High Efficiency Refrigerated Display Case

Final Report

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Prepared by:

Abby Wiseman VEIC

Christine White VEIC

Leila Nikdel VEIC

Nicole Duquette VEIC

Juan Catano, PhD NREL

Ramin Faramarzi, PE NREL

Cu Khan NREL

Alex Bulk NREL

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Abbreviations and Acronyms

Acronym	Meaning
AHJ	Authorities having jurisdiction
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
Btu	British thermal units
CFC	Chlorofluorocarbons
CZ	Climate zone
DAC	Disadvantaged communities
DEER	Database for Energy Efficiency Resources
DOE	Department of Energy
EEV	Electronic expansion valve
EPA	Environmental Protection Agency
EUI	Energy use intensity
FDA	Food & Drug Administration
FCM	Fluid-conditioning module
GHG	Greenhouse gases
GWP	Global warming potential
GPM	Gallons per minute
HC	Hydrocarbon
HERC	High efficiency refrigerated case
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HTR	Hard-to-reach

Acronym	Meaning
HVAC	Heating, ventilation, and air conditioning
IECC	Internation Energy Conservation Code
IOU	Investor-owned utility
NASRC	North American Sustainable Refrigeration Council
NREL	National Renewable Energy Laboratory
RIC	Reach-in cooler
RC	Remote condensing
SC	Self-contained condensing unit
USDA	US Department of Agriculture
VCT	Vertical closed
VFD	Variable-frequency drive
VOP	Vertical open

Executive Summary

This report is the market potential study and technology performance assessment of high efficiency, liquid-cooled, low-greenhouse-warming-potential (GWP), self-contained, medium-temperature, refrigerated display cases with advanced controls. The main objectives of this report are to quantify the energy use of these cases and to use the results to develop a building energy model to quantify the whole-building energy implications of using liquid-cooled cases. The results from the market study and assessment help to quantify energy use and opportunities for small (< 8,000 square feet) and large (> 8,000 square feet) grocery stores to transition to low-GWP refrigerants using micro-distributed systems (MDS). The recommendations provided in this study can be used to inform California investor-owned utility (IOU) energy efficiency programs to increase the adoption of high efficiency, liquid-cooled, self-contained, low-GWP refrigerated cases. Commercially available, these cases can play an instrumental role in achieving California's energy efficiency and greenhouse gas reduction targets.

Key Findings and Outcomes

1. The high efficiency, liquid-cooled, R-290, self-contained, medium-temperature, refrigerated display operated at an inlet temperature of 55 °F showed five percent savings over the benchmark R-513a case and 45 percent savings over the benchmark R-134a case when comparing Wh/day/ft^3 total energy normalized to internal volume.

Table 1: Comparison Between the Energy Efficient and Benchmark Cases Total Daily Energy, Normalized by Case Volume

Total Energy (Wh/day/ft^3)						
	Efficient Case (at various inlet temperatures)				Benchmark Cases	
	55 °F	80 °F	95 °F	108 °F	R-134a Reach-In Case	R-513a Reach-In Case
ASHRAE 72 Conditions	126.2	173.2	215.1	233.2	233.2	157.2
Average Store Conditions	120.8	155.4	204.9	232.1	217.4	126.9

2. The energy modeling shows savings for small and large grocery stores when replacing either closed or open reach-in fixtures, as follows:

    a. Four percent annual savings for small grocery stores and five percent energy savings for large grocery stores, when replacing all medium-temperature, closed, reach-in fixtures with high efficiency, medium-temperature, water-cooled, R-290, reach-in display cases.

    b. Nineteen percent annual energy savings for small grocery stores and nine percent energy savings for large grocery stores, when replacing all medium-temperature open reach-in fixtures with high efficiency, medium-temperature, water-cooled, R-290, reach-in display cases.

3. Medium-temperature, vertical cases comprised nearly 42.6 percent of shipped linear feet of refrigerated cases in the United States in 2020. Of the total cases shipped per year, California receives an estimated 142,000 refrigerated cases annually. Every one percent increment in market adoption of high efficiency, liquid-cooled, low-GWP, self-contained, medium-temperature, refrigerated display cases with advanced controls would result in annual electric savings of ~243 MWh, annual gas savings of ~872 MMBtu, and annual GHG reductions of ~98 MT CO_2e.
4. The following notable market barriers were identified:
    a. Equipment acceptance and understanding
    b. First costs
    c. Contractor reluctance and education

Key Recommendations

The project team recommends:

- Additional research to characterize the range of energy savings from retrofit versus market opportunity, small grocery versus large supermarket, low versus medium-temperature cases, open versus closed baseline, self-contained versus remote condensing baseline, and mechanically cooled versus naturally cooled buildings.
- California IOUs incentivize existing propane refrigeration systems, including packaged hydrocarbon and natural refrigerant condensing units and self-contained refrigerated cases. Additionally, IOUs can promote contractor education and certification on the safe handling of propane equipment.
- Accelerating the adoption of increased propane charge size limits in federal, state, and regional codes and standards, including US Environmental Protection Agency Significant New Alternatives Policy (EPA SNAP) and ASHRAE 15 safety standards, and local building codes.

Introduction

California has ambitious greenhouse gas (GHG) emissions targets, with a goal of 85 percent reduction (relative to 1990) by 2045[1]. Supermarkets and grocery stores can contribute by reducing energy demand and reducing potential GHG emissions from the release of refrigerants into the atmosphere.

The commercial sector accounts for nearly 18 percent of the energy use in California. Supermarkets and grocery stores have some of the highest energy use intensities (EUIs) in the commercial building sector, with electric use typically ranging from 40 to 60 kWh per square foot. Refrigeration systems account for 50 to 70 percent of the electric energy used in these buildings; and these systems leak up to 25 percent of their refrigerant annually. Nationally, this leaked refrigerant results in GHG emissions equivalent to powering 12 million homes(California Code of Regulations Title 20).

Traditional refrigerants have high Global Warming Potential (GWP), values ranging from 1,200 to more than 4,000. To reduce GHG emissions from refrigeration systems, the industry is seeing a shift towards natural refrigerants and low-GWP alternatives, including hydrocarbons, which have GWP values less than 10.

Historically, large commercial food retailers have been required to perform a full multi-plex rack system retrofit when seeking to shift from traditional hydrofluorocarbon (HFC) refrigerants to low-GWP natural refrigerants, which is possible in some cases, but expensive and disruptive. For smaller stores, self-contained air-cooled hydrocarbon cases have been an affordable and feasible natural refrigerant option. However, a major gap in the market remains. Small-to-medium grocery and food retailers that have refrigerated cases served by a combination of self-contained units, remote condensing units, and small rack systems represent a major market segment that has been unable to install low-GWP and natural refrigerant technologies due to cost and feasibility concerns.

Air-cooled, self-contained cases offer an opportunity for small-to-medium stores to shift to low-GWP refrigerant technology without the high capital investment or disruptions required to install a centralized low-GWP rack system. However, these cases reject heat to the sales floor, which can increase cooling loads. Additionally, food retailers with smaller store footprints are less likely to have air conditioning systems at all. The market for high efficiency, liquid-cooled, self-contained cases extends beyond the traditional market for air-cooled cases by offering additional energy savings potential and greater control, while maintaining system flexibility for small, medium, and even large retailers.

Background

In addition to California's GHG reduction targets, the United States ratified the Kigali Amendment to the Montreal Protocol in October of 2022, committing to reducing HFC production and consumption

[1] California Releases World's First Plan to Achieve Net Zero Carbon Pollution | Governor of California

by 80 to 85 percent; the subsequent American Innovation and Manufacturing (AIM) Act 2024 HFC allocation rule set forth a target of 85 percent reduction in HFCs by 2036 in the United States (US EPA 2022). In addition, the state of California is pursuing more ambitious targets. The California Air Resource Board (CARB) has implemented California Significant New Alternatives Policy (SNAP) legislation stating that all new retail food refrigeration systems containing more than 50 pounds of refrigerant must use refrigerants with a GWP less than 150.

These goals and regulations lay the foundation for reduced production and consumption of commonly used, high-GWP HFC refrigerants, increasing the urgency for businesses with high refrigeration needs to consider low-GWP and natural refrigerants in their capital investment decision-making (US EPA 2024). The continuous evolution of refrigerant legislation is also driving refrigeration equipment manufacturers to develop new high efficiency, low-GWP and natural refrigerant equipment to ensure compliance with evolving federal standards. As new refrigerated case technologies and low-GWP refrigerant options enter the market, high efficiency, self-contained, liquid-cooled refrigerated display cases present energy efficient and low-carbon solutions for food retailers to consider.

California is home to nearly 23,000 food retail establishments, including convenience stores, grocery stores, supermarkets, warehouse clubs, and supercenters, as estimated from the 2021 Census data. These retailers operate nearly eight million linear feet of self-contained and remote condensing refrigerated cases(DOE 2021). As California policymakers enforce new regulations such as Senate Bill 1383 to achieve state GHG reduction goals, it is critical to understand the energy efficiency implications of low-GWP refrigerants in commercial food retail applications.

Food sales and food retail establishments operate on low profit margins of just three to five percent. As energy codes and refrigerant legislation become more stringent, it is increasingly difficult for these retailers to remain in compliance and remain open. Helping to keep smaller and independent food retailers in business by providing cost-effective, energy efficient, and reliable solutions for their operations will reduce food deserts, which are more likely to be located in hard-to-reach (HTR) and disadvantaged community (DAC) areas typically with low-income populations and having limited or low access to healthy food choices(Ploeg 2010).

Low income and low access populations are defined as areas where a significant number or share of residents are more than one mile (urban) or 10 miles (rural) from the nearest food retailer. According to the US Department of Agriculture (USDA) Food Access Research Atlas, in 2019, there were 536 census tracts in California, supporting an estimated population of 2.67 million people, with limited access to supermarkets, supercenters, grocery stores, and other sources of healthy and affordable foods. Increasing knowledge of and access to innovative technologies for food retailers in these areas will help reduce food insecurity for HTR and DAC communities. This study aims to increase transparency and support programs for climate-friendly supermarkets in these areas. A map of current HFC-free and low-GWP food retailers is shown in Appendix F: Climate-Friendly Supermarkets.

Objectives

The objectives of this study were to:

- Prepare a market characterization study that presents data on current market inventory, national and local sales, key market actors, applicable codes and standards, and technical specifications of baseline and high efficiency equipment.
- Perform a laboratory assessment and collect data on a high efficiency refrigerated display case in controlled environment conditions for 24 hours as per ANSI/ASHRAE 72-2018 Method of Testing.
- Compare results with those from two previous studies of air-cooled cases (Bulk, et al. 2022) and(Bulk, Wheeler and Faramarzi 2023).
- Create a building energy model using the EnergyPlus hourly simulation platform for the baseline and proposed technologies in California Climate Zone 9 (CZ 9), including interactive effects on the heating, ventilation, and air-conditioning (HVAC) system and the potential for compressor waste heat recovery.
- Present recommendations for California IOUs to continue future research and develop an energy efficiency measure package.

Methodology and Approach

This study began with a literature review of the market for refrigerated cases, to understand relevant codes and standards, clarify the supply chain and equipment availability, and understand the trends and barriers around low-GWP refrigerated cases. Available high efficiency components were reviewed to understand how they might influence outcomes of a laboratory assessment compared to their standard efficiency counterparts. A liquid-cooled, self-contained, medium-temperature, low-GWP (R-290), reach-in refrigerated case with advanced controls was selected for laboratory study, and the laboratory assessment methodology was aligned with previous laboratory assessments for R-134a and R-513a cases for benchmarking. Laboratory assessment results were used to create building models in EnergyPlus to understand the interactive effects of installation of liquid-cooled cases on overall building energy performance, compared to typical food retail equipment setups.

Market Characterization

The market characterization study defined and evaluated the California market potential for liquid-cooled, self-contained, medium-temperature, low-GWP, reach-in cases with advanced controls through a review of existing research and literature, and through engagement with manufacturers, contractors, and end use retailers.

Regulatory Landscape

Regulations around energy use are constantly evolving to help meet climate and energy goals. To understand the influence of regulatory changes and the overall regulatory landscape on the availability of efficient refrigeration system technologies, this study reviewed the codes and standards listed below and sought to identify the potential influence these regulations have on adoption of high efficiency liquid-cooled refrigerated display case technologies for commercial food retailers.

- The Code of Federal Regulations
- Title 20 California Appliance Efficiency Standards (Title 20)
- Title 24 California Building Energy Efficiency Standards (Title 24)

Literature Review of Market Trends

A literature review of current national market trends in the low-GWP and natural refrigerant space examined recent market research conducted through the North American Sustainable Refrigeration Council (NASRC) and other top organizations in the field. For a high-level overview of the market size and potential in California, the project team scaled national equipment shipments available through the Department of Energy (DOE) to the California market using US Census data of the share of small and large grocery retailers in California.

Refrigerated case data from the DOE Compliance Certification Database demonstrated the energy use and energy use trends of different case types. We focused data analysis on vertical medium-temperature refrigerated display cases in both remote condensing and self-contained configurations to understand the general availability in the market, the energy savings above code, and the technological feasibility.

Stakeholder Outreach

To gather additional information about trends specific to the California market, the team identified key manufacturers and stakeholders, including program administrators, contractors, and end-users located in California or familiar with the California market. We conducted a total of seven interviews to gather additional nuanced information about adoption trends and supply chain channels specific to California.

From data collected and analyzed, the team evaluated barriers to market adoption, quantified the energy efficient technologies available, and assessed the implications of low-GWP refrigerants, which helped inform the scalability and support for measure adoption into IOU program portfolios. Table 2 lists those contacted and interviewed.

Table 2: Summary of Stakeholder Engagement

Stakeholders	Purpose and Status of Engagement	Number Contacted	Number of Interviews
Manufacturers	To gain understanding of the state of the market for propane cases, as well as cost differentials and technological and market feasibility of the proposed application versus a typical system.	3	1

Stakeholders	Purpose and Status of Engagement	Number Contacted	Number of Interviews
Contractors	To discuss market and technology barriers, installation requirements, equipment expenses, and training opportunities for propane systems, as well as to understand the general acceptance and confidence of contractors in working with the proposed technology.	3	1
Energy efficiency program administrators	To gain insights on challenges programs face when implementing refrigeration measures or the challenges of programs focused on propane refrigerant technologies; to assess optimal program design for increasing adoption of this technology and market.	3	3
End users	To gain better understanding of the decision-making process, including the priorities and barriers these stakeholders face when purchasing and procuring new equipment.	2	2

Source: Project team.

Technology Review

The technology review aimed to identify the performance advantages of high efficiency, liquid-cooled refrigerated cases versus air-cooled refrigerated cases, and to outline the potential benefits and energy savings when used with heat reclaimed from the coolant loop in micro-distributed systems.

Efficiency Components

Many efficiency component options are available to retailers purchasing refrigerated display cases. Each feature or component provides additional energy savings potential while often adding additional costs. Cases can be tailored to retailer application needs. The following efficiency features within refrigerated cases demonstrate energy savings measures available to food retailers:

- Energy efficient lighting and controls
- Panel insulation
- Condenser fan motors
- Heat exchangers
- Variable-speed compressors
- Electronic expansion valve (EEV)
- Advanced controls
    - Temperature differential
    - Modulating fan motor controls

- Advanced defrost controls

The common types of heat rejection equipment in commercial refrigeration systems are air- and evaporatively cooled condensers and gas and fluid coolers. Heat rejection fans also play a crucial role in enhancing heat transfer efficiency and overall system performance. Additional energy savings can be gained from liquid-cooled refrigeration systems through the coolant-loop connected to the heat rejection equipment as part of a micro-distributed system. Heat rejection equipment was included in this review to understand the total system energy use, best-use applications, and energy savings potential in commercial refrigeration systems from liquid-cooled refrigerated cases. NREL used estimates of energy use required by the heat rejection equipment within the building energy model to identify the interactive effects of these cases with the overall building systems (described in the following sections in more detail).

Laboratory Assessment Approach

The laboratory evaluation conducted by NREL captured the performance of a single, high efficiency refrigerated case set up to simulate typical grocery store operation. The test was conducted under prescribed environmental conditions that best represented the targeted end-users' usage profiles and that generally aligned with ANSI/ASHRAE 72 test standards. Where more accurate data on the food retail industry was available, the test method was modified to align with the operating conditions of this market sector. The assessment used NREL's state-of-the-art research laboratory to conduct the tests, which ran approximately 24 hours and were repeated for convergence. The parameters of the test included ambient conditions — dry-bulb temperature, wet-bulb temperature, temperature gradients, and air velocity — and door openings and closings to simulate typical equipment operation. The lab assessment also measured the rejected heat from the liquid coolant and that rejected heat was used to estimate the energy demand required by auxiliary heat rejection equipment. A summary of the performance assessment design and instrumentation used, and the analysis of the data collected are presented in the Laboratory Assessment section.

Benchmark Cases for Laboratory Assessment

The team selected a R-134a reach-in cooler (RIC) because R-134a is one of the most common refrigerants used in medium-temperature refrigeration today. The use of R-134a became prevalent in the United States after the EPA banned the sale and manufacture of chlorofluorocarbons (CFCs) in the late 1970s. However, starting January of 2020 the EPA placed a ban on the manufacture of refrigeration systems using R-134a due to their high GWP (UNEP 2016). Although the ban has halted R-134a manufacturing, the EPA continues to allow the use of these refrigerants.

The R-513a RIC was selected because R-513a is a drop-in replacement for R-134a with less than half the GWP of R-134a, although R-513a still has a relatively high GWP of 573 (Mota-Babiloni, et al. 2017, 682-688). This refrigerated case is still commercially available and contains other energy efficient components including efficient lighting, more efficient evaporator and condenser fans, and efficient heat exchanger materials and design.

In this approach, the high-efficiency, low-GWP case option is evaluated against two benchmark cases: (1) a widely used refrigerated case containing a high-GWP refrigerant, and (2) a more efficient, commercially available alternative with a medium-GWP refrigerant. This analysis can help utilities develop incentives for replacing existing refrigerated cases and refrigerants with more environmentally friendly and energy efficient solutions by providing a range of savings for various operating conditions.

Building Energy Model Approach

The project team integrated data collected from the benchmark and efficient technologies into the energy model and used EnergyPlus modeling software to evaluate the impacts of the proposed technology on a building scale, including the interactive effects on the HVAC system and the potential for compressor waste heat reclaim. Performance characterization maps were developed to estimate the range of energy, demand, and carbon savings across the food retail market sector in California's Climate Zone 9 (CZ 9). The modeling study leveraged laboratory data collected from the single refrigerated case to scale and assess the entire system performance. The comprehensive assessment of liquid-cooled, low-GWP, self-contained, reach-in, medium-temperature cases accounts for multiple refrigerated cases, the power consumed by the liquid coolant conditioning system, and any building-level effects on HVAC systems associated with less heat being rejected to the conditioned space. California utilities can use this information to develop plans for customer education, technology transfer, and incentives for equipment retrofits to help achieve their decarbonization goals. The modeling parameters and results are provided in the Whole-Building Hourly Energy Modeling section.

Technical Review

Overview of the Micro-Distributed System

The equipment and systems included in this study are illustrated in Figure 1. The baseline case is represented by the stand-alone, air-cooled, self-contained cases that reject heat into the conditioned interior retail space (A). To replace the baseline cases, a micro-distributed system, typically installed with liquid-cooled self-contained low- and medium-temperature cases, allow for the rejected heat to be transported via a closed liquid coolant loop (D) to the outside or reused elsewhere using a heat reclaim system. The micro-distributed system functions by connecting liquid-cooled, self-contained, low- and medium-temperature cases (B) — as well as walk-in coolers and freezers — to the coolant loop (D) by flowing liquid through condensers (C) located at the top of the cases or walk-ins. The liquid coolant absorbs the rejected heat from the case condensers and, under continuous flow, uses redundant pumps (E) to transport the rejected heat to a fluid cooler (F) external to the building. The fluid cooler, often referred to as a gas cooler, can be air- or evaporatively cooled or may use a cooling tower. In some systems, the pumps reject heat into a heat reclaim system, not shown, that can be used to preheat domestic hot water or condition space heat. More information about this system's components is provided in the Technology Review section.

