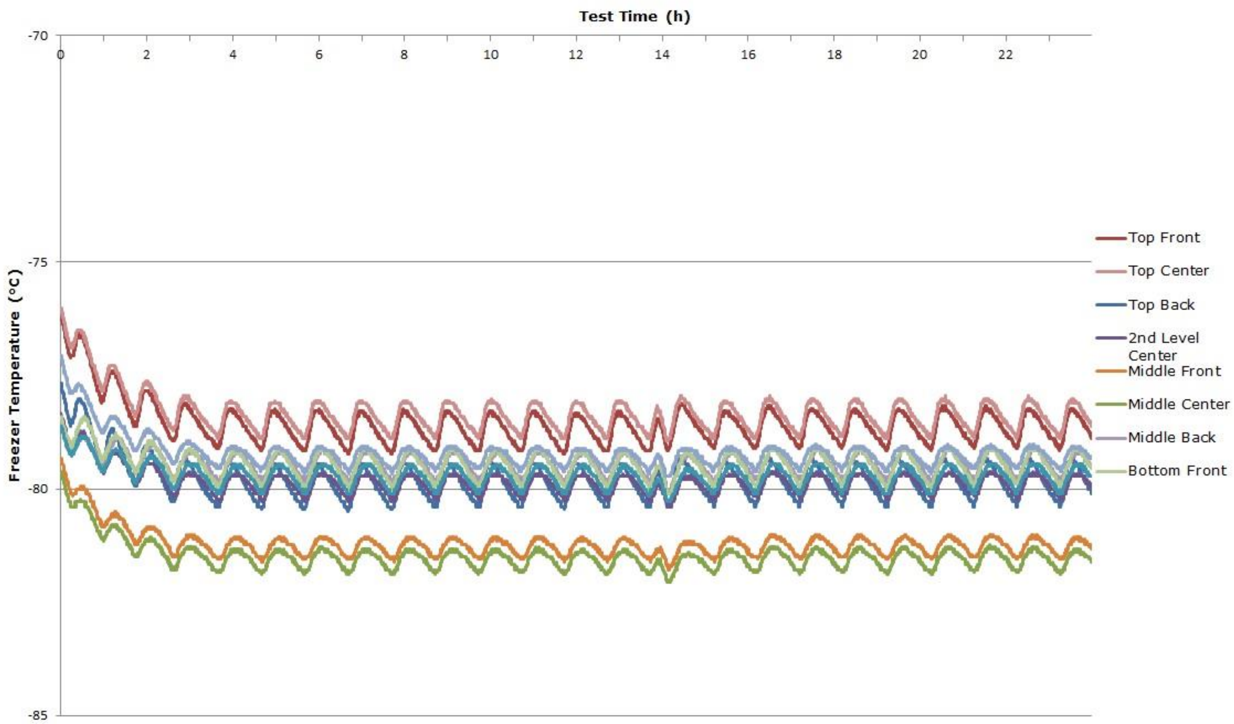


FIGURE 22: FREEZER J TC READINGS WITH DOOR OPENINGS AT -80°C

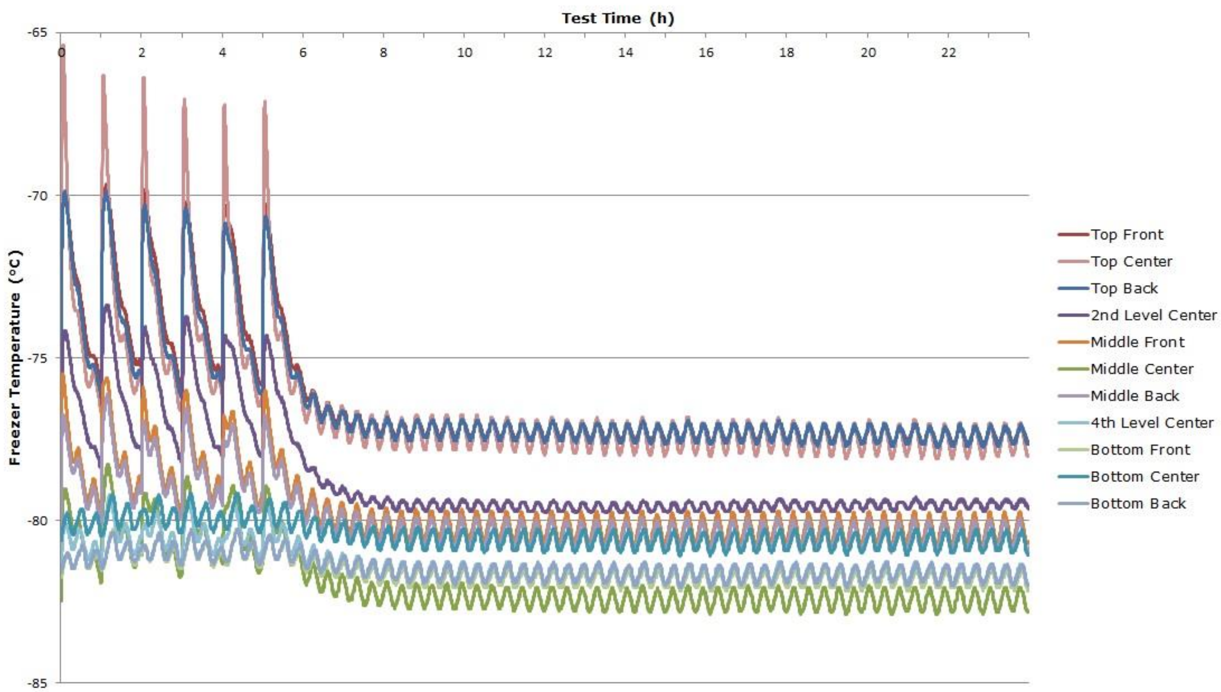
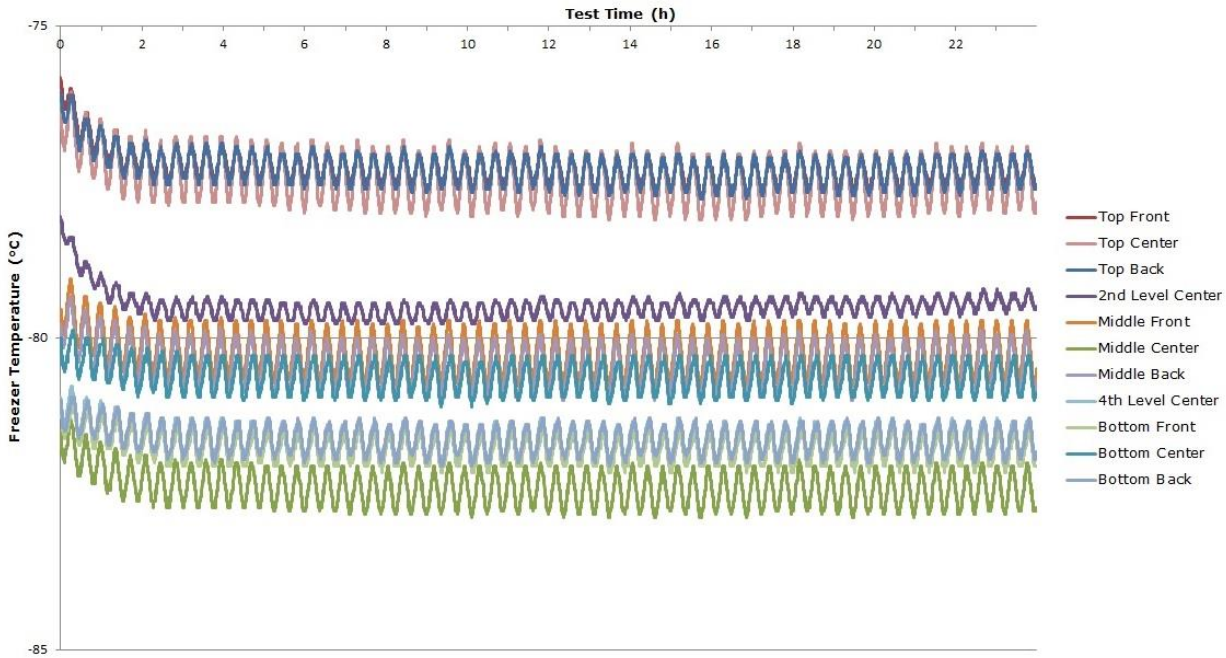


FIGURE 23: FREEZER J TC READINGS WITHOUT DOOR OPENINGS AT -80°C



Each freezer required a different amount of time and energy for the temperature to stabilize after the last door opening. Freezer G displayed more frequent compressor cycles after the last door opening for the first four hours of the 24-hour test, whereas Freezer J maintained the same compressor cycle frequency in order for the temperature to stabilize. Energy consumption was recorded for the different 24 hour periods with and without 6 door openings for the first 6 hours. Freezers consumed 4 to 14% more energy during the 24 hour period with 6 door openings. Based on similar door opening scenarios in the field, ULT freezers are expected to use 7% more energy on a typical weekday than on a weekend day or a holiday.

TABLE 9: ULT FREEZER DOOR OPENING ENERGY DIFFERENCE

ULT FREEZER	ENERGY CONSUMPTION AT -75°C WITH 6 DOOR OPENINGS (KWH/DAY)	ENERGY CONSUMPTION AT -75°C WITH NO DOOR OPENINGS (KWH/DAY)	% DIFFERENCE
A	10.97	10.04	9%
B	13.50	12.65	7%
C	19.03	17.81	7%
D	17.88	17.10	5%
E	23.76	22.52	6%
F	8.83	7.72	14%
G	10.49	9.44	11%
H	9.08	8.35	9%
I	7.86	6.86	14%
J	16.91	15.35	10%
K	12.94	12.78	1%
L	16.74	15.86	6%
M	13.22	12.74	4%
N	17.82	17.01	5%
O	15.17	14.66	4%
		Average	**7%**

FREEZER SET POINT TEMPERATURE CHARACTERIZATION

Per the ENERGY STAR test method, the ULT freezers were tested at both -80°C and -70°C average internal temperatures. The results were then normalized to -75°C; this was done by linear interpolation between the two test conditions, using the average measured temperatures and total energy consumption at each condition. The freezer energy consumption at -75°C is therefore given by the following formula:

$$E1 + \left[(-75 - T1) \times \frac{(E2 - E1)}{(T2 - T1)}\right]$$

where:

T1: overall average of all recorded interior temperature measurements over the course of the test at -70°C test condition

T2: overall average of all recorded interior temperature measurements over the course of the test at -80°C test condition

E1: total energy consumption during the test at -70°C test condition

E2: total energy consumption during the test at -80°C test condition

All freezers consumed more energy at -80°C than -70°C, and the inner compartments were generally warmer at -70°C than at -80°C. Figures 24 and 25 below demonstrate a typical example of temperature characteristics at both set points.

FIGURE 24: FREEZER A TC READINGS WITH DOOR OPENINGS AT -80°C

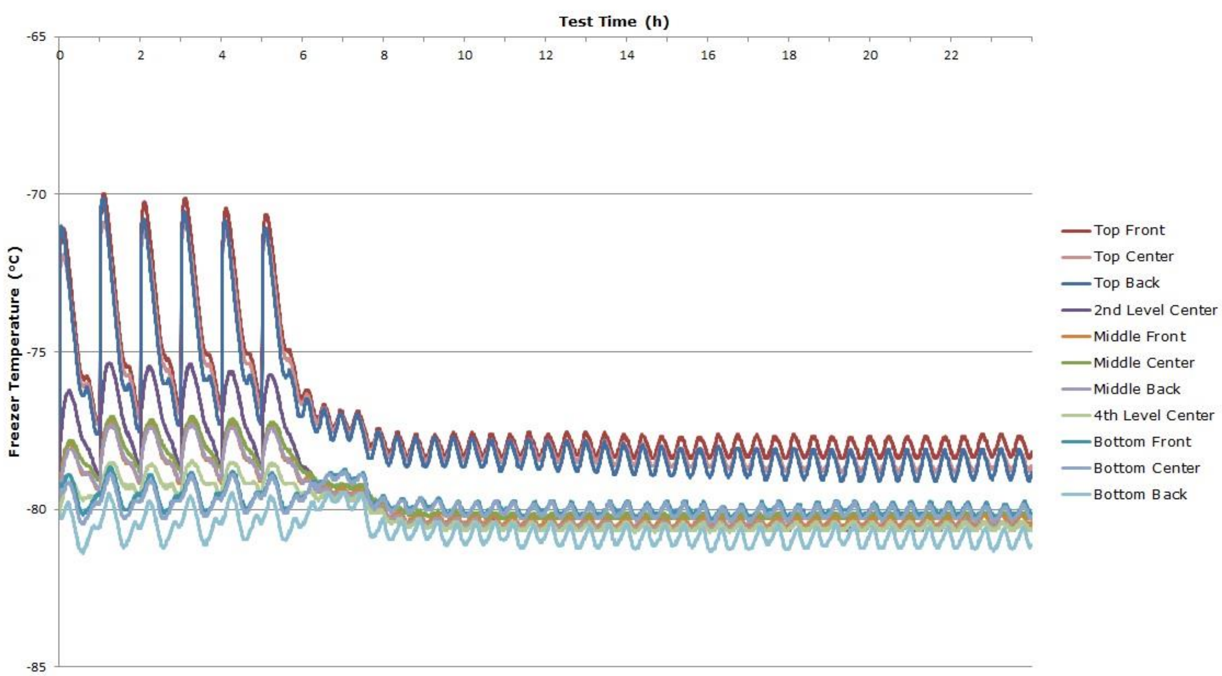
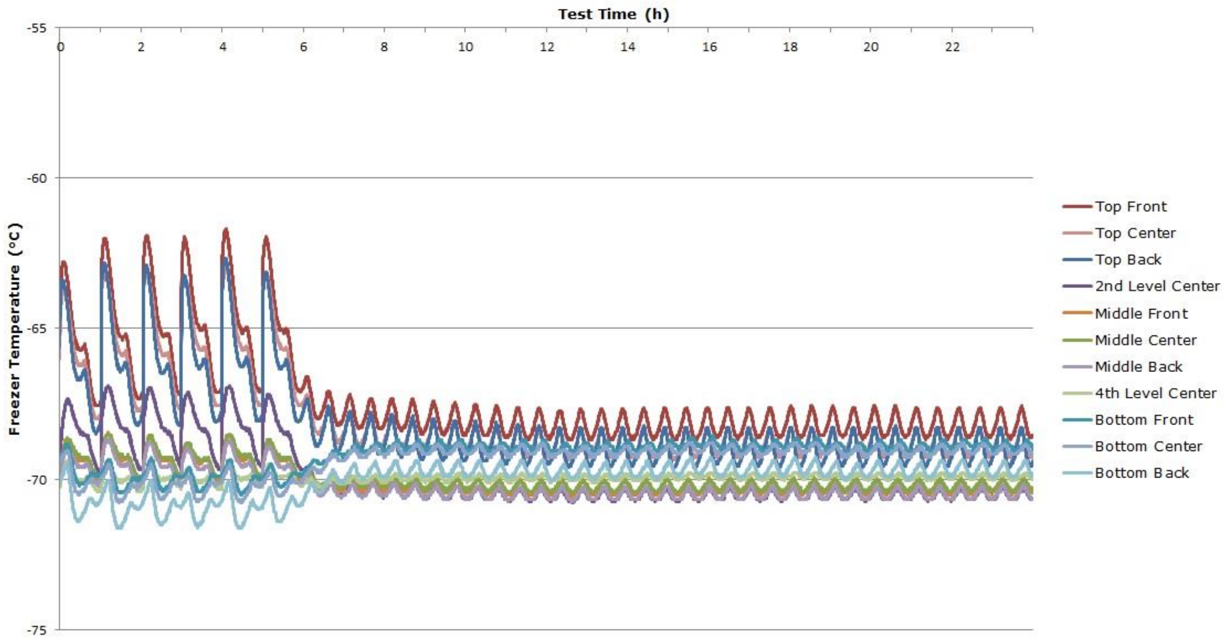


FIGURE 25: FREEZER A TC READINGS WITH DOOR OPENINGS AT-70°C



The increase in energy consumption when decreasing the temperature from -70°C to -80°C ranged between 25% and 50% for different freezer models. The average energy difference between the two set points was 37%. An energy-efficient ULT operating at -80°C may use more energy than an inefficient unit at -70°C. Some ULT freezers exhibited different temperature variances and uniformity at different temperature set points.

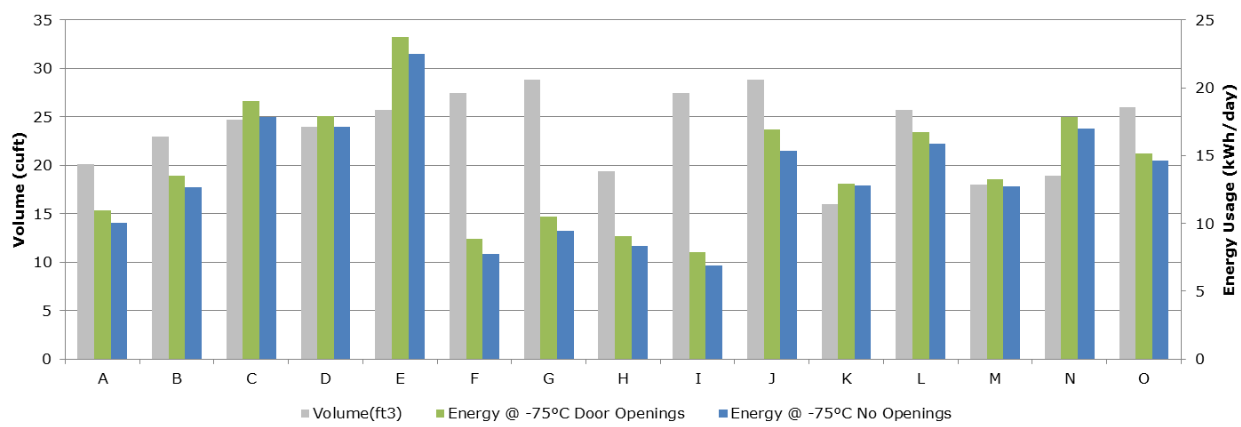
TABLE 10: ULT FREEZER ENERGY CONSUMPTION AT DIFFERENT TEMPERATURE SET POINTS

ULT FREEZER	ENERGY CONSUMPTION AT -80°C SET POINT (KWH/DAY)	ENERGY CONSUMPTION AT -70°C SET POINT (KWH/DAY)	% DIFFERENCE
A	12.64	8.68	46%
B	14.89	11.78	26%
C	22.52	15.11	49%
D	20.46	14.04	46%
E	26.71	19.85	35%
F	9.68	7.89	23%
G	12.12	8.05	50%
H	10.44	7.06	48%
I	8.72	6.96	25%
J	19.96	13.76	45%
K	14.66	11.06	33%
L	18.89	14.44	31%
M	14.84	11.72	27%
N	20.43	14.99	36%
O	17.72	12.64	40%
		Average	37%

ULT FREEZER SIZE AND TOTAL ENERGY CONSUMPTION

ULT freezers tested ranged between 16 and 29 cubic feet in internal volume. Energy usage was found to be proportional to size only within the same model series. Larger freezers within the same model series used less energy per unit volume than smaller units; however, some larger energy-efficient freezers used less total energy than smaller, standard-efficiency freezers.

FIGURE 26: ULT FREEZER VOLUME AND DAILY ENERGY CONSUMPTION



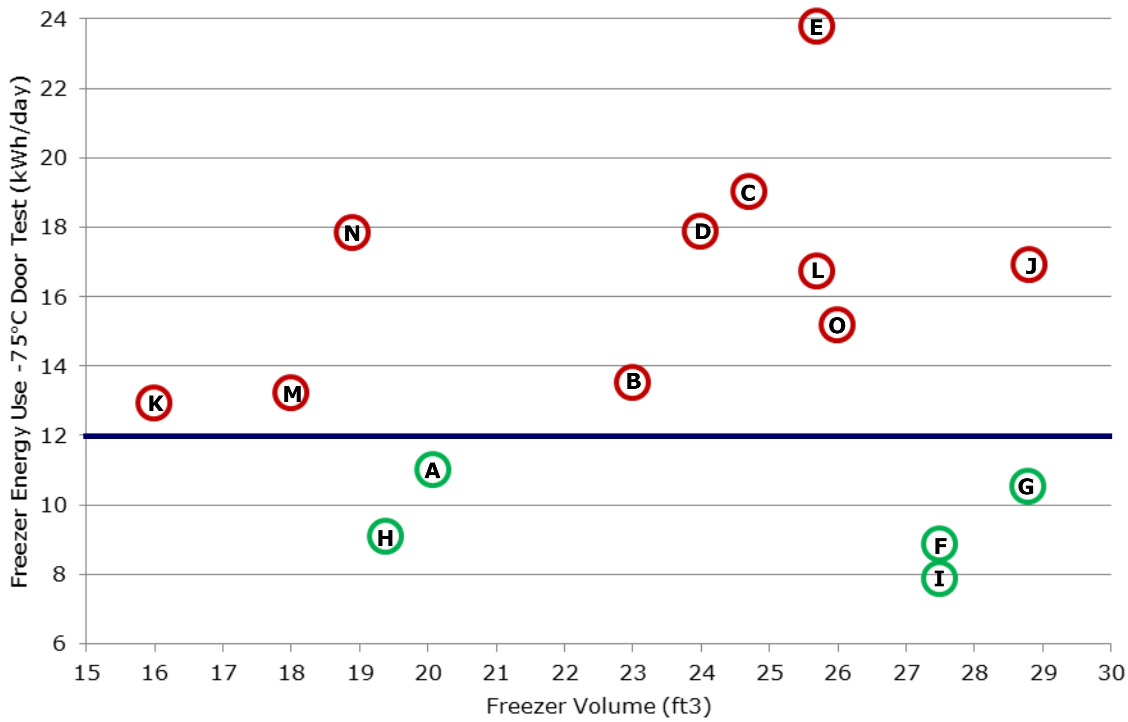
Daily energy consumption for the ULT freezers tested ranged from 7 kWh to 23 kWh.

TABLE 11: ULT FREEZER SIZE AND ENERGY CONSUMPTION

ULT FREEZER	VOLUME (FT^3)	ENERGY @ -75°C WITH DOOR OPENINGS (KWH/DAY)	KWH/FT^3/DAY
A	20.1	10.97	0.546
B	23.0	13.50	0.587
C	24.7	19.03	0.770
D	24.0	17.88	0.745
E	25.7	23.76	0.925
F	27.5	8.83	0.321
G	28.8	10.49	0.364
H	19.4	9.08	0.468
I	27.5	7.86	0.286
J	28.8	16.91	0.587
K	16.0	12.94	0.809
L	25.7	16.74	0.651
M	18.0	13.22	0.734
N	18.9	17.82	0.943
O	26.0	15.17	0.584
Average	**23.6**	**14.28**	**0.621**

The average size (volume) of the ULT freezers tested was 23.6 ft^3. The average energy use of a new freezer tested in the lab was 14.3 kWh/day at -75°C, with 6 door openings per day. The average energy usage per unit volume was 0.621 kWh/ft^3/day at -75°C with 6 door openings per day. The more energy-efficient freezers with natural refrigerant cooling systems and vacuum insulated panels consumed between 0.28 and 0.55 kWh/ft^3/day. The least energy-efficient ULT freezers consumed between 0.58 and 0.94 kWh/ft^3/day. This means that some freezers used half the energy of others while maintaining the same average internal temperature. Variance, uniformity and stability differed for all units regardless of their energy usage, with no clear correlation. Energy-efficient freezers ranging from 19 to 29 ft^3 used between 7 and 11 kWh/day; their standard-efficiency counterparts of a similar size range used between 17 and 24 kWh/day. Thus, at an average size of 24 ft^3, energy-efficient freezers used 9.4 kWh/day, whereas standard-efficiency units used 16.7 kWh/day.

FIGURE 27: ULT FREEZER ENERGY CONSUMPTION: DETERMINING ENERGY EFFICIENCY, ENERGY STAR TEST



As Figure 27 above summarizes, Freezers A, F, G, H and I, shown in green, were found to be energy efficient. The line on the graph delineates the most energy-efficient freezers (top 33%) from the remaining units. These top performing ULT freezers are also marketed as being energy efficient by their respective manufacturers.

BASELINE EVALUATION OF EXISTING FREEZERS IN THE FIELD

Dozens of field studies on ULT freezers have been conducted in the past several years. These studies have typically focused on collecting baseline energy data from existing freezer models, with data collection usually lasting from 24 hours to several months. Because these studies were done in isolation, in uncontrolled conditions, it is not possible to make direct comparisons among them. However, looking at them as a whole, some obvious trends about baseline energy consumption of ULT freezers emerge. The data presented below represent a compilation of published data on ULT energy consumption as well as data collected independently by individual institutions. Freezer brand, model, age, and temperature information is provided whenever available; some publications chose not to disclose this information.

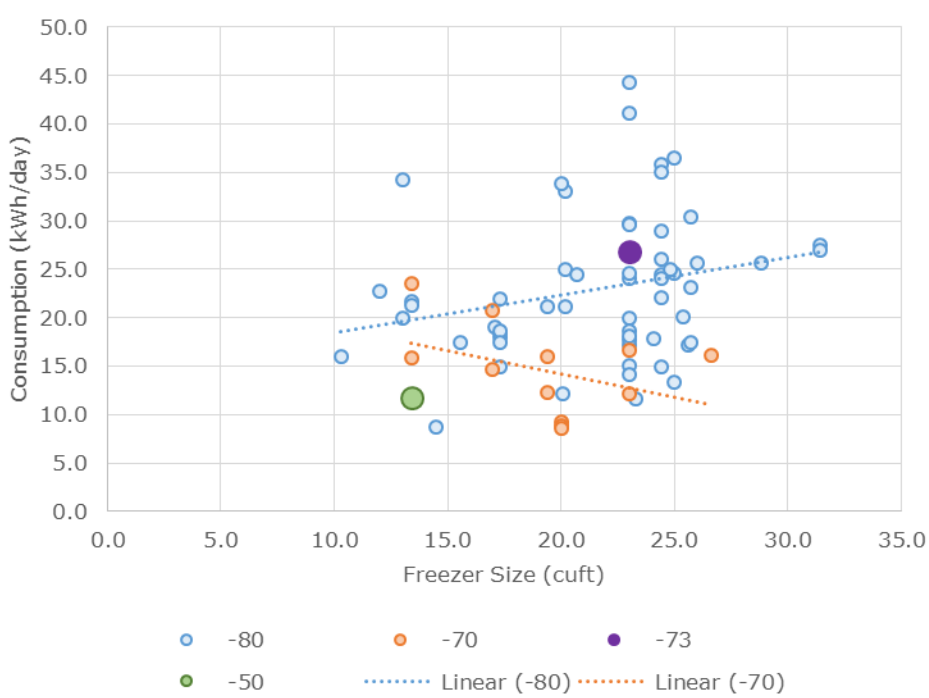
The earliest controlled study of ULT freezer baseline energy consumption came from the DOE and the Better Buildings Alliance. Their 2014 report found that the energy consumption of four ULT freezers (brands, ages, and sizes not disclosed), ranged from just over 1 kWh/ft^3/day to just under 0.5 kWh/ft^3/day. The study also evaluated temperature variation among these freezers, finding that the largest energy consumers also had the largest average deviation from set point, namely 6.5°C warmer for one, and 3.5°C colder for the other. The mid-range energy consumer, at 0.8 kWh/ft^3/day, was found to have an average deviation from set point of 2.1°C warmer.

The University of California, Riverside, recently completed a baseline energy study of ULT freezers as a function of age.[18] They metered 11 different freezers, and found that energy consumption ranged from 15 kWh/day to 32 kWh/day (capacity and kWh/ft^3/day were not given) for freezers that ranged in age from 2 – 16 years old. The oldest model consumed as much energy per day as a model purchased in 2013; however, models purchased between 2003 and 2011 consumed more energy on average than their newer counterparts. That these effects may be due to differences in freezer capacity, rather than age, cannot be discounted.

In an effort to understand the true relationship between freezer energy consumption, size, age, temperature set point and brand, this current study sought data from institutions that had already metered their freezers. Though the methods of data collection varied widely, from simple Watts Up plug energy meters to long-term performance monitoring systems like TRAXX, it was possible to see some trends from the dataset. The dataset included 101 freezers, but not all parameters were available for all freezers.

It is not surprising that a relationship between ULT freezer size and energy consumption was found. Figure 28 below depicts the measured energy consumption of 59 freezers set to -80°C and 12 freezers set to -70°C.

FIGURE 28: ULT FREEZER ENERGY CONSUMPTION AS A FUNCTION OF CAPACITY AT DIFFERENT TEMPERATURES



It is clear that on average, for freezers set to -80°C, as freezer capacity increases, energy consumption also increases, in spite of the obvious scatter around 25 cubic feet. Interestingly, the opposite is true of the freezers set to -70°C. This could be due to the outsized energy consumption of the very small freezers set to -70°C. With such a small sample size set to -70°C it is difficult to draw any definitive conclusions from the graph above, with the exception that ULT freezers set to -70°C appear to consume less energy on average.

Normalizing the energy consumption as a function of freezer capacity reveals that the average energy consumption of the ULT freezers set to -80°C in the study is 1.1 kWh/ft^3/day, and the average energy consumption of ULT freezers set to -70°C is 0.8 kWh/ft^3/day. Thus setting the freezer temperature to -70°C reduces energy consumption by 29% on average. This is less than the average reduction in energy observed in the controlled environment test (37%). One possible reason for this discrepancy is that again, the sample size above consists of several smaller ULT freezers set to -70°C, and these freezers appear to be consuming quite a lot of energy in general.

Energy consumption at -80°C as a function of brand is depicted in Table 12.

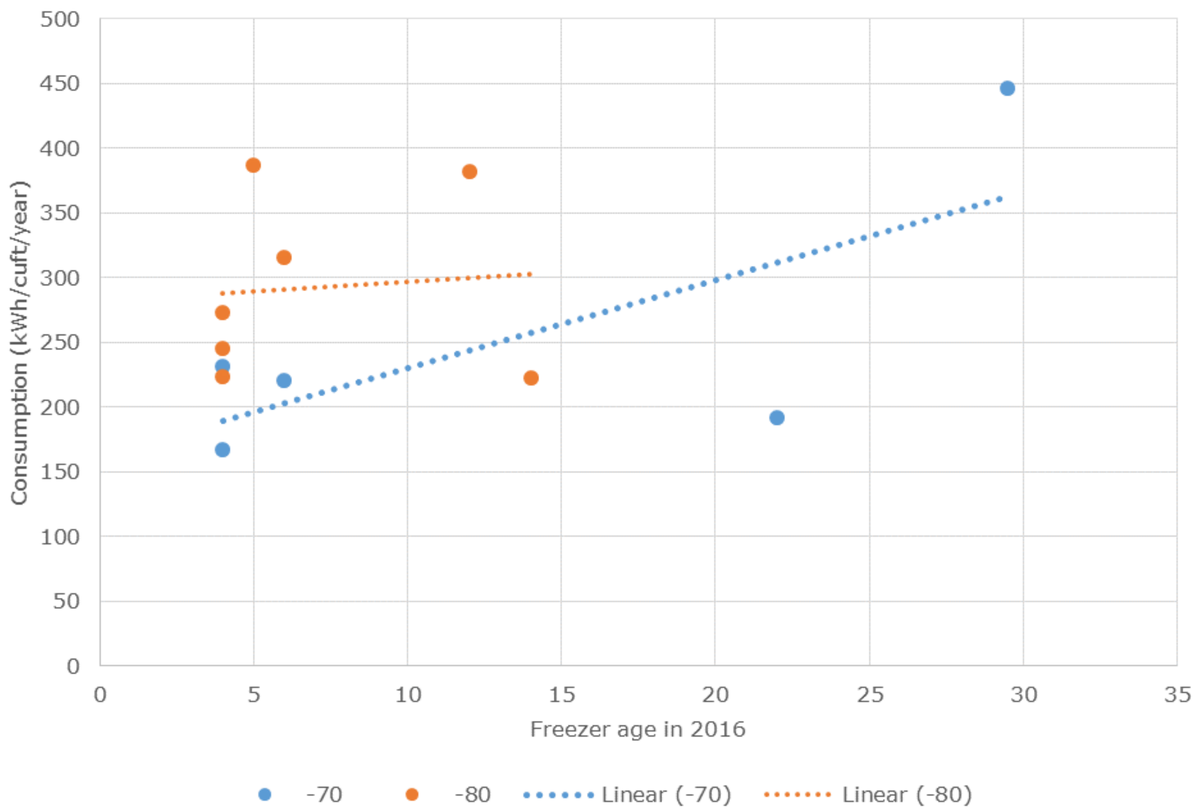
TABLE 12: ULT FREEZER ENERGY CONSUMPTION

FREEZER	NUMBER	KWH/DAY/FT^3
Manufacturer A	6	0.7
Manufacturer B	6	1.6
Manufacturer G	14	0.9
Manufacturer J	20	1.2
Manufacturer L	1	1.1
Manufacturer P	6	0.9
Manufacturer Q	3	0.9
Manufacturer R	1	0.9

The energy data above came from a variety of sources. Twenty-one freezers were metered using TRAXX, a device that calculates wattage from amperage readings; 24 freezers were metered using devices similar to Watts Up meters, which are simple plug-and-play meters that give direct energy information. Data from the remaining 28 freezers came from the Labs21 Wiki, in which metering information is not disclosed, or from 3rd party program providers, who also did not disclose their metering methods.

Of the 71 freezers in this study, a small subset of freezer ages were known. Figure 29 shows the relationship between freezer age and energy consumption.

FIGURE 29: ULT FREEZER ENERGY CONSUMPTION AS A FUNCTION OF AGE AT DIFFERENT TEMPERATURES



There are several reasons why older freezers, especially those that are greater than 20 years old, consume more energy than newer freezers. Freezer maintenance is often overlooked for older freezers, as the fear that they may not restart prevents many labs from turning them off to defrost them. Air filters and freezer coils are rarely, if ever cleaned, contributing to an increase in energy consumption. In addition, gaskets sealing the door often start to break down with age, and poor door seals are associated with increased compressor cycling and thus increased energy consumption due to increased infiltration of room air leading to higher cooling loads. And finally, older freezers often employ older, less efficient technology. Although it is not known how these freezers performed when they were new, it is likely that they consumed more energy out-of-the-box than their more modern counterparts.

While these studies contain a wealth of information, they rarely expanded their reach to include variables beyond age and capacity. Freezer location, capacity, door opening frequency and duration, and ambient conditions were often unaccounted for, or were not tested. For the purposes of the baseline field study conducted for this project, all of these variables were deemed important. Freezer location may have an impact on heating, ventilation and air conditioning (HVAC) requirements, the effects of which are further described below. The extent to which the freezer is filled to capacity has been shown to influence energy consumption and thermal stability, as have the frequency and duration of door openings. Moreover, the ENERGY STAR test method, the standard to which new ULT freezers were tested in the previous chapter, specifies certain ambient conditions and operational procedures, the details of which had not been corroborated by field data. For these reasons, new field studies on existing ULT freezers were carried out as part of this study.

Two field test sites were chosen to evaluate existing ULT freezers. One was an academic facility in Northern California, and the other was a quantitative biosciences incubator, also located in Northern California. Energy consumption and door openings were monitored at both sites. Together, the sites presented a unique opportunity to understand how existing ULT freezers are operated and how much energy they use in a real life situation. In all cases, freezers were monitored for a period of no less than two weeks. Those two weeks included at least one weekend, and no holidays or school breaks were included in the study. All freezers were full upon inspection, though it should be noted it was not possible to inspect every rack and box.

The bioscience incubator's freezers were located in the main laboratory. All five freezers (of which one was unplugged and is used as a backup freezer only) were side-by-side against a back wall. These freezers are shared among the various labs that are housed in the incubator, such that two or three labs may share a single freezer. The four operating freezers were identical Freezer Ls. Each of the four freezers has a capacity 25.7 cubic feet; the freezers are relatively new. Freezer L uses a cascade refrigeration system with R-404A and R-508B refrigerants as well as Vacuum Insulated Panels (VIPs). The energy usage of Freezer L was fairly similar across the four units, ranging from 18 to 22 kWh/day (Table 12 below).

The duty cycle is the fraction of time during which the compressor operates. The compressor duty cycles for four of the freezers ranged between 65% and 79% (Table 13). The peak power measured ~1400W, and off-cycle control and fan energy measured ~50W.

TABLE 13: FREEZER L AT BIOSCIENCE LAB FIELD SITE: ENERGY CONSUMPTION AND DUTY CYCLE

FREEZER	ENERGY PER DAY (KWH/DAY)	DUTY CYCLE (%)
Freezer L	21.5	79%
Freezer L	19.6	70%
Freezer L	18.4	65%
Freezer L	19.1	69%

The freezers were opened 5-11 times per day, with the average door opening duration being 56 seconds, as measured by a door sensor. The door sensor location is given in Chapter 4. Note that in order for the sensor to remain stationary during the study it often had to be secured with tape. Most door openings occurred between 8am and 6pm on weekdays. The energy consumption was related to the number and duration of door openings, as shown below in Table 14. The weekday average energy usage was approximately 100W higher than on weekends without door openings. Therefore the door openings accounted for a 10% increase in energy consumption.

TABLE 14: FREEZER L AT BIOSCIENCES INCUBATOR: ENERGY CONSUMPTION AND DOOR OPENING

Freezer	Energy per Day (kWh/day)	Door Openings Per Day	Avg. Door Opening Duration (Seconds)
Freezer L	21.5	10.5	63
Freezer L	19.6	5.8	64
Freezer L	18.4	8.1	44
Freezer L	19.1	5.3	52

These data indicate that the ENERGY STAR test method used in the laboratory testing portion of this study may not accurately reflect how ULT freezers are used in the field. The test method calls for six door openings of 23 seconds each; the data gathered at the bioscience incubator test site would suggest that longer door openings would be more appropriate. It is important to note that since these freezers are shared by multiple labs, it is possible that these data do not accurately reflect a one-freezer-per-lab scenario, such as that described in the academic lab below.

The ambient temperature at the bioscience incubator site was also monitored for the duration of the study (6 weeks). The ambient temperature sensor was placed on the door-opening side of a ULT freezer that was being monitored; the sensor was moved three times in six weeks to different freezers. All four freezers were located in a row and thus the temperature was not expected to vary too much as the sensor was moved between freezers. The ambient temperature was found to fluctuate between 70°F and 80°F, with an average of 75.0°F.

Two ULT freezers were monitored at the University field site, one from Manufacturer P and the other from Manufacturer S. Manufacturer S's unit was nearly 20 years old and has an estimated capacity of >30 cubic feet; Manufacturer P's unit was purchased within the last five years and has a 25 cubic foot storage capacity.

Manufacturer P's ULT freezer consumed 17.6 kWh/day with a 78% duty cycle (see Table 12). The maximum measured input rate was 1200W upon compressor start. The average input rate of the compressor was found to be ~900W. Literature from the manufacturer states that this freezer uses 19.7 kWh/day, which is close to the observed energy consumption in the field.

Manufacturer S's ULT freezer had a 30A 120V power supply with a maximum measured input rate of 3600W at compressor start and a steady state input rate of 2600W with the compressor on. The duty cycle was 65%, due to the freezer's oversized compressor. The fans and controls consumed nearly 200W. Not surprisingly the unit consumed considerably more energy than most ULT freezers at 33.0 kWh/day.

TABLE 15: ULT FREEZERS AT UNIVERSITY FIELD SITE: ENERGY CONSUMPTION AND DUTY CYCLE

Freezer	Energy Consumption (kWh/day)	Compressor Duty Cycle (%)
Manufacturer P	17.6	78%
Manufacturer S	33.0	65%

The number and duration of door openings for both freezers at the University site more closely approximated the ENERGY STAR test method than those at the bioscience incubator, as seen in the table below. On average, the doors were opened eight times per day for an average of 30 seconds. The door openings occurred between the hours of 8am and 6pm, with most of these between 10am and 2pm. The doors were opened more often on weekdays; however, there were a few weekend door openings between 10am and noon. The door openings increased the average energy consumption by 60-80W during weekdays, which corresponds to a ~10% increase in energy usage during hours of heavy operation.

TABLE 16: ULT FREEZERS AT UNIVERSITY FIELD SITE: ENERGY CONSUMPTION AND DOOR OPENING

FREEZER	ENERGY CONSUMPTION (KWH/DAY)	AVG. DOOR OPENINGS PER DAY	AVG. DOOR OPENING DURATION (SECONDS)
Manufacturer P	17.6	8.3	32
Manufacturer S	33.0	7.9	29

The two freezers metered at the university were owned and operated by an individual lab in the Immunology Department, and thus their operation more closely approximated that seen in a 'typical' lab where each freezer is individually owned (compared to the shared freezers at the incubator site). As such, the door opening data from Manufacturer P's ULT freezer was used to develop the protocol for the subsequent field test of new ULT freezers.

Ambient temperatures at the university test site were consistent day-to-day in a conditioned environment, with an average temperature of 74.9°F and relative humidity of 37%. As before, the ambient temperature sensor was placed on the door-opening side of the ULT freezer for the duration of the test. Door openings were not found to affect ambient temperature readings.

CONTROLLED FIELD TESTS OF ULT FREEZERS

The field tests described above were the best method for determining the present ULT freezer landscape. However, owing to the many variables involved with field tests of random freezer samples, such as freezer age, location, capacity, door opening frequency and duration, and ambient temperature, it is difficult to draw any clear conclusions from the data other than an overall energy consumption average. Furthermore, because the ULT freezers tested in the controlled environment facility were tested under specific conditions outlined by the EPA and not under normal operating conditions, it would have been difficult to extrapolate the controlled environment test data to the field with any confidence in the absence of additional field tests. Therefore, this study sought to conduct standardized field tests on seven of the 15 freezers tested in the controlled environment test. The field tests were controlled for, and thus standardized, in several key ways: all freezers were tested in the same row in a freezer farm, in which the ambient conditions were relatively unchanged during the test, all freezers were subject to a door opening protocol that reflected door opening frequency and duration observed in real-life laboratory settings (from the University field site), and finally all freezers were filled to capacity during the test. This allowed the study to focus on the variables of interest, namely energy consumption and performance in the form of thermal stability and uniformity.

The seven ULT freezers tested in the field were chosen on the basis of their performance in the controlled environment test, their size, and their brand. The models marketed as 'energy efficient' comprised three of the seven ULT freezers, and the other four represented ULT freezers of similar size from different brands. Altogether, seven different brands were represented in the field study.

ULT freezers were temporarily installed in the basement freezer farm of a life science building at Amgen's facilities in Thousand Oaks. The freezer farm contains over 50 ULT freezers. Several spaces in a middle row were kept open for this study. The field test commenced in mid-May, at which time four of the seven ULT freezers were delivered, and finished in mid-August.

ULT Freezer Calibration

The freezers were calibrated by Al-Tar Services, and the results of their calibrations are shown in Table 17 below.

Table 17: ULT Freezer Calibrations

Freezer	Set Point (°C)	Standard as Found Reading (°C)	Display as Found Reading (°C)
Freezer A	-80	-80.804	-80
Freezer B	-80	-79.208	-80
Freezer C	-80	-79.003	-80
Freezer D	-80	-79.762	-80
Freezer E	-80	-79.931	-81
Freezer F	-80	-83.160	-80
Freezer G	-80	-79.384	-80

The calibration data shown above differs from that observed in the lab at the FSTC. This is due to the use of different quantities and locations of TC measurements which resulted in a different measured (average) internal temperatures. Field calibration used 18-23 TCs, which were evenly spaced throughout a full freezer. In contrast, the controlled environment test's TCs were suspended in vials in an empty freezer. For the purposes of the data reported in the field study, the calibrations in Table 17 will be used.

ULT Freezer Validation

Amgen required all freezers being tested at their facility to be validated. As standard practice, any ULT freezer purchased by Amgen and used in manufacturing applications must be validated. Validating the freezers ensured that the results from this study could be applied not only to Amgen, but to any academic, biotech, pharmaceutical or hospital institution. While validation is not a requirement in all cases, it is a requirement for applications with strict temperature tolerances. All freezers tested in this study passed the validation requirements, and thus all were subject to further testing.

The calibration information above was used by Azzur to validate the ULT freezers. Freezers were validated according to the protocol outlined in Chapter 4. Prior to beginning the freezer validation, all freezers were outfitted with an energy meter and a door sensor. In all cases, all TC temperatures met the acceptance criteria of ≤-65°C, and all TCs passed post-verification calibration. For complete validation results see Appendix B.

ULT Freezer Controlled Field Tests - Energy

The ULT freezer configurations used for the validation studies remained in place throughout the duration of the field study. In other words, the TCs were unmoved, the energy meters and door sensors remained in place, and the freezers were tested at capacity. Additionally, a door opening log was posted prominently on each freezer door. In the case of Freezer C, where the door sensor fell off during the study, the door opening log data were used in place of the door sensor.

Not surprisingly, many of the freezers exhibited a door-opening-dependent increase in energy consumption, as evidenced by the graphs below. Data for Freezers B, D and F are shown at both -80°C and -70°C. These freezers were chosen as representative cases; complete data sets can be found in Appendix C. Freezers A and B exhibited a similar behavior, with clear changes in energy consumption for prolonged periods of time in response to door openings. Freezers C, D, E and G exhibited a different energy profile, in which the freezer seemingly rapidly recovered from door openings. Freezer F's energy profile more closely matched those of Freezers A and B, but was nevertheless unique enough to present by itself. Note that in all cases, the horizontal axis reflects the date and time of the measurement, and the vertical axis is the energy consumption in watts.

The first set of graphs show Freezers B, D and F responding to door openings at -80°C; the second set of graphs show the same ULT freezers responding to door openings at -70°C.

FIGURE 30: FREEZER B ENERGY CONSUMPTION WITH DOOR OPENINGS AT -80°C

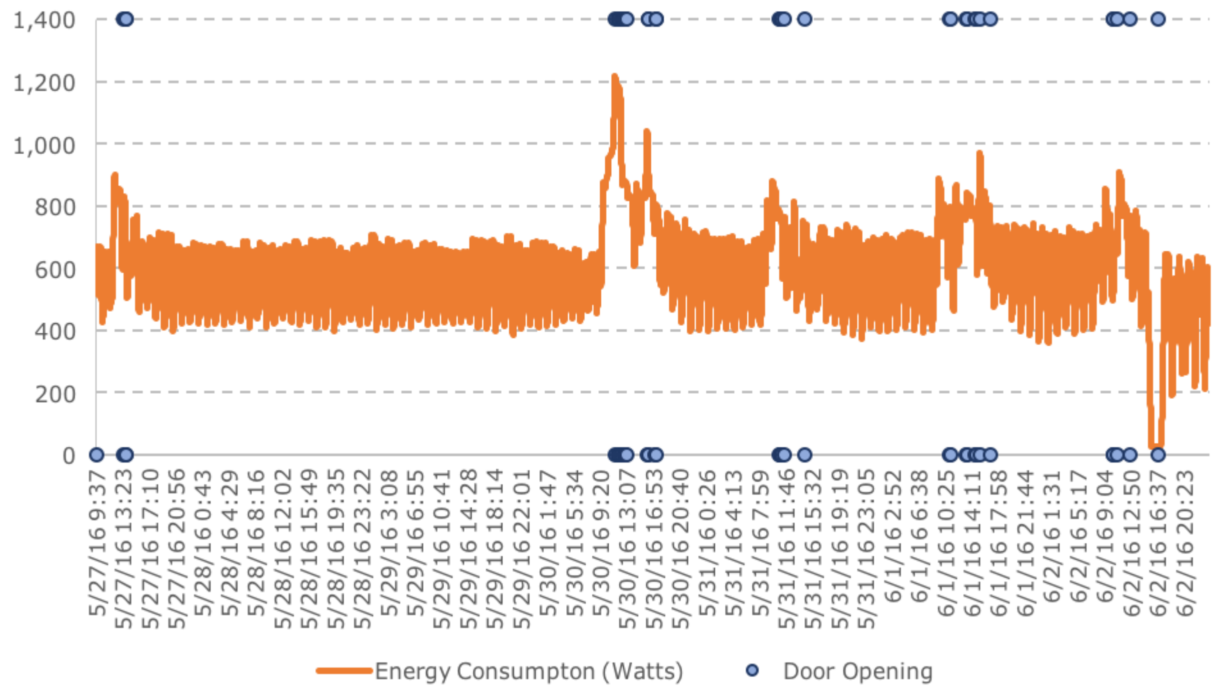


FIGURE 31: FREEZER D ENERGY CONSUMPTION WITH DOOR OPENINGS AT -80°C

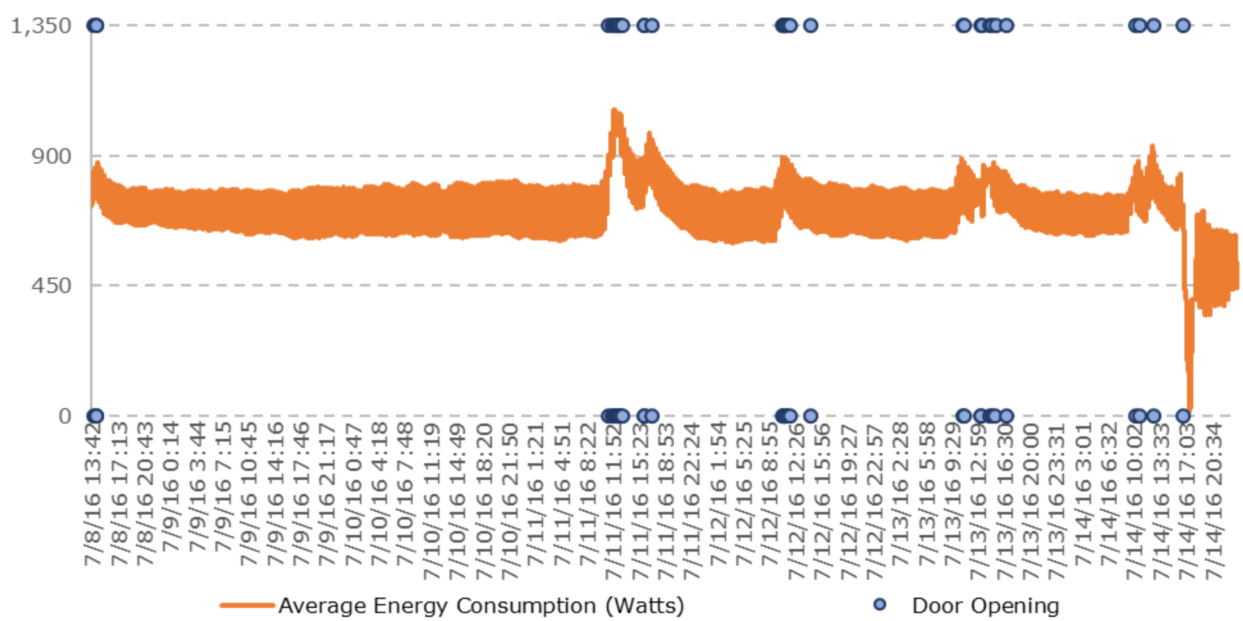


FIGURE 32: FREEZER F ENERGY CONSUMPTION WITH DOOR OPENINGS AT -80°C

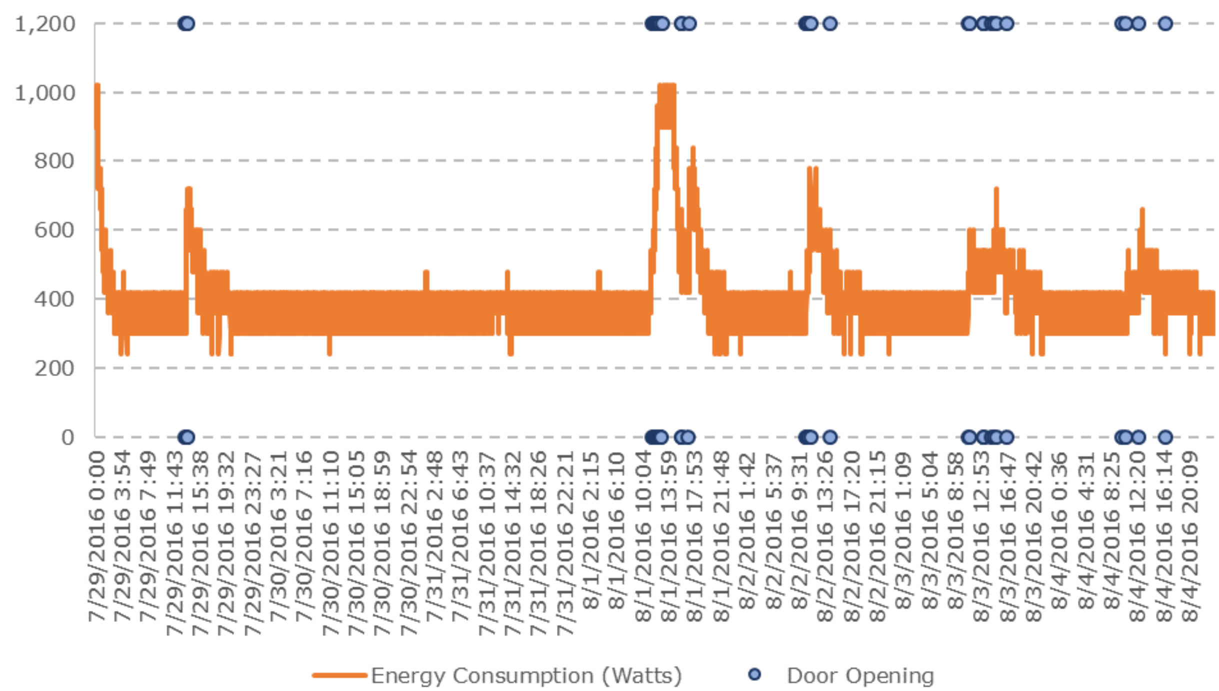


FIGURE 33: FREEZER B ENERGY CONSUMPTION WITH DOOR OPENINGS AT -70°C

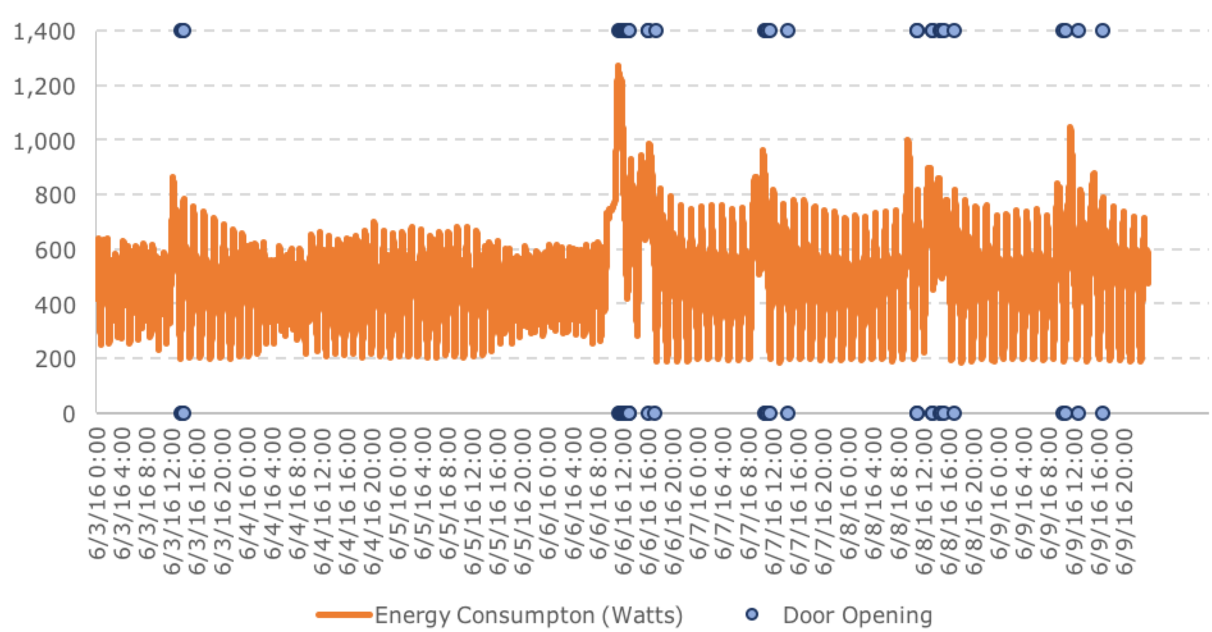


FIGURE 34: FREEZER D ENERGY CONSUMPTION WITH DOOR OPENINGS AT -70°C

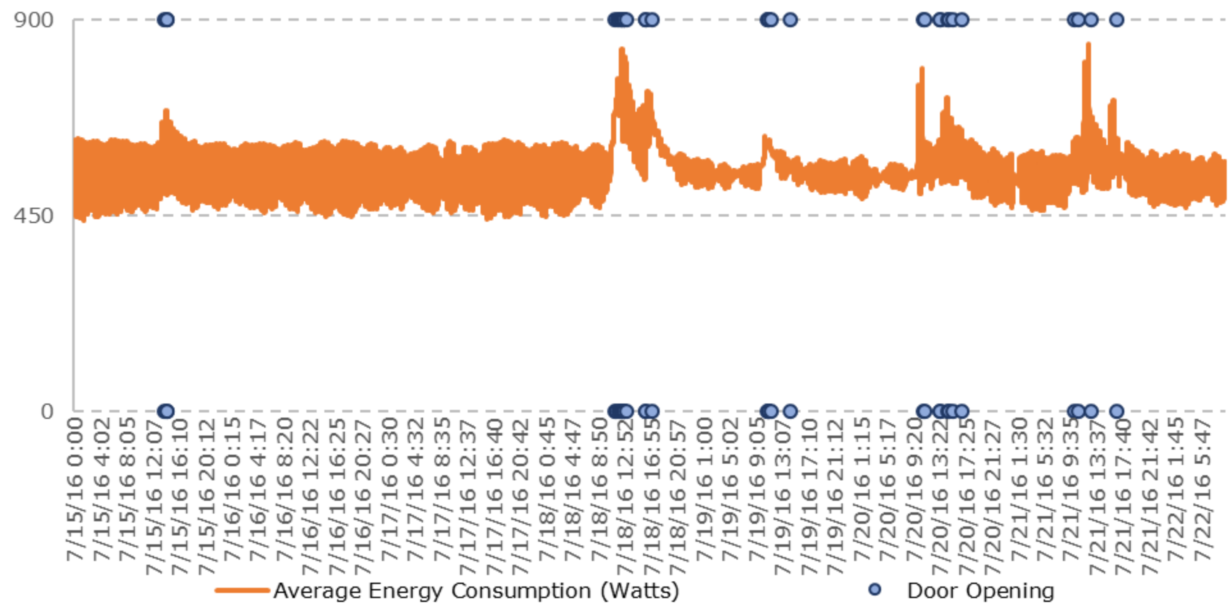
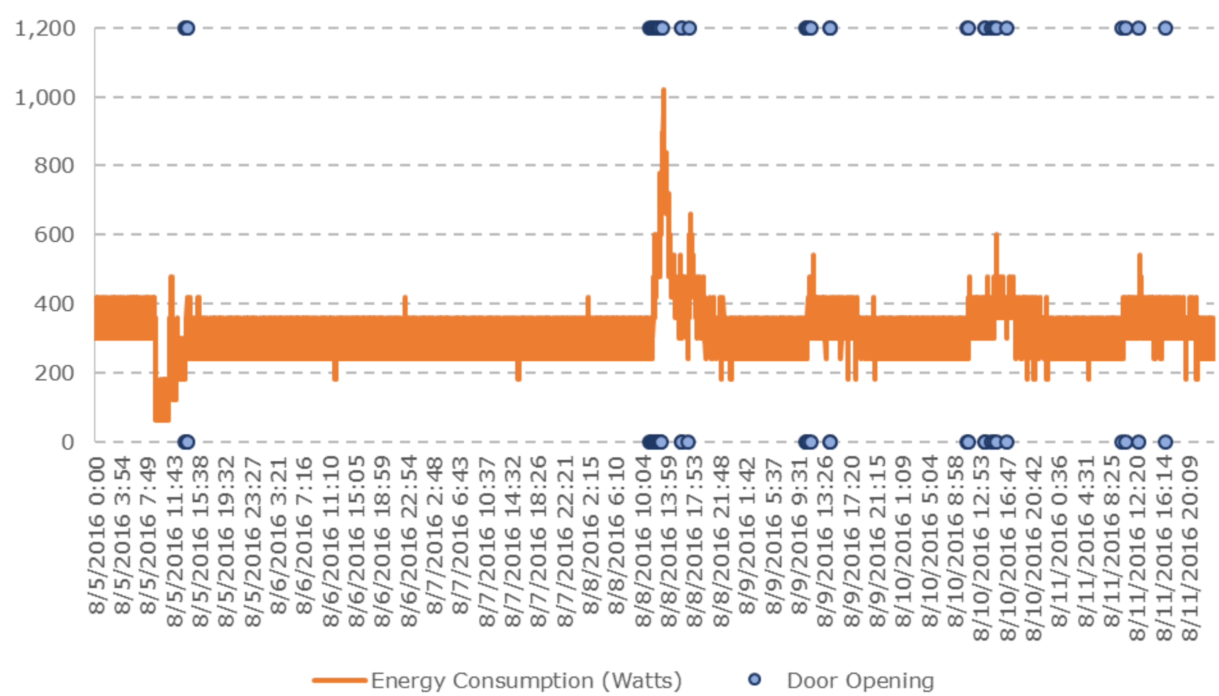


FIGURE 35: FREEZER F ENERGY CONSUMPTION WITH DOOR OPENINGS AT -70°C



The daily effects of the door opening protocol can be seen in the representative graphs below from Freezers B, D and F. A complete accounting of how each ULT freezer studied was affected by the Tuesday and Thursday door opening schedule can be found in Appendix E.

Note that Freezer B's energy consumption remains high after many door openings in a row when the freezer is set to -80°C. This pattern of sustained energy consumption was not seen at -70°C.

FIGURE 36: FREEZER B ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -80°C

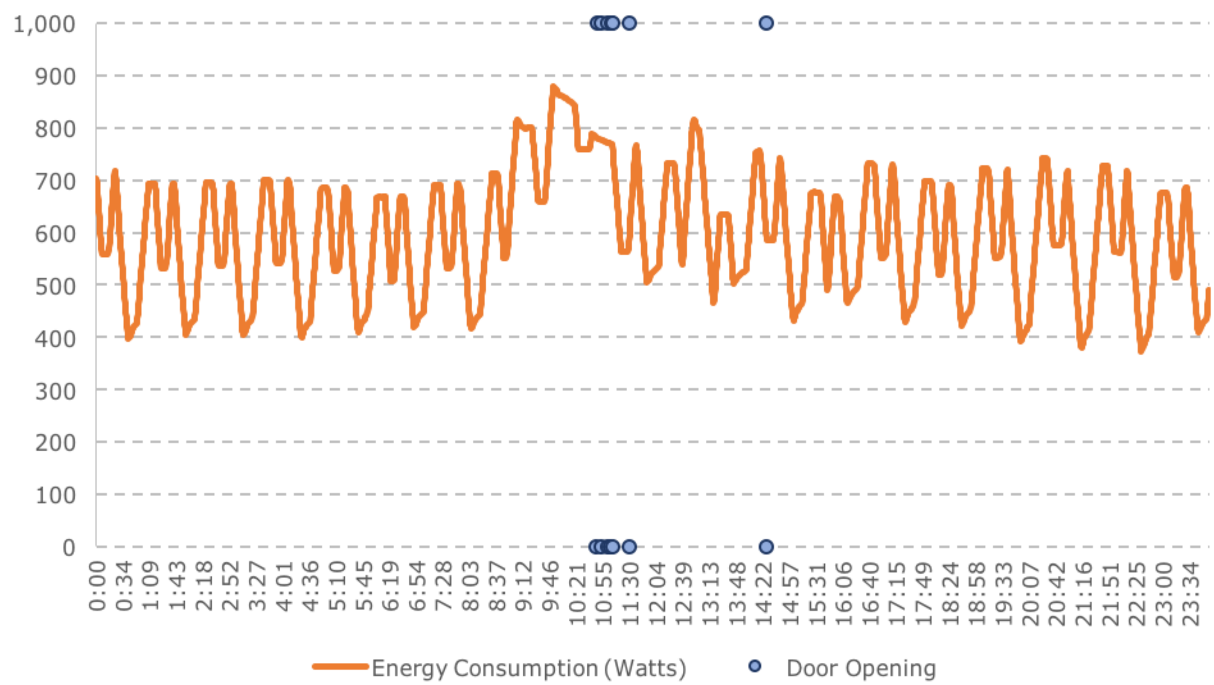
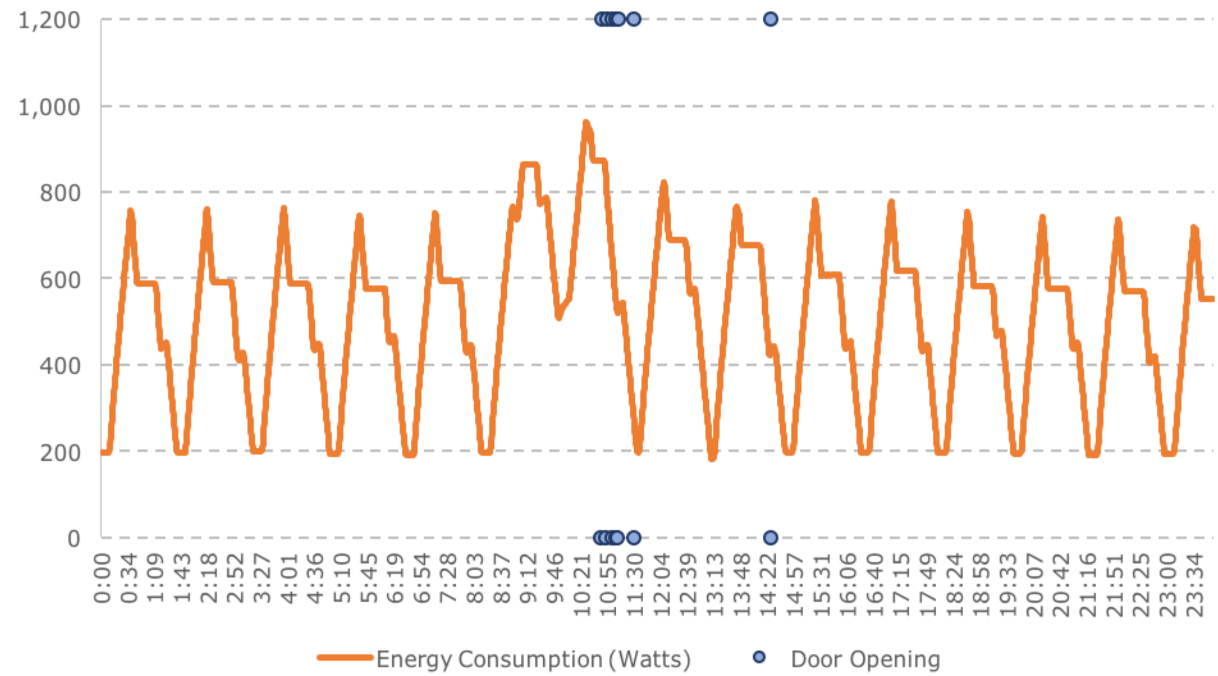


FIGURE 37: FREEZER B ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -70°C



Freezer D had much more frequent compressor cycling than Freezer B, regardless of the initial set point of the freezer. This can be seen in the graphs below.

FIGURE 38: FREEZER D ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -80°C

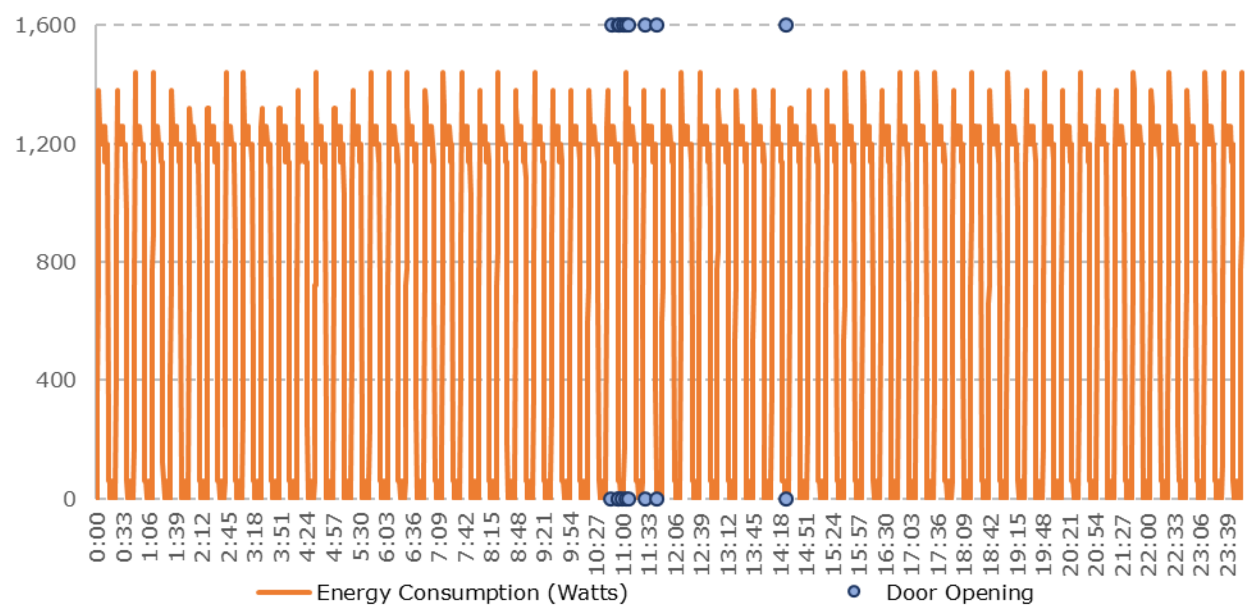
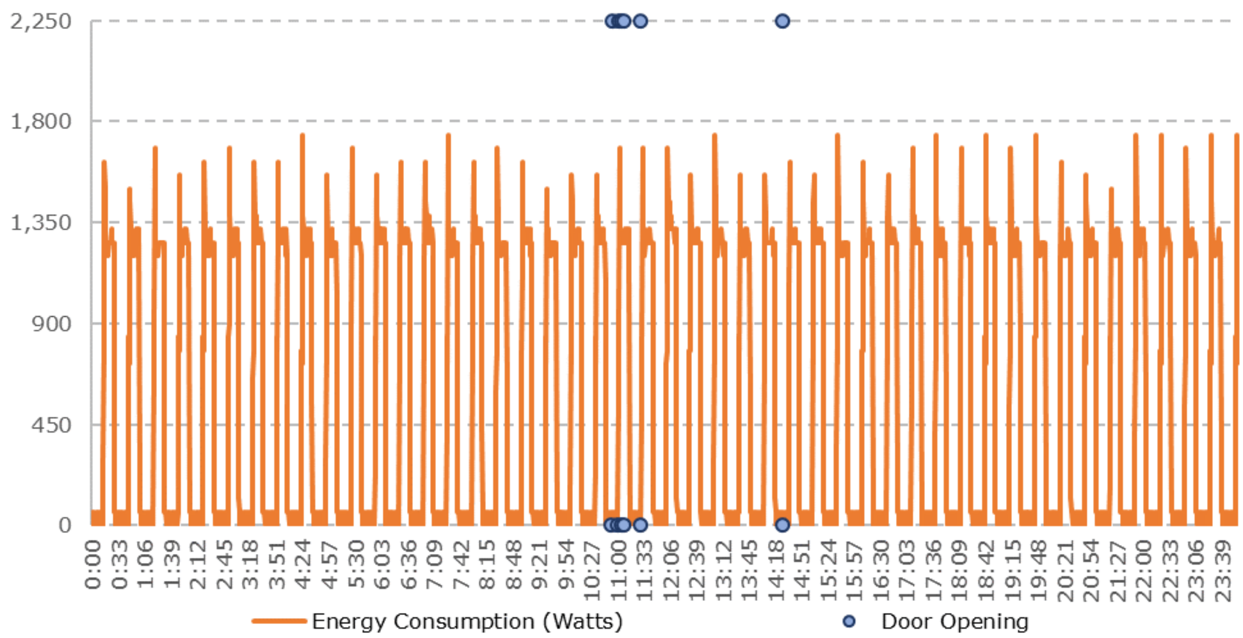


FIGURE 39: FREEZER D ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -70°C



Freezer F's energy consumption increased in direct proportion to the number and duration of door openings. This pattern was unique to this particular ULT freezer, though it most closely resembles what was seen in Freezer B.

FIGURE 40: FREEZER F ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -80°C

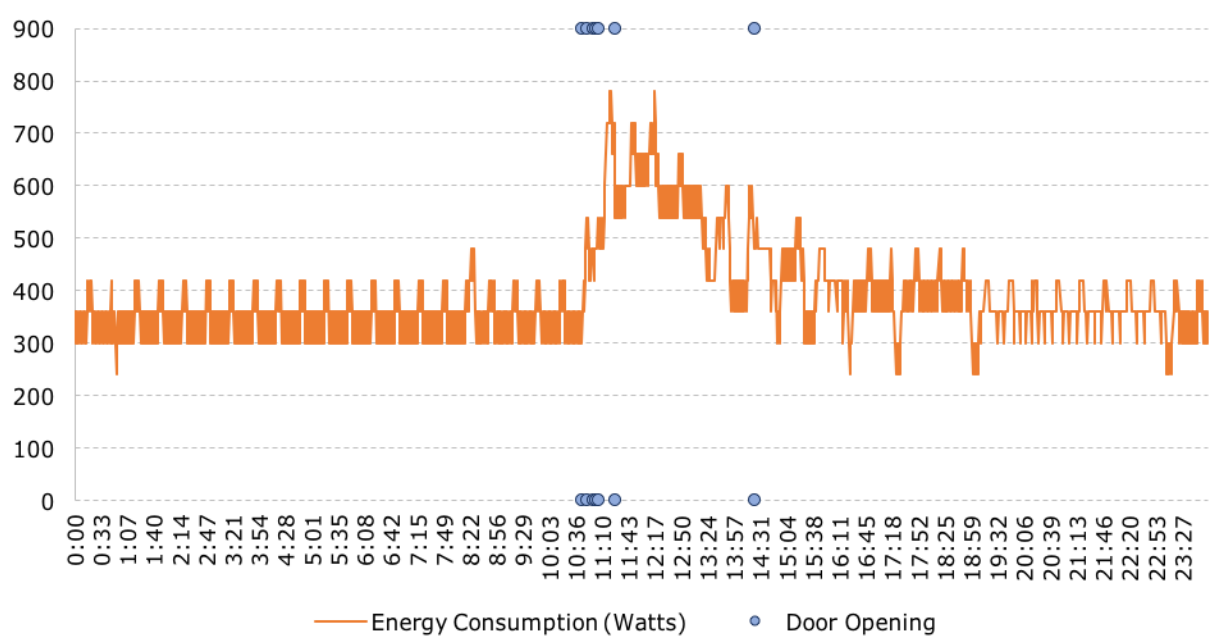


FIGURE 41: FREEZER F ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -70°C

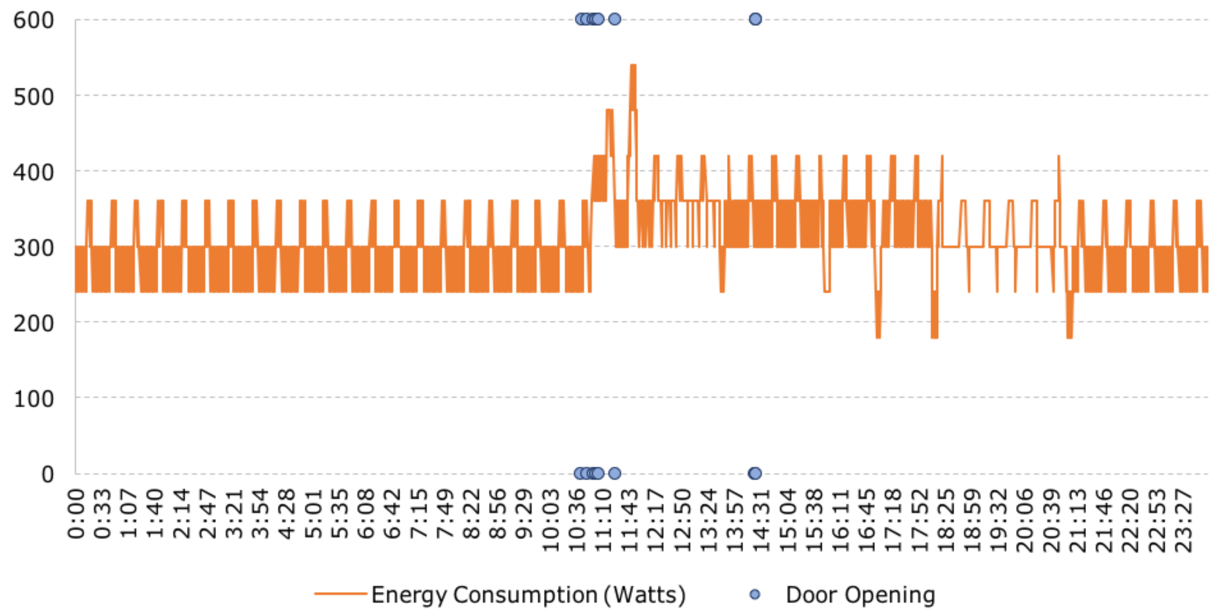


Table 18 shows the average energy consumption of the seven freezers tested in the field. The numbers reflect the average energy consumption per day throughout the duration of the study, including door openings and weekends. All of the ULT freezers used the same amount or less energy during the field test than they did during the controlled environment test; this is likely due to the humidity conditions and the freezer loading of the controlled environment test. The ambient drybulb temperature in the controlled environment test and in the field was similar (75°F), but the relative humidity during the controlled environment testing was much higher (60%) than the field test site (40%). In addition, the freezers in the field were filled with boxes and other thermal mass, whereas under the controlled environment testing the freezers were mostly empty. The empty interior combined with higher ambient humidity resulted in a greater load being placed on the refrigeration systems during door openings in the controlled environment test compared to the field. This is because more air fills the extra space in the empty freezer when the door is opened, and the higher humidity causes the freezer to work harder remove the high internal latent load. The full freezers in the field study were filled with less air, and less humid air, when the door was opened.

TABLE 18: AVERAGE ULT FREEZER ENERGY CONSUMPTION AT -80°C AND -70°C

FREEZER	ENERGY CONSUMPTION (KWH/DAY) AT -80°C	ENERGY CONSUMPTION (KWH/DAY) AT -70°C
Freezer A	10.0	7.2
Freezer B	14.5	12.0
Freezer C	18.1	10.5
Freezer D	16.9	13.4
Freezer E	23.3	17.9
Freezer F	9.6	7.6
Freezer G	9.5	7.5

Averaging the energy results at -80°C and -70°C in the same manner prescribed by the ENERGY STAR test method gives the results shown in the table below (-75°C). Comparing the field study results with the controlled environment ENERGY STAR results reveals that in many cases the field study data mirrored those from the controlled environment ENERGY STAR test. However, there were a few key instances in which the ULT freezers consumed less energy under the field conditions, notably Freezers A, C, D and E. Based on performance in the field, Freezers A, F, and G consumed the least amount of energy. These findings corroborate those from the controlled environment study. Note in all cases energy consumption was calculated over the duration of the study, including days with door openings and days without door openings.

TABLE 19: AVERAGE ULT FREEZER ENERGY CONSUMPTION AT -75°C: ENERGY STAR AND FIELD TESTS

FREEZER	ENERGY CONSUMPTION (KWH/DAY) AT -75°C, ENERGY STAR TEST	ENERGY CONSUMPTION (KWH/DAY) AT -75°C, FIELD TEST
Freezer A	10.97	9.44
Freezer B	13.50	13.01
Freezer C	19.03	14.74
Freezer D	17.88	16.11
Freezer E	23.76	21.77
Freezer F	8.83	8.61
Freezer G	10.49	10.22

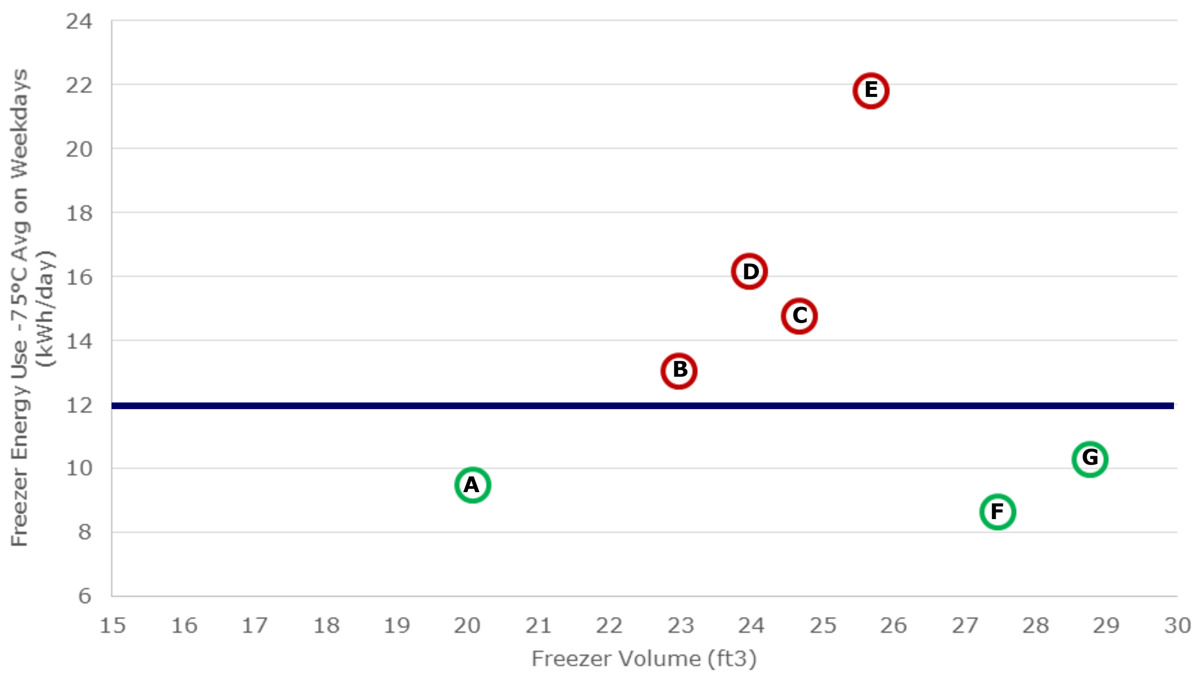
Normalizing these data on a cubic foot basis yields the results shown below in Table 19.

TABLE 20: NORMALIZED AVERAGE ULT FREEZER ENERGY CONSUMPTION AT -80°C AND -70°C

FREEZER	ENERGY CONSUMPTION (kWh/ft^3/DAY) AT -80°C	ENERGY CONSUMPTION (kWh/ft^3/DAY) AT -70°C
Freezer A	0.50	0.36
Freezer B	0.63	0.52
Freezer C	0.73	0.43
Freezer D	0.70	0.56
Freezer E	0.91	0.70
Freezer F	0.35	0.28
Freezer G	0.33	0.26

When viewed in this way, both Freezers F and G clearly consume the least amount of energy for a given storage capacity. Freezer A, by comparison, which seemed to be nearly the same in energy consumption, is revealed to consume 30% more than Freezers F and G when normalized by freezer capacity. Nevertheless, these three freezers remain the most energy efficient of the units tested in the field, as evidenced by the graph below, supporting the delineation between standard-efficiency and energy-efficient ULT freezers determined from the controlled environment ENERGY STAR tests. The line on the graph delineates the top 33% most energy-efficient freezers from the remaining units. Note, the data from Freezer C at -80°C were based on data collected from a single day in the field, with door openings.

FIGURE 42: ULT FREEZER ENERGY CONSUMPTION: DETERMINING ENERGY EFFICIENCY, FIELD TEST



ULT FREEZER CONTROLLED FIELD TESTS – TEMPERATURE PERFORMANCE

Temperature performance is perhaps the most critical parameter on which to evaluate ULT freezer performance. ULT freezers that are unable to maintain temperature adequately for a given application are unlikely to have success in the market. Thus it was important to investigate how energy-efficient ULT freezers performed in terms of temperature uniformity and stability relative to their less-efficient peers.

In order to assess temperature performance, ULT freezers in the field were subjected to a rigorous door opening schedule as outlined in Appendix E. On some days the freezers experienced a high frequency of door openings within a short amount of time, and on other days the time between door openings was several hours. Unlike the energy data above, the temperature performance data did not fall into neatly-defined groups; each ULT freezer exhibited its own unique response to the door opening schedule. Moreover, many of the ULT freezers performed differently at -80°C than at -70°C. A summary of the findings for Monday and Thursday door openings at -80°C is presented below. For a more detailed account see Appendix D.

STANDARD ULT FREEZER TEMPERATURE DATA, MONDAY DOOR OPENING SCHEDULE AT -80°C

Monday's door opening schedule was the most challenging. There were ten door openings in less than two hours, the longest of which lasted nearly 2.5 minutes. The thermal response to this schedule from standard-efficiency ULT freezers, namely Freezers B, C, D and E, can be seen below.

In Freezer B nearly all of the TCs registered a higher temperature reading in response to the rapid door openings at the beginning of the day. In fact, not all of the TCs had returned to their baseline reading before the afternoon door openings began.

The temperature change seen in Freezers C, D and E was less remarkable. Freezer D had only three TCs respond to the door openings with a large temperature change, and while many of the TCs registered an increase in temperature in Freezers C and E, they seemed to recover quickly as evidenced by the narrow peaks in their graphs.

The peak internal temperature measured in these ULT freezers ranged from -55°C (Freezer B) to nearly 10°C (Freezer C). However, Freezer C appears to have a much higher internal temperature in general: most TCs registered temperatures above -80°C in spite of the -80°C set point. It is important to note that although the ULT freezers were calibrated prior to the field test, the calibration was done to ensure that the temperature reading on the ULT freezer matched the temperature reading of the internal temperature probe that exists within each freezer. Thus it is expected that there will be different temperature readings throughout the freezer that do not match the set point.

The warmest areas in Freezers B, C, D, and E were the top shelves, regardless of the set point, and the coldest areas were the center/bottom shelves. With the exception of Freezer D, this pattern remained regardless of which freezer compartment was opened.

At -70°C the ULT freezers generally exhibited less drastic temperature swings but the overall internal freezer cabinet was warmer.

FIGURE 43: FREEZER B TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C

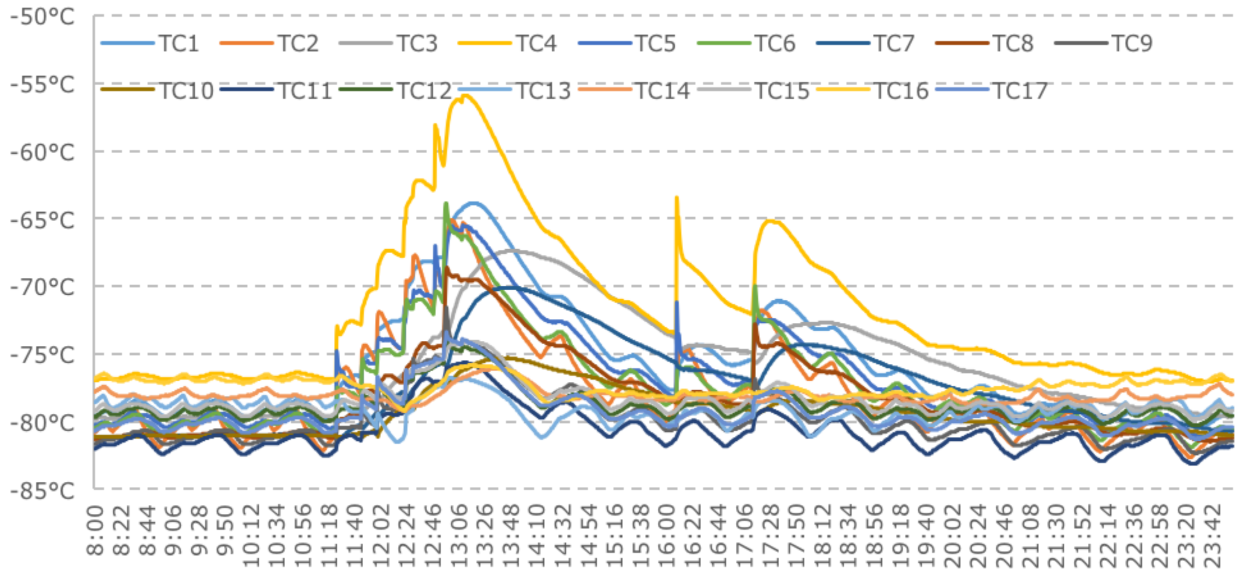


FIGURE 44: FREEZER C TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C

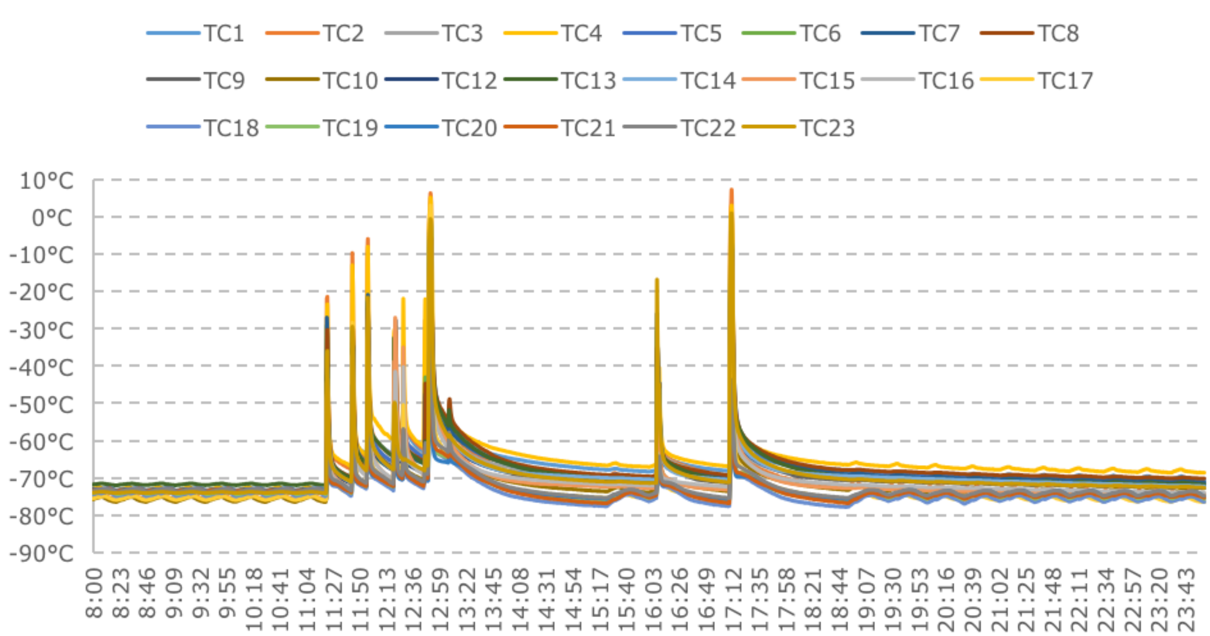


FIGURE 45: FREEZER D TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C

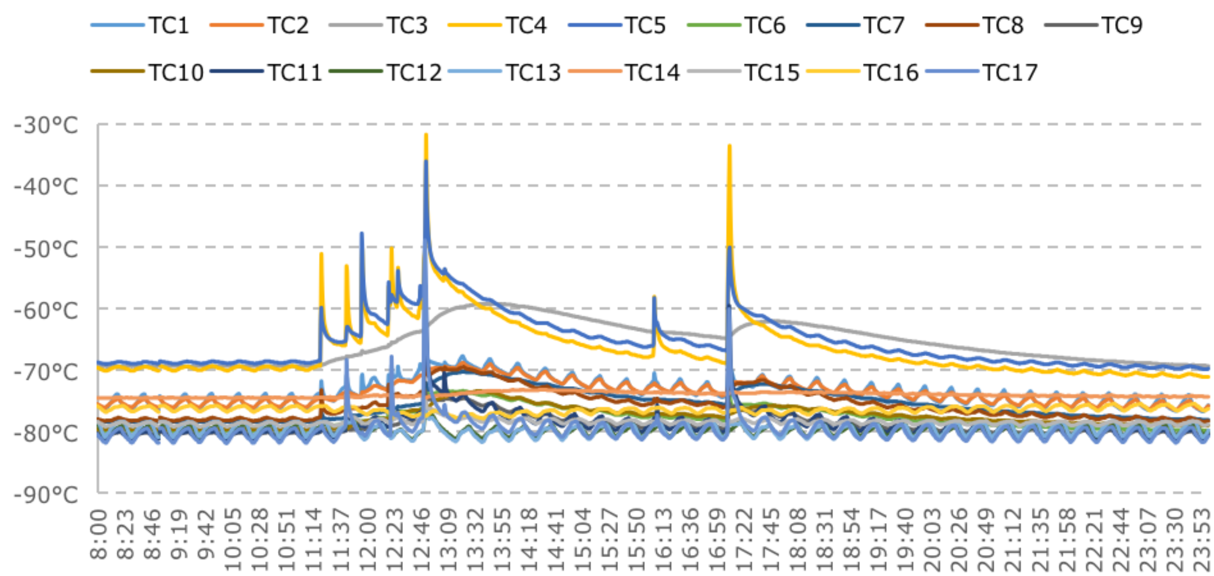
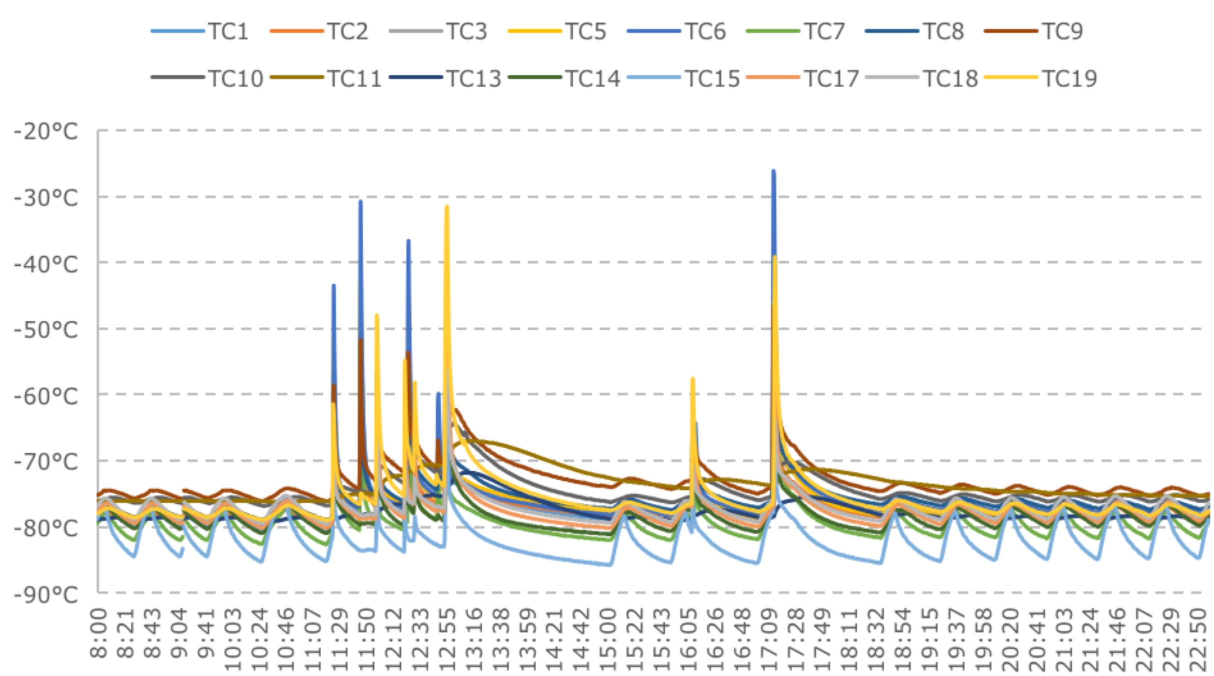


FIGURE 46: FREEZER E TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C



ENERGY-EFFICIENT ULT FREEZER TEMPERATURE DATA, MONDAY DOOR OPENING SCHEDULE AT -80°C

Comparing energy-efficient ULT freezers to standard-efficiency models reveals very little difference in general. The temperature data gathered from Freezers A and G in response to the Monday door opening schedule look very similar to those gathered from Freezers C and E. Freezer A's peak internal temperature is similar to that seen in Freezer C, although Freezer A maintains an overall set point closer to -80°C.

Freezer F's temperature profile is unique. When the door was opened, many of the TCs responded with a decrease in temperature. The overall temperature profile appeared to reflect an attempt to maintain an average internal temperature equal to the set point.

Freezer A did not have conventional warm/cool zones inside the freezer; the TCs reading the warmest temperatures were often in the same compartment or very close to the TCs reading the coldest temperatures. This was true at -70°C as well. Freezers F and G on the other hand followed the pattern seen in the other ULT freezers, with the top shelves often registering the warmest temperatures and the bottom shelves registering the coldest, regardless of the set point.

FIGURE 47: FREEZER A TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C

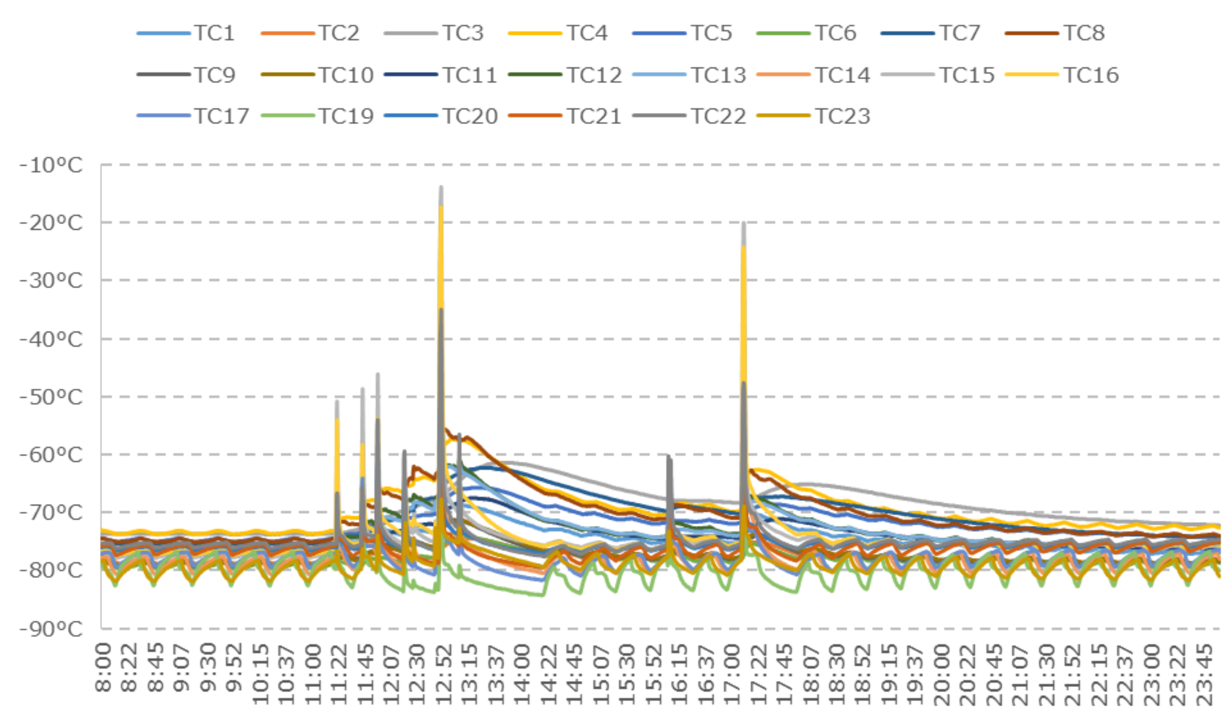


FIGURE 48: FREEZER F TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C

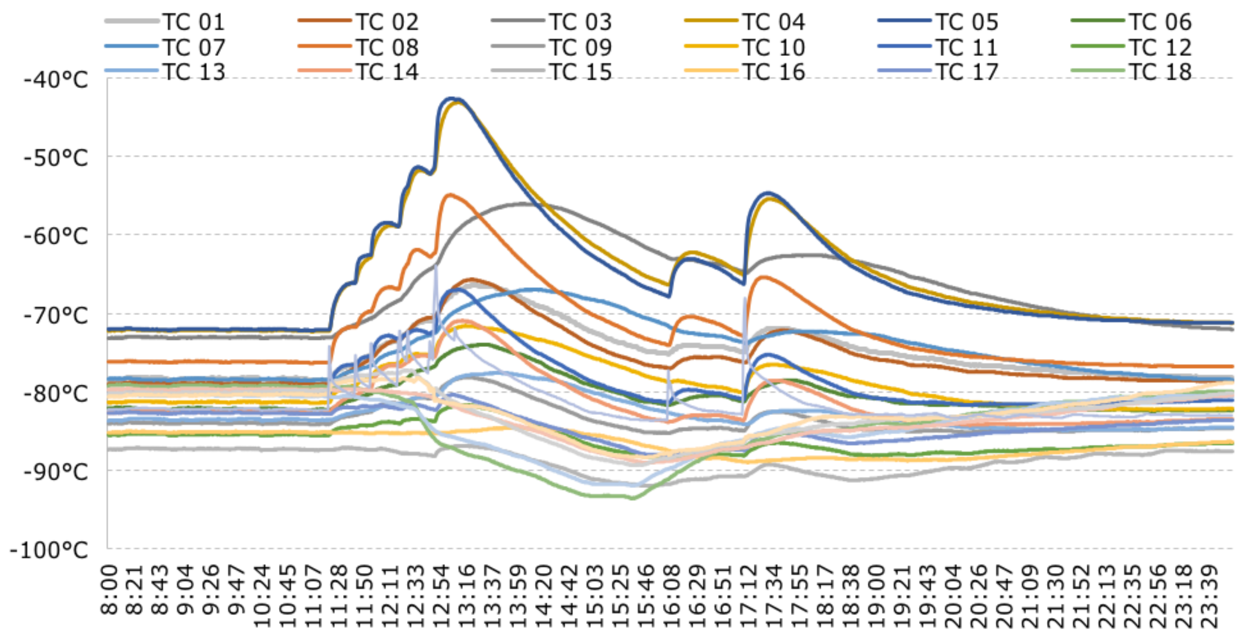
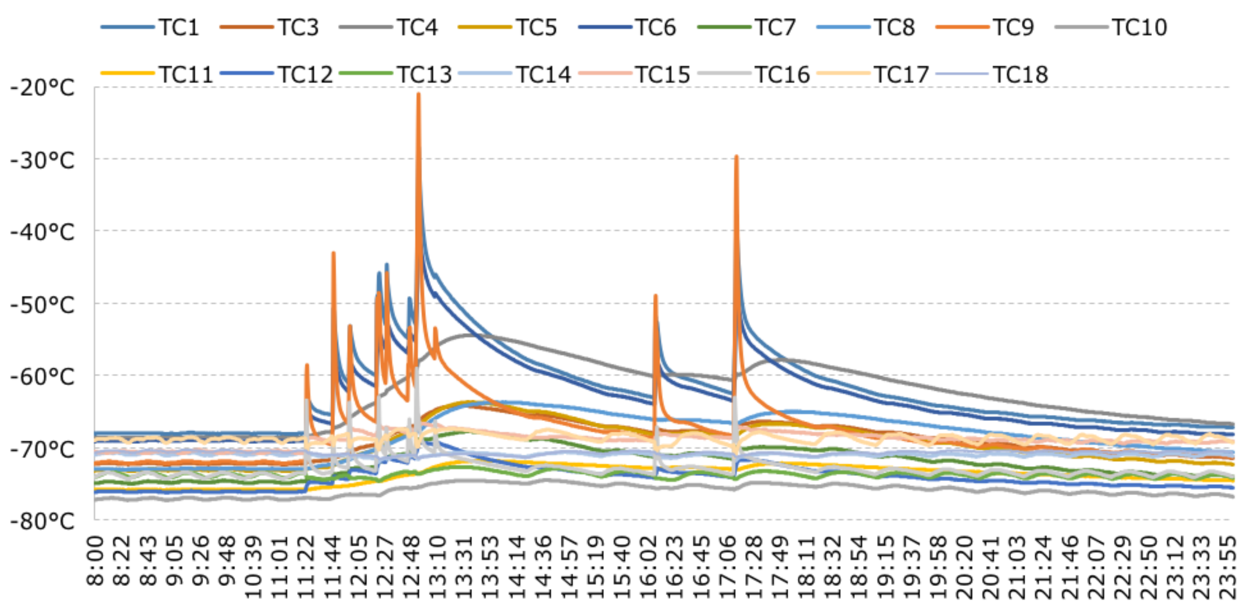


FIGURE 49: FREEZER G TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C



STANDARD ULT FREEZER TEMPERATURE DATA, THURSDAY DOOR OPENING SCHEDULE AT -80°C

The door opening schedule on Thursday had far fewer door openings than Monday's schedule and there were longer spaces between them. Thus the data presented below represent a best-case scenario in contrast to Monday's worst-case scenario.

The temperature profile on Thursday for Freezer B stands in stark contrast to that seen on Monday – only TC5 seems to be substantially affected by the door opening, and it's temperature increase is only 10 degrees above baseline. The other TCs barely register that the door has been opened.

The responses of Freezers C, D and E are very similar, with a few TCs registering an increase in temperature, but recovering quite quickly.

FIGURE 50: FREEZER B TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C

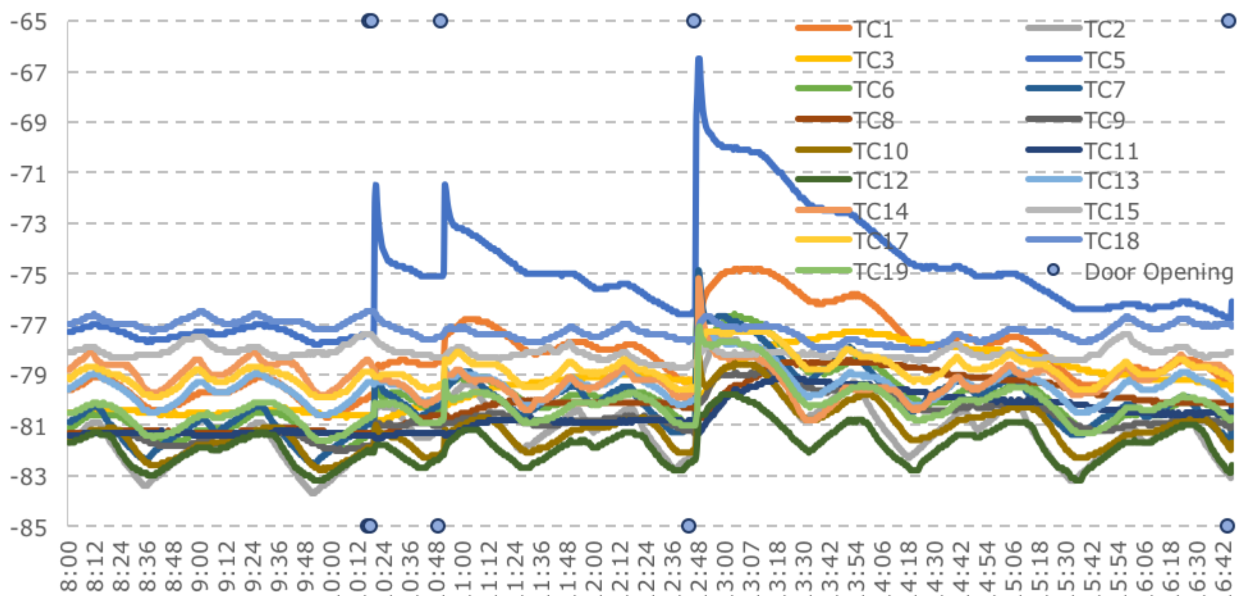


FIGURE 51: FREEZER C TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C

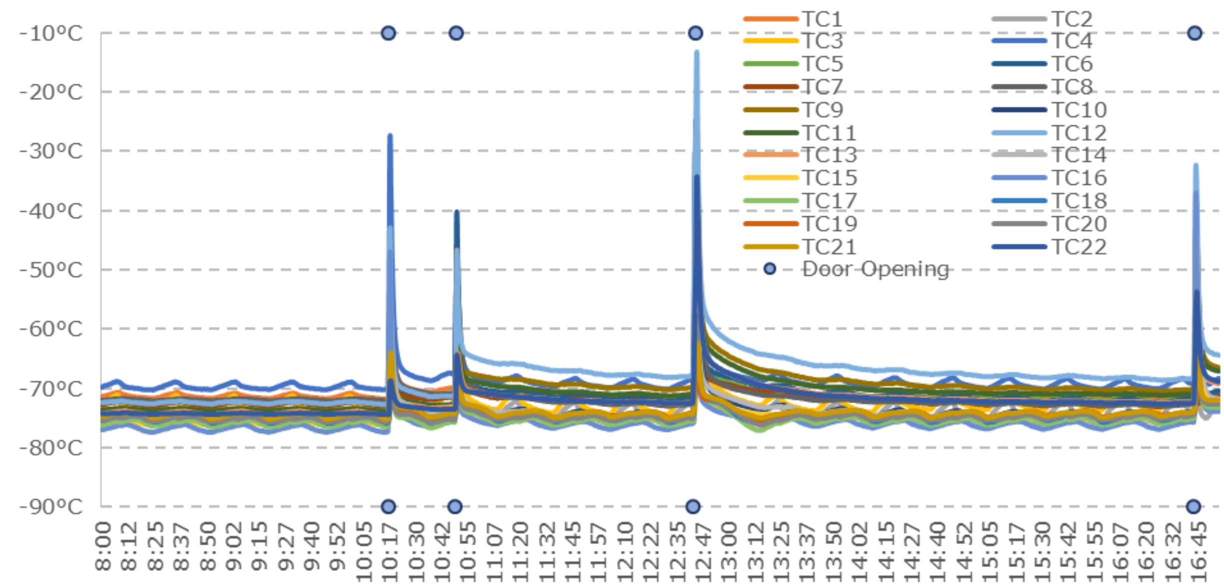


FIGURE 52: FREEZER D TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C

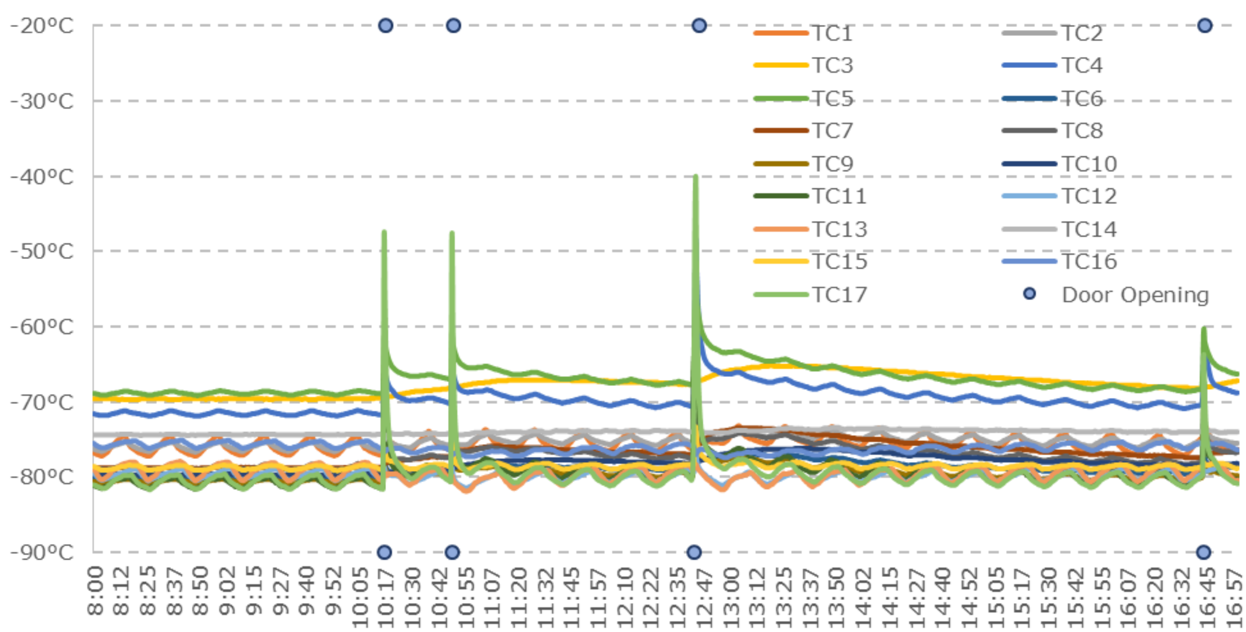
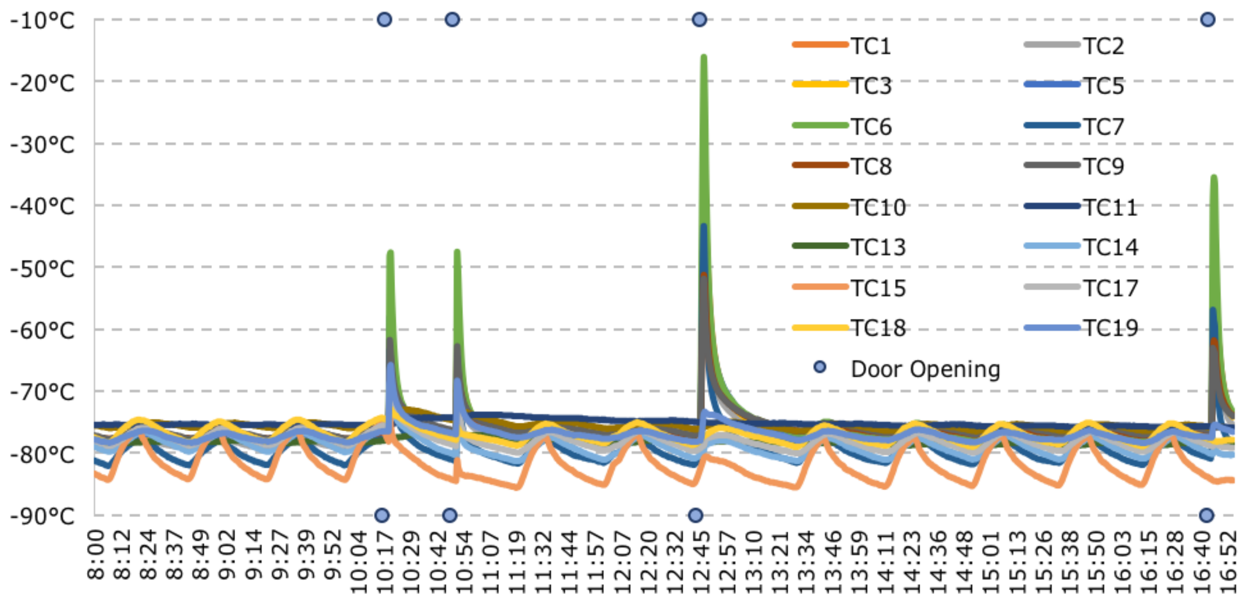


FIGURE 53: FREEZER E TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C



ENERGY-EFFICIENT ULT FREEZER TEMPERATURE DATA, THURSDAY DOOR OPENING SCHEDULE AT -80°C

As before, the temperature profiles of the ULT freezers marketed as energy-efficient are remarkably similar to their standard-efficiency peers when compared on the basis of the Thursday door opening schedule. Freezers A and G look no different from Freezers C, D and E above. Freezer F remains unique in its response to door openings. None of the TCs registers a lower temperature in the graph below; in this case all TCs seem to respond in tandem with a temperature increase, with some TCs exhibiting a larger temperature differential than others.

FIGURE 54: FREEZER A TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C

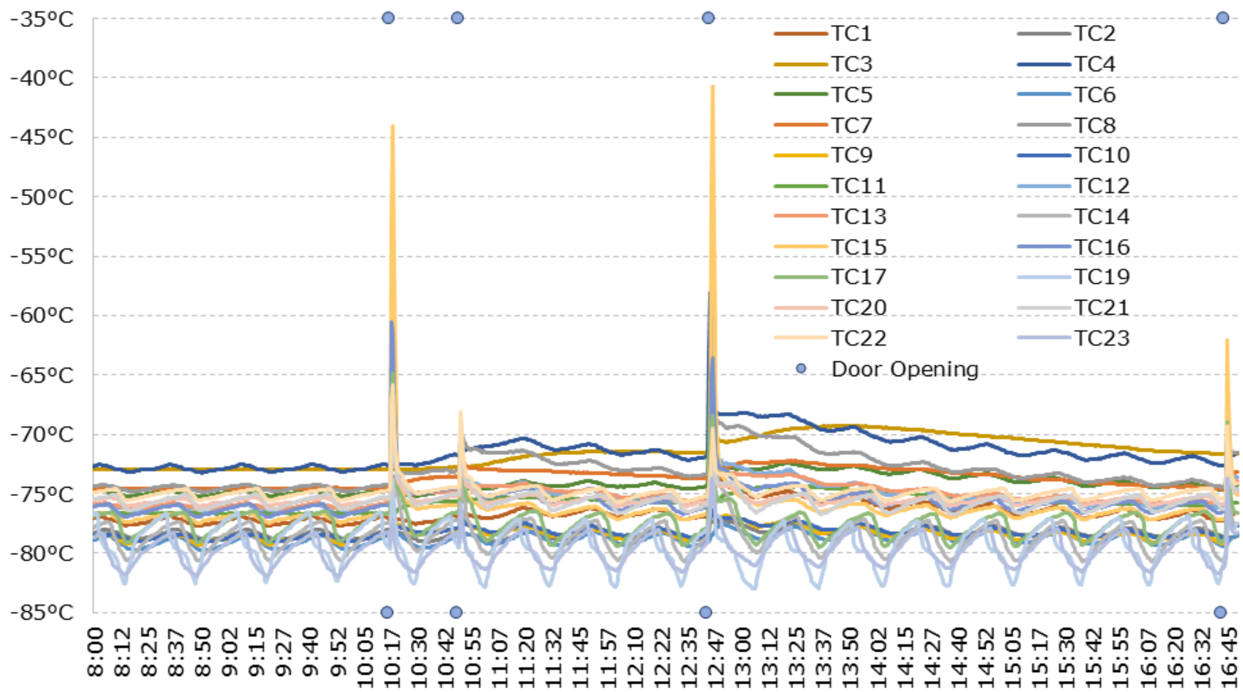


FIGURE 55: FREEZER F TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C

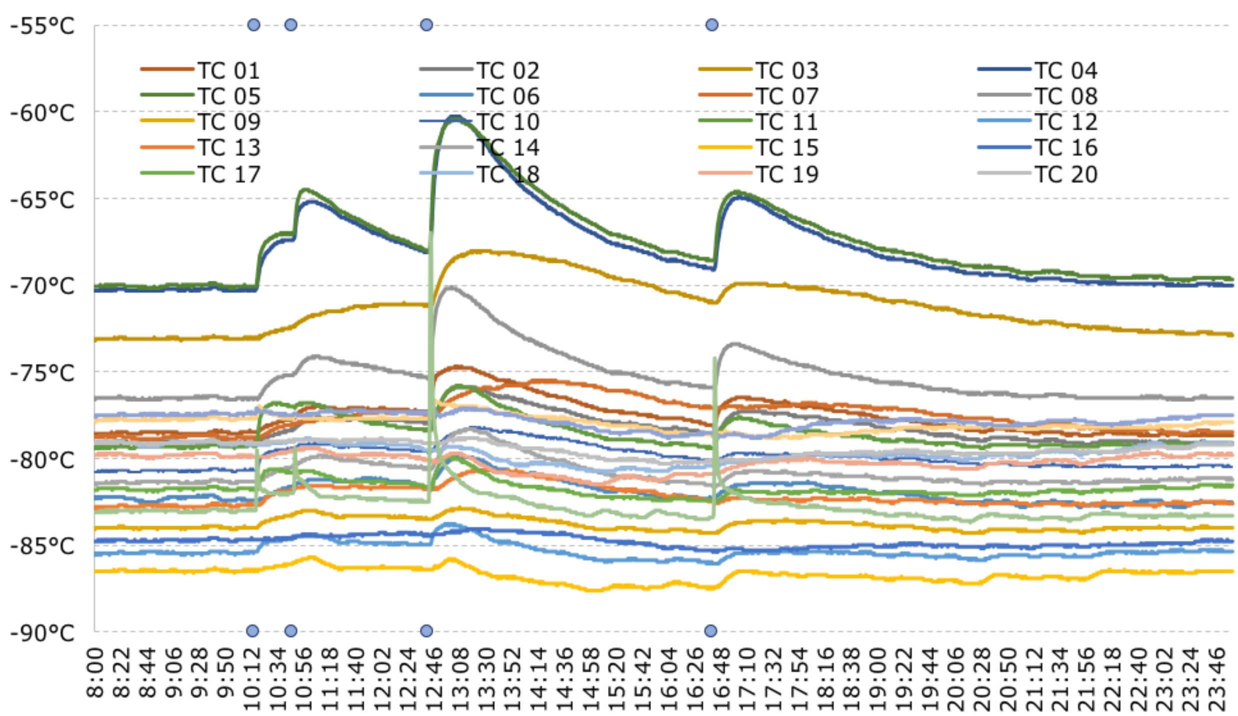
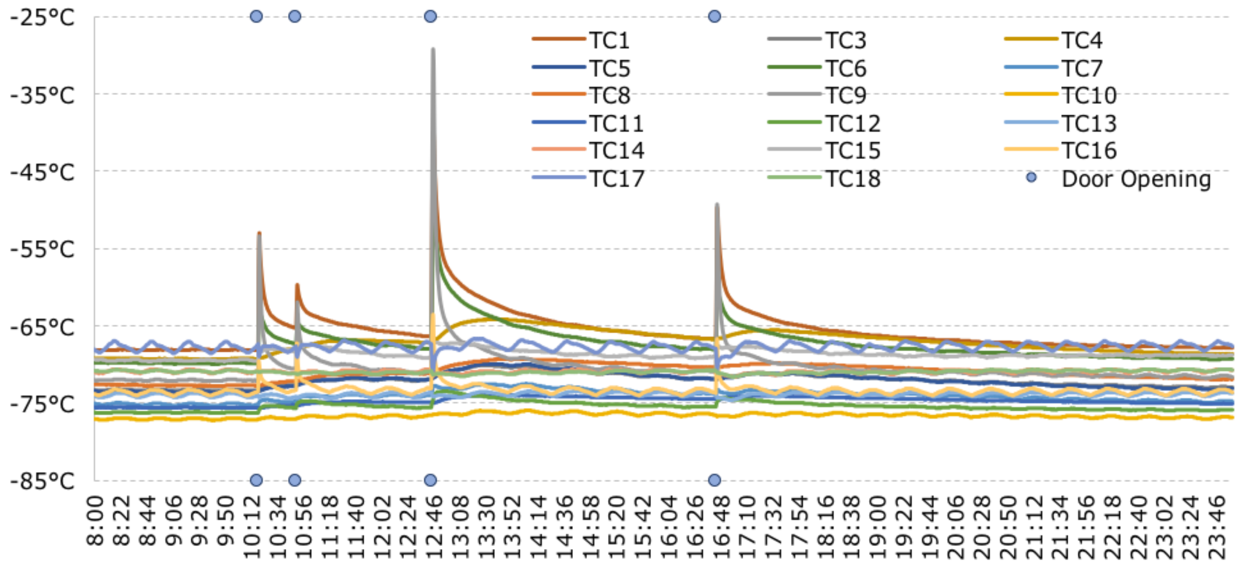


FIGURE 56: FREEZER G TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C



STANDARD ULT FREEZER TEMPERATURE DATA, SUMMARY OF TEMPERATURE VARIANCE

The figures below depict the temperature variance, or temperature spread, observed in each freezer. The average temperature of the TC probes is shown in dark blue, the standard deviation is shown in dark gray, and the amplitude of the difference between the warmest and coldest TC reading is shown in pastel. Door openings are shown by the circles in blue at the top of the graphs. Note that all ULT freezers depicted below were tested at -80°C before being tested at -70°C in the second portion of the test.

Freezer B maintained average temperatures of -80°C and -70°C when set to those temperature set points. However, both the standard deviation and the temperature spread nearly doubled when the set point changed from -80°C to -70°C. None of the other standard ULT freezers tested exhibited this type of behavior.

Freezers D displayed a large standard deviation in comparison to the other freezers in the test; both Freezers C and E had very small temperature deviations. However Freezer C was found to have an average internal temperature that was several degrees warmer than Freezers B, C, and E at both -80°C and -70°C set points. Freezer D was slightly warmer than -80°C on average when set to this temperature, but this warming effect was not seen at -70°C.

FIGURE 57: FREEZER B TEMPERATURE VARIANCE

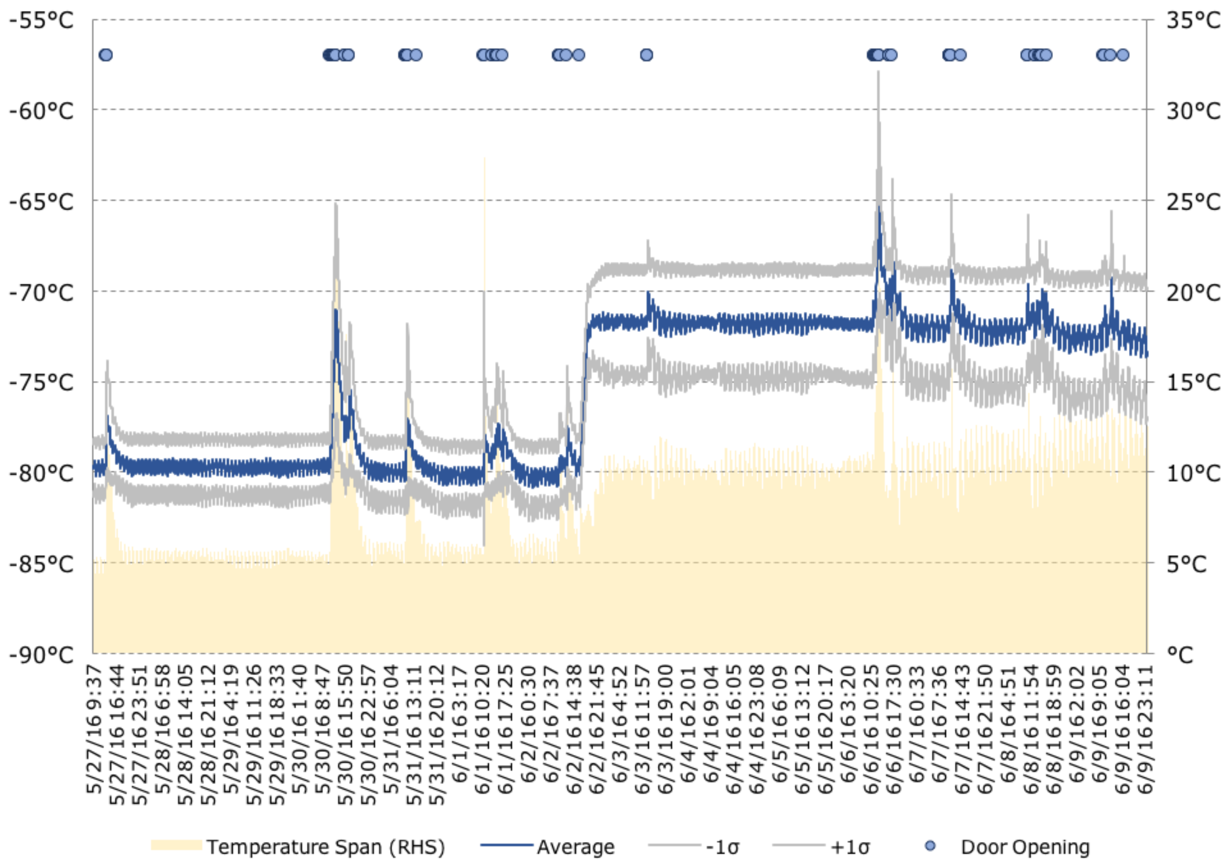


FIGURE 58: FREEZER C TEMPERATURE VARIANCE

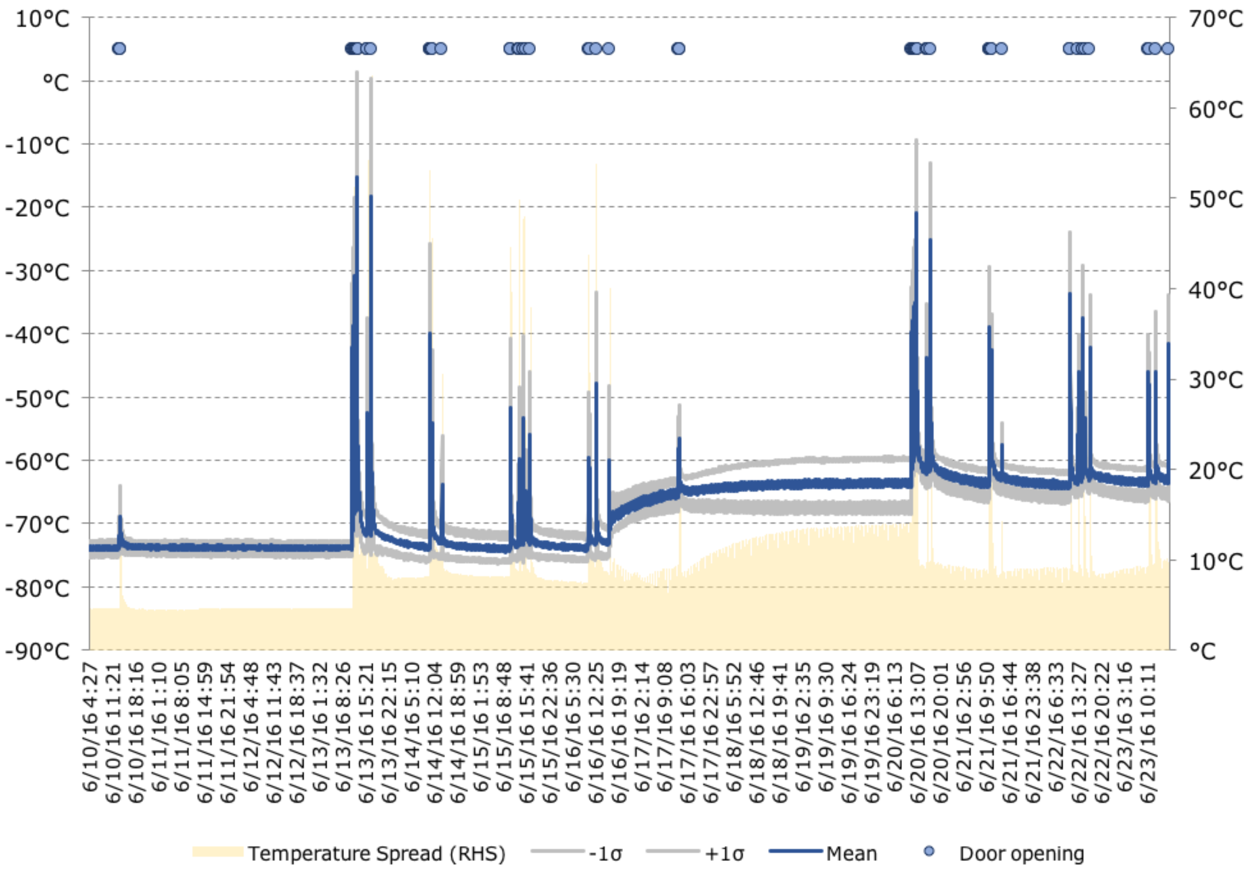


FIGURE 59: FREEZER D TEMPERATURE VARIANCE

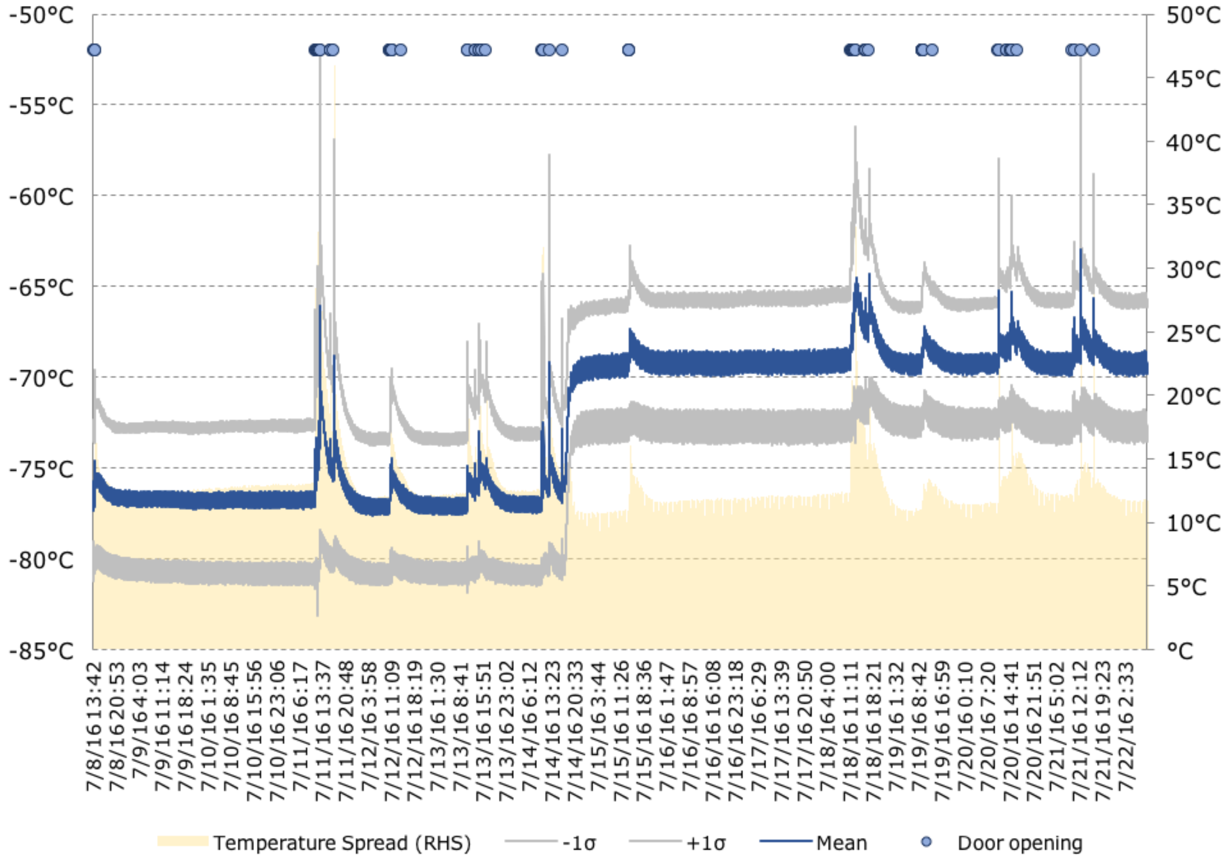
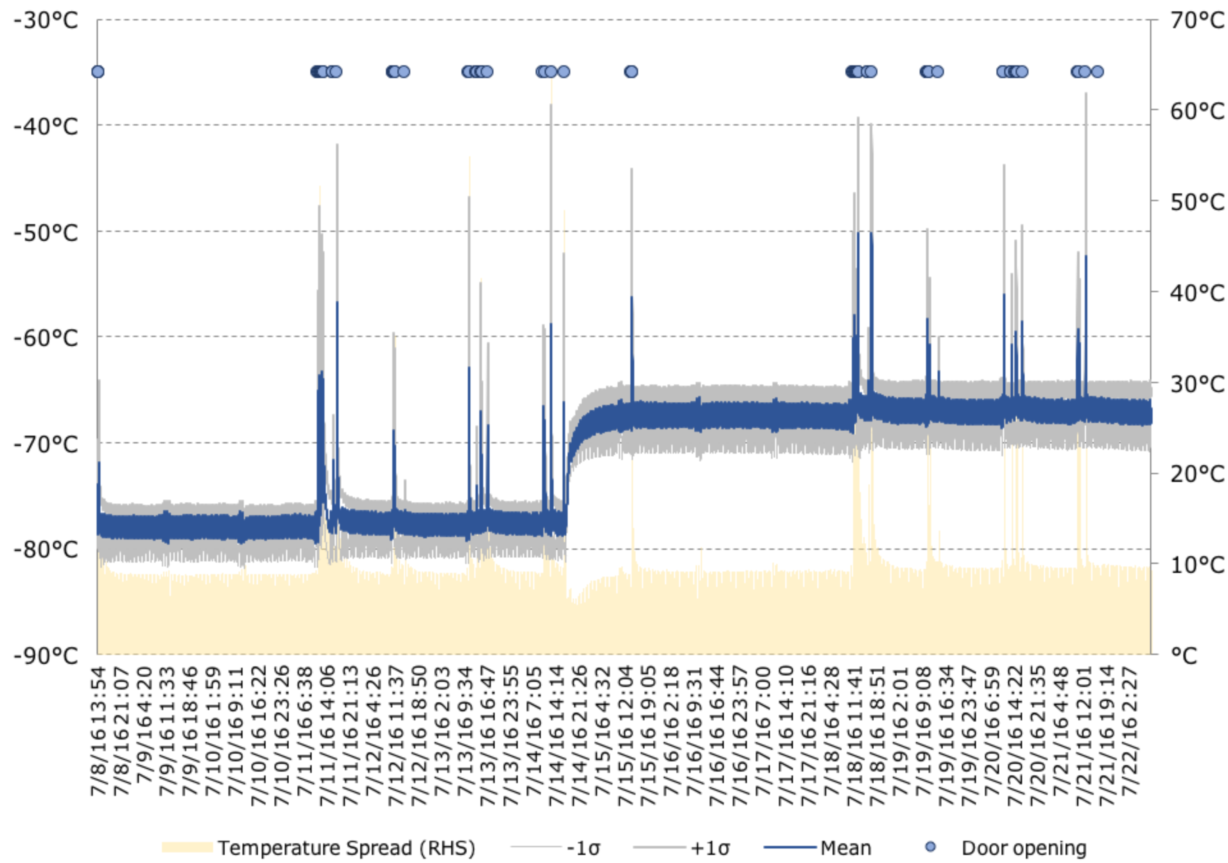


FIGURE 60: FREEZER E TEMPERATURE VARIANCE



ENERGY-EFFICIENT ULT FREEZER TEMPERATURE DATA, SUMMARY OF TEMPERATURE VARIANCE

The energy-efficient ULT freezer results were relatively similar to those of the standard-efficiency models, with Freezers A and G once again being comparable to Freezers C and E.

Freezer F displayed a larger variance than the other freezers tested in the field, irrespective of the temperature set point. The differential seen in Freezer F remained at or above 15 degrees throughout the duration of the study, and was the largest value observed. Notably, unlike the other ULT freezers in the study, the lower standard deviation was found to be at least ~5°C below the temperature set point, and this deviation line's response to door openings – a decrease in temperature – was far more pronounced than the other freezers. It appears as though some parts of Freezer F experience an over-cooling effect when the door is opened.

Freezer G had a higher average internal temperature in general, compared to the other ULT freezers tested in this study, and in this way the data from this freezer most closely resemble those from Freezer C.

FIGURE 61: FREEZER A TEMPERATURE VARIANCE

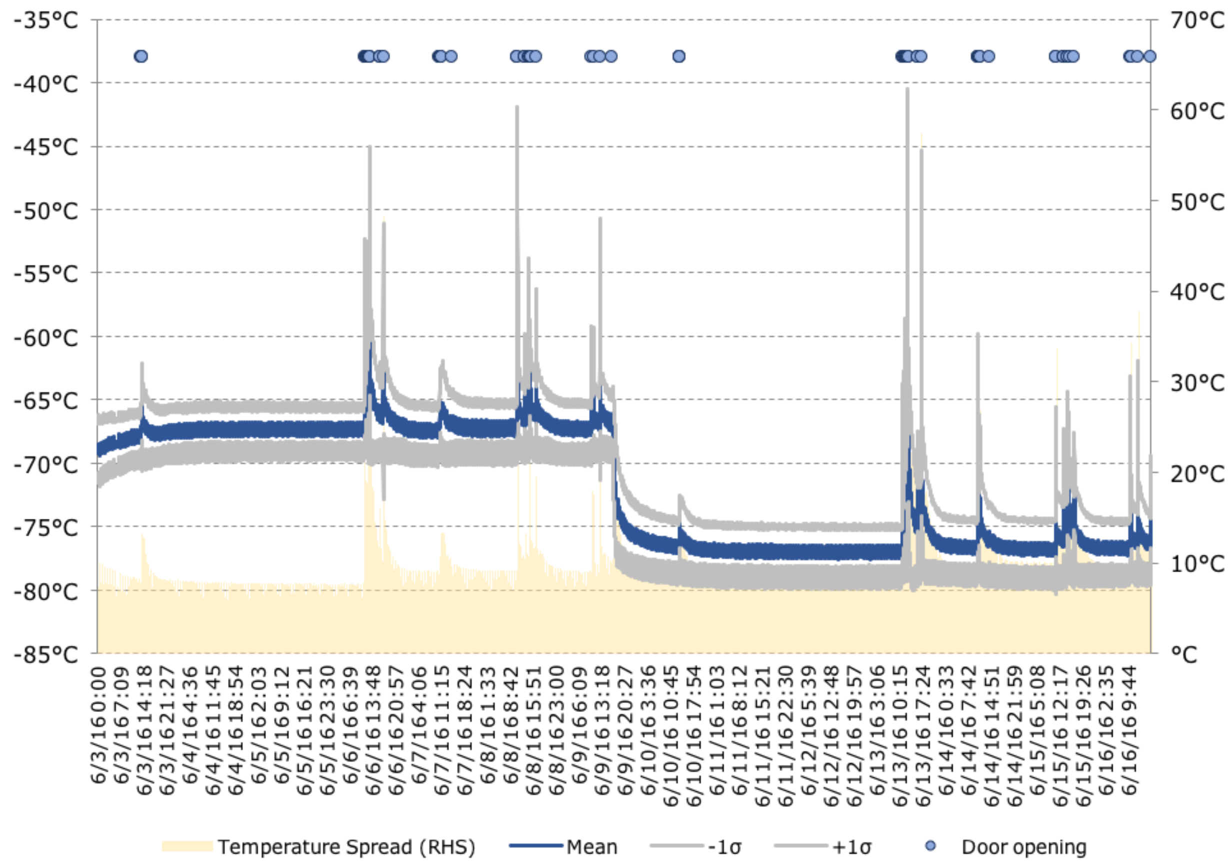


FIGURE 62: FREEZER F TEMPERATURE VARIANCE

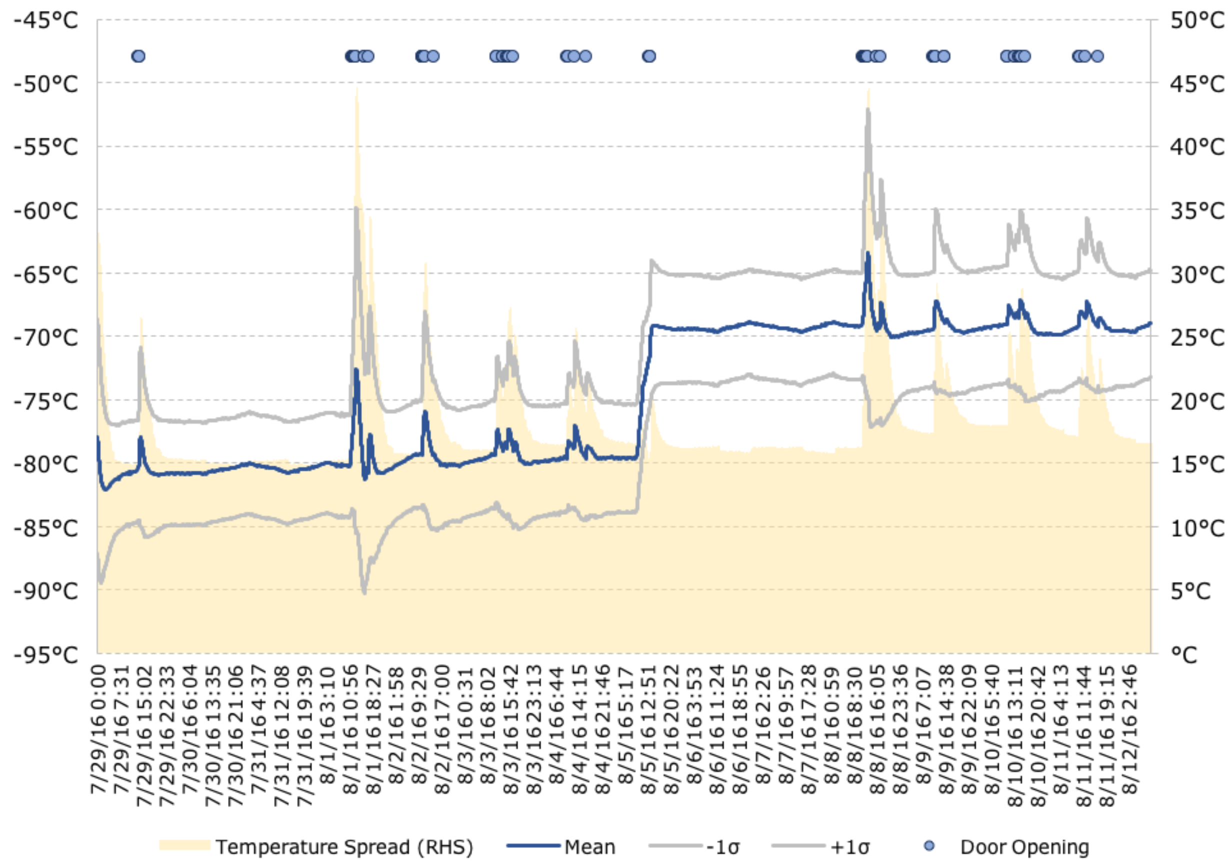
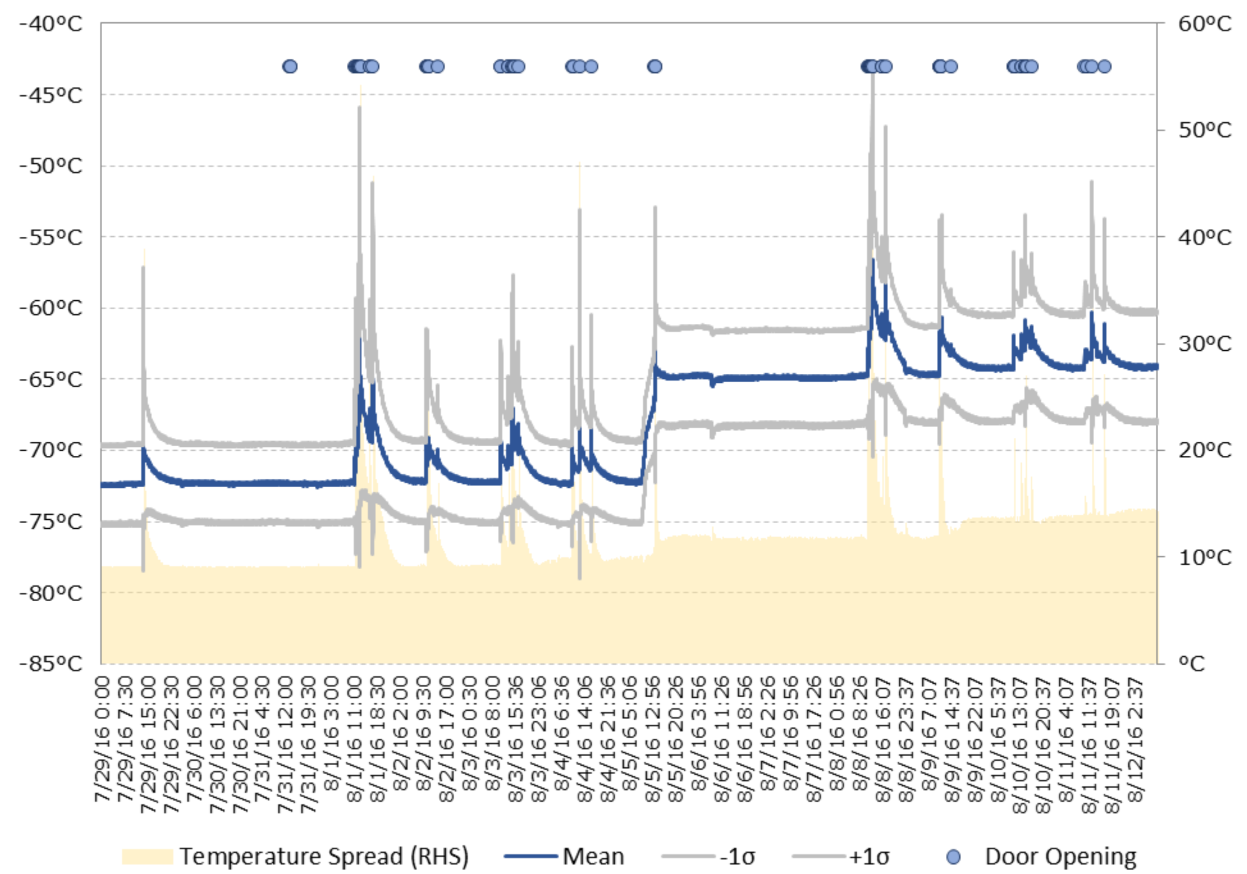


FIGURE 63: FREEZER G TEMPERATURE VARIANCE



A summary of the findings depicted in the graphs above is shown in Table 21 below. To avoid the influence of door openings, only observations from 12:00am on Saturday to 11:59pm on Sunday are included in the data.