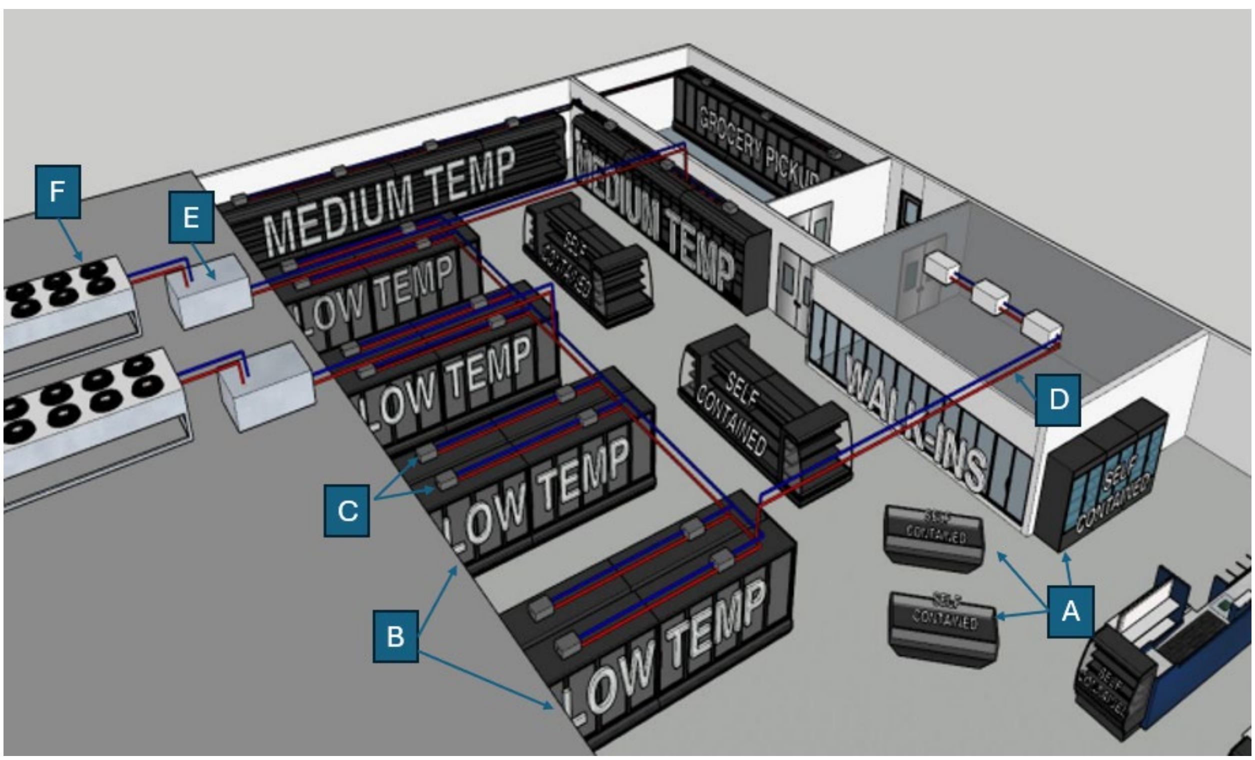


Figure 1: Schematic of a micro-distributed system in a typical grocery store.

Modified from ASHRAE 2021.

Review of Codes and Standards

For commercial refrigeration systems, manufacturers and contractors must comply with federal and State of California codes and standards, which define the baseline that all systems, equipment, and designs must meet to comply. High efficiency is defined as technologies with an incremental increase in efficiency above the code-minimum baseline based on certain equipment features, for example open versus closed cases or upright versus coffin-style cases. To understand the baseline, the applicable regulations reviewed include:

- The Code of Federal Regulations
- Title 20
- Title 24

Code of Federal Regulations

Commercial refrigeration products sold within the US must comply with the following sections of Title 10 of the Code of Federal Regulations:

- Part 429 Subpart B §429.42 Commercial refrigerators, freezers, and refrigerator-freezers outlines the certification procedures for compliance with energy codes set forth in Part 431.
- Part 431 Subpart C Commercial Refrigerators, Freezers and Refrigerator-Freezers provides guidance on energy use, energy conservation standards and testing procedures as outlined in the following sections:
    - § 431.66 Energy conservation standards and their effective dates, which outlines the energy consumption requirements.
    - Appendix B to Subpart C of Part 431 sets forth the appropriate testing method to measure the daily energy consumption and volume or total display area of each covered commercial refrigerator, freezer, or refrigerator-freezer.

State of California Regulations

California retailers must also comply with state and local regulations, including Title 20 and Title 24, which pertain to refrigeration units and systems with a distinction between retail and beverage stores with less than 8,000 square feet of conditioned space, and those with more.

TITLE 20

For food retail and beverage stores less than 8,000 square feet, California's Title 20 Appliance Efficiency Regulations apply. This generally includes systems found in convenience stores, quick service restaurants, and cafes. Title 20 section 1605.1(a) covering commercial refrigeration appliances refers to the federal standards as a guide.

Title 20 has published system performance requirements for various system configurations and end uses. If the measure is considered new construction, then the cumulative performance of the equipment shall minimally comply with the performance metrics published within the Federal and State Standards for Federally Regulated Appliances within Title 20. Table 3 details performance requirements for refrigeration equipment families that utilize a remote condensing unit.

Table 3: Performance Standards for Commercial Refrigerators and Freezers with a Remote Condensing Unit, and that are not Commercial Hybrid Units

Equipment Family	Rating Temperature (F°)	Operating Temperature (F°)	Equipment Class Designation	Maximum Daily Energy Consumption (kWh)
Vertical open (VOP)	38 (M) 0 (L)	≥ 32 < 32	VOP, RC, M VOP, RC, L	0.64 × TDA + 4.07 2.20 × TDA + 6.85
Vertical closed transparent (VCT)	38 (M) 0 (L)	≥ 32 < 32	VCT, RC, M VCT, RC, L	0.15 × TDA + 1.95 0.49 × TDA + 2.61

Title 20 Section 1605.1(a)2(A) Table A-5.

Refrigerated Cases can also operate as a self-contained condensing unit (SC). Below, Table 4 shows Title 20 requirements for the refrigeration equipment families that utilize a self-contained condensing unit. There are no additional efficiency requirements specific to condensing units and evaporators reflected in Title 20 regulations. It should be noted that total display area (TDA) is used to calculate the maximum daily energy consumption for vertical open self-contained cases, while case volume (V) is used for vertical closed transparent self-contained condensing units.

Table 4: Standards for Commercial Refrigerators and Freezers with a Self-Contained Condensing Unit, and that are not Commercial Hybrid Units

Equipment Family	Rating Temperature (°F)	Operating Temperature (°F)	Equipment Class Designation	Maximum Daily Energy Consumption (kWh)
Vertical closed transparent (VCT)	38 (M) 0 (L)	≥ 32 < 32	VCT, SC, M VCT, SC, L	0.1 x V + 0.86 0.29 x V + 2.95
Vertical open (VOP)	38 (M) 0 (L)	≥ 32 < 32	VOP, SC, M VOP, SC, L	1.69 x TDA + 4.71 4.25 x TDA +11.82

Title 20 Section 1605.1(a)2(A) Table A-4.

TITLE 24

Title 24, Section 120.6(b) applies to commercial refrigeration systems, which are defined as retail food or beverage stores with 8,000 square feet or more of conditioned floor area that use either refrigerated display cases or walk-in coolers or freezers. This includes most grocery stores, supermarkets, wholesale distribution retailers, independent markets, schools, hospitals, institutional cafeterias, and larger restaurants. Code requirements are expanded beyond refrigerated case requirements to include heat rejection equipment, due to a comprehensive evaluation of the whole system rather than just self-contained cases. Section 120.6(b) sets energy efficiency requirements for condensers serving refrigeration systems and for compressor systems.

- Section 120.6(b)1 on condensers serving refrigeration systems applies only to stand-alone refrigeration condensers and states that condenser fans must be continuously variable speed and the speed of all fans serving a common condenser high side must be controlled in unison. Additionally, the minimum specific efficiency for fan powered condensers is 45 Btu/watt for condensers in Adiabatic Dry Mode.

- This project does not test condenser equipment but will reference the minimum efficiency standards for condensers to inform the energy use estimates for the liquid coolant conditioning system that is used to build the energy model. The conditioning system serves as the heat rejection equipment to remove the heat from the liquid-cooled condensing unit. The conditioning system differs from a typical condenser in that no phase change occurs, so it functions as a fluid cooler (also known as a gas cooler). The fluid cooler is less efficient than a conventional condenser because it cannot take advantage of the energetics of phase change. Minimum efficiency standards are used as a reference for the liquid-coolant conditioning system in the absence of other applicable codes.
- Section 120.6(b)3 on refrigerated display cases mandates that lighting in display cases are controlled by either an automatic time switch to turn off lights during nonbusiness hours or by motion sensor controls that reduce display case lighting power by 50 percent within 30 minutes of the nearby area being vacated.
- Section 120.6(b)4 on refrigeration heat recovery requires that at least 25 percent of the sum of the design total heat of rejection of all refrigeration systems possessing individual total heat of rejection values of 150,000 Btu/h or greater at design conditions be used for space heating. Title 24 does give exceptions to this rule for stores in Climate Zone 15 or those for which the design total heat of rejections of all refrigeration systems is less than or equal to 500,000 Btu/h.

For both new construction and retrofit measures, the California Building Energy Efficiency standard Title 24 requires fan-powered condensers to meet specific energy requirements listed in Table 5.

Table 5: Fan Powered Condensers – Specific Efficiency Requirements

Condenser Type	Min. Specific Efficiency	Rating Condition
Evaporative cooled	160 Btuh/W	100 °F saturated condensing temperature (SCT) 70 °F entering wet-bulb temperature (WB)
Air-cooled	65 Btuh/W	105 °F SCT 95 °F entering DB
Adiabatic dry mode	45 Btuh/W	105 °F SCT 95 °F DB

Title 24 Section 120.6(b)1G & Table 120.6-C.

However, Title 24 makes multiple exceptions to the requirements, including the following, which may be applicable to measure development:

- Section 120.6(b)1G:
    - Exception 1 – Condensers with a total heat rejection capacity of less than 150 kBtuh at the specified rating condition.
    - Exception 2 – Stores in Climate Zone 1.
- Exception to Section 120.6(b)1B through G – Transcritical CO_2 refrigeration systems.

Retail food stores over 8,000 square feet of conditioned floor area and that use either refrigerated display cases or walk-in cooler/freezers are required by Title 24 to comply with the applicable state and federal appliance standards. Equipment not covered under those standards is expected to meet the requirements detailed in Title 24 Section 120.6(b) as shown in Table 6.

Table 6: Title 24 Condenser Controls Requirements

Equipment	Requirement
Condenser fan	Variable speed control
Condensing unit	Condensing temperature reset
Compressor	Suction pressure reset for variable capacity capability

Title 24 Section 120.6(b)1 – 2.

Finally, under Title 24, Section 120.6(b), retail food or beverage stores with 8,000 square feet or more of conditioned floor area and that utilize either refrigerated display cases, or walk-in coolers or freezers, shall meet all applicable state and federal appliance and equipment standards consistent with Title 24, Sections 110.0 and 110.1. For equipment not subject to such standards, the requirements outlined in Subsections 1 through 4 apply.

Review of High Efficiency Components in Refrigerated Cases

Energy Efficient Lighting and Lighting Controls

LED lighting and controls to minimize lighting run-time based on store occupancy and aisle motion further improve case efficiency by decreasing additional refrigeration loads required to offset lighting heat generation as well as energy use.

Panel Insulation

Improved case insulation can reduce energy consumption by reducing refrigeration load.

Condenser Fan Motors

Adaptive fan controls allow the modulation of the condenser fans' motors to meet demand based on the air temperature setpoint measured at the location of the condenser. Different control sequences and fan cycling methods can be used if the condenser fans automatically reduce speed when the refrigerant gas temperature exceeds the setpoint temperature. Temperature setpoints should be programmed using the unit's control system interface.

Heat Exchangers

A unit's heat exchanger can use design elements that are more efficient than those used in standard units. An efficient heat exchanger maximizes surface area for heat rejection to the environment, and may use a microchannel, plate-and-frame, or fin tube design. The heat rejection surface area can be maximized by choosing the largest cabinet size available for the specified compressor. A more-efficient heat exchanger increases heat rejection capacity and lowers energy demand.

Variable Speed Compressors

Compressors keep a system's refrigerant pressurized and flowing. Of all components in the system, they consume the largest amount of energy. A variable-speed compressor offers the potential for energy savings because, when cooling demand is less than the maximum, the compressor adapts to reduce its speed to save energy. Variable speed capability must be enabled through the unit's control system interface.

Electronic Expansion Valve (EEV)

An expansion valve regulates the flow of liquid refrigerant into the evaporator heat exchanger. The EEV allows precise tuning based on refrigerant pressure and temperature at the evaporator inlet using the unit's control system interface.

As the liquid refrigerant moves through the evaporator coil, it absorbs heat and changes phase or "boils" into gas. As the refrigerant vapor moves through the evaporator coil, it absorbs more heat, to ensure that no liquid refrigerant, i.e., non-compressible fluid, is returned to the compressor. The heat absorbed beyond the vaporization point is called "superheat." With an EEV, superheat can be more finely tuned and decreased further than it can with other types of expansion valves. This reduces unnecessary refrigerant flow and saves energy.

Advanced Controls

The measures listed below describe features that could be included in manufacturer and equipment specific advanced controllers and could be implemented in refrigerated cases. However, it is important to note that some of these measures are embedded into cases while others can be added to existing cases. Advanced controls measures that exceed baseline code requirements set in Title 24 include:

- Temperature differential
- Variable speed or fully modulating evaporator fan motor controls
- Advanced defrost controls

TEMPERATURE DIFFERENTIAL

Most refrigeration systems have an automatic temperature differential (ΔT) programmed into their system, but advanced controls can work to reduce the ΔT, which effectively reduces overcooling and consequently reduces the lift on the compressor. A typical ΔT for medium-temperature systems is 10 degrees. For efficiency, the ΔT could be reduced to five degrees(Orr 2020).

MODULATING FAN MOTOR CONTROLS

Adaptive fan controls allow modulation of the evaporator fans' motors to meet demand based on a temperature setpoint of the refrigerated space. Different control sequences and fan cycling methods can be used if evaporator fans automatically reduce speed when a refrigerated space is cooler than needed. Temperature setpoints should be programmed using the unit's control system interface.

ADVANCED DEFROST CONTROLS

Evaporator heat exchangers need to be defrosted periodically to prevent ice build-up on the coils. Adaptive, smart, or on-demand defrost controls allow the system to shorten or skip defrost cycles when no ice is detected. Medium-temperature cases can have air or electric defrost; air defrost is more efficient. In air defrost, the system closes the EEV when a defrost cycle is activated, stopping the flow of refrigerant through the pipes, and turns on the evaporator fans. The air passing over the coils then melts any frost that has accumulated on the coils. When a defrost cycle is activated in a case with electric defrost, the electric defrost element is turned on, blowing hot air over the heat exchanger to melt ice on the coils. Smart controls adjust defrost cycles based on evaporator performance to prevent unnecessary energy demand on the system and reduce waste heat being added to the refrigerated space.

Review of Heat Rejection Equipment

Condensers

In HVAC systems, refrigeration systems, and power plants, condensers are used to condense refrigerant vapor or steam by transferring heat to a cooling medium, typically water or air. In smaller systems, condensers are often integrated into the condensing unit along with the compressor and other components. This compact design allows for easier installation and maintenance. These units can be installed either indoors or outdoors, depending on space and ventilation requirements. For larger systems and multi-plex racks, the condenser is typically separate from the compressors and other components. These standalone condensers are usually outside the building or facility. Separating the condenser from the main components allows for greater flexibility in system design and installation, especially for systems with higher capacity or multiple units working together. Placing the condenser outdoors also helps with heat dissipation and reduces the impact of heat on indoor spaces. The outdoor units usually have propeller fans and finned refrigerant coils housed in a weatherproof casing(CED Engineering).

The energy use of condensers depends on factors such as the design of the condenser, the cooling medium used, and the operating conditions. Condenser efficiency is typically measured by the condenser's approach temperature, which is the temperature difference between the condensing medium and the saturation temperature of the vapor or gas being condensed. Higher approach temperatures indicate lower efficiency.

There are two types of condensers:

- Air-Cooled Condensers

    Air-cooled condensers consist of finned tubes through which refrigerant vapors flow; ambient air is blown over the tubes to remove heat. Air is a less effective heat conductor than water is, necessitating larger and less efficient condensers than evaporative condensers. These units typically operate with a temperature difference of 10 to 30°F between the refrigerant and ambient air. With rising ambient air temperatures, condensing temperature increases, causing a decrease in net cooling capacity by approximately two percent for every five - degree rise in condensing temperature(CED Engineering).

The energy usage of air-cooled condensers depends on factors such as ambient temperature, airflow rate, and condensing temperature. Operation costs include electricity consumption for fan operation, periodic cleaning, maintenance of finned tubes to remove dirt and debris, and potential costs associated with higher condensing pressures due to ambient temperature variations.

- Evaporative condensers

  Evaporative condensers are similar to wet cooling towers but are specifically designed for condensing refrigerant vapors by using a combination of air and water cooling. They offer higher efficiency compared to air-cooled condensers by utilizing latent heat of vaporization. Energy usage is influenced by factors such as ambient conditions, water quality, and the design of the condenser. Operation costs include electricity consumption for fans and pumps, water treatment expenses, and periodic maintenance for cleaning and inspection of heat exchange surfaces and water distribution systems.

Gas Coolers and Fluid Coolers

Gas coolers and fluid coolers transfer heat from a gas, vapor, or liquid to ambient air without causing a phase change in the medium being cooled. Compared to condensers, gas and fluid coolers have a lower heat transfer coefficient due to the absence of the latent heat process of condensation. They are commonly used in industrial processes, power plants, and refrigeration systems, especially where water availability or water quality is a concern from an evaporative process standpoint such as in remote locations, mobile refrigeration units, or applications with stringent environmental regulations. Gas and fluid coolers in refrigeration systems feature a capacity range from 2 to 275 tons and are often sited outdoors or in well-ventilated areas to ensure proper airflow for heat rejection. They can be integrated into rooftop or ground-mounted refrigeration units. According to the 2022 Building Energy Efficiency Standards (Title 24, part 6), air-cooled gas coolers are prohibited in California Climate Zones 10 through 15(CEC 2022).

Gas and fluid coolers consume energy for fan operation, which depends on factors such as ambient conditions, airflow rates, fan performance, and refrigerant flow rates. Proper design and maintenance are essential for maximizing efficiency. Operation costs include electricity consumption for fans, periodic cleaning, maintenance of heat exchange surfaces to remove dirt and debris, and potential costs associated with higher operating temperatures compared to evaporative cooling systems.

Heat Rejection Fans

FAN TYPES AND CONFIGURATIONS

In heat rejection equipment, fan configurations play a crucial role in enhancing heat transfer efficiency and overall system performance. Common fan types include axial or propeller fans and centrifugal or radial fans with forced draft or induced draft configurations in counterflow or crossflow arrangements.

Axial Fans: These fans have blades that rotate around an axis parallel to the airflow. They are commonly used when large airflow volumes are required at relatively low pressures. Axial fans are efficient for moving air through ducts or across heat exchanger surfaces. They are classified based on the adjustability of their blades, with C-wheel, A-wheel, and K-wheel types offering varying levels of efficiency and adaptability.

Centrifugal Fans (Radial Fans): Centrifugal fans move air perpendicular to the fan blade's rotation axis. They generate higher pressure than axial fans do, making them suitable for applications requiring airflow against resistance, such as cooling coils with high pressure drops. They come in different blade configurations including F-wheel, B-wheel, P-wheel, and T-wheel, each offering distinct benefits such as high efficiency, low noise emission, and self-cleaning.

FORCED DRAFT CONFIGURATION

In a forced draft configuration, fans are positioned at the inlet of the heat rejection equipment, pushing air through the system. This setup ensures a constant supply of air to the heat exchanger or condenser, improving heat transfer rates by maintaining airflow. Below, we describe three forced draft configurations typically used in refrigeration systems.

Induced Draft Configuration: In an induced draft configuration, fans are located at the outlet of the heat rejection equipment, pulling air through the system. This configuration creates a negative pressure zone within the equipment, aiding in the removal of heat and exhaust gases. Induced draft setups are often used in boilers and cooling towers.

Counterflow Arrangement: In a counterflow arrangement, air flows in one direction while the heat exchange medium, e.g., refrigerant or water, flows in the opposite direction. This configuration maximizes the temperature difference between the two fluids along the entire heat exchange surface, resulting in efficient heat transfer.

Crossflow Arrangement: In a crossflow arrangement, air flows perpendicular to the direction of the heat exchange medium. This configuration is common in cooling towers and air-cooled condensers. While crossflow arrangements are simpler and more compact, they may not achieve as high heat transfer efficiency as counterflow configurations.

Table 7: Common Types of Fans and Their Characteristics

Fan Type	Wheel Type	Static Pressure (in H_2O)	Wheel Diameter (in)	Air Flow (cfm)	Brake Horsepower (Bhp)
Centrifugal	Backward inclined	0 – 12	10 – 75	500 – 125,000	0.33 – 200
	Backward inclined airfoil	0 – 14	20 – 120	1500 – 450,000	0.33 – 1,500
Propeller axial	Direct drive	0 – 1	10 – 50	50 – 50,000	0.17 – 10

The Engineering Toolbox 2005.

FAN CONTROL METHODS

The energy consumption of a heat rejection system depends largely on the method used to control the fans. By implementing the right control strategy, significant energy savings can be achieved. Typically, three methods are employed: cycling the fans, using a two-speed fan, and using a variable-frequency drive (VFD).

1. **Cycling**: The fan is either on or off, with no in-between speeds. While simple, this method can lead to energy waste as the fan may be running at full speed when not necessary.

2. **Two-speed**: The fan has low- and high-speed settings. This offers more flexibility than cycling, but it still lacks the fine control of other methods.

3. **VFD**: Variable speed control allows the speed of heat rejection fans to be adjusted according to the cooling demand. Instead of running at full speed all the time, the fans slow down when less cooling is needed, saving energy. ASHRAE 90.1-2016 mandates VFDs on any fan system on a heat rejection device with a power of five horsepower or more to ensure that the fan motor's demand does not exceed 30 percent of the design wattage when operating at 50 percent of the design airflow. The 2022 Building Energy Efficiency Standards (Title 24, part 6), however, requires VFDs on any fan system powered by a motor of 7.5 hp (5.6 kW) or larger(CEC 2022).

FAN STAGING

Fan staging is a critical aspect of optimizing heat rejection equipment. In single fan staging setups, typically found in smaller-scale systems or those with relatively steady cooling demands, a single fan operates to meet the system's cooling requirements. These fans typically range in capacity from five to 100 tons of cooling, with corresponding horsepower ratings ranging from 0.5 to 10 hp. On the other hand, double fan staging configurations, commonly employed in larger-scale applications or systems with variable cooling loads, involve the operation of two fans that can work independently or in tandem. The capacity range for double fan staging setups is broader, spanning from 50 to 500 tons of cooling, with horsepower ratings ranging from 5 to 50 hp per fan. This dual-fan setup provides greater flexibility and efficiency, especially during partial load conditions, ensuring optimal performance and energy usage in heat rejection processes. The specific capacity ranges and hp ratings for fans can vary depending on factors such as the size of the heat rejection equipment, the cooling requirements of the process being served, and the design specifications of the individual fan units.

When multiple heat rejection equipment is used, devices can be arranged in parallel or series. In a parallel configuration, each device operates independently, allowing for more efficient use of the heat rejection surface. Series configuration requires each device to handle the heat rejected by the equipment before it, which can lead to inefficiencies.

Fluid Coolers for Micro-Distributed Refrigerated Cases

In this study, we focus on heat rejection equipment referred to as closed-circuit towers, commonly known as fluid coolers. Fluid coolers are the most commonly used equipment to serve liquid-cooled refrigerated cases, so the team used fluid coolers to estimate the energy use of the liquid-cooled refrigerated cases in the building-level energy model. The primary advantage of a closed-circuit fluid cooler lies in its protection against environmental exposure. This feature reduces costly water treatments, enhances energy efficiency, and reduces health risks related to *Legionella* bacteria.

These benefits often justify the higher initial investment for closed-circuit towers in various applications.

Fluid coolers are commonly installed with the liquid-cooled refrigerated cases that are being tested as part of the lab assessment. The applications and capacities of this equipment have proven to be the most cost-effective method to remove heat from the refrigerated cases on the sales floor to the ambient outdoor air.

AIR-COOLED FLUID COOLER

An air-cooled fluid cooler in refrigeration systems is a heat exchanger that uses ambient air to cool a fluid (such as water, refrigerant, or oil) without the need for water. Fans blow air over finned tubes or coils containing the fluid to be cooled (Figure 2). Heat is transferred from the fluid to the air, causing the fluid temperature to decrease. Maximizing airflow and surface area are crucial for optimizing the effectiveness of air-cooled fluid coolers. Some manufacturers provide innovative designs, such as the V-configuration, to maximize surface area per footprint, thus improving heat rejection capacities. Air-cooled fluid coolers are simple to install, require minimal maintenance, and are suitable for locations where water availability or quality is limited. They can, however, handle a smaller cooling capacity than evaporative and adiabatic coolers with the same power and footprint setup.

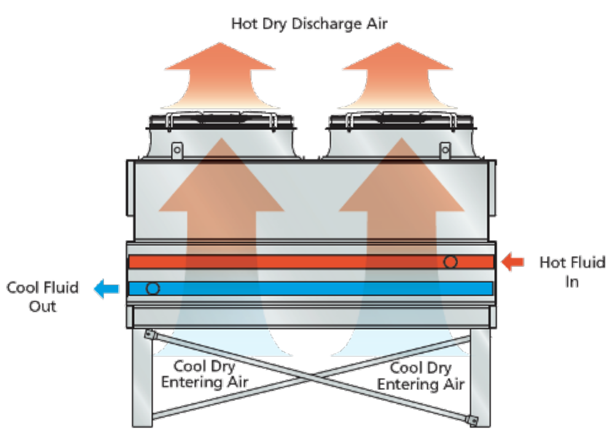


Figure 2: Closed-circuit, air-cooled fluid cooler.

EVAPCO 2024.

ADIABATIC FLUID COOLER

An adiabatic fluid cooler, also known as a dry cooler with adiabatic pre-cooling, combines dry air cooling with intermittent wetting of the coils or tubes with water to further cool the air through evaporative cooling, increasing cooling efficiency (Figure 3). Adiabatic fluid coolers are commonly used in air conditioning systems for commercial buildings and in process-cooling applications such as in HVAC systems and data centers where improved cooling efficiency and energy savings are desired, and water conservation is a priority. They offer higher cooling capacity and efficiency in a smaller footprint than conventional air-cooled fluid coolers, especially in warmer climates. Further, they consume 95 percent less water than typical wet cooling towers(Nimbus 2024).

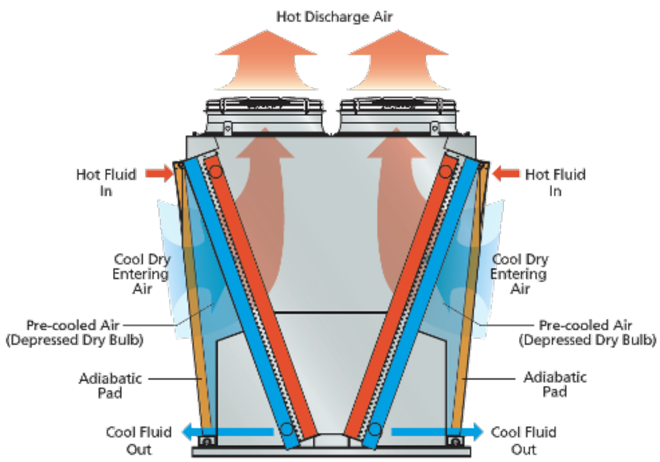


Figure 3: Adiabatic fluid cooler.

EVAPCO 2024.

The "dry-bulb switchover temperature" is the threshold at which a closed-circuit adiabatic cooler can function fully dry without spray pumps to reject the entire design heat load. Higher dry-bulb switchover temperatures lead to decreased water consumption over time. Adiabatic coolers incorporating extended surface fins on coils can achieve notably higher dry-bulb switchover temperatures due to increased coil surface area. For instance, employing finned coil technology can achieve dry-bulb switchover temperatures of up to 45 F° under full load conditions in some products. In hybrid equipment offered by some manufactures, featuring dry cooling in series with evaporative cooling, the ambient dry-bulb switchover temperature rises to 65 F° at full load.

EVAPORATIVE FLUID COOLER

An evaporative fluid cooler like a wet cooling tower uses water evaporation to cool a fluid (such as water or refrigerant), but with the advantage of protecting the working fluid from environmental exposure. Hot fluid from a process or system passes through a tube bundle, upon which water is sprayed and a fan-induced draft applied (Figure 4). A portion of the sprayed water is evaporated, removing the heat from the working fluid. Moist air is drawn to the top of the closed-circuit cooler by the fan and released into the atmosphere. The used water accumulated at the bottom of the cooler is pumped back up through the water distribution system and over the coils again. This design minimizes the risk of water contamination and reduces water consumption compared to open-circuit cooling towers.

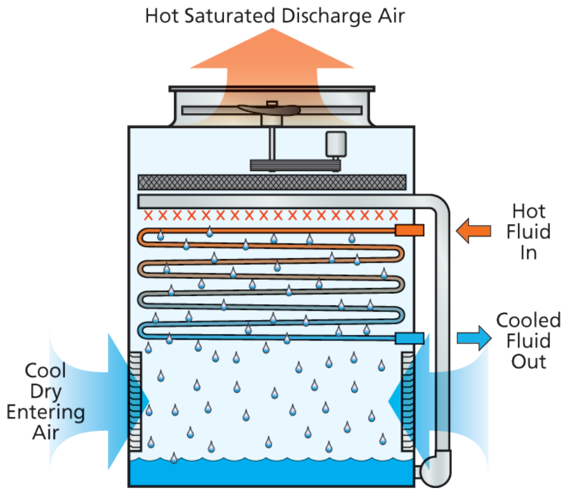


Figure 4: Closed-circuit evaporative fluid cooler.

EVAPCO 2024.

Evaporative fluid coolers offer high cooling capacity and efficiency, especially in very hot and dry climates. They also provide effective water conservation through the reuse of evaporated water. However, evaporative cooling systems have drawbacks, including high air pressure drops within the system, leading to relatively high investment and operating costs for fans. There's also a heightened risk of corrosion, particularly affecting components exposed to water spray(Zalewski, Niezgoda-Żelasko and Litwin 2000). Some manufacturers offer designs that can resist corrosion by, for example, using copper tubing inside the coil bundles.

In closed-circuit cooling towers, axial fans with induced draft configuration — in which fans are positioned at the top of the tower to draw air upwards — are common. This setup creates a negative pressure zone within the tower, removing large volumes of air from the tower efficiently. Axial fans in an induced draft configuration offer several advantages for closed-circuit cooling towers, including efficient airflow distribution, reduced energy consumption, and enhanced heat transfer efficiency. The induced draft setup helps ensure that air is drawn uniformly through the tower, optimizing cooling performance. Furthermore, axial fans allow for better control over airflow rates and fan speeds, enabling operators to adjust cooling capacity as needed. Additionally, axial fans typically require less maintenance compared to other fan configurations, contributing to overall system reliability and uptime.

Heat Rejection Equipment Selection

The selection of heat rejection equipment traditionally involves weighing the higher energy consumption of air-cooled solutions against the water consumption of water-cooled alternatives. Air-cooled fluid coolers, the simplest form of heat rejection, are common, cost-effective, and easy to operate and maintain. However, adiabatic and evaporative fluid coolers offer superior energy performance, especially in hot and dry climates, and can handle larger cooling demands with a smaller footprint.

Adiabatic coolers use water only during periods of high demand, e.g., the hottest days, resulting in limited water use, while evaporative systems have consistent water consumption. Water consumption poses various challenges that influence the selection decision between the two systems. These challenges include costs associated with water treatment, the potential formation of vapor plumes in cold seasons, and the risk of ice formation. Moreover, the presence of water can have significant health and hygienic implications. Additionally, adiabatic coolers typically have lower efficiency than evaporative towers and usually require a larger footprint. While adiabatic coolers can sometimes replace evaporative coolers, there are limitations in capacity and thermal performance to consider. Drawbacks common to adiabatic and evaporative coolers, compared to air-cooled fluid coolers, include the complexity of control systems, water treatment and cleaning costs, and an increased risk of corrosion in components exposed to water spray(Torraval Cooling).

Energy Estimates

Evaporative cooling is more effective than dry air cooling because it takes less energy to reject heat to water than it does to air due to the higher heat absorption capacity of water. Specifically, while one kilogram of water can absorb 2,256 kJ of heat at 100°C (970.1 Btu/lb at 212 °F), known as latent heat of vaporization, one kilogram of air can only absorb approximately 1 kJ of heat (0.43 Btu/lb) per degree Celsius increase in temperature at constant pressure. The coefficient of performance (COP) in evaporative coolers may be as much as 39 percent higher than that of air-cooled coolers, research has shown(Taler, Jagieła and Jarem 2021).

Air-cooled fluid coolers are generally less energy efficient than evaporative coolers because they rely solely on ambient air for heat transfer. However, advancements in fan design, motor efficiency, and coil construction have improved their efficiency over the years. Energy-efficient models may feature variable-speed fans, optimized airflow patterns, and enhanced heat transfer surfaces to minimize energy consumption. The minimum required performance for air-cooled fluid coolers according to the 2022 Building Energy Efficiency Standards (Title 24, part 6) is 4.5 gallons per minute (GPM) per horsepower (hp)(CEC 2022, 133).

Adiabatic fluid coolers offer higher energy efficiency than conventional air-cooled fluid coolers due to the additional cooling effect provided by intermittent wetting of the coils. By pre-cooling the air using evaporation, adiabatic coolers reduce the temperature of the air entering the heat exchanger, improving overall cooling efficiency. However, energy consumption may increase during wetting cycles when water is pumped to wet the coils.

Evaporative fluid coolers are among the most energy efficient heat rejection solutions available. They use the latent heat of water evaporation to cool the fluid being circulated, resulting in significant energy savings compared to air-cooled systems. Additionally, they offer smaller size (requiring less space by up to 50 percent), lower investment cost (material savings up to 50 percent) and decreased energy consumption (the driving power of a fan is about three times lower due to the required lower air volume flow rate) than air-cooled systems(Zalewski, Niezgoda-Żelasko and Litwin 2000). However, energy consumption associated with water pumps must be considered. Variable-speed drives and energy efficient motors can help optimize energy usage. According to the 2022 Building Energy Efficiency Standards (Title 24, part 6), 2018 International Energy Conservation Code (IECC), and ASHRAE 90.1-2016, the minimum performance required for closed-circuit cooling towers (evaporative fluid coolers) with a propeller or axial fan is 16.1 gpm/hp.

Study-Specific Technologies

Technology Description

The technology under evaluation is a liquid-cooled, medium-temperature, reach-in, self-contained refrigerated display case with R-290 refrigerant. This technology is ideal for the owners of California commercial buildings with refrigeration who are attempting to reduce fugitive emissions and energy consumption. R-290 has a GWP of 3 compared to R-134a with GWP of 1300 and R-513a with GWP of 573. Previous studies have shown that liquid-cooled refrigerated cases can reduce energy consumption by 35 to 54 percent (Bulk, Wheeler and Faramarzi 2023). However, these studies considered only the self-contained refrigerated case, which contains an air-cooled condenser that rejects heat at the case. These studies did not look at the entire system, including the heat rejection equipment needed to remove the heat from the refrigerated case to the ambient air, as depicted by the liquid coolant conditioning system shown in Figure 1. The heat rejection equipment allows the heat that is removed from the refrigerated case to be rejected outside of the store, rather than onto the sales floor, which helps reduce the space cooling demand.

A liquid-cooled refrigerated case requires a system to provide liquid coolant, typically a water or propylene glycol solution, at a temperature ranging from 45°F to 105°F. For businesses operating refrigerated cases — convenience stores, supermarkets, cafeterias, and restaurants, for example — this could involve implementing a pumping system to supply coolant to one or multiple refrigerated cases. Liquid coolant could be supplied from various sources in either an open loop using groundwater or city main water, or in a closed loop using a cooling tower, fluid cooler, or chiller. An example of the closed loop configuration is shown in Figure 5. The liquid loop also affects building-level performance based on both the interaction of the refrigerated case with the HVAC system and the energy consumption of the liquid coolant conditioning system.

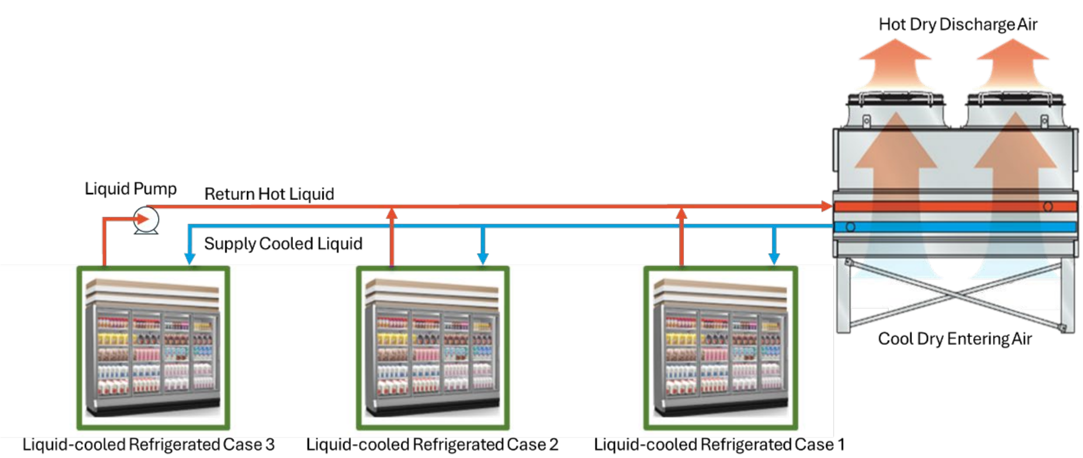


Figure 5: Example liquid-cooled loop for commercial refrigeration using a closed-circuit air-cooled fluid cooler

as the liquid coolant conditioning system.

Benchmark Technologies

The project team selected two different refrigerated cases to use as benchmarks for the laboratory experiments. These were assessed in a 2022 NREL study, Performance Assessment of High efficiency Refrigerated Display Cases with Low-GWP Refrigerants (Bulk, et al. 2022).

- Refrigerated Case Option 1, R-134a reach-in case (R-134a RIC): A 6.5', 3-door unit using a 0.5-hp fixed-speed compressor with HFC refrigerant R-134a with a GWP of 1,300.
- Refrigerated Case Option 2, R-513a reach-in case (R-513a RIC): A 6.5', 3-door unit using a 0.5-hp fixed-speed compressor with HFC refrigerant R-513a with a GWP of 573.

The R-134a RIC was purchased prior to the EPA ban at the end of 2019. Due to the ban, the manufacturer subsequently produced the same model with an upgraded evaporator and condenser using R-513a refrigerant. This unit was purchased at the start of 2020. Hence, the R-134a RIC and R-513a RIC have the same external and internal dimensions shown in Figure 7.

Both RICs contain air-cooled condensers and the same 0.5 hp fixed-speed reciprocating compressor model. R-134a RIC has a rated capacity of 2,600 Btu/h and uses a traditional fin-and-tube evaporator. The capacity rating of the R-513a RIC was not provided, but R-134a and R-513a have similar compressor capacity ratings for medium-temperature systems. See Figure 6 below for capacity comparison (Tecumseh Products Company LLC 2018). The R-513a case contained upgraded evaporator and condenser heat exchangers and canopy lighting, which increased the efficiency and are assumed to increase the capacity as well. It is assumed that either of these 3-door benchmark cases would represent what a customer would implement absent energy efficiency utility program involvement.

Capacity Relative to R-134a		
Refrigerant	Evaporator Temperature	
	Low	Medium
R-513A	99%	100%

COP Relative to R-134a		
Refrigerant	Evaporator Temperature	
	Low	Medium
R-513A	104%	102%

Figure 6: Performance comparison of R-134a to R-513a.