TABLE 21: SUMMARY OF TEMPERATURE PERFORMANCE AT -80°C

FREEZER	AVG. TEMP. (°C)	AVG. TEMP. SPREAD (°C)	AVG. ST. DEV. σ (°C)
Freezer A	-76.9	6.82	1.92
Freezer B	-79.7	5.02	1.53
Freezer C	-73.8	4.14	0.97
Freezer D	-76.7	11.56	3.96
Freezer E	-78.0	6.40	1.62
Freezer F	-80.5	15.03	4.01
Freezer G	-72.3	8.94	2.74

TABLE 22: SUMMARY OF TEMPERATURE PERFORMANCE AT -70°C

FREEZER	AVG. TEMP. (°C)	AVG. TEMP. SPREAD (°C)	AVG. ST. DEV. σ (°C)
Freezer A	-67.4	6.18	1.74
Freezer B	-71.8	9.58	2.92
Freezer C	-64.0	11.20	3.60
Freezer D	-69.2	10.48	3.46
Freezer E	-67.4	6.36	1.88
Freezer F	-69.3	16.05	4.20
Freezer G	-64.9	11.52	3.36

At -80°C and at -70°C Freezers F and G maintained the closest average temperature to the set point. However, Freezer F displayed a large amount of temperature variation and had the largest temperature differential. The energy-efficient ULT freezers performed as well as, and in some cases better than, the other ULT freezers in the study.

Table 23 illustrates the maximum temperature differential observed in the ULT freezers. The 'maximum temperature differential overall' shows the temperature difference when the freezer was in use (i.e. it includes the effect of door openings); the 'maximum temperature differential resting' shows the temperature difference when the freezer was not accessed (i.e. over the weekend).

TABLE 23: MAXIMUM TEMPERATURE DIFFERENTIAL

FREEZER	MAX TEMP DIFFERENTIAL OVERALL	MAX TEMP DIFFERENTIAL RESTING
Freezer A	62.4	9.2
Freezer B	30.9	11.6
Freezer C	63.6	13.8
Freezer D	46.0	13.0
Freezer E	64.6	11.8
Freezer F	44.7	16.4
Freezer G	54.2	12.9

As seen in the table above, Freezer B exhibited the smallest difference between the warmest and coldest temperature readings when the door was opened, but Freezer A had the smallest differential when the freezer was at rest. Freezers D, F and G had relatively low temperature fluctuations when the freezer was in use. At rest Freezer F showed the largest temperature differential. Taken together, the energy-efficient freezers can be said to perform comparably to the other ULT freezers on the market.

The temperature differentials observed in the field study were much higher than those observed in the controlled environment study; many of the ULT freezers that seemed to perform well in the field did not perform as well in the controlled environment study, and vice versa. In both studies Freezer A had the least variation in temperature. This was closely followed by Freezer F in the controlled environment study, and by Freezer C, under conditions in which the door was unopened. In contrast, in the field study Freezer F had the largest temperature spread while this designation belonged to Freezer C in the controlled environment study. When the door was opened, Freezer F displayed the most variation in temperature, followed by Freezer D.

These discrepancies are likely due to several key differences between the two studies – the placement of the TCs, the thermal load on the freezer, and the protocol for door openings. Specifically, the controlled environment study placed TCs inside of vials containing a glycerol solution. The field study placed TCs inside of weights on the shelf of the freezer. TCs inside the glycol-filled vials had a cold thermal mass that dampened temperature changes, whereas the field TCs were surrounded by cold thermal mass, but were nevertheless directly exposed to air. Moreover, the field study TCs were not threaded through the port on the side of the freezer; instead the TC wires traversed the door seal. Thus in the field study the TCs were much more likely to be sensitive to thermal fluctuations that a real sample stored in a ULT freezer might not see. In addition, the field study used full freezers as a test parameter; the controlled environment study used empty ULT freezers. Empty ULT freezers are meant to mimic a worst-case scenario (this is evidenced by the validation data above). Therefore real samples in the ULT freezers tested are unlikely to experience the large temperature variations observed in this study, especially in response to the door being opened. And finally, the two studies utilized different door opening protocols. The field study protocol was intended to be much more stressful for the ULT freezers, and the temperature variation observed in the study reflects this.

Taken together, samples stored in the traditional manner, i.e. inside of vials or tubes, which are then located inside of a box, are unlikely to experience dramatic changes in temperature throughout the day, even when the door is opened. The largest potential variations might be seen by Freezers D and F, if the door were to be left open for long periods of time and the freezers were unable to recover. But this is not the case, as evidenced by the data shown in the next section. The most vulnerable samples in the ULT freezers are those that are unprotected, such as bottles of reagents or samples stored in plastic bags. These would most likely experience the temperature variations seen in the field study, and care should be taken to store these types of samples on the shelves that are least susceptible to temperature change (usually the bottom shelves).

In order to compare the field study results with those observed in the controlled environment study, temperature uniformity and stability were also calculated for each of the ULT freezers studied. The figures below depict ULT freezer temperature uniformity, stability, and energy consumption at -80°C and -70°C.

At -80°C, Freezer F displayed the least amount of uniformity, but exhibited a high degree of stability. Freezers C and G also showed a relative lack of temperature uniformity, but both freezers were stable. Freezer C was found to lack temperature stability, as seen previously in the figures above. A similar pattern was observed at -70°C for each ULT freezer.

FIGURE 64: ULT FREEZER TEMPERATURE UNIFORMITY AND STABILITY AT -80°C

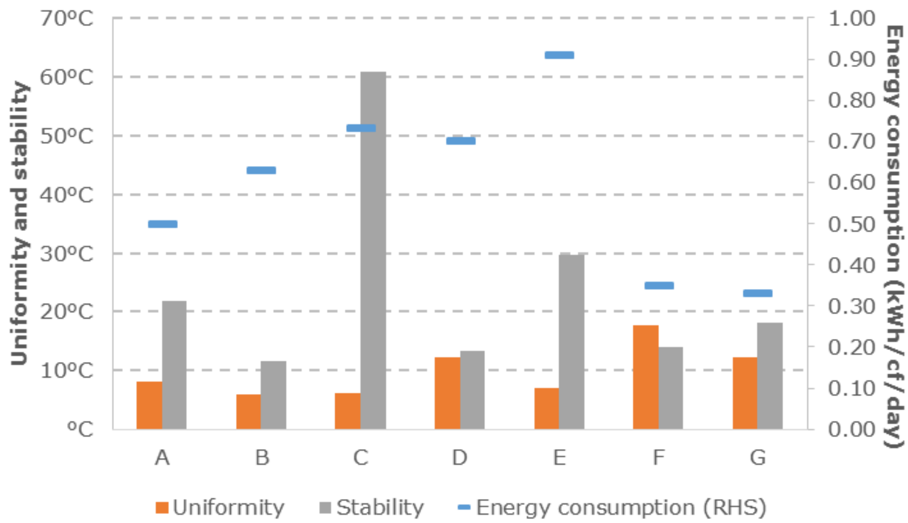
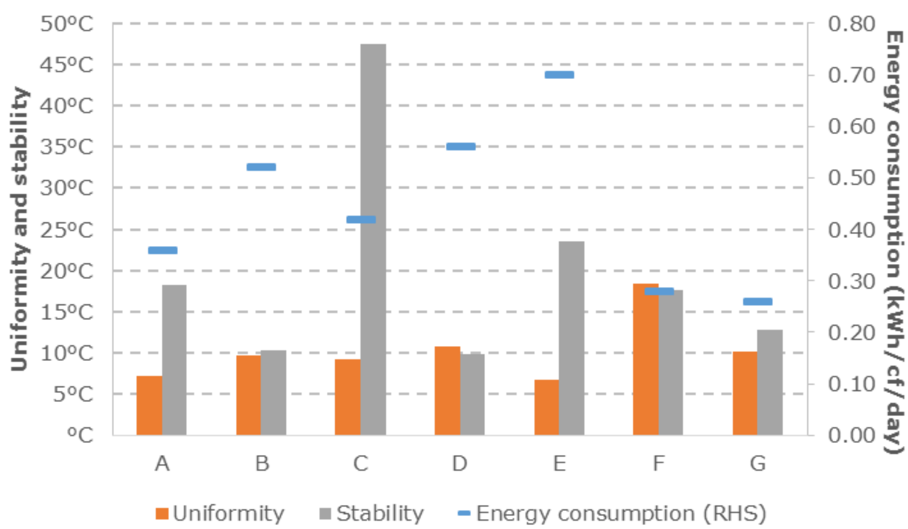


FIGURE 65: ULT FREEZER TEMPERATURE UNIFORMITY AND STABILITY AT -70°C



Importantly, the performance of the energy-efficient freezers was comparable to, and in many cases better than, the performance of the standard baseline ULT freezer models.

ULT FREEZER RECOVERY TIME

The recovery of the field test ULT freezers in response to a single door opening can be seen in the figures below. This door opening was performed at 4:53pm on a Wednesday, over an hour after the previous door opening, and it lasted for 48 seconds. There were no other door openings that day.

Baseline temperature readings were taken just before the door opening, and the average temperature reading from baseline is shown on the vertical axis. The recovery time is shown on the horizontal axis. Freezer C had the largest temperature change in response to the door opening, both at -80°C and at -70°C. At -80°C this was followed by Freezer E, which displayed a nearly 10°C temperature change immediately following the door opening, and Freezer A, which had a 5°C temperature change. At -70°C, Freezer E exhibited a ~9°C temperature change and the Freezer A showed a ~6°C temperature change. The remaining ULT freezers showed a less change in temperature ≤ 4°C from baseline upon opening the door.

After the door opening, Freezer E fully recovered within 30 minutes at -80°C and within 60 minutes at -70°C. At -80°C Freezers B and D were back to baseline within 3 hours, and the remaining freezers were within 1°C of baseline. At -70°C only Freezer B recovered more quickly than Freezer E – within 45 minutes. Freezer F also recovered rather quickly, within 2 hours. The remaining ULT freezers did not fully recover back to baseline within 3 hours, although Freezer D was within 1°C of baseline. Freezers C and G were between 2°C and 3°C of baseline. In addition, Freezer F did not experience a spike in average temperature due to the door opening, and thus in many ways could be seen as having never really left baseline. This phenomenon is due to the fact that Freezer F's TCs experienced both warmer and colder temperatures when the door was opened, effectively neutralizing the effect when averaged.

Thus at -80°C, the energy-efficient ULT freezers performed as well as, and in some cases better than, the standard baseline ULT models in recovering set point temperature following door openings. The same cannot be said for the -70°C set point, in which Freezer G, an energy-efficient ULT freezer, performed relatively poorly.

Another way to view the results is to compare ULT freezer recovery relative not to the average baseline temperature for the freezer, but to the average temperature 1-2 minutes prior to the door opening. Looked at from this perspective, all ULT freezers recovered after 3 hours at -80°C, and at -70°C only Freezers A and G did not fully recover, although they were within less than 1°C from recovering after 3 hours.

FIGURE 66: ULT FREEZER RECOVERY, -80°C

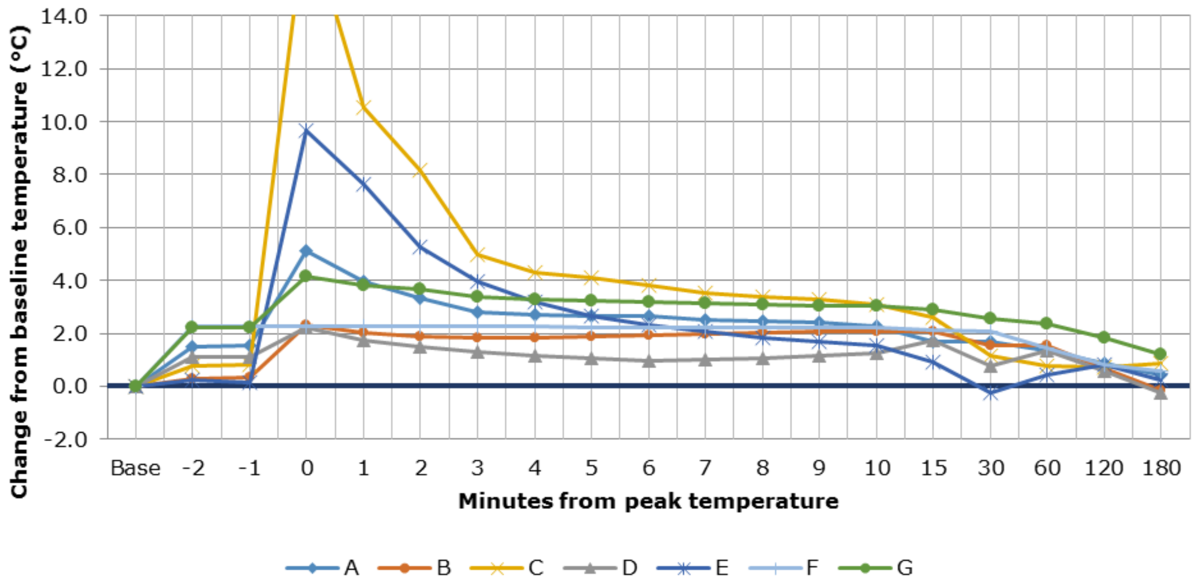


FIGURE 67: ULT FREEZER RECOVERY, -70°C

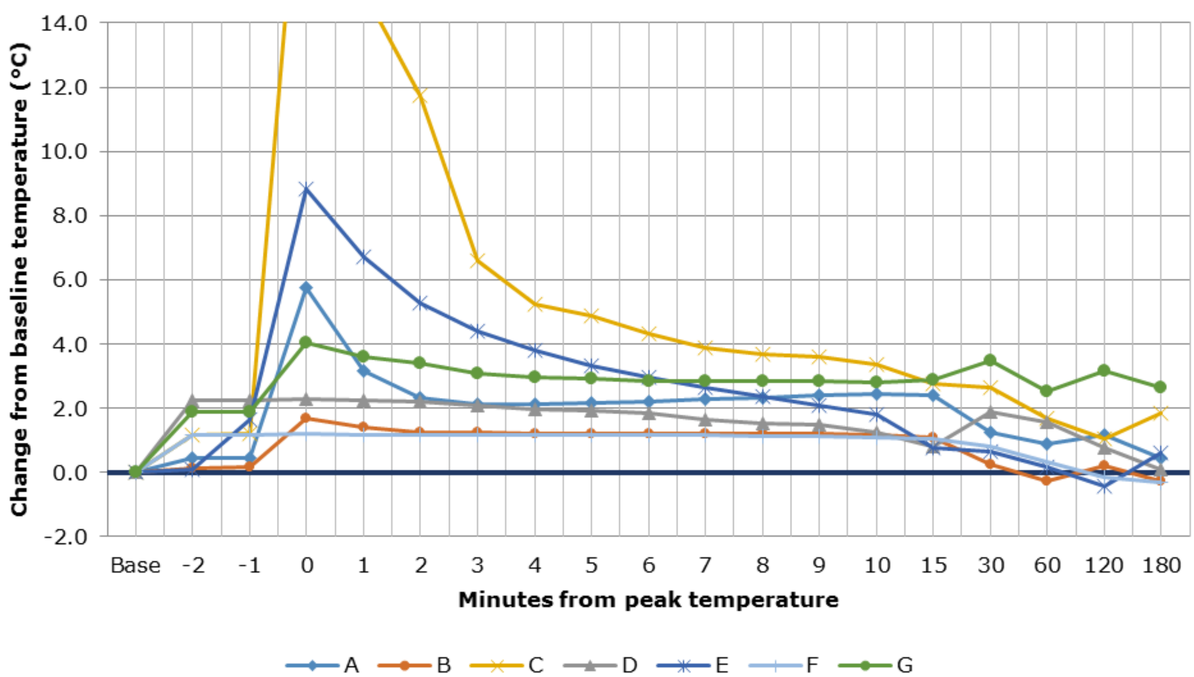


TABLE 24: SUMMARY OF ULT FREEZER RECOVERY

SPEED OF RECOVERY	RECOVERY AT -80°C	RECOVERY AT -70°C
Fastest	Freezer E	Freezer B
	Freezers B, D	Freezer E
	Freezers A, F	Freezer F
	Freezers C, G	Freezer D
		Freezer A
		Freezer C
Slowest		Freezer G

HVAC ENERGY IMPACT

In addition to energy saved directly, the use of more efficient lab equipment can affect the amount of energy used to condition lab spaces. ULT freezers may have a considerable impact on the energy consumed by laboratory HVAC systems. This section details the first effort to quantify the magnitude of this impact for labs in California.

LAB HVAC SYSTEMS AND PLUG LOADS

For safety reasons, lab spaces are typically conditioned using once-through air (i.e. 100% outside air). Labs are usually ventilated continuously at rates ranging from six to 20 air changes per hour (ACH), resulting in high HVAC energy use.

As illustrated in the CEEL Laboratory Market Assessment report published last year, equipment loads in labs are higher than for most other space types. In many lab buildings, ventilation air is delivered at low temperature to offset the heat gain from plug loads. Higher equipment efficiency means reduced plug loads, which in the simplest case permits reduced cooling airflow and results in reduced HVAC system energy use. In extreme cases, removing plug loads from a critical "rogue zone" could allow AHU supply air temperature to be reset upwards (either automatically or manually), producing overall system-wide savings far exceeding the original ULT freezer energy reduction.

Reduced plug loads may also result in an HVAC system energy penalty. In many labs, ventilation rates are fixed at high values due to safety policies or to accommodate the largest conceivable equipment load for the space. Under these circumstances, the supply of cool air is larger than required to offset the space loads and the air is automatically "reheated" at the zone level (usually using hot water coils) to avoid overcooling the space. In this case, a reduction in equipment load means that the supply air requires *more* heat, i.e. the HVAC system must consume more energy to condition the space as a result of the improved equipment efficiency.[19] In the worst-case scenario, that of high flow rates of cold air via a system employing electric resistance reheat coils, there may be no net energy benefit to the use of efficient lab equipment. This worst-case scenario is likely to be uncommon.

If warm air leaving plug load equipment is directly exhausted from the space without mixing with room air (or if the cooling system is loaded beyond capacity, as is common in hallways or storage spaces filled with ULT freezers), changing the efficiency of the plug load equipment may have no impact on the HVAC system energy consumption. Because warm air leaving freezer condenser coils carries the heat pumped out of the freezer cabinet as well as the heat dissipated by the compressor, a freezer with direct exhaust of condenser air may even be a net source of cooling to its parent space. In this uncommon situation, the HVAC impact associated with a change in freezer performance would depend on whether the modification involved a change in freezer cooling load or in refrigeration system efficiency.

The *location* of freezers within labs is a key component of the HVAC energy impact. ULT freezers are often clustered in "freezer farms," or placed with other energy intensive equipment in equipment rooms. In such spaces, the total equipment loads are high and the parent zone is unlikely to be in reheat mode, i.e. HVAC energy savings (cooling and perhaps fan energy) are likely to be associated with a switch to energy-efficient freezers. However, other freezers are located in open lab spaces, where total space loads are usually sufficiently low that the supply air is reheated to some extent. In these zones, as explained above, the HVAC system often experiences a heating energy penalty due to improved plug load efficiency. These effects, and the space types in which they commonly occur, are summarized in the table below.

TABLE 25: SUMMARY OF EXPECTED HVAC ENERGY IMPACT FOR COMMON LAB BUILDING SITUATIONS

SCENARIO	HVAC ENERGY IMPACT OF REDUCED FREEZER ELECTRICAL CONSUMPTION	TYPICAL SPACE TYPE IN LAB BUILDING
High Equipment Loads Met by Cooling System	Additional cooling and/or fan savings	Equipment room; freezer farm
Direct Exhaust of Warm Air	Minimal (or potentially cooling penalty/heating savings)	Not common
Overloaded Cooling System	Minimal	Hallways; other spaces not designed for lab equipment loads
Low to Medium Equipment Loads with Reheat	Heating penalty	Open lab areas

The type of HVAC system used to condition and ventilate a lab, and the control scheme used to program the system (including supply air temperature and airflow controls), are also key variables in determining the HVAC impact of equipment efficiency.

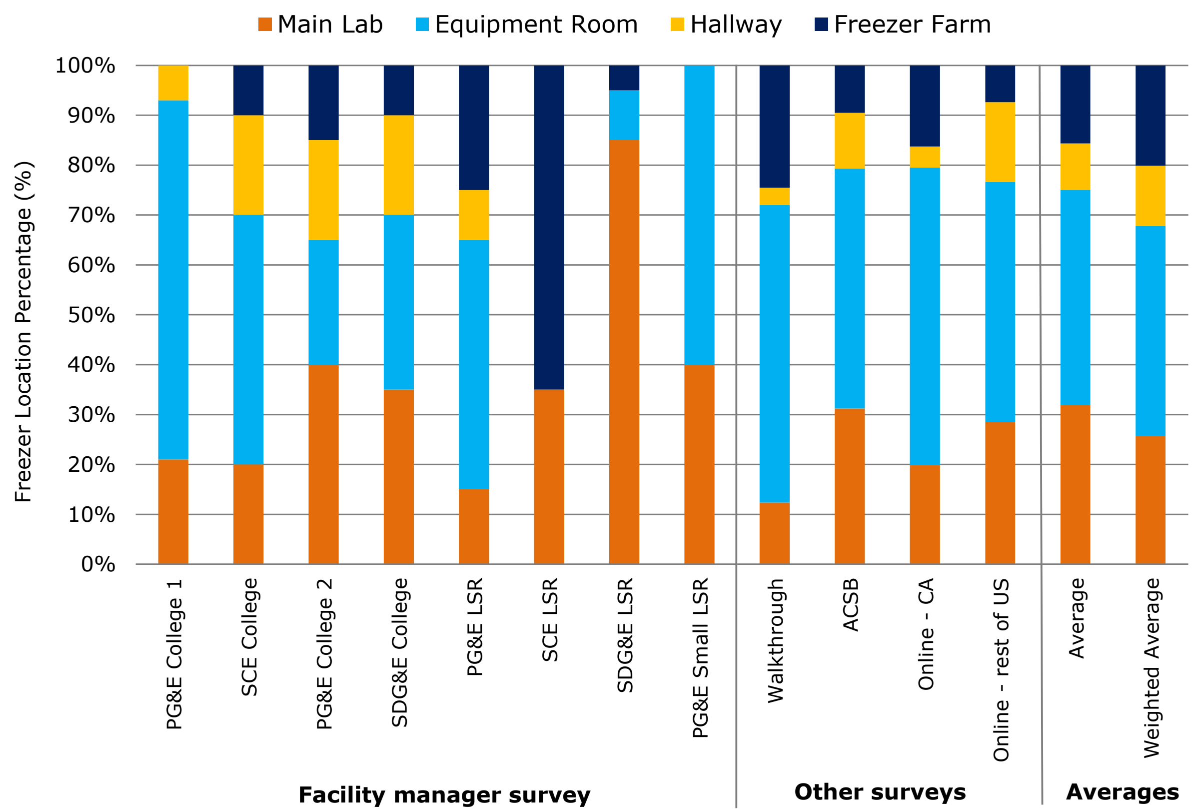
In this study, both ULT freezer locations within lab buildings and HVAC system demographics were investigated via targeted industry surveys (described in detail in the Methods section of this report). The HVAC survey results were used to construct a prototype California lab building model which was used to generate HVAC energy impact estimates for four location types and three climate zones. The results of the modeling exercise were then weighted by the ULT freezer location data to determine overall average HVAC impacts of improving ULT freezer efficiency in California.

ULT Freezer Locations: Results

The ULT freezer location data obtained from the surveys is summarized in Figure 68 and Table 26. Location breakdown data are shown separately for each facility from the facility manager survey; data from the scientist surveys are aggregated. A simple average across all datasets and an average weighted by the number of freezers in each set are also shown in the figure and table.

Full details of the survey results are provided in Appendix F.

Figure 68: ULT Freezer Locations by Survey and Facility



Because facility policies and research needs vary, it is expected that ULT freezer location distributions will vary somewhat between individual facilities. This effect is seen in the data, e.g. the majority of the ULT freezers at SCE Life Science Research (LSR) are located in a large freezer farm, while there are no freezer farms on the campus of PG&E College 1. More variation is seen between LSR facilities than between colleges.

General patterns can however be seen in the data; the results of the scientist surveys are broadly consistent with the average of the facility manager responses. The largest fraction of ULT freezers appears to be found in equipment rooms; these spaces are designed for high equipment loads and generally operate in cooling mode. The second largest portion of the freezer population is located in open lab spaces, which at typical ventilation rates are in reheat mode for most of the year.

The weighted average location data are used throughout the rest of this study.

TABLE 26: FREEZER LOCATION DISTRIBUTIONS

LOCATION	EQUIPMENT ROOM/EQUIPMENT CORRIDOR	FREEZER FARM	LAB	HALLWAY
Average % in Location	43	16	32	9
Weighted Average % in Location	42	20	26	12

HVAC SYSTEM TYPES: RESULTS

The results of the HVAC survey from the eight participating facilities were found to be relatively consistent. Typical parameters were easily extracted from the data. A summary of the HVAC system type data is presented in Table 27; details of individual responses are provided in Appendix F. The parameters shown in Table 27 were used to guide the construction of the eQUEST prototype lab building model.

TABLE 27: TYPICAL SYSTEM PARAMETERS (DERIVED FROM HVAC SURVEY)

LOCATION	SYSTEM TYPE	COOLING SAT	MIN VENT ACH	NIGHT SETBACK?	COOLING SOURCE	TYP. ROOM TEMP (°F)
Main Lab	100% OA VAV	60	8	N	CHW	70-75
Equipment Room	100% OA VAV	60	8	N	CHW	73-78
Hallway	100% OA VAV	60	4	N	CHW	73-78
Freezer Farm	FCUs	N/A	N/A	N	CHW	73-78

THE LAB PROTOTYPE MODEL

Critical modeling parameters are shown in Tables 28 and 29; detailed parameters are provided in Appendix G. The modeling parameters were derived from the results of the facility manager survey, from the audit back catalog survey, and from selected studies on lab space plug load energy intensity (see Appendix G).

TABLE 28: CRITICAL PARAMETERS USED IN EQUEST MODEL

PARAMETER	VALUE	JUSTIFICATION
Building area	90,000 sf	Median from audit back catalog is 85,000 sf
Lab area fraction	40%	Median from Labs21 dataset is 43%
Lab ceiling height	10 ft	Typical; note plenums not modeled.
HVAC system serving labs	100% OA VAV with hot water reheat	Facility manager HVAC survey
SAT set point	60°F (constant)	Facility manager HVAC survey
Supply fan total static pressure	6" w.c.	Typical
Supply fan control	VFD	Typical
Exhaust fan total static pressure	5" w.c.	Typical
Exhaust fan control	Constant volume	Represents typical OA bypass used in lab buildings to maintain stack velocity
HVAC system serving freezer farm	Recirculating CHW fan coil units	Facility manager HVAC survey
HVAC system operation	24/7	Typical
CHW system	2 water-cooled non-VFD centrifugal chillers	Typical
Chiller full-load coefficient of performance	5.5	CA Title 24 2013 (and typical) for 166-ton chillers
HW system	2 forced-draft natural gas-fired boilers	Typical
Boiler efficiency	80%	CA Title 24 2013 (and typical)

TABLE 29: PARAMETERS USED FOR SPACES WITH FREEZERS IN EQUEST MODEL

SPACE TYPE	SERVED BY SYSTEM	COOLING SAT (°F)	MIN VENT ACH	HEATING SET POINT (°F)	COOLING SET POINT (°F)	EQUIP LOAD (W/SF)	RESULTING HVAC MODE
Main Lab	Lab VAV	60	8 const	72	75	1.5	Zone in reheat
Equipment Room			8 const	72	78	10	Zone in cooling
Hallways			4 const	72	75	4*	Zone in cooling (overwhelmed)
Freezer Farm	FCUs	N/A	N/A	N/A	78	10	Zone in cooling

*only in core space used to represent overloading with plug loads

HVAC Energy Impacts: Results

As described in Chapter 4, the eQUEST model was used to determine the HVAC energy impact per direct (ULT freezer) kWh saved, for each space type and for three representative California climate zones. The results are presented in Table 30.

Source energy impacts were calculated using the standard ENERGY STAR Portfolio Manager value for electricity (site to source ratio of 3.14). Source energy values are intended to be illustrative only, to allow electricity and gas impacts to be combined to illustrate the overall impact of freezer efficiency improvements. Note that large campus facilities often include central cogeneration or other district energy plants; these are neglected here.

Table 30: Results - HVAC Energy Impact Factors by Space Type

	HVAC Energy Savings per Direct ULT kWh Reduction								
	Electric (kWh/direct kWh)			Natural Gas (therms/direct kWh)			Source Energy (% of direct savings)		
Space Type	CZ3	CZ9	CZ15	CZ3	CZ9	CZ15	CZ3	CZ9	CZ15
Main Lab	0.008	0.036	0.100	-0.036	-0.033	-0.030	-33%	-27%	-18%
Equip Room	0.233	0.310	0.342	0.000	0.000	-0.001	23%	31%	33%
Hallway	0.023	0.035	0.035	-0.003	-0.003	-0.003	-1%	0%	1%
Freezer Farm	0.257	0.210	0.206	0.000	0.000	0.000	25%	21%	21%

As expected, there are significant differences between the HVAC impacts associated with improving the efficiency of ULT freezers located in different space types. A reheat energy penalty is seen in open (main) lab spaces, while cooling and/or fan energy bonuses occur in cooling-dominated equipment rooms and freezer farms. In hallways, where the model was set up to represent a zone operating above its cooling capacity, the impact on energy consumption is small (but room space temperature moves closer to set point).

Some variations are also seen between climate zones. Generally speaking, heating penalties are largest in cooler climate zones because the main lab spaces spend a larger fraction of the year in full reheat mode. Fan power savings, where present, are larger for warmer climate zones because the fan systems generally spend a larger fraction of the year at higher fan speeds.

Using the results of the freezer location surveys (weighted averages from Table 26) and the HVAC energy impacts derived from the prototype building model (Table 30 above), the average energy impact of improving ULT freezer efficiency can be calculated. The results of this calculation are shown in Table 31.

Table 31: Results - Weighted HVAC Energy Savings by Space Type

	Electric (kWh/direct kWh)			Natural Gas (therms/direct kWh)			Source Energy (% of direct savings)		
	CZ3	CZ9	CZ15	CZ3	CZ9	CZ15	CZ3	CZ9	CZ15
Weighted Average over space types	0.154	0.186	0.215	-0.010	-0.009	-0.009	6%	10%	13%
Average over climate zones	**0.185**			**-0.009**			**10%**		

The HVAC energy penalties from open lab spaces cancel out much of the bonus expected from equipment rooms and freezer farms. The overall effect is a net positive 10% HVAC bonus to source energy savings.

Note that these HVAC savings metrics apply to ULT freezer energy savings of all types, including both technology improvements and behavior changes (e.g. set point adjustments).

Market Assessment Results

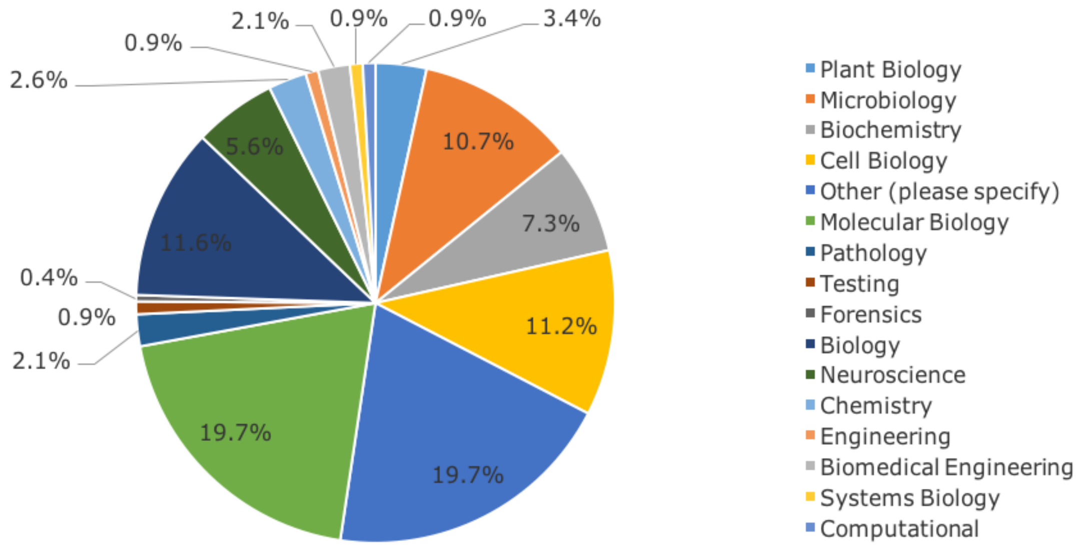
Data were acquired through a SurveyMonkey survey that respondents from 48 California laboratories completed online. Of these laboratories, 33 were at universities and 15 resided in non-academic sectors such as biopharmaceutical companies from the life science research market, hospitals, and medical testing centers. From outside of California, representatives from 185 laboratories provided responses. Of these, 123 were at universities and 62 were in other market sectors.

Below is a summary of the responses to each topic surveyed, followed by additional analysis of the data. Not all respondents replied to each topic, and response rates are noted.

Survey Respondents

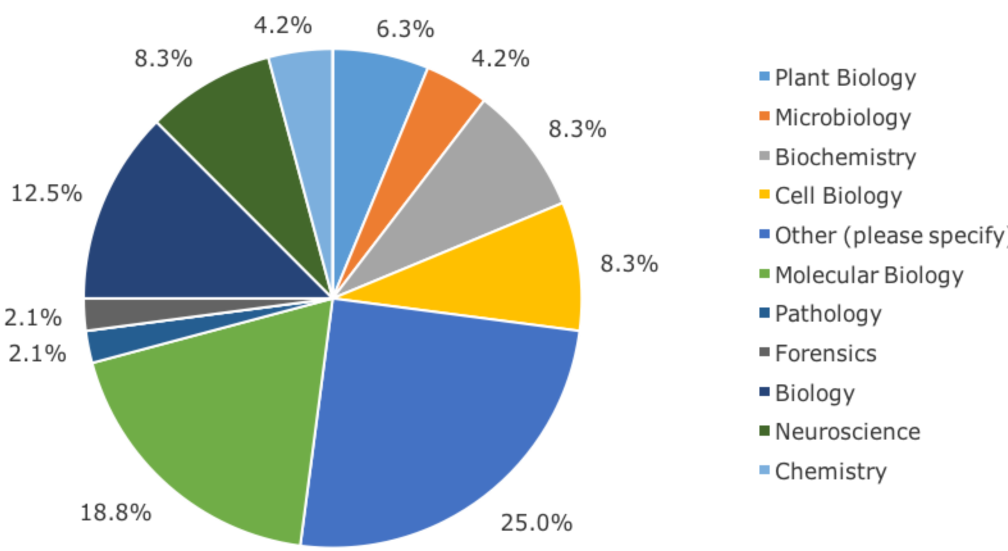
Across the survey, respondents hailed from over 15 scientific disciplines. Molecular biology was the most common, followed by biology, cell biology, and microbiology.

FIGURE 69: SURVEY RESPONDENTS BY DISCIPLINE – ALL RESPONDENTS



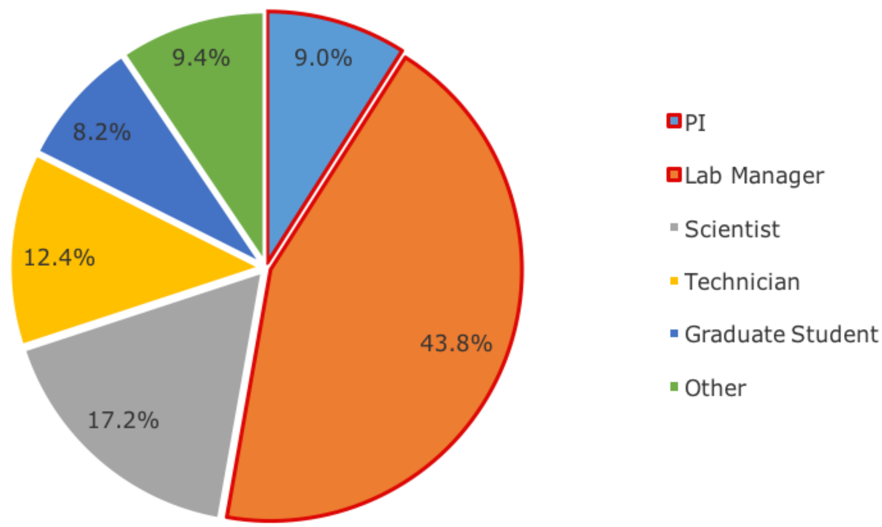
In California specifically, respondents represented over 13 scientific disciplines. Molecular biology was the most common, followed by biology and plant biology.

FIGURE 70: CALIFORNIA RESPONDENTS BY DISCIPLINE



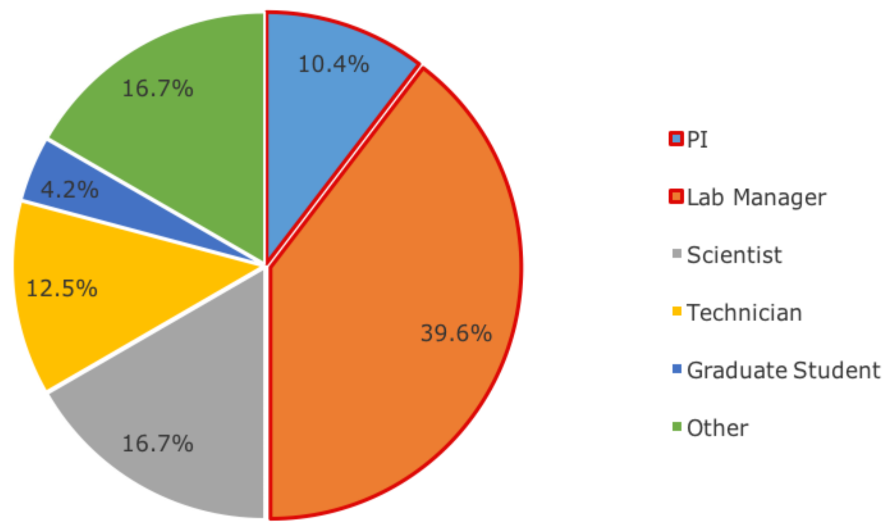
Of all respondents, 52.8% were either principal investigators (PIs) or laboratory managers. PIs and lab managers are considered to be key decision makers in the laboratory equipment purchasing process. This is particularly true for the purchase of ULT freezers, whose initial cost is substantial enough to impact the annual budget of a lab.

FIGURE 71: SURVEY RESPONDENTS BY POSITION – ALL RESPONDENTS



Of the respondents located in California, 50% were either PIs or laboratory managers, similar to the quotient for the national results.

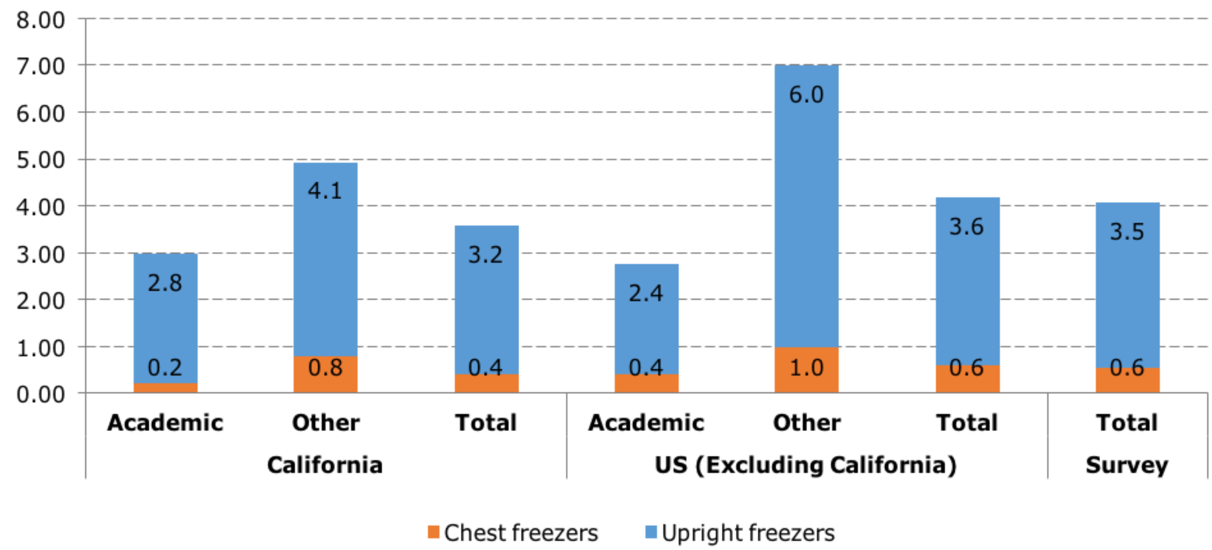
FIGURE 72: CALIFORNIA SURVEY RESPONDENTS BY POSITION



ULT FREEZER QUANTITIES

On average, each lab surveyed had 3.51 upright freezers and 0.49 chest freezers. Academic labs reported fewer freezers than non-academic labs, and non-academic labs outside of California reported the highest freezer quantities in the survey. The number of freezers per lab found in this study is 20% higher than previously reported. This is not surprising as the respondents in this study were asked to participate because they had ULT freezers in their lab. The previous study included labs of all types, which may or may not have had ULT freezers.

FIGURE 73: AVERAGE NUMBER OF FREEZERS PER LAB



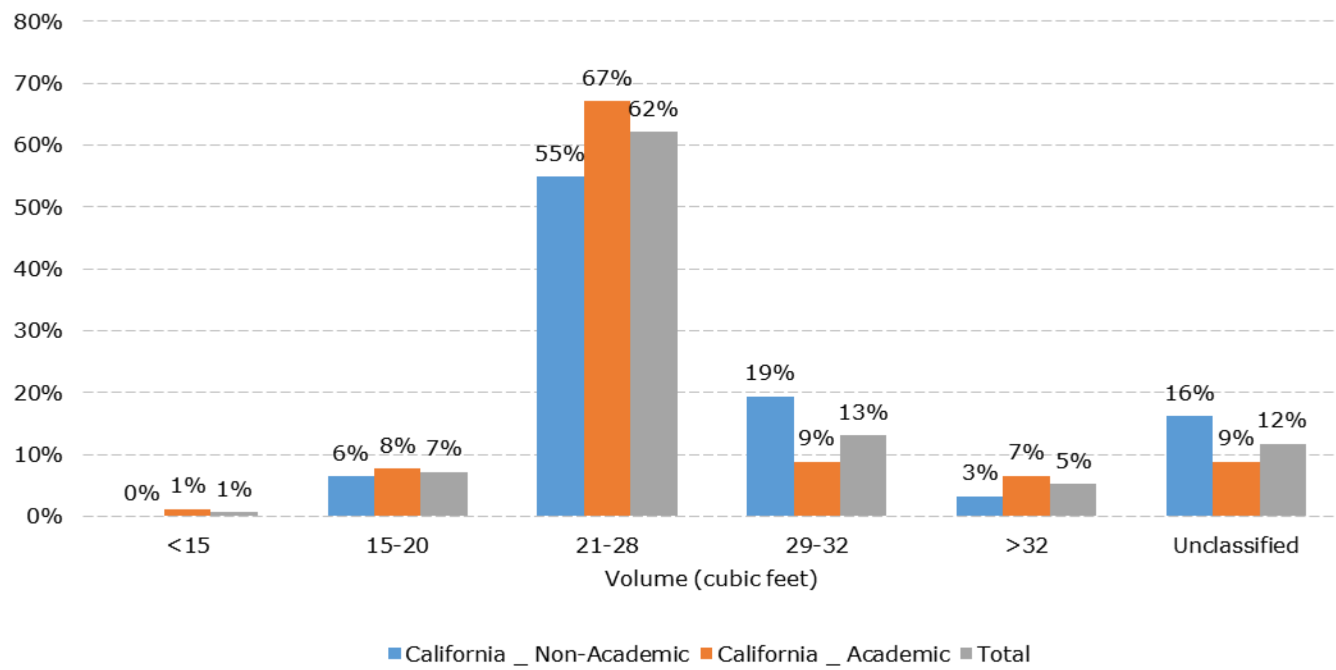
The non-academic sample size for California was rather small, and thus it is difficult to draw conclusions as to why the average number of ULT freezers per lab should be smaller in California than in the rest of the United States. The academic sample size in both California and the greater United States was robust enough to support the conclusion that California's labs have slightly more ULT freezers on average than other labs in the country. This conclusion is similar to the one found in the CEEL Laboratory Market Assessment, in which the discrepancy was attributed to a differential in research funding allocation.

A key finding from this survey is that chest freezers comprise between just 7% and 16% of the ULT freezer market. On average, in California and the United States, chest freezers represent ~12% of the installed base, and they are most often used in non-academic institutions. This finding supports this project's focus on upright ULT freezers.

ULT FREEZER SIZE – UPRIGHT FREEZERS

In addition to quantity of freezers, respondents from California also provided information regarding the sizes of upright freezers in their labs. Larger freezers were found to be more common, with the 21-28 ft^3 segment dominating the survey (over 50%), followed by 29-32 ft^3.

FIGURE 74: DISTRIBUTION OF UPRIGHT ULT FREEZER SIZE – CALIFORNIA, ONLINE SURVEY RESULTS



A further analysis of ULT freezer capacity in California was performed by gathering data from laboratory audits and procurement records for various institutions across the state. The results from that analysis are below (Figures 75 and 76).

More than 50% of the ULT freezers in academic and non-academic institutions were found to be 23-27 ft^3 in size. In fact, 71% of ULT freezers in academic labs and 82% of ULT freezers in non-academic labs had a capacity between 19 and 29 ft^3.

The ULT freezers assessed for this study had capacities between 18 and 29 ft^3, and thus the data from the study is broadly applicable to the majority of the ULT freezer market.

FIGURE 75: ACADEMIC FREEZER INVENTORY BY CAPACITY (CUBIC FEET) – FROM AUDITS AND PROCUREMENT RECORDS

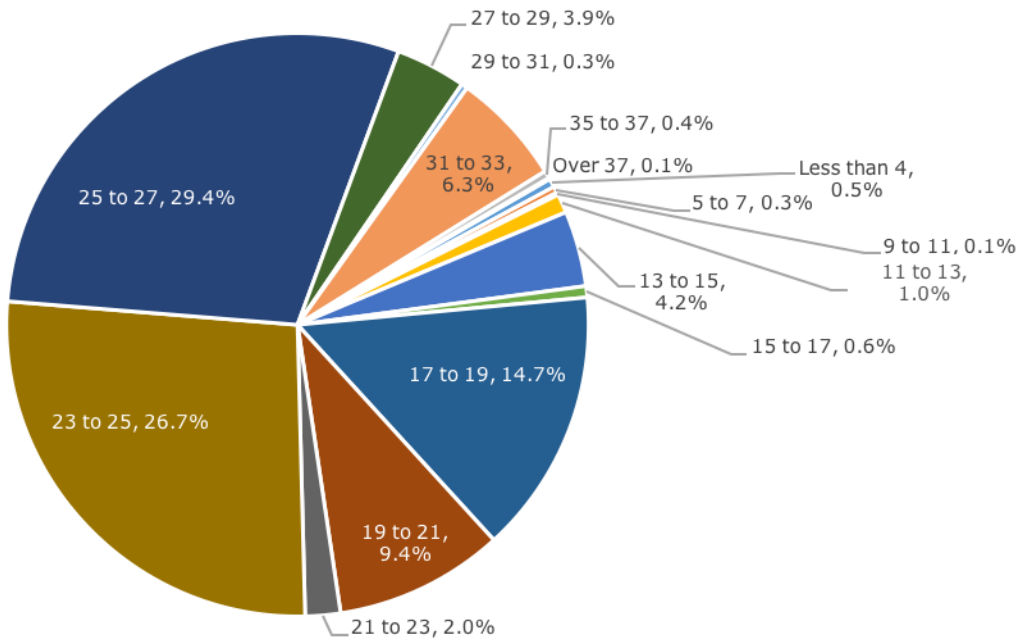
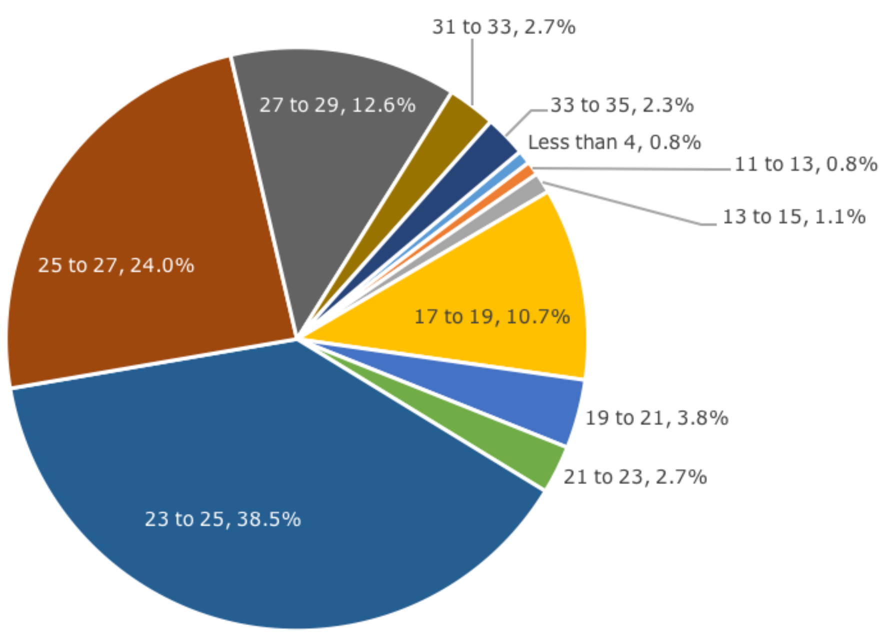
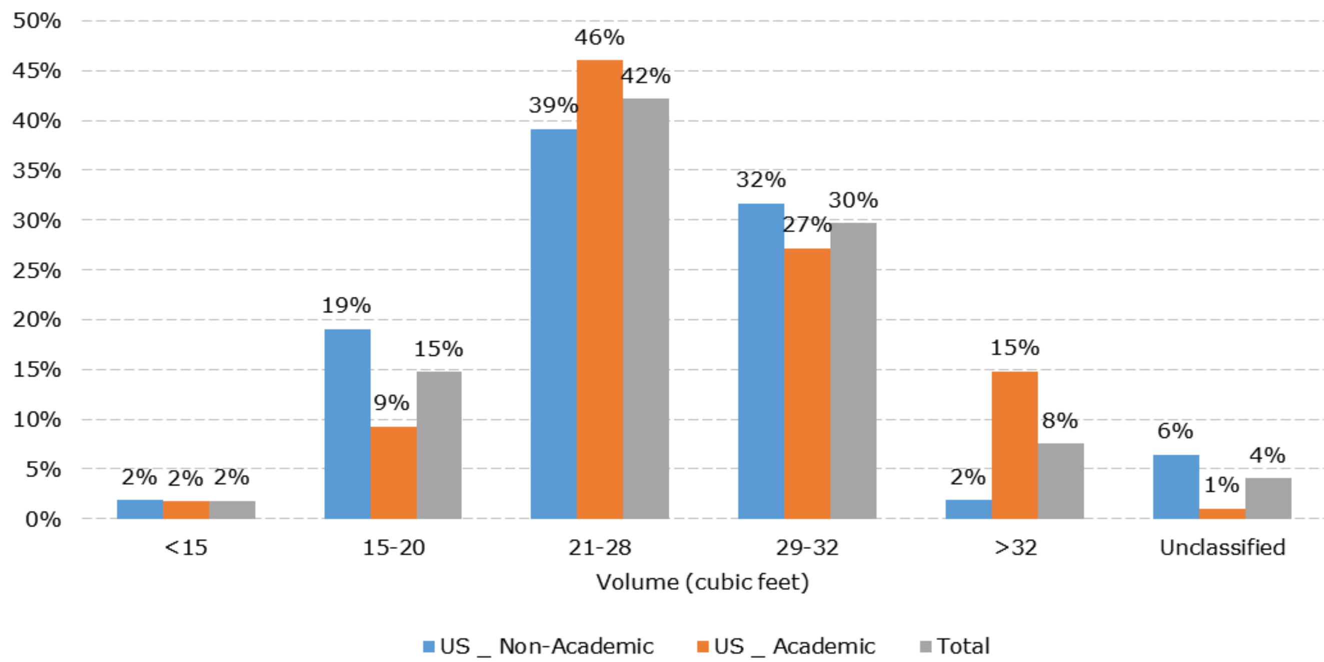


FIGURE 76: NON-ACADEMIC FREEZER INVENTORY BY CAPACITY (CUBIC FEET) – FROM AUDITS AND PROCUREMENT RECORDS



As compared to the California data, the national data show a more even split between the 21-28 ft^3 and 29-32 ft^3 segments.

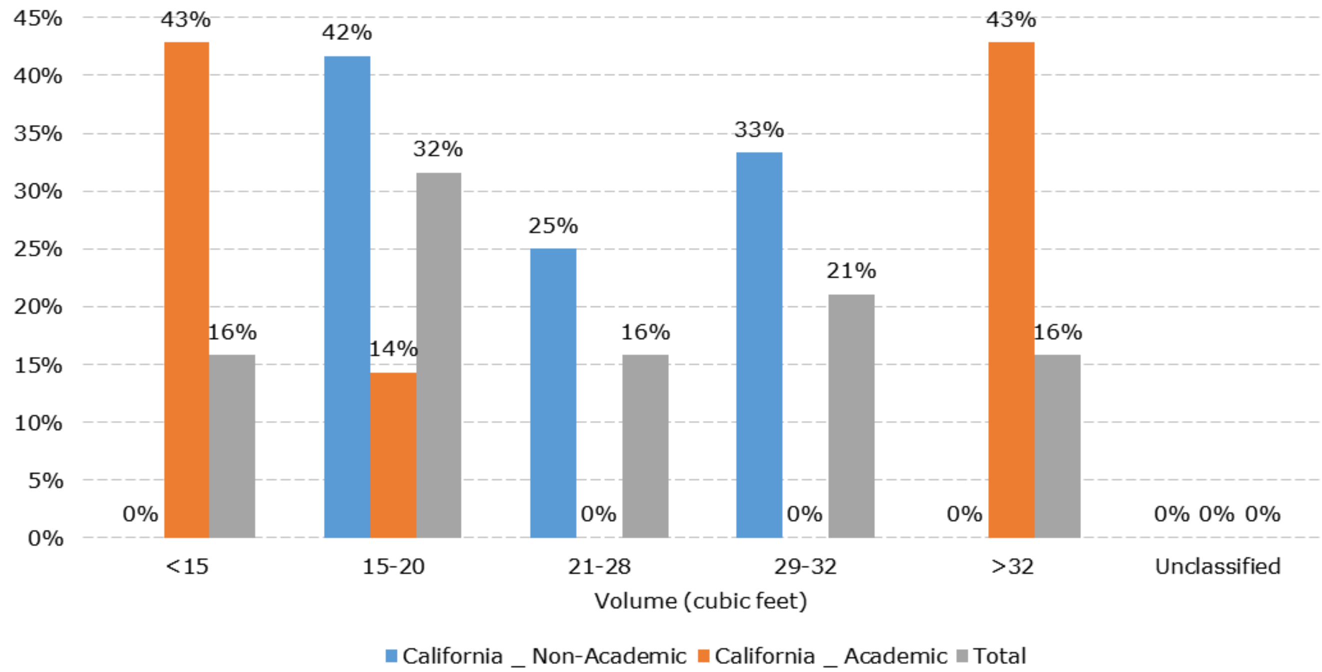
FIGURE 77: DISTRIBUTION OF UPRIGHT FREEZER SIZE PER LAB – UNITED STATES (EXCLUDING CALIFORNIA), ONLINE SURVEY RESULTS



ULT FREEZER SIZE – CHEST FREEZERS

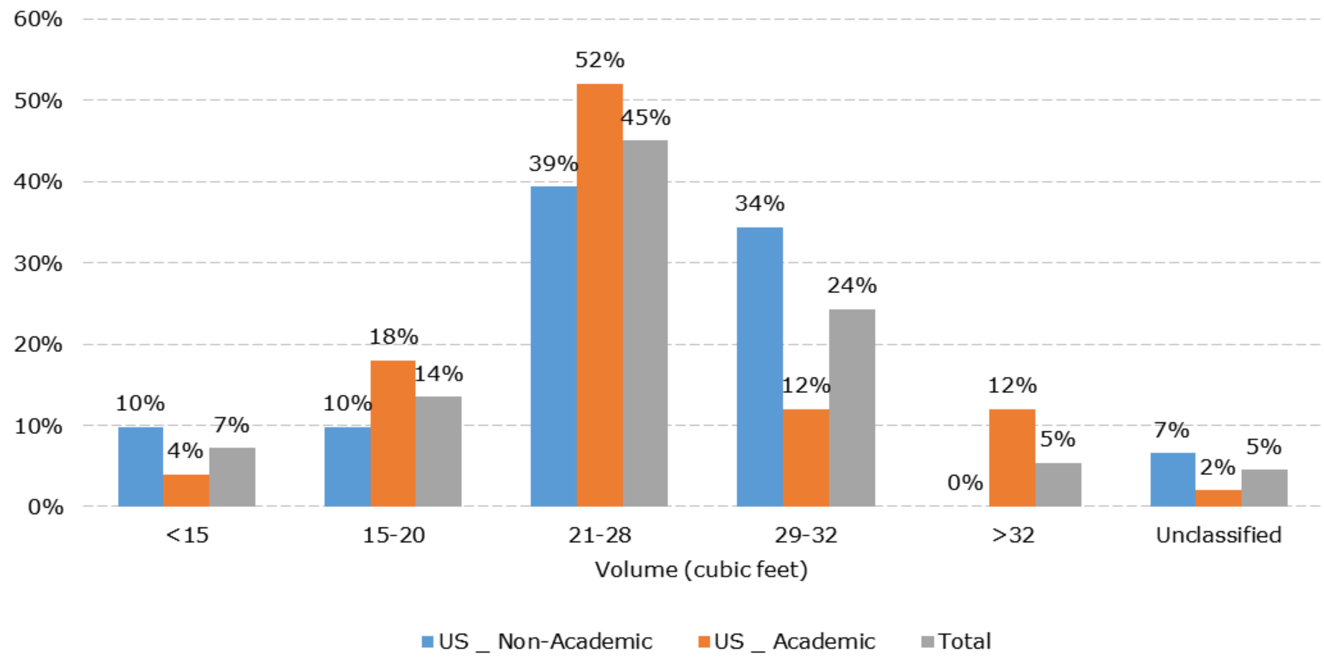
The non-academic labs in California reported approximately four times as many chest freezers per lab as the academic labs. Interestingly, academic labs reported having either very small or very large chest ULT freezers – none reported freezer sizes between 20 ft^3 and 32 ft^3. In contrast, the non-academic chest ULT freezers were all reported to be between 15 ft^3 and 32 ft^3.

FIGURE 78: DISTRIBUTION OF CHEST FREEZER SIZE – CALIFORNIA



The distribution of chest ULT freezers in labs across the United States was much more even, with the majority of both academic and non-academic labs reporting their chest ULT freezer sizes between 21 and 28 ft^3. As seen in the data from California, academic labs were the only ones with chest ULT freezers of >32 ft^3 capacity; they also had a slightly higher percentage of chest ULT freezers with <20 ft^3 capacity.

FIGURE 79: DISTRIBUTION OF CHEST FREEZER SIZE – UNITED STATES (EXCLUDING CALIFORNIA)



The differences seen between the California data and the data from the rest of the United States is likely not significant, given that chest ULT freezers represent just 11% of the total ULT freezer market in California: there simply were not enough data points to draw reasonable conclusions.

ULT Freezer Brands

Figure 80: Percentage of Labs Surveyed Using Each Brand (California)

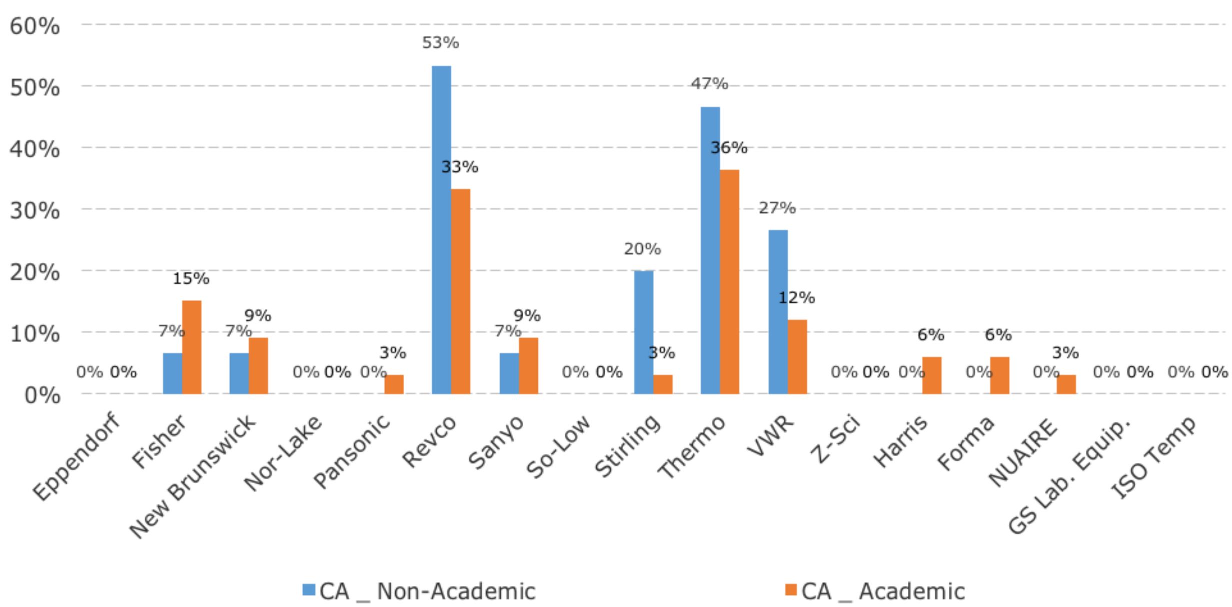


Figure 80 above demonstrates that in the labs surveyed in California the majority of respondents had a Thermo-Fisher owned brand (Revco, Thermo, and Fisher) regardless of their institutional background. VWR had the second largest market penetration in California. Eppendorf-owned brands Eppendorf and New Brunswick had a market penetration comparable to that of Panasonic-owned Panasonic and Sanyo. Interestingly, Stirling brand freezers were well-represented in the non-academic sector but showed little market penetration in the academic arena. As before, it is likely that the non-academic data were slightly skewed owing to the low sample size.

Although the online survey provided important insight into ULT freezer brand preference, it did not reveal brand market share because respondents were only asked if they had a particular brand, not what quantity of all ULT freezers in their lab were from a certain brand. In order to ascertain the market share of particular ULT freezer brands in California, in-person audits of laboratories across the state were done, and procurement lists from various institutions in California were obtained. From these data a more comprehensive picture of market share emerged, as seen below in Figures 81 and 82.

Revco and Thermo brand freezers enjoy the majority of the ULT freezer market share in academic labs in California, representing 55% of the market. Thermo-owned Forma was found to have a 9% market share, nearly as much as Sanyo (10%), and slightly more than Panasonic (5%). Notably Stirling was found to have very little market penetration at just 0.5%. This is somewhat less than reported in the online market assessment (3%).

Thermo dominated the non-academic market with 58.7% market share, followed closely by Thermo-owned subsidiaries Forma and Revco. Other brands, such as VWR and Panasonic, were found to have slightly less market share than Forma and Revco. Stirling's market penetration in the non-academic sector in California was found to be quite high at 8%. This finding is considerably lower than reported in the online survey.

FIGURE 81: ACADEMIC FREEZER INVENTORY BY BRAND – CALIFORNIA, FROM AUDITS AND PROCUREMENT RECORDS

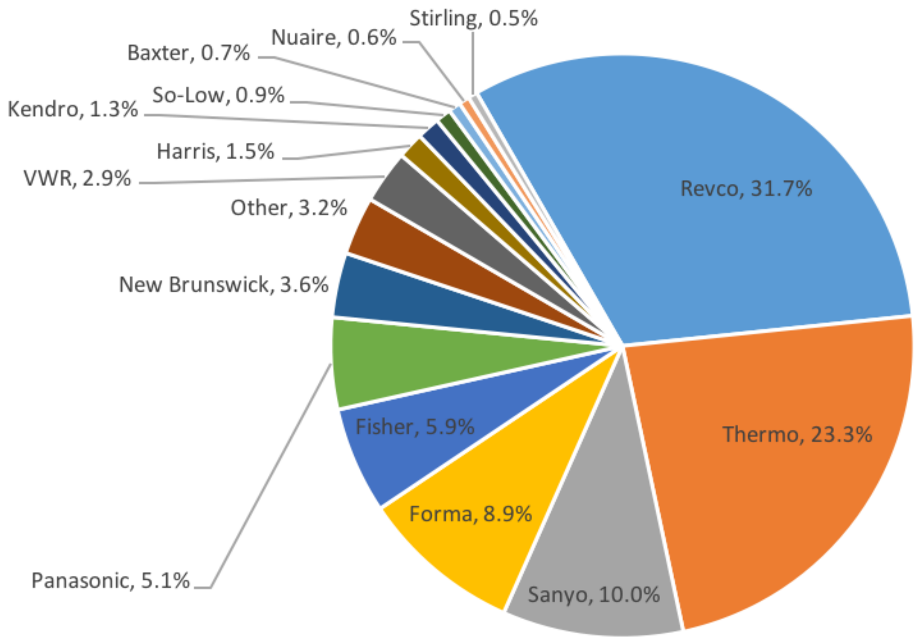
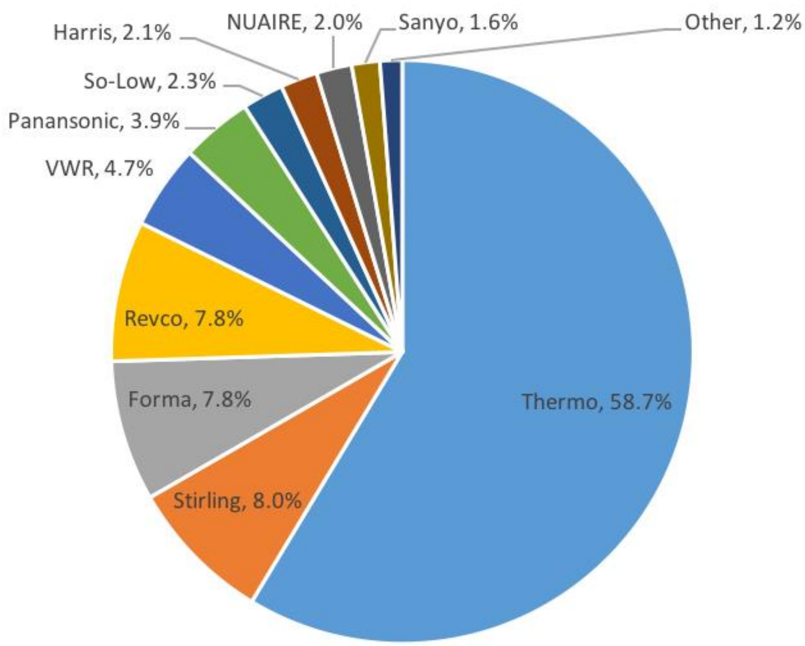


FIGURE 82: NON-ACADEMIC FREEZER INVENTORY BY BRAND – CALIFORNIA, FROM AUDITS AND PROCUREMENT RECORDS



Based on the data collected from labs in California it can be said with conviction that the brands tested in the controlled environment and field studies represented 80% of the ULT freezer market in the state.

Brand loyalty to a single brand is not particularly strong, as evidenced by the data in Figure 83 below. These data were taken from the online survey. Labs with more than one freezer tended to have more than one brand. Again, the sample size is too small to draw a strong conclusion from this trend.

FIGURE 83: BRANDS PER LAB (CALIFORNIA)

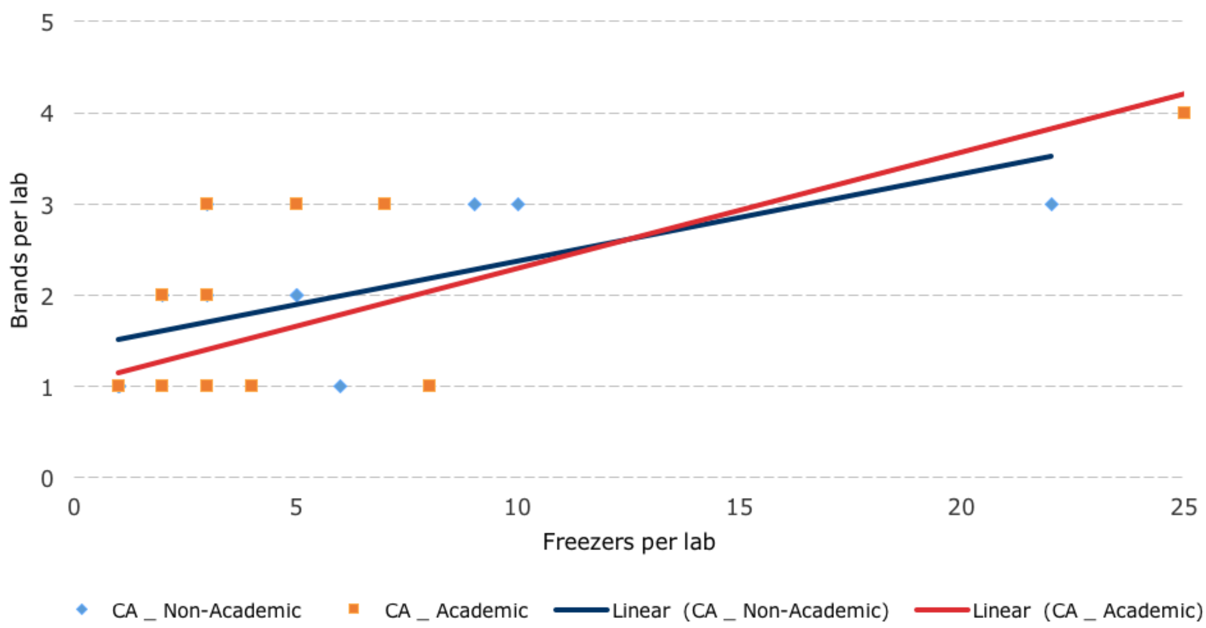
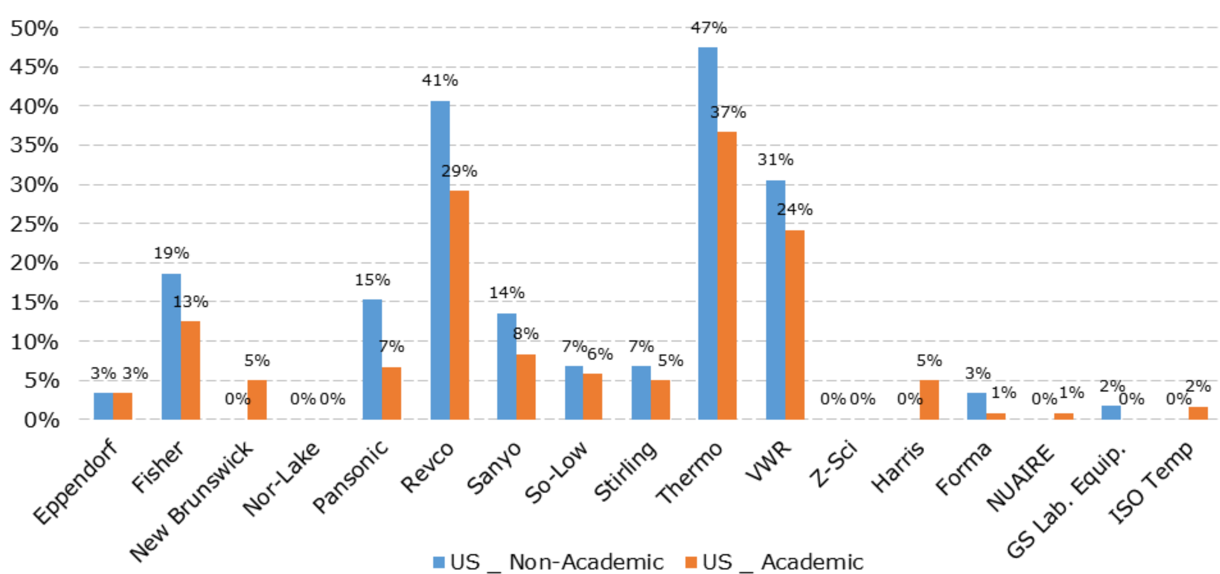


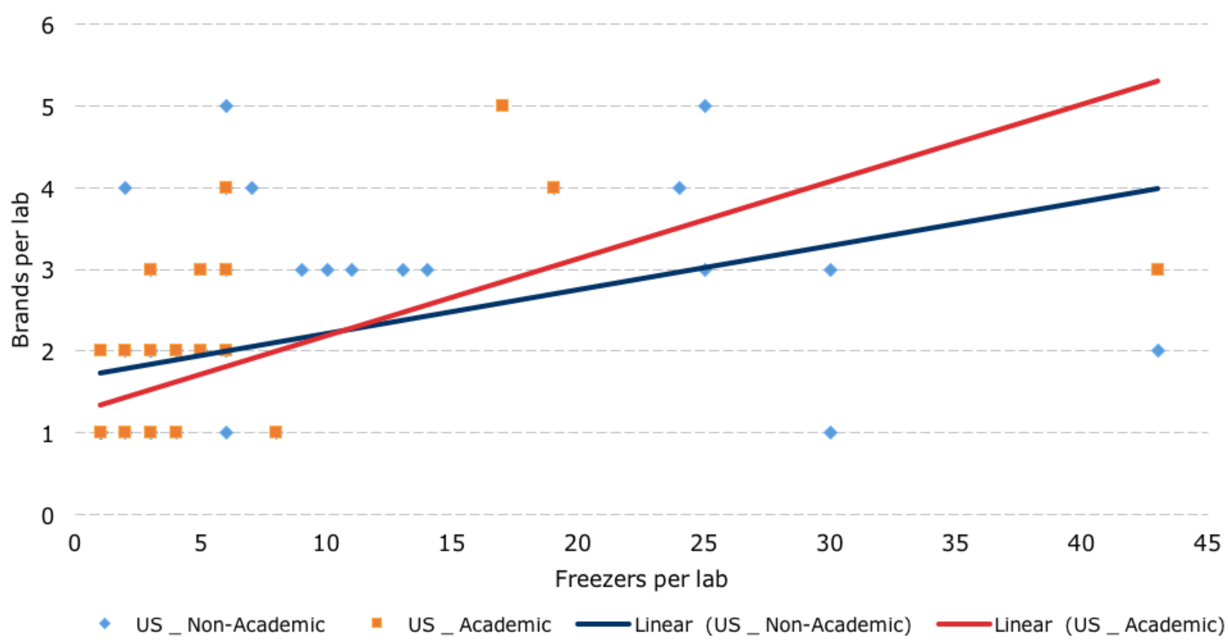
Figure 84 below shows the distribution of ULT freezer brands in the greater United States as obtained from the online survey.