Both benchmark cases (Figure 7) were evaluated based on ASHRAE 72-2018 indoor environmental conditions (ASHRAE 2018) and the representative environmental and operational conditions observed in real supermarkets (Bulk, et al. 2022). Tests were conducted over 24-hour periods with product simulators and door actuators to simulate the flow of customer traffic in and out of the case. Power was monitored for the evaporator, condenser fans, compressor, and lighting/controllers. In this study, the same test conditions were replicated for the high efficiency refrigerated case with detailed results and comparisons against the benchmark cases presented in the Energy and Power Consumption Results section.

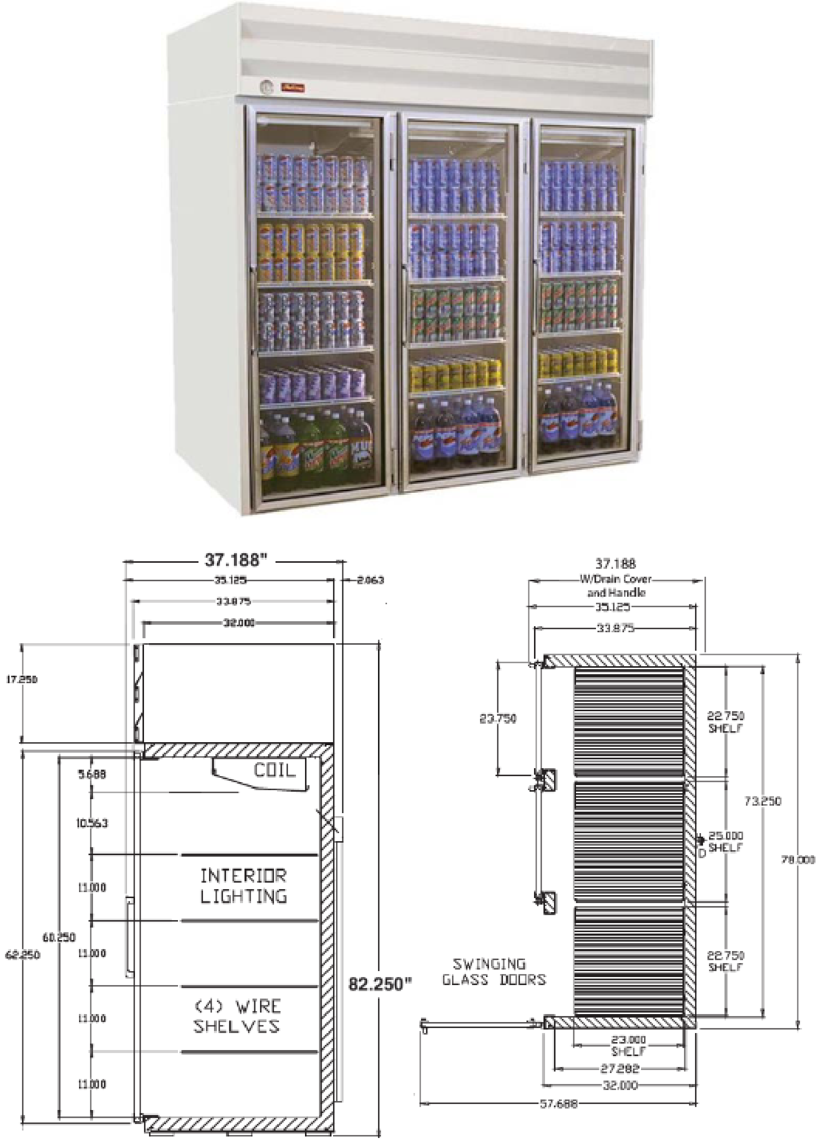


Figure 7: Benchmark cases 1 and 2, catalogue image (above) and drawing (below).

Additional refrigeration parameters and specifications are presented in Table 8.

Table 8: General Refrigerated Display Case Parameter Specifications for Selected Benchmarks

	Benchmark R-134a Reach-In Case	Benchmark R-513a Reach-In Case
Refrigerant	R-134a	R-513a
Refrigerant GWP	1300	573

	Benchmark R-134a Reach-In Case	Benchmark R-513a Reach-In Case
Compressor type	0.5-hp fixed-speed compressor	0.5-hp fixed-speed compressor
Rated cooling capacity (Btu/h)	2600	Not provided
Rated current (A)	13.8	Not provided
Default cut-out/cut-in temp. (°F)	32/40	32/40
Evaporator fan cycling	Continuous	With compressor cycling
Scheduled daily defrost cycles	1	2
Expansion device	Capillary tube	Capillary tube
Evaporator fan type	Dual 7.5-in. plastic fans	8.5-in. aluminum fan
Evaporator coil dimensions	15.75 in. x 35.25 in. x 5.25 in.	17.5 in. x 36.25 in. x 5 in.
Condenser fan type	11.75-in. aluminum fan	10.5-in. aluminum fan
Condenser coil dimensions	13.25 in. x 12.25 in. x 5 in.	12 in. x 11.25 in. x 3.5 in.
Evaporator fan motor hp	0.03	0.02
Condenser fan motor hp	N/A	N/A
Case internal volumetric capacity	48.29 ft^3	48.29 ft^3

	Benchmark R-134a Reach-In Case	Benchmark R-513a Reach-In Case
Anti-sweat heater controls	No anti-sweat heater	No anti-sweat heater
Defrost controls	Temperature terminated at 50°F	Temperature terminated at 50°F

To ensure environmental conditions were appropriately maintained, ambient measurements within the environmental chamber were closely monitored and recorded. To ensure proper control of the case compressor cycling, product simulator temperatures were monitored, ensuring stability within ASHRAE 72, AHRI 1200, NSF7, and FDA Food Code throughout the duration of the tests. Condensate mass was also measured after each experimentation to quantify the total heat rejection in each case.

Efficient Technology

The high efficiency refrigerated case (HERC) tested in the laboratory performance assessment as part of this study is a liquid-cooled, self-contained, R-290 (propane), reach-in refrigerated case with three doors. The case was manufactured by Hussmann and is part of their RMN series rated at 2,355 Btuh. It uses a single 0.25-hp fixed-speed compressor. This case contains many of the components outlined in the Review of High Efficiency Components in Refrigerated Cases section above, including a high efficiency heat exchanger, LED lighting, anti-sweat heaters within the doors, and integrated case controls — compressor on/off, and compressor safety (high pressure switch), fans, lights, and defrost start. The technical specifications of the case are provided below and detailed in the quote provided in Appendix G .

This HERC was evaluated in the same environmentally controlled test chamber and under the same ASHRAE 72 and typical supermarket test conditions as the benchmark cases.

The “water connections” label in Figure 8 shows where the refrigerated case would typically connect to the liquid coolant conditioning system. In this test scenario, the water connection is where the heat rejected into the water loop is measured using a Coriolis mass flow meter and thermocouple wells at the condenser inlet and outlet.

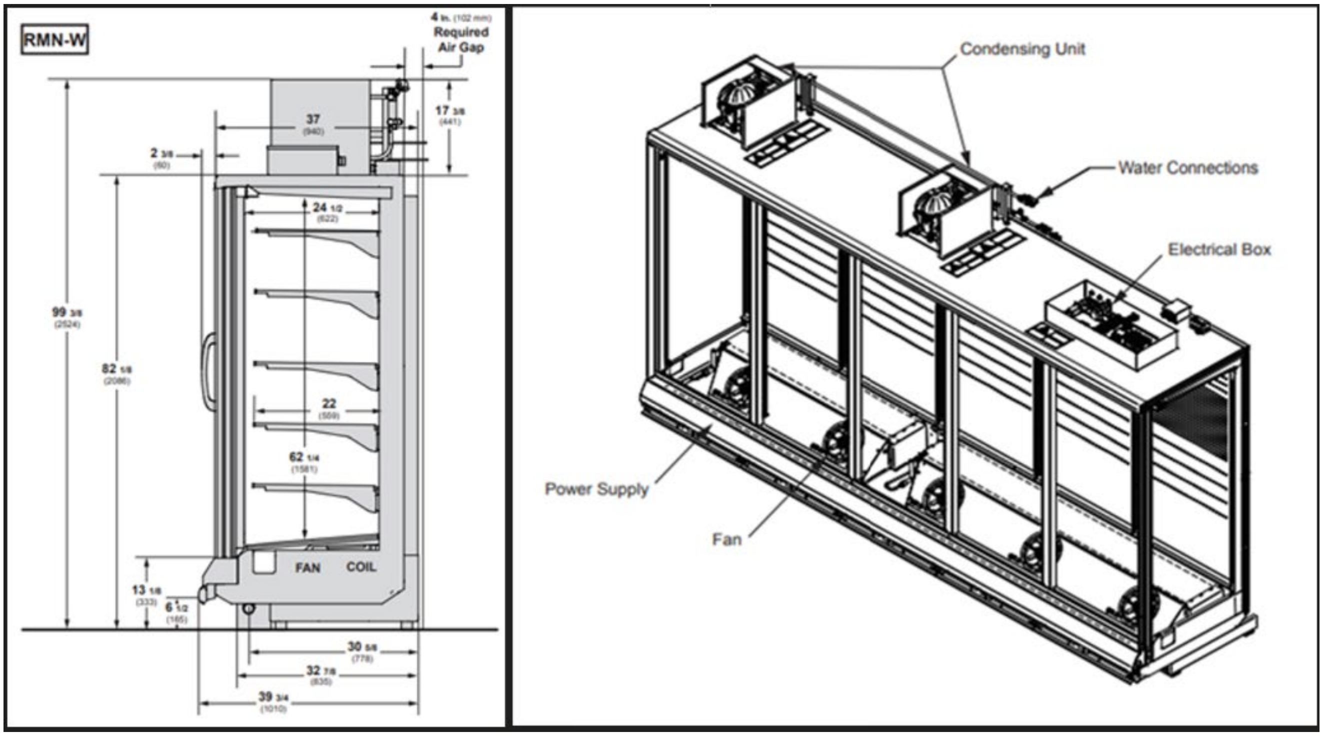


Figure 8: Liquid-cooled, high efficiency refrigerated case diagram and dimensions taken from the product specification sheet for Hussman RMNW case. The case used in this assessment has three doors, not the five shown in the figure.

Table 9: Product Specifications of the High Efficiency Hussman RMNW Case Assessed in this Study

	High Efficiency Case
Refrigerant	R-290
Refrigerant GWP	3
Compressor type	0.25-hp fixed-speed compressor
Rated cooling capacity (Btu/h)	2355
Rated current (A)	6.6
Default cut-out/cut-in temp. (°F)	33.5/39.5

	High Efficiency Case
Evaporator fan cycling	Continuous
Scheduled daily defrost cycles	1
Expansion device	Capillary tube
Evaporator fan type	Three 8.25-in. plastic fans
Evaporator coil dimensions	7.2 in W x 9.25 in H x 86 in L
Condenser type	Brazed plate heat exchanger
Condenser dimensions	3 in W x 12.3 in H x 1.5 in L
Evaporator fan motor hp	0.016
Condenser fan motor hp	No fan (liquid cooled)
Case internal volumetric capacity	74.9 ft^3
Anti-sweat heater controls	Always on
Defrost controls	Temperature terminated at 48°F

Market Overview

This study defined and evaluated the California market potential for liquid-cooled, self-contained, medium-temperature, low-GWP, reach-in cases with advanced controls connected to a liquid-coolant loop through both a review of existing research and literature, and engagement with manufacturers, contractors, and end use retailers. Results enabled the team to identify potential barriers to market adoption, quantify the energy efficiency impacts, and assess the implications of low-GWP refrigerants. These details inform the scalability and support for measure adoption into IOU program portfolios.

Review of Available Equipment

The energy use of self-contained cases in the DOE database only includes the refrigerated case and not the system energy use associated with the heat rejection loop to remove waste heat from the sales floor. Analysis shows that self-contained propane cases perform well in low-temperature applications, but low-temperature equipment is a smaller share of the market than medium-temperature, so medium-temperature cases were identified as the most relevant focus for the study. Additionally, closed door cases and those with semi-vertical or horizontal configurations are not included in this evaluation.

Medium-temperature, vertical cases make up nearly 42.6 percent of shipped linear feet of refrigerated cases in the United States in 2020 (DOE 2021). The percentages of shipped linear feet by equipment class for vertical open (VOP) and vertical closed transparent door (VCT), vertical closed solid door (VCS), remote-condensing (RC) and self-contained (SC), medium-temperature (M) display cases are shown in Table 10. The average energy savings above code per available unit by equipment class are shown below in Table 11. For reference, a typical three-door unit is about six linear feet.

Table 10: Percentage of Linear Feet Shipped by DOE Equipment Class

Equipment Family, Class	Percentage of Shipped Linear Feet
VOP.RC.M	10.3 %
VOP.SC.M	1.3 %
VCT.RC.M	0.8 %
VCT.SC.M	4.8 %
VCS.SC.M	25.4 %

DOE 2021

Table 11: Average Energy Savings Above Code by Equipment Class

Equipment Family, Class	Number of Available Cases	Average Energy Savings per Unit [ΔkWh]	Average Percent Savings per Unit
Vertical open, RC, M	4,237	1,310.5	14 %
Vertical closed transparent, RC, M	3,998	541.9	18 %
Vertical open, SC, M	1,061	2,182.4	11 %

Equipment Family, Class	Number of Available Cases	Average Energy Savings per Unit [ΔkWh]	Average Percent Savings per Unit
Vertical closed transparent, SC, M	3,425	248.2	10 %
Vertical closed solid, SC, M	3,998	212.3	23 %

DOE Compliance Certification Database.

Over 50 percent of all medium-temperature, vertical open, and vertical closed transparent cases available on the market offer greater than 10 percent energy savings over code baseline, and six percent of remote condensing medium-temperature, vertical open, and vertical closed transparent cases available demonstrate 75 percent or greater energy savings over the baseline. The average savings for all units in this category is 14 percent; and the top 50 percent best-performing medium-temperature, vertical open and vertical closed transparent cases have an average savings 26.5 percent over the baseline. The energy usage by size of DOE-listed refrigerated cases is shown in Figure 9 with their comparison to the code energy requirements and lines depicting the additional savings thresholds of 10 percent, 30 percent, 50 percent, and 75 percent energy savings above code.

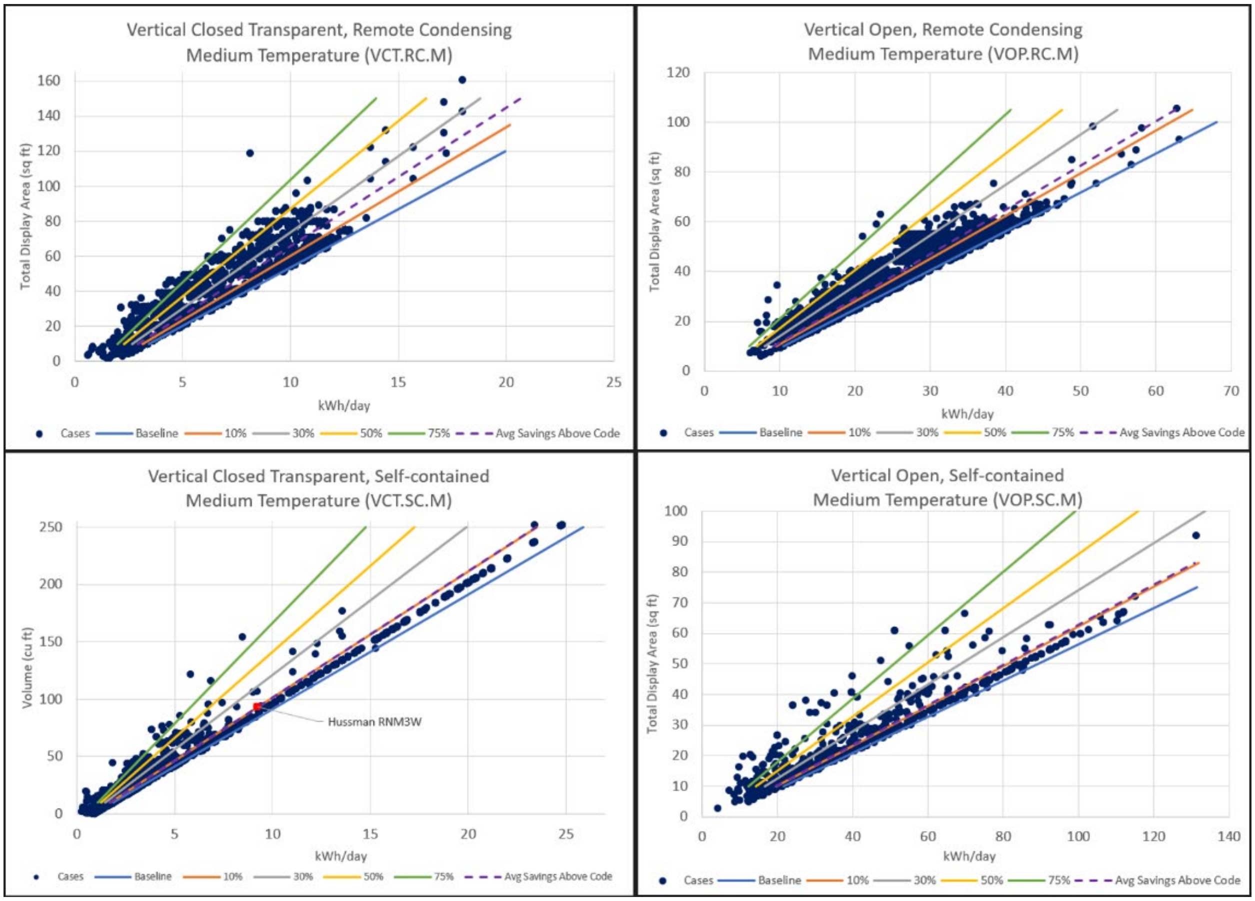


Figure 9: Daily energy consumption from the DOE compliance certification database for each IECC-designated equipment family and class compared to the code baseline. The bottom left graph shows the Hussman RMN3W case used in the laboratory assessment.

Supply Chain Overview

This report includes a summary of research conducted for relevant industry adoption trends and the sales and distribution mechanisms to clarify consumer market demand for certain technologies and features as well as the near-term potential for new technology uptake. The team gathered additional information through manufacturer interviews, including estimated equipment costs, end-user adoption rates, and equipment sales projections. The interviews also helped identify potential barriers, opportunities and additional considerations that might influence near-term industry trends or the supply chain. An example supply chain model is shown in Figure 10.

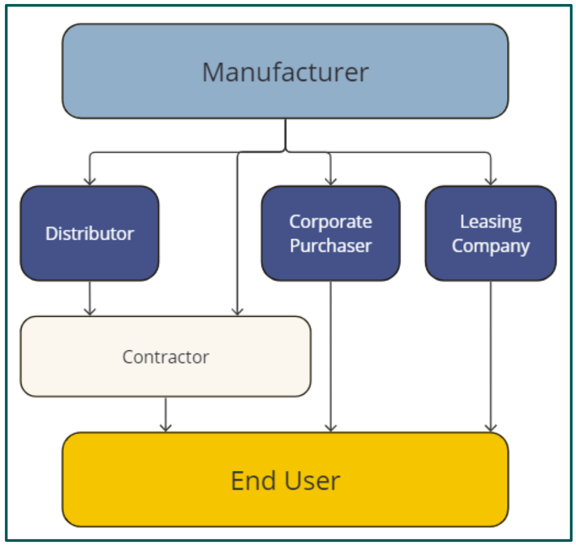


Figure 10: Example supply chain model.

Industry Trends

A mix of self-contained cases and cases with remote condensing units is still common in small and independent retailers. Large grocery stores and supermarkets have historically relied on remote condensing and multiplex rack systems. However, the high costs of maintaining large connected remote condensing refrigerated rack system and retrofitting rack systems with low-GWP refrigerants have created an emerging trend in larger stores towards a system of connected self-contained refrigerated cases, also known as a micro-distributed system, to replace traditional remote condensing and multiplex rack systems(NASRC). According to the NASRC, US grocery stores and supermarkets, including many in California, have installed more than 900,000 self-contained units utilizing propane and other hydrocarbon refrigerant. These trends were confirmed through stakeholder discussions with leading grocery consultants and stakeholder groups interviewed as part of this study.