FIGURE 84: PERCENTAGE OF LABS SURVEYED USING EACH BRAND (UNITED STATES, EXCLUDING CALIFORNIA)



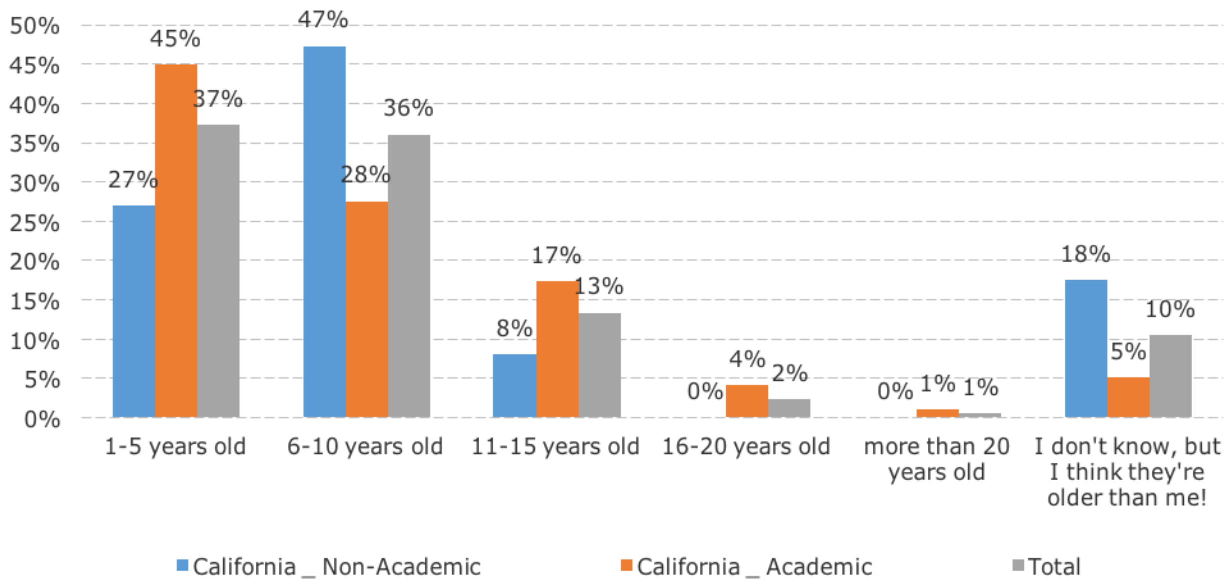
Brand loyalty to a single brand throughout the United States is not strong, as seen in Figure 85 below. These results are further confirmed through the responses to the question regarding the most important purchasing factor, seen in Figure 98.

FIGURE 85: BRANDS PER LAB (UNITED STATES, EXCLUDING CALIFORNIA)



ULT Freezer Age

Figure 86: Freezer Age – California, From Online Survey Results



Seventy-three percent of respondents have freezers that are less than 10 years old. Many of the respondents from the non-academic sector were unsure of how old their freezers were. Since purchasing of ULT freezers in non-academic labs tends to be more centralized, it is not surprising that researchers might not know the ages of their freezers in these facilities. It is also not surprising that academic labs tend to have more ULT freezers that are older than 11 years, and that this was the only sector that reported having ULT freezers older than 16 years. These results speak to the well-known funding discrepancies between the two market segments.

A further analysis of ULT freezer age in California was performed by gathering data from laboratory audits and procurement records for various institutions across the state. The results from that analysis are below (Figures 87 and 88). It should be noted that whereas non-academic institutions keep up-to-date records of their assets, academic institutions often will only have records of assets that have been purchased, not of assets that have been retired or moved off-site. This discrepancy explains the large number of ULT freezers found in academic procurement records that appear to be older than 15 years. In spite of this, the findings from these data corroborate the online survey results in suggesting that the average lifetime of a ULT freezer is ~10 years.

FIGURE 87: ACADEMIC FREEZER INVENTORY BY AGE, FROM AUDITS AND PROCUREMENT RECORDS

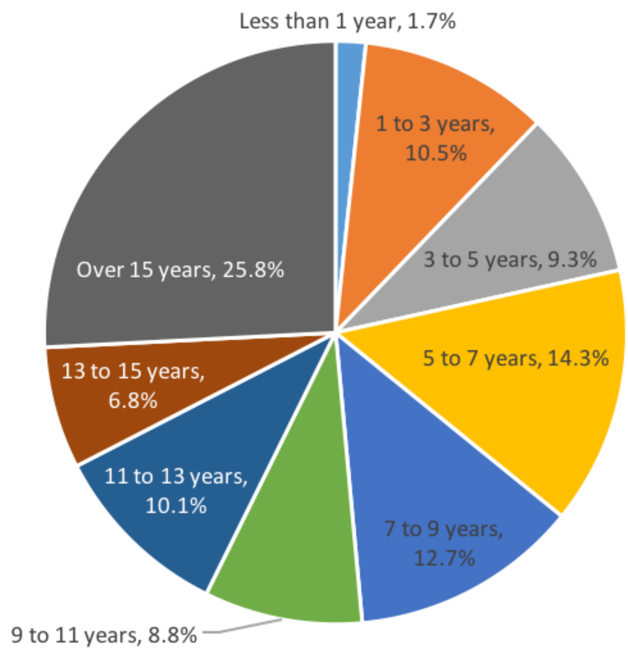


FIGURE 88: NON-ACADEMIC FREEZER INVENTORY BY AGE, FROM AUDITS AND PROCUREMENT RECORDS

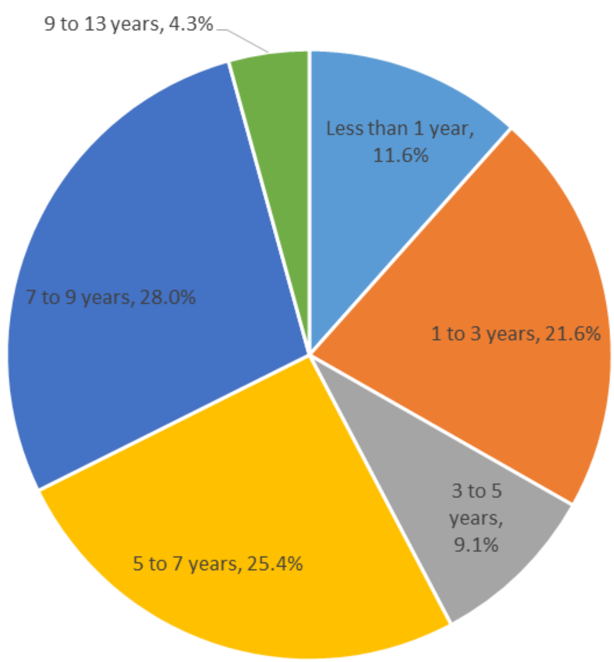
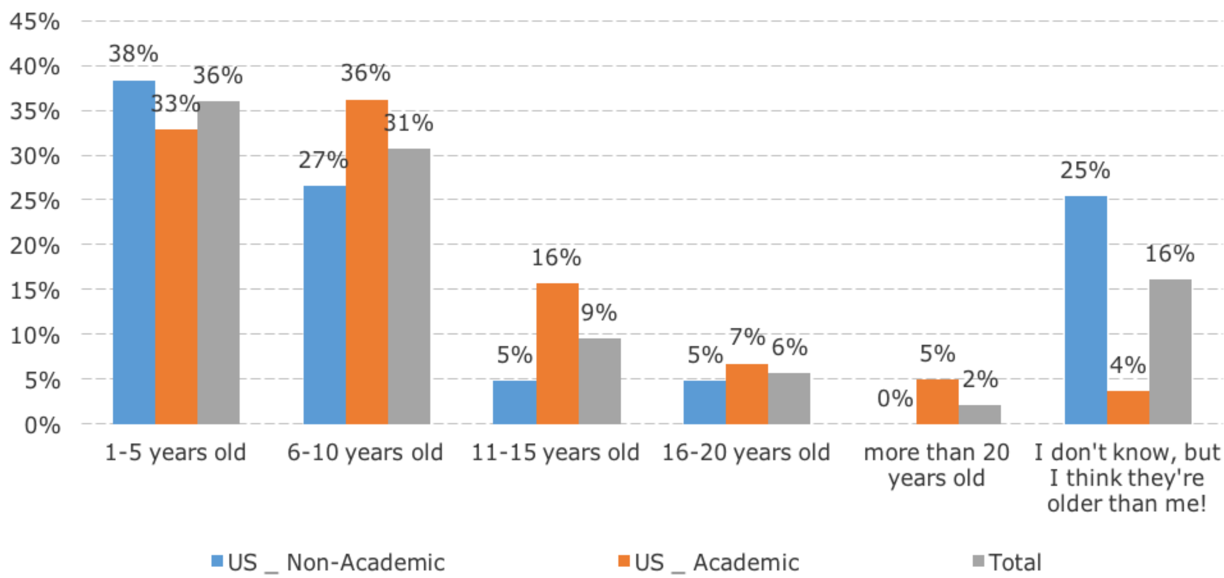


FIGURE 89: FREEZER AGE – UNITED STATES, EXCLUDING CALIFORNIA, FROM ONLINE SURVEY RESULTS

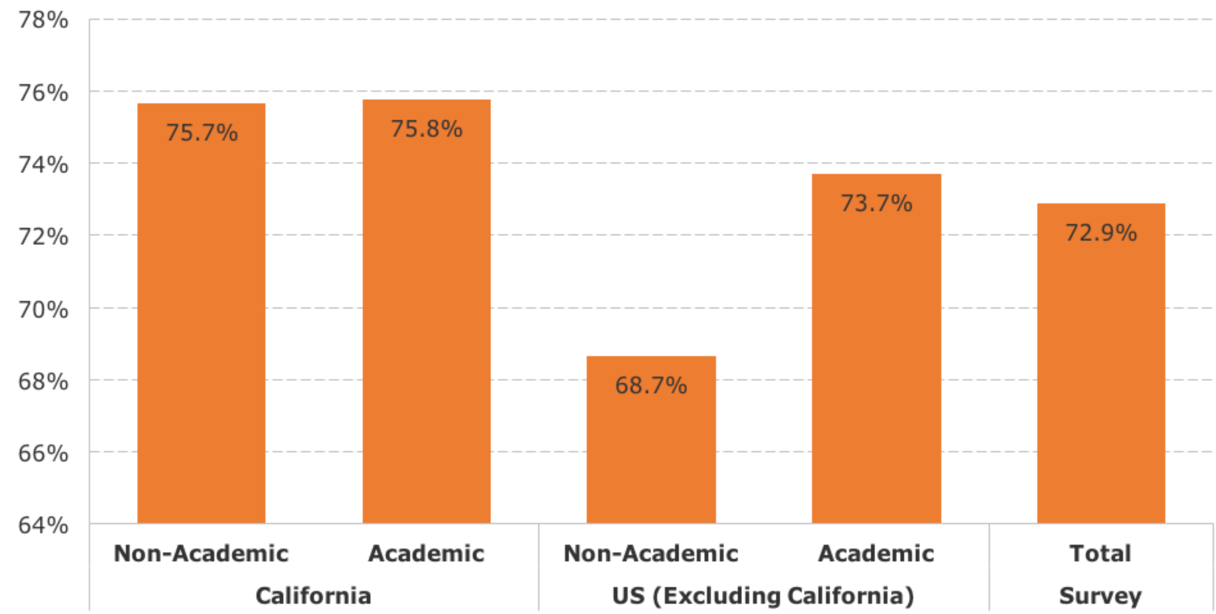


The average ages of ULT freezers across the United States was similar to that seen in California. Again, the majority of freezers were reported as being less than 10 years old, and academic labs reported having older freezers than non-academic labs. As before, the data suggest that the average lifetime of a ULT freezer is 10 years.

ULT FREEZER CAPACITY UTILIZATION

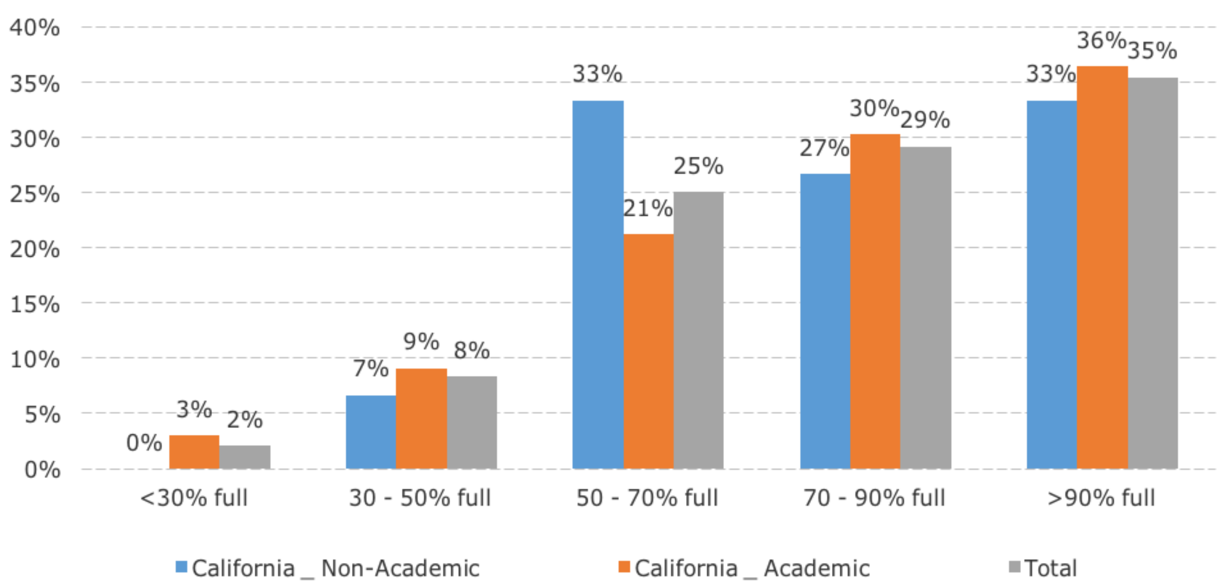
In addition to finding that most ULT freezers in California are between 1-10 years old, the survey found that ULT freezers are approximately 75% full on average. Respondents were asked directly to what extent their ULT freezers are full.

FIGURE 90: AVERAGE CAPACITY UTILIZATION BY RESPONDENT CATEGORY



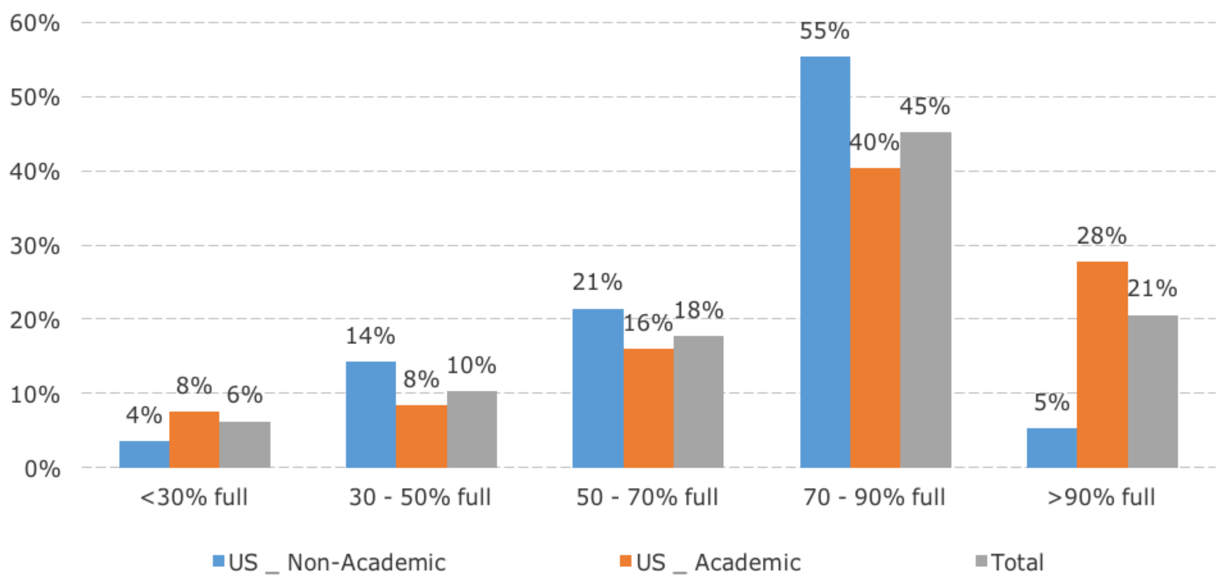
Looking at the question of freezer capacity more closely reveals that 35% of ULT freezers in the market are at or near capacity, and another nearly 30% of freezers are between 70% and 90% full. Non-academic labs in California reported having more freezers at less than 70% capacity. Very few ULT freezers were reported as being less than 30% full, suggesting that even new freezers are quickly filled with samples.

FIGURE 91: CAPACITY UTILIZATION – CALIFORNIA



The results from the rest of the United States showed that, on average, 21% of ULT freezers across the country were at or near capacity (compared to the California data showing 35% in the same situation). In contrast to the results from California, labs in the other states reported utilizing their ULT freezers to a higher capacity: 45% of their ULT freezers were between 70% and 90% full, with another 28% reporting freezer utilization ranging between 30% and 70%. Notably, academic labs were more likely to have freezers at or near capacity, perhaps reflecting the more austere circumstances of working in an academic lab.

FIGURE 92: CAPACITY UTILIZATION – UNITED STATES, EXCLUDING CALIFORNIA



It was hypothesized that the more ULT freezers a lab had, the less full they would be. In fact there was a positive correlation between the number of ULT freezers and their capacity utilization; if anything the correlation appeared to be the inverse, that the more ULT freezers a lab has, the more they appear to be utilized.

Figure 93: Correlation of Freezer Count and Capacity Utilization – California

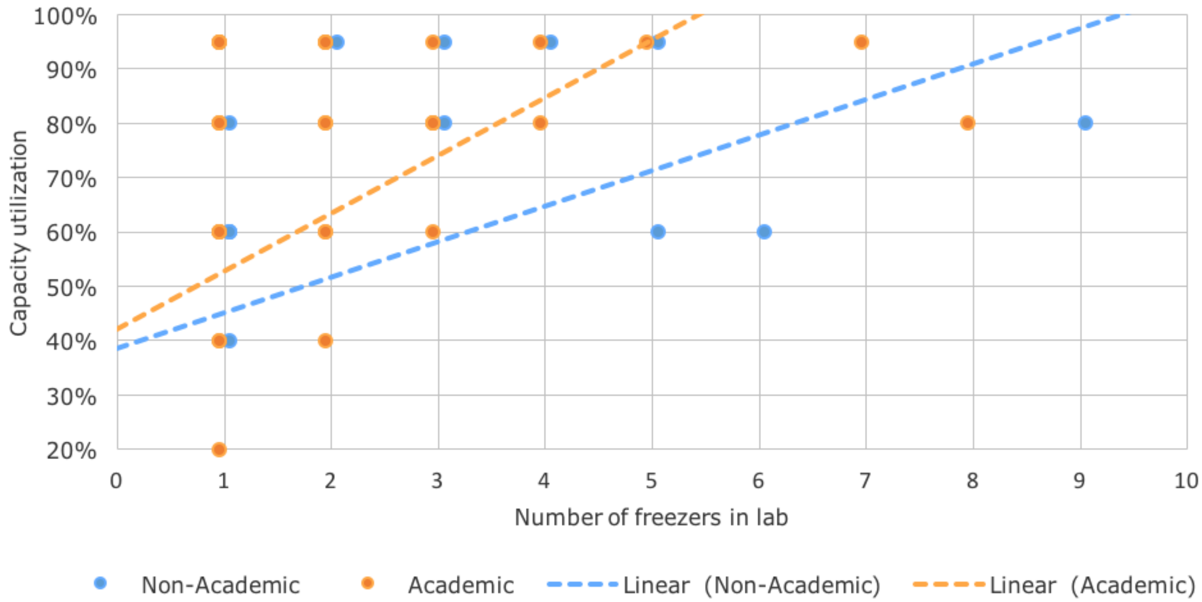
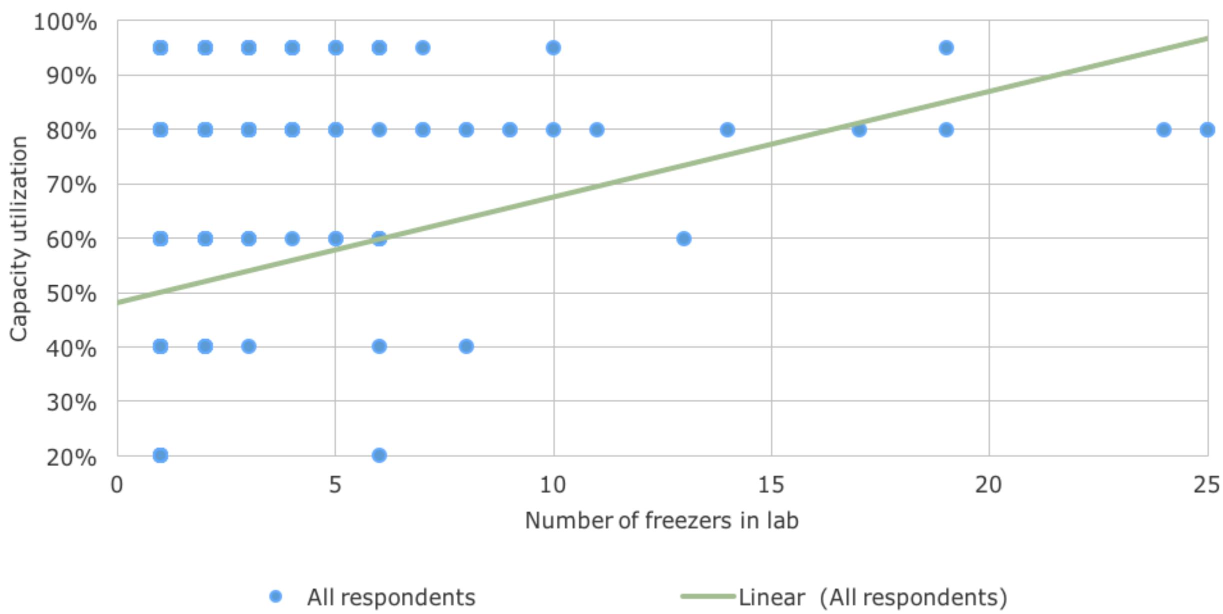


Figure 94: Correlation of Freezer Count and Capacity Utilization – National, all Responses Combined



ULT Freezer Purchase History

The frequency with which ULT freezers are purchased was queried by the survey. California responses indicate that researchers purchase freezers when they need them, and not with obvious regularity. Non-academic respondents indicated that they have a higher freezer purchase rate than academic labs, with 40% of respondents saying that they purchase a ULT freezer every 1-3 years. This frequency explains why the average number of ULT freezers in non-academic labs is higher than in academia.

The ULT freezer purchase frequency in the United States mirrors that seen in California, with there being a relatively even distribution across the options. Non-academic labs appear to purchase freezers with more frequency than academic labs, although the reported frequency was 4-6 years rather than 1-3 years reported by California.

The fact that the majority of respondents indicated that they purchase new ULT freezers within a 12 year time frame lends credence to the conclusions from Figures 86-89 that ULT freezer lifetime is ~10 years.

Figure 95: Purchase Frequency – California

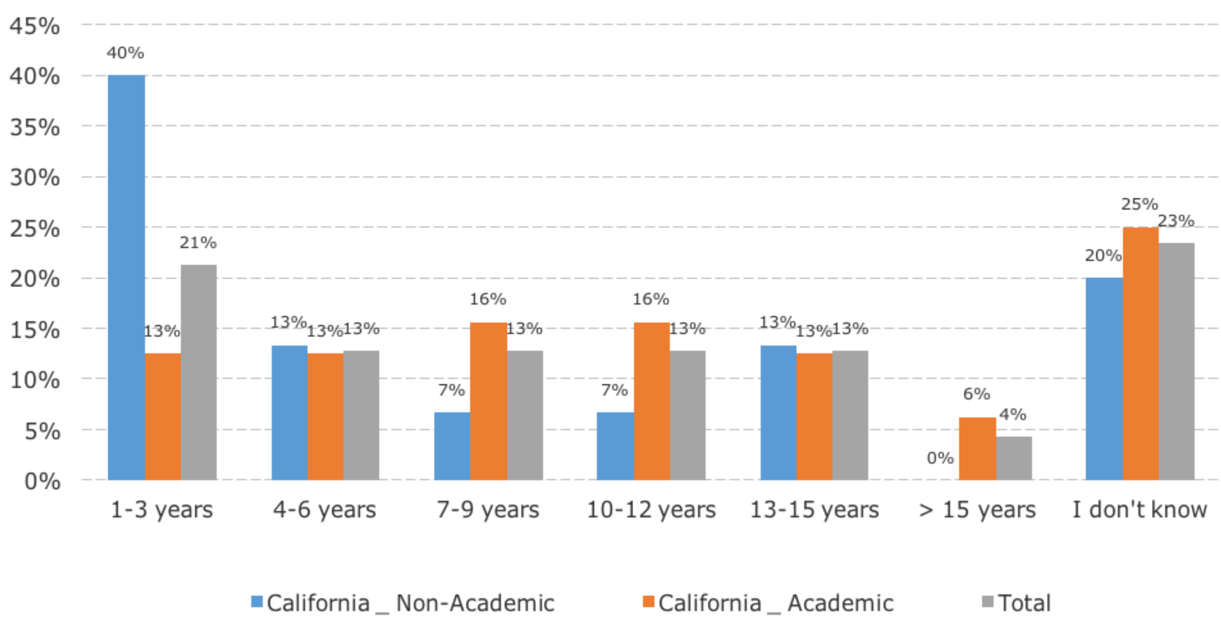
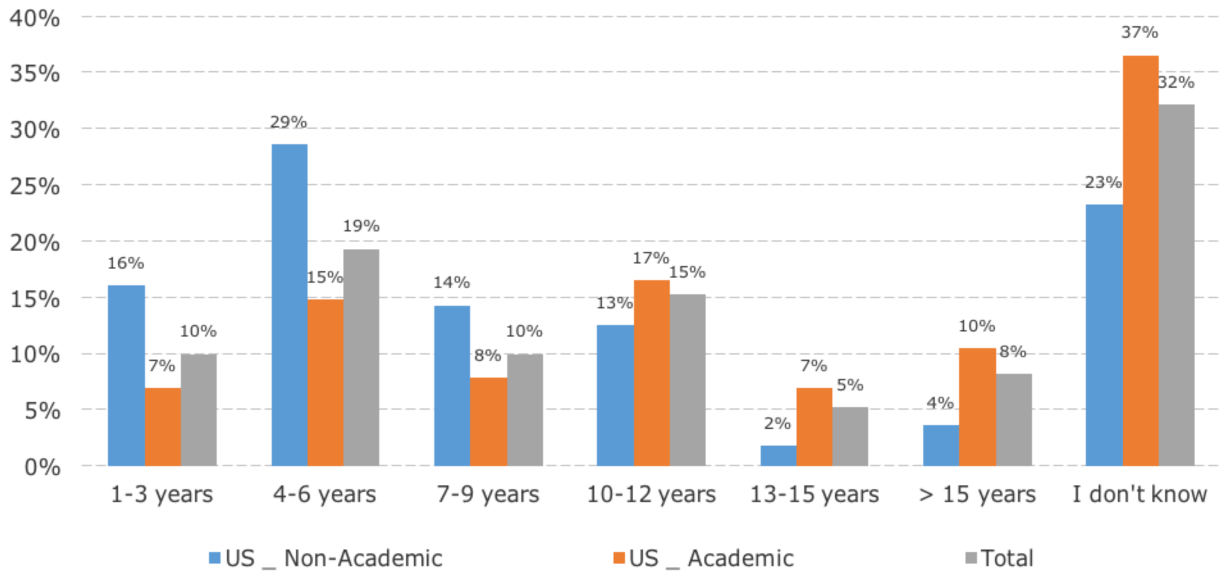


FIGURE 96: PURCHASE FREQUENCY – UNITED STATES, EXCLUDING CALIFORNIA

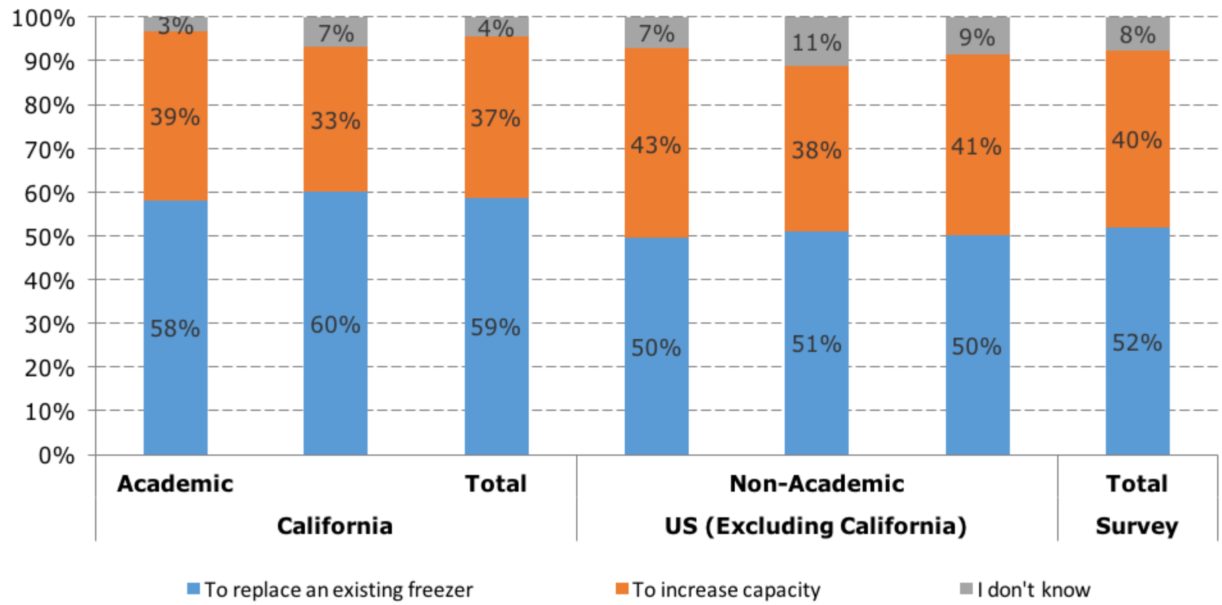


ULT FREEZER PURCHASE RATIONALE

At least 50% of respondents in California and the United States said that they purchase a new ULT freezer to replace an existing freezer; the remaining respondents indicated that they purchase a new ULT freezer to increase capacity, or for reasons that they did not know. Combined with the information provided in previous figures the data suggest ULT freezer lifetimes of ~10 years.

In addition, the results below make it clear that efforts to increase the storage capacity of a single unit, or methods of alternative storage would have a significant effect on the total number of ULT freezers in the market.

FIGURE 97: PURCHASE RATIONALE BY RESPONDENT CATEGORY



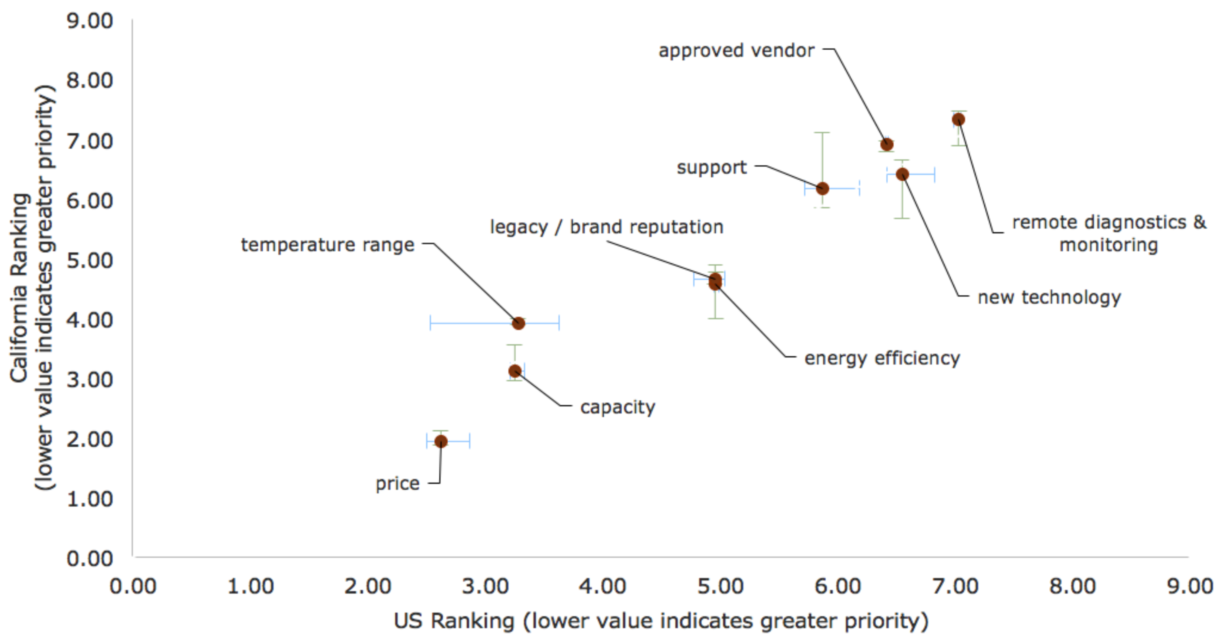
ULT Freezer Priorities and Purchasing Factors

Survey respondents were asked to rank the importance of various purchasing factors on a scale from 1 to 9, in which '1' was deemed the most important factor, and '9' the least important. The results from California and the greater United States were similar.

Price was universally acknowledged as being the most important factor considered when purchasing a new ULT freezer. This was followed by capacity and temperature range, which together could be taken to be 'freezer performance'. Respondents from California ranked capacity as being more important than temperature range, but the remaining respondents viewed these two options as being equally important in their purchasing decision. There was a large amount of variability in the responses to the temperature range option, which is noted by the blue error bars.

Somewhat surprisingly, legacy/brand reputation and energy efficiency were regarded as equally important, although neither was considered to be of great import to the respondents. The reported importance of brand reputation is corroborated by the findings reported in Figures 83 and 85 that show that labs with multiple freezers tend to have more than one brand. It is notable that energy efficiency is considered to be more important on average than support, new technology, approved vendor status (which usually confers special pricing and an ease of purchasing not afforded non-approved vendors), and remote diagnostics and monitoring.

FIGURE 98: RELATIVE IMPORTANCE OF PURCHASE FACTORS BY SURVEY REGION AND RESPONDENT CATEGORY

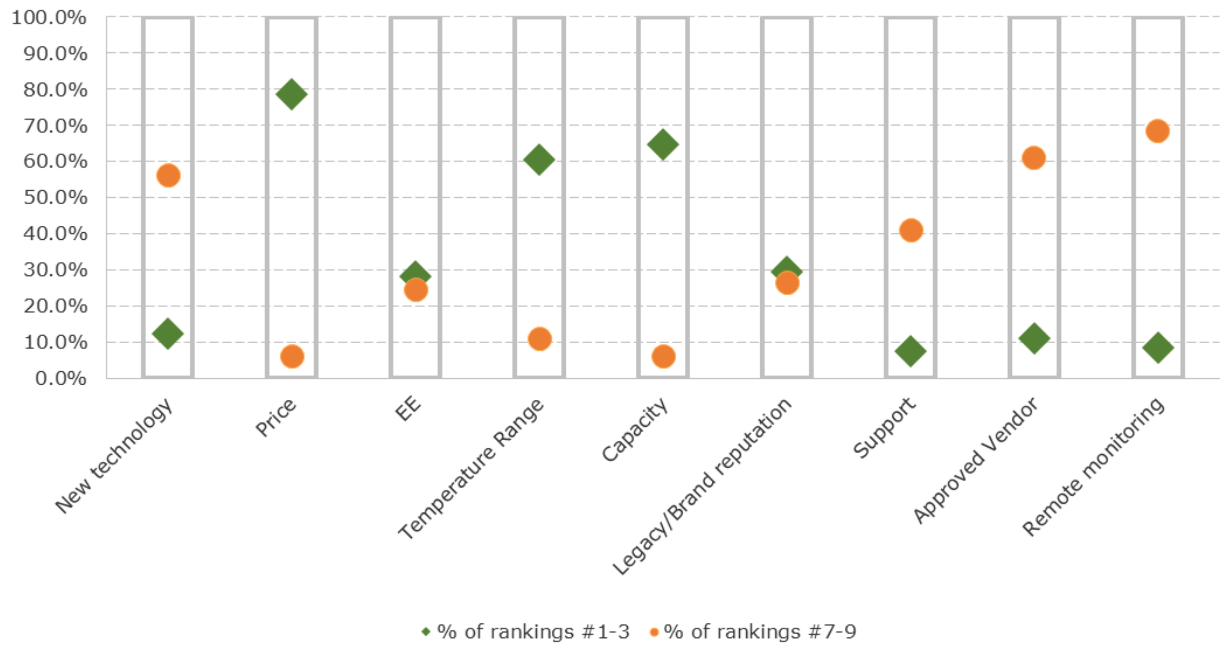


A more detailed analysis of the responses to the question about purchasing priorities can be found in Figure 99 below.

Eighty percent of respondents ranked price as having a priority of 1-3; less than 10% ranked it as being unimportant. Across the board price was universally recognized as being the single most important factor in purchasing a ULT freezer.

Interestingly, respondents appeared to view energy efficiency and legacy/brand recognition as either being very important or not at all important. These two categories were the only ones in which the responses were so divided; all of the other factors, with the exception of support, were ranked similarly by >50% of respondents. Thus, to those for whom energy efficiency and brand are important, they are viewed as being very important, and to those for whom energy efficiency and brand are not important, they are viewed as being very unimportant. Nevertheless, nearly three times more respondents ranked energy efficiency as being a higher priority than support, approved vendor status, and remote monitoring.

FIGURE 99: TOP AND BOTTOM RESPONSES – NATIONAL, ALL RESPONSES COMBINED

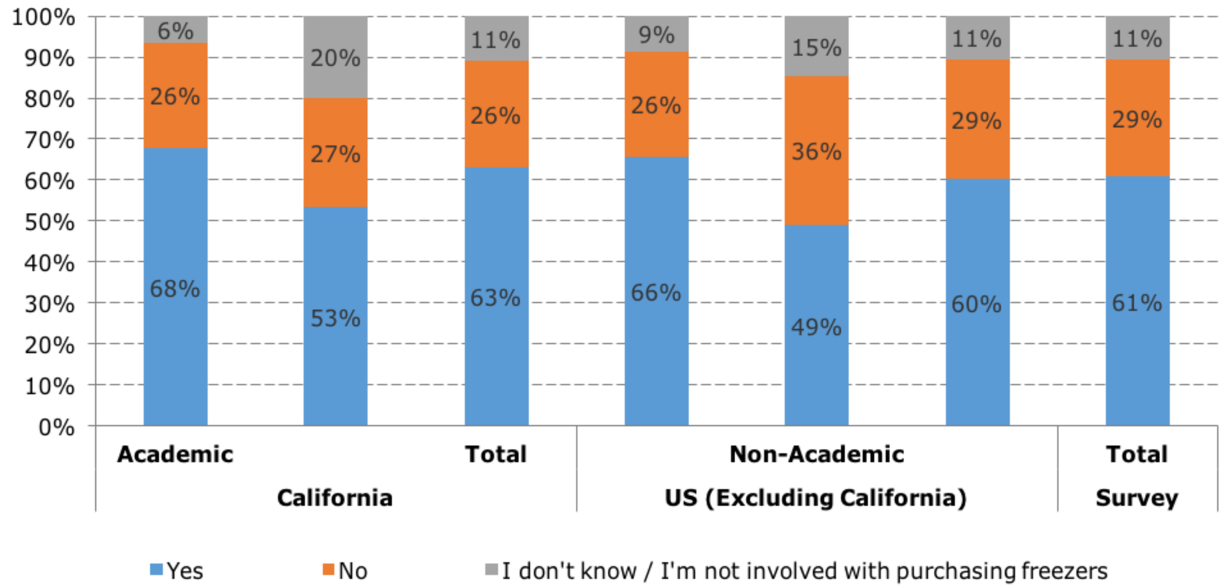


ENERGY EFFICIENCY

Looking at the importance of energy efficiency more closely, over 65% of academic labs in California and the United States responded affirmatively, that they do in fact consider energy efficiency when purchasing a new ULT freezer. Non-academic labs had a slightly less positive response, with just over 50% in California and just under 50% in the United States reporting that they consider energy efficiency. However, 15-20% of respondents from non-academic labs did not know whether energy efficiency was considered or were not empowered with making a decision about such things. This is likely due to the fact that purchasing tends to be more centralized in these institutions.

The data shown in Figure 100 support the findings from Figure 99. Overall, 61% of respondents said that they consider energy efficiency when purchasing a new freezer, which matches the ~60% of respondents who ranked energy efficiency as having a priority ≥ 6.

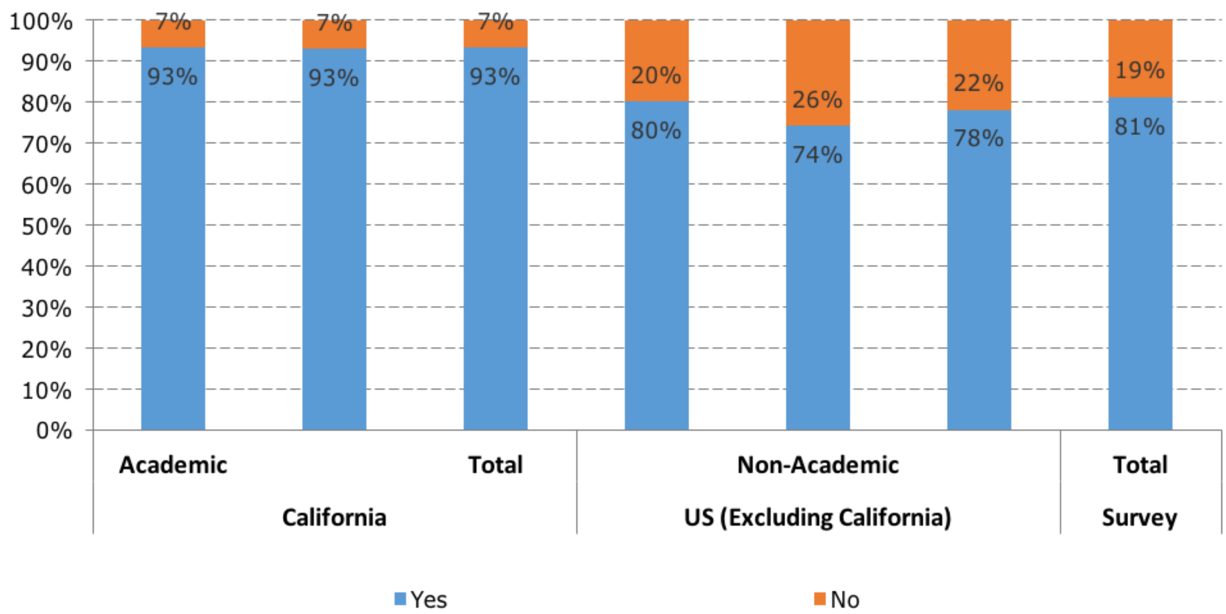
FIGURE 100: DO YOU CONSIDER ENERGY EFFICIENCY WHEN PURCHASING A NEW FREEZER?



ENERGY STAR RATING

Over 90% of respondents in California, and over 75% of respondents in the United States, indicated that an energy efficiency rating, such as ENERGY STAR, would influence their decision to purchase a ULT freezer. These results are in alignment with the findings from the previous three figures.

FIGURE 101: WOULD AN ENERGY EFFICIENCY RATING, SUCH AS ENERGYSTAR, INFLUENCE YOUR PURCHASE DECISION?



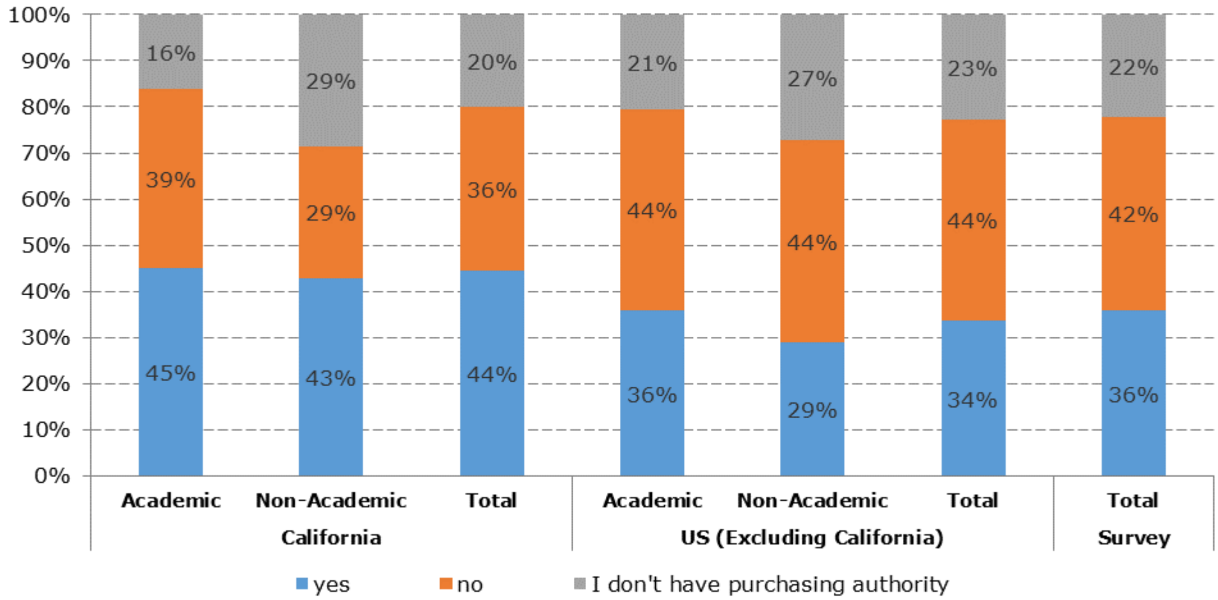
ENERGY EFFICIENCY PREMIUM

As shown in Figure 101 below, more respondents from California indicated that they would be willing to pay a premium for an energy-efficient ULT freezer (44%) than respondents from the rest of the United States (34%). These results speak to the complex relationship between price and energy efficiency. Clearly the overwhelming majority of researchers surveyed value energy efficiency, but only about half of those respondents are willing to pay more for that added value (when removing the respondents who did not have purchasing authority). And while more labs in California would be willing to pay a premium than not, regardless of whether they reside in academic or non-academic institutions, the same cannot be said for labs in the rest of the United States, where the majority of respondents indicated an unwillingness to pay a premium for energy efficiency.

These results differ slightly from those reported in the CEEL Laboratory Market Assessment report, in which ~80% of respondents indicated that they would be willing to pay a premium, however small, for increased energy efficiency. This question did not ask about a specific type of laboratory equipment, and therefore it is possible that when respondents answered this question they had a particular piece of equipment in mind that may not have been ULT freezers.

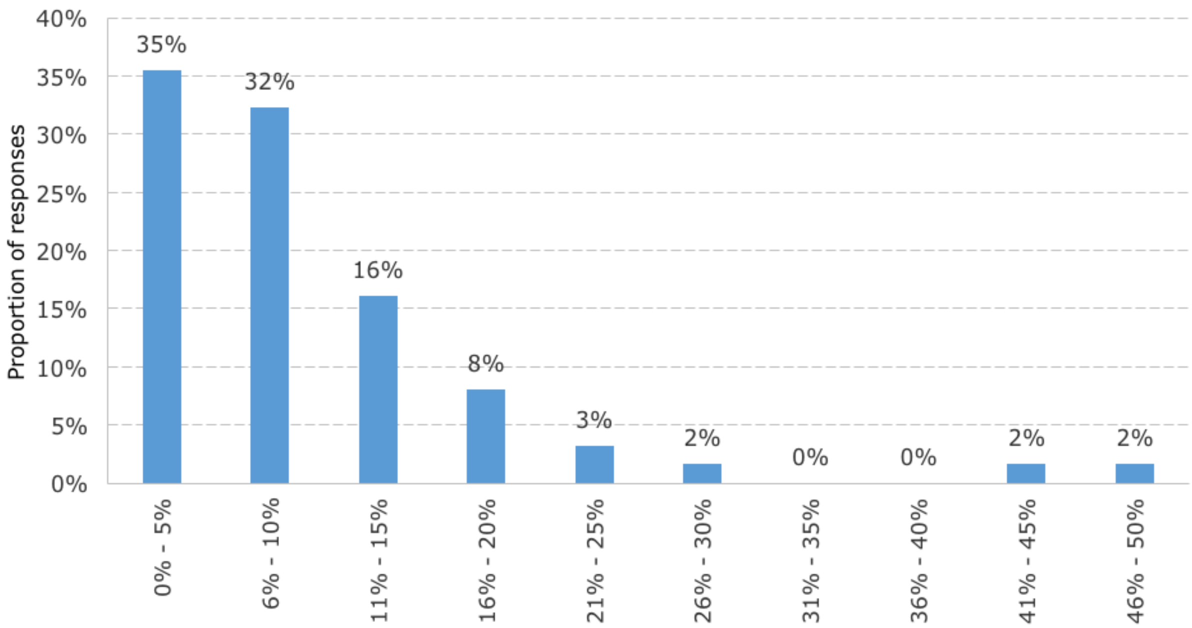
Nevertheless, in a market in which energy efficiency is a relatively new concept, and price dominates purchasing decisions, it is significant that 36% of all respondents, and 46% of all respondents who make purchasing decisions, would be willing to pay more for an energy-efficient ULT freezer.

FIGURE 102: WOULD YOU BE WILLING TO PAY A PREMIUM FOR AN ENERGY-EFFICIENT -80 FREEZER?



Of those would be willing to pay an energy efficiency premium, 67% would be willing to pay up to 10% more for an energy-efficient unit. Just 16% would be willing to pay between 11% and 15% more, and the few remaining respondents indicated that they would be willing to pay more than 15%. Respondents were asked to write in their answers, and thus these results do not reflect a bias in the survey questions toward any particular response.

FIGURE 103: HOW LARGE A PREMIUM WOULD BE ACCEPTABLE?



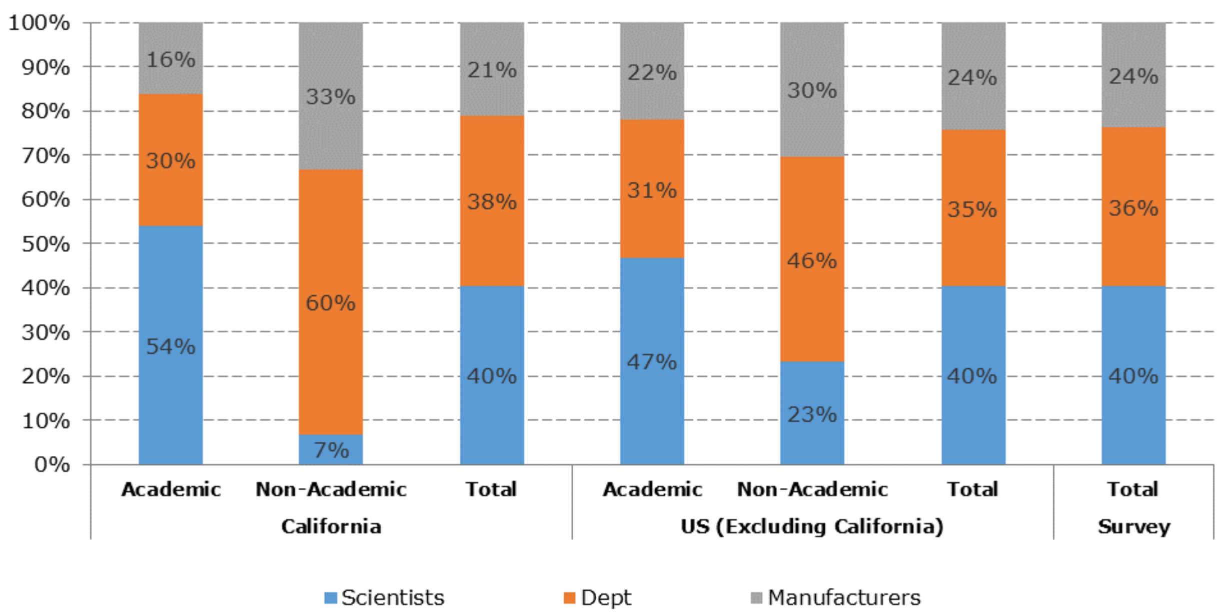
DISTRIBUTION OF FINANCIAL INCENTIVES FOR ENERGY EFFICIENCY

Given that most laboratories are interested in energy efficiency but not willing to pay a high premium for it, the survey asked scientists about rebate programs designed to reduce the purchase price of ULT freezers. Specifically, researchers were asked to whom a financial incentive for energy efficiency should go if one were available. Academic and non-academic labs had very different opinions on who should receive an incentive, with academic labs overwhelmingly favoring scientists as the recipients, and non-academic labs favoring departments instead. Only 25% of respondents felt that a rebate ought to go to a manufacturer to offset the retail price.

It is important to appreciate that funding for academic and non-academic labs can be very different, and that the responses given to this question by these two types of labs in fact might be functionally the same. Scientists would prefer that the rebate directly help them by reducing their costs. In academic labs, the lab itself pays for ULT freezers, and thus it is understandable why labs would want the rebate to go to them directly. In non-academic labs, purchasing is more centralized, so a rebate that went back to a department would likely ultimately benefit the lab itself by leaving more money in the departmental budget to purchase other supplies or equipment.

The topic of financial incentives will be further explored in the Discussion below.

FIGURE 104: FAVORED DISTRIBUTION OF PURCHASE INCENTIVES



CHAPTER 6: DISCUSSION

ENERGY EFFICIENCY AND PERFORMANCE

One of the primary goals of this study was to determine whether new ULT freezer technology is more energy-efficient than older technology, and whether this greater efficiency comes at the expense of temperature performance.

This study looked at a range of ULT freezer sizes from 16 to 29 ft^3. In an effort to equitably evaluate the efficiency of the ULT freezers tested, energy consumption was compared as a function of interior capacity (kWh/ft^3/day) rather than per freezer (kWh/day). Larger ULT freezers were found to consume less energy per cubic foot than smaller ULT freezers when normalized energy consumption values were compared. However, ULT freezer manufacturers prefer the kWh/day metric, and Freezers A, F, G, H, and I are currently marketed as energy efficient on that basis. These same models were also found to be energy efficient in this study, confirming manufacturer claims.

A summary of the energy and temperature performance results for the 15 units tested can be found in Table 32 below. The reported energy consumption under the ENERGY STAR test method (reported as the average of the test results at -80°C and -70°C) is given in the fourth column. In most cases these numbers are very close to those found in the field study when the ULT freezers were set to -80°C. Of those ULT freezers included in both the controlled environment and field studies, Freezers F and G competed for the title of "most energy efficient," with Freezer F edging out Freezer G in the ENERGY STAR results, and Freezer G consuming slightly less energy in the field study. It should be noted that in the field study, Freezer G demonstrated a higher average internal temperature than Freezer F (and than many of the other ULT freezers in the study), and this may account for the energy differences seen.

The most energy-efficient ULT freezers, Freezers A, F, G, H and I, exhibited comparable temperature performance to their standard-efficiency counterparts. Temperature uniformity and temperature stability are given in columns six and seven, respectively. The data collected in the controlled environment study are denoted by 'CE' and the data collected in the field are denoted by 'F'. Freezer A had among the best temperature stability and uniformity results across the board. Freezer G's temperature uniformity in the field was slightly higher than average, but was comparable to the results seen in Freezer C, a less-efficient freezer. Freezer F exhibited the least uniformity in the field, but in the controlled environment test it outperformed many of its peers. Freezers H and I were not tested in the field, but their controlled environment results are also comparable to the other, standard-efficiency ULTs tested. In terms of stability, Freezers F and G were found to be as stable as, if not more stable than, the other ULT freezers tested in the field study. In the controlled environment study Freezers F and G displayed a below-average amount of stability; Freezer F registered the worst performance. Freezers H and I displayed a level of temperature stability equivalent to the other ULT freezers tested in this study.

As a group, energy-efficient Freezers A, F, G, H and I, which employ new, energy-efficient technology, can be said to exhibit temperature performance similar to ULT freezers that use standard, traditional technology.

TABLE 32: ULT FREEZER CONTROLLED ENVIRONMENT AND FIELD TEST RESULTS

FREEZER	FREEZER VOLUME (FT^3)	REFRIGERANT TYPE	KWH PER FT^3 PER DAY @-75°C (ENERGY STAR TEST RESULTS)	KWH PER FT^3 PER DAY @ -80°C (FIELD RESULTS)	TEMP UNIFORMITY @ -80°C	TEMP STABILITY @ -80°C	DETERMINED TO BE ENERGY EFFICIENT?
A	20.1	HFC	0.546	0.50	6.5 (CE) 8.2 (F)	4.0 (CE) 21.9 (F)	Yes
B	23.0	HFC/Natural Blend	0.587	0.63	7.4 (CE) 6.0 (F)	6.3 (CE) 11.7 (F)	
C	24.7	HFC	0.770	0.70	6.7 (CE) 12.4 (F)	4.2 (CE) 13.3 (F)	
D	24.0	HFC	0.745	0.72	15.9 (CE) 6.2 (F)	3.5 (CE) 60.9 (F)	
E	27.5	HFC	0.925	0.91	4.0 (CE) 7.1 (F)	4.2 (CE) 29.7 (F)	
F	27.5	Natural	0.321	0.35	15.4 (CE) 17.7 (F)	8.4 (CE) 13.9 (F)	Yes
G	28.8	Natural	0.364	0.33	5.2 (CE) 12.2 (F)	6.3 (CE) 18.2 (F)	Yes
H	19.4	Natural	0.468		6.9 (CE)	4.4 (CE)	Yes
I	27.5	Natural	0.286		13.5 (CE)	6.3 (CE)	Yes
J	28.8	HFC/Natural Blend	0.587		8.4 (CE)	4.8 (CE)	
K	16.0	HFC	0.809		7.5 (CE)	3.8 (CE)	
L	25.7	HFC	0.651		8.2 (CE)	4.3 (CE)	
M	18.0	HFC	0.734		6.8 (CE)	3.6 (CE)	
N	18.9	HFC	0.943		8.9 (CE)	4.6 (CE)	
O	26.0	HFC	0.584		9.2 (CE)	2.9 (CE)	

EFFECT OF FINANCIAL INCENTIVES FOR ENERGY EFFICIENCY

In additional to determining that energy efficiency does not come at the cost of performance, the study also found that researchers value energy efficiency. Taken together, these conclusions raise the question of why energy-efficient ULT freezer technology has not been widely adopted, particularly given that at least one of the energy-efficient ULT freezers has been available for at least five years. One potential reason could be the fact that until now, there has been no third-party verification of manufacturer energy-efficiency claims. Another is that energy-efficiency freezers are more expensive, and cost influences purchase decisions more than any other factor. In the survey's ranking of purchase factors, price was found to be more important than even temperature stability and capacity, and far more important than some factors that might intuitively seem important, such as brand and customer support.

Like most capital equipment sold into the research market, the list price of ULT freezers rarely reflects the sales price. In a market this competitive, special pricing abounds; in fact, two identical units may be sold to the same institution for two different prices. An analysis of 742 ULT freezers bought by a single academic institution in California revealed that prices for the same freezer model differed by as much as $7,000, or 40%, in the same year. For units of comparable size across multiple manufacturers, sales prices ranged from $7,600 to $16,000, while list prices ranged from $11,000 to $30,000. Looking back over the past six years, the average sales price of a ~25 ft^3 ULT freezer at this organization was $10,540, and the average sales price of a ~20 ft^3 ULT freezer was $10,024.

In comparison, the average sales price of the few energy-efficient ULT freezers sold into this institution was $15,340, approximately $5,000 – or 50% – higher. Of the 126 ULT freezers sold into this university between 2013 and 2015, only 6.3% were models marketed as energy-efficient (and subsequently determined to be so in this study).

Additional ULT freezer pricing information from the manufacturers that participated in this study corroborate the general trend described above. Reported list prices for Freezers A–O ranged from $15,300 to $30,000, with ULT freezers of 21-29 ft^3 capacity slightly more expensive than 15-20 ft^3 ULT freezers. Sales prices for these freezers were at least 25% below the list price, and sometimes more than 50% below, with most manufacturers reporting an average discount of 30%. Customers from academic and non-academic institutions reported a similar average discount, but a wider variation was reported in non-academic institutions. Importantly, this data set included price information for newer energy-efficient ULT models, and this revealed that their price premium over standard-efficiency models was less than what was noted in the above example. Specifically, two of the three manufacturers of energy-efficient units described average energy-efficiency premiums of ~$1,000 over their own standard-efficiency models, less than the $5,000 figure noted above. This more apples-to-apples price comparison confirms that while energy-efficient ULT freezers are in fact more expensive than their standard-efficiency peers, the premium paid for them is often not more than 30%. In fact, a cumulative analysis of all ULT freezers used in the study revealed an average difference of $1,700 between energy-efficient and standard-efficiency units, and comparing units on an equivalent size basis reveals an incremental cost difference of $1,200 and an energy savings of $350/year.

A case study from California earlier this year provides substantial evidence that lowering prices for energy-efficient freezers can directly result in greater market penetration. The University of California worked with a manufacturer of energy-efficient ULT freezers to offer special pricing on all units sold between February 1, 2016 and April 30, 2016. The promotional price was approximately $10,000, 50% below the freezer's $20,000 list price, and perhaps more importantly, nearly identical to the price of new standard-efficiency models. During this period, 71 energy-efficient ULT freezers were sold into the University of

California school system. By comparison, only four energy-efficient units lacking the incentive were purchased during the same timeframe, and less than ten energy-efficient units had been sold into the system during the previous year. After the promotion the number of energy-efficient units sold also dropped precipitously.

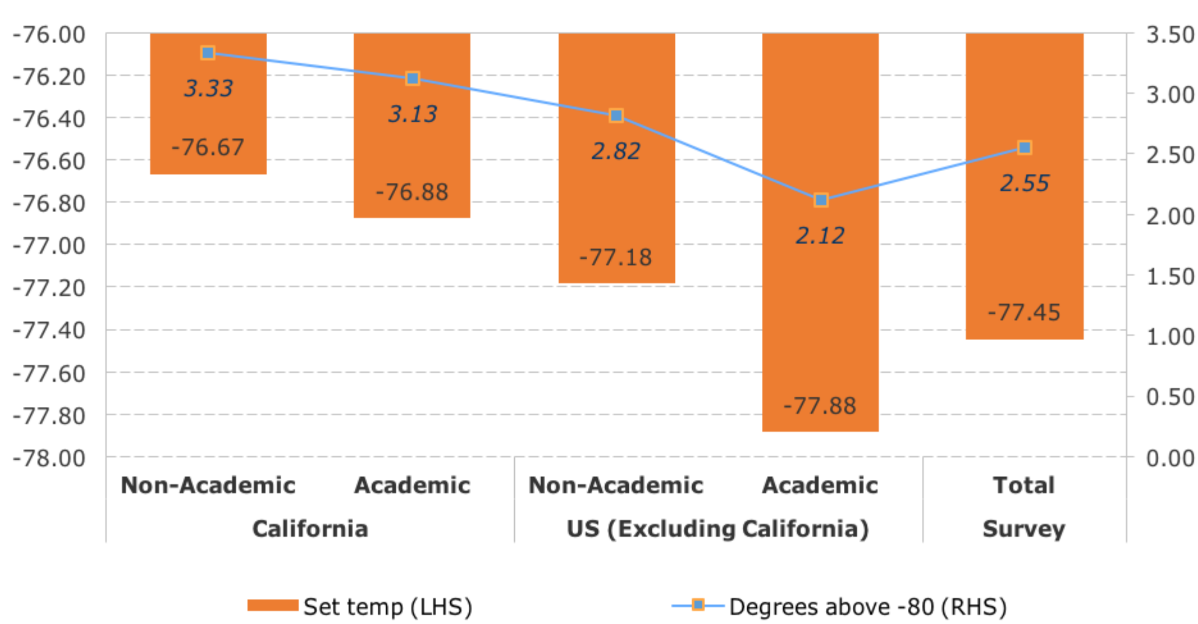
Many universities across the United States, from the University of California to Harvard University, have found that offering financial incentives to researchers for purchasing energy-efficient ULT freezers increases the number of energy-efficient units sold. Non-academic institutions have also offered similar incentives, or have looked to their local utility companies to do the same.

QUANTIFYING DIRECT ENERGY SAVINGS

The first step in structuring financial incentives for energy efficiency is to quantify the energy savings. Throughout the study, ULT freezers were tested at two different temperature set points, -80°C and -70°C. Energy consumption at -70°C was consistently found to be less than at -80°C. The EPA ENERGY STAR test method incorporates all of these information by requiring that the average of the two temperature readings be reported. However, in order to determine actual energy savings it is helpful to first understand at what temperature these freezers are usually set.

In the 1980s and 1990s ULT freezers were generally set to -70°C. Changes in laboratory culture resulted in a temperature creep to -80°C, and for years these freezers have been known colloquially as 'minus 80s'. Respondents to the online survey were asked about their ULT freezer set points. Figure 105 below shows that ULT freezers are likely to be operating at temperatures just slightly above -80°C, at an average of -77.5°C.

FIGURE 105: OPERATING TEMPERATURE BY RESPONDENT CATEGORY



Ignoring for the moment the potential energy savings from behavior change, which are addressed in more detail below, it makes sense to base an energy savings calculation on a temperature equal to or below the -75°C set point used in the ENERGY STAR study. This would provide a conservative estimate of energy savings, because ULT freezers operating at higher temperatures consume less energy.

Based on the controlled environment tests, the average energy consumption of a standard 21-29 ft^3 ULT freezer is 16.7 kWh/day, and the average energy consumption of an equivalently-sized energy-efficient model is 9.7 kWh/day, implying potential energy savings of ~7 kWh/day.

Normalized for capacity, the average energy consumption of 21-29 ft^3 ULT freezers is 0.65 kWh/day/ft^3 for standard ULT freezers and 0.35 kWh/ft^3/day for energy-efficient models, implying savings of 0.30 kWh/ft^3/day. The average size of a ULT freezer within this category is 26.1 ft^3, which suggests a 7.8 kWh load reduction per unit.

Smaller capacity ULT freezers, sized 15-20 ft^3, demonstrated an average energy consumption of 14.6 kWh/day. Energy-efficient ULT freezers in this size range consumed 10.0 kWh/day, saving 4.6 kWh/day. Normalizing these data for ULT freezer capacity, a standard ULT freezer model consumes 0.83 kWh/ft^3/day, and an energy-efficient model consumes 0.51 kWh/ft^3/day. The average size of a ULT freezer within this smaller size category is 18.5 ft^3. Therefore the energy savings per day amounts to 6.0 kWh based on the normalized data.

The market assessment determined that ~60% of all ULT freezers in California fall into the larger size range (21-29 ft^3), and that ~17% fall into the smaller size range (15-20 ft^3). ULT freezers are replaced approximately every 10 years, and there are ~58,000 ULT freezers in California, so approximately 5,800 'replacement' purchases are made annually statewide. If these purchases were all of energy-efficient ULT freezers, as opposed to standard-efficiency models, savings would total 12 million kWh/year, comprised of 9.9 million kWh/year for the larger freezers and 2.2 million kWh/year for the smaller freezers. Because these savings would be generated from replacement purchases only, they would increase to the extent that incremental freezers purchases were made of energy-efficiency models. Thus the second year would yield an additional 12 million kWh in savings, bringing the total annual savings in year two to 24 million kWh. In year 10 and beyond, the savings associated with purchasing energy-efficient freezers (over standard-efficiency freezers) would be 120 million kWh/yr.

These are only the savings provided by new energy-efficient ULT freezers over new standard-efficiency units. When compared to California's existing installed base – which is far less energy efficient than even today's standard-efficiency models, the replacement savings from energy-efficiency freezers is much greater. Baseline energy studies on existing ULT freezers in the field revealed that these freezers consume an average of 1.1 kWh/ft^3/day. With energy-efficient freezers consuming 0.35 kWh/ft^3/day, the savings for replacing 10% of the ULT freezer market in California would be over 41 million kWh/year. Again, these savings would persist for the life of the freezers, compounding with time as more units are replaced. After 10 years, the savings from replacing all existing 58,000 ULT freezers with energy-efficient models at a rate of 10% per year would be 2,255 million kWh – and there would still be an additional 1,845 million kWh left to capture.

Extrapolating these findings to the greater United States yields even greater savings potential. The market assessment concluded that at least 40%, or approximately 240,000 ULT freezers, in the United States fall within the 21 to 29 ft^3 size range. At an energy savings rate of 0.75 kWh/ft^3/day, replacing 10% of the existing ULT freezer market with energy-efficient ULT freezers would yield savings of ~171 million kWh/year for the first year alone.

INTEGRATING SECONDARY ENERGY SAVINGS

The calculation above does not take into account secondary energy impacts associated with the HVAC systems serving spaces containing ULT freezers.

As described in detail in Chapter 5, the HVAC energy impact of improved ULT freezer efficiency is a strong function of the type of space in which the freezer is located. The greatest HVAC energy savings are obtained in cooling-dominated spaces in which cooling energy usage (and in some cases fan energy usage) is reduced as a result of the reduced equipment load in the space. This typically occurs in lab equipment rooms and dedicated freezer farms. The combined results of the surveys performed for this study, as described in the results section, show that the majority of ULT freezers in California (62%) reside in one of these two space types. All else being equal, choosing to improve the efficiency of freezers located in equipment rooms or freezer farms over those located elsewhere would have the largest overall energy savings impact.

The HVAC impact may be minimal in other types of spaces: the presence of ULT freezers will typically overwhelm the cooling systems serving spaces not originally designed for high equipment loads, such as hallways or offices. Approximately 12% of ULT freezers were found to be located in hallways. In main open lab spaces (where 26% of ULT freezers are located), which typically operate at high ventilation rates with relatively low average equipment loads, the HVAC impact most often consists of a heating energy penalty.

Using the typical HVAC design parameters and distribution of ULT freezer locations found in this study, and performing an average over California climate zones, the statewide total annual energy savings associated with replacing 10% (5,800 freezers) of California's installed base with energy-efficiency ULT models, including secondary impacts, are shown in Table 33 below.

TABLE 33: TOTAL STATEWIDE ANNUAL ENERGY SAVINGS, INCLUDING SECONDARY HVAC ENERGY IMPACTS, ASSOCIATED WITH IMPROVING THE EFFICIENCY OF 10% OF THE ULT FREEZER POPULATION

	DIRECT SAVINGS (KWH/YR)	HVAC ELECTRIC SAVINGS (KWH/YR)	TOTAL ELECTRIC SAVINGS (KWH/YR)	NATURAL GAS PENALTY (THERMS/YR)
Savings Over New Standard Efficiency Freezers	12 million	2.2 million	14 million	110,000
Savings Over Existing Older Model Freezers	41 million	7.6 million	49 million	370,000

Note that the HVAC savings metrics presented here can be applied to the replacement of an existing ULT freezer with a more efficient unit, or to the selection of a new high-efficiency ULT freezer over a standard-efficiency model. The factors can also be used to calculate the HVAC impact of a change in set point temperature for existing freezers. However, the impact factors presented here *cannot* be used to assess the best location within a facility (from a total energy consumption standpoint) for a new freezer. A discussion of the optimization of freezer locations and HVAC systems is beyond the scope of this report.

REBATE POTENTIAL FOR ULT FREEZERS

For the past several years, energy-efficient ULT freezers have been incentivized by the California IOUs through customized rebate programs. Under these programs, the incentive amount is explicitly calculated for a specific site, based on the measured energy consumption of its existing baseline and replacement ULT freezer models. Considerable time and effort are required to perform the necessary calculations and many organizations are not equipped to undergo this process.

In contrast, deemed rebates are not site-specific and compare a generic baseline model to an energy-efficiency threshold for a replacement unit in order to determine a fixed rebate amount. Deemed rebates are preferable for most organizations because not only are the organizations not required to meter equipment, but they also know the incentive amount *a priori*, before purchasing new equipment. In order to create a deemed product category for ULT freezers, utilities must gather controlled environment laboratory data on annual energy consumption of both standard-efficiency and energy-efficient units, and corroborate this with field study data that show energy use in actual operating environments. The work performed in this study provides the California IOUs with a substantial amount of laboratory and field data from which to establish an energy-efficiency threshold.

Table 34 shows pertinent energy and operational data used to calculate energy usage for two ULT freezers of similar size. Energy usage data was based on the units tested in the controlled environment study and hours of operation (i.e. 24/7) are based on units tested in the field. The daily energy usage is based on the internal volume of the freezer and the energy use per cubic foot. Annual energy usage is based the assumption that the ULT freezer is operated at -75°C internal temperature and is opened six times a day on weekdays with an average duration of 15 seconds per door opening.

TABLE 34: ULT FREEZER ANNUAL ENERGY USAGE ESTIMATION

PARAMETER	BASELINE ULT FREEZER	ENERGY-EFFICIENT ULT FREEZER
Internal Volume (ft^3)	28.8	28.8
Energy Usage with Door Openings -75°C ($kWh/ft^3/day$)	0.587	0.364
Energy Usage without Door Openings -75°C ($kWh/ft^3/day$)	0.533	0.328
Daily Energy Usage with Door Openings (kWh/day)	16.91	10.49
Daily Energy Usage without Door Openings (kWh/day)	15.35	9.44
Annual Operation (days)	365	
No Door Openings (days per week)	2	
Electricity Cost ($ /kWh)	$0.13	
Annual Energy Usage (kWh/year)	6,009	3,719
Annual Energy Savings (kWh/year)	-	2,290
Annual Energy Operation Cost ($)	$781	$484
Annual Energy Cost Savings (kWh/year)	-	$293
Incremental Retail Price of the Energy-Efficient ULT Freezer ($)	-	$1,015
Simple Payback Time (years)	-	3.4

DISTRIBUTING FINANCIAL INCENTIVES FOR ENERGY-EFFICIENT ULT FREEZERS

Respondents to the online and in-person surveys were clear about who they think should receive the financial incentive for purchasing energy-efficient ULT freezers – themselves. Unfortunately, the structure of many academic and non-academic facilities makes it very difficult for money to flow directly to a PI or individual lab. And financial incentives that are given generally to a department are viewed less favorably, and have historically had less of an impact, than those that are directed to the researchers purchasing the equipment.

One of the most important barriers to the purchase of energy-efficient equipment has been product availability from the equipment dealers and distributors. Many dealers and distributors are unwilling to take stock of more expensive energy-efficient equipment from the manufacturers when there is a limited demand. This practice adds a market barrier to facilities purchasing equipment and increases the cost of energy-efficient equipment to customers.

Including the rebate as part of the purchasing process, known as a point-of-sale (POS) rebate, was identified by program managers as one way to increase the number of high-efficiency units sold. A small additional incentive to cover administrative costs associated with implementing the POS incentive for the equipment dealers and distributors helps to secure their support and promotion of the program. In this model, vendors would be responsible for procuring the rebate for, and passing along the savings to, their customers. This would allow researchers to feel as though the rebate were coming to them directly, and would eliminate the complications of having to figure out how to refund grants or lab-specific funds after a rebate has been obtained.

The model of providing POS financial incentives to vendors was successfully introduced to the commercial food service sector by PG&E in 2012. A six-month POS pilot included an analysis of eligible products sold by the participating dealers for the 24 months prior to initiating the program and the sales of qualifying models during the pilot period. The program included an added incentive for the dealer to cover the cost of administering the program, and a customer feedback survey to gauge the impact of this new market delivery channel.

The 2012 POS pilot resulted in a 35% increase in foodservice rebate program participation, a 95% customer approval rating of the program (with 85% of responding customers indicating that the POS incentive directly influenced their purchasing decision), and a dramatic reduction in rebate processing costs by bulk processing rebate submittals uploaded by the dealers.

After the successful pilot, the program was rolled out to all eligible foodservice equipment dealers in the fourth quarter of 2012, changing the stocking behavior of participating dealers, who began to carry and promote more qualifying equipment models. Today, the POS program accounts for significant portion of the overall commercial foodservice incentive program.

The effect of a POS rebate program in the life science research sector could be significant in reducing California's energy consumption in commercial buildings in much the same way that this type of program has positively impacted the foodservice industry. Moreover, existing in-house incentive programs for ULT freezers at many institutions across the state follow a very similar model, in which the researcher realizes direct financial benefits from the incentive. Thus a POS program would allow for an easy transition.

THE IMPACT OF TEMPERATURE TUNING

The potential impact of adjusting ULT freezer set points is substantial. This study has shown that changing the temperature set point of ULT freezers from -80°C to -70°C can reduce energy consumption by an average of 37%. Taking the calculations from above, if all ULT freezers in the state of California that fall within the 21-28 ft^3 size range were adjusted to -70°C (34,800 freezers) the resulting savings would be 135 million kWh/year.

Importantly, this study also showed that ULT freezer temperature stability and uniformity were generally not adversely affected by a -70°C set point (see Appendix D). Freezers A and G exhibited slightly improved uniformity and stability at -70°C, and the observed effects on Freezers B, C, D, E and F were minimal. In addition, ULT freezer temperature recovery at -70°C was nearly the same as at -80°C, with the majority of ULT freezers recovering to within 1°C of baseline two hours after a door opening stress test.

Recommended sample and reagent storage conditions must be taken into account when considering an adjustment from -80°C to -70°C, but such an adjustment should be seriously considered whenever it is a practical possibility.

CHAPTER 7: SUMMARY AND RECOMMENDATIONS

This comprehensive study of controlled environment and field surveys of ULT freezers found that energy-efficient ULT freezers perform as well as, and in some cases better than, their standard-efficiency peers, while consuming at least 25%, and in some cases up to 70%, less energy. Even new, standard-efficiency ULT freezers were found to consume at least 20% less energy than the average ULT freezer in California's installed base. Energy-efficient ULT freezers, defined as the top 33% of the freezers tested, were found to consume less than 11 kWh/day or 0.55 kWh/cf/day.

The findings from this study have revealed opportunities for energy reduction through behavior change. It was found that adjusting ULT freezer temperature set points from -80°C to -70°C could result in significant energy savings. If all laboratories adopted a -70°C setting, the overall energy use of ULT freezers could be reduced by 37%, without impacting ULT performance in terms of temperature stability. And targeting ULT freezers in freezer farms for both ULT replacement and behavior change programs would ensure that the energy savings go beyond the plug to extend to HVAC systems as well.

Importantly, the energy use rankings from the controlled environment ENERGY STAR test did not differ substantially from those of the controlled field study, despite the noteworthy differences in operation, including the number and duration of door openings and the amount of material in the freezer. Therefore the ENERGY STAR test method for ULT freezers is a reasonable and accurate test for comparing the standardized energy consumption and temperature performance of ULT freezers.

The findings from this study have also revealed several opportunities for manufacturers. The use of natural, low global warming potential (GWP) refrigerants such as R290 and R170 may reduce energy consumption of freezer compressors. Four out of fifteen freezers used natural refrigerants and exhibited the lowest energy usage (see Chapter 5 – Freezer Size and Total Energy). However it is important to note that natural refrigerants are more flammable than the high GWP refrigerants that they are replacing, so ULT freezer manufacturers should continue to improve safety during manufacturing processes and improve reliability during operation. Manufacturers should also look to reduce the use of high GWP refrigerants as blowing agents for panel insulation.

ULT freezer temperature uniformity and stability could be improved with increased air circulation inside the freezer and strategic evaporator placement.

Sample loss due to freezer failure can be a significant problem for laboratories. Many manufacturers utilize redundant or backup systems and alarms to alert users of potential failures. In cases where ULT freezer failure has not yet occurred but may be imminent, it may be possible to detect component failure prior to overall freezer failure if refrigerant pressures and temperatures are monitored. This may be done indirectly through monitoring of the rate of cooling of the condenser (if the rate of cooling of the condenser, measured through the time it takes refrigerant to reach a certain temperature, is slower than expected, there may be a problem with the refrigeration system). Other technologies monitor energy consumption as predictors for freezer failure. In all cases these data must be given directly to a qualified technician in order to address the issue.

Considering the commonly held view that more energy-efficient ULT freezers will compromise temperature performance, it is recommended that manufacturers report their units' temperature performance per the ENERGY STAR test method. It is also recommended that ULT freezer manufacturers communicate to their customers the energy consumption of their freezers in terms of both kWh/ft^3/day and kWh/day in order to facilitate precise and meaningful comparisons between units.

Given the significant potential for energy savings and the historical efficacy of rebates, it is recommended that the IOUs consider incentivizing the purchase of energy-efficient ULT freezers in California. Due to end-users' preeminent focus on price, and the price difference of $1,000-3,000 between energy-efficient and standard-efficiency models on average, the success of any program will likely be proportional to the extent to which the IOUs help bridge this price gap and educate customers on the benefits of using energy-efficient ULT freezers.

In conclusion, this study found that energy-efficient ULT freezers use 30-40% less energy on average than standard-efficiency ULT freezers. Taking advantage of these efficiencies, as well as those that arise from HVAC-related energy savings, would result in substantial energy savings. Simply incentivizing the purchase of energy-efficient freezers for new freezer purchases could result in savings of at least 14 million kWh/year, while the replacement of 10% of the existing installed base with more efficient models could save at least 49 million kWh annually.

ENDNOTES

[1] Paradise, Allison (March 2015), 'Market Assessment of Energy Efficient Opportunities in Laboratories'.

[2] Gillenwater, Todd and Claude, Peter (2015), 'California Biomedical Report'.

[3] *Ibid*.

[4] Battelle/BIO (2014), 'State Bioscience Jobs, Investments and Innovation 2015'.

[5] Battelle Technology Partnership Practice (2013), 'The Economic Impact of the U.S. Biopharmaceutical Industry'.

[6] Ernst and Young (2013), 'Beyond Borders'. Carnegie Classification of Institutions of Higher Education.

[7] National Venture Capital Association and Thomson Reuters (2013).

[8] Better Buildings Alliance: http://betterbuildingssolutioncenter.energy.gov/alliance/activities/technology-solutions-teams/laboratories

[9] Paradise 2015 *Op. Cit*.

[10] Buie, John (November 10, 2010), 'Evolution of Lab Refrigerators and Freezers', *Lab Manager Magazine*.

[11] Legett, Rebecca (September 2014), 'Field Demonstration of High-Efficiency Ultra-Low-Temperature Laboratory Freezers', *Department of Energy*.

[12] Baust, J. (February 2016), 'Biopreservation: The Impact of Freezing and Cold Storage on Sample Quality'.

[13] Paradise 2015 *Op. Cit*.

[14] The two CA DEER prototypes closest to a laboratory facility are a single-story, 200,000-sf bio-manufacturing facility and a three-story, 250,000-sf hospital. Neither of these buildings is expected to be representative of the population of lab buildings in the state.

[15] Exergy analysis of a domestic refrigerator using eco-friendly R290/R600a refrigerant mixture as an alternative to R134a http://link.springer.com/article/10.1007/s10973-013-3264-3.

[16] Application of natural refrigerant propane and propane/isobutane in large capacity chest freezer http://www.sciencedirect.com/science/article/pii/S1359431114004736.

[17] Natural refrigerants: current developments and trends http://www.eurammon.com/sites/default/files/attachments/eurammon_background-article_energy-efficiency_engl.pdf.

[18] Faugeroux, Delphine (2016), 'Ultra Low Temperature Freezer Study: Three Energy Efficient Models Performance and Energy Use Tested', University of California, Riverside.

[19] This is a similar situation to the heating penalty incurred by lighting retrofit projects, with the important exception that (depending on the climate, building envelope, and the HVAC control sequences), the penalty may be present year-round and not just in winter.

APPENDIX A: FIELD STUDY TC PLACEMENT

The figures below indicate the locations of the TCs for each of the ULT freezers studied in the field.

FIGURE 106: THERMOCOUPLE PLACEMENT – FREEZER A

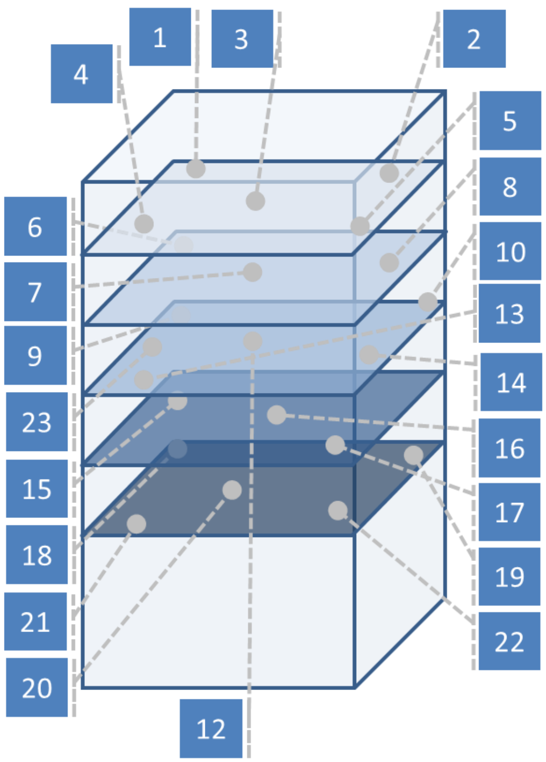


FIGURE 107: THERMOCOUPLE PLACEMENT – FREEZER B

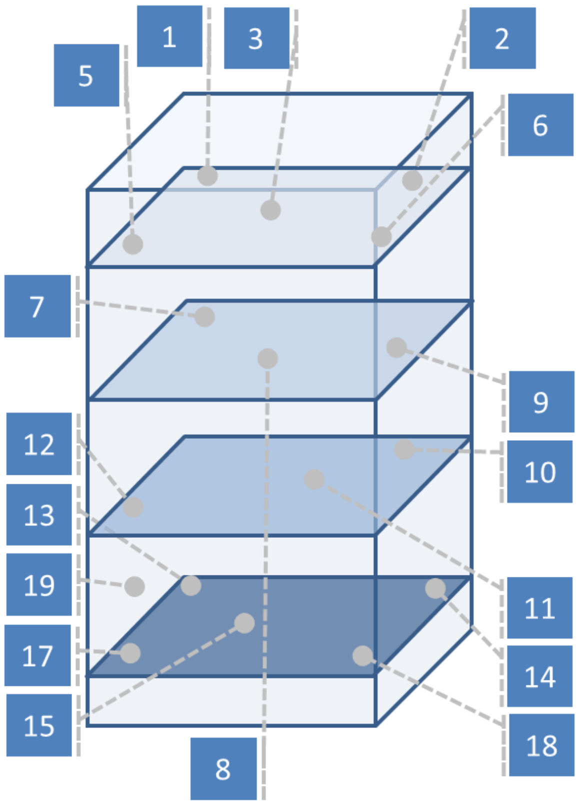


FIGURE 108: THERMOCOUPLE PLACEMENT – FREEZER C

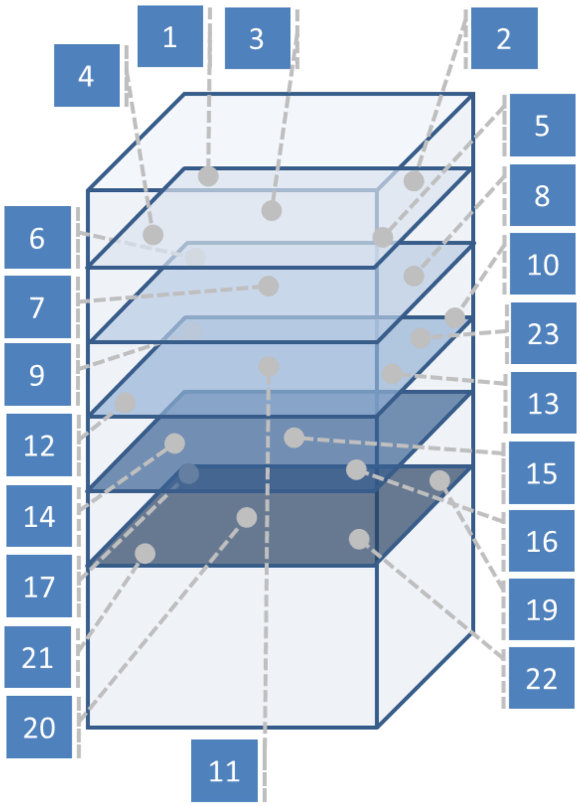


FIGURE 109: THERMOCOUPLE PLACEMENT – FREEZER D

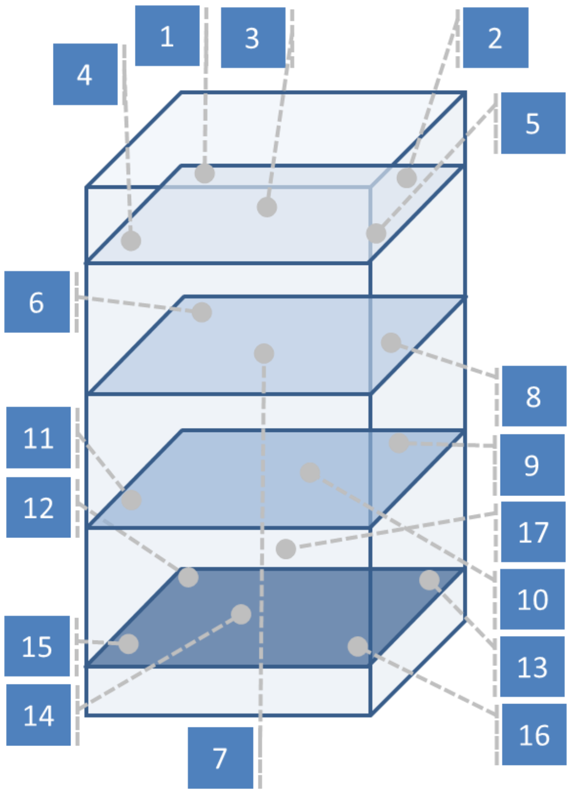


FIGURE 110: THERMOCOUPLE PLACEMENT – FREEZER E

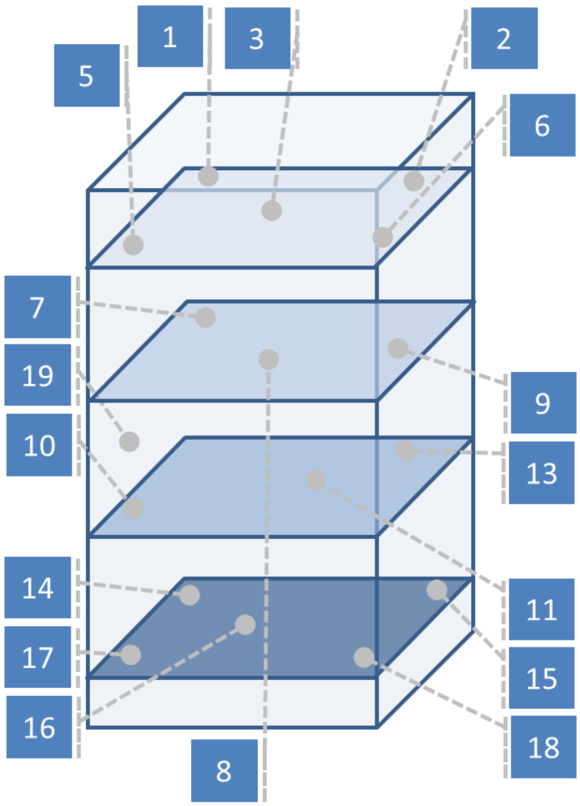


FIGURE 111: THERMOCOUPLE PLACEMENT – FREEZER F

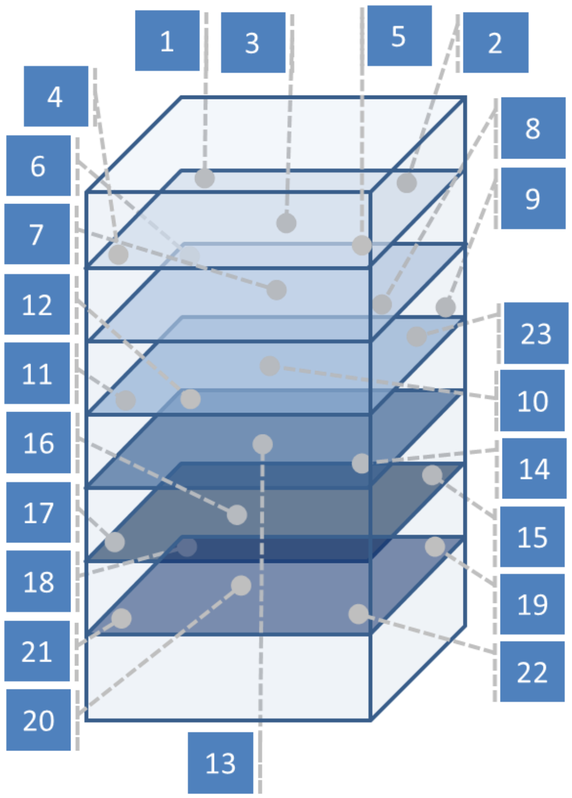
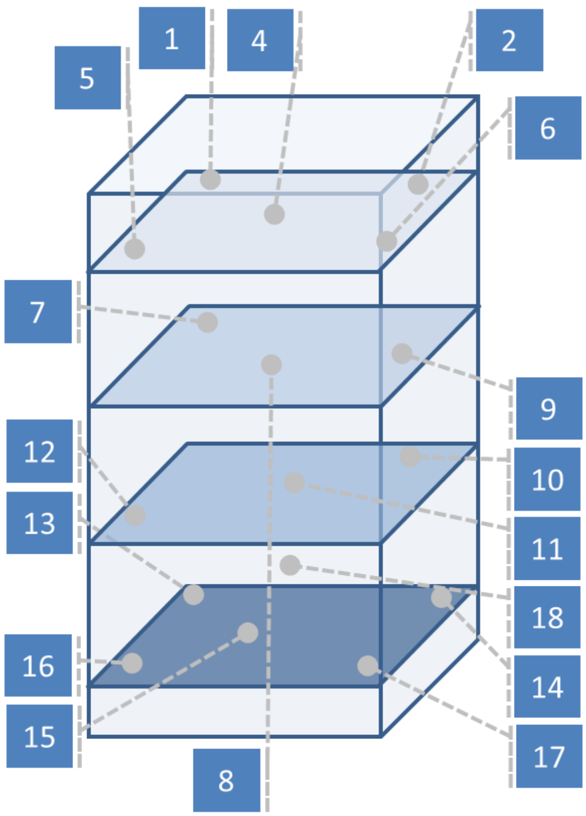


FIGURE 112: THERMOCOUPLE PLACEMENT – FREEZER G



APPENDIX B: VALIDATION RESULTS

TABLE 35: FREEZER A EMPTY CHAMBER RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-77.5	-74.1	-76.0
2	-77.6	-74.4	-76.3
3	-77.5	-73.7	-75.8
4	-77.2	-73.5	-75.5
5	-77.0	-74.0	-75.7
6	-78.4	-76.3	-77.5
7	-78.1	-76.3	-77.3
8	-77.6	-75.9	-76.9
9	-78.9	-76.9	-78.0
10	-78.8	-76.8	-77.9
11	-78.5	-76.7	-77.7
12	-78.2	-76.7	-77.5
13	-78.2	-76.5	-77.4
14	-78.5	-77.0	-77.8
15	-78.2	-76.8	-77.5
16	-78.2	-77.0	-77.6
17	-78.8	-76.8	-77.7
19	-78.4	-76.6	-77.3
20	-78.2	-76.6	-77.3
21	-77.5	-75.9	-76.7
22	-77.5	-76.1	-76.8
23	-78.7	-76.9	-77.9
Overall	**-78.9**	**-73.5**	**-77.1**

TABLE 36: FREEZER A MAXIMUM LOAD RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-77.9	-76.6	-77.3
2	-78.5	-77.6	-78.0
3	-73.6	-73.4	-73.5
4	-74.5	-74.0	-74.3
5	-72.2	-71.3	-71.8
6	-80.0	-79.1	-79.6
7	-75.4	-74.2	-75.0
8	-75.9	-75.3	-75.7
9	-78.9	-76.7	-78.1
10	-79.0	-77.4	-78.4
11	-76.4	-73.2	-75.5
12	-76.6	-74.5	-75.9
13	-76.1	-73.7	-75.4
14	-78.0	-72.9	-76.2
15	-76.8	-70.8	-74.8
16	-77.4	-71.8	-75.5
17	-79.5	-73.7	-76.9
19	-82.0	-74.6	-78.6
20	-77.2	-69.9	-74.7
21	-79.2	-76.9	-76.5
22	-76.7	-70.2	-74.3
23	-79.6	-77.9	-78.9
Overall	**-82.0**	**-69.9**	**-76.1**

TABLE 37: FREEZER B EMPTY CHAMBER RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-80.8	-76.1	-78.5
2	-81.7	-76.4	-79.1
3	-80.9	-75.7	-78.4
4	-81.1	-77.3	-79.3
5	-80.5	-75.6	-78.1
6	-83.2	-78.6	-81.0
7	-83.1	-78.5	-80.9
8	-82.6	-78.4	-80.6
9	-84.5	-79.4	-81.9
10	-85.0	-79.9	-82.2
11	-84.3	-79.5	-81.8
12	-80.5	-77.8	-79.1
13	-81.7	-77.6	-79.4
14	-82.1	-78.4	-80.1
15	-82.1	-78.4	-80.1
16	-81.5	-78.0	-79.7
17	-82.5	-78.5	-80.3
Overall	**-85.0**	**-75.6**	**-80.0**

TABLE 38: FREEZER B MAXIMUM LOAD RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-80.2	-78.7	-79.4
2	-82.4	-79.6	-80.9
3	-79.9	-79.4	-79.7
4	-77.5	-76.8	-77.2
5	-81.0	-79.4	-80.3
6	-81.1	-79.3	-80.2
7	-80.9	-80.5	-80.8
8	-81.0	-80.2	-80.7
9	-82.0	-80.6	-81.3
10	-81.3	-81.1	-81.2
11	-82.6	-81.0	-81.8
12	-80.2	-79.0	-79.5
13	-79.1	-78.1	-78.6
14	-78.4	-77.4	-78.1
15	-79.7	-78.7	-79.1
16	-77.3	-76.5	-77.0
17	-81.1	-79.7	-80.3
Overall	**-82.6**	**-76.5**	**-79.8**

Table 39: Freezer C Empty Chamber Run

TC	Minimum (°C)	Maximum (°C)	Average (°C)
1	-76.0	-72.5	-74.5
2	-75.9	-72.8	-74.6
3	-75.8	-72.8	-74.5
4	-75.2	-71.9	-73.8
5	-75.3	-71.9	-73.9
6	-76.5	-74.6	-75.7
7	-76.0	-74.2	-75.2
8	-75.4	-73.3	-74.6
9	-78.7	-76.6	-77.7
10	-79.2	-76.9	-78.1
12	-78.1	-76.1	-77.2
13	-78.0	-76.2	-77.1
14	-77.7	-75.9	-76.9
15	-79.1	-77.4	-78.3
16	-79.0	-77.4	-78.2
17	-78.3	-76.9	-77.6
18	-77.1	-75.8	-76.4
19	-77.1	-75.5	-76.1
20	-76.8	-75.6	-76.2
21	-76.8	-75.6	-76.1
22	-76.4	-75.0	-75.6
23	-78.7	-76.9	-77.8
Overall	**-79.2**	**-71.9**	**-76.2**

TABLE 40: FREEZER C MAXIMUM LOAD RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-77.6	-75.1	-77.2
3	-80.1	-78.0	-79.8
4	-75.9	-73.4	-75.4
5	-74.3	-69.4	-73.9
6	-73.8	-69.1	-73.5
7	-81.5	-79.2	-81.2
8	-79.7	-78.7	-79.5
9	-78.9	-75.8	-78.3
10	-83.6	-83.3	-83.5
11	-84.8	-84.2	-84.5
12	-84.6	-83.3	-84.2
13	-86.1	-85.2	-85.5
14	-85.3	-84.7	-85.1
15	-84.2	-83.4	-83.7
16	-88.0	-86.6	-87.2
17	-85.8	-84.8	-85.2
18	-86.8	-85.0	-85.4
19	-82.9	-82.0	-82.3
20	-83.9	-82.4	-83.2
21	-83.6	-79.8	-80.3
22	-81.2	-79.4	-79.8
23	-81.9	-80.3	-80.9
24	-79.7	-77.7	-79.4
Overall	**-88.0**	**-69.1**	**-81.3**

Note the TC numbers between the empty chamber and maximum load were due to the use of different Kaye units between the runs.

TABLE 41: FREEZER D EMPTY CHAMBER RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-76.7	-72.6	-75.0
2	-76.4	-71.2	-74.2
3	-75.8	-70.8	-73.7
4	-74.7	-72.1	-73.5
5	-75.7	-70.6	-73.6
6	-82.0	-77.2	-80.0
7	-80.5	-76.9	-79.1
8	-80.7	-76.9	-79.1
9	-82.1	-78.8	-80.6
10	-81.9	-78.3	-80.3
11	-81.9	-78.6	-80.4
12	-83.4	-78.9	-81.0
13	-83.3	-78.5	-80.7
14	-82.0	-78.3	-80.1
15	-82.7	-78.5	-80.4
16	-82.1	-77.7	-79.8
17	-82.1	-78.4	-80.3
Overall	**-83.4**	**-70.6**	**-78.3**

TABLE 42: FREEZER D MAXIMUM LOAD RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-76.4	-72.8	-75.1
2	-75.5	-72.0	-74.5
3	-71.3	-65.3	-70.4
4	-72.2	-69.4	-71.6
5	-71.4	-68.6	-70.6
6	-79.8	-77.5	-79.2
7	-78.2	-74.3	-77.6
8	-78.1	-74.9	-77.4
9	-80.8	-78.8	-80.2
10	-79.7	-77.1	-79.3
11	-81.4	-78.5	-80.4
12	-80.7	-78.7	-79.7
13	-81.2	-78.4	-79.6
14	-74.8	-73.3	-74.5
15	-79.3	-78.4	-78.8
16	-77.0	-75.7	-76.3
17	-82.2	-78.9	-80.8
Overall	**-82.2**	**-65.3**	**-76.8**

TABLE 43: FREEZER E EMPTY CHAMBER RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-80.7	-77.0	-79.2
2	-80.7	-76.4	-78.9
3	-80.1	-76.6	-78.7
5	-79.9	-76.3	-78.5
6	-79.9	-75.9	-78.3
7	-81.1	-77.1	-79.1
8	-79.4	-77.1	-78.0
9	-78.7	-76.3	-77.4
10	-77.6	-75.8	-76.4
11	-78.5	-76.3	-77.1
13	-78.6	-75.6	-77.1
14	-80.4	-75.5	-77.8
15	-80.1	-75.4	-78.0
16	-83.1	-75.1	-77.2
17	-79.1	-74.7	-76.8
18	-78.4	-74.7	-76.4
19	-78.7	-75.5	-76.9
Overall	**-83.1**	**-75.5**	**-77.8**

TABLE 44: FREEZER E MAXIMUM LOAD RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-79.8	-78.1	-79.2
2	-79.7	-78.5	-79.2
3	-78.0	-77.3	-77.7
5	-77.1	-76.2	-76.6
6	-78.6	-76.6	-77.5
7	-81.0	-77.8	-79.4
8	-77.7	-77.1	-77.3
9	-76.9	-76.0	-76.4
10	-76.9	-75.8	-76.2
11	-76.1	-75.7	-75.9
13	-79.4	-78.6	-78.9
14	-81.5	-78.1	-79.6
15	-81.2	-77.8	-79.5
16	-78.5	-78.2	-78.3
17	-78.9	-76.7	-77.5
18	-78.6	-76.5	-77.3
19	-78.2	-76.4	-77.3
Overall	**-81.5**	**-75.7**	**-77.9**

TABLE 45: FREEZER F EMPTY CHAMBER RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-77.4	-76.6	-76.9
2	-77.7	-76.9	-77.3
3	-71.6	-70.9	-71.2
4	-70.7	-69.9	-70.2
5	-70.0	-69.1	-69.5
6	-82.0	-81.0	-81.5
7	-78.5	-77.7	-78.0
8	-76.6	-75.8	-76.1
9	-84.2	-83.3	-83.7
10	-80.8	-80.0	-80.3
11	-78.9	-78.0	-78.4
12	-85.2	-84.2	-84.7
13	-82.5	-81.6	-82.0
14	-81.8	-80.9	-81.3
15	-86.7	-85.7	-86.1
16	-84.8	-83.8	-84.2
17	-80.8	-79.9	-80.3
18	-79.1	-78.0	-78.4
19	-79.5	-78.2	-78.7
20	-79.2	-78.1	-78.6
21	-77.6	-76.6	-77.0
22	-79.9	-77.4	-78.9
23	-82.9	-82.0	-82.4
Overall	**-86.7**	**-69.1**	**-78.9**

TABLE 46: FREEZER F MAXIMUM LOAD RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-77.4	-76.6	-77.0
2	-77.7	-76.9	-77.3
3	-71.6	-70.9	-71.3
4	-70.6	-69.9	-70.3
5	-70.0	-69.2	-69.6
6	-81.9	-81.0	-81.5
7	-78.4	-77.7	-78.1
8	-76.5	-75.8	-76.2
9	-84.2	-83.3	-83.7
10	-80.7	-80.0	-80.4
11	-78.8	-78.0	-78.4
12	-85.2	-84.2	-84.7
13	-82.4	-81.6	-82.0
14	-81.8	-80.9	-81.4
15	-86.8	-85.6	-86.2
16	-84.7	-83.8	-84.2
17	-80.8	-79.9	-80.3
18	-78.8	-77.8	-78.3
19	-79.4	-78.2	-78.7
20	-79.2	-78.0	-78.6
21	-77.4	-76.4	-76.9
22	-79.8	-77.2	-78.8
23	-82.9	-82.0	-82.5
Overall	**-86.8**	**-69.2**	**-79.0**

TABLE 47: FREEZER G EMPTY CHAMBER RUN

TC	MINIMUM (°C)	MAXIMUM (°C)	AVERAGE (°C)
1	-76.6	-74.1	-75.4
3	-76.5	-74.5	-75.6
4	-76.7	-74.3	-75.5
5	-76.6	-75.2	-75.9
6	-76.1	-74.6	-75.3
7	-78.3	-76.6	-77.4
8	-78.1	-76.3	-77.2
9	-77.9	-76.0	-76.9
10	-78.6	-76.9	-77.7
11	-78.5	-76.9	-77.6
12	-78.4	-76.8	-77.5
13	-77.2	-75.4	-76.2
14	-77.5	-75.8	-76.6
15	-76.4	-75.1	-75.6
16	-76.3	-74.7	-75.4
17	-76.6	-74.7	-75.6
18	-76.8	-75.5	-76.1
Overall	**-78.6**	**-74.1**	**-76.3**

Table 48: Freezer G Maximum Load Run

TC	Minimum (°C)	Maximum (°C)	Average (°C)
1	-68.4	-66.1	-67.9
3	-72.6	-70.5	-72.2
4	-69.3	-65.6	-68.6
5	-73.6	-71.6	-73.1
6	-69.6	-67.2	-69.1
7	-75.2	-72.9	-74.7
8	-73.2	-68.6	-72.3
9	-72.5	-70.0	-72.0
10	-77.3	-75.7	-76.9
11	-75.9	-72.2	-75.2
12	-76.2	-74.1	-75.8
13	-74.5	-73.5	-73.9
14	-71.4	-70.8	-71.0
15	-70.5	-68.8	-70.1
16	-74.8	-73.9	-74.4
17	-69.5	-68.0	-68.7
18	-70.7	-70.0	-70.5
Overall	**-77.3**	**-65.6**	**-72.1**

Appendix C: ULT Freezer Energy Consumption – Standardized Field Test

ULT Energy Consumption Charts at -80°C

Below are the week-long charts showing energy consumption of Freezers A-G at -80°C and -70°C. Note that the end-of-the-week readings seen for Freezer A appear different because the freezer was tested first at -70°C and then at -80°C, as opposed to the other way around, like the rest of the ULT freezers. Due to technical difficulties with the energy meter for Freezer C it was not possible to obtain energy data over the same time frame for that freezer.

Figure 113: Freezer A Energy Consumption with Door Openings at -80°C

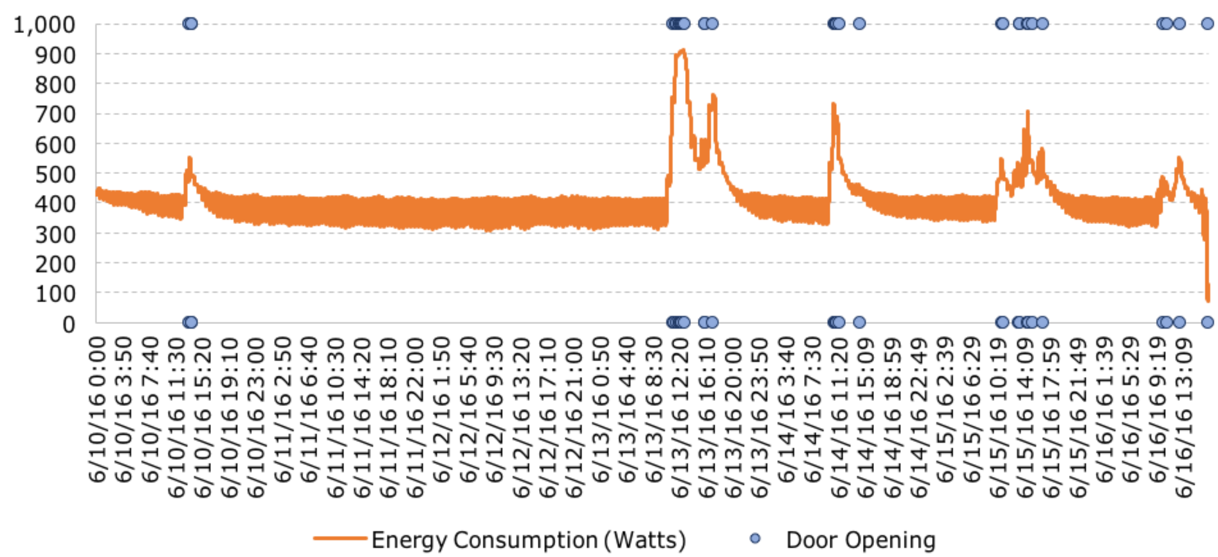


FIGURE 114: FREEZER B ENERGY CONSUMPTION WITH DOOR OPENINGS AT -80°C

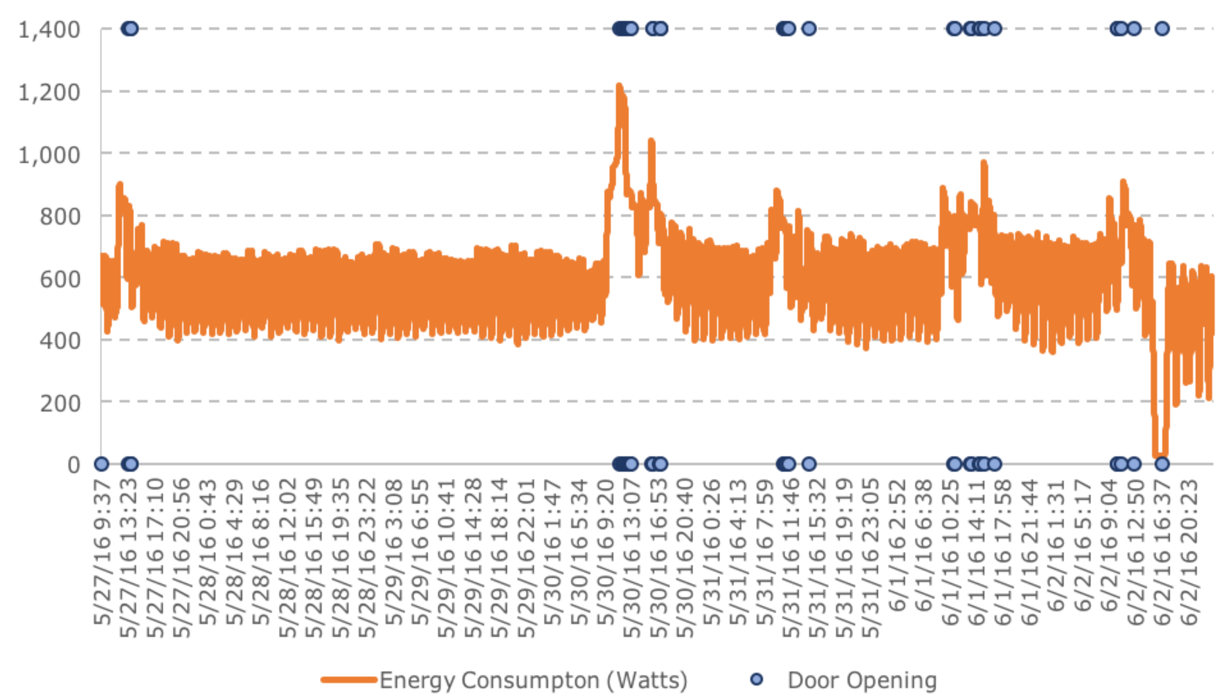


FIGURE 115: FREEZER D ENERGY CONSUMPTION WITH DOOR OPENINGS AT -80°C

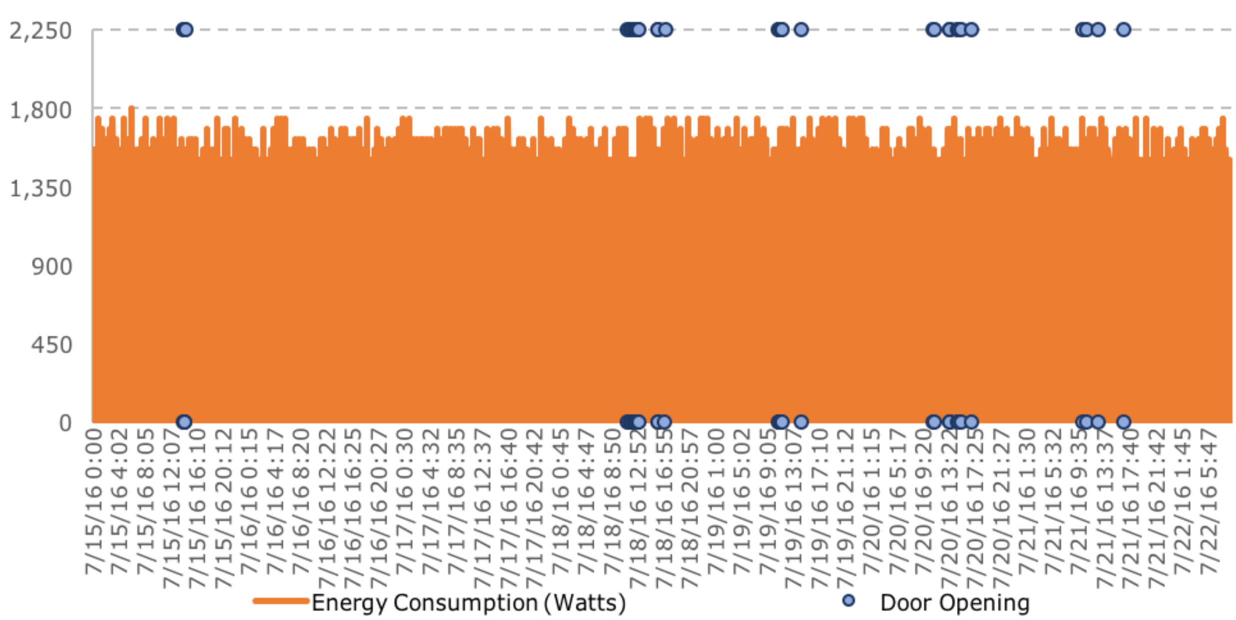


FIGURE 116: FREEZER E ENERGY CONSUMPTION WITH DOOR OPENINGS AT -80°C

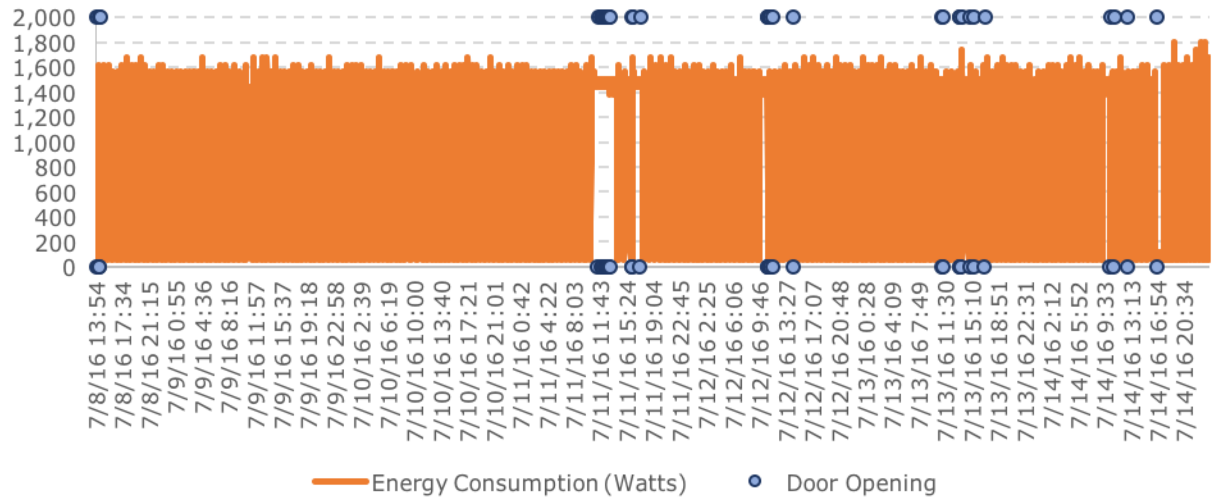


FIGURE 117: FREEZER F ENERGY CONSUMPTION WITH DOOR OPENINGS AT -80°C

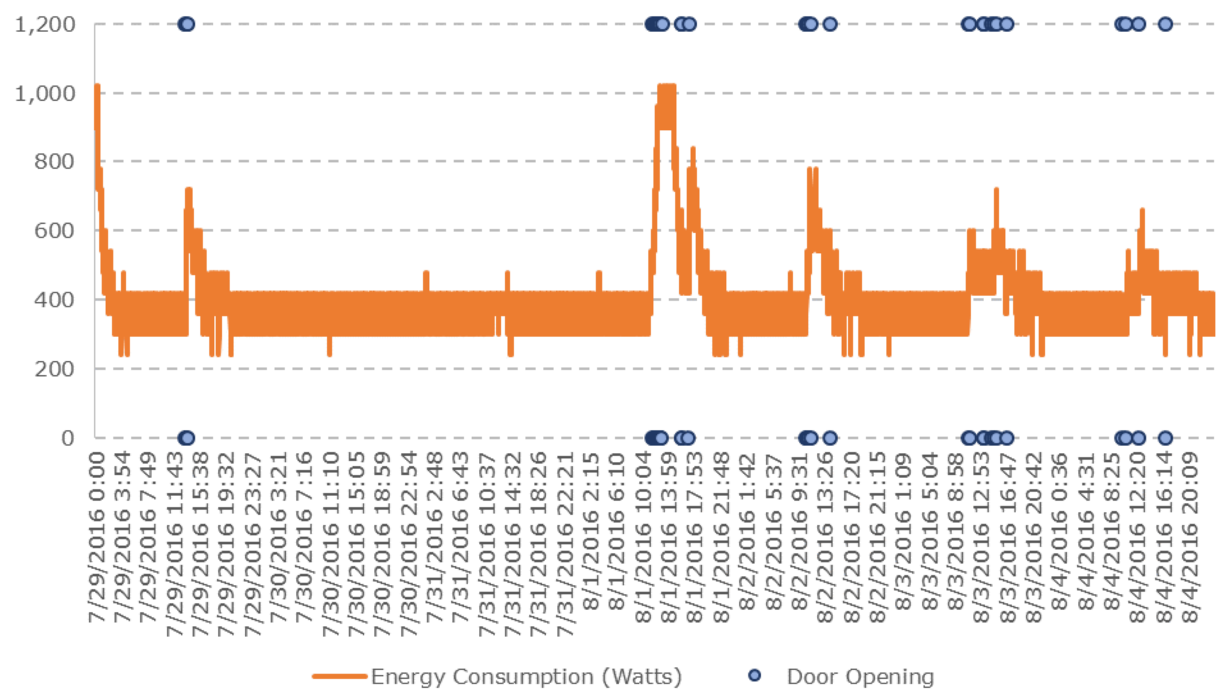


FIGURE 118: FREEZER G ENERGY CONSUMPTION WITH DOOR OPENINGS AT -80°C

ULT Energy Consumption Charts at -70°C

Figure 119: Freezer A Energy Consumption with Door Openings at -70°C

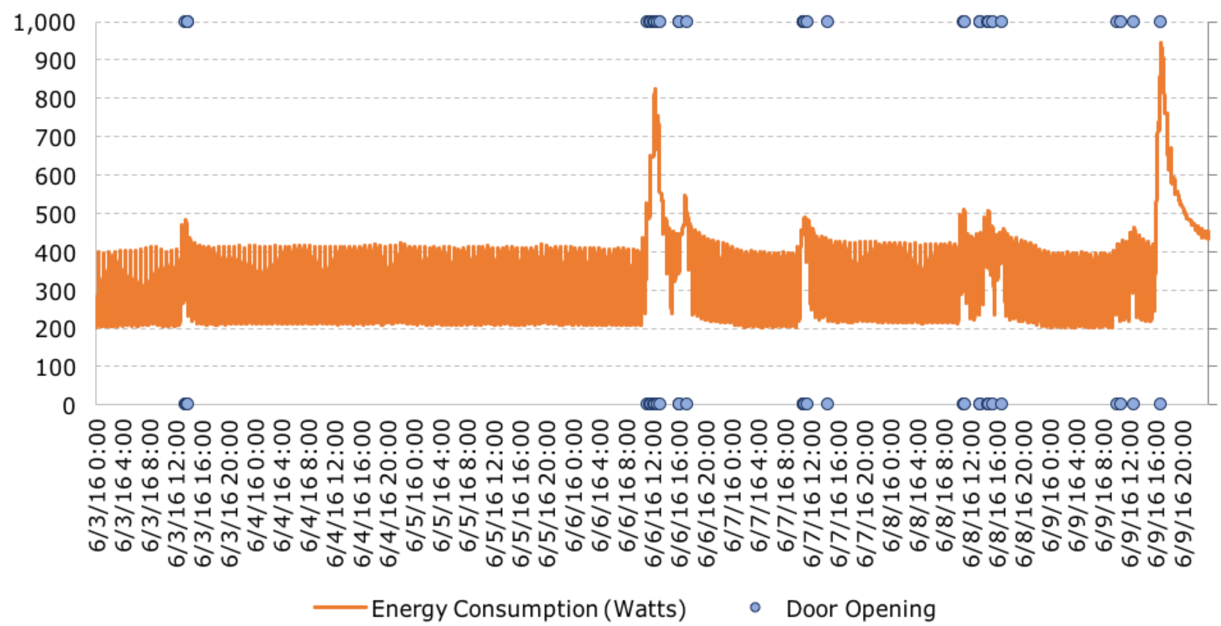


Figure 120: Freezer B Energy Consumption with Door Openings at -70°C

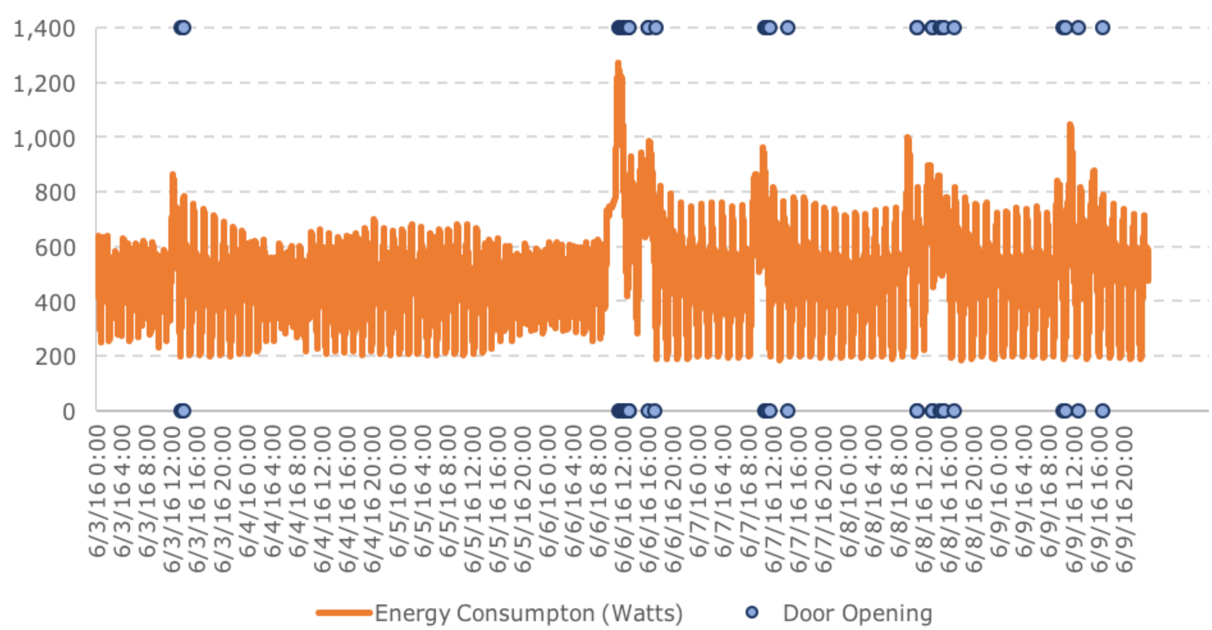


FIGURE 121: FREEZER D ENERGY CONSUMPTION WITH DOOR OPENINGS AT -70°C

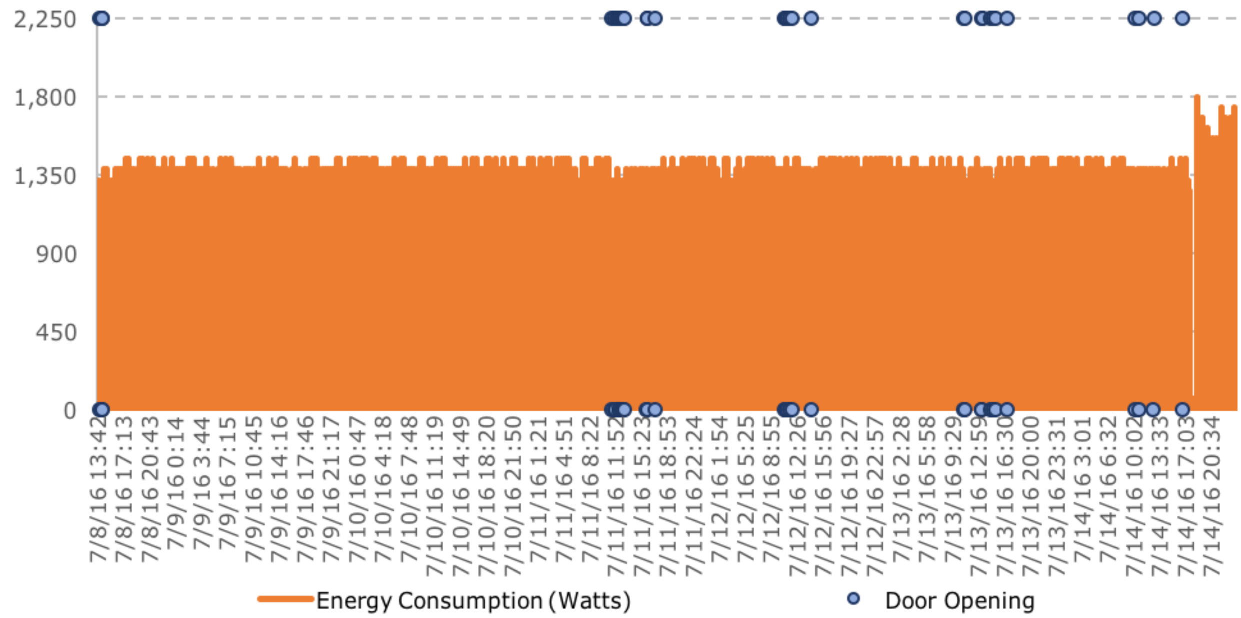


FIGURE 122: FREEZER E ENERGY CONSUMPTION WITH DOOR OPENINGS AT -70°C

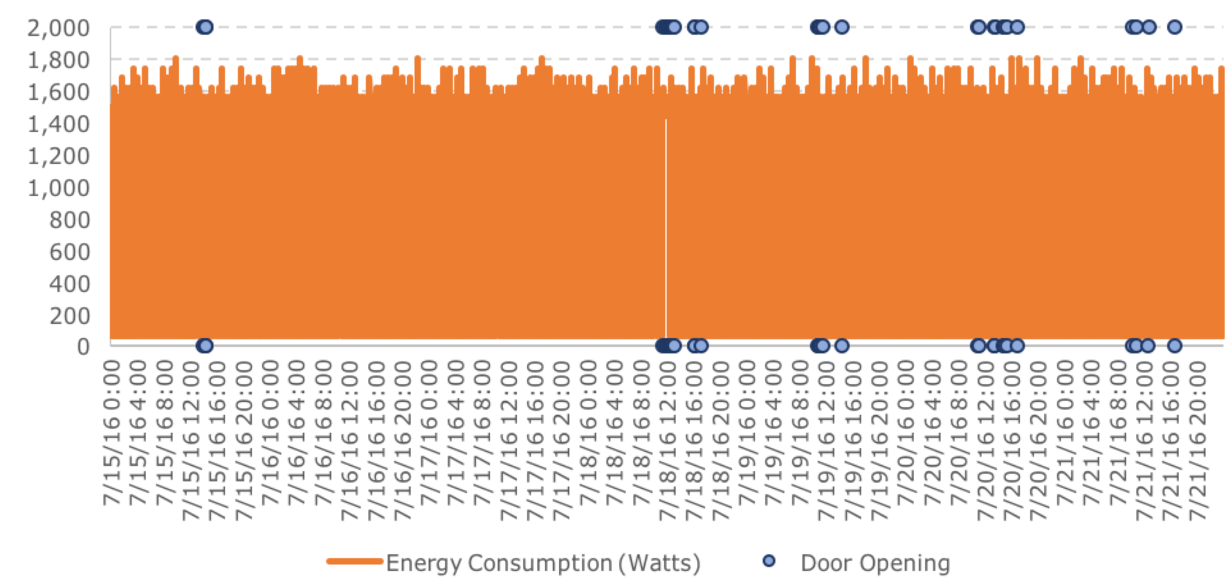


FIGURE 123: FREEZER F ENERGY CONSUMPTION WITH DOOR OPENINGS AT -70°C

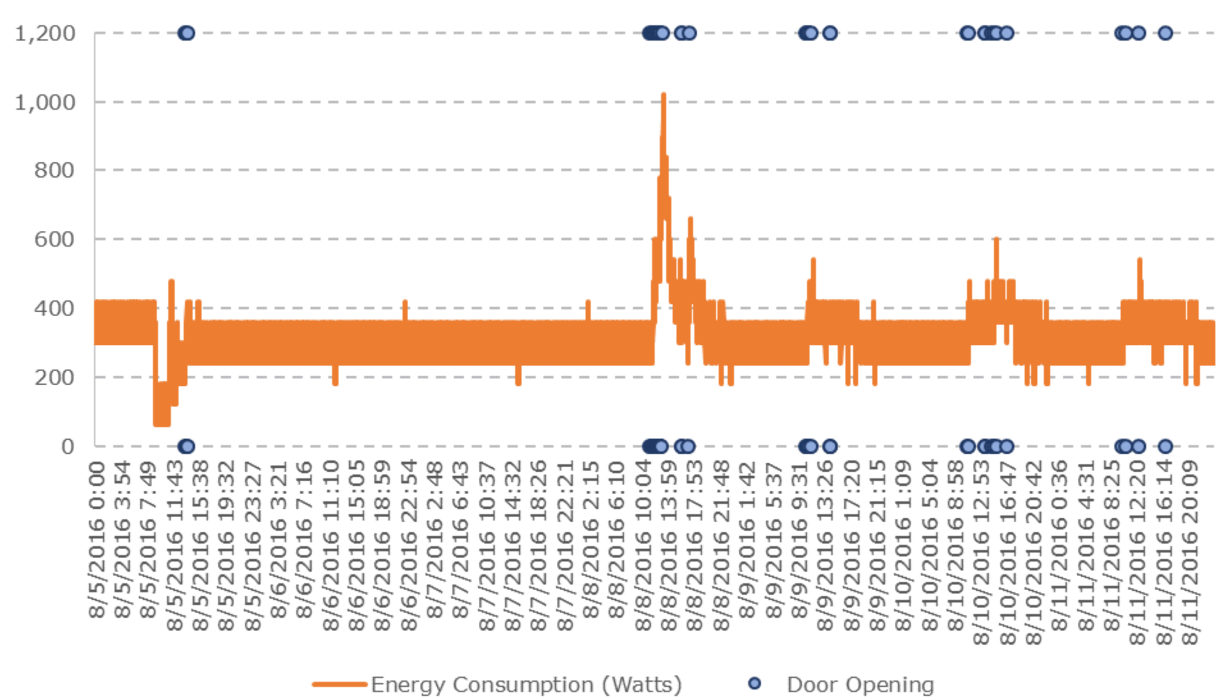
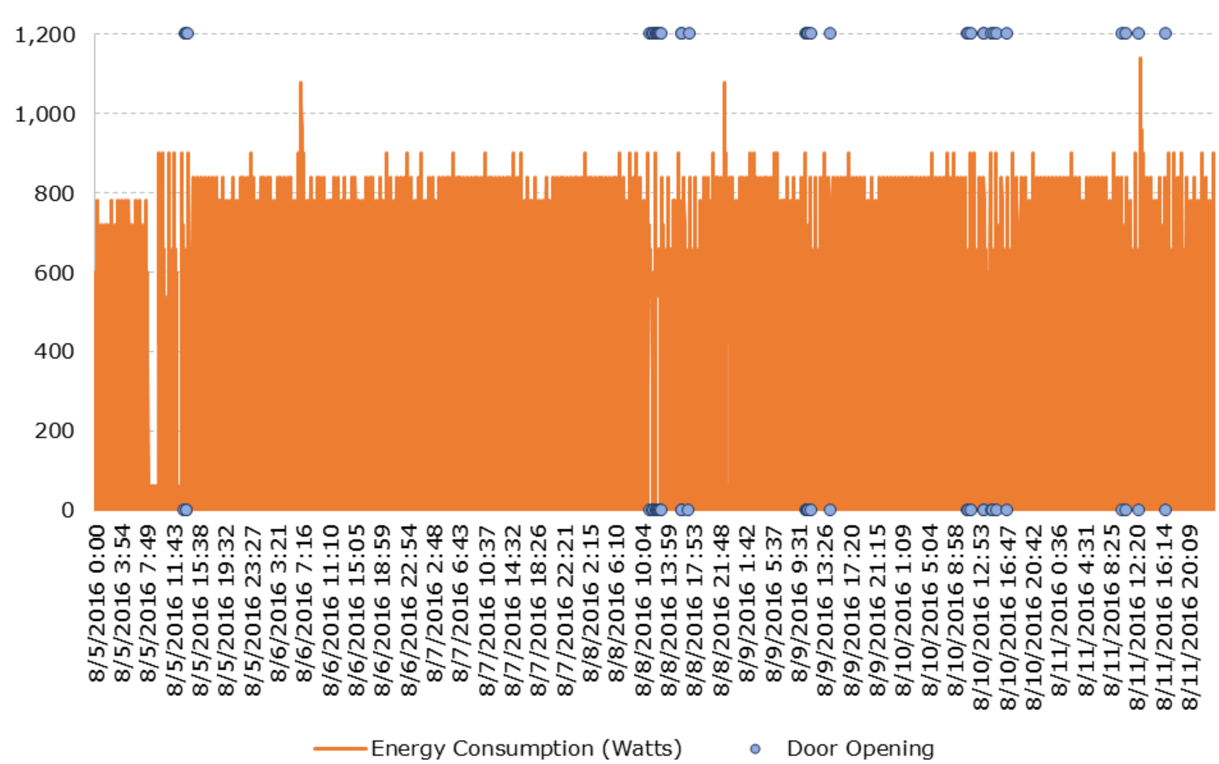


FIGURE 124: FREEZER G ENERGY CONSUMPTION WITH DOOR OPENINGS AT -70°C



ULT Freezer Energy Consumption By Day

In an effort to explore the effect of door openings on energy consumption more closely, energy data from Tuesday and Thursday door openings were examined. Those data are shown below. These days were chosen because the door opening schedules for the two days were very different. The Tuesday door opening schedule had quite a few door openings with very little space between them in the morning, followed by one door opening in the afternoon, and the Thursday door opening schedule consisted of several relatively evenly-spaced door openings throughout the day.

It was found that Freezer A responded for a longer time at -80°C than at -70°C to maintain temperature in the wake of the Tuesday and Thursday door opening schedule. At -80°C Freezer A energy consumption peaked at over 700W, and averaged 400-500W, and at -70°C energy consumption peaked at 500W, and averaged somewhat lower, around 300W.

Figure 125: Freezer A Energy Consumption, Tuesday Door Openings at -80°C

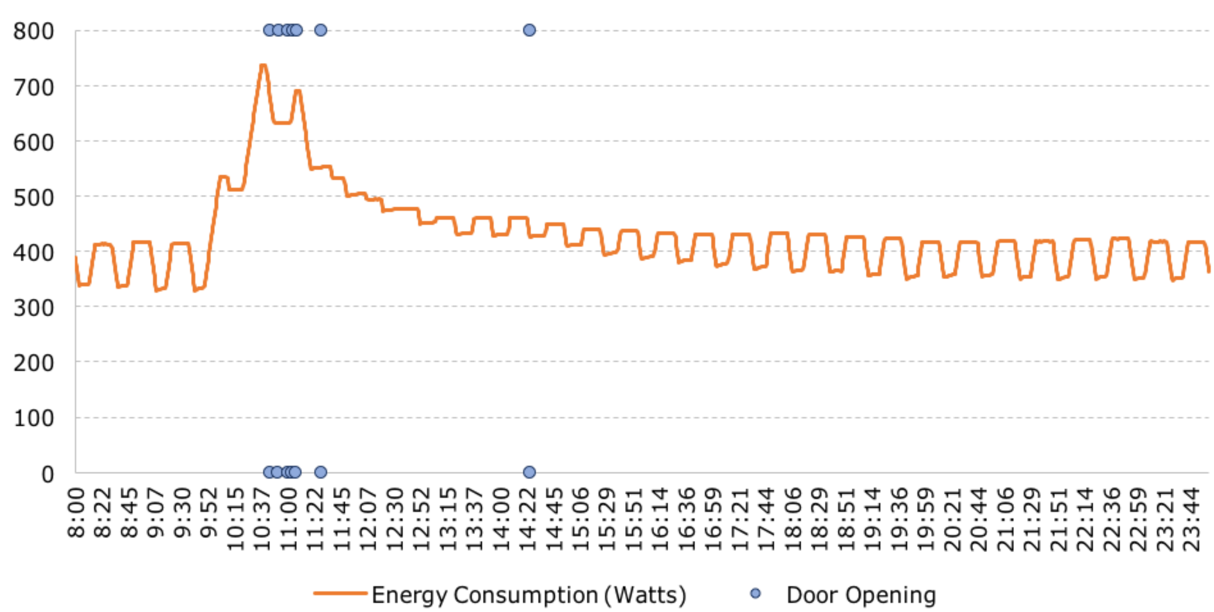


FIGURE 126: FREEZER A ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -70°C

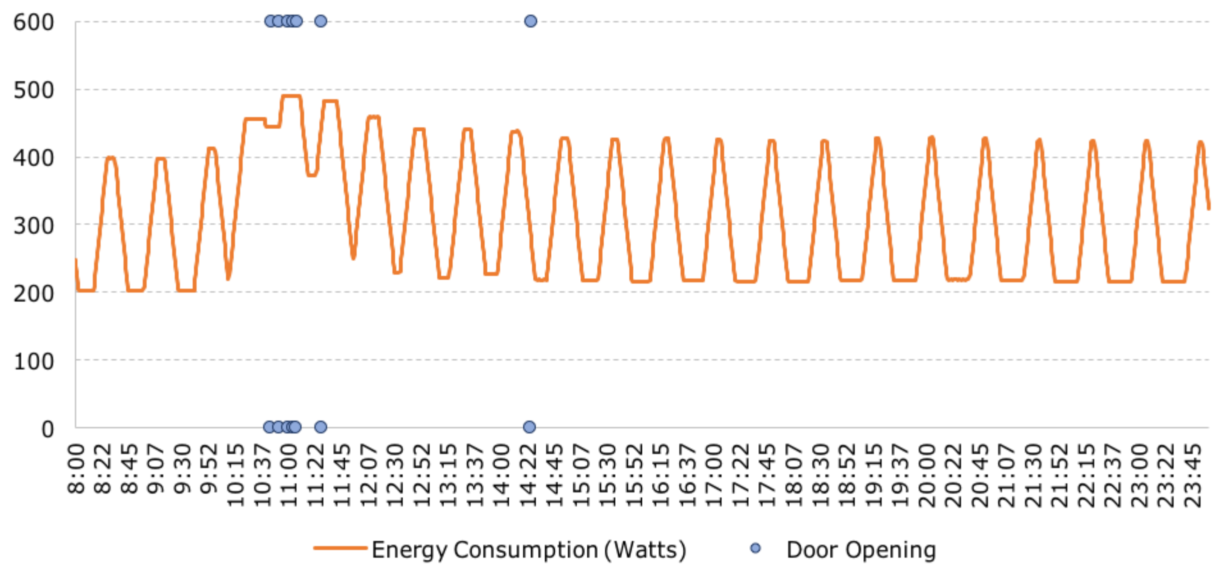


FIGURE 127: FREEZER A ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -80°C

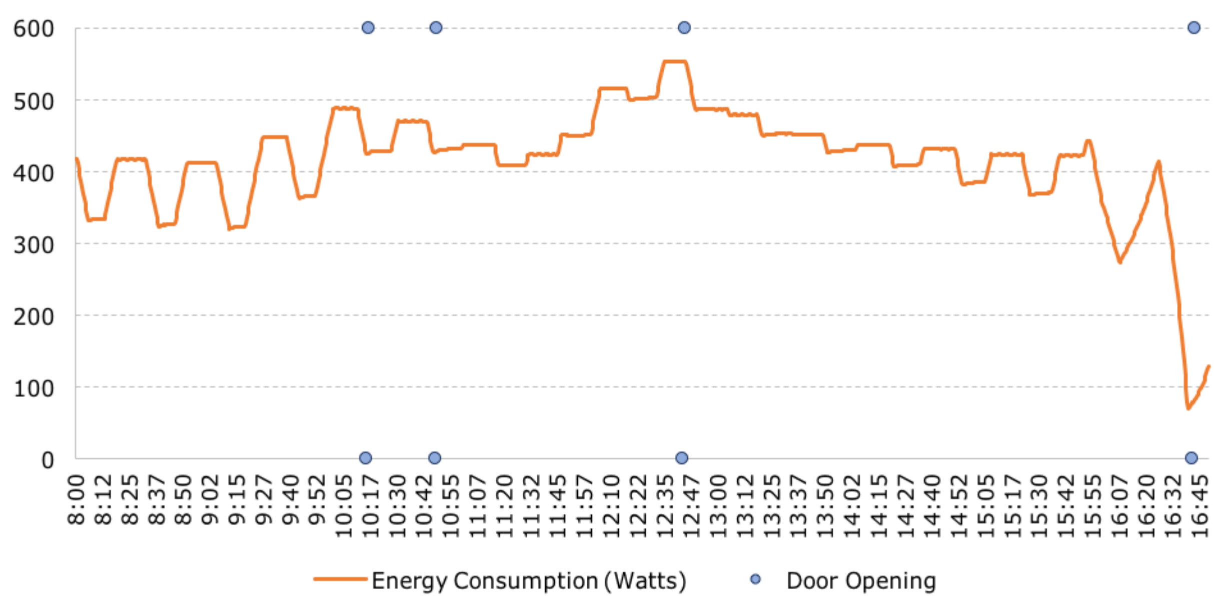
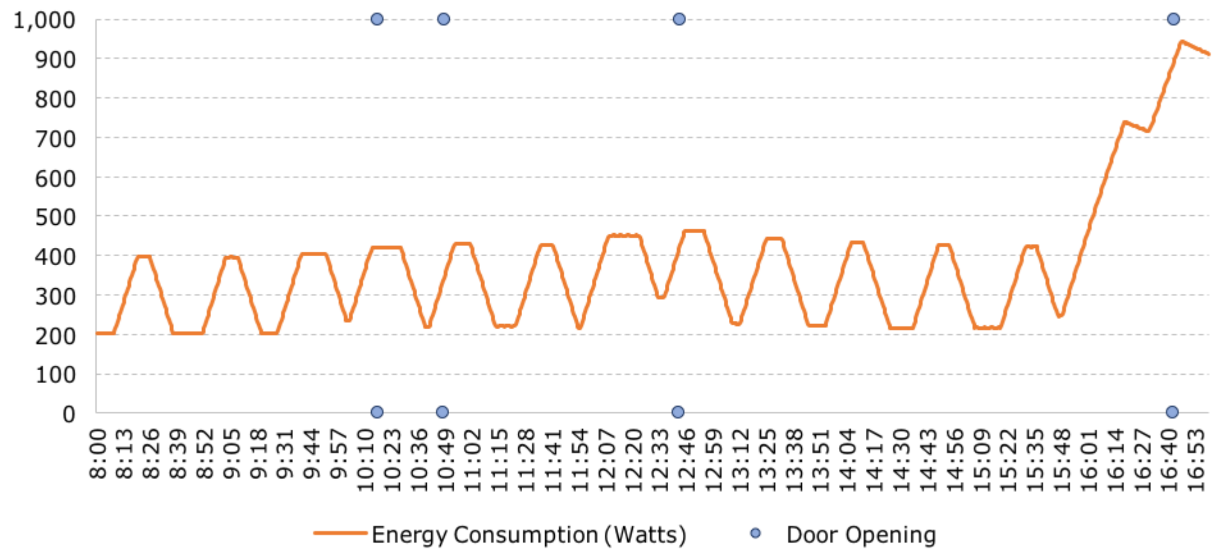


FIGURE 128: FREEZER A ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -70°C



Note the Thursday readings seen for Freezer A appear different because the freezer was tested first at -70°C and then at -80°C, as opposed to the other way around, like the rest of the ULT freezers in the study.

Freezer B also appeared to have a more difficult time stabilizing at -80°C than at -70°C. Maximum energy consumption was higher at -70°C for Freezer B than at -80°C, but the average energy consumption was lower at -70◦C.