Sales and Distribution

The sales and distribution channels for standard efficiency versus high efficiency display cases may vary based on manufacturer or distributor marketing and outreach, contractor engagement and training, and customer project goals and business objectives. This study identified the most common paths to end user acquisition of new refrigerated display cases, highlighted differences in the sales in distribution channels of baseline and high efficiency products and clarified the typical selection processes for components that increase product efficiency.

There is a resale market for refrigeration equipment, with contractors, distributors, used equipment retailers, and auction houses dedicated to the resale and donation of used cases. The resale market exists because larger and more profitable food retailers often have a capital budget cycle for replacing older equipment before it reaches the end of life. These retailers have several options for recycling and reselling used cases, including relocating used cases to another retailer within their brand, selling to another brand within their company, selling to a competitor, donating to food shelves and food pantries, and auctioning off older cases in international markets. The resale market is difficult to study. Additionally, the micro-distributed system technologies described in this study are relatively new, and due to their emergence in the market, they are not common enough to have a resale market at this time.

Stakeholder and Market Actor Outreach Findings

Conversations with market stakeholders including manufacturers, contractors, efficiency utility program managers, and end users provided vital details about the market's current state from various perspectives in the procurement cycle. The project team conducted interviews with:

- Several people from one manufacturing company, including representatives from sales, data science, product management, and development departments
- Program managers from three different utility energy efficiency programs, representing the California market and beyond
- Two refrigeration sustainability managers from end-user national grocers with a presence in California
- One engineer from a California-based decarbonization-focused refrigeration contractor company.

Overall, market actor interviews offered information representative of the entire state except for two of the utility efficiency program managers, who shared insights from rebate programs active in other states.

Equipment Knowledge and Acceptance

Manufacturers were familiar with the cases and refrigerants included in this study but shared that the current market is made up of less than 20 percent natural refrigerants, with a 50/50 breakdown of propane and CO_2. They reported that CO_2 is often a better fit and more efficient for the new and large grocery store market. It was noted that some new stores are installing micro-distributed systems, but this is often a better option for retrofits of smaller stores, as it offers less equipment downtime. While it is difficult to put a number on the incremental cost difference of these emerging technologies due to their installation often involving an entire new system design and a switch to self-contained cases with more components, increasing costs for high-GWP refrigerants are increasing favorability of project economics for low-GWP and natural refrigerants. Manufacturers noted an overall market wide preference wide toward existing, well-established technologies, but reported that acceptance of emerging, efficient technologies is increasing, with original equipment manufacturers (OEMs) often being the most common early adopters.

Contractor and Customer Education and Economics

According to the manufacturers interviewed, most commercial refrigeration customers rely on contractors' knowledge to recommend equipment that fits a customer's operational needs and existing systems. They noted that while customer purchasing habits are starting to change, there is a need for significant education to increase familiarity with the equipment and confidence in the performance and reliance — for both customers and contractors. Contractors interviewed agreed with this, adding that they are uncertain of the reasons to pursue these natural refrigerant systems. While contractors often have the most success working with medium-to-large stores and national chains, the major barriers they often encounter include energy use; system requirements related to energy and building codes; and end-of-life equipment shutdown.

Representatives of end users expressed a lack of familiarity with the technology and hesitancy about its ability to work on larger case lineups given the increased number of compressors, maintenance load, etc. They mentioned their potential applicability for smaller operations, such as convenience stores. These representatives shared that while they are interested in the potential and future of propane cases, end users would need additional education and pilot case studies to become more accepting and likely to adopt the technologies.

In addition, manufacturers shared that incremental costs of these systems are still high, often 10 to 20 percent higher than traditional HFC systems. Costs are likely decrease as the market share of self-contained, water-cooled systems increases. Product rebates have the potential to contribute to increasing adoption, but manufacturers shared their hesitancy with the current rebate market's ability to drive purchasing habits. One contractor working in the California market noted they were not aware of a project that had gone through an efficiency program based on a natural refrigerant change out. When asked about project upgrades and economics, a representative of large grocery store chain shared that about eight to 10 percent of stores in the company get new cases each year, and that they often aim for a two-year return on investment, although remodels have different criteria as they are more sales-based.

Utility Efficiency Programs

The project team spoke with one utility efficiency program manager representing a California utility efficiency program and others with programs elsewhere. Their perspectives provided valuable insights on successful incentive levels, program design for different markets, and where to engage in the supply chain. Incentive program managers described several different refrigeration rebate programs offered for new construction, small business, and retrofits. Program managers shared that the highest program uptake occurs at the manufacturer level and through vendors, because bigger grocery chains often hire projects out to vendors who are familiar with existing incentives. Interviewees noted that some utilities have offered bonus rebates on natural refrigerants in the past, but a significant barrier has been the issue of not being able to incentivize greenhouse gas savings alone. California's adoption of the TSB metric has helped the market overcome this barrier, making natural refrigerants the cost-effective choice. An added barrier, program managers shared, is that current incentive levels need to be higher to get customers to move on projects.

Summary of Key Market Barriers Identified

There are numerous barriers to widespread adoption of high efficiency, liquid-cooled cases with natural refrigerants. Manufacturers, contractors, and end users commonly mentioned:

- **Equipment acceptance and understanding:** Energy performance and reliability are not well understood and the system design is new and different from older systems. Bringing equipment out onto sales floors, in view of customers, poses a perceived risk to business and sales, in addition to bringing operations and maintenance work onto the sales floor. That said, it is important to note that these systems have built-in resilience because they are micro-distributed; when one system fails, the entire case lineup is not impacted the way it is with centralized systems.

- **First costs:** While most stores currently replace equipment as it fails in order to reduce project first costs, these systems require an entire case lineup to be replaced at the same time, due to the need to run new water or glycol lines on the sales floor and connect these lines to the heat rejection equipment. Moreover, since these types of cases are relatively new to the market, there is not yet a resale market, so customers must buy new equipment. These factors can limit cost savings and may result in high incremental costs compared to resold standard cases.

- **Contractor and end user reluctance and education:** Installers and end users are reluctant to learn a new system and trust in the design due to real and perceived risks to their business. If installation does not go smoothly and results in extended downtimes, or if equipment doesn't perform well and results in higher maintenance and operational costs, this reflects poorly on both the contracting firm and the business. Equipment reliability is crucial, and contractors feel less comfortable with new and unfamiliar technologies, components, and controls.

Laboratory Assessment

This experimental laboratory assessment is meant to provide energy performance of the refrigeration system described earlier in the Study-Specific Technologies section, including the case and heat rejection equipment, under typical operational conditions. The results inform the whole-building hourly energy modeling assessment. This project is not intended to replicate any tests performed by rating entities for medium-temperature refrigerated cases. However, where applicable, the laboratory assessment procedure is based on relevant rating standards — ANSI/ASHRAE 72-2018 and ANSI/AHRI 1200-2013— which prescribe key parameters and conditions under which performance assessments should be conducted, and the range under which mean product temperatures must be maintained to satisfy the Food & Drug Administration (FDA) requirements (AHRI 2013) (ASHRAE 2018). Furthermore, the laboratory procedure includes at least one additional test that is more representative of actual store conditions, as described in Table 12.

Laboratory Procedures and Setup

Table 12: Environmental Chamber and Product Temperature Conditions for Refrigerated Case Assessment

Test	Environmental Chamber Dry-Bulb Temp (°F)	Environmental Chamber Wet-Bulb Temp (°F)	Product Temperature (°F)
ANSI/ASHRAE 72-2018	75.2 ± 1.8	64.4 ± 1.8	38 ± 2

Test	Environmental Chamber Dry-Bulb Temp (°F)	Environmental Chamber Wet-Bulb Temp (°F)	Product Temperature (°F)
Average store condition	70 ± 1.8	51.8 ± 1.8	38 ±2

Each experiment consisted of data collection at one-second intervals for a 24-hour period, initiated at the start of a defrost cycle. Data collection included the following measurements and sensors (Table 13)

Temperature measurements:

- Product simulators placed at various locations within each case according to standard ASHRAE 72
- Air discharge temperatures leaving the evaporator
- Air inlet temperatures to the evaporator
- Case interior air temperature
- Refrigerant temperatures at the inlet/outlet to the two heat exchangers, capillary tube, and compressor

Power measurements:

- Compressor
- Condenser fan
- Evaporator fan
- Lighting
- Controls
- Anti-sweat heaters
- Total

Pressure measurements:

- Liquid cooled condenser inlet
- Liquid cooled condenser outlet

Table 13: List of Instruments Used to Monitor the Refrigerated case, Models and Accuracies

Measurement	Brand/Model	Type	Accuracy
Product simulator, internal air, and chamber dry-bulb temperatures	Omega/TMQSS-062U-6	1/16" Type-T thermocouple probes	± 0.50 °C (± 0.90 °F)

Measurement	Brand/Model	Type	Accuracy
Chamber dew-point temperature	EdgeTech/DewTrak II DPS3	chilled-mirror dew-point hygrometer	± 0.22 °C (± 0.4 °F)
Refrigerant piping surface temperatures	Omega/SA1-T-SRTC	Type-T surface temperature thermocouple	± 0.50 °C (± 0.90 °F)
Condenser water inlet/outlet temperature	Martin/K28G-006-00-4	1/8" T-Type Thermocouple Probe	± 0.50 °C (± 0.90 °F)
Condenser water mass flowrate	Emerson-Micromotion/CMF050M322N2 meter, 2700R12B transmitter	Coriolis flow meter	± 0.05 %
Case total plug and compressor power	Continental Control Systems/WMC-3Y-208-MB, Accu-CT ACTL-0750	Wattnode power meter, 20 A current transformer	± 0.50 %
Evaporator fans, lighting, controller, and anti-sweat heater power		Wattnode power meter, 5 A current transformer	
Condensate mass	SellEton/SL7510	24"x24", 500-lb capacity floor scale	± 0.05 lbs
Condenser water inlet Pressure	Ashcroft/G2 UPC	0 – 50 PSIG liquid pressure transducer	± 0.50 %
Condenser water outlet Pressure	Omega/PX309-050GI	0 – 50 PSIG liquid pressure transducer	± 0.25 %

Liquid loop measurements are used to calculate the heat rejected by the case (temperatures and flow rates) and the power required to pump the liquid (pressures and flow rates) from the case to the liquid coolant conditioning system.

Customer traffic and door openings were replicated by installing and programming automatic Olide 120B-model door actuators mounted above each door. The case door actuators were operated based on the schedule described in ASHRAE 72-2018 (ASHRAE 2018), designed to reflect typical operations in a store. Three hours after the start of each assessment, the left door was opened for six seconds, with a 10-minute interval before the next door was opened for six seconds. This process was repeated for eight hours, and the case doors then remained closed for the final 13 hours of each assessment.

Experiments were performed within an environmental chamber at controlled indoor environmental conditions (Figure 11). The interior of the chamber is 85 inches wide x 142.5 inches in length, with a 144-inch high ceiling. The case was aligned parallel to the long end of the chamber facing away from the chamber's discharge steam/air vent. The case was oriented exactly 12 inches from the back wall and centered in the chamber at least 24 inches from each side wall, as required by ASHRAE 72.

a) b)

Figure 11: a) High efficiency water-cooled, low-GWP, refrigerated display case before testing and b) inside in the environmental chamber.

Product Simulators, Filler Material, and Case Temperature Control

For a medium-temperature display case, FDA regulations require that average product temperatures be maintained at 38 ± 2°F (3.33 ± 1.11°C) (Ayub 2003, 3-16). The case controller is adjusted to keep the average temperature of internal "product simulators" within these FDA limits. As shown in Figure 12, 18 product simulator temperatures were measured at the left, center, and right ends of the top shelf, middle shelf, and bottom decks. At each location, two simulators were placed at the front and rear of the shelf up to the product load line. The product simulators specifications (ASHRAE 72) were as follows (UNEP 2016):

- Product simulators consisted of 3-inch x 3-inch (base) x 2.5-inch (height) plastic containers.
- Simulators were filled with grout sponges soaked in a 50/50 (± 2 percent) mix of food-grade propylene glycol and deionized water.
- Simulators were inserted with thermocouple probes (with ± 0.9 °F accuracy).

- Thermocouple probes were inserted through a drillhole in the simulator lid such that the tip of each probe would rest 1.5 inches from the bottom.

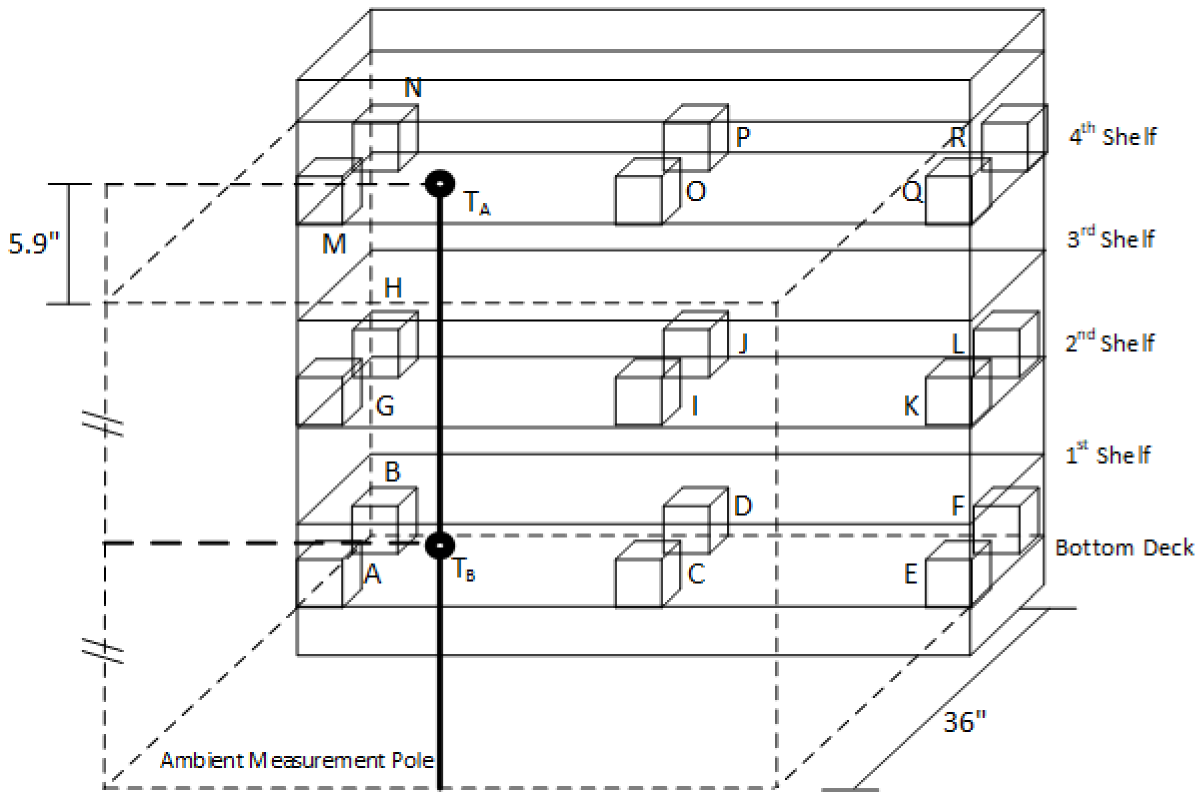


Figure 12: Product simulator temperature measurement locations (A–R), and ambient temperature locations (T_A and T_B).

Image modified from ASHRAE 2018.

The net usable interior volume of the cases was loaded with “filler material” to simulate the thermal mass of food product. Due to NREL’s safety requirements, the filler material used in the experiment was a set of 11-inch tall, 1-Liter bottles filled with water. This configuration generated openings between the bottles to allow for more uniform airflow.

The laboratory is located at 1,773-m altitude in Golden, Colorado. At this altitude, air density is nearly 20 percent less than at sea level, which reduces the volumetric flow rate of the evaporator fan, thereby reducing heat transfer through the evaporator. To compensate for the effect of altitude, the temperature setpoint was adjusted on the web controller for the Hussmann RMN case until the average of the product simulator temperatures was maintained within AHRI/FDA requirements and stabilized for 12 hours. The Hussmann case controller allows the user to select a setpoint at which the compressor cuts in or out at temperatures three degrees above or below the setpoint, as measured by an internal probe in the case’s discharge air grille. To maintain temperatures around 38 °F as required by the standard, the setpoint was required to be 36.5 °F.

Chamber Condition Instrumentation/Control

To monitor and maintain conditions within the environmental test chamber, an "ambient measurement pole" was mounted 36 inches from the front of the case, as required by ASHRAE standards and as shown in Figure 12. Measurements were made at different heights along the pole specified by T_A and T_B. Location T_A is 5.9 inches above the top edge of the case air curtain discharge, this probe is used for maintaining chamber conditions described in Figure 12. Location T_B is at the height of the geometric center of the air curtain, which varies depending on the specific case and is determined by the top edge height and the bottom sill height. The location T_B dry-bulb temperature probe is at the height of the geometric center of the case doors, and the temperature must be maintained such that the gradient between T_A and T_B is lower than 1 °F/foot.

Location T_A was fitted with both a thermocouple probe and a dew-point hygrometer probe. Location TB was fitted with only a thermocouple probe. The chamber was controlled to a constant dry-bulb temperature and dew point to match the benchmark case data. Measurements were taken at one-second intervals during the entire test.

Liquid-Loop Controls and Evaluation Conditions

To supply coolant to the condenser of the liquid-cooled refrigerated case at a controlled temperature and flowrate, NREL's fluid-conditioning module (FCM) was connected to the refrigerated case in the environmental chamber. The FCM, prefabricated for use in related projects, is shown in Figure 13. The FCM consists of two independent coolant pumped loops, with each loop having its own variable-speed pump and two braze-plate heat exchangers connected to a hot-water supply coming from an external boiler and a cold-water supply from an external chiller. The FCM can condition liquid to any flow rate within 5 to 50 GPM and any temperature within 40 to 115°F. The inlet water temperature to the condenser was varied to investigate its impact on the condenser thermal load and compressor electrical load, and the flow rates were set to 1 gpm to satisfy manufacturer's specifications. The water inlet temperatures were selected to match conditions from previous studies with liquid-cooled open vertical case (A. Bulk, 2023) and to meet manufacturer temperature limits (41 to 118 °F) (Table 14). A midpoint temperature of 80.0 °F was selected to best represent a typical city main water or water tower temperature. The lower limit temperature of 55 °F was used to represent chiller or winter water line conditions typical in most California climate zones. A water inlet water temperature of 108 °F was used to replicate the saturated condensing temperature of the air-cooled baselines. Finally, a 95 °F inlet temperature was used to provide an additional reference value.

Table 14: Evaluation Test Matrix of Chamber Conditions and Condenser Inlet Water Temperatures

	55°F Inlet Temperature	80°F Inlet Temperature	95°F Inlet Temperature	108°F Inlet Temperature
ANSI/ASHRAE 72-2018	X	X	X	X
Average store condition	X	X	X	X

Figure 13: NREL's fluid-conditioning module can provide 5 to 50 GPM liquid in temperatures ranging from 40 to 140°F.

Energy and Power Consumption Results

The total daily energy consumption, mean power consumption, and mean power consumption during the compressor on-cycle are presented in Table 15 and compared against the selected benchmark cases. For comparison, the data is normalized to the total refrigerated volume.

Table 15: Comparison Between the Energy Efficient and Benchmark Case Total Energy, Mean Power, and Compressor On-Cycling, with Mean Power Normalized to Interior Volume

Total Energy ($Wh/day/ft^3$)						
	Efficient Case (at given inlet temperatures)				Benchmark Cases	
	55 °F	80 °F	95 °F	108 °F	R-134a RIC	R-513a RIC
ASHRAE 72 conditions	126.2	173.2	215.1	233.2	233.2	157.2

Total Energy (Wh/day/ft³)						
Average store conditions	120.8	155.4	204.9	232.1	217.4	126.9
Mean Power (W/ft³)						
	55 °F	80 °F	95 °F	108 °F	R-134a RIC	R-513a RIC
ASHRAE 72 conditions	5.3	7.2	9.0	9.7	9.7	6.6
Average store conditions	5.0	6.5	8.5	9.7	9.1	5.3
Mean Power Only During Compressor On-Cycling (W/ft³)						
	55 °F	80 °F	95 °F	108 °F	R-134a RIC	R-513a RIC
ASHRAE 72 conditions	7.4	8.5	9.3	10.0	19.3	18.5
Average store conditions	7.4	8.5	9.2	10.0	18.8	18.4

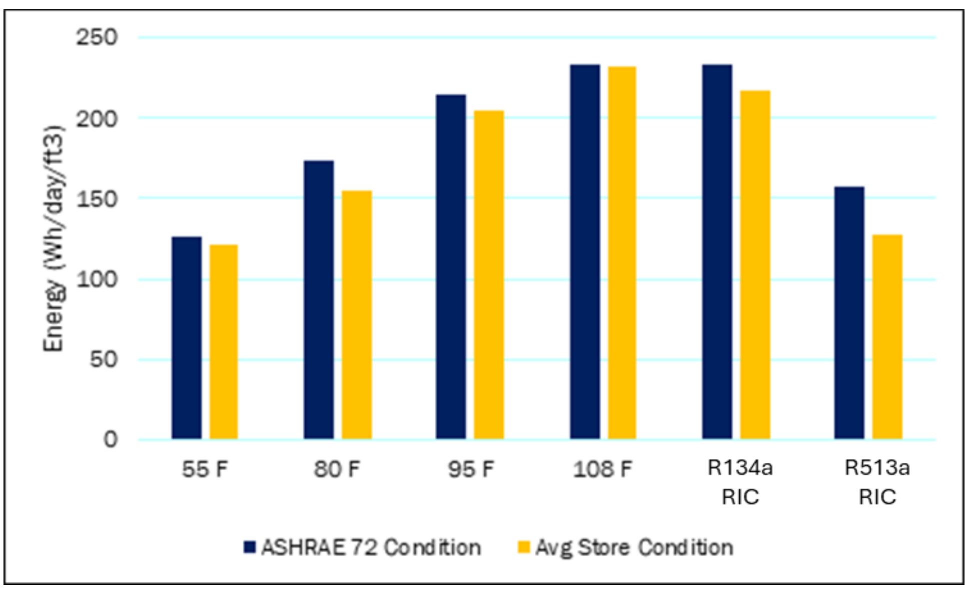


Figure 14: Comparison between energy use by the energy efficient and benchmark refrigerated cases normalized to interior volume.

At an inlet water temperature of 55°F, the test case used less daily energy and mean power than both benchmark cases under each chamber condition when normalized to interior volume, demonstrating that it is more efficient. However, at water inlet temperatures of 80°F and higher, the tested case consumed more energy than the R-513a RIC. The tested case showed enhanced performance compared to the R-134a RIC in all tested conditions except at an inlet water temperature of 108 °F. An inlet water temperature of 108 °F was used to replicate the saturated condensing temperature of an air-cooled condensing unit at ASHRAE 72 conditions. At this temperature, the tested case consumed the same energy and mean power than the R-134a RIC; however, this inlet water temperature is higher than typical scenarios and is not expected in most applications. The mean power consumption during compressor on-cycling was 46 to 62 percent lower in the test case than both benchmark cases, which would result in peak power consumption savings.

Detailed component energy and power consumption results are presented in Table 16, Table 17, and Table 18.

Table 16: Efficient Refrigerated Case Component Energy Consumption Over 24-h Evaluation

Energy (kWh)	Compressor	Evaporator Fans	Lighting	Anti-Sweat Heaters	Controller	Total
ASHRAE 72 55 °F	5.0	1.3	1.3	1.7	0.1	9.5
Average store 55 °F	4.6	1.3	1.3	1.7	0.1	9.0
ASHRAE 72 80 °F	8.5	1.3	1.3	1.7	0.1	13.0
Average store 80 °F	7.2	1.3	1.3	1.7	0.1	11.6
ASHRAE 72 95 °F	11.7	1.3	1.3	1.7	0.1	16.1
Average store 95 °F	10.9	1.3	1.3	1.7	0.1	15.3
ASHRAE 72 108 °F	13.0	1.3	1.3	1.7	0.1	17.5
Average store 108 °F	13.0	1.3	1.3	1.7	0.1	17.4

Table 17: Efficient Refrigerated Case Component Mean Power Over 24-h Evaluation

Mean Power (W)	Compressor	Evaporator Fans	Lighting	Anti-Sweat Heaters	Controller	Total
ASHRAE 72 – 55 °F	209.4	54.0	55.6	71.0	4.0	393.9
Average store – 55 °F	192.4	54.0	55.6	71.0	4.0	376.9
ASHRAE 72 – 80 °F	356.0	54.0	55.6	71.0	4.2	540.8
Average store – 80 °F	300.5	54.0	55.6	71.0	4.0	485.1
ASHRAE 72 – 95 °F	487.0	54.0	55.6	71.0	4.0	671.6
Average store – 95 °F	454.8	54.0	55.6	71.0	4.0	639.4
ASHRAE 72 – 108 °F	543.1	54.0	55.6	71.0	4.2	727.9
Average store – 108 °F	539.7	54.0	55.6	71.0	4.1	724.4

Table 18: Efficient Refrigerated Case Component Mean Power Only During Compressor On-Cycling

Mean Power (W)	Compressor	Evaporator Fans	Lighting	Anti-Sweat Heaters	Controller	Total
ASHRAE 72 – 55 °F	369.8	54.0	55.6	71.0	4.1	554.5
Average store – 55 °F	367.7	54.0	55.6	71.0	4.1	552.4
ASHRAE 72 – 80 °F	455.1	54.0	55.6	71.0	4.3	640.0

Mean Power (W)	Compressor	Evaporator Fans	Lighting	Anti-Sweat Heaters	Controller	Total
Average store – 80 °F	455.5	54.0	55.6	71.0	4.1	640.2
ASHRAE 72 – 95 °F	508.3	54.0	55.6	71.0	4.0	692.9
Average store – 95 °F	505.5	54.0	55.6	71.0	4.1	690.2
ASHRAE 72 – 108 °F	567.0	54.0	55.6	71.0	4.2	751.8
Average store – 108 °F	563.7	54.0	55.6	71.0	4.1	748.4

The variation in energy consumption across inlet water conditions is attributed to the change in compressor power and compressor on-cycling. The compressor mean power varies considerably with inlet water temperature. Table 18 shows that during the on cycle, the mean compressor power is more than 50 percent higher between the minimum and maximum inlet water temperatures of 55 and 108°F. Additionally, a comparison of Table 17 and Table 18 shows that the 24-hour mean power and the compressor on-cycle mean power are nearly the same at the maximum temperature, indicating that the compressor is running almost constantly. Whereas at the minimum temperature, the 24-hour mean power is 56 percent lower than the compressor on-cycle power, which indicates, as expected, that the compressor is off much more frequently.

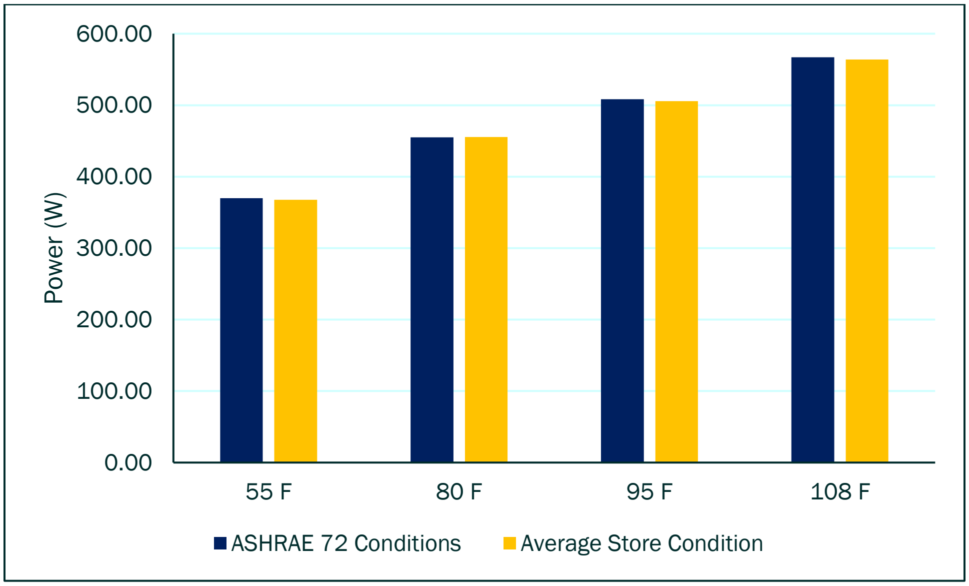


Figure 15: Power consumed by the compressor for different condenser inlet water temperatures and store conditions.

Whole-Building Hourly Energy Modeling

Data from the benchmarked cases tested in the laboratory was used to inform the development of an hourly baseline energy modeling assessment.

Background Statistics for Developing Baseline Model

Grocery stores, including supermarkets, and convenience stores are categorized as 'Food Sales' building type in the latest CBECS survey report (EIA 2018). Both these building segments occupy a large floor area in the commercial sector and have significant refrigeration load. The 2023 version of the building type report (EIA 2018) indicates that most food sales buildings are convenience stores: 74 percent by number and 60 percent by total floorspace.

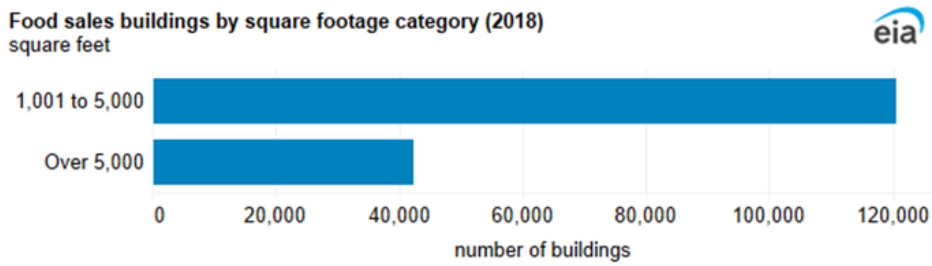


Figure 16: Food sales buildings by square footage (EIA 2018)

The average square footage of food sales buildings is 6,200 square feet, and three-fourths are under 5,000 square feet (Figure 16). Roughly 92 percent of these buildings are single-floor buildings.

Building Modeling Approach

The building energy modeling in this project leveraged the EnergyPlus hourly simulation platform coupled with the display case performance characterization data obtained from the laboratory experimentation of the benchmark and high efficiency refrigerated display cases. Energy modeling allowed for the quantification of the annual energy, demand, GHG and economic impacts of four baseline scenarios described below. The energy modeling was performed in California CZ 9 and leveraged pertinent electric and gas rate structures.

The team’s approach was based on developing a range of normalized annual energy savings as a function of building segment, type of display case, and linear foot of display case to help inform potential program development. Under this flexible approach, IOU program designers would be able to establish boundaries for more realistic annual saving values with direct relevance to the actual customer's operational characteristics. Based on the statistics for food sales buildings, two building configurations were selected: a small grocery store and a large supermarket. Two scenarios for each building configuration were developed: one with 100 percent medium-temperature open vertical cases, and one with 100 percent reach-in cases. This created four baseline energy models.

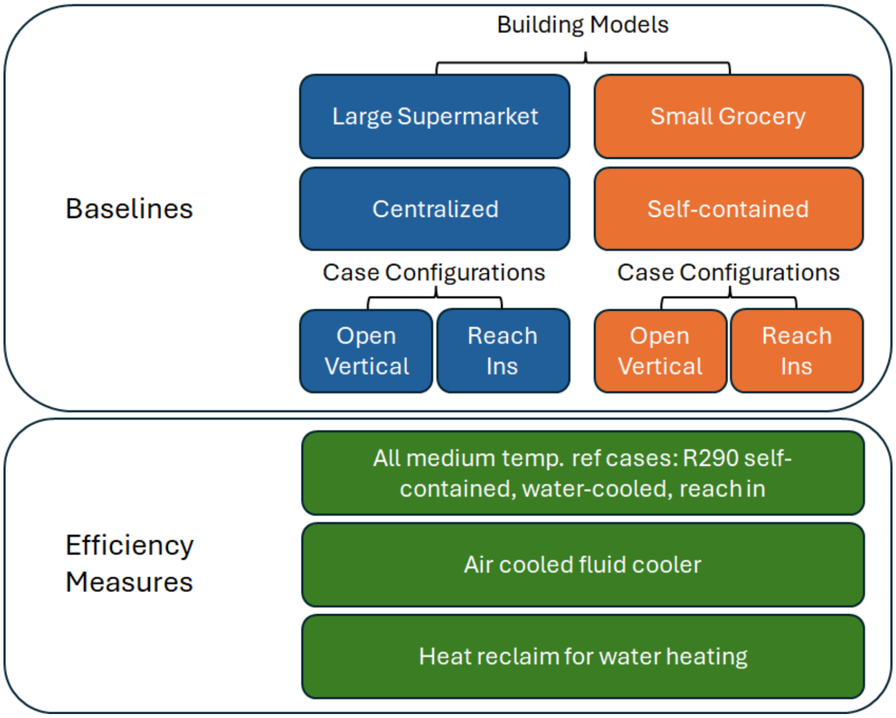


Figure 17 depicts the general model descriptions, key variants, and proposed upgrade measures. This methodology eliminated reliance on a single savings value and enabled program administrators to interpolate energy savings as a function of building type and mix of display case types available at the customer site.

The energy models were developed using performance data from the benchmarked and HERC cases obtained during laboratory experimentation. In addition to energy, demand, and GHG impacts at the whole-building level, energy modeling captured interactive effects of the proposed technology on the HVAC system and the potential natural gas savings from waste heat reclaim.

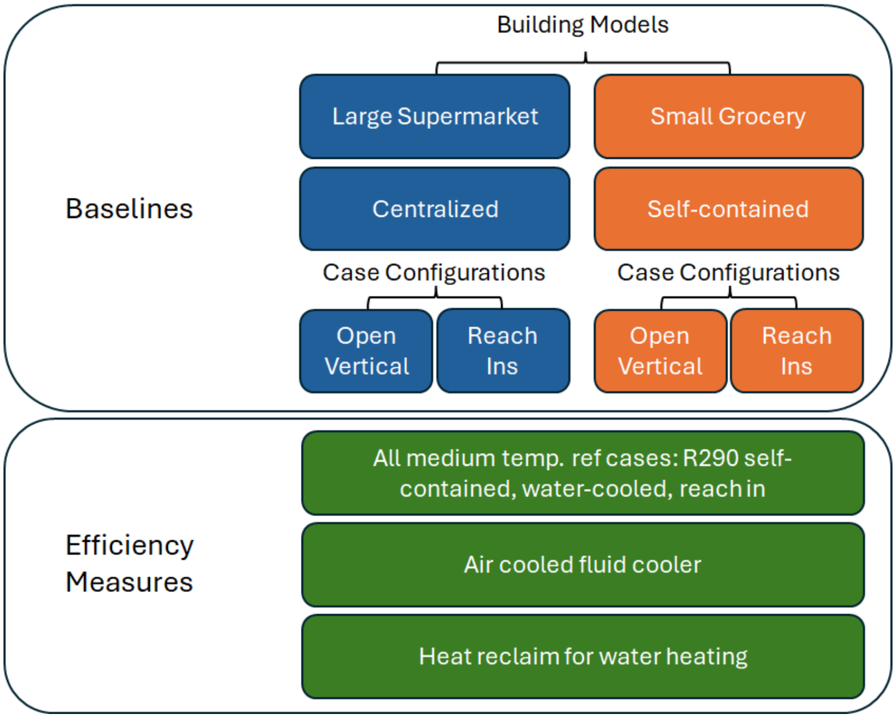


Figure 17: Schematic of baseline assumptions and proposed efficiency measures.

The baseline large supermarket model was built on DEER assumptions as documented in CalBEM Benchmarking Database and is currently published at Github repo DEER Prototype EnergyPlus in the IDF format model (Edison 2023). The small grocery store input data was based on the 2014 report of the California Commercial Saturation Survey and the CBECS database for food sales by building type (EIA 2018). The default values from the DEER assumptions of a large supermarket were also applied for a small grocery store where pertinent information was missing. The development of a building model for small grocery stores originally leveraged the DEER assumptions for a large supermarket. Then additional modifications were made by extracting information from various relevant sources including a database generated by California implementers who have been active in audit projects involving small grocery stores (CalBEM Benchmarking Database n.d.). Combining assumptions from these sources resulted in the modified DEER based grocery model with a reduced floor area.

As described previously, for each of the building models — small grocery store and large supermarket — two refrigerated display case configurations were developed. The first baseline case configuration assumed all MT display cases were open vertical cases, and the second assumed all were closed reach-in cases. The proposed models for both building types and case configurations replace the baseline display cases with the HERC comprised of self-contained, R-290, water-cooled, reach-in units with the heat reclaim feature. The water-cooled heat rejection mechanism is expected to enhance the energy efficiency of the case by operating at a lower temperature lift, while the heat reclaim capability is expected to reduce the water heating load of the proposed by using the waste heat to preheat DHW.

Using the DEER-based model is important because the energy efficiency standards and appliance efficiency standards requirements in California are already embedded in these models. With this approach the savings associated with replacing open display cases with reach-in cases can be assessed by comparing baseline scenario one with baseline scenario two. Then the savings of adding liquid-cooled refrigerated cases in a typical store (baseline scenario one) can be compared against adding these novel cases to a more efficient baseline (baseline scenario two).

Baseline Model Assumptions

This section provides the general assumptions used to develop the small grocery store and large supermarket models (Table 19). Except for a small number of self-contained display cases, the entire medium-temperature refrigeration system including display case lineups and walk-ins in a large supermarket was modeled as a centralized system served by a multiplex rack system.

Table 19: Model Input Assumptions

Category	Components	Small Store Baseline	Small Model Upgraded	Large Store Baseline	Large Store Model Upgraded
Version	Vintage	Same as DEER baseline	Upgraded Refrigeration	DEER baseline	Upgraded Refrigeration
Geometry	Area (square feet)	6,200		50,000	
	Geometric form	Square (1:1)		Square (1:1)	
	Floor number	one floor			
	Height (feet)	15		25	
	WWR	0.14		0.07	
	Sale area ratio	80 %		80 %	
Envelope	Envelope characteristics	Wall, Roof and Windows: Climate zone dependent R values and SHGC			
Internal loads	Internal loads intensity (W/ft^2)	ACM Reference Manual Appendix 5.4B			
Schedules	Operation Schedules	ACM Reference Manual Appendix 5.4B 24/7			

Category	Components	Small Store Baseline	Small Model Upgraded	Large Store Baseline	Large Store Model Upgraded
HVAC	HVAC system type	Cooling: Packaged RTU CAV Heating: Packaged RTU CAV furnace gas coil		Cooling: Packaged RTU CAV Heating: Packaged RTU CAV furnace gas coil	
DHW	DHW system	Natural gas water heating 0.26 gpm		Natural gas water heating 2.2 gpm	
	Heat recovery	No	Yes	No	Yes
Refrigeration	Condenser options	air-cooled condenser	air-cooled fluid cooler	air-cooled condenser	air-cooled fluid cooler

Table 20 provides the DEER refrigeration information used for the prototypical large supermarket model.

Table 20: Large Supermarket Refrigeration Equipment Description

Medium-Temperature Cases					
Name	**Nominal Capacity (Btuh/feet)**	**Length (feet)**	**Total Capacity (Btuh)**	**Type**	**Water Cooled upgrade**
Self-contained	1,040	10	10,396	Open/Reach-In	No
Meat	415	16	6,637	Open/Reach-In	Yes
Fish	700	20	13,993	Open/Reach-In	Yes
Bakery	1,474	20	29,484	Open/Reach-In	Yes
Deli	1,674	25	41,845	Open/Reach-In	Yes
DeliServ	409	16	6,537	Open/Reach-In	Yes
Meat2	409	36	14,709	Open/Reach-In	Yes

Medium-Temperature Cases					
Meat3	1,674	35	58,583	Open/Reach-In	Yes
Dairy1	1,674	67.5	112,982	Open/Reach-In	Yes
Dairy2	1,674	67.5	112,982	Open/Reach-In	Yes
Produce	769	112	86,165	Open/Reach-In	Yes
Sum		**425**	**494,315**		

Low-Temperature Cases					
Name	Nominal Capacity (Btuh/feet)	Length (feet)	Total Capacity (Btuh)	Type	Water Cooled upgrade
Reach-in case1	543	35	18,994	Reach-In	No
Reach-in case2	543	35	18,994	Reach-In	No
ICE reach-ins	586	39	22,868	Reach-In	No
Dual temp case1	550	80	43,997	Reach-In	No
Dual temp case2	550	80	43,997	Reach-In	No
Sum		**269**	**148,851**		

Walk-Ins					
Name	Nominal Capacity (Btuh/feet)	Length (feet)	Total Capacity (Btuh)	Type	Water Cooled upgrade
Freezer			59,961	-	No
Cooler			74,952	-	No
Sum			**134,913**		

The small grocery store model didn't have as much data available as the large supermarket model, so the team applied the nominal capacity ratings from the large supermarket model to similar cases in the small grocery model. Table 21 and Table 22 summarize the refrigeration system assumptions that were extrapolated for the small grocery store model.