FIGURE 129: FREEZER B ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -80°C

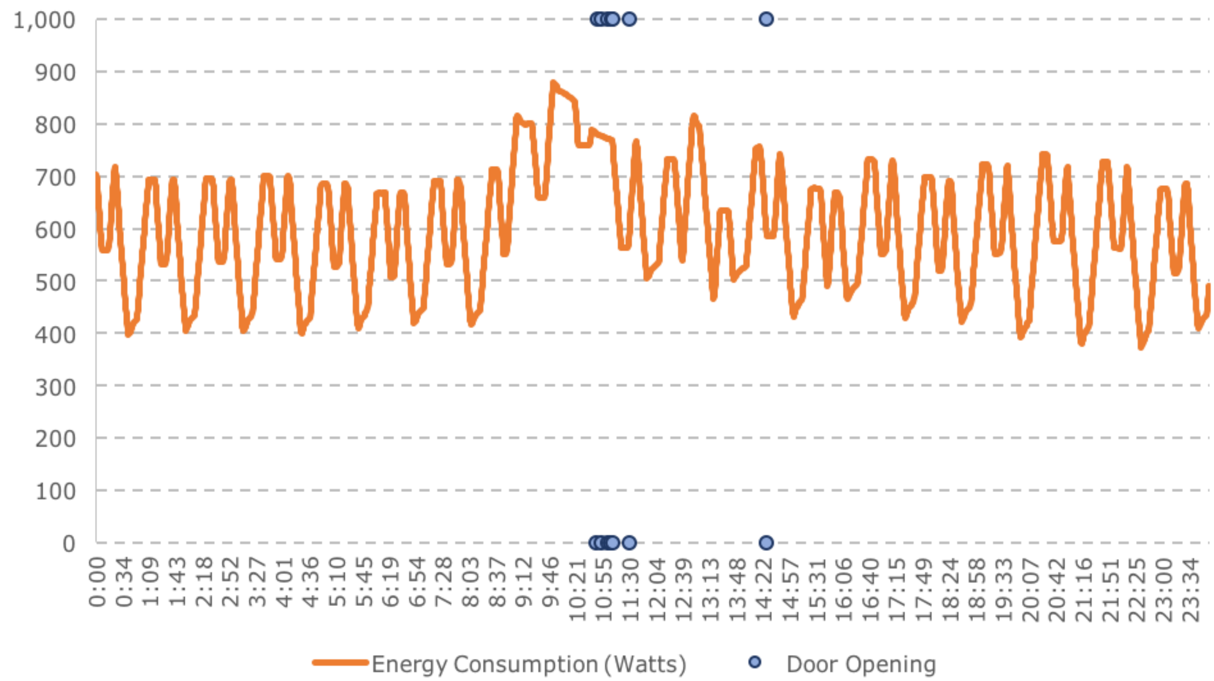


FIGURE 130: FREEZER B ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -70°C

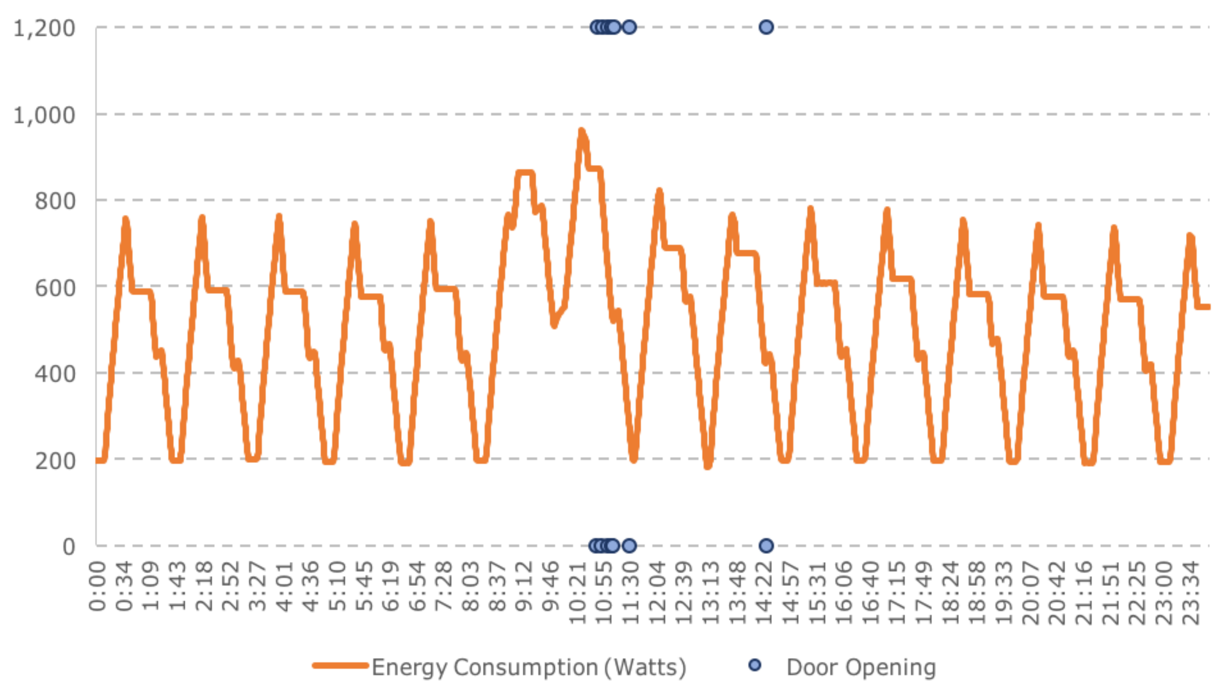


FIGURE 131: FREEZER B ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -80°C

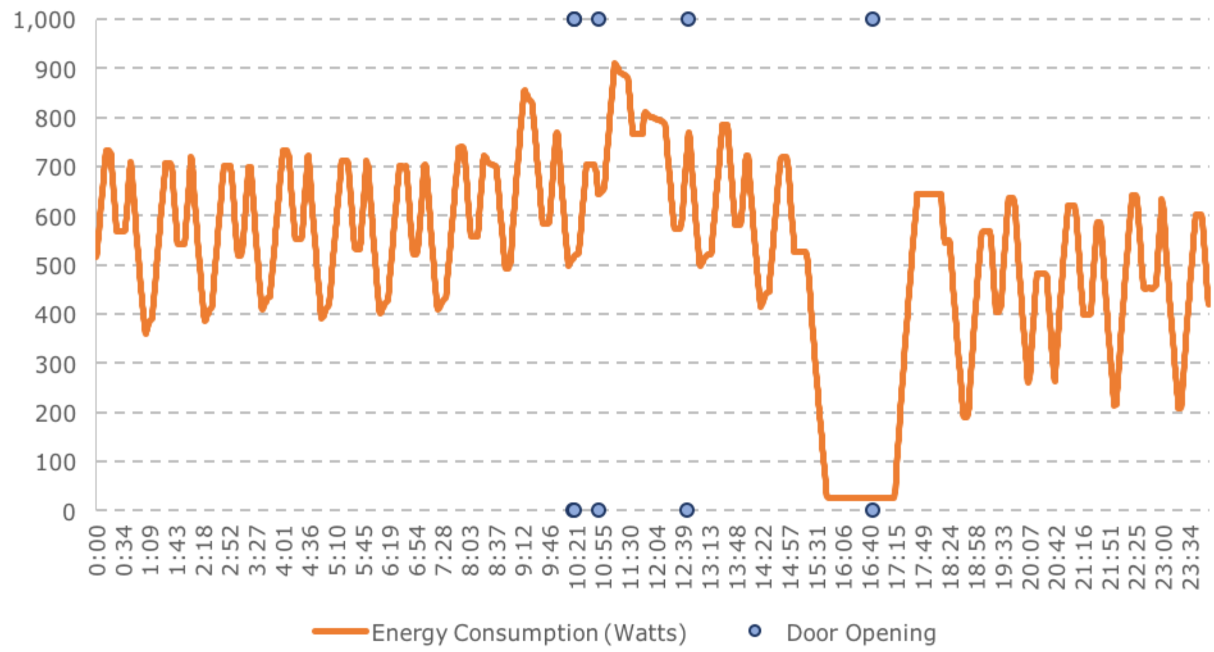
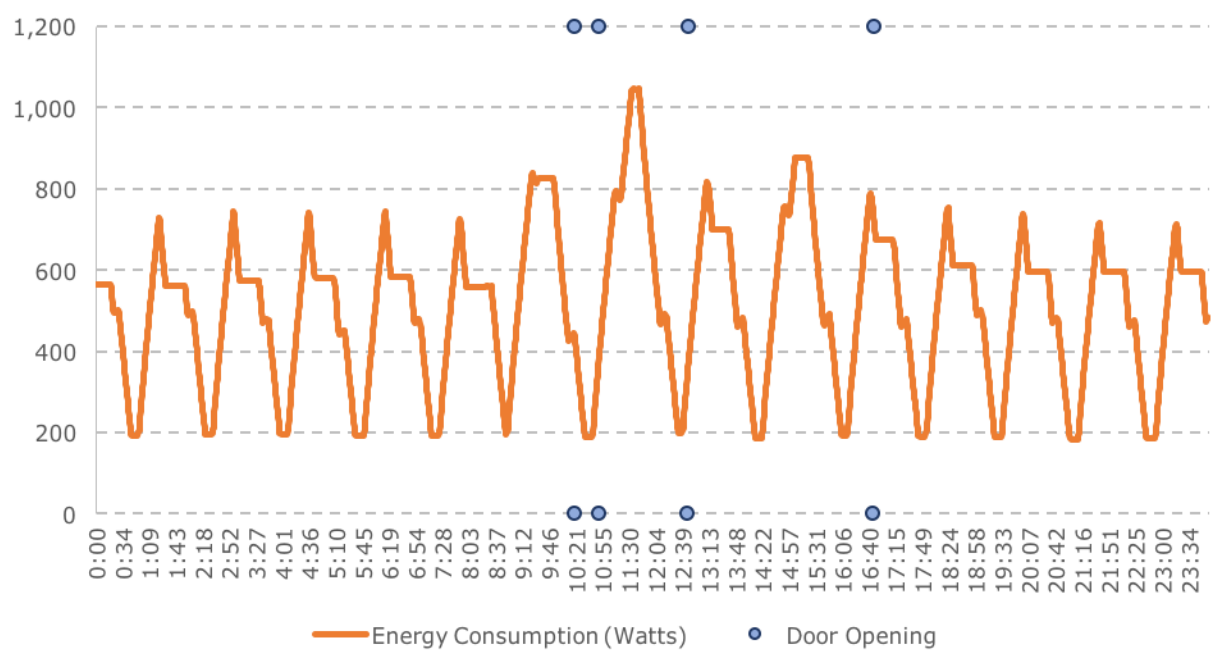


FIGURE 132: FREEZER B ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -70°C



Comparable energy consumption versus door opening graphs were not obtained for Freezer C. The door sensor fell off during the field study, and equipment was unavailable to repeat the study in full. The data below come from a smaller, one-week version of the study in which the door was opened according to the Monday door opening schedule at both -80°C and -70°C.

Freezer C displayed a maximum energy consumption of ~1400W at -80°C and ~1600W at -70°C. Notably, Freezer C was one of only two ULT freezers whose energy consumption reached 0W during the study.

FIGURE 133: FREEZER C ENERGY CONSUMPTION, MONDAY DOOR OPENINGS AT -80°C

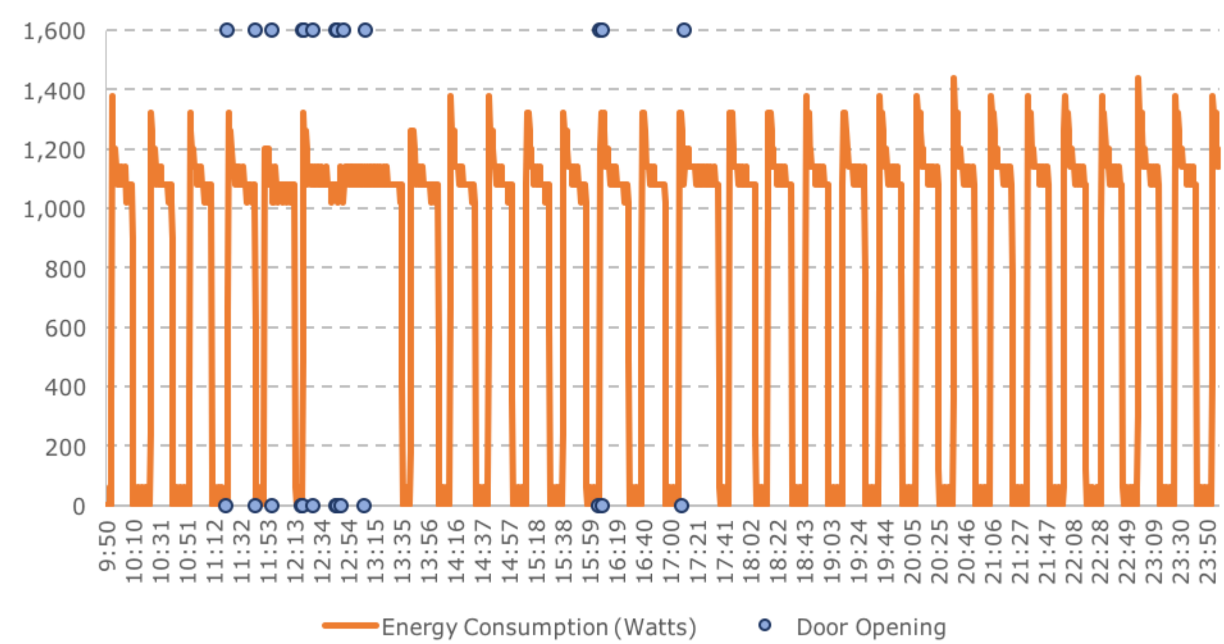
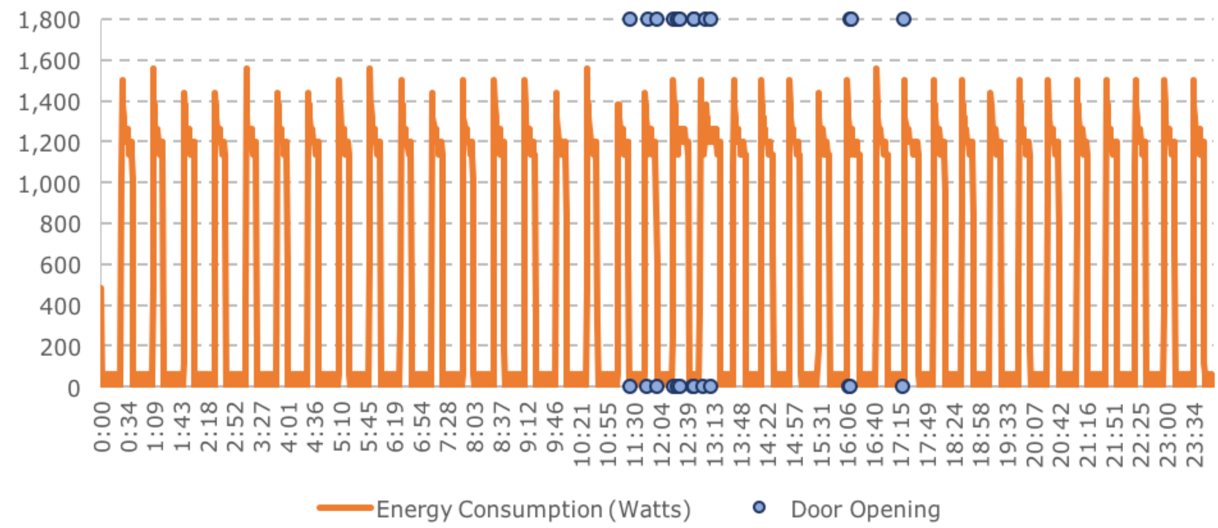


FIGURE 134: FREEZER C ENERGY CONSUMPTION, MONDAY DOOR OPENINGS AT -70°C



In contrast to Freezers A and B, Freezer D appeared relatively unaffected by the door openings in most cases, with -80°C on Thursday being the notable exception.

FIGURE 135: FREEZER D ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -80°C

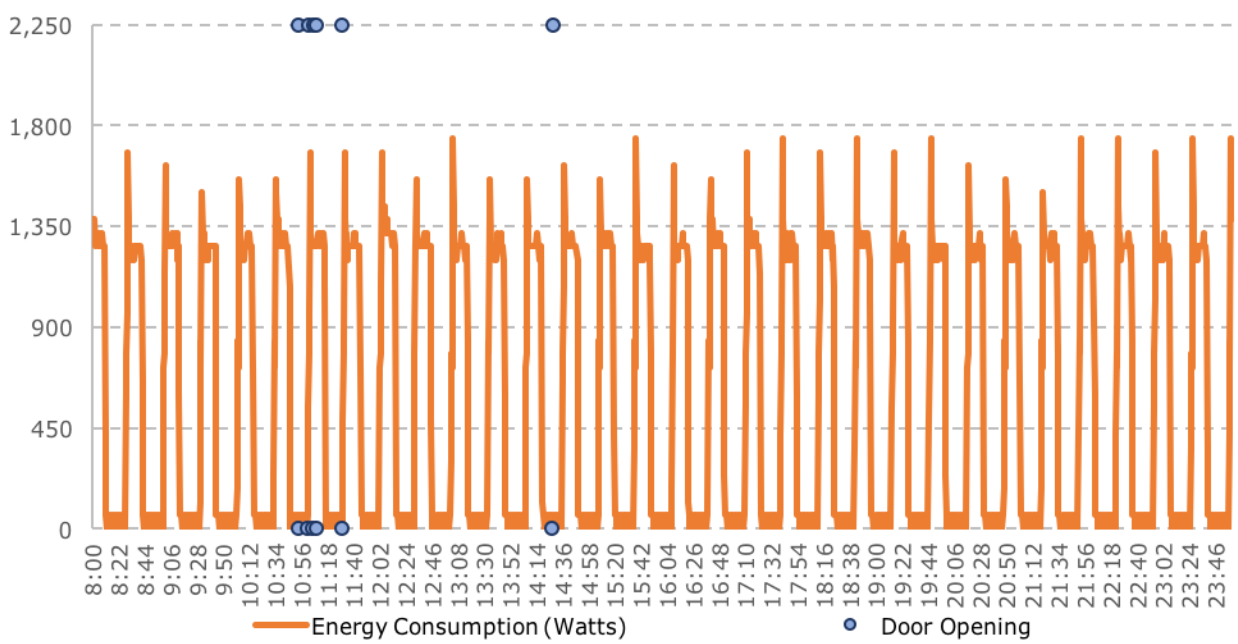


FIGURE 136: FREEZER D ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -70°C

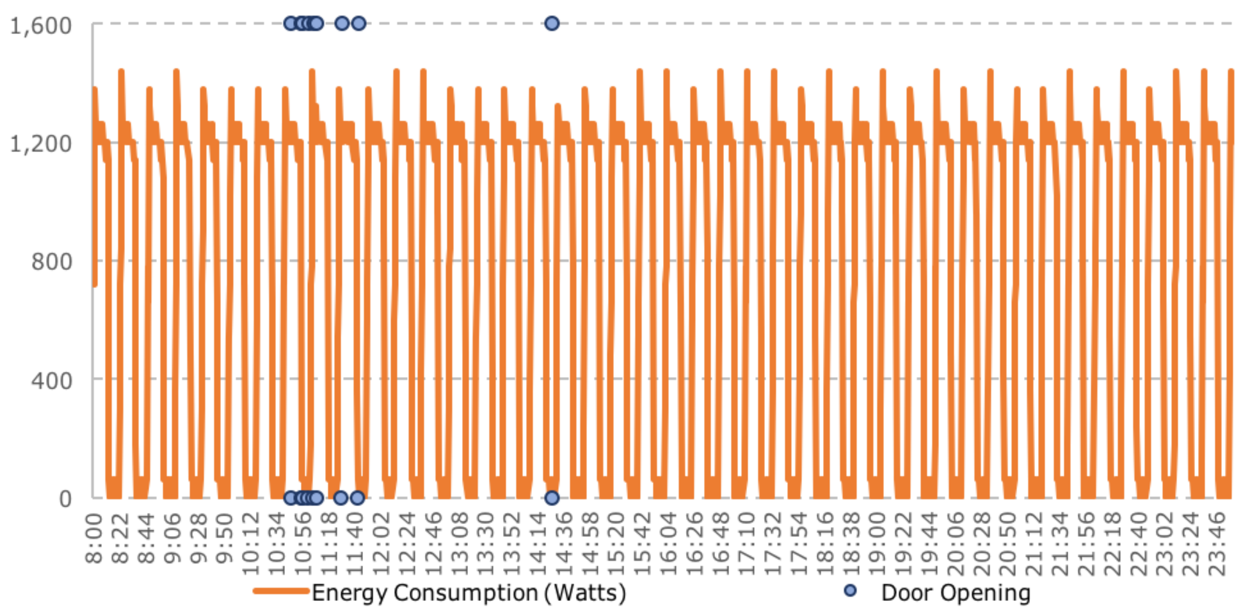


FIGURE 137: FREEZER D ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -80°C

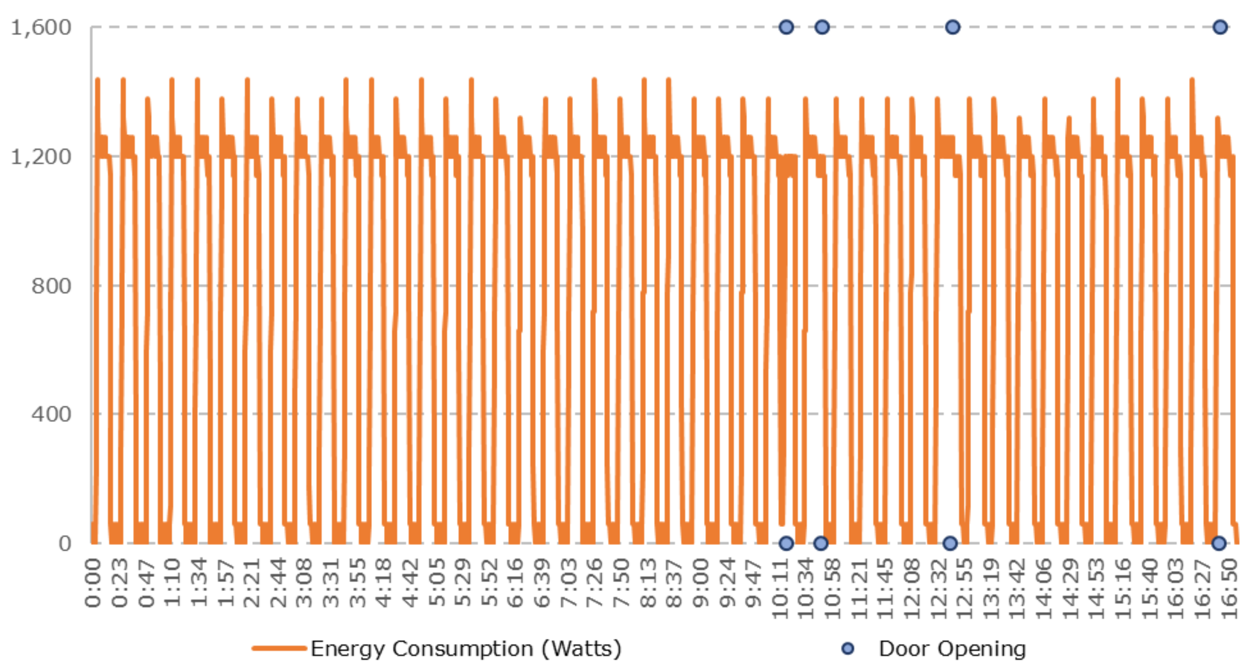
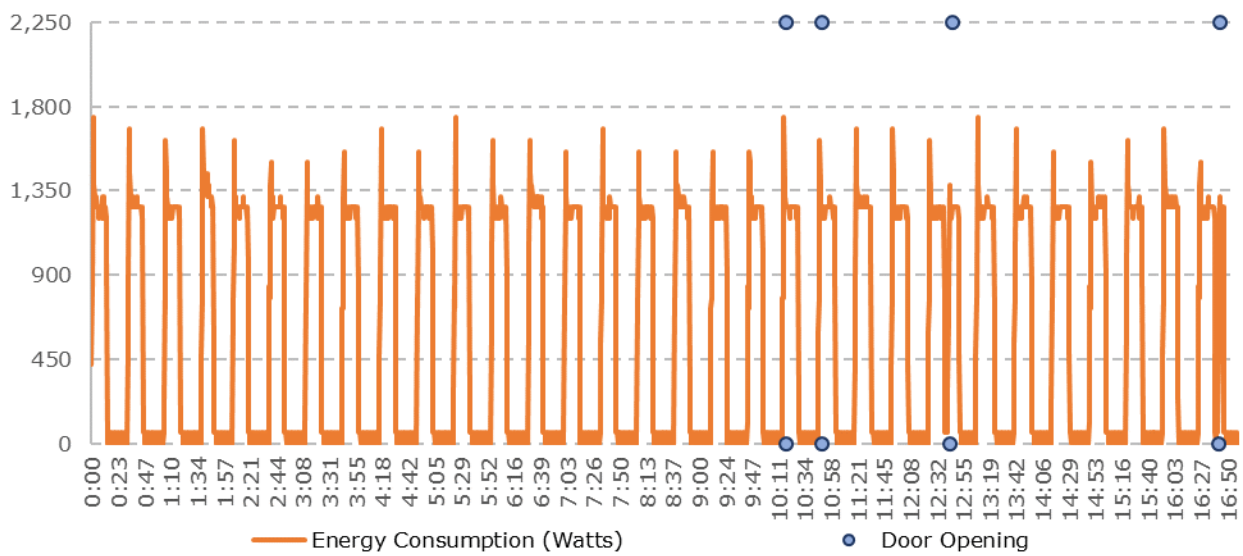


FIGURE 138: FREEZER D ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -70°C



Although Freezer E was more affected by the door opening schedule at -80°C than -70°C, the freezer seemed to recover faster from the door openings than many of the other freezers (compare Freezer A to Freezer E, for example). Freezer E reached a maximum energy consumption of 1800W at both -80°C and -70°C as a result of the Tuesday and Thursday door opening schedule.

FIGURE 139: FREEZER E ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -80°C

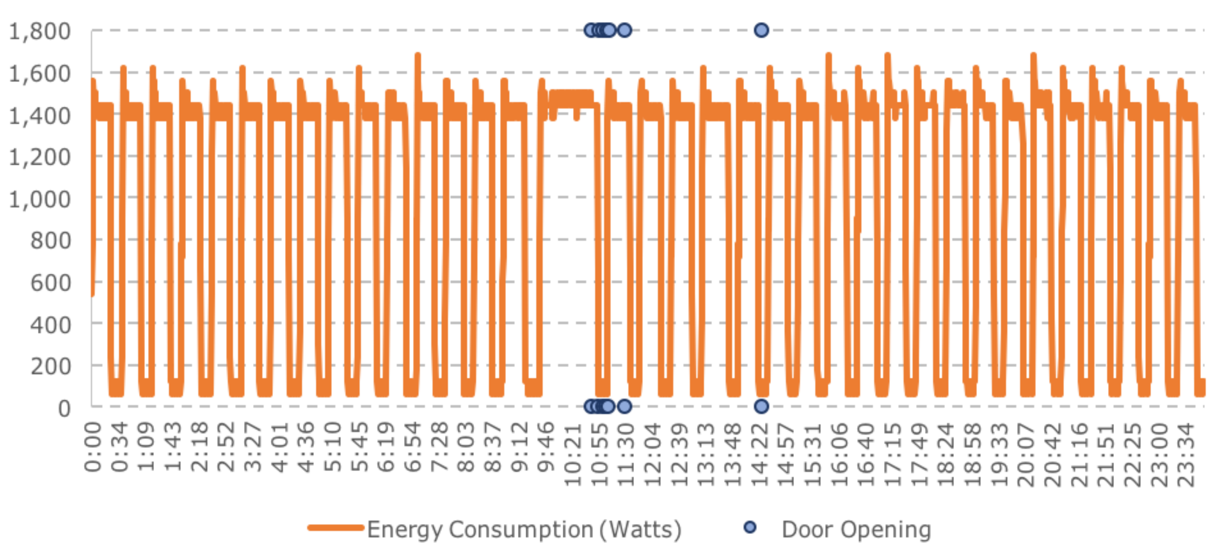


FIGURE 140: FREEZER E ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -70°C

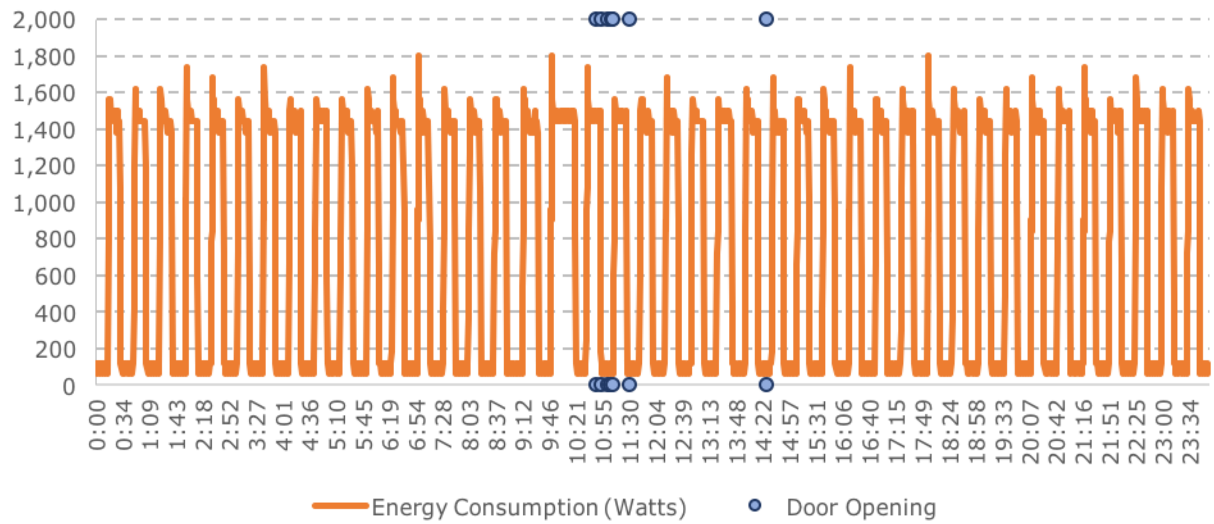


FIGURE 141: FREEZER E ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -80°C

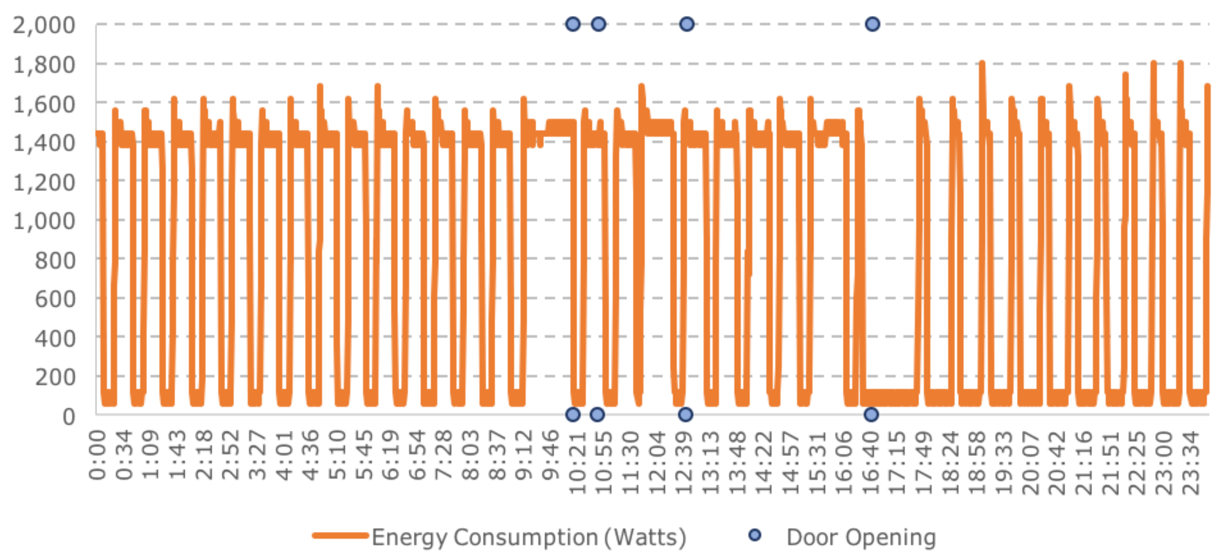
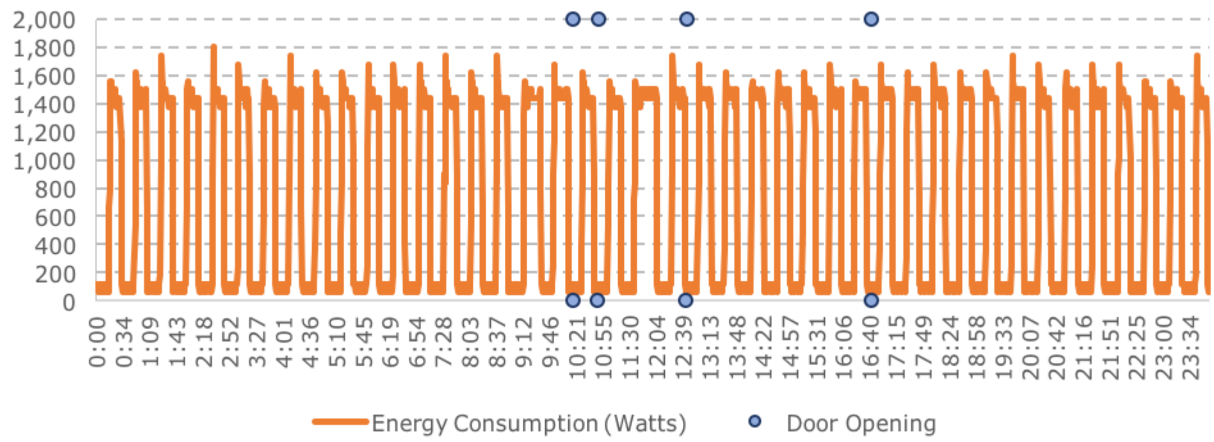


FIGURE 142: FREEZER E ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -70°C



Freezer F's energy consumption increased in direct proportion to the number and duration of door openings. This pattern was unique to this particular ULT freezer.

FIGURE 143: FREEZER F ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -80°C

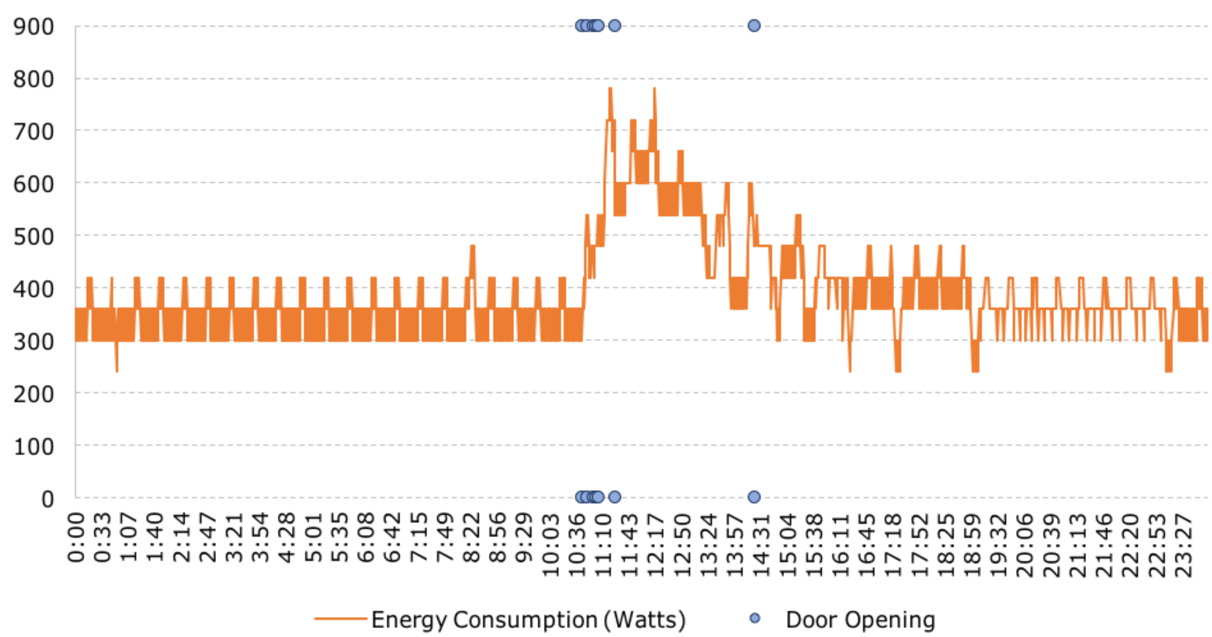


FIGURE 144: FREEZER F ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -70°C

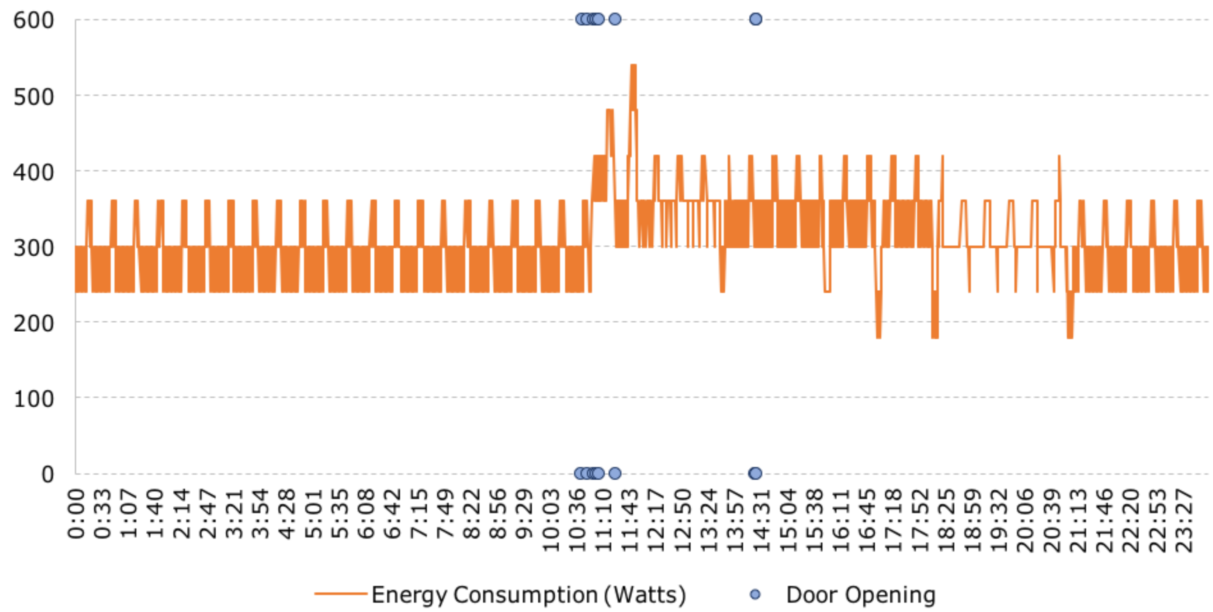


FIGURE 145: FREEZER F ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -80°C

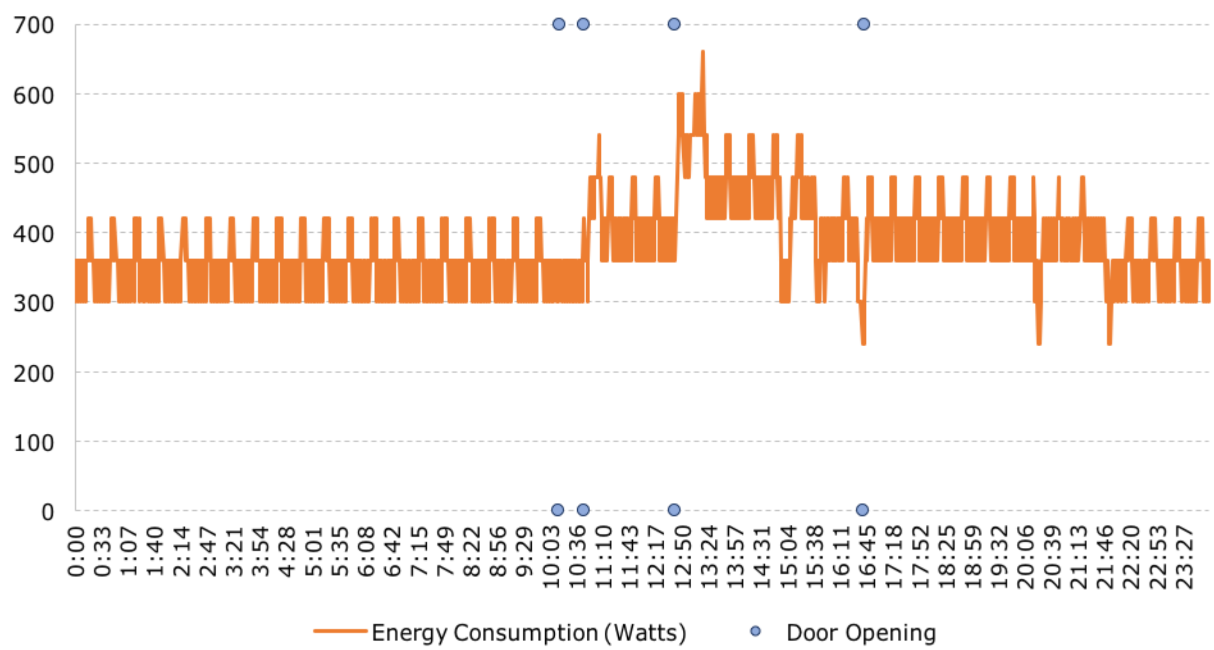
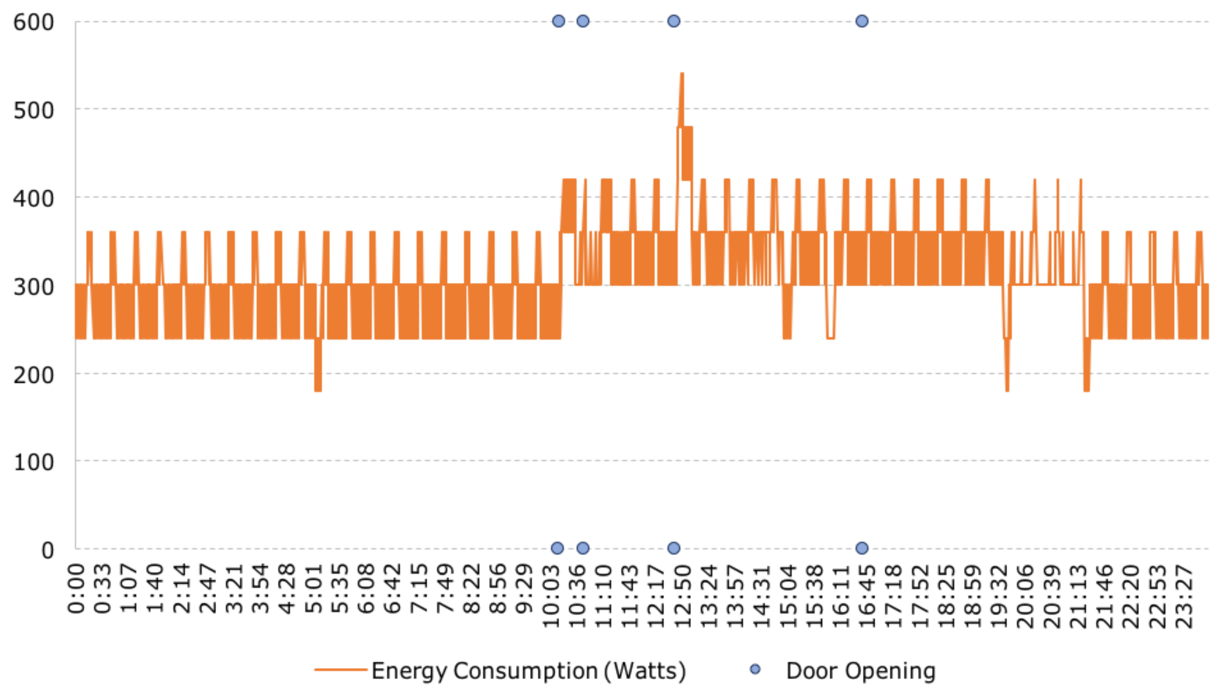


FIGURE 146: FREEZER F ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -70°C



Like Freezer C, Freezer G's energy consumption cycles between 0W and positive values. The energy use of this ULT freezer increases in response to door openings, as seen in the figures below.

FIGURE 147: FREEZER G ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -80°C

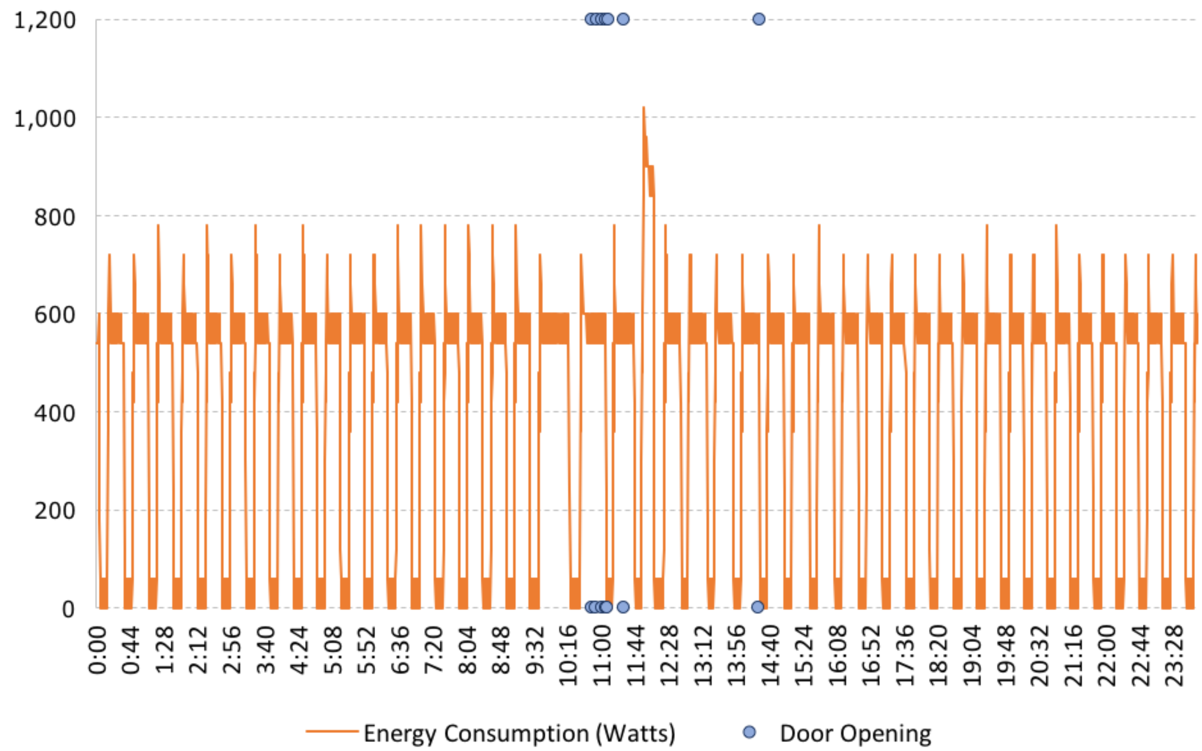


FIGURE 148: FREEZER G ENERGY CONSUMPTION, TUESDAY DOOR OPENINGS AT -70°C

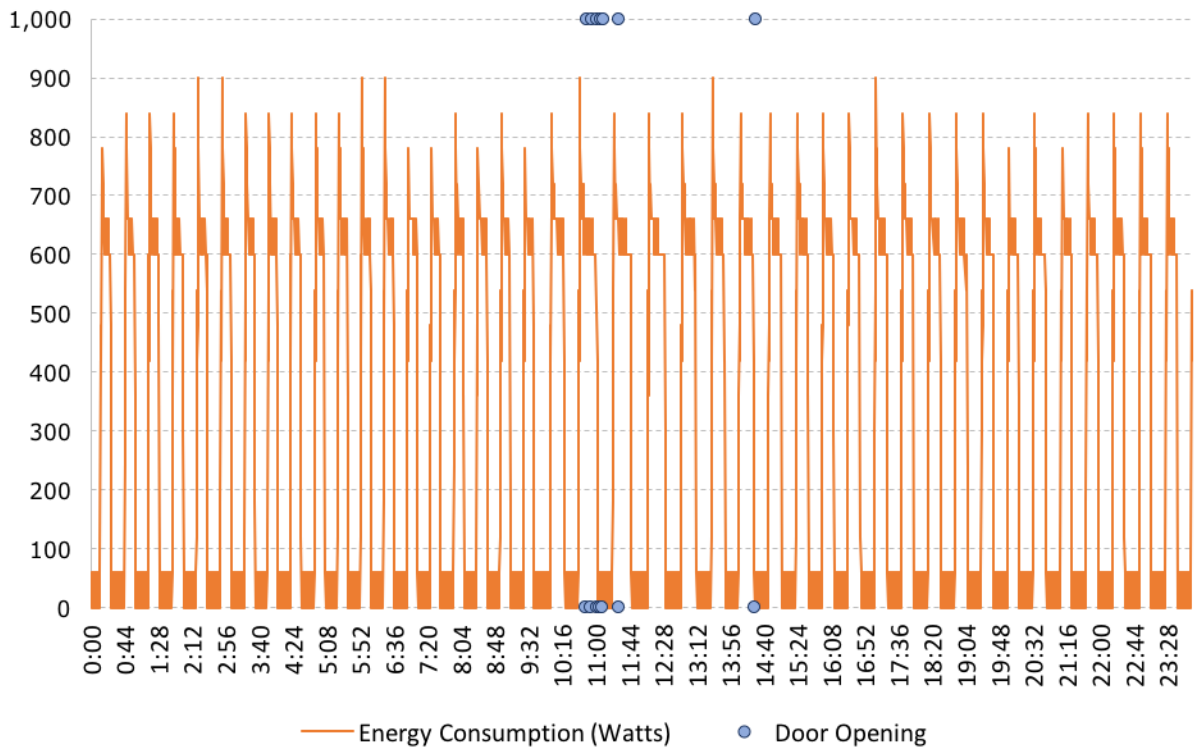


FIGURE 149: FREEZER G ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -80°C

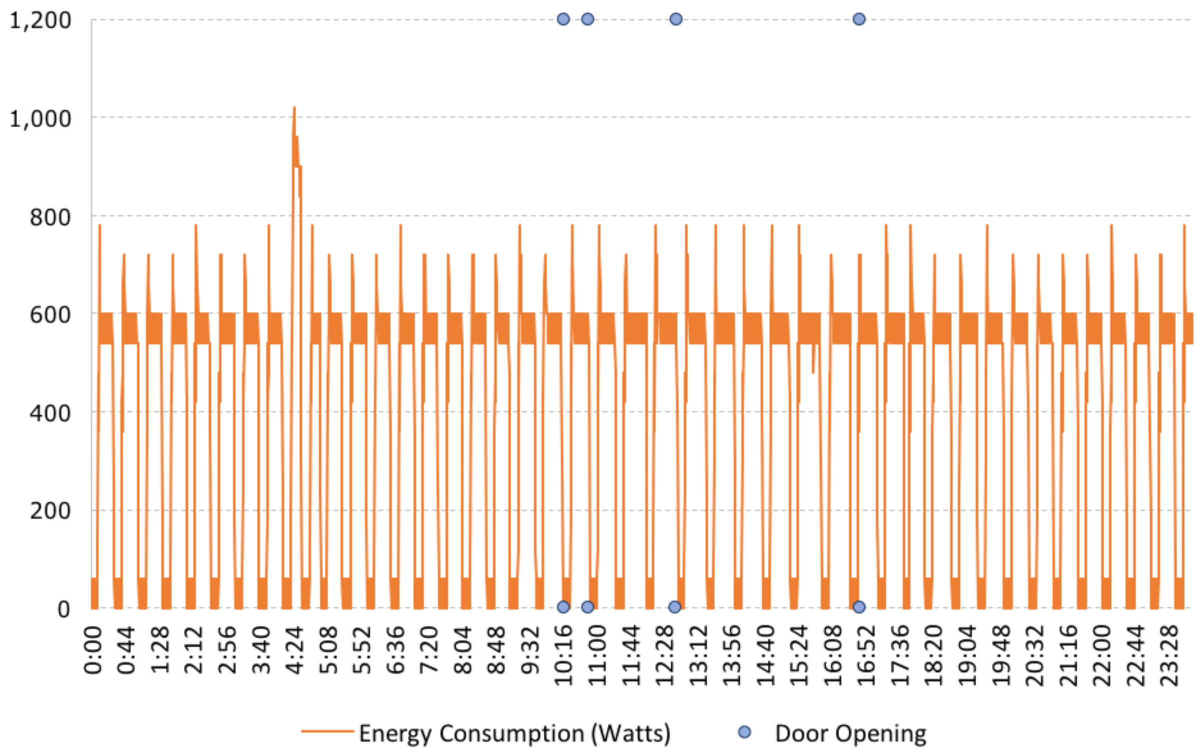
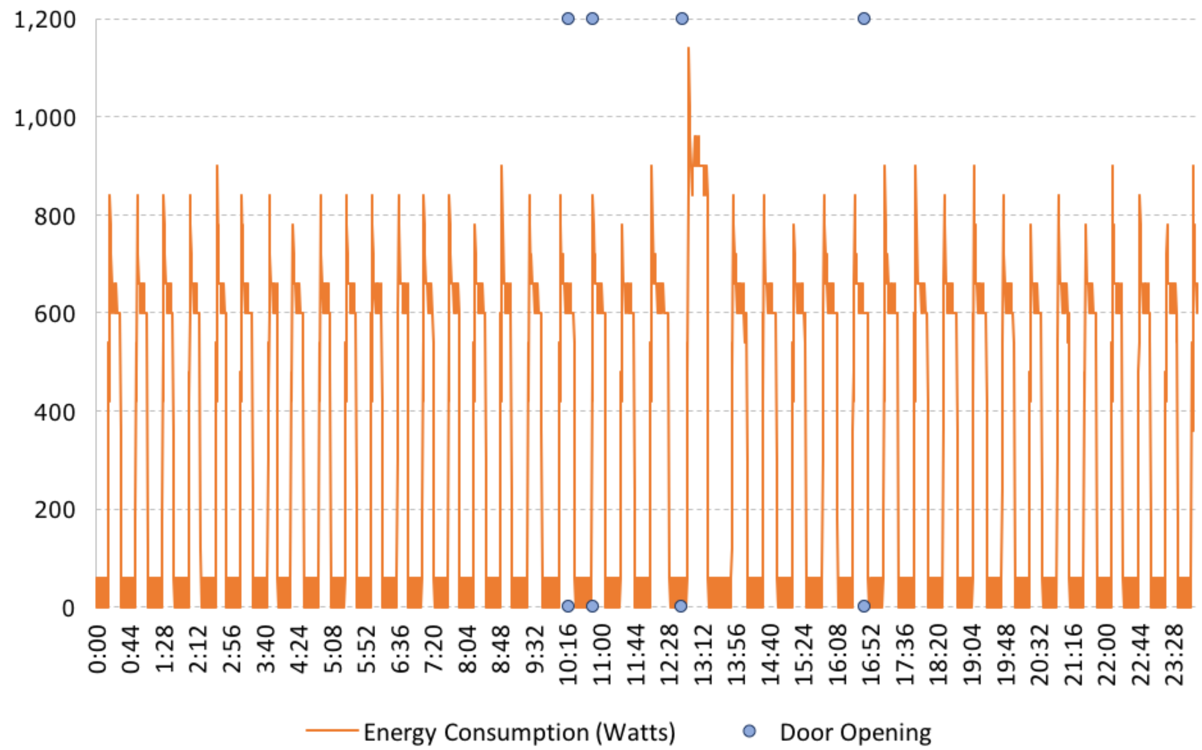


FIGURE 150: FREEZER G ENERGY CONSUMPTION, THURSDAY DOOR OPENINGS AT -70°C



APPENDIX D: ULT FREEZER TEMPERATURE PROFILES

ULT freezer temperature profiles for Freezers A-G can be seen below. The first set of data are demonstrate the response of the freezer to Monday's door opening schedule, which was deemed the most difficult owing to the number and duration of door openings. The subsequent sets of data overlay door openings with temperature information, and clearly show that while most ULT freezers in the study struggled to return to set point in the face of multiple door openings in short succession (Tuesday), they were able to recover rather well when the door was opened periodically throughout the day (Thursday).

ULT FREEZER TEMPERATURE PROFILES – MONDAY DOOR OPENING SCHEDULE

TEMPERATURE PROFILES AT -80°C

FIGURE 151: FREEZER A TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C

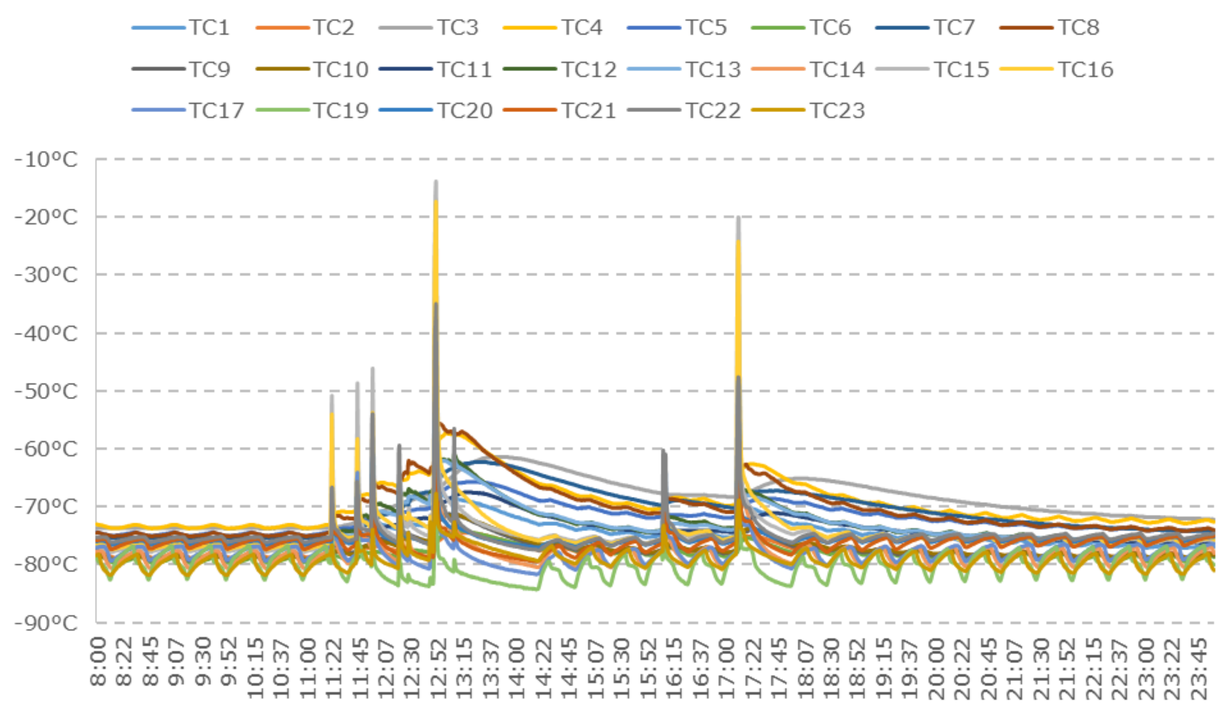


FIGURE 152: FREEZER B TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C

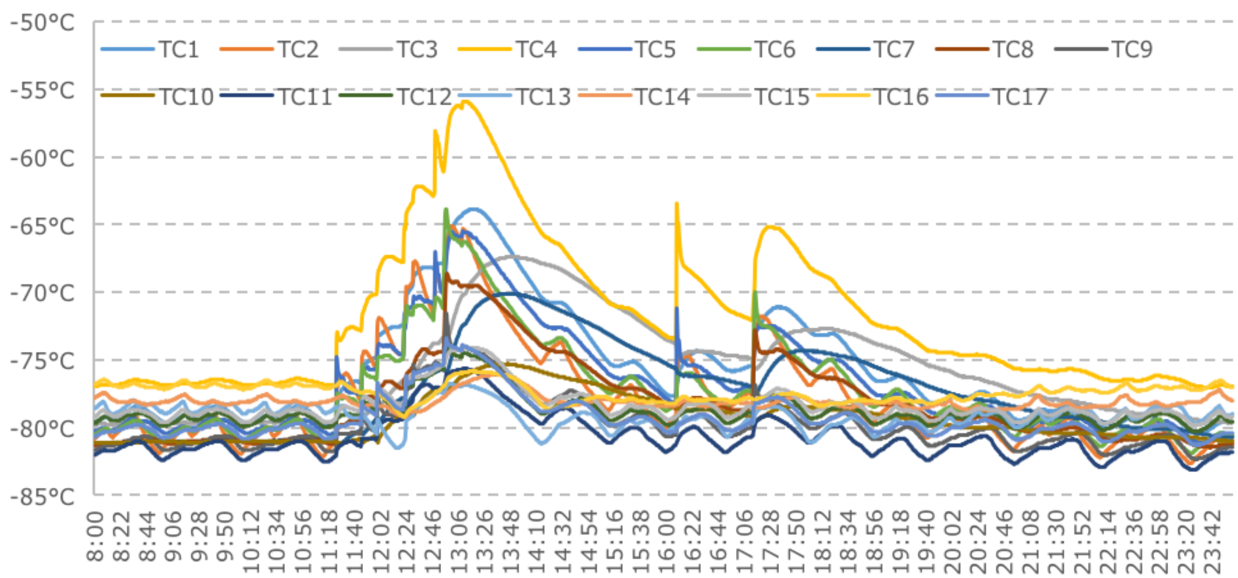
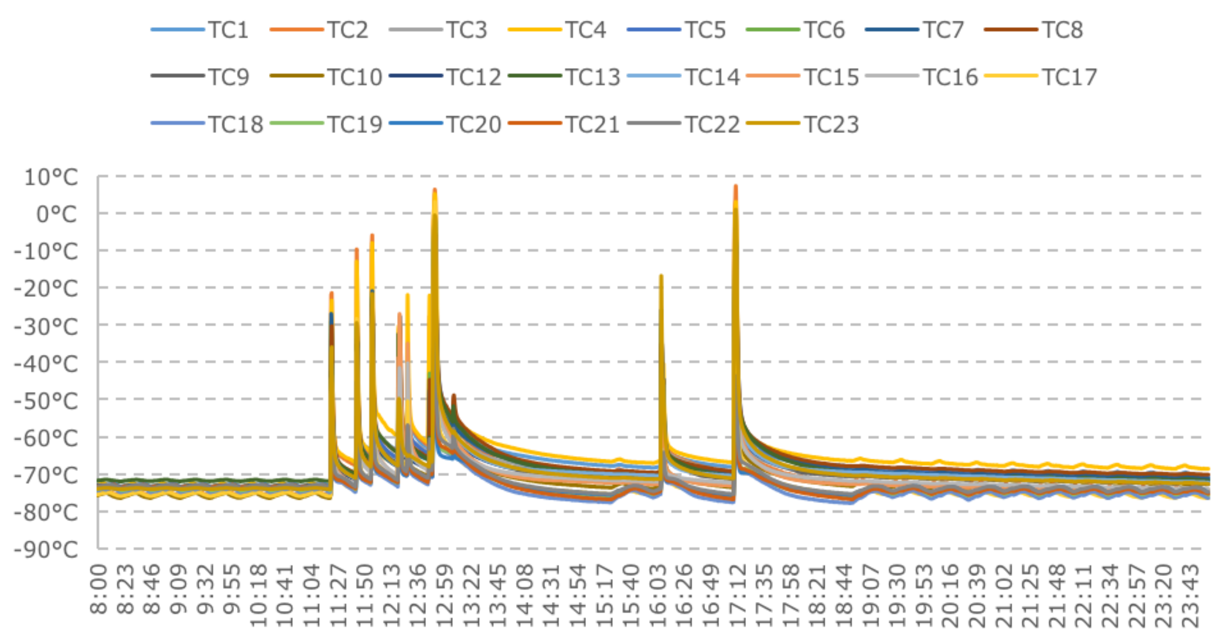


FIGURE 153: FREEZER C TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C



Note that the breaks in the graphs for Freezer D represent times during which the temperature readings from the TCs were read out. This was done later in the study to mitigate the software crashes seen earlier that were the result of too much data being written to the laptop.

FIGURE 154: FREEZER D TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C

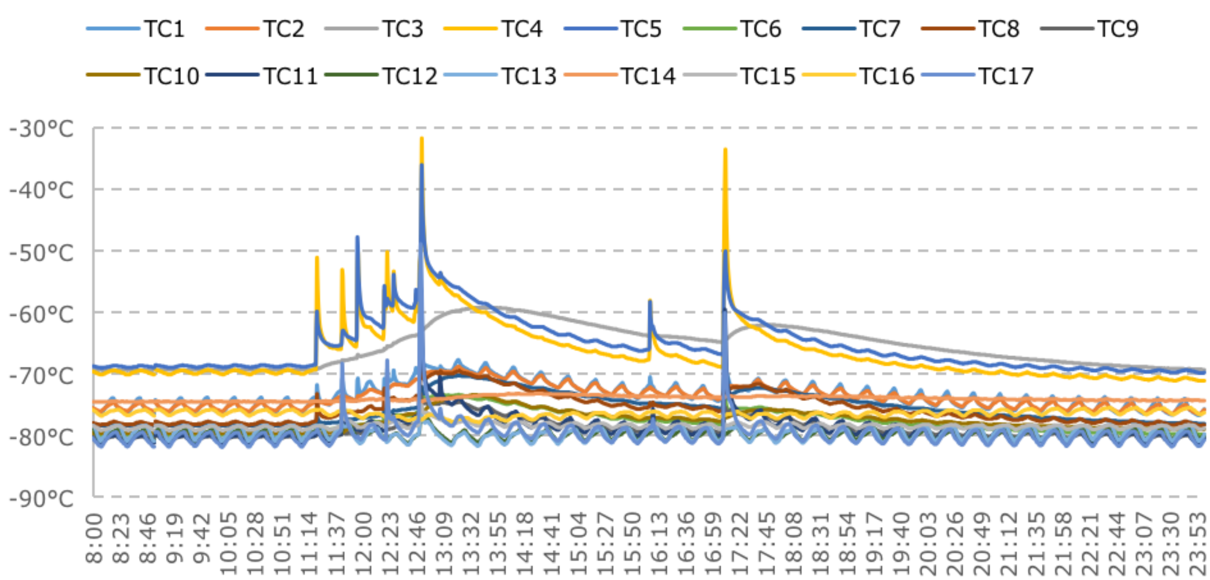


FIGURE 155: FREEZER E TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C

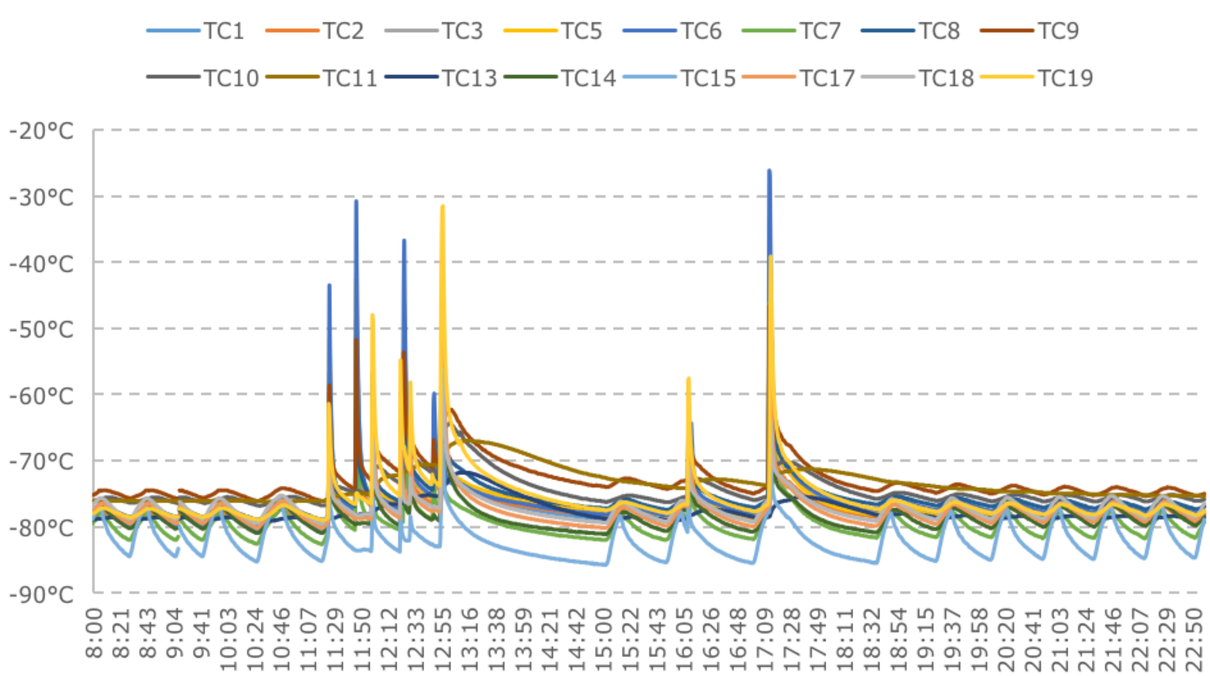


FIGURE 156: FREEZER F TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C

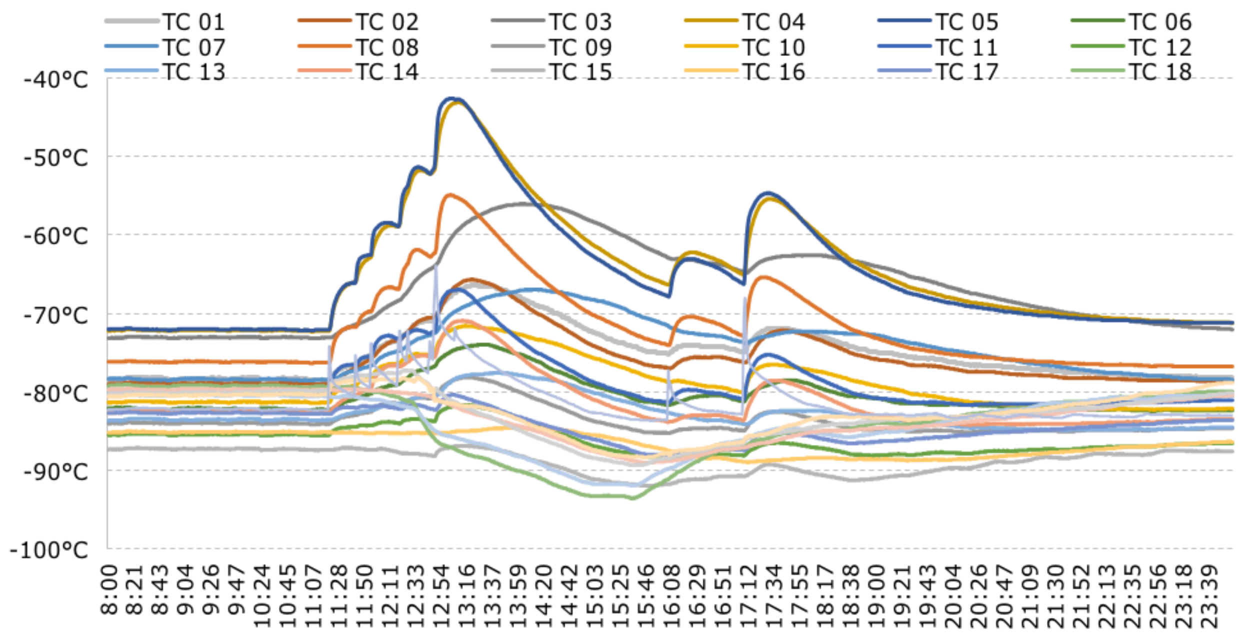
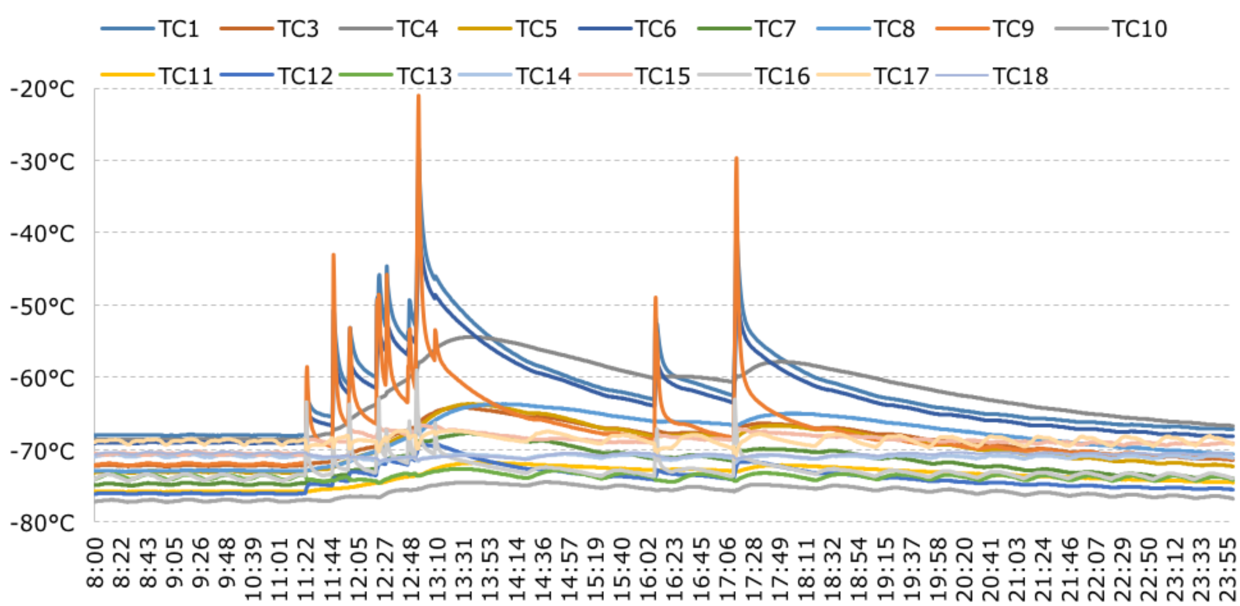


FIGURE 157: FREEZER G TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -80°C