Table 21: Breakdown of Display Case Types

Medium-Temperature Cases	Low-Temp Cases
87 %	13 %
Medium Temp Nominal Capacity	
1,040 Btuh/feet	
Medium Temp Self-Contained Cases	Medium Temp Centralized Cases
56 % (59 feet)	41 % (47 feet)

Table 22: Small Grocery Refrigeration Equipment Description

Medium-Temperature Cases					
Name	**Nominal Capacity (Btuh/feet)**	**Length (feet)**	**Total Capacity (Btuh)**	**Type**	**Water Cooled Upgrade**
Self-Contained			61,380	Open/Reach-In	Yes
Centralized			48,532	Open/Reach-In	No
Sum			109,912		
Low Temperature Cases					
Name	**Nominal Capacity (Btuh/feet)**	**Length (feet)**	**Total Capacity (Btuh)**	**Type**	**Water Cooled Upgrade**
Centralized			15,735	Reach-In	No
Walk-ins					

Name	Btuh/feet	feet length	Btuh		Water Cooled Upgrade
Freezer			7,383	-	No
Cooler			21,960	-	No
Sum			**29,343**		

Display Case Model Development Overview

The display case modeling approach captured the energy efficiency features of the proposed display case technology which included water-cooled condenser, heat reclaim and potentially more favorable propane thermodynamic cycle. Using this approach, the energy savings associated with the proposed liquid-cooled refrigerated cases can be assessed relative to baseline store models. Additionally, the savings from replacing open display cases with reach-in cases can be evaluated by comparing the two baseline case configurations.

Baseline Display Case Model

Two baseline refrigerated display case configurations, open vertical and closed reach-in, were developed to establish a range of savings when compared to the proposed HERC technology. Assumptions from measure SWCR015-04 Med-Temp Case Doors published in California Electronic Technical Reference Manual (California Technical Forum 2024) were applied to account for the interactive effects of display cases with doors on HVAC systems, as compared to open vertical display case baselines:

- 77 percent reduction in sensible display case credits
- 4 °F increase in evaporating temperature
- 50 percent reduction in scheduled defrost time

EnergyPlus uses various thermal inputs, including heat rejection from refrigeration, to model the hourly heat balance for a zone. This impacts HVAC loads, energy use, and temperature conditions. A separate analysis was performed to quantify the heat rejected by refrigeration systems from the baseline air-cooled fixtures into the conditioned space. In this process, the heat of compression and refrigeration load were combined to estimate the sensible case credits. These case credits were then provided as inputs to EnergyPlus, which leverages them to calculate the zone heat balance on an hourly basis, reflecting the thermal interactions between the refrigerated cases and the surrounding space.

Proposed High Efficiency Display Case Model

The manufacturers' technical specifications for the proposed display case were used as a starting point to develop the system-level model. Then, the team used NREL's laboratory experimentation results to enhance the proposed display case model based on the actual performance data, including:

- Compressor power curve trend
- Defrost cycle controls, including potential dynamics of the evaporator fans, compressor
- Liquid coolant inlet and outlet temperatures

Figure 18 depicts the water-cooled heat rejection circuit, heat reclaim coil, circulating pump, and air-cooled fluid cooler as part of the proposed display case system. This configuration was modeled in EnergyPlus.

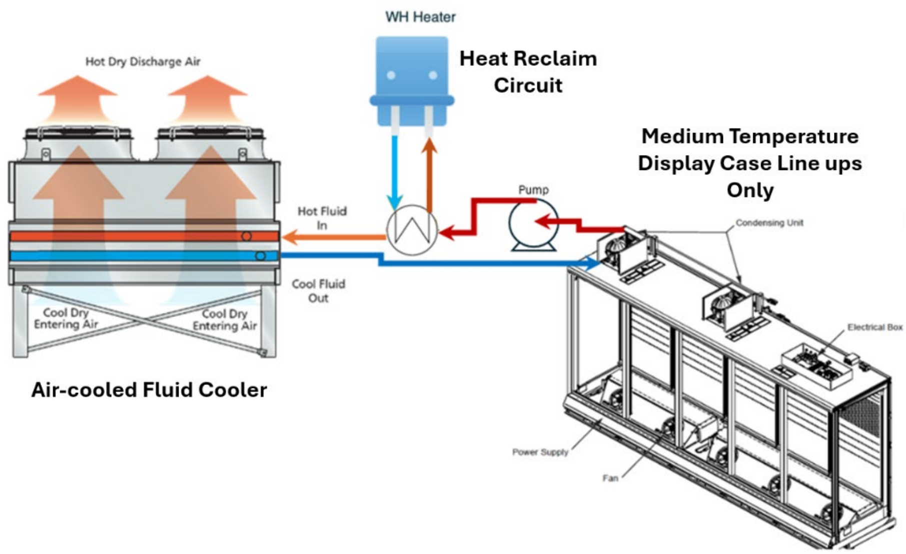


Figure 18: Schematic of water-cooled refrigerated case connected to the fluid cooler and hot water heater.

The power consumed from the liquid coolant conditioning system pumps was calculated based on pressure drops across each liquid-cooled refrigerated case and the additional piping length. The proposed display cases are equipped with glass doors. The 77-percent reduction in the case credit based on the DEER assumptions was used to capture both the interactive effects of doors on the HVAC system and the zonal conditions in EnergyPlus. The power consumption values for the evaporator fan, anti-sweat heater, and lighting of the proposed high efficiency case were obtained from the OEM manual and are shown in Table 23:. The defrost mechanism of the proposed high efficiency display case was modeled with time-initiated/time-terminated off-cycle defrost, scheduled for 30-minute intervals per 24 hours. Table 23: shows the power values of the auxiliary components that were used in the model.

Table 23: Upgraded Display Case Input

HERC Case Component	Connected Load per Linear Length of Display Case (W/feet)
Evaporator fan	7.0
Lighting	7.2
Anti-sweater	9.2

The heat rejection of the proposed water-cooled display cases was modeled based on floating head pressure controls. The floating head pressure controls maintained a 9 °F temperature differential above the inlet water temperature to the condenser as seen in Figure 19 below. The air-cooled condenser within all building modes was simulated based on a fixed condensing temperature of 125 °F based on AHRI 460 rating conditions for remote mechanical air-cooled condensers and replicating the use of a head-master valve. The low-temperature refrigeration systems under all scenarios were equipped with the air-cooled condenser, which is the same type of heat rejection equipment for the medium-temperature systems. The model used a heat reclaim heat exchanger that increases the inlet water temperature of the water heater by 9 °F. Figure 20 below depicts the monthly representative condensing temperature of the self-contained display case for small grocery store in baseline and for the water-cooled display cases. The baseline condensing temperature was established based on a design temperature differential of 20 °F above the indoor zone air temperature.

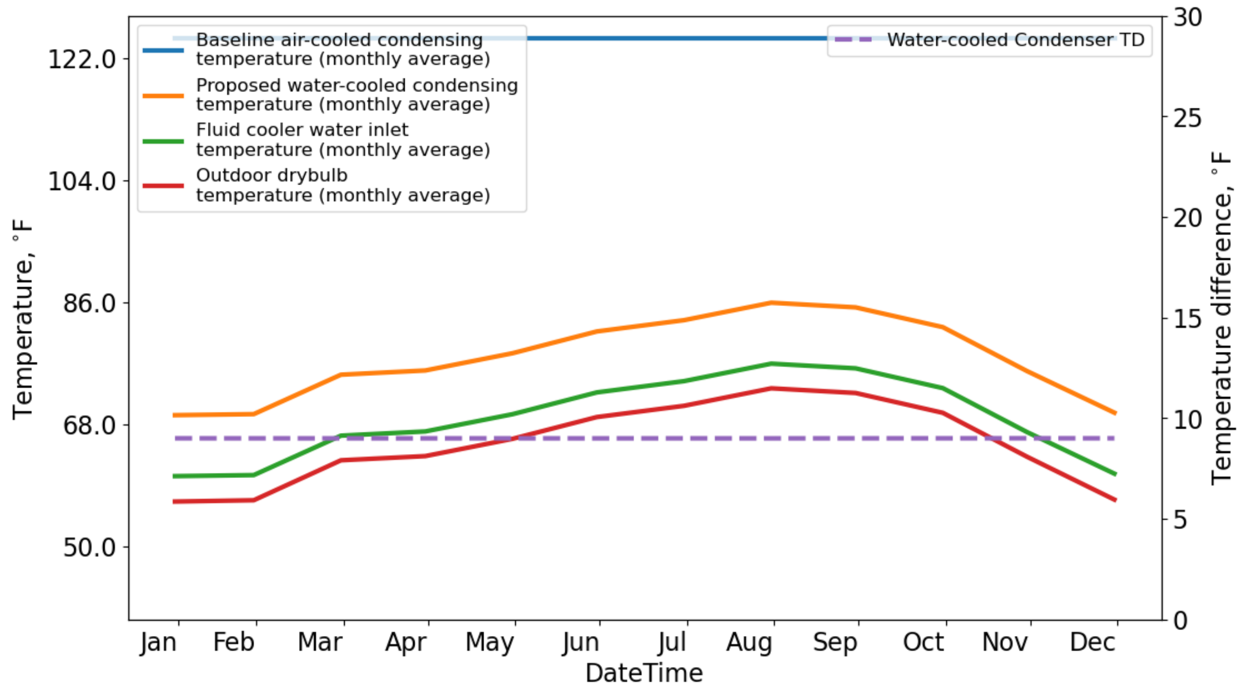


Figure 19: Condensing temperature and fluid cooler water temperature for summer days in California.

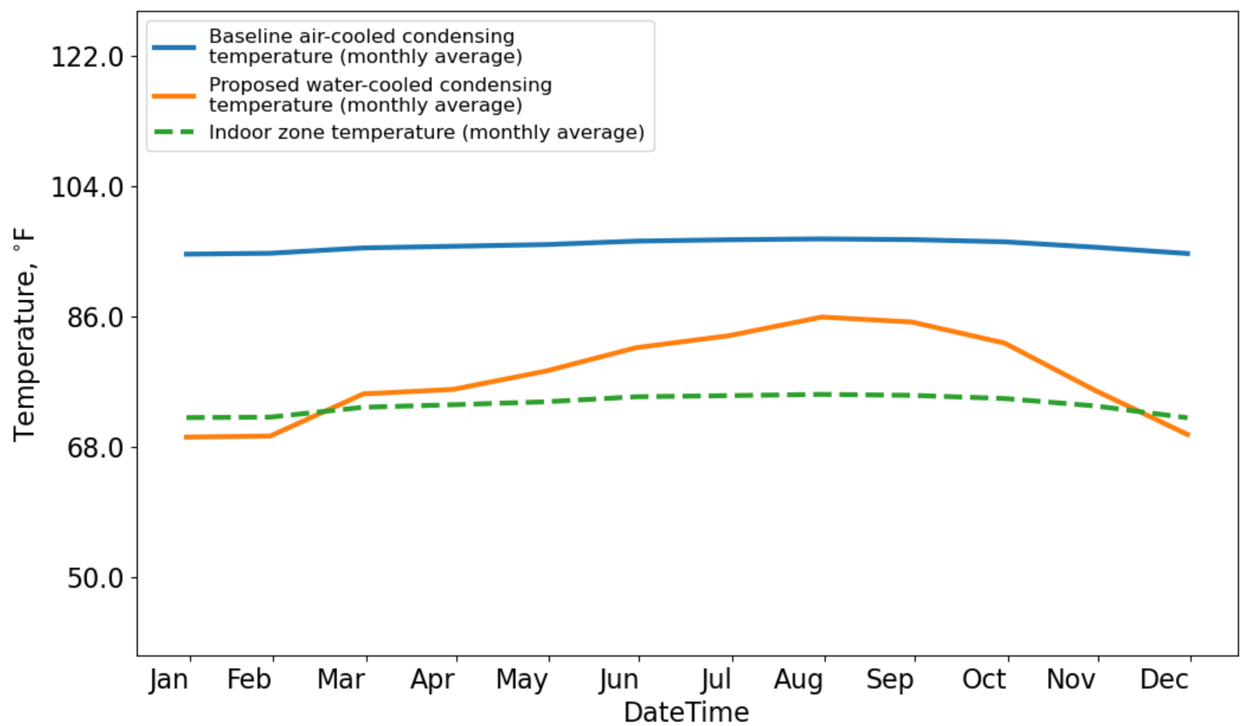


Figure 20: Monthly condensing temperature of self-contained fixture for small grocery.

Energy Model Results

Based on simulation results, the high efficiency, medium-temp, water-cooled R-290 reach-in display case provided 9 percent annual electric energy savings for the small grocery with all closed reach-in fixtures. Savings increased to 14 percent under the baseline case configuration with all open vertical cases. In the large supermarket model, under similar two baseline case configurations, the annual electric energy savings range was from 4 percent to 9 percent, respectively. These savings include the energy penalty associated with the water loop pumping system. Table 24 summarizes electric energy usage and savings of the models under both baseline scenarios.

Table 24: Summary of Electricity Usage

Building type	Small Grocery			Supermarket		
Models	Baseline Self-Containe d OVDC	Baseline Self-Contained Reach-In	High-Eff. Water-Cooled, Reach-In	Baseline Self-Contained OVDC	Baseline Self-Contained Reach-In	High-Eff. Water-Cooled, Reach-In
Lighting (MWh)	45.7	45.7	45.7	368.7	368.7	368.7
Plug load (MWh)	20.9	20.9	20.9	177.6	177.6	177.6
HVAC (MWh)	43.8	37.6	28.9	226.7	272.2	272.0
WC circulator pump (MWh)			0.1			0.9
Refrigeration (MWh)	97.7	90.5	82.6	885.5	753.2	690.3
Total (MWh)	208.1	194.7	178.1	1658.6	1571.7	1510.2
Energy savings vs. OVDC (MWh)			**30.0 (14.4)**			**148.4 (8.9)**
Energy savings vs. RI (MWh)			**16.6 (8.5)**			**61.6 (3.9)**
EUI ($kWh/ft^2/year$)	33.6	31.4	**28.7**	33.2	31.4	**30.2**

In both building models, the refrigeration components accounted for most of the savings. As expected, refrigeration savings are larger in both case configurations where the fixtures being replaced were all open vertical cases. Additionally, the proposed system's water-cooled heat rejection mechanism improves the overall refrigeration efficiency by operating at lower condensing temperatures.

In the small grocery store model, the HVAC energy use drops due to the transfer of the heat rejected from the refrigerated cases in the sales area to the water loop. In the large supermarket, however, HVAC energy use increased in comparison to the baseline when the 77 percent reduction in sensible energy was applied, as per assumptions from measure SWCR015-04 in the California Electric TRM. This metric may need to be reevaluated as part of a new measure characterization that would require further research.

Integration of the heat reclaim system with the proposed system water loop resulted in a 9°F increase in water inlet temperature to the water heater. This slight boost in water inlet temperature yielded 11 percent and 12 percent reductions in annual water heating energy use in the small grocery and large supermarkets, respectively. The following table provides the annual site energy usage in MMBtu for both store models under the different baseline scenarios.

Table 25: Summary of Site Energy

Building type	Small Grocery			Supermarket		
Models	Baseline Self-Contained OVDC	Baseline Self-Contained Reach-In	High-Eff. Water-Cooled, Reach-In	Baseline Self-Contained OVDC	Baseline Self-Contained Reach-In	High-Eff. Water-Cooled, Reach-In
Lighting (MMBtu)	155.9	155.9	155.9	1257.9	1257.9	1257.9
Plug load (MMBtu)	71.3	71.3	71.3	606.2	606.2	606.2
Cooling and ventilation (MMBtu)	149.5	128.1	98.7	773.6	928.7	928.3
Space heating (MMBtu)	2.0	2.1	5.4	14.6	4.7	4.7
Water heating (MMBtu)	30.9	30.9	27.5	242.0	242.0	213.9
WC circulator pump (MMBtu)			0.2			5.2
Refrigeration (MMBtu)	333.2	308.9	281.7	3021.4	2569.9	2355.2
Total site energy (MMBtu)	742.7	697.1	640.6	5915.8	5609.5	5371.4

Building type	Small Grocery			Supermarket		
Energy savings vs. OVDC (MMBtu)			102.2 (13.8)			544.3 (9.2)
Energy savings vs. RI (MMBtu)			56.5 (8.1)			238.0 (4.2)
EUI (MMBtu/ft^2/year)	0.120	0.112	**0.103**	0.118	0.112	**0.107**

Annual GHG emissions of both models under different scenarios are presented in Table 26Table 26. The emissions conversion factors used in this analysis are as follows: 497.44 lb CO_2 per MWh of electricity and 53.06 kg CO_2 per 1 MMBtu of natural gas. The conversion rates were obtained from California Climate Investments Quantification Methodology (CCI 2023).

Table 26: Annual GHG emissions

Building type	Small Grocery			Supermarket		
Models	Baseline Self-Contained OVDC	Baseline Self-Contained Reach-In	High-Eff. Water-Cooled, Reach-In	Baseline Self-Contained OVDC	Baseline Self-Contained Reach-In	High-Eff. Water-Cooled, Reach-In
Electricity emissions (metric tons CO_2e)	46.9	43.9	40.2	374.2	354.6	340.7
Gas emissions (metric tons CO_2e)	1.7	1.7	1.7	13.3	13.1	11.6
Total emissions (metric tons CO_2e)	48.7	45.7	41.9	387.9	367.7	352.3

Market Potential

Using the results from the laboratory study and the modeling, different market penetrations were applied to estimate potential program savings for both energy and GHG due to the use of propane instead of other high GWP synthetic refrigerants (404a). Annual market penetrations of 1 percent, 3 percent and 5 percent were assumed to model a low, medium, and high market penetration and their associated savings are shown in Table 27. These ranges account for 84 to 420 thousand linear feet of annual shipped cases based on historical case shipments.

California makes up roughly 11 percent of the total United States food retail establishments per the 2021 US Census. Table 27 demonstrates the forecasted energy and gas savings from each building energy model, utilizing the energy savings found in the market characteristics and assuming California receives 11 percent of all shipped linear feet of cases in the United States annually. Additionally, 2022 eGrid data is applied to the energy savings and 2024 EPA Emission Factors to the gas savings to calculate GHG reduction potential.

Table 27: Potential Program Energy and Gas Savings in California for Low, Medium, and High Adoption Rates

	1 % Adoption	3 % Adoption	5 % Adoption
Energy Savings			
Small groceries	69.2 MWh	207.6 MWh	346.0 MWh
Supermarkets	174.3 MWh	522.8 MWh	871.4 MWh
Total (MWh)	243.5 MWh	730.5 MWh	1,217.4 MWh
Gas Savings			
Small groceries	627.5 MMBtu	1882.4 MMBtu	3137.3 MMBtu
Supermarkets	244.5 MMBtu	733.5 MMBtu	1222.6 MMBtu
Total (MMBtu)	872.0 MMBtu	2,615.9 MMBtu	4,359.8 MMBtu

The GWP reduction is 99.9 percent from traditional HFC self-contained cases to natural refrigerant R-290 self-contained cases. Utilizing an average leak rate of two percent per year and an average charge size of 1.02 pounds refrigerant per case, Table 28 shows the potential GHG reduction from the refrigerant swap from 404a to R-290. These estimates are based on conservative estimates from the Efficiency Vermont Technical Resource Manual and actual GHG reduction is likely larger. (Technical Reference Manual 2023) The Efficiency Vermont TRM was used in the absence of a California specific metric. This metric should be evaluated as part of future measure characterization.