Temperature Profiles at -70°C

Figure 158: Freezer A Temperature Readings, Monday Door Openings at -70°C

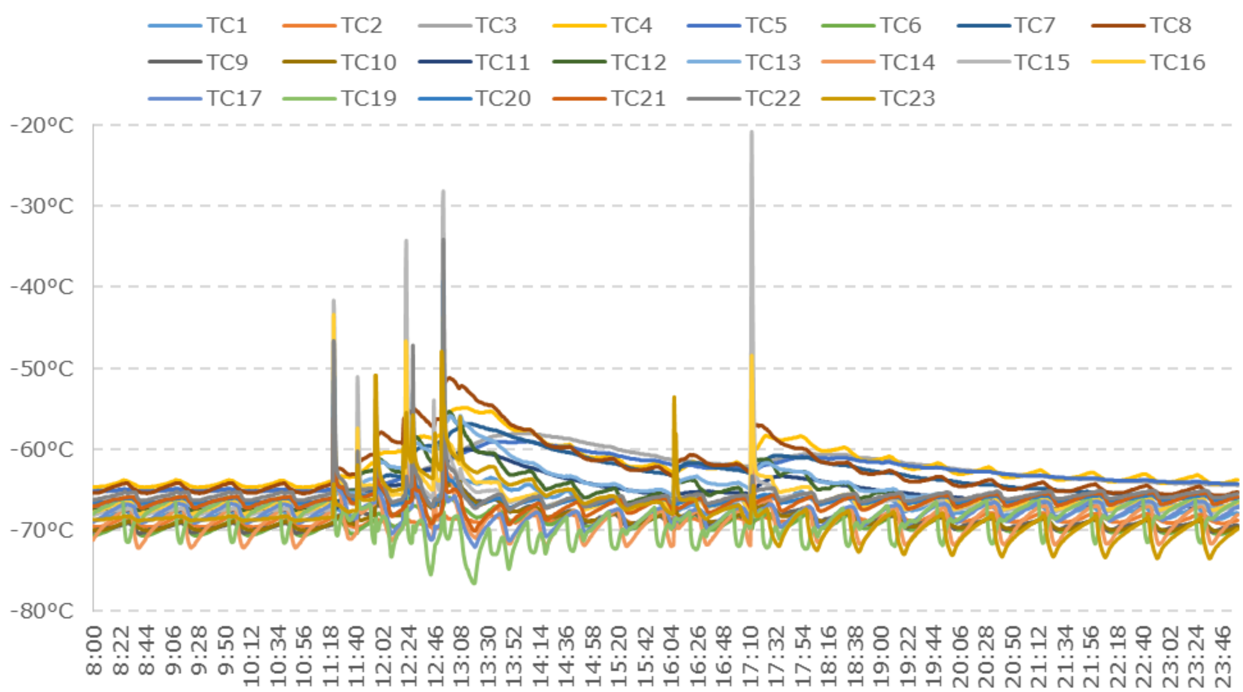


Figure 159: Freezer B Temperature Readings, Monday Door Openings at -70°C

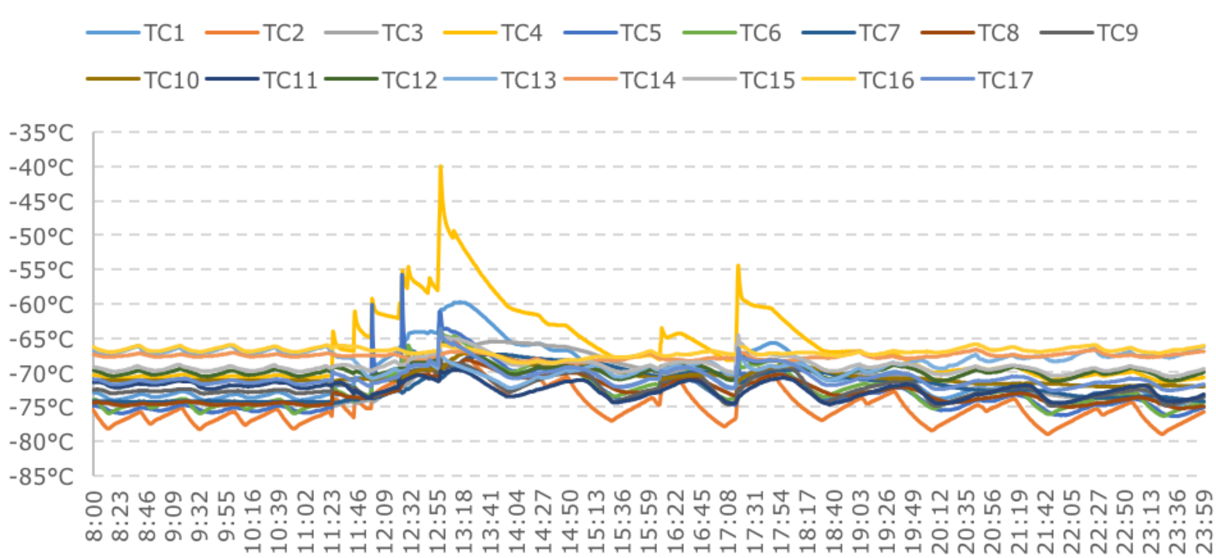


FIGURE 160: FREEZER C TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -70°C

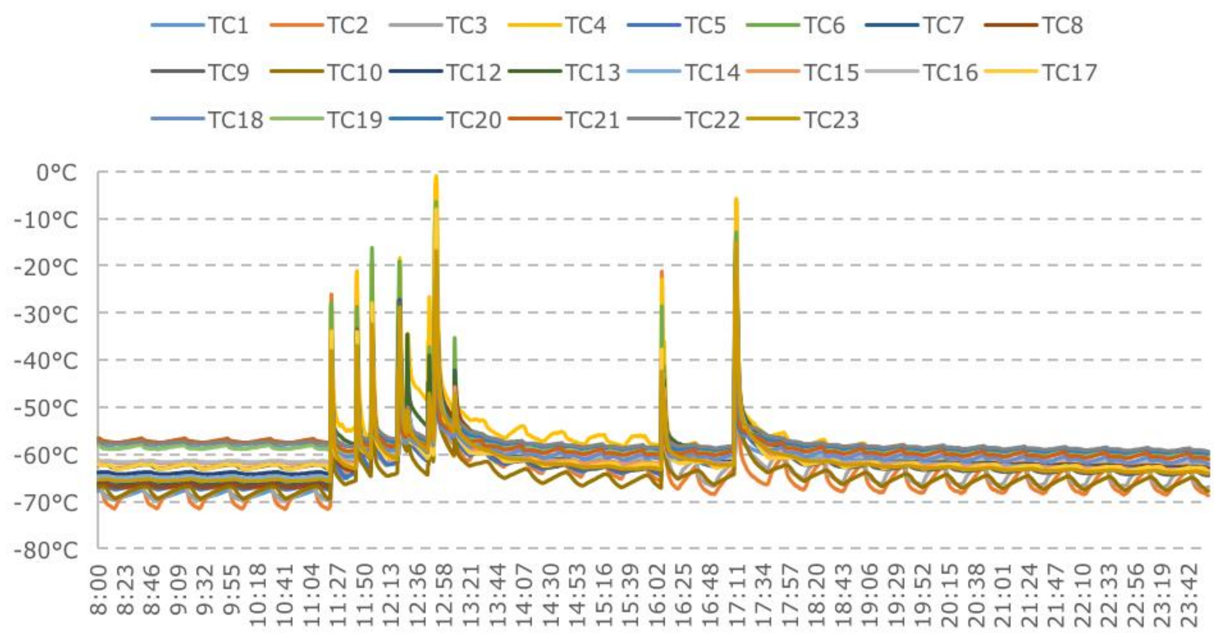


FIGURE 161: FREEZER D TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -70°C

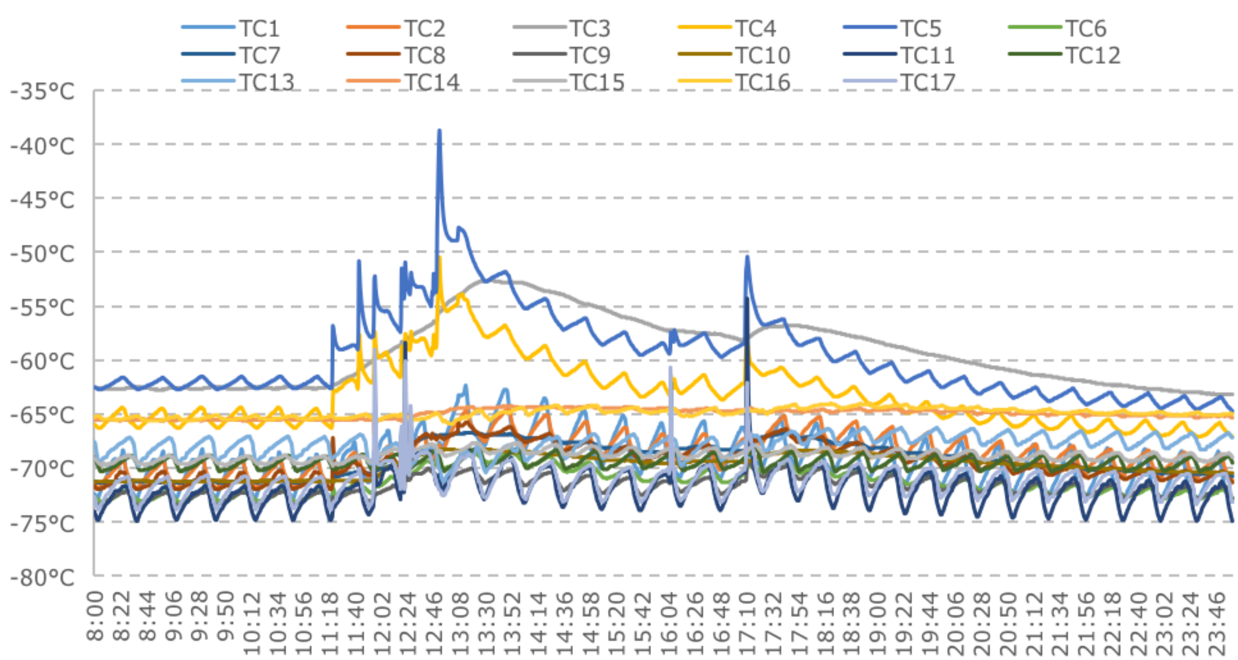


FIGURE 162: FREEZER E TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -70°C

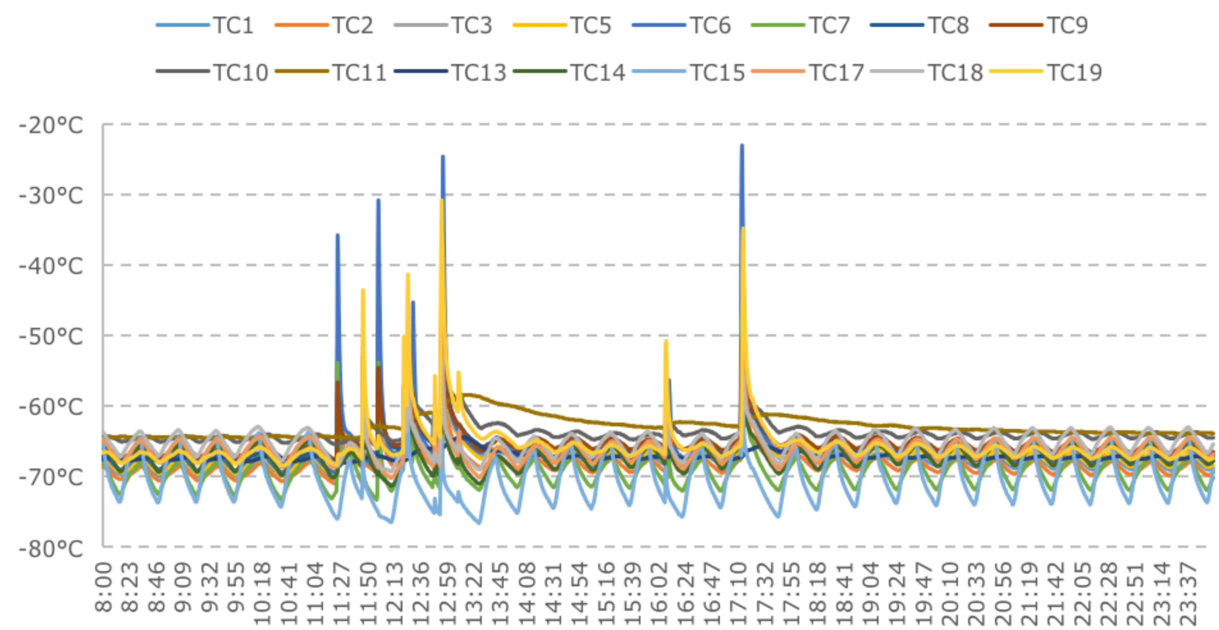


FIGURE 163: FREEZER F TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -70°C

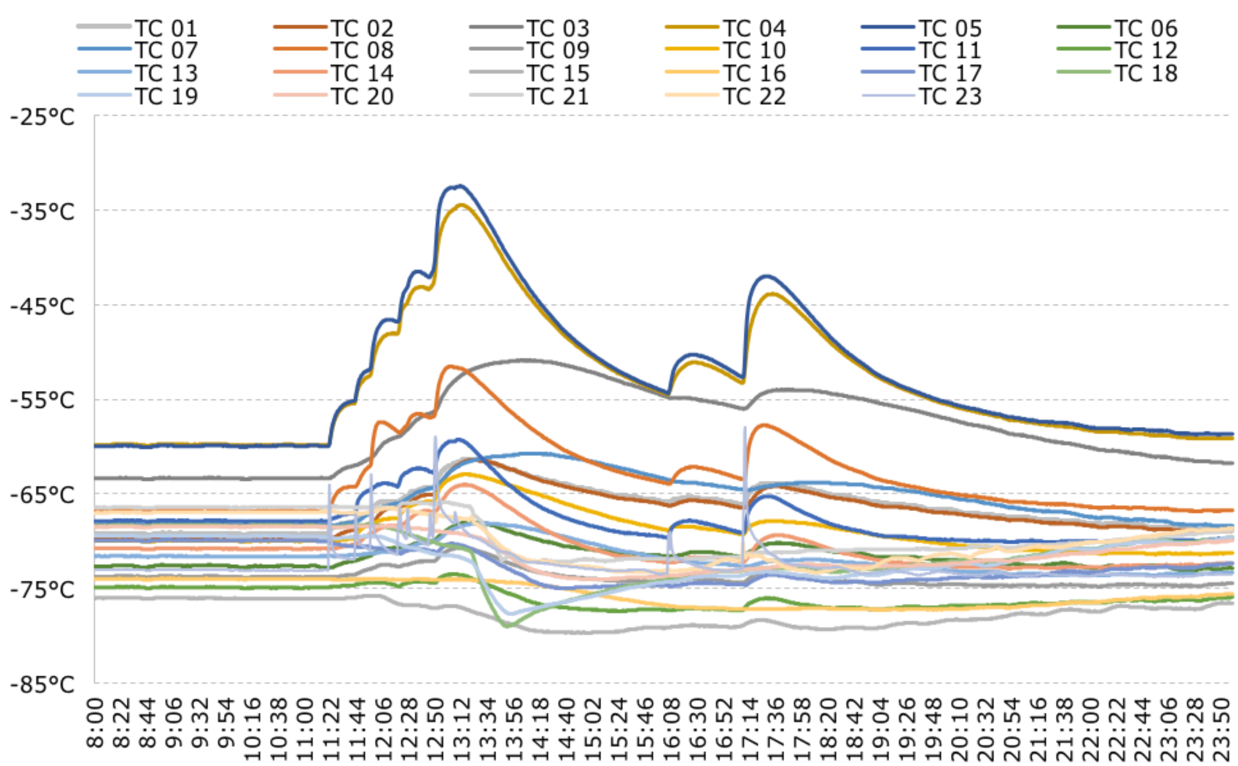
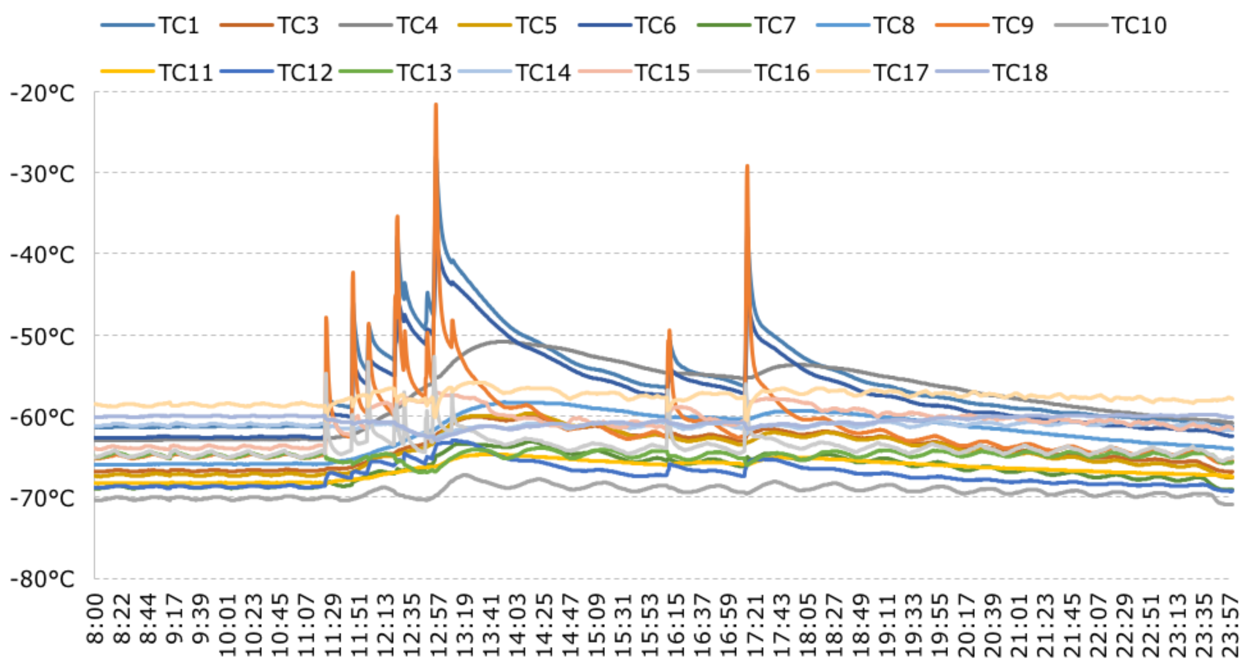


FIGURE 164: FREEZER G TEMPERATURE READINGS, MONDAY DOOR OPENINGS AT -70°C



ULT Freezer Temperature Profiles – Tuesday Door Opening Schedule

Temperature Profiles at -80°C

Figure 165: Freezer A Temperature Readings, Tuesday Door Openings at -80°C

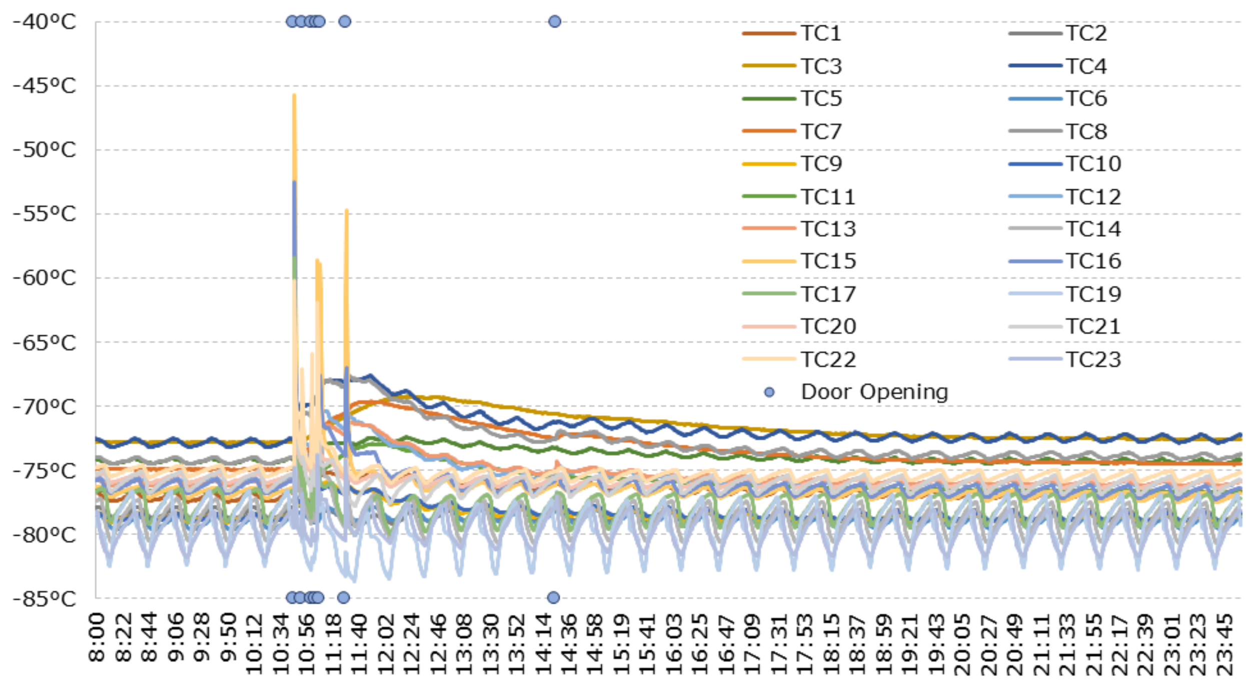


FIGURE 166: FREEZER B TEMPERATURE READINGS, TUESDAY DOOR OPENINGS AT -80°C

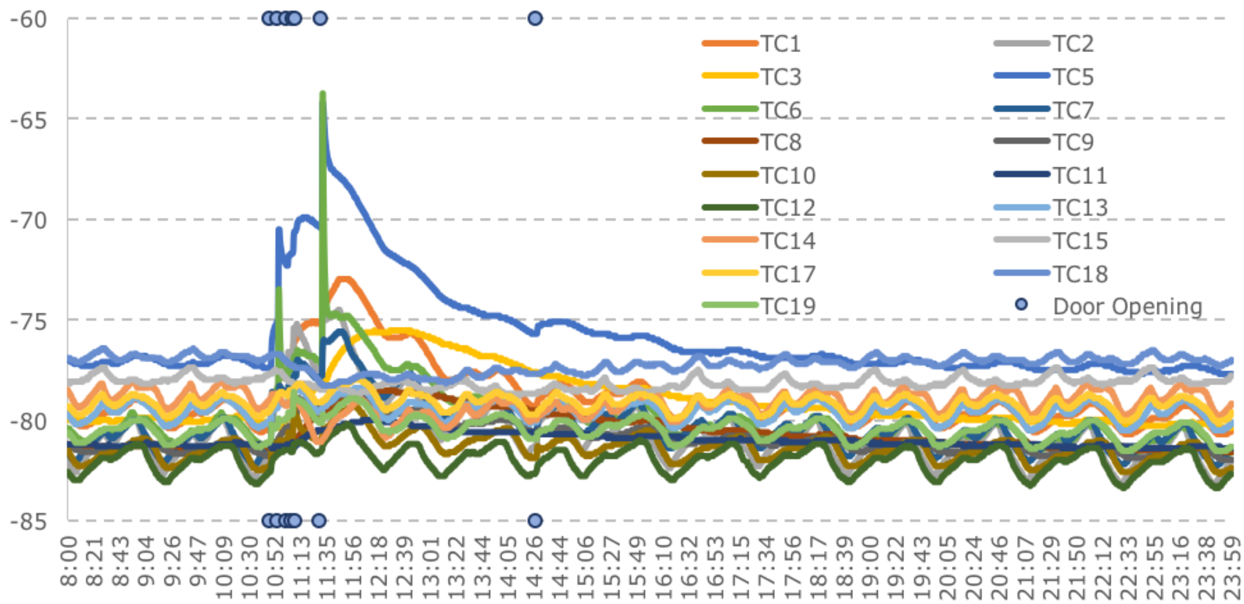


FIGURE 167: FREEZER C TEMPERATURE READINGS, TUESDAY DOOR OPENINGS AT -80°C

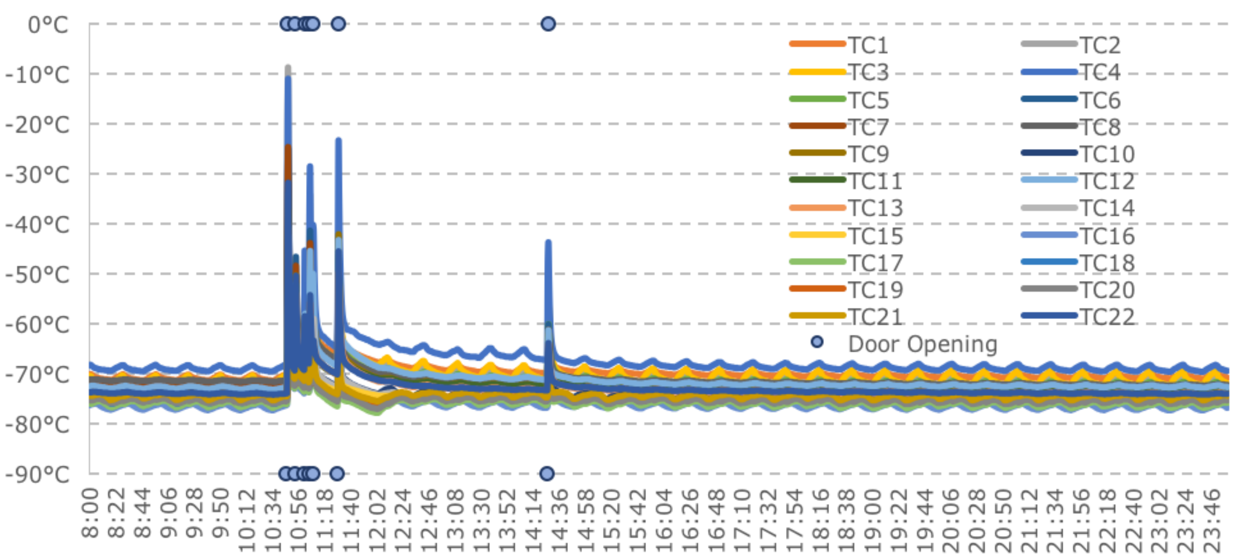


FIGURE 168: FREEZER D TEMPERATURE READINGS, TUESDAY DOOR OPENINGS AT -80°C

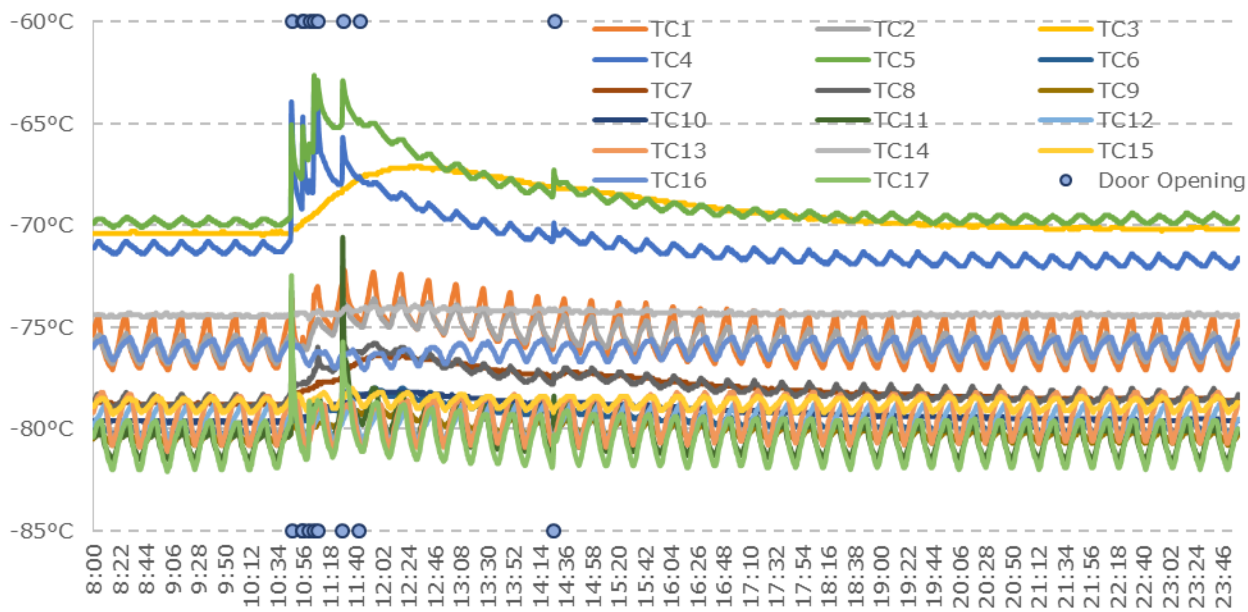


FIGURE 169: FREEZER E TEMPERATURE READINGS, TUESDAY DOOR OPENINGS AT -80°C

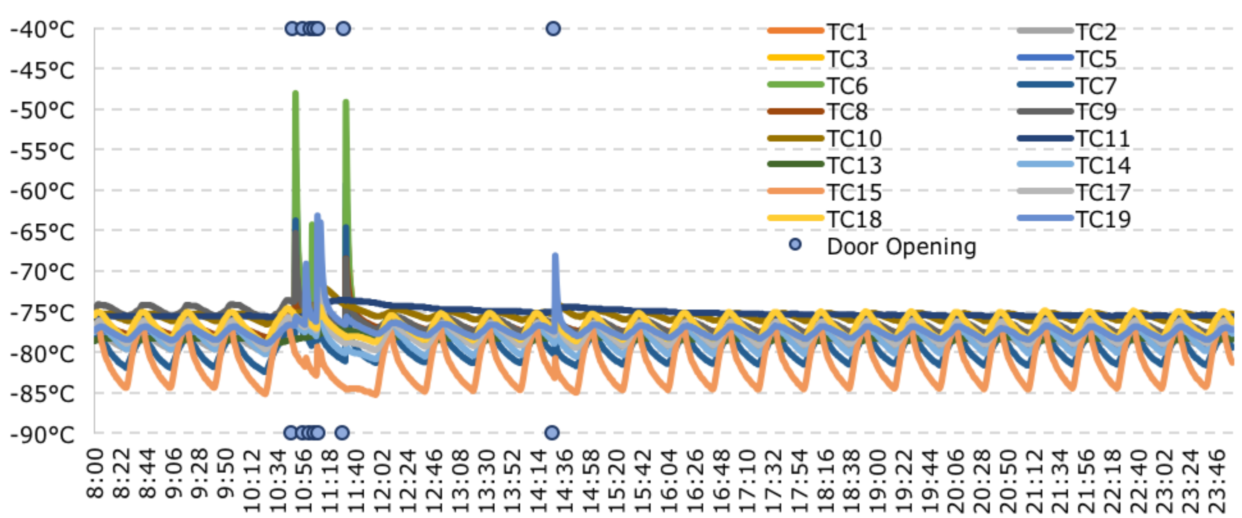


FIGURE 170: FREEZER F TEMPERATURE READINGS, TUESDAY DOOR OPENINGS AT -80°C

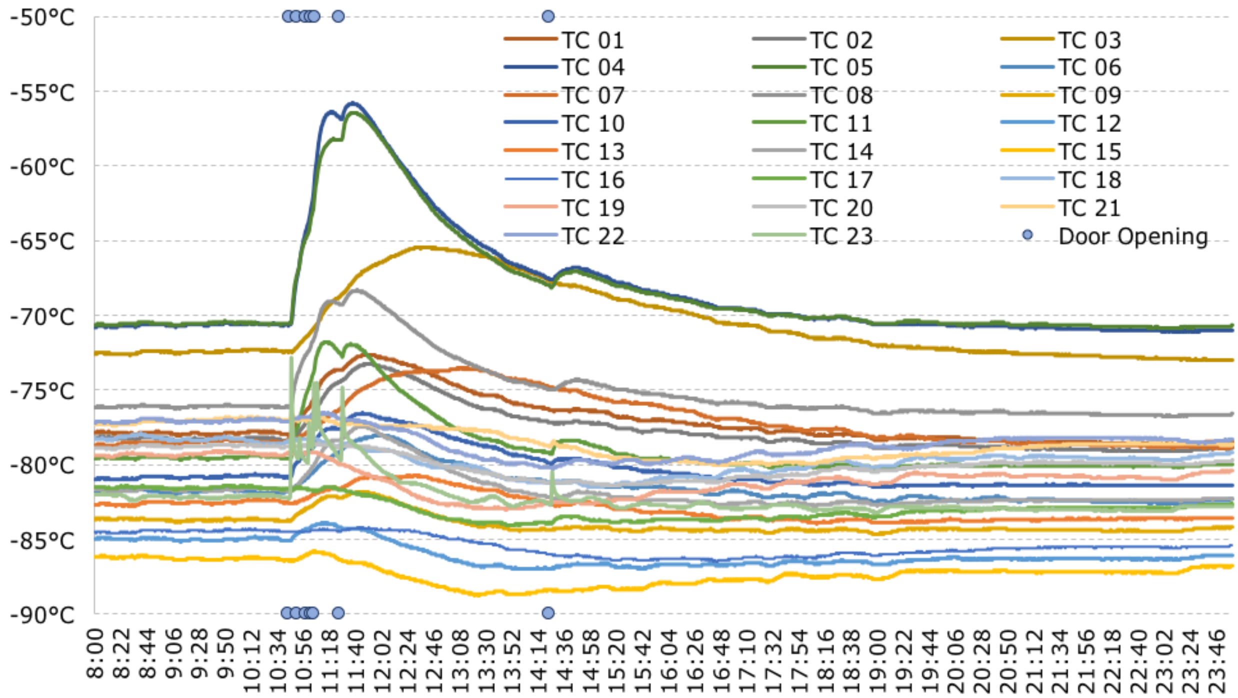
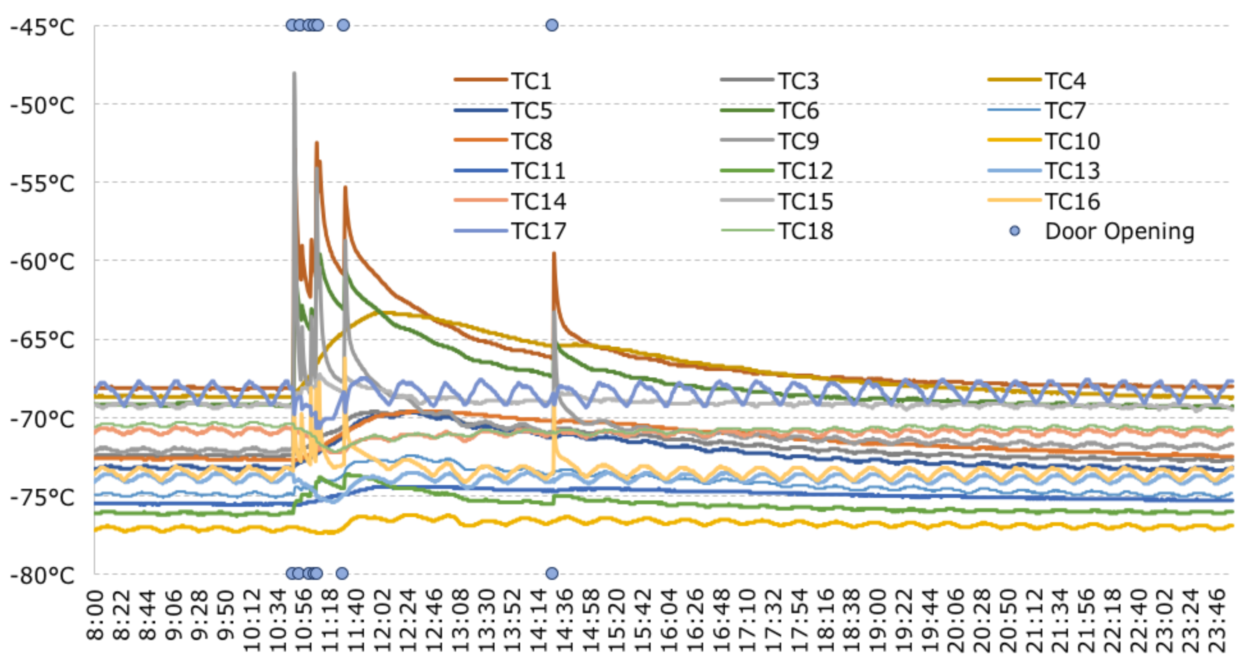


FIGURE 171: FREEZER G TEMPERATURE READINGS, TUESDAY DOOR OPENINGS AT -80°C



Temperature Profiles at -70°C

Figure 172: Freezer A Temperature Readings, Tuesday Door Openings at -70°C

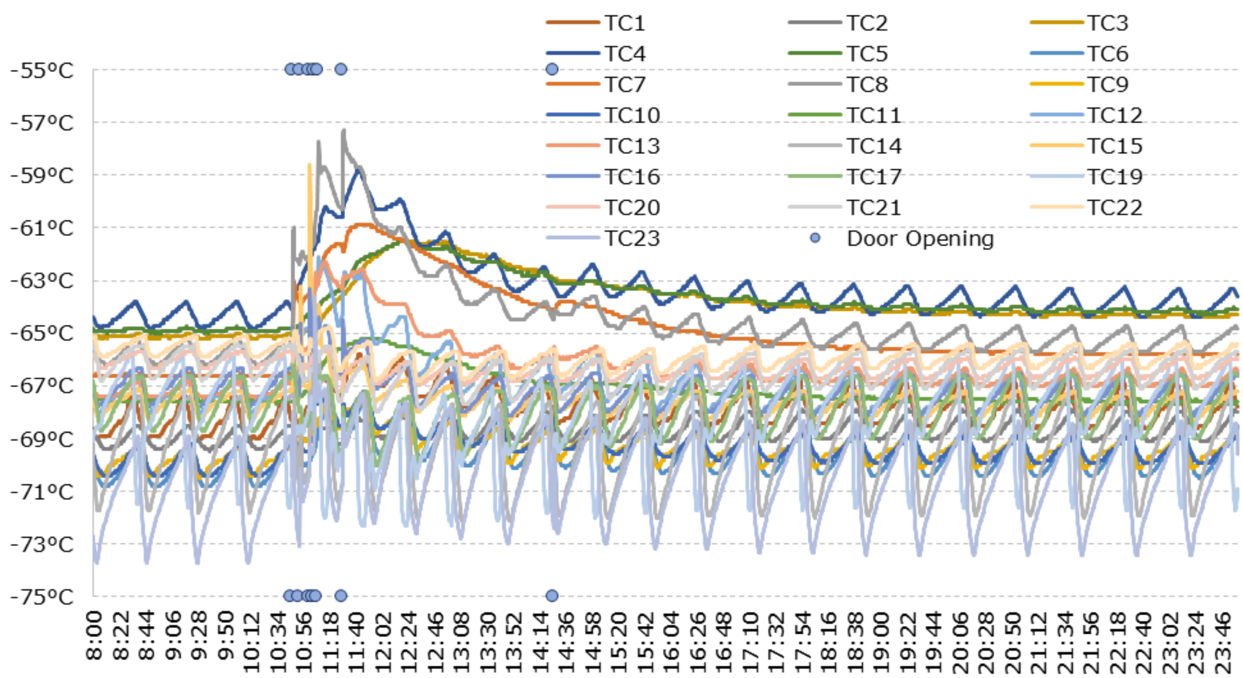


Figure 173: Freezer B Temperature Readings, Tuesday Door Openings at -70°C

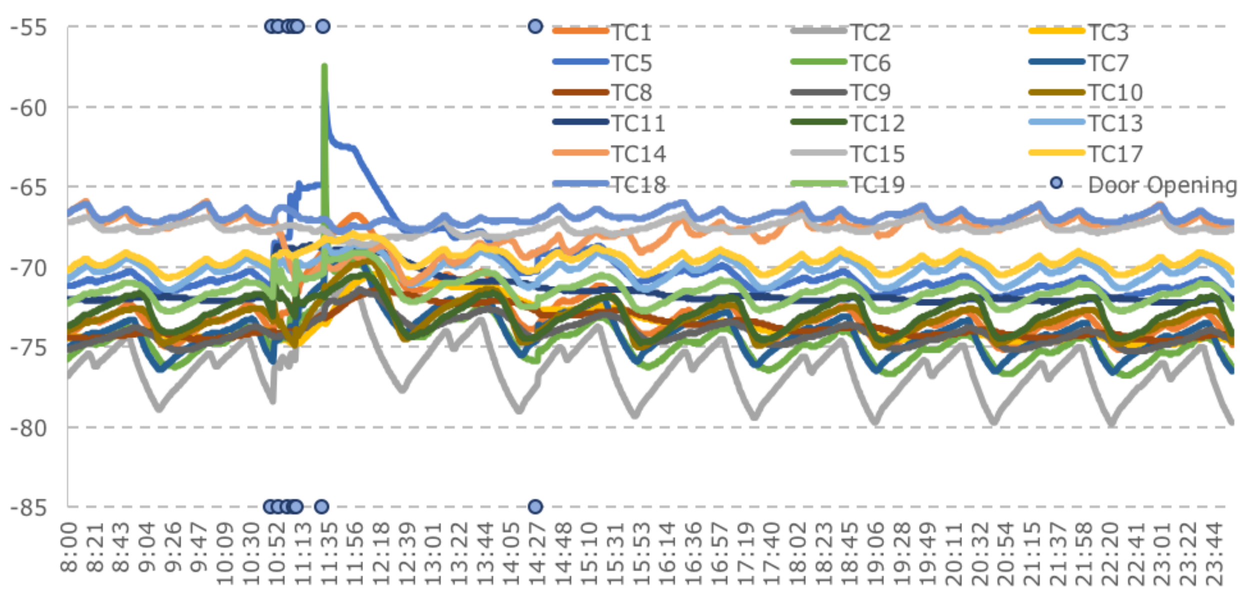


FIGURE 174: FREEZER C TEMPERATURE READINGS, TUESDAY DOOR OPENINGS AT -70°C

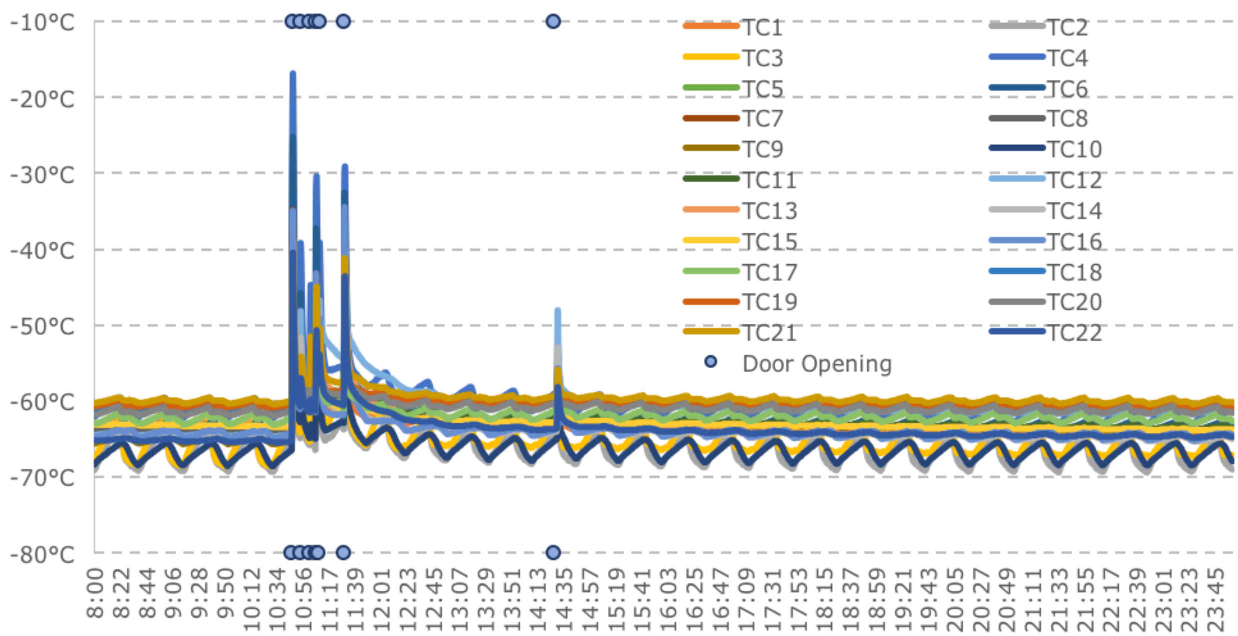


FIGURE 175: FREEZER D TEMPERATURE READINGS, TUESDAY DOOR OPENINGS AT -70°C

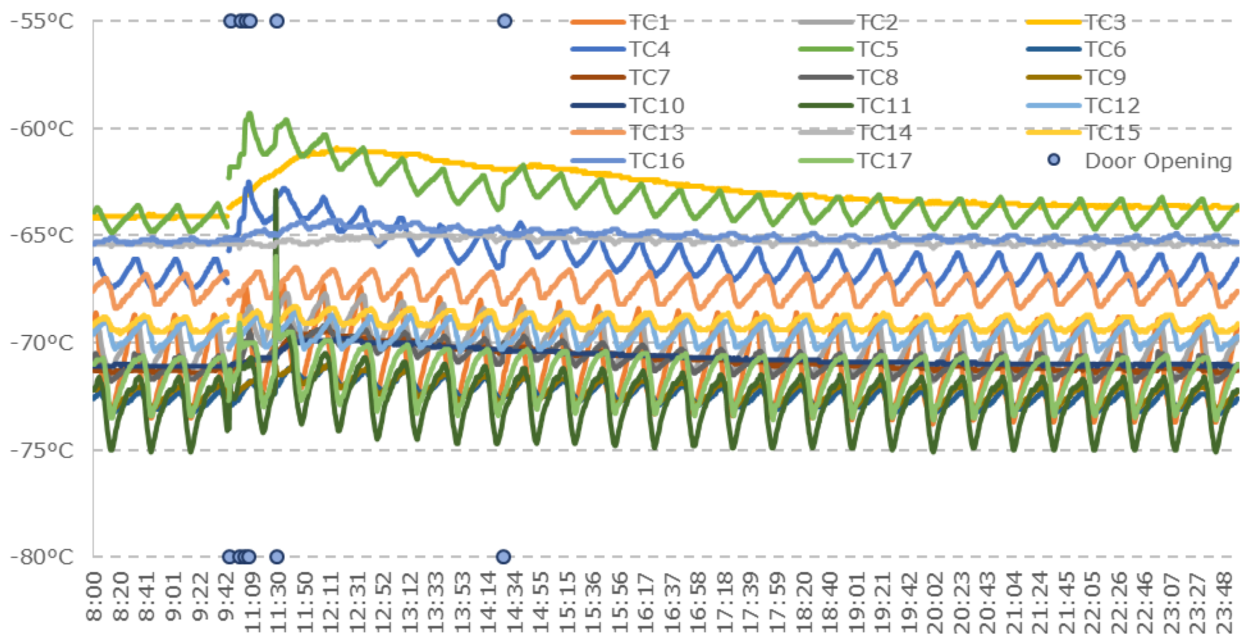


FIGURE 176: FREEZER E TEMPERATURE READINGS, TUESDAY DOOR OPENINGS AT -70°C

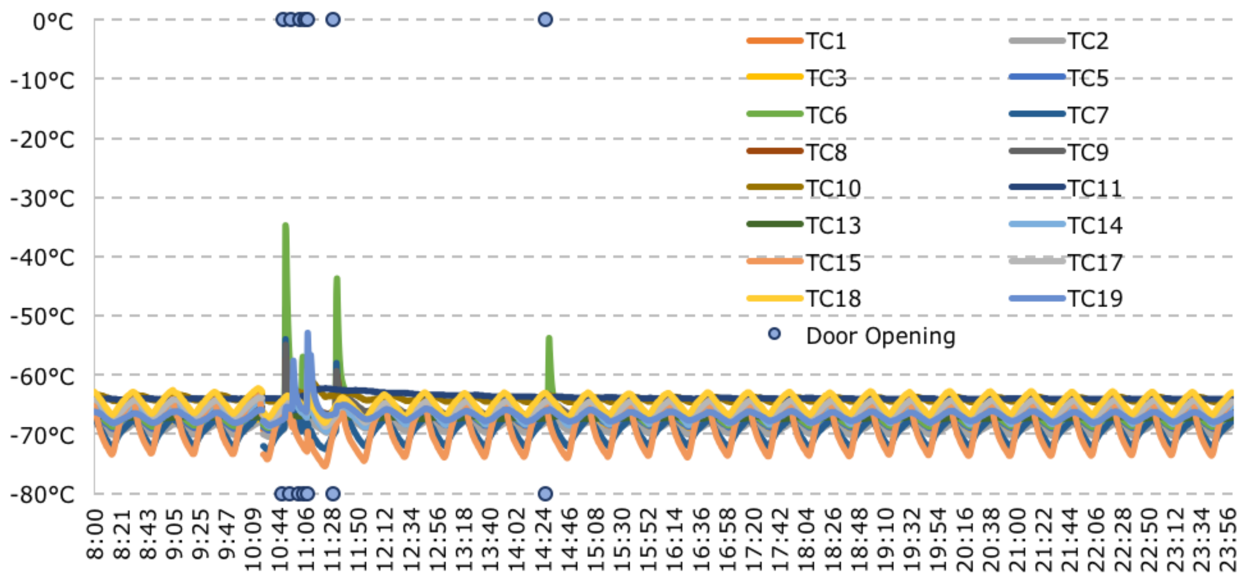


FIGURE 177: FREEZER F TEMPERATURE READINGS, TUESDAY DOOR OPENINGS AT -70°C

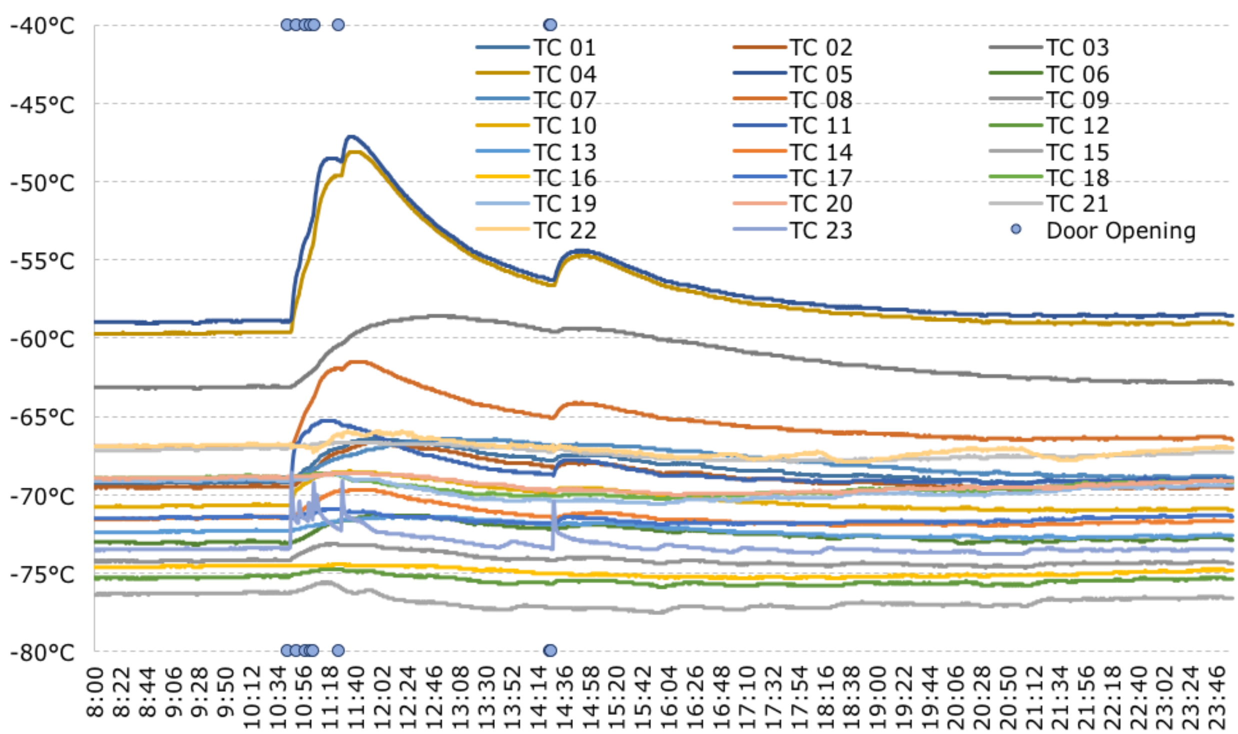
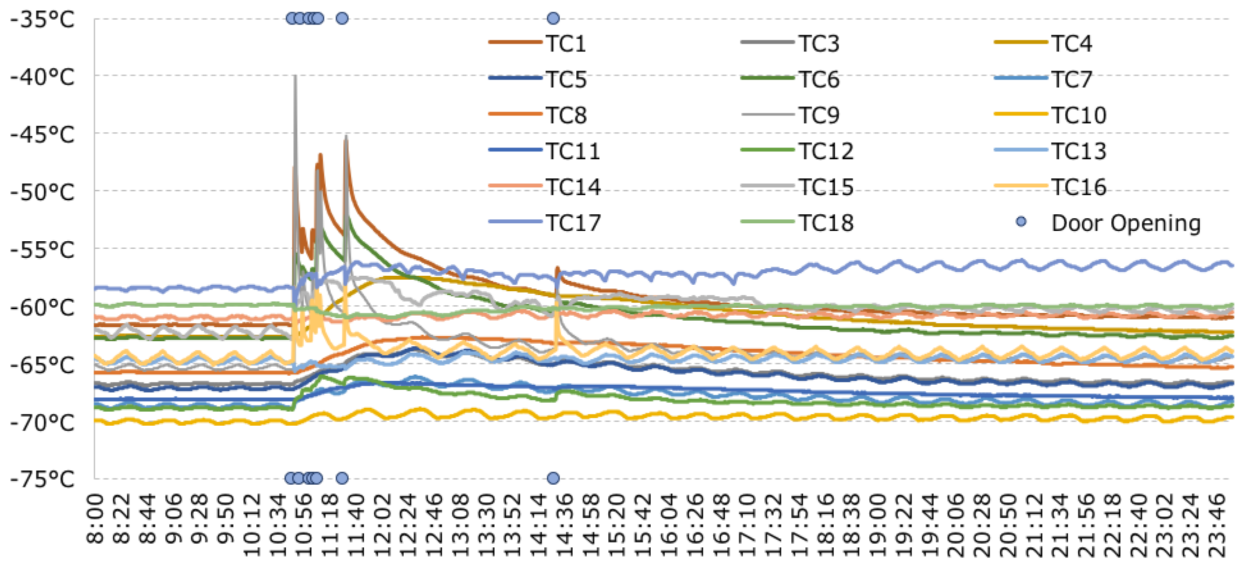


FIGURE 178: FREEZER G TEMPERATURE READINGS, TUESDAY DOOR OPENINGS AT -70°C



ULT FREEZER TEMPERATURE PROFILES – THURSDAY DOOR OPENING SCHEDULE

TEMPERATURE PROFILES AT -80°C

FIGURE 179: FREEZER A TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C

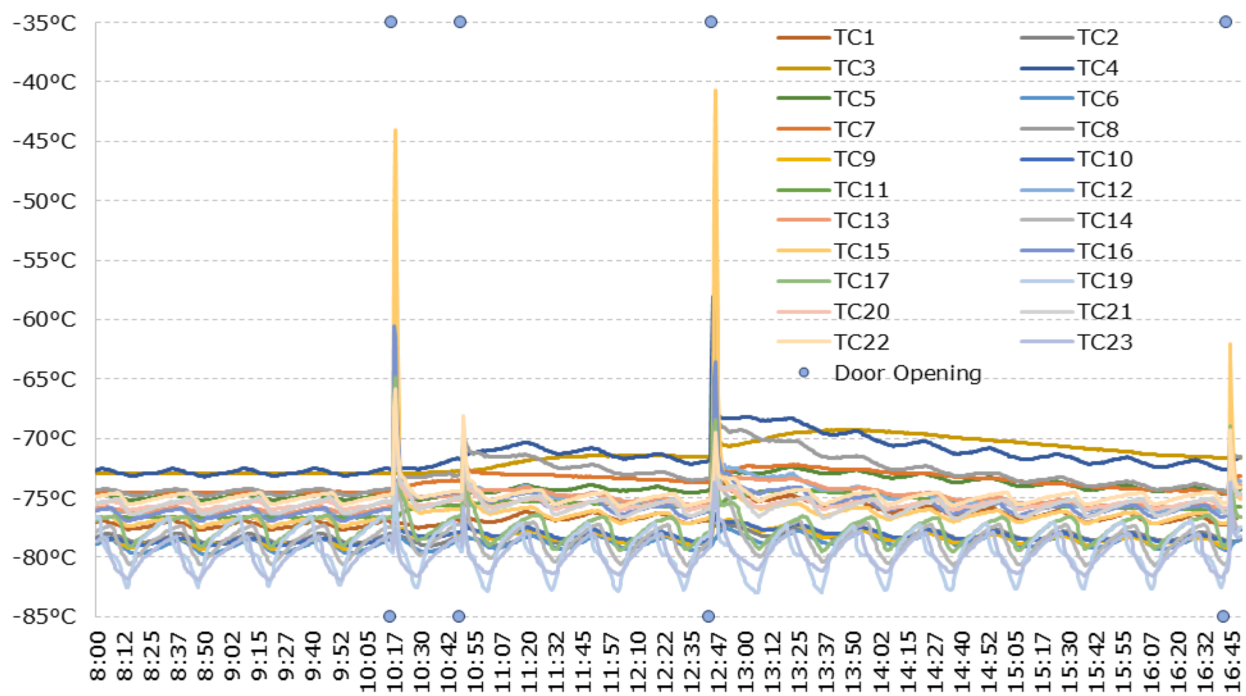


FIGURE 180: FREEZER B TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C

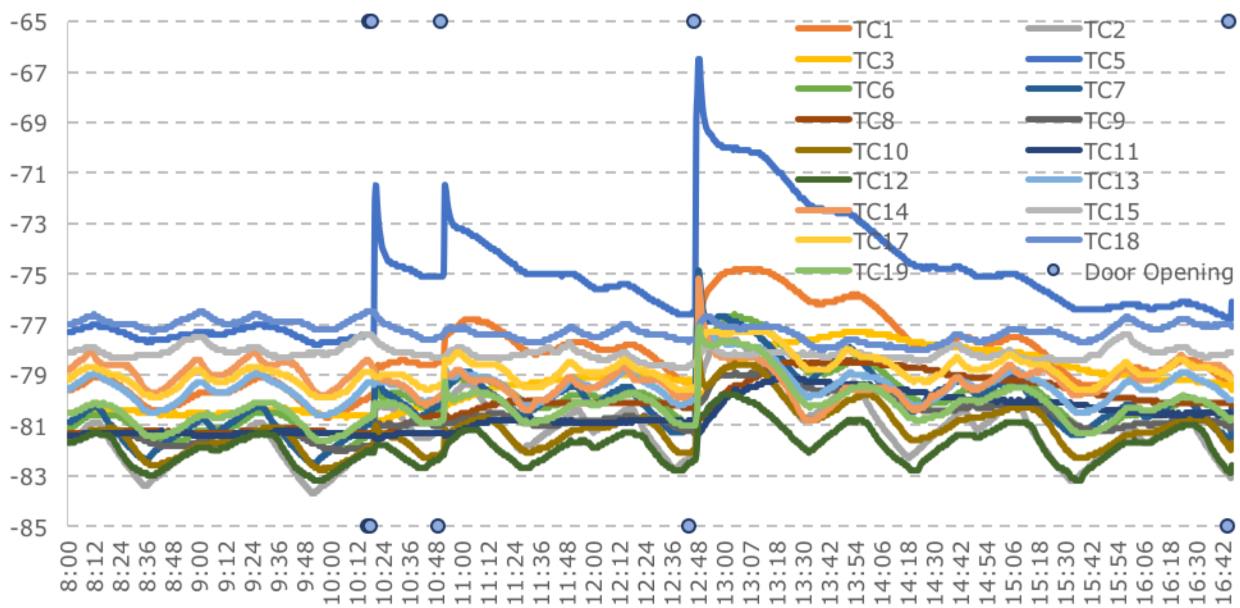


FIGURE 181: FREEZER C TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C

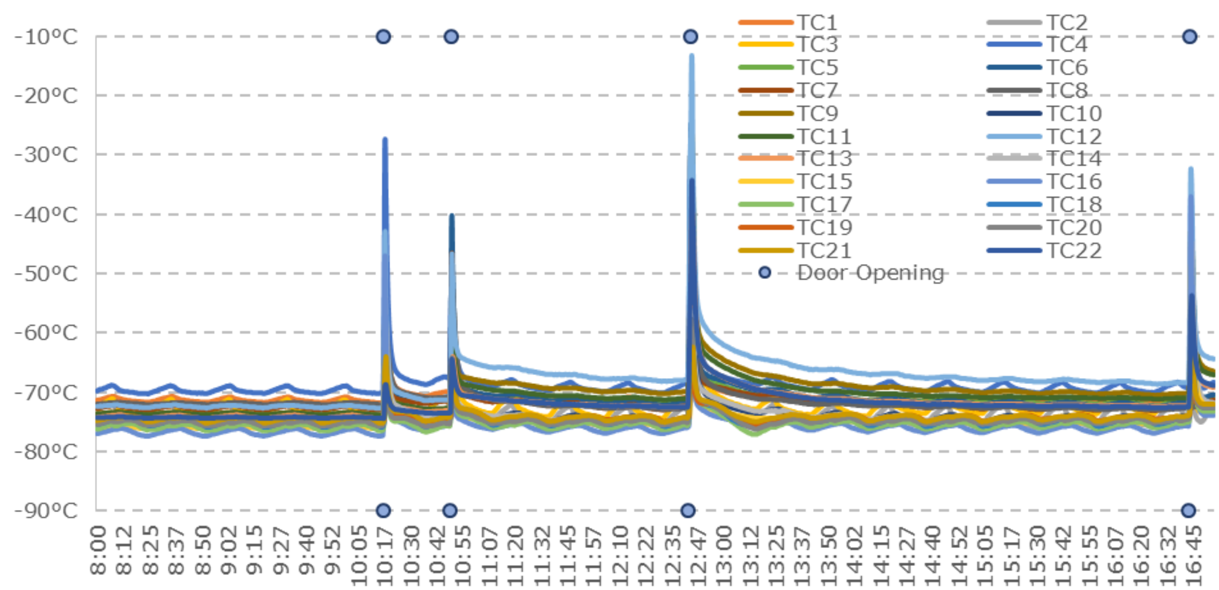


Figure 182: Freezer D Temperature Readings, Thursday Door Openings at -80°C

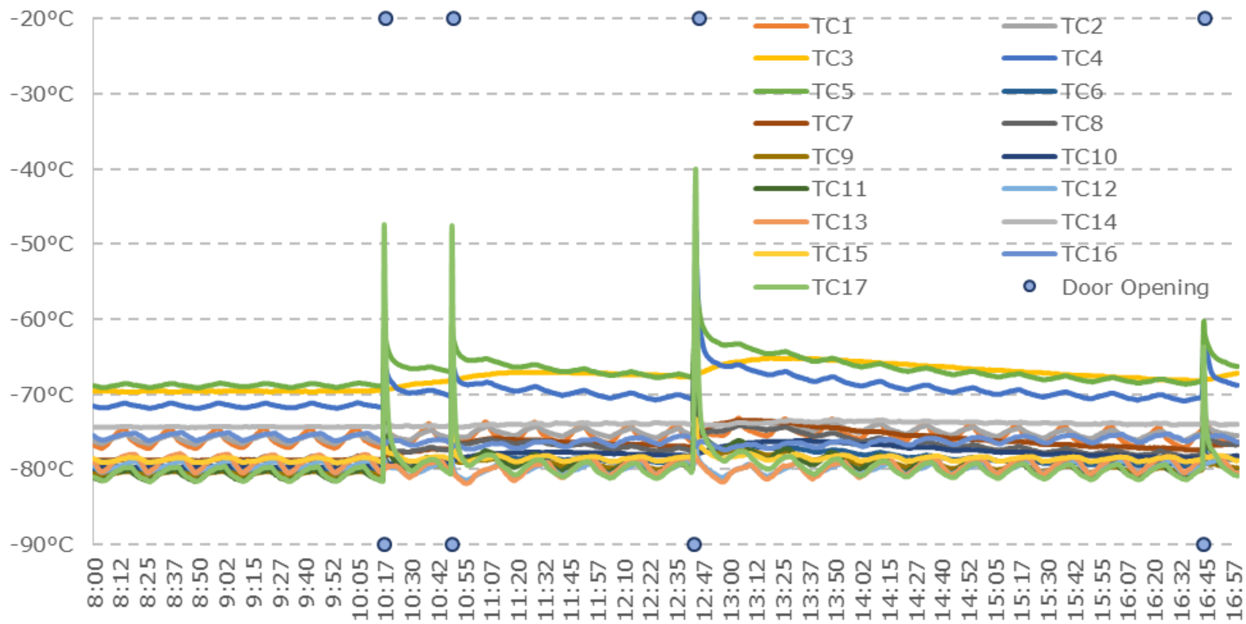


Figure 183: Freezer E Temperature Readings, Thursday Door Openings at -80°C

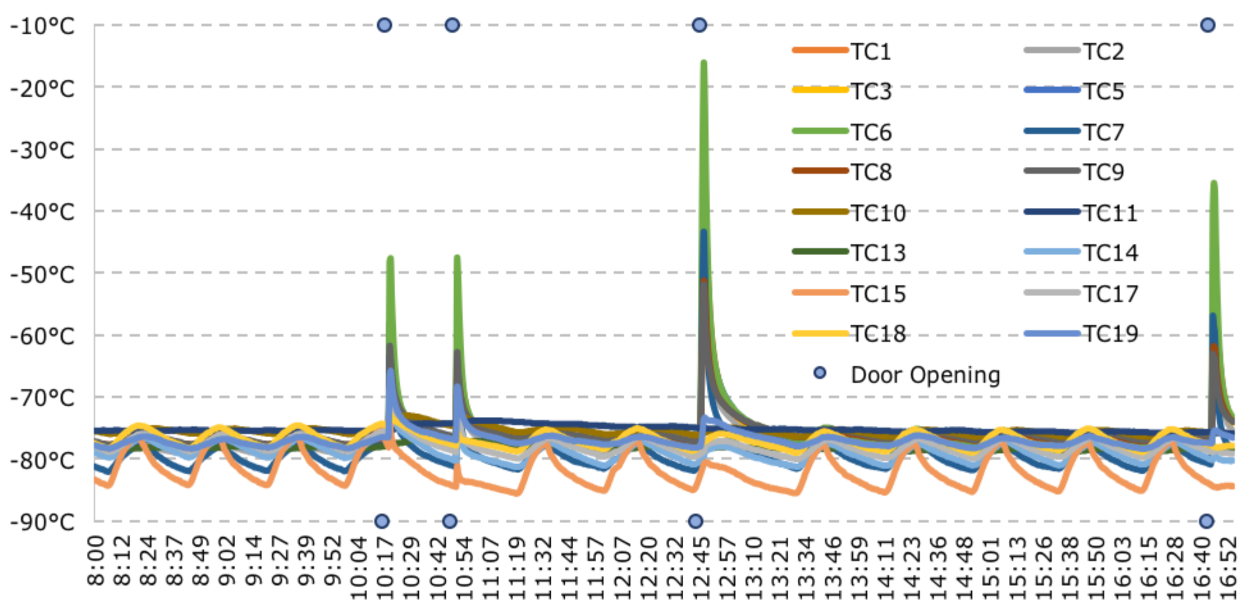


FIGURE 184: FREEZER F TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C

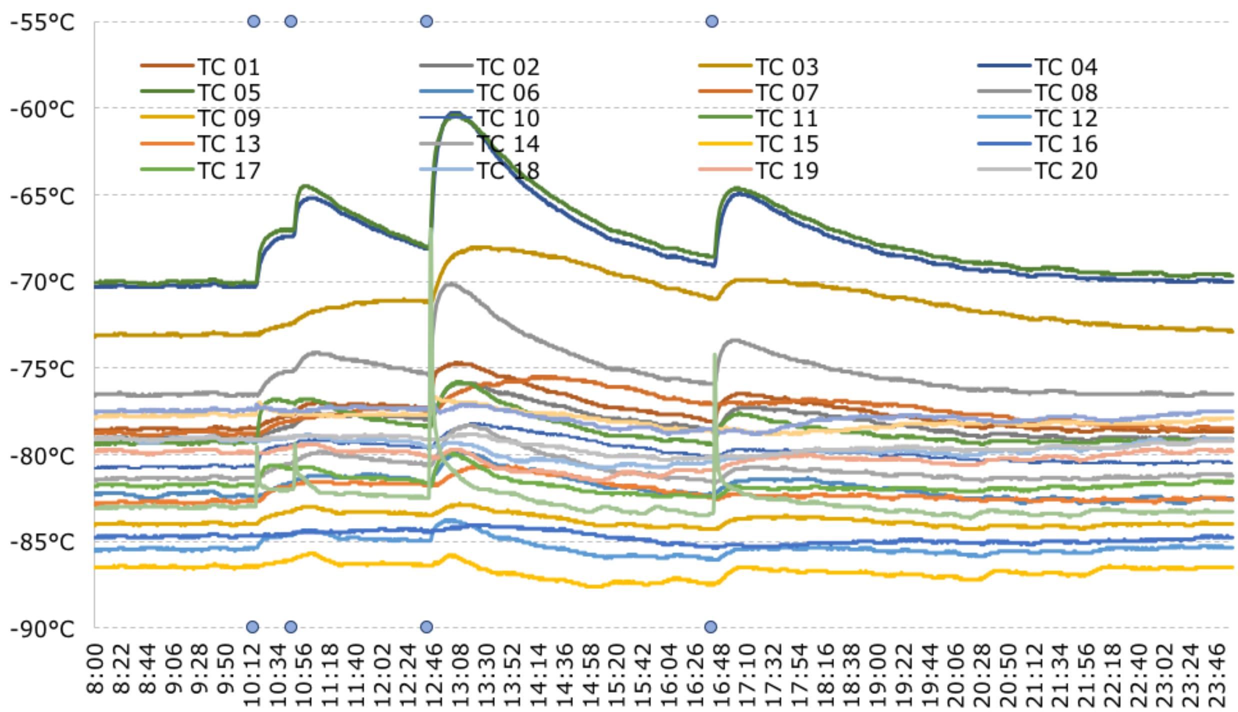
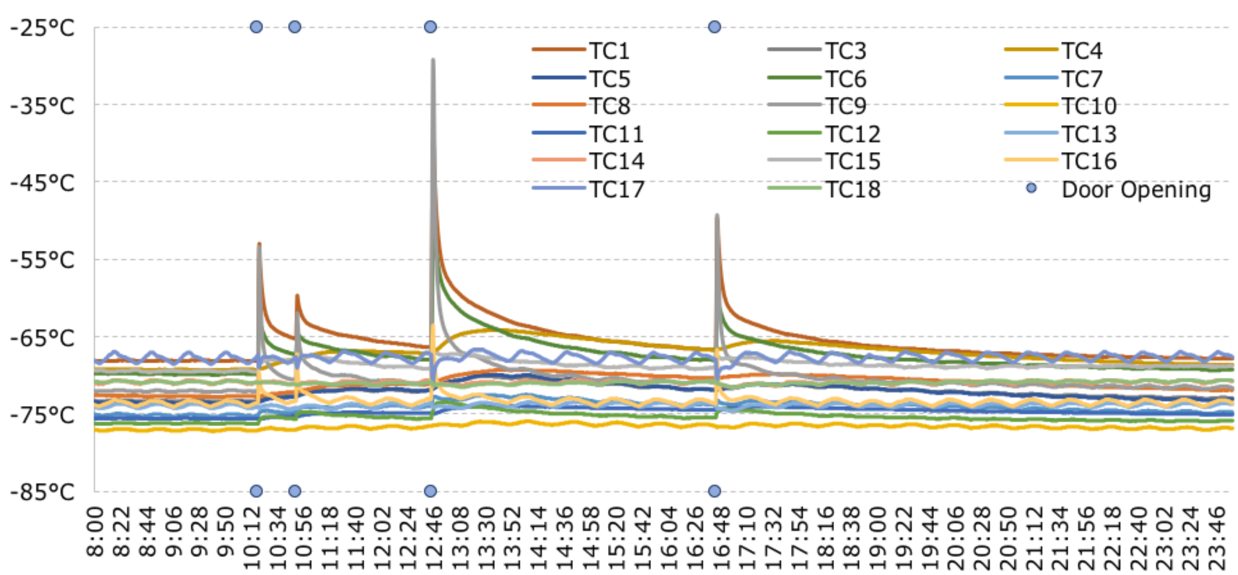


FIGURE 185: FREEZER G TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -80°C



TEMPERATURE PROFILES AT -70°C

FIGURE 186: FREEZER A TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -70°C

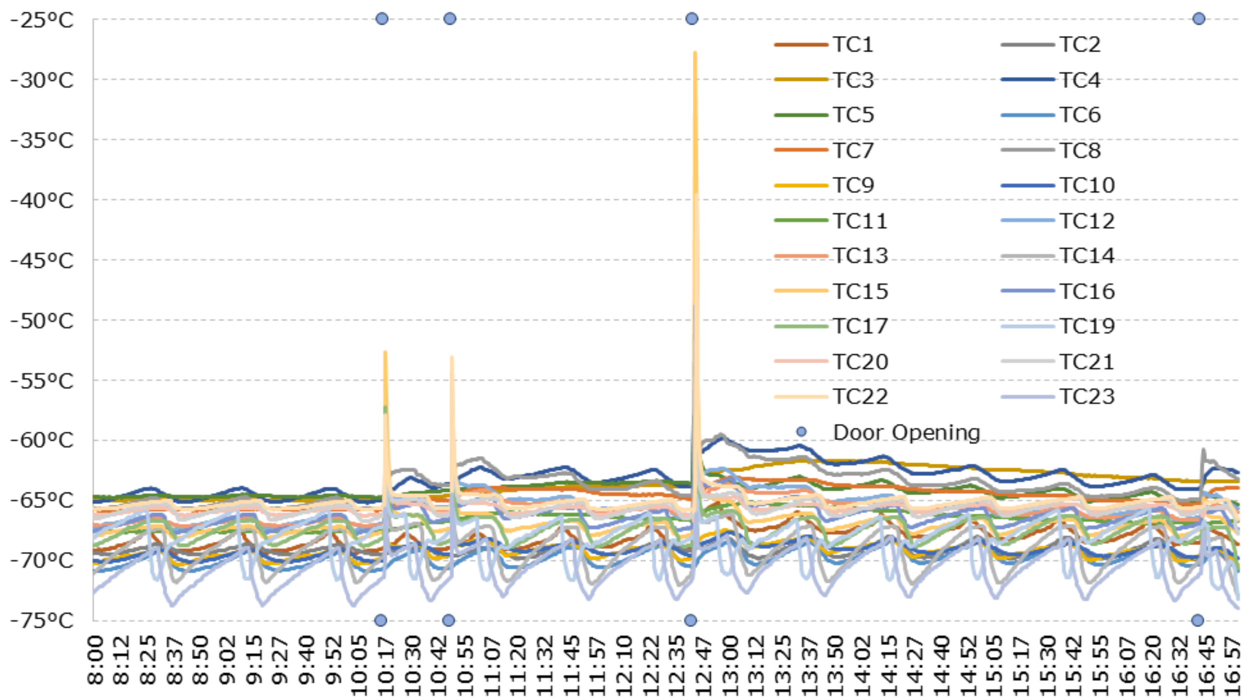


FIGURE 187: FREEZER B TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -70°C

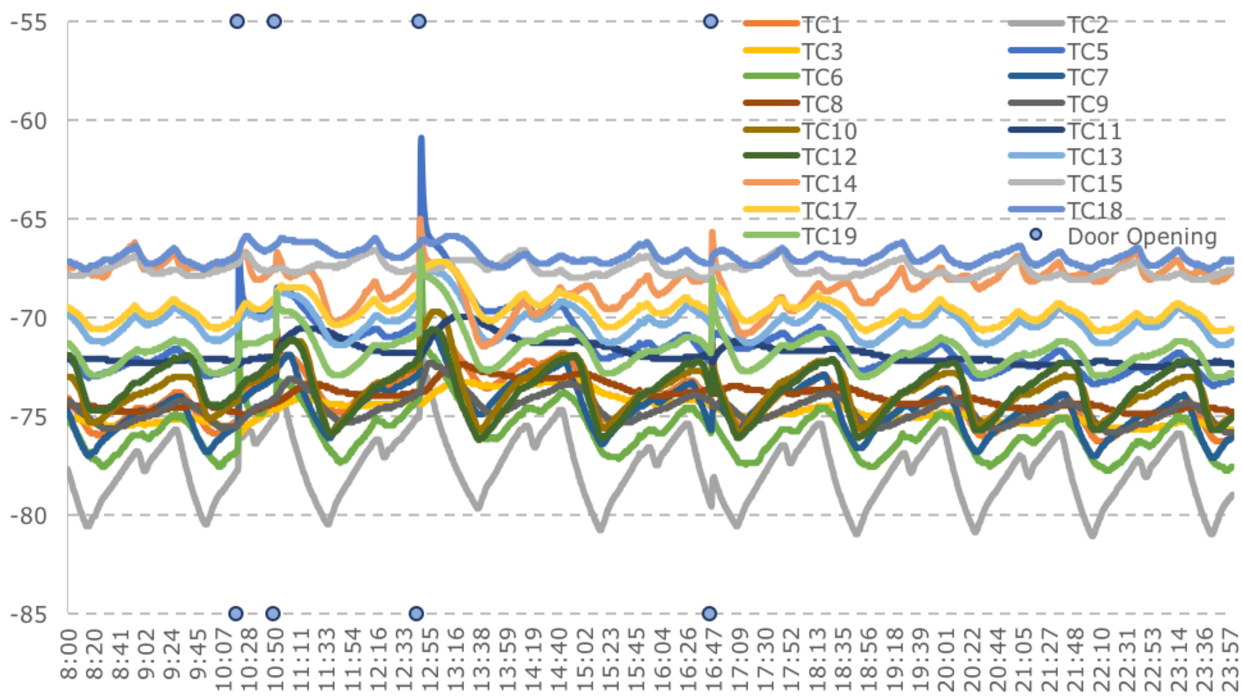


FIGURE 188: FREEZER C TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -70°C

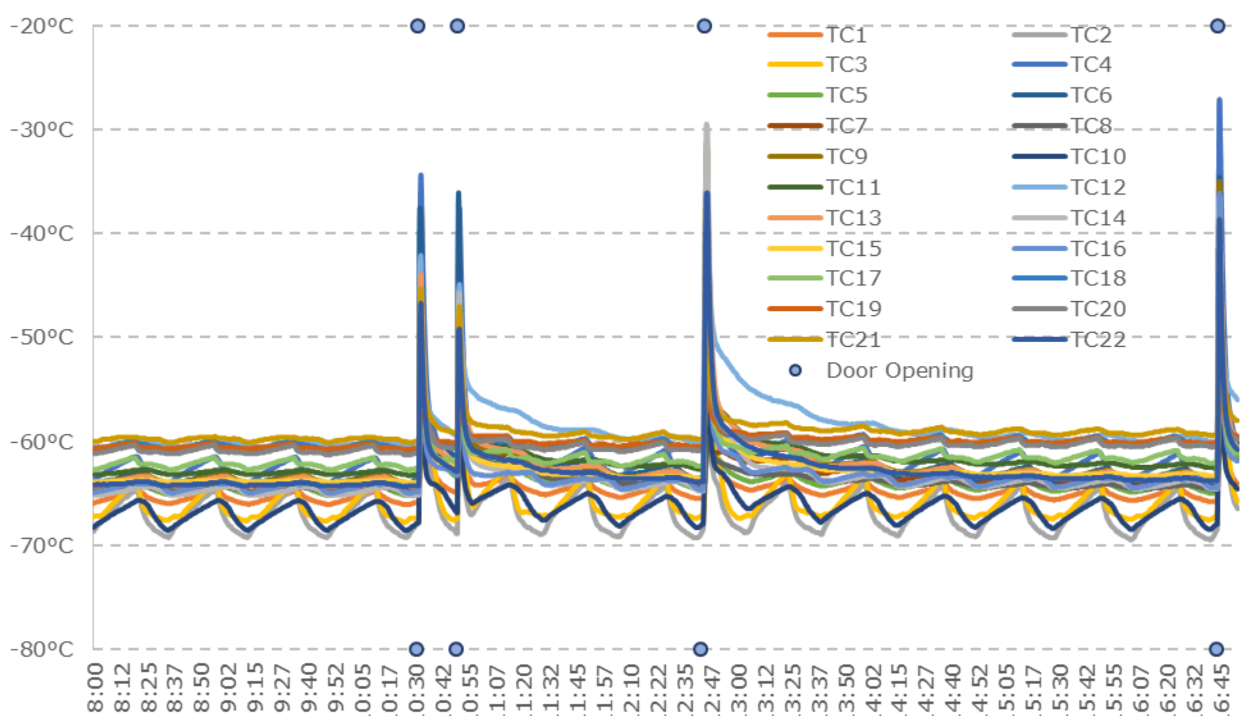


FIGURE 189: FREEZER D TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -70°C

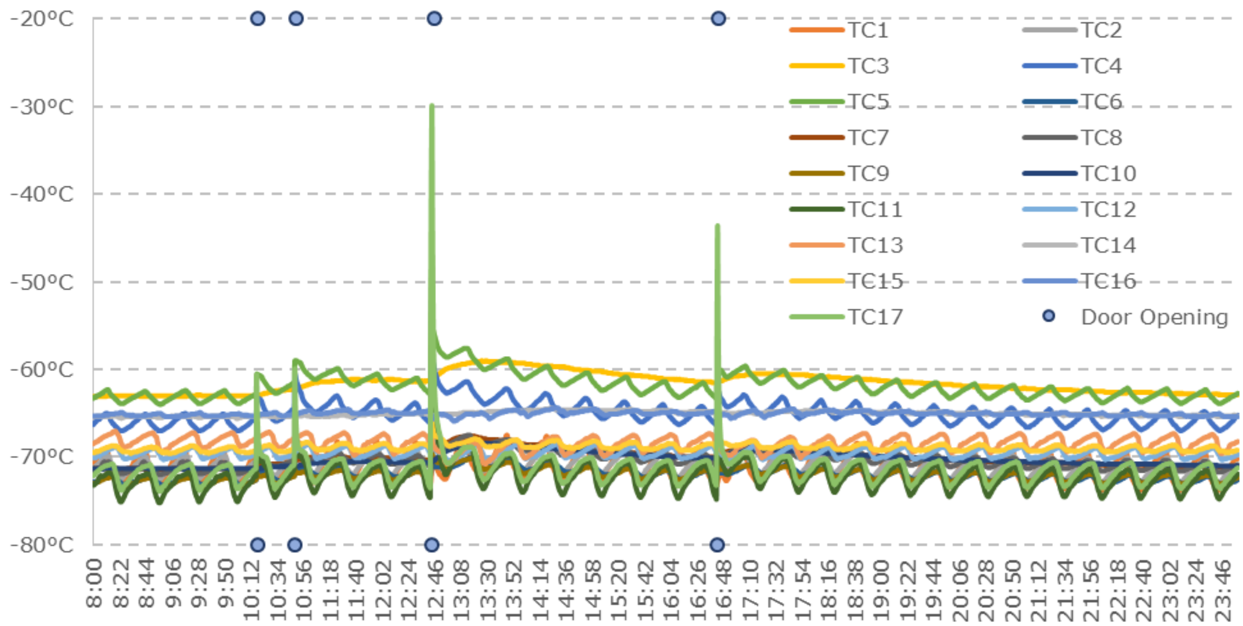


FIGURE 190: FREEZER E TEMPERATURE READINGS, THURSDAY DOOR OPENINGS AT -70°C

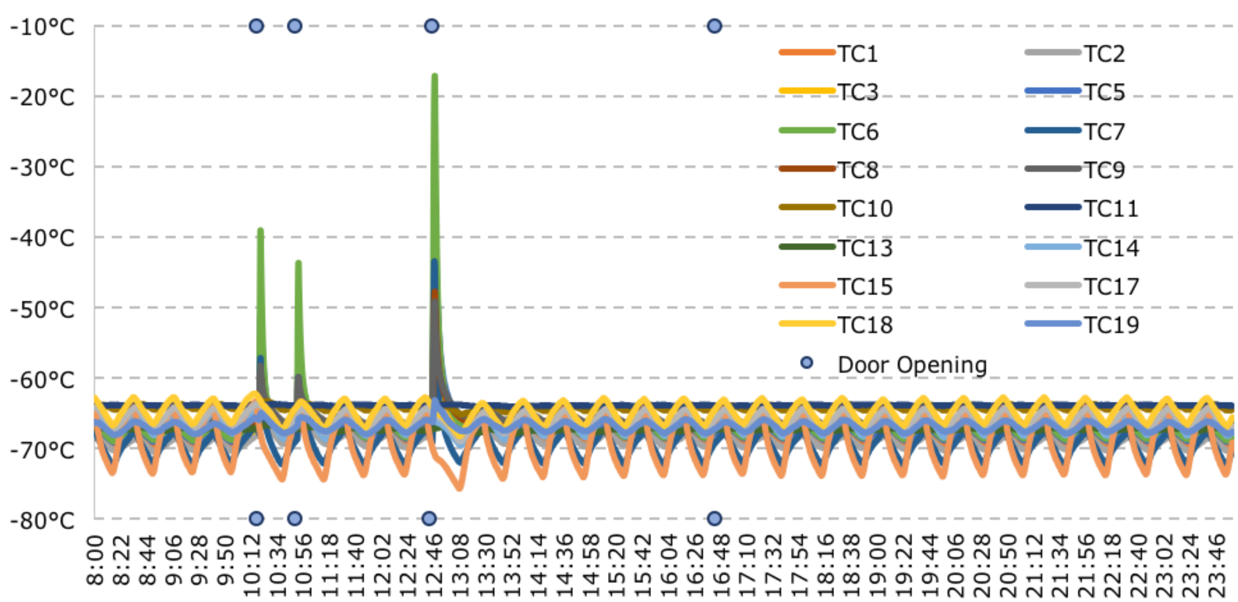


Figure 191: Freezer F Temperature Readings, Thursday Door Openings at -70°C

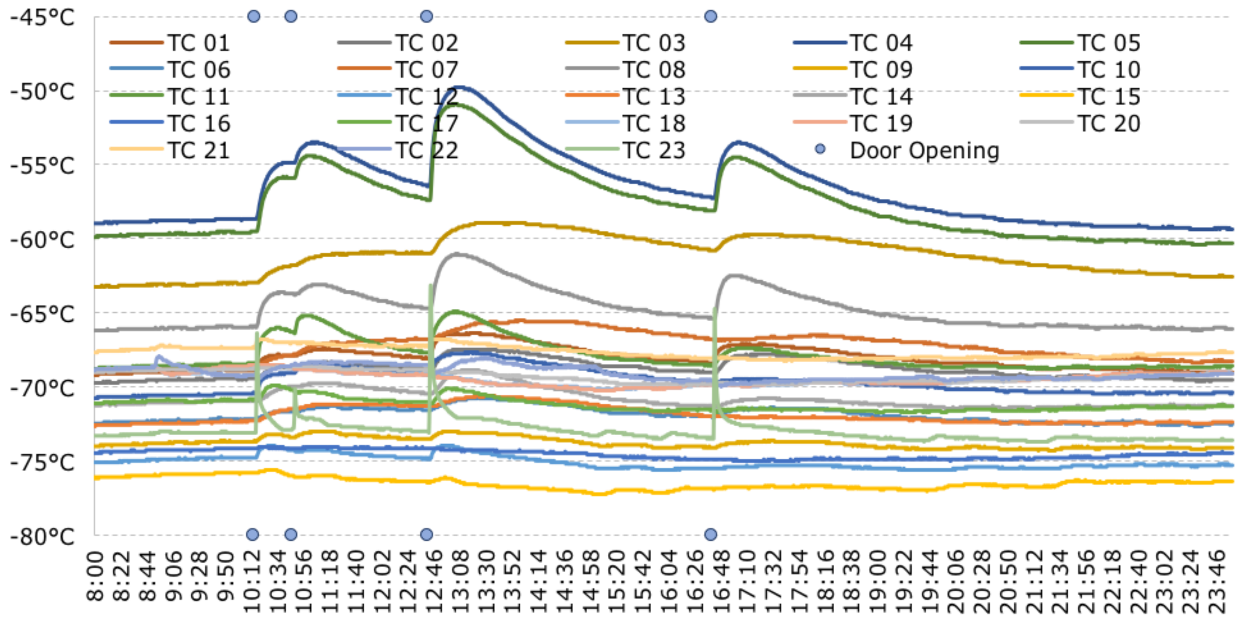
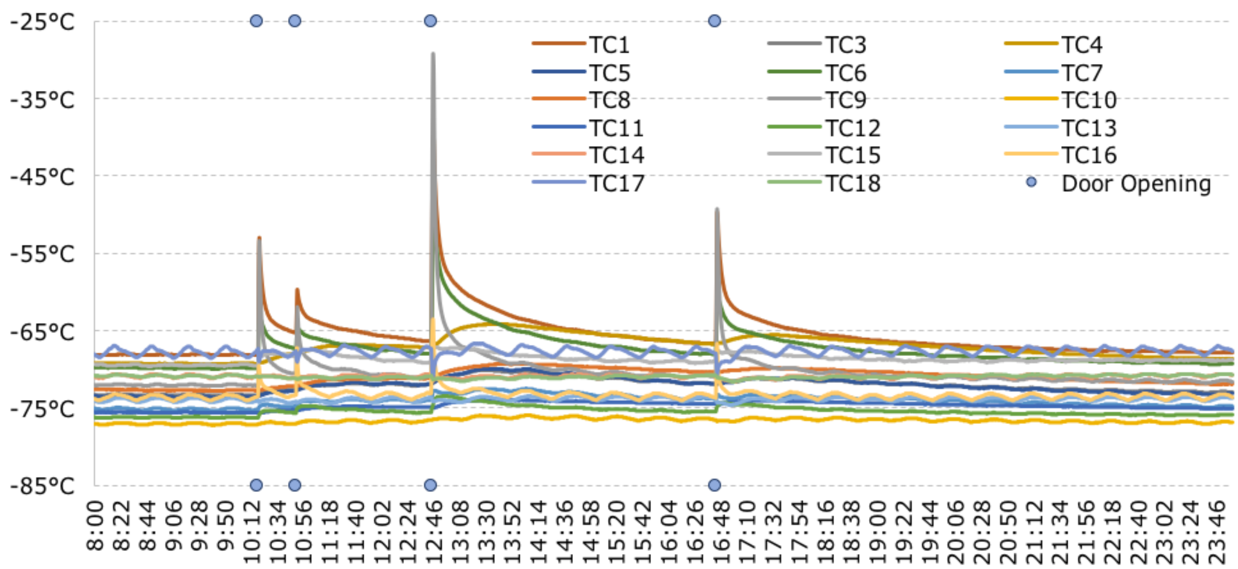


Figure 192: Freezer G Temperature Readings, Thursday Door Openings at -70°C



Appendix E: Door Opening Schedule

Friday

1:30pm: 21 seconds

1:46pm: 57 seconds

1:53pm: 11 seconds

Monday

11:21: 44 seconds

11:43: 45 seconds

11:56: 51 seconds

12:19: 32 seconds

12:20: 41 seconds

12:27: 23 seconds

12:45: 11 seconds

12:46: 14 seconds

12:49: 2mins 29 seconds

1:07: 11 seconds

4:06: 33 seconds

4:08: 11 seconds

5:09: 2mins 7 seconds

TUESDAY

10:46: 44 seconds

10:53: 12 seconds

11:01: 10 seconds

11:05: 24 seconds

11:08: 11 seconds

11:29: 30 seconds

2:26: 12 seconds

WEDNESDAY

10:59: 27 seconds

11:07: 55 seconds

1:28: 10 seconds

1:31: 28 seconds

2:40: 43 seconds

2:55: 44 seconds

3:25: 8 seconds

4:53: 48 seconds

THURSDAY

10:17: 32 seconds

10:49: 26 seconds

12:43: 1 minute 32 seconds

4:43: 44 seconds

APPENDIX F: HVAC SURVEY

HVAC SURVEY QUESTIONS

ULT Freezers and HVAC

Your info

*** 1. Please enter your name and contact information. (For our information only; we will not share your info.)**

First Name	
Last Name	
Email Address	
Zipcode	
Job Title	

Prev Next

ULT Freezers and HVAC

There are only 3 questions in this survey!

2. Please provide an estimate of the total number of ULT freezers at your institution. A rough number is OK.

3. Please estimate the *fraction* of ULT freezers at your institution in each type of space listed below.

For each row, describe the most common HVAC system serving that space type by choosing the *closest match* from the listed options (leave blank if space type contains no ULT freezers).

% of ULT freezers	HVAC system type serving location	Cooling supply air temp	Min ventilation rate (daytime)	Night airflow setbacks?	Cooling source	Typical room space temp
Location: **main lab** (with benches etc.)						
Location: **equipment room** or **equipment corridor**						
Location: regular **corridor** (an otherwise empty hallway)						
Location: **freezer farm** (room with >20 freezers)						

Please verify that total % ULT freezers adds up to 100%.

Abbreviations used above: OA = outside air; CHW = chilled water; AHU = air handler; ACH = air changes per hour; VAV = variable air volume; CV = constant air volume.

HVAC Survey Results

Table 49: Summary of Freezer Location Data from All Surveys

Facility or Survey	Main Lab (%)	Equipment Room (%)	Hallway (%)	Freezer Farm (%)	Total # Freezers
PG&E College 1	21	72	7	0	731
SCE College	20	50	20	10	1,374
PG&E College 2	40	25	20	15	1,200
SDG&E College	35	35	20	10	700
PG&E LSR	15	50	10	25	2,500
SCE LSR	35	0	0	65	1,000
SDG&E LSR	85	10	0	5	135
PG&E Small LSR	40	60	0	0	7
Walkthrough	12	60	3	25	461
ACSB	31	48	11	10	493
Online - CA	20	60	4	16	166
Online - rest of US	29	48	16	7	719
Average %	**32**	**43**	**9**	**16**	
Weighted Average %	**26**	**42**	**12**	**20**	
		# ULTs surveyed			9,486
		# ULTs surveyed in CA			8,767

TABLE 50: DETAILED RESULTS FROM HVAC SURVEY

MAIN LAB	SOURCE	SYSTEM TYPE	COOLING SAT (°F)	MIN VENT ACH	NIGHT SETBACK?	COOLING SOURCE	ROOM TEMP
Typical	Experience	100% OA VAV	60	8	N	CHW	72-74
SCE College	Survey	100% OA VAV	55	4	Y	CHW	70-75
PG&E College 2	Survey	100% OA VAV	60-65	6	N	CHW	70-75
SDG&E College	Survey	100% OA VAV	55-60	4	Y	CHW	70-75
PG&E LSR	Survey	100% OA VAV	55-60	8	N	CHW	75-80
SDG&E LSR	Survey	100% OA VAV	60-65	8	Y	CHW	70-75
SCE LSR	Survey	100% OA VAV	50-55	8	Y	CHW	70-75
PG&E College	Experience	100% OA VAV	55-60	6	N	CHW	70-75
Used in study	**Typical (from above)**	**100% OA VAV**	**60**	**8**	**N**	**CHW**	**70-75**

EQUIPMENT ROOM	SOURCE	SYSTEM TYPE	COOLING SAT (°F)	MIN VENT ACH	NIGHT SETBACK?	COOLING SOURCE	ROOM TEMP
Typical	Experience	100% OA VAV	60	8	N	CHW	75-80
SCE College	Survey	100% OA VAV	55	4	Y	CHW	75-80
PG&E College 2	Survey	100% OA VAV	55-60	6	N	CHW	70-75
SDG&E College	Survey	100% OA VAV	55-60	4	Y	CHW	75-80
PG&E LSR	Survey	100% OA VAV	55-60	10+	N	CHW	75-80
SDG&E LSR	Survey	100% OA VAV	60-65	8	Y	CHW	70-75
SCE LSR	Survey	100% OA VAV	50-55	8	Y	CHW	70-75
PG&E College	Experience	100% OA VAV	55-60	6	N	CHW	70-75
Used in study	**Typical (from above)**	**100% OA VAV**	**60**	**8**	**N**	**CHW**	**73-78**

HALLWAY	SOURCE	SYSTEM TYPE	COOLING SAT (°F)	MIN VENT ACH	NIGHT SETBACK?	COOLING SOURCE	ROOM TEMP
Typical	Experience	100% OA VAV	60	4	N	CHW	75-80
SCE College	Survey	100% OA VAV	55	4	Y	CHW	70-75
PG&E College 2	Survey	100% OA VAV	60-65	6	N	CHW	70-75
SDG&E College	Survey	100% OA VAV	55-60	4	Y	CHW	70-75
PG&E LSR	Survey	100% OA VAV	55-60	8	N	CHW	75-80
SDG&E LSR	Survey	100% OA VAV	60-65	8	Y	CHW	70-75
SCE LSR	Survey	100% OA VAV	50-55	8	Y	CHW	70-75
PG&E College	Experience	100% OA VAV	55-60	6	N	CHW	70-75
Used in study	**Typical (from above)**	**100% OA VAV**	**60**	**4**	**N**	**CHW**	**73-78**

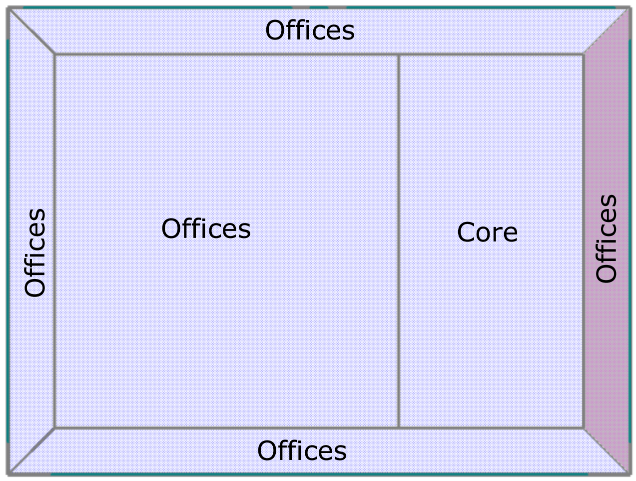
FREEZER FARM	SOURCE	SYSTEM TYPE	COOLING SAT (°F)	MIN VENT ACH	NIGHT SETBACK?	COOLING SOURCE	ROOM TEMP
Typical	Experience	FCUs	55	0	N	CHW	75-80
SCE College	Survey	FCUs	55	2	Y	CHW	75-80
PG&E College 2	Survey	FCUs	60-65	6	N	CHW	70-75
SDG&E College	Survey	FCUs	55-60	4	Y	CHW	70-75
PG&E LSR	Survey	SZ/FCUs	60-65	6	N	DX	70-75
SDG&E LSR	Survey	SZ	60-65	2	N	DX	70-75
SCE LSR	Survey	100% OA VAV	50-55	8	Y	CHW	70-75
PG&E College	(no freezer farms)						
Used in study	**Typical (from above)**	**FCUs**	**N/A**	**N/A**	**N**	**CHW**	**73-78**

Note: No HVAC system data were obtained from the PG&E Small LSR facility shown in the freezer location summary table.

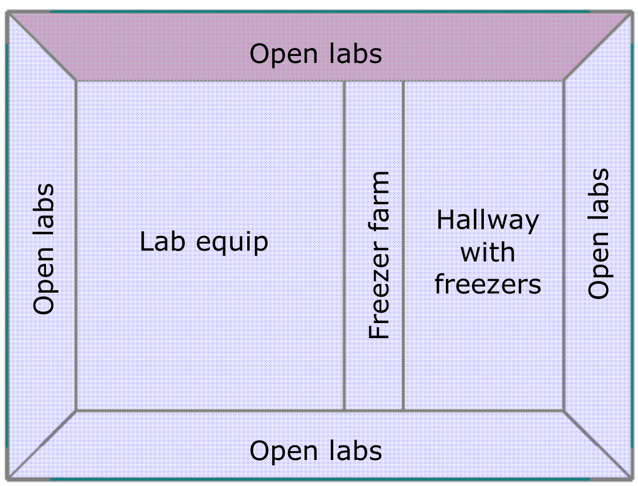
APPENDIX G: EQUEST MODEL

FIGURE 193: EQUEST MODEL GEOMETRY

Floor 1 (non-lab):



Floor 2 (lab):



Floor 3 (lab):

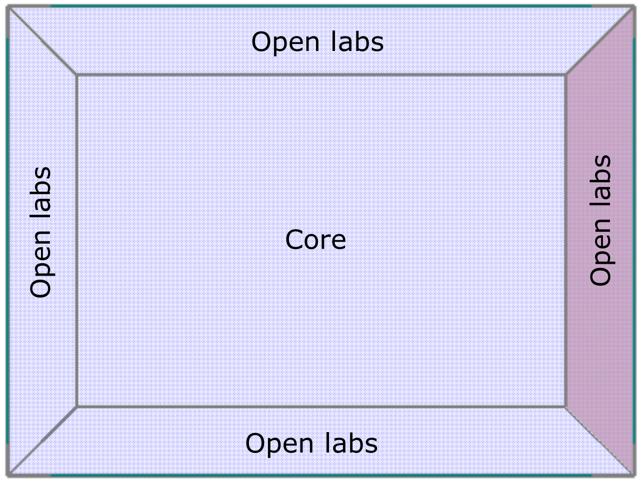


TABLE 51: DETAILED MODELING INPUTS

PARAMETER TYPE	PARAMETER	MODEL INPUT (CRITICAL INPUTS IN RED)	BASIS OF INPUT
Building Geometry and Composition	Total building area	90,000 sf	Audit back catalog
	Number of floors above ground	3	Audit back catalog
	Perimeter zone depth for office spaces	15 ft	Typical
	Perimeter zone depth for lab spaces	22 ft	Typical
	Floor to floor height	15 ft	Typical; assume 10 ft ceiling height
	Office area	25%	Typical
	Open lab area	30%	Median lab+lab support fraction from Labs21 dataset is 43%
	Equipment room area	10%	See above
	Core space area	35%	Typical
Envelope Construction	Roof	Built-up roof, minimal insulation. U-0.111	Typical
	Exterior wall	Steel-framed with stucco and minimal insulation. U-0.151	Typical
	Window properties	Aluminum frames, clear double glazing. Assembly U-0.6, SHGC-0.4	Typical
	Window area	30% of vertical wall area	Typical
Internal Loads	Lighting power density	1 W/sf	Typical
	Equipment power density, office	1 W/sf	Typical
	Equipment power density, lab	1.5 W/sf	See Table ??
	Equipment power density, equip room	10 W/sf	See Table ??
Schedules	Equipment power density, core	0.25 W/sf	Typical
	Lab and equipment room equipment	WD 7am-7pm 100%; 80% at other times	Typical; note 100% of typical max load, not of design load for HVAC sizing purposes.
	Non-lab equipment	WD 7am-7pm 80%; 40% at other times	Typical; note 100% of typical max load, not of design load for HVAC sizing purposes.
	Lighting	WD 7am-7pm 90%; 25% at other times	Typical
	HVAC	24/7	Common

Non-lab AHU	Service	Floor 1	
	Air handler type	VAV mixing unit with economizer and HW reheat	Typical
	Supply fan TSP	4" w.c.	Typical
	Return fan TSP	1.5" w.c.	Typical
	Fan speed control	VFD	Typical
	Cooling/heating sources	CHW/HW loops	Typical
	Minimum outside air fraction	25%	Typical
	Minimum zone level flow	50% of design	Typical
Lab AHU	Air handler type	100% OA VAV unit with HW reheat	HVAC survey
	Supply fan TSP	6" w.c.	Typical
	Exhaust fan TSP	5" w.c.	Typical
	Supply fan control	VFD	Typical
	Exhaust fan control	Constant volume	Outside air bypass assumed; typical
	Exhaust air heat recovery	None	Typical
	Cooling/heating sources	CHW/HW	HVAC survey
CHW system	Number of chillers	2	Typical
	Chiller type	Water cooled centrifugal	Typical
	Chiller capacity	166 tons each	Autosized
	Chiller full-load COP	5.5	CA Title 24 2013; typical
	Minimum loop flow	25% of design flow	Typical
	Chilled water pumps	Primary pump per chiller; secondary loop pump with VFD	Typical
	Condenser water pumps	1 constant speed pump per chiller	Typical
	Tower water control	1 cooling tower with VFD fan; 75F constant set point	Typical
	Chilled water valve type	2-way throughout	Typical of newer buildings
HW system	Number of boilers	2	Typical
	Boiler type	Forced draft, natural-gas fired	Typical
	Boiler efficiency	80% at full load	Typical
	Boiler capacity	2 MMBH each	Autosized
	Minimum loop flow	25% of design	Typical
	Pumps	One VFD loop pump	Typical
	Hot water valve type	2-way throughout	Typical of newer buildings

TABLE 52: LAB PLUG LOAD DATASETS USED TO CONSTRUCT MODEL

ORGANIZATION/SOURCE	KWH/SF/YR	AVERAGED OVER AREA	AVERAGE W/SF	METHODOLOGY
Labs21 benchmarking dataset	12	Whole building	1.4	Online owner-submitted data from sub-metering; small national sample.
Stanford University	7-9	Whole building	0.8-1.0	Campus-wide plug load inventory; does not include unusual equipment types. Range reflects low and high intensity lab building types.
UC Irvine	13	Labs and lab support spaces	1.5	<1 W/sf average in open labs; higher in support spaces.
CEEL Phase I report	7-28	Labs and lab support spaces	0.8-3.2	Lab equipment inventories via online and in-person surveys. Range reflects uncertainty in consumption of pieces of equipment.

TABLE 53: DETAILED EQUEST OUTPUTS FOR EACH CLIMATE ZONE

Climate Zone: CZ03	Model Run:	Base case	Lab ULT	Equip ULT	Corr ULT	Farm ULT
Electricity Consumption (kWh)	Area Lights	364,297	364,297	364,297	364,297	364,297
	Misc Equip	1,548,741	1,520,699	1,545,214	1,545,214	1,545,214
	Space Heating	4,927	4,979	4,927	4,928	4,927
	Space Cooling	291,921	291,866	291,799	291,873	291,023
	Heat Rejection	5,828	5,825	5,822	5,827	5,822
	Pumps & Aux.	122,644	122,645	122,643	122,644	122,643
	Vent Fans	1,177,320	1,177,094	1,176,628	1,177,286	1,177,320
	Total	**3,515,678**	**3,487,405**	**3,511,330**	**3,512,069**	**3,511,246**
Natural Gas Consumption (therms)	Space Heating	79,992	81,000	79,992	80,004	79,993
	Domestic Hot Water	2,172	2,172	2,172	2,172	2,172
	Total	**82,164**	**83,172**	**82,164**	**82,176**	**82,165**
Electricity Savings (kWh)	Area Lights		0	0	0	0
	Misc Equip		28,042	3,527	3,527	3,527
	Space Heating		-52	0	-1	0
	Space Cooling		55	122	48	898
	Heat Rejection		3	6	1	6
	Pumps & Aux.		-1	1	0	1
	Vent Fans		226	692	34	0
	Total		**28,273**	**4,348**	**3,609**	**4,432**
Natural Gas Savings (therms)	Space Heating		-1,008	0	-12	-1
	Domestic Hot Water		0	0	0	0
	Total		**-1,008**	**0**	**-12**	**-1**

		Lab ULT	Equip ULT	Corr ULT	Farm ULT
HVAC Savings / Direct Savings	Direct kWh savings	28,042	3,527	3,527	3,527
	HVAC kWh/direct kWh	0.008	0.233	0.023	0.257
	HVAC therms/direct kWh	-0.036	0.000	-0.003	0.000
HVAC/Direct Source Energy Savings	Direct savings (MMBtu/kWh)	0.0107	0.0107	0.0107	0.0107
	HVAC savings (MMBtu/kWh)	-0.0035	0.0025	-0.0001	0.0027
	HVAC/direct (%)	-33%	23%	-1%	25%

Climate Zone: CZ09	Model Run:	Base case	Lab ULT	Equip ULT	Corr ULT	Farm ULT
Electricity Consumption (kWh)	Area Lights	364,297	364,297	364,297	364,297	364,297
	Misc Equip	1,548,741	1,520,699	1,545,214	1,545,214	1,545,214
	Space Heating	4,033	4,086	4,033	4,034	4,033
	Space Cooling	468,250	468,189	468,017	468,192	467,527
	Heat Rejection	24,652	24,684	24,633	24,645	24,638
	Pumps & Aux.	133,056	133,101	133,043	133,048	133,053
	Vent Fans	1,205,514	1,204,438	1,204,686	1,205,462	1,205,513
	Total	**3,748,543**	**3,719,494**	**3,743,923**	**3,744,892**	**3,744,275**
Natural Gas Consumption (therms)	Space Heating	61,829	62,762	61,828	61,841	61,829
	Domestic Hot Water	2,002	2,002	2,002	2,002	2,002
	Total	**63,831**	**64,764**	**63,830**	**63,843**	**63,831**
Electricity Savings (kWh)	Area Lights		0	0	0	0
	Misc Equip		28,042	3,527	3,527	3,527
	Space Heating		-53	0	-1	0
	Space Cooling		61	233	58	723
	Heat Rejection		-32	19	7	14
	Pumps & Aux.		-45	13	8	3
	Vent Fans		1,076	828	52	1
	Total		**29,049**	**4,620**	**3,651**	**4,268**
Natural Gas Savings (therms)	Space Heating		-933	1	-12	0
	Domestic Hot Water		0	0	0	0
	Total		**-933**	**1**	**-12**	**0**

		Lab ULT	Equip ULT	Corr ULT	Farm ULT
HVAC Savings / Direct Savings	Direct kWh savings	28,042	3,527	3,527	3,527
	HVAC kWh/direct kWh	0.036	0.310	0.035	0.210
	HVAC therms/direct kWh	-0.033	0.000	-0.003	0.000
HVAC/Direct Source Energy Savings	Direct savings (MMBtu/kWh)	0.0107	0.0107	0.0107	0.0107
	HVAC savings (MMBtu/kWh)	-0.0029	0.0033	0.0000	0.0023
	HVAC/direct (%)	-27%	31%	0%	21%

Climate Zone: CZ15	Model Run:	Base case	Lab ULT	Equip ULT	Corr ULT	Farm ULT
Electricity Consumption (kWh)	Area Lights	364,297	364,297	364,297	364,297	364,297
	Misc Equip	1,548,741	1,520,699	1,545,214	1,545,214	1,545,214
	Space Heating	3,338	3,391	3,338	3,338	3,338
	Space Cooling	726,780	726,071	726,478	726,728	726,118
	Heat Rejection	51,442	51,352	51,410	51,438	51,410
	Pumps & Aux.	158,115	158,154	158,100	158,116	158,091
	Vent Fans	1,242,402	1,240,314	1,241,545	1,242,333	1,242,395
	Total	**4,095,115**	**4,064,278**	**4,090,382**	**4,091,464**	**4,090,863**
Natural Gas Consumption (therms)	Space Heating	50,927	51,772	50,932	50,937	50,927
	Domestic Hot Water	1,727	1,727	1,727	1,727	1,727
	Total	**52,654**	**53,499**	**52,659**	**52,664**	**52,654**
Electricity Savings (kWh)	Area Lights		0	0	0	0
	Misc Equip		28,042	3,527	3,527	3,527
	Space Heating		-53	0	0	0
	Space Cooling		709	302	52	662
	Heat Rejection		90	32	4	32
	Pumps & Aux.		-39	15	-1	24
	Vent Fans		2,088	857	69	7
	Total		**30,837**	**4,733**	**3,651**	**4,252**
Natural Gas Savings (therms)	Space Heating		-845	-5	-10	0
	Domestic Hot Water		0	0	0	0
	Total		**-845**	**-5**	**-10**	**0**

		Lab ULT	Equip ULT	Corr ULT	Farm ULT
HVAC Savings / Direct Savings	Direct kWh savings	28,042	3,527	3,527	3,527
	HVAC kWh/direct kWh	0.100	0.342	0.035	0.206
	HVAC therms/direct kWh	-0.030	-0.001	-0.003	0.000
HVAC/Direct Source Energy Savings	Direct savings (MMBtu/kWh)	0.0107	0.0107	0.0107	0.0107
	HVAC savings (MMBtu/kWh)	-0.0019	0.0035	0.0001	0.0022
	HVAC/direct (%)	-18%	33%	1%	21%

APPENDIX H: ONLINE SURVEY QUESTIONS

My Green Lab, a 501(c)3 non-profit, is leading the effort to bring ENERGY STAR ratings to new ultra-low temperature freezers (-80s), and we need your help. In order to properly develop the standards, we need to know more about which freezers are already in the market. Please fill out the survey below, and be a part of the first-ever effort to bring ENERGY STAR to lab equipment. All responses will remain completely confidential. You will not be contacted by us, or any vendors, as a result of your participation.

Your help with this project is greatly appreciated. If you do not know the answers to any of the questions please leave them blank; please do not guess.

At the end of the survey you may enter into a contest to win a set of Sonos speakers for you, or your lab, by providing us with your contact information. We will NOT contact you regarding the survey for any reason outside of the contest.

Thank you for your help! And don't forget to look for ENERGY STAR rated freezers and associated rebates soon!

-My Green Lab

1. What is the name of your organization?

2. City

3. State/Country

4. Which of the following best classifies the research done in your lab?

- ◯ Biology
- ◯ Biochemistry
- ◯ Biomedical Engineering
- ◯ Cell Biology
- ◯ Chemistry
- ◯ Computational
- ◯ Engineering
- ◯ Forensics
- ◯ Marine Biology
- ◯ Microbiology
- ◯ Molecular Biology
- ◯ Neuroscience
- ◯ Pathology
- ◯ Plant Biology
- ◯ Physics
- ◯ Systems Biology
- ◯ Testing
- ◯ Other (please specify)

5. What is your role in your organization?

General Freezer Information

6. What is the total number of upright -80 freezers in your lab?

7. Number of upright -80 freezers that are:

<15 cubic feet

15 - 20 cubic feet

21 - 28 cubic feet

29 - 32 cubic feet

>32 cubic feet

8. What is the total number of chest -80 freezers in your lab?

9. Number of chest -80 freezers that are:

<15 cubic feet

15 - 20 cubic feet

21 - 28 cubic feet

29 - 32 cubic feet

>32 cubic feet

10. How many of your freezers use a CO2 or LN2 backup system?

11. Where are your -80 freezers (upright and chest) located? Please indicate the number of freezers in each location.

Dedicated equipment room / equipment hallway

Hallway (otherwise empty corridor)

Freezer Farm

In the main lab

12. How often do you access the freezers in each location? Please be as specific as possible, e.g. twice a day, once a week.

	per day	per week	per month
Dedicated equipment room / equipment hallway			
Hallway (otherwise empty corridor)			
Freezer Farm			
In the main lab			

13. Which of these -80 freezer brands do you have in your lab? Check all that apply.

- ☐ Eppendorf
- ☐ Pansonic
- ☐ Stirling
- ☐ Fisher
- ☐ Revco
- ☐ Thermo
- ☐ New Brunswick
- ☐ Sanyo
- ☐ VWR
- ☐ Nor-Lake
- ☐ So-Low
- ☐ Z-Sci
- ☐ Other (please specify)

14. How many -80 freezers in your lab are:

1-5 years old	
6-10 years old	
11-15 years old	
16-20 years old	
more than 20 years old	
I don't know, but I think they're older than me!	

15. What is the average temperature of your ultra-low temperature freezers?

16. How full are your freezers?

Freezer Purchasing Information

17. How often does your lab purchase a new ultra-low temperature (-80) freezer?

18. When you purchase a new freezer, what is your primary reason for doing so?

- To replace an existing freezer
- To increase capacity
- I don't know
- Other (please specify)

19. What is most important to you when purchasing a new freezer? Please rank the following in order from most important (1) to least important (9).

	1 - most important	2	3	4	5	6	7	8	9 - least important	N/A
New technology										
Price										
Energy efficiency/ENERGY STAR rating										
Temperature range										
Capacity										
Legacy/Brand reputation										
Support										
Approved vendor										
Remote diagnostics/monitoring										

Other (please specify)

20. Do you consider energy efficiency when purchasing a new freezer?

- ◯ Yes
- ◯ No
- ◯ I don't know / I'm not involved with purchasing freezers for our lab

21. Would an energy efficiency rating, such as ENERGY STAR, influence your decision on which freezer to purchase?

- ◯ Yes
- ◯ No

22. Would you be willing to pay a premium for an energy-efficient -80 freezer?

- ◯ Yes
- ◯ No
- ◯ I don't have purchasing authority

23. If yes, what percent (%) premium would you be willing to pay?

24. If a financial incentive were available to purchase an energy efficient freezer, such as an ENERGY STAR rebate, who should receive the incentive in order for it to be effective? In other words, would you still be incentivized to purchase an energy efficient freezer if the rebate went to your department, or your organization, instead of directly to your lab?

- ☐ Scientists
- ☐ Departments / research organizations
- ☐ Manufacturers (in order to reduce the initial purchase price)
- ☐ Other (please specify)

25. Do you use room temperature sample storage in lieu of ultra-low temperature freezers?

- ◯ Yes, a majority of our samples are stored at room temperature
- ◯ Yes, some of our samples are stored at room temperature
- ◯ No, none of our sample are stored at room temperature
- ◯ I don't know

General Lab Information

26. Has your lab or your organization instituted any energy savings programs in the past?

- ◯ Yes
- ◯ No
- ◯ I don't know

27. If you answered yes above, what lab equipment or operations have these programs targeted? (check all that apply)

- ☐ Ventilation
- ☐ Fume Hoods
- ☐ ULT freezers
- ☐ ULT freezer storage
- ☐ Lighting
- ☐ Computers
- ☐ Other (please specify)

28. How many people are in your lab?

29. What is the name of your PI or lab group? We are asking this to prevent counting duplicate responses from the same lab.

Thank you!

Thank you so much for your time!

If you would like to be entered into a contest to win a pair of Sonos Play:1 speakers for yourself (or for your favorite labmates) please enter your contact information below.

30. Address

Name	
Address	
Address 2	
City/Town	
State/Province	
ZIP/Postal Code	
Country	
Email Address	

Appendix I: Analysis of Online Survey

The sustainability index

In order to better analyze the data and identify trends across responses, each survey respondent was given an indexed score. This score describes the extent to which the respondent's survey answers suggested a prioritization of energy efficiency, both in opinion and in action. The index has two components: a "priority index," meant to reflect the extent to which the respondent's opinions and institutional priorities exhibit a focus on sustainability and energy efficiency, and a "behavioral index," meant to demonstrate the extent to which the respondent's actions reflect a high prioritization of sustainability. Each of the priority and behavioral indices has a maximum score of 1.00, and were added to determine a total sustainability index score, the maximum for which was therefore 2.00.

By comparing, for example, the priority index scores to freezer capacity utilization on a respondent-by-respondent level, it was possible to determine whether respondents who "talked" about making energy efficiency a priority actually tried to maximize efficiency through their behaviors in their laboratories.

The components of the priority and behavioral indices are laid out below.

Figure 194: Sustainability index components

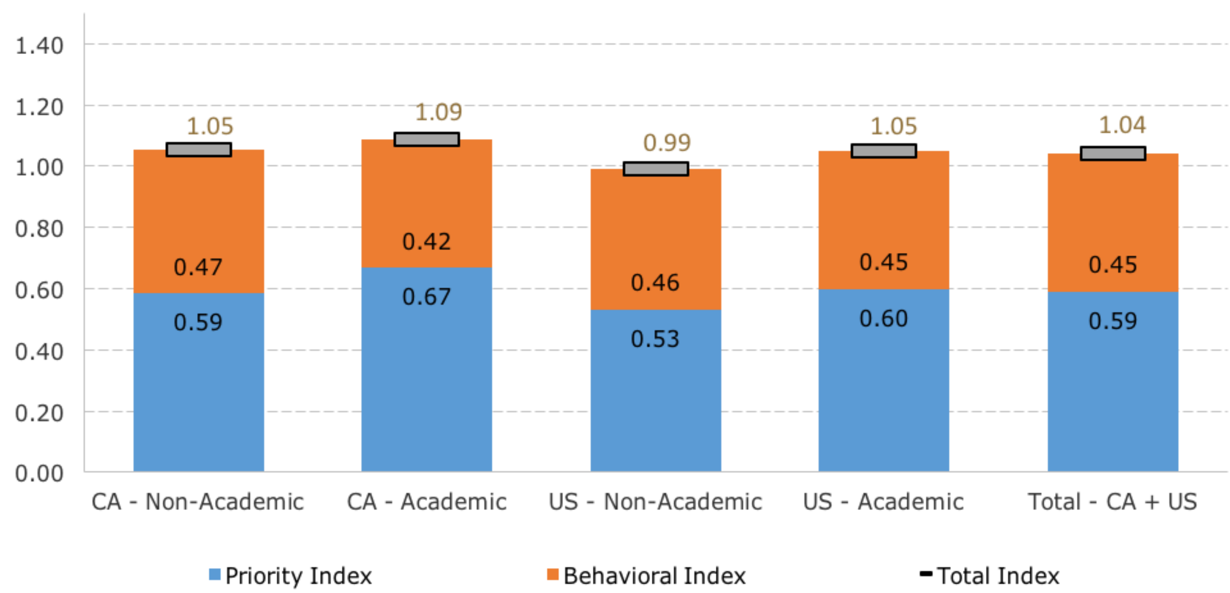
Priority index factors	Factor Weight	Max Score	Max Index
- Has an institutional energy efficiency program	0.25	1.00	0.25
- Considers energy efficiency in purchasing	0.25	1.00	0.25
- Ranks energy efficiency as a relatively important purchasing factor	0.25	1.00	0.25
- Would value an ENERGY STAR rating	0.25	1.00	0.25
Total priority index			**1.00**
Behavioral index factors	**Factor Weight**	**Max Score**	**Max Index**
- Uses room temperature storage	0.17	1.00	0.17
- Owns a Stirling freezer	0.17	1.00	0.17
- Has a freezer temperature set point over 80%	0.33	1.00	0.33
- Has freezer capacity utilization above 80%	0.33	1.00	0.33
Total behavior index			**1.00**
Total sustainability index			**2.00**

RESPONDENT SUSTAINABILITY INDEX SCORES

In general, California-based respondents had slightly higher sustainability index scores than respondents from other states. Across the study, academic institutions had higher scores. However, it is interesting that the higher scores at universities were entirely the result of higher priority indices; indeed, universities had lower behavioral index scores both inside and outside of California. In other words, while universities "talk more" about a focus on sustainability, it is the non-universities that engage in more sustainable behaviors.

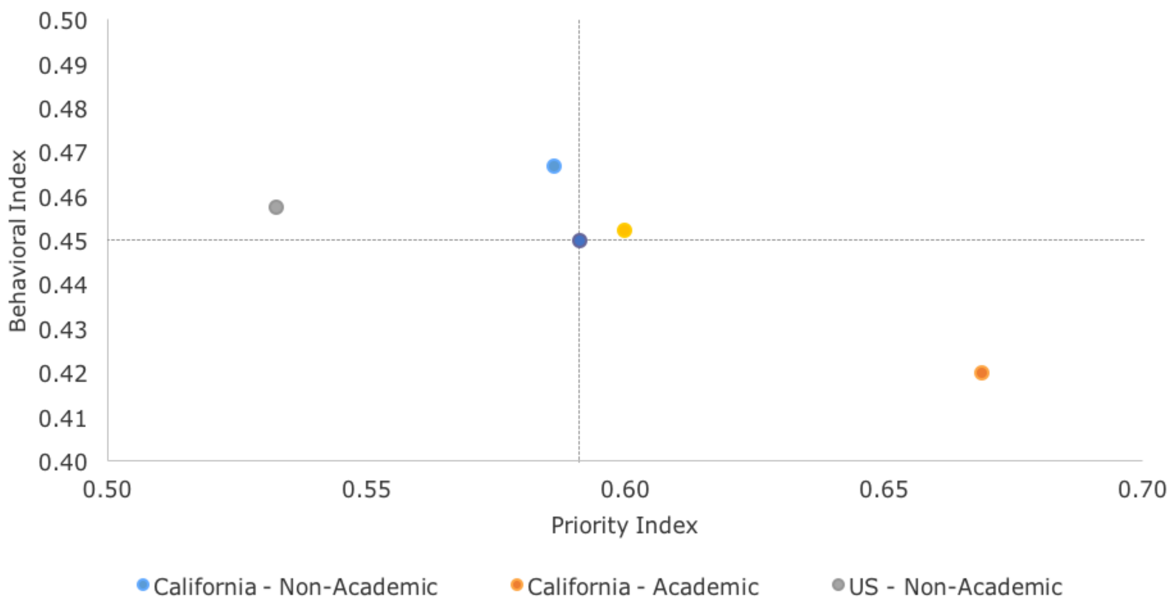
Average sustainability index scores for the respondent categories are shown below.

FIGURE 195: SUSTAINABILITY INDEX SCORES BY RESPONDENT CATEGORY



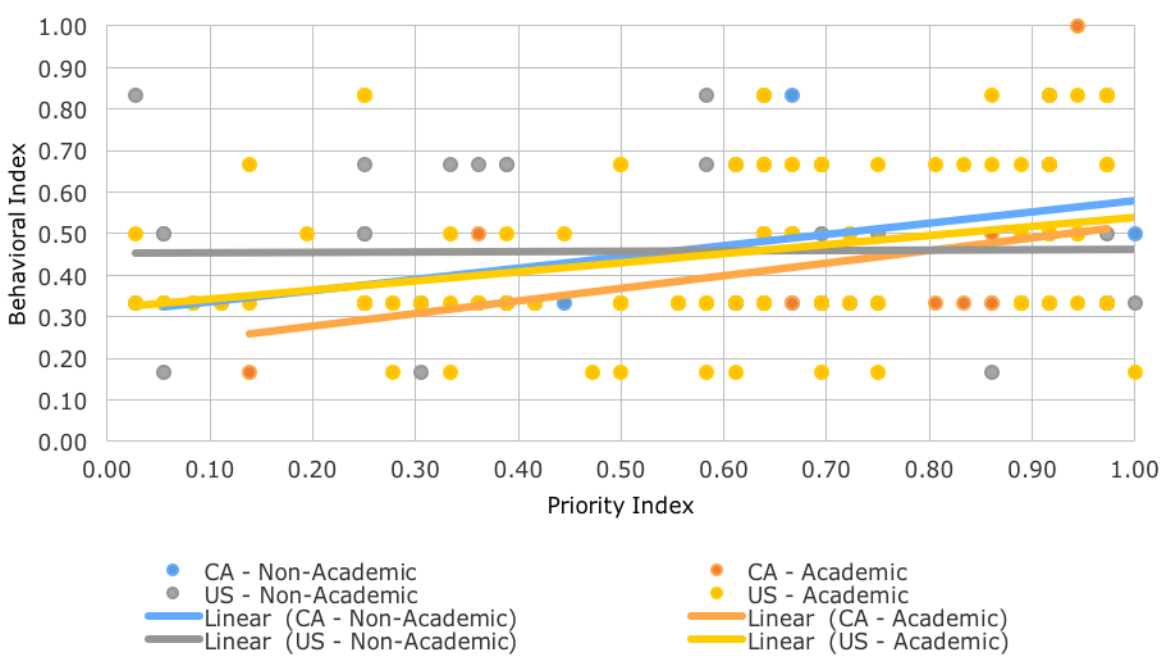
The below scatter plot directly compares priority and behavioral index scores for each respondent category. Note that both non-university categories plot in the upper-left quadrant, indicating higher behavioral index scores relative to their priority index scores. The California universities, plotted in the lower-right quadrant, exhibit the weakest behavioral index score, despite holding strong individual and institutions opinions about the importance of sustainability.

FIGURE 196: SUSTAINABILITY INDEX COMPONENTS BY RESPONDENT CATEGORY



While these observations suggest clear and important differences between the respondent categories, it is notable that – with the exception of the non-academic respondents outside of California – respondent priority and behavior index scores tend to vary directly.

FIGURE 197: CORRELATION OF BEHAVIORAL INDEX TO PRIORITY INDEX



PRIORITY INDEX SCORES AND BEHAVIORS

FIGURE 198: ULT FREEZER TEMPERATURE AS A FUNCTION OF PRIORITY INDEX SCORES – ALL SURVEY RESPONDENTS

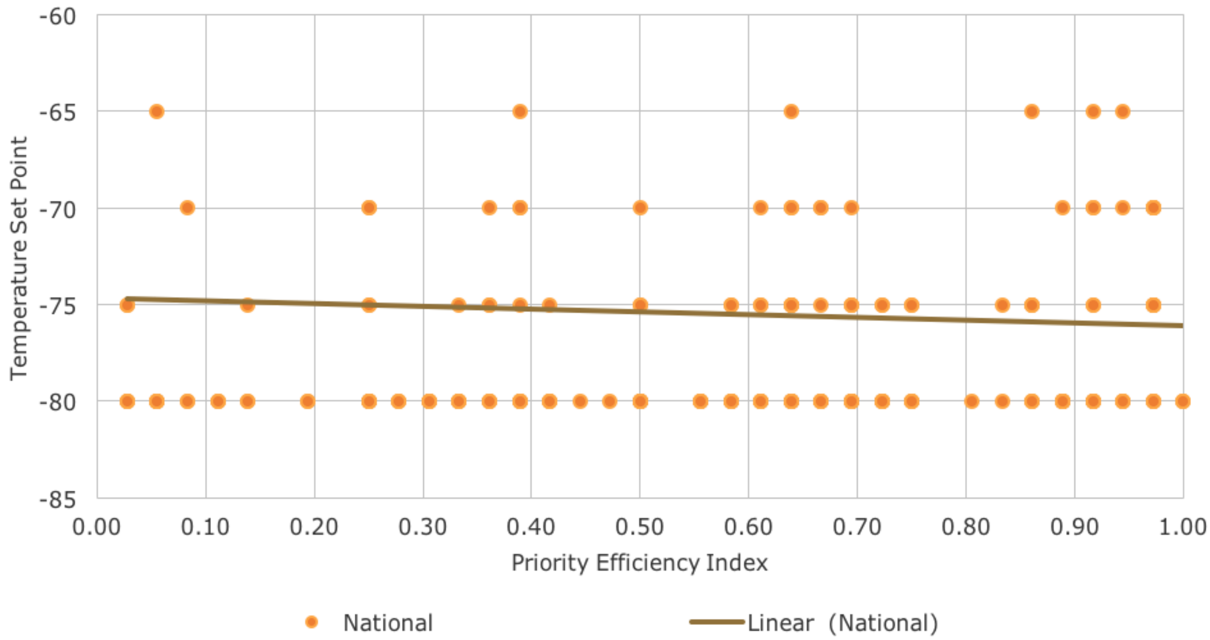
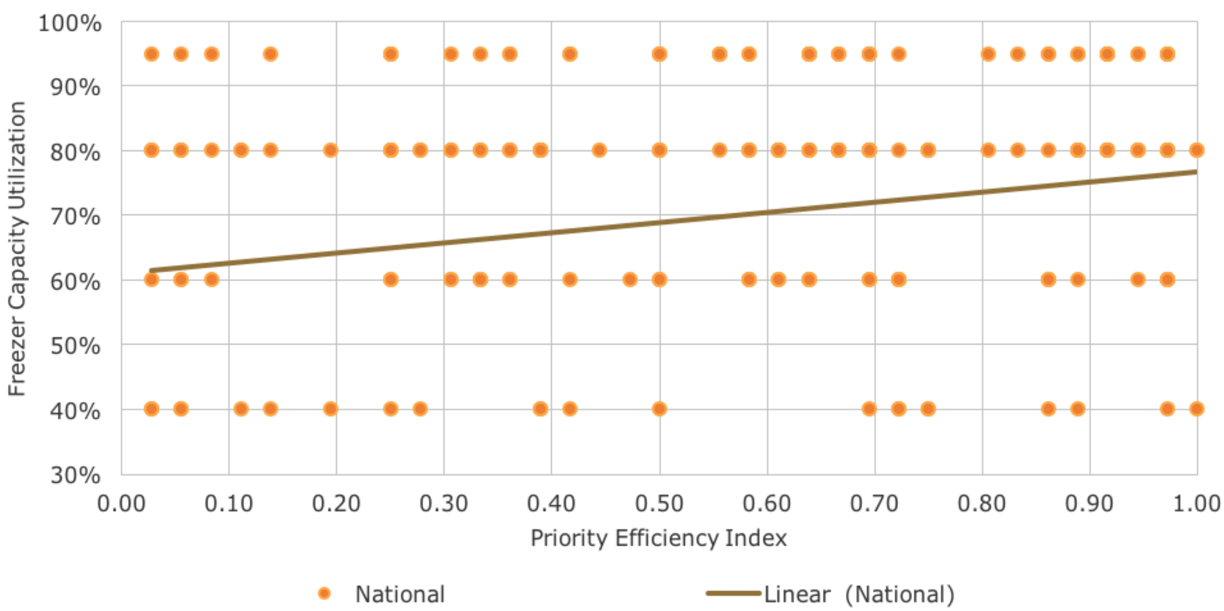


FIGURE 199: ULT FREEZER CAPACITY UTILIZATION AS A FUNCTION OF PRIORITY INDEX SCORES – ALL SURVEY RESPONDENTS



CORRELATION BETWEEN SURVEY RESPONSES

FIGURE 200: CORRELATION BETWEEN SURVEY RESPONSES

	Institutional EE program	Considers EE in purchasing	EE #1 importance in purchasing	Uses room temp storage	Values an ENERGY STAR rating	Stirling freezer	Setpoint above -80	Capacity utilization >=80%
Institutional EE program		73%	3%	27%	85%	14%	36%	74%
Considers EE in purchasing	48%		4%	27%	95%	10%	35%	66%
EE #1 importance in purchasing	43%	71%		14%	86%	29%	29%	57%
Uses room temp storage	44%	67%	2%		75%	8%	27%	63%
Values an ENERGY STAR rating	42%	72%	3%	23%		8%	33%	65%
Stirling freezer	86%	93%	14%	29%	93%		57%	64%
Setpoint above -80	46%	69%	3%	21%	85%	12%		66%
Capacity utilization >=80%	47%	64%	3%	24%	82%	7%	32%	

APPENDIX J: ASCB SURVEY RESULTS

SURVEY DEMOGRAPHICS

In addition to surveying scientists through an online survey, scientists were also surveyed about their ULT freezers at a scientific meeting for the American Society of Cell Biology (ASCB). At this conference, 276 researchers responded to questions about the quantity, age, size, and location of their ULT freezers. Their responses are presented below.

Thirty percent of the respondents were from California, and just over 53% were cell biologists or biochemists. Labs from California were overrepresented because the conference was held locally, in San Diego, this year. All of the research areas cited in the survey could be grouped together as representing 'life science research'.

FIGURE 201: LABORATORY LOCATION OF ASCB SURVEY RESPONDENTS, BY STATE

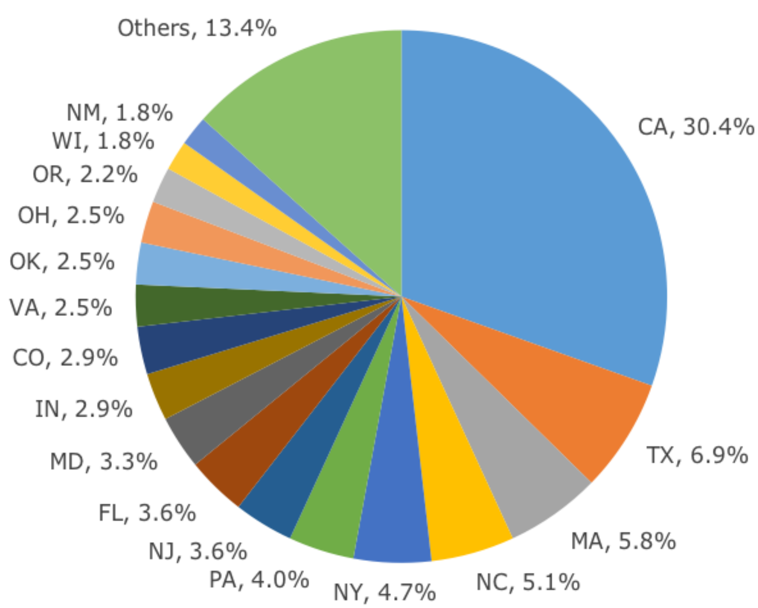
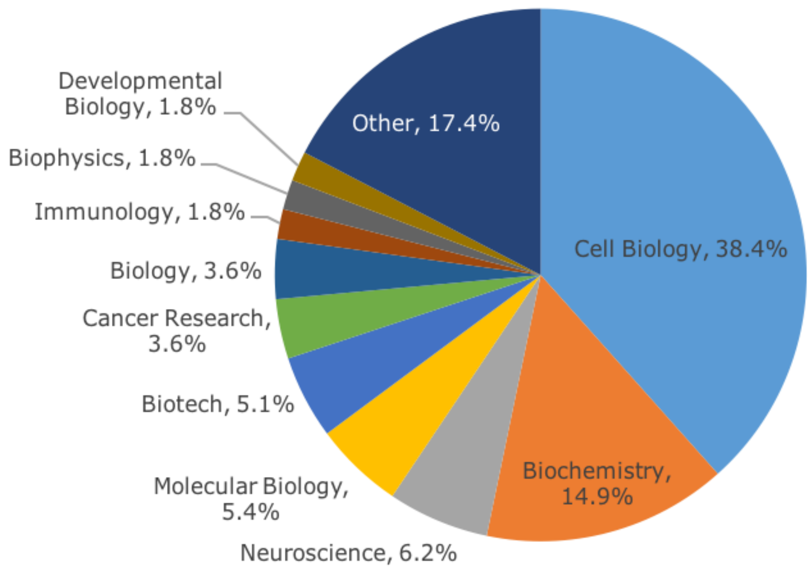


FIGURE 202: SCIENTIFIC AREA OF FOCUS OF ASCB SURVEY RESPONDENTS



FREEZER INVENTORY

Respondents from ASCB reported an average of 1.5 upright ULT freezers per academic lab, and 3.8 upright ULT freezer per non-academic lab. These numbers are slightly lower than what was reported through the online survey (2.8 and 4.1, respectively). A similar trend of in-person reporting of fewer freezers and pieces of laboratory equipment in general were observed in a previous market assessment. Results from a scientific meeting found scientists reporting 40-50% fewer units than respondents to an online survey. It is likely that this is due to the fact that it is difficult for respondents to remember all of their equipment when they are not in the lab; presumably the respondents who participated in the online survey were in their labs when responding to the questions. Nevertheless, the trend of non-academic labs having more upright ULT freezers per lab than academic labs held true in the ASCB survey results.

Interestingly the opposite trend was seen for chest ULT freezers, with academic labs reporting an average of 0.46 per lab, and non-academic labs reporting an average of 1.9 per lab. These numbers are twice as much as were reported in the online survey. The online survey found that chest freezers comprised between 7% and 16% of the ULT freezer market; the ASCB survey puts that number at just above 20%. Based on laboratory audits done of several hundred freezers in California (see Chapter 5), 20% is likely a bit higher than the actual number. However, once again, the data suggest that upright ULT freezers dominate the marketplace, and thus were the correct type of freezer on which to focus the attention of this study.

FIGURE 203: NUMBER OF UPRIGHT FREEZERS PER LAB FOR ASCB SURVEY RESPONDENTS

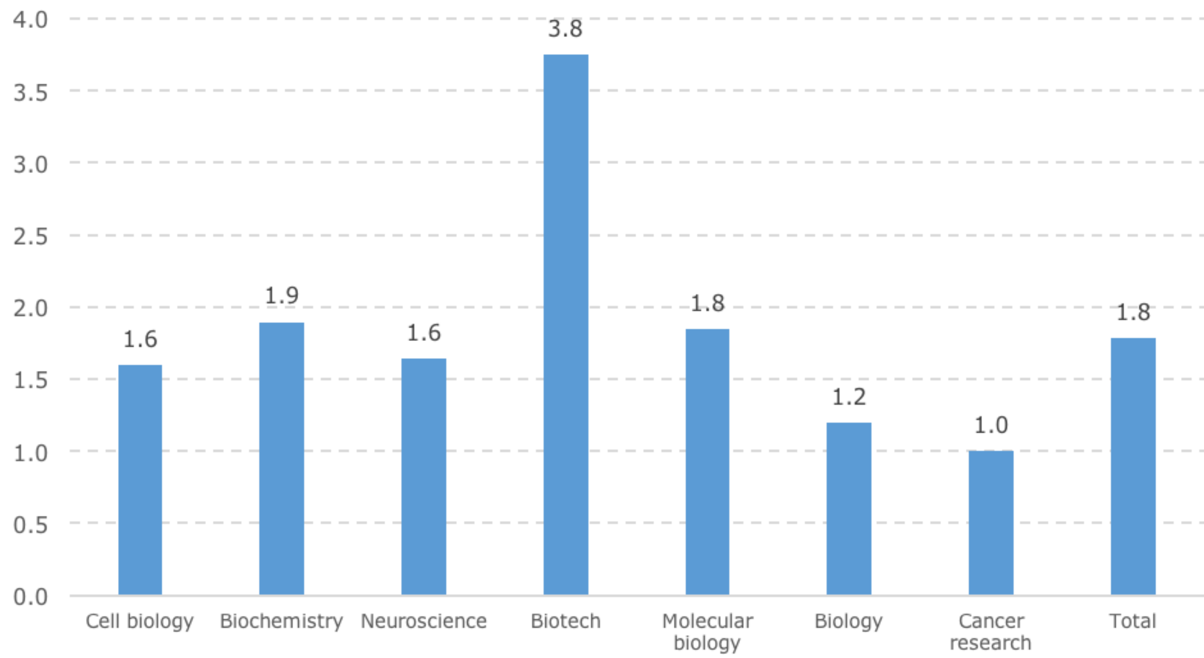
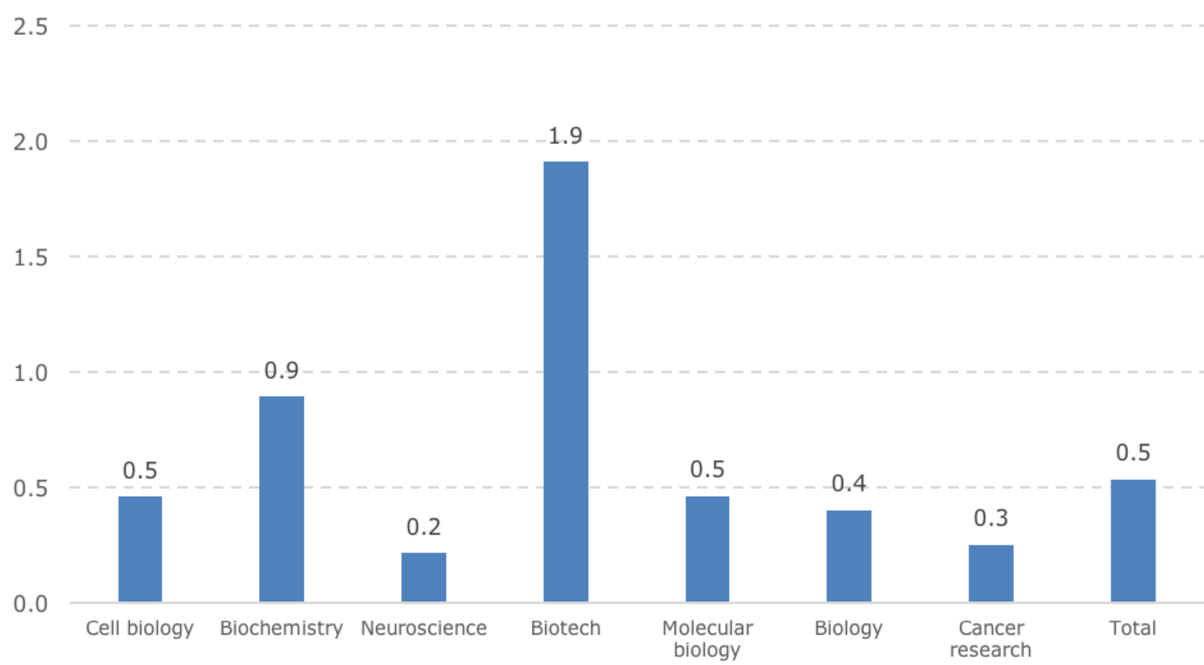


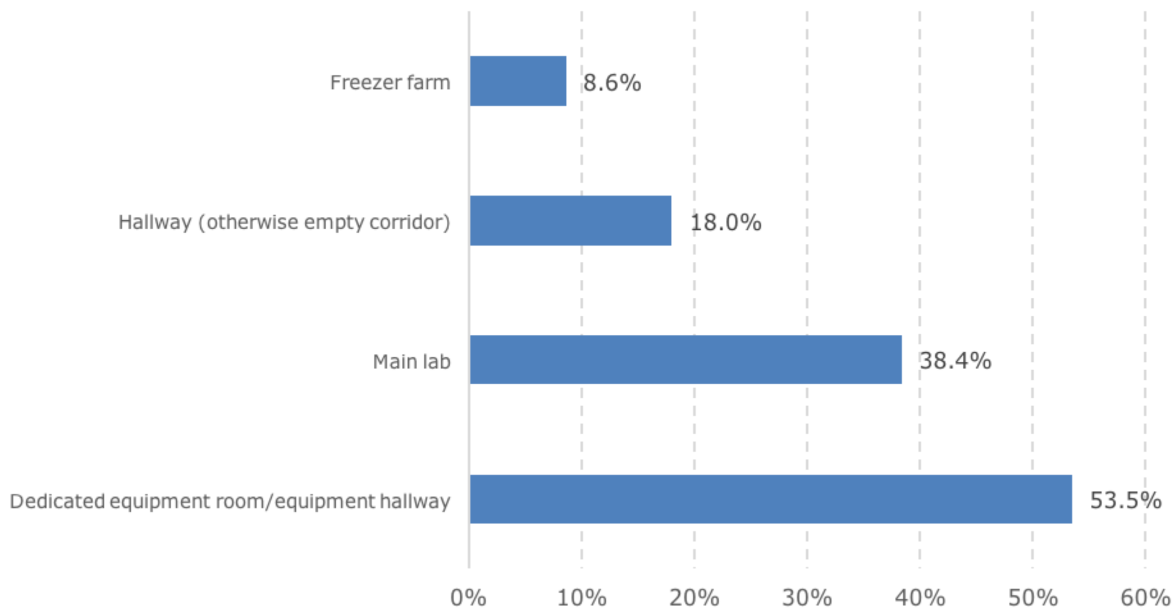
FIGURE 204: NUMBER OF CHEST FREEZERS PER LAB FOR ASCB SURVEY RESPONDENTS



FREEZER LOCATION

Over 50% of respondents to the ASCB survey indicated that their ULT freezers were located in dedicated equipment rooms or equipment hallways. This was followed by the main lab, and then general hallways. These results are in alignment with the data collected from the online survey, suggesting that indeed, most ULT freezers are found in either dedicated spaces or in the lab itself.

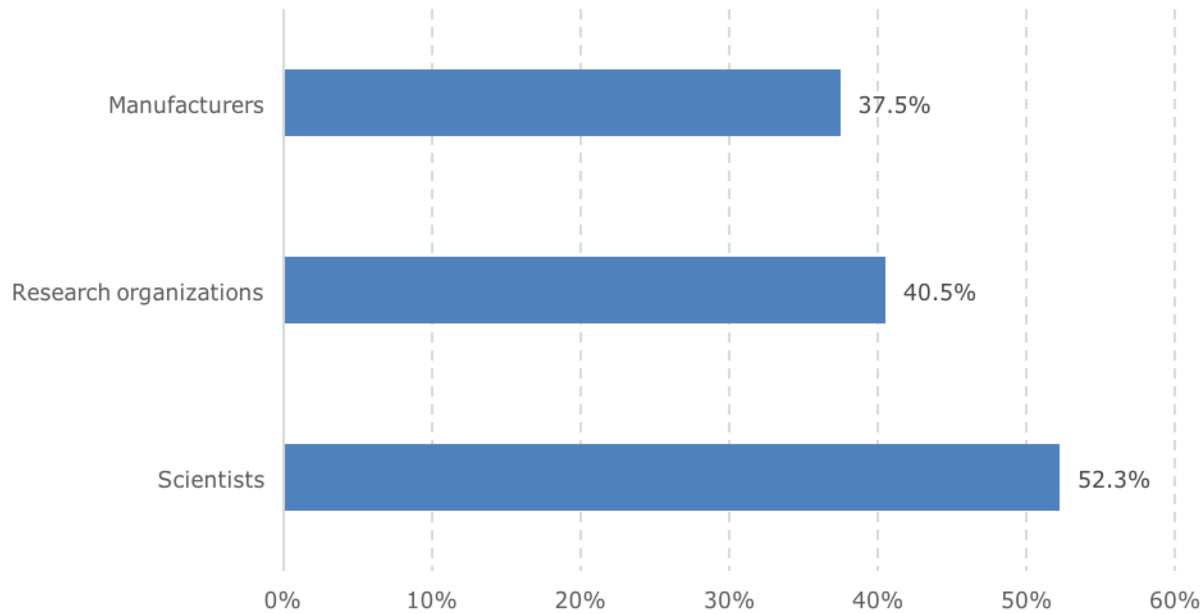
FIGURE 205: FREEZER LOCATIONS FOR ASCB SURVEY RESPONDENTS



PURCHASE INCENTIVES

The ASCB data trends matched those observed in the online survey in terms of scientists' responses to the question of who should receive a financial incentive for energy efficient equipment. The majority of respondents agreed that incentives should go first to scientists themselves, then to research organizations, and finally to manufacturers.

FIGURE 206: PREFERRED TARGET OF PURCHASE INCENTIVES FOR ASCB SURVEY RESPONDENTS



FREEZER BRANDS

Thermo Fisher ULT freezer brands dominated the ASCB survey responses to the question of which ULT freezer brands labs have. As seen in Figure 207 below, Thermo, Revco, and Forma (all Thermo brands), accounted for 71% of ULT freezers in the survey. VWR had the second-most market share among respondents, accounting for 12% of ULT freezers, followed closely by Panasonic at 9.3%. These results mirror those seen in the online survey, and in the in-person audits of laboratory ULT freezers in California.

FIGURE 207: FREEZER BRANDS IN LABS OF ASCB RESPONDENTS