Table 28: Potential Program Non-Energy GHG Savings in California for Low, Medium, and High Adoption Rates

	1 % Adoption	3 % Adoption	5 % Adoption
Small groceries	1.0 MT CO_2e	2.9 MT CO_2e	4.7 MT CO_2e
Supermarkets	0.5 MT CO_2e	1.5 MT CO_2e	2.6 MT CO_2e
Total non-energy GHG reduction potential	1.5 MT CO_2e	4.4 MT CO_2e	7.3 MT CO_2e
Total GHG reduction potential	98.3 MT CO_2e	294.8 MT CO_2e	491.3 MT CO_2e

Conclusions

To advance the adoption of high efficiency, liquid-cooled, low-GWP refrigerated display cases, future research should focus on further characterizing energy performance across diverse climate conditions and equipment configurations. Additional laboratory and field studies can provide insights into system interactions, maintenance requirements, and long-term cost benefits. Furthermore, research into optimizing system components, such as advanced heat rejection technologies and integrated controls, can enhance performance and cost-effectiveness. Expanding industry education initiatives and workforce training programs will also be essential to overcoming adoption barriers for contractors and end-users.

For technology development and program design, utility incentive structures should be tailored to encourage adoption by differentiating measures based on market segment and existing equipment. Collaborating with manufacturers to accelerate the commercialization of higher-capacity propane systems will help scale adoption and reduce costs. Policy efforts should continue to push for updates to codes and standards, such as increasing allowable propane charge limits and aligning safety regulations with technological advancements. Future incentive programs should integrate findings from this study to design prescriptive or semi-prescriptive measures that align with existing commercial refrigeration initiatives, ensuring a smooth transition to more efficient and environmentally friendly refrigeration solutions.

Recommendations

Measure Characterization

Based on the findings in this study, VEIC recommends potential utility measures to support the adoption of high efficiency water-cooled, low GWP, reach-in, self-contained, medium-temperature refrigerated cases in small grocery stores and large supermarkets.

This measure would be ideal for retrofits of existing systems where it would be costly to install all new low-GWP refrigeration equipment at once. Since the savings results are different for small grocery stores versus large supermarkets and vary with a baseline of open cases versus a baseline of closed transparent doors, the measure should be differentiated based on the both the store type and the baseline case. The team recommends applying incentives based on the savings per door. The example below shows the energy savings for the modeled stores with 6,200 square feet for the small grocery store, and 50,000 square feet for the large grocery store.

Table 29: Potential Program Savings for High Efficiency Water-Cooled, Low-GWP, Reach-In, Self-Contained, Medium-Temperature Refrigerated Cases.

	Annual Electric Savings (MWh/door)		Annual Gas Savings (MMBtu/door)	
Baseline	Small Grocery	Large Supermarket	Small Grocery	Large Supermarket
Vertical open cases	0.9	0.7	133.1	182.4
Vertical closed transparent	0.2	0.4	-0.2	135.7

Stakeholder Feedback

Program administrators indicate that this measure could be integrated into existing grocery, refrigeration, and commercial kitchen equipment program portfolios as a prescriptive or semi-prescriptive measure. The program could be structured similar to existing commercial refrigeration measures for Medium or Low-Temperature Display Case With Doors (SWCR021-04). Additional research would be needed to characterize the energy consumption of the system components, including heat rejection equipment, and the building HVAC interactions, all of which were explored in this project but not characterized.

Manufacturers are waiting for approval of higher propane charge limits so that they can increase the capacity of their systems. This will help reduce the number of compressors and individual refrigeration circuits located on the sales floor, consequently driving down the cost of new systems.

Contractors generally require additional education and exposure to propane refrigeration systems to become more familiar with the performance, operation, and maintenance of this technology. Supporting trainings and continuing education opportunities will help develop their skills and build their confidence so that they feel more comfortable recommending this equipment with their customer base.

To ensure the best possible success for incentivized utility measures focused on accelerated adoption of this technology, IOUs should focus attention on cultivating trusting relationships among customers, suppliers and distributors, contractors, and utility staff through contractor and customer training and education. The identified barriers can be reduced through trust building, ensuring customers feel supported and can rely on knowledgeable contractors, suppliers, and distributors who follow best practices.

Codes and Standards Updates

Accelerating the rate of adoption of flammable refrigerants into federal, state, and local building codes will help increase market uptake. The UL 60335-2-89 safety standard was updated in 2021 which allows the use of propane in self-contained cases up to 300 grams in closed cases and 500 grams in open cases in the United States. There is an urgent need to update remaining safety standards, including US EPA SNAP, ASHRAE 15, and local building codes.

Areas of Future Research

This research covers energy savings and GHG savings from medium-temperature refrigerated cases; however, 25 percent of cases in grocery stores are low-temperature cases. Understanding the additional energy savings potential of high efficiency, water-cooled, low-GWP, reach-in, self-contained, low-temperature refrigerated cases could result in the development of additional utility measures to support greater building efficiencies in the grocery sector. Furthermore, the sizing of the heating equipment and the square footage of the building affect the gas use and gas savings — or penalty. Additional modeling would illuminate how the savings change with the size of the grocery store, the type of heat rejection equipment, and size of the heat recovery circuit.

Appendix A: List of Interviewees

Organization	Stakeholder Type	Participants
Hussmann	Manufacturer	Ron Shebik
KW Engineering	Contractor	Graham Lierley
Eversource	Utility Program	Ivon Louis-Letang
United Illuminating	Utility Program	Shea Kirwin
Sacramento Municipal Utility District	Utility Program	Zach Lawrence
Albertson's	End User	Wade Krieger
Grocery Outlet	End User	Megan Rodriguez

Appendix B: Interview Questions and Topics

Stakeholder Group	Topics and Questions Asked
Manufacturers	• National and local sales data – breakdown of HFC, hydrofluoroolefin (HFO), hydrocarbon (HC), and natural refrigerants • Customer purchasing habits – requests, priorities, preferences, cycles • Costs – incremental costs of high efficiency over standard efficiency, percent • Supply chain – how does equipment get to market – wholesalers, contractors, end users • Energy efficiency savings – high efficiency units over standard efficiency units • Energy efficiency measures – modulating compressors, integral advanced case controllers, superheat control, floating suction pressures, defrost optimization, LED occupancy controls, electronically commutated fan motors and controls • New innovations – refrigerants, energy efficiency measures, technologies
Contractors	• What services do they provide? • What markets/customers do they serve? • What equipment do they service? • What refrigerants do they work with? • Have they installed water-cooled propane systems? ○ If yes, what is their comfort level and how many systems? • Do they purchase refrigeration systems and equipment direct from manufacturers? • Do they purchase used or pre-owned refrigeration systems and equipment?

Stakeholder Group	Topics and Questions Asked

Utility energy efficiency program managers	• Do they have existing programs to support refrigerated display cases?
	  o If yes,
	    · What are program requirements – equipment, eligibility, limitations, baseline?
	    · Would custom or prescriptive savings and incentives be appropriate?
	    · How are savings calculated – what is baseline and efficient?
	    · Program utilization – customers, contractors or distributors?
	    · Incentive levels?
	  o If no
	    · Are they considering one?
	    · What would be needed to implement one?
	• Does utility have existing refrigeration, grocery or commercial kitchen equipment programs?
	• Do they offer hydrocarbon or natural refrigerant bonus incentives?
	• Have they incentivized other natural refrigerant projects, systems, or equipment?

End users	• Why have they chosen to install cases using propane?
	  o What are the systems specs – size, equipment, loads?
	  o What equipment did the propane system replace?
	• When did they install the cases using propane?
	• How did the project go?
	• What were project economics?
	• Did they receive incentives?
	• Who did they work with – contractors, manufacturers, trade organizations, state or municipal orgs, authorities having jurisdiction (AHJs), local building codes, fire marshal?
	• What hurdles or barriers have they faced?
	• What are their operations and maintenance procedures?
	• How is the system performing – food quality, safety, energy?
	• What heat rejection equipment do they have?
	• Any monitoring equipment installed – energy, performance?
	• Have they had any leaks, do they monitor?
	• Do they ever buy used or pre-owned equipment?
	• Do they have a capital equipment replacement cycle, and if so, how many years is the effective useful life of refrigerated cases?

Appendix C: Sensors and Data Acquisition System, Supplementary Information

Total and component power was measured with six Continental Control Systems Wattnode power meters, model WMC-3Y-208-MB. A meter box containing each of the Wattnodes was constructed to allow the case to be plugged directly to the box to monitor total plug power which also utilized current transformers (CTs). The CTs were wired externally into the refrigerated case's electrical enclosure to monitor the energy consumption of the individual components. Five model CTs — Accu-CT model ACTL-0750 — were instrumented the refrigerated cases' components: compressor, evaporator fans, lighting, case controller, and anti-sweat heaters. A diagram of the constructed power submeter enclosure and a diagram of the case electrical drawing showing submetering locations are provided in Figure 21 and Figure 22, respectively. For the case total and compressor, 20 A CTs were used, and five A CTs were clamped around the loads for all other components. The CT power measurement accuracy is ±0.5 percent. An image of the constructed meter box is shown in the left image of Figure 21. Energy was calculated by integrating measured power consumption.

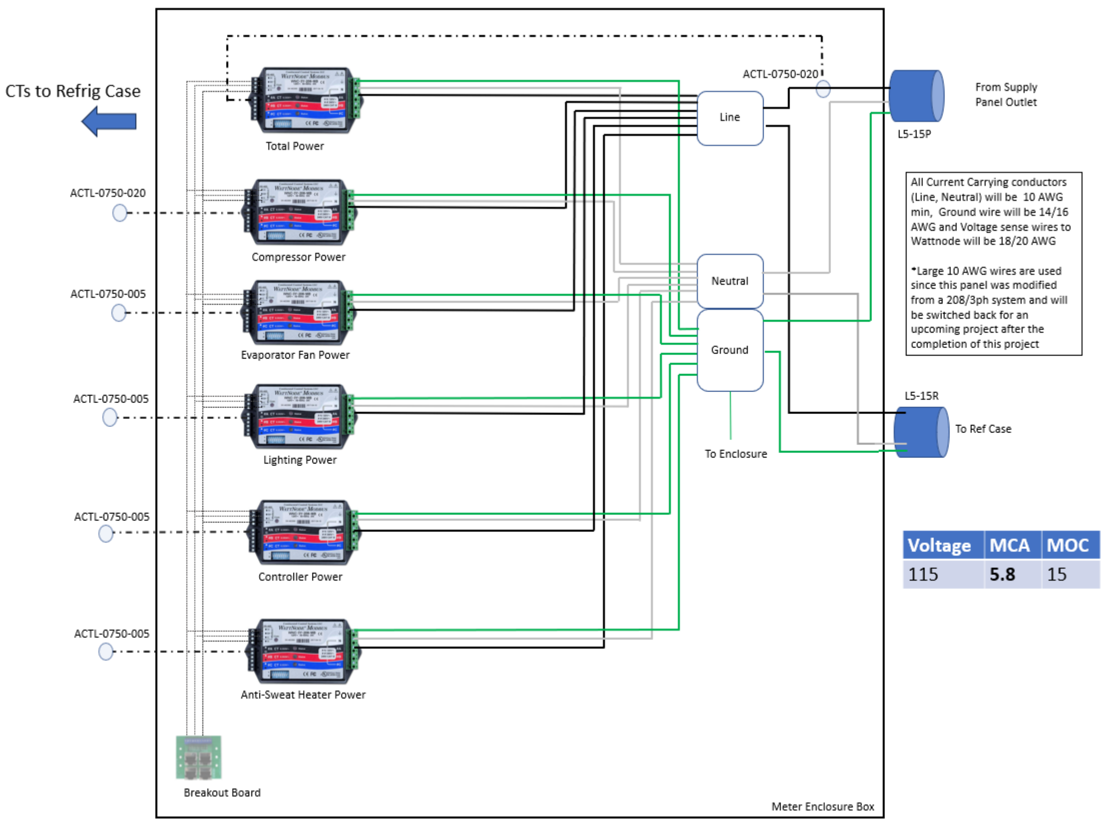


Figure 21: Drawing of power meter enclosure used for monitoring case total plug and component loads.

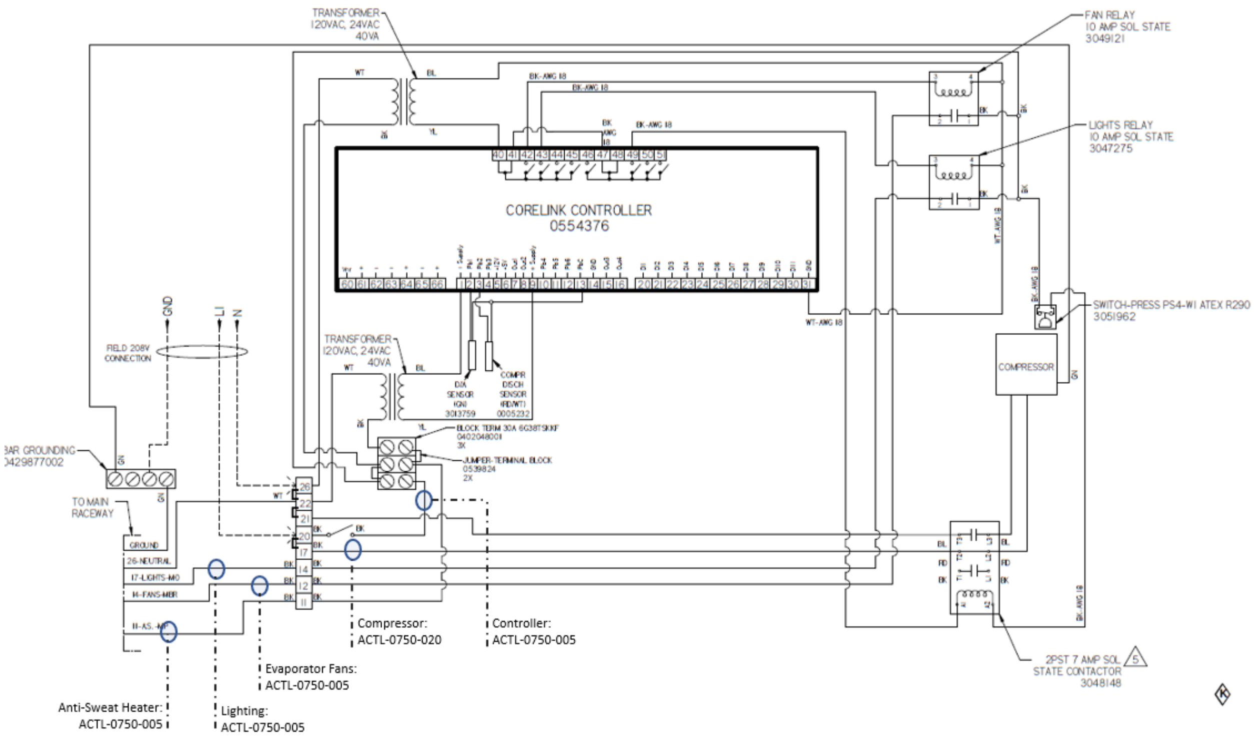


Figure 22: Refrigerated case electrical drawing including current transformer locations for case component loads.

NREL's local data acquisition system was used to record measurements and control the FCM. The data acquisition system recorded all measurement data at a sampling rate of 1 Hz. Thermocouples, voltage inputs (e.g., the dew-point hygrometer and pressure transducers), current inputs (the condensate weigh scale and Coriolis flow meter) and digital output wiring (e.g., FCM pump and blower VFDs and FCM valves) were connected to terminal panels situated throughout the evaluation laboratory (Figure 23, middle image). Power measurements from the Wattnode meter box were supplied via Modbus through an RJ50 cable that was connected to a data acquisition Modbus interface (Figure 23, right image). Within the data acquisition software's user interface, separate power measurements at each meter were selected from different Modbus registers.

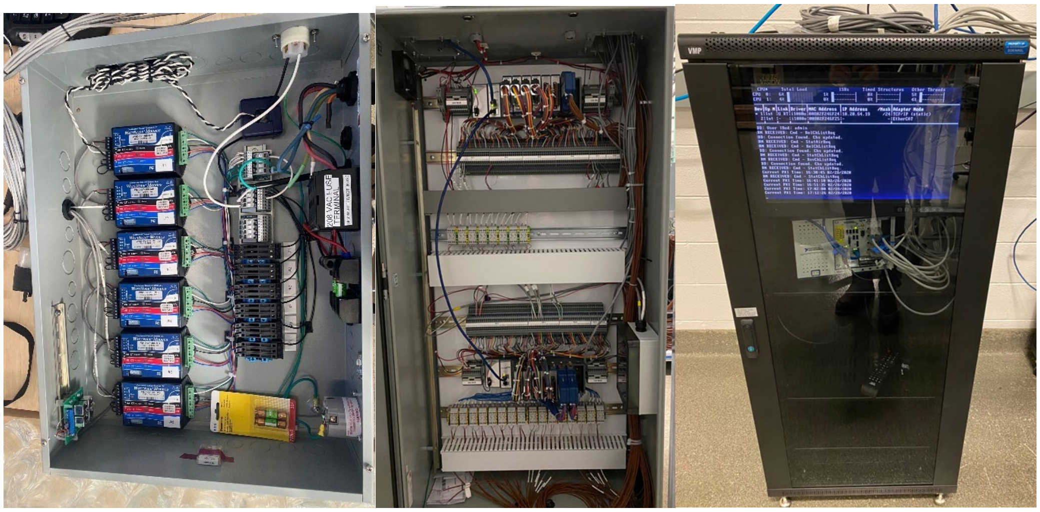


Figure 23: Wattnode meter box to measure power (left). Data acquisition system terminal panel (middle). Communication interface for data acquisition system (right).

Air and Refrigerant Temperature Measurements

Five types of interior air temperature measurements were recorded inside the refrigerated case. At each location, three separate probes were instrumented at lateral positions aligned with the center of the case's evaporator fans. The five locations are displayed in the Figure 24 diagram which include the (1) evaporator inlet, (2) evaporator outlet, (3) discharge grille, (4) return grille, and (5) the geometric center of the case product loading area. The air probes at each location consist of the same model 1/16" T-type thermocouple probes used for the product simulator and ambient measurements. The diagram in Figure 24 also shows the direction of air flow from the evaporators to the air discharge, including the release of air from perforations on the rear panel of the case.

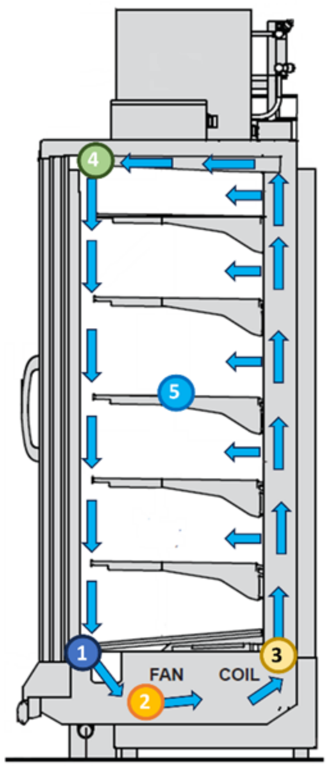


Figure 24: Diagram of refrigerated case showing direction of airflow and temperature measurement locations.

Due to security requirements within the lab that ensure flammable refrigerants remain self-contained, refrigerant thermocouples were not tapped into the refrigerant line but were mounted on the surface of the pipes using heavily insulated adhesive thermocouples. Omega engineering model SA1-T-SRTC Type-T surface temperature thermocouples with ±0.90 °F accuracy were used to collect these measurements. Although these thermocouples were sufficiently insulated, conductive resistance in the refrigerant piping likely cause deviations in the mean refrigerant temperature across the pipe, and therefore they cannot be considered a truly accurate representation.

Refrigerant temperature measurements were collected at six locations on the case and condensing unit. At the condensing unit, which is shown in the left image of Figure 25 below, the measurements were taken at (1) the compressor suction line, (2) the compressor discharge, (3) the condenser inlet, and (4) the condenser outlet/capillary tube inlet. The thermocouples were located under the insulation numbered accordingly in the figure. Below the case in the evaporator panel, shown in the right image of Figure 25 (also numbered accordingly), refrigerant temperature measurements were collected at (1) the capillary tube outlet/evaporator inlet, and (2) the evaporator outlet. Within the evaporator panel at the midpoint of the coil, an additional surface thermocouple was placed to estimate the evaporating saturation temperature.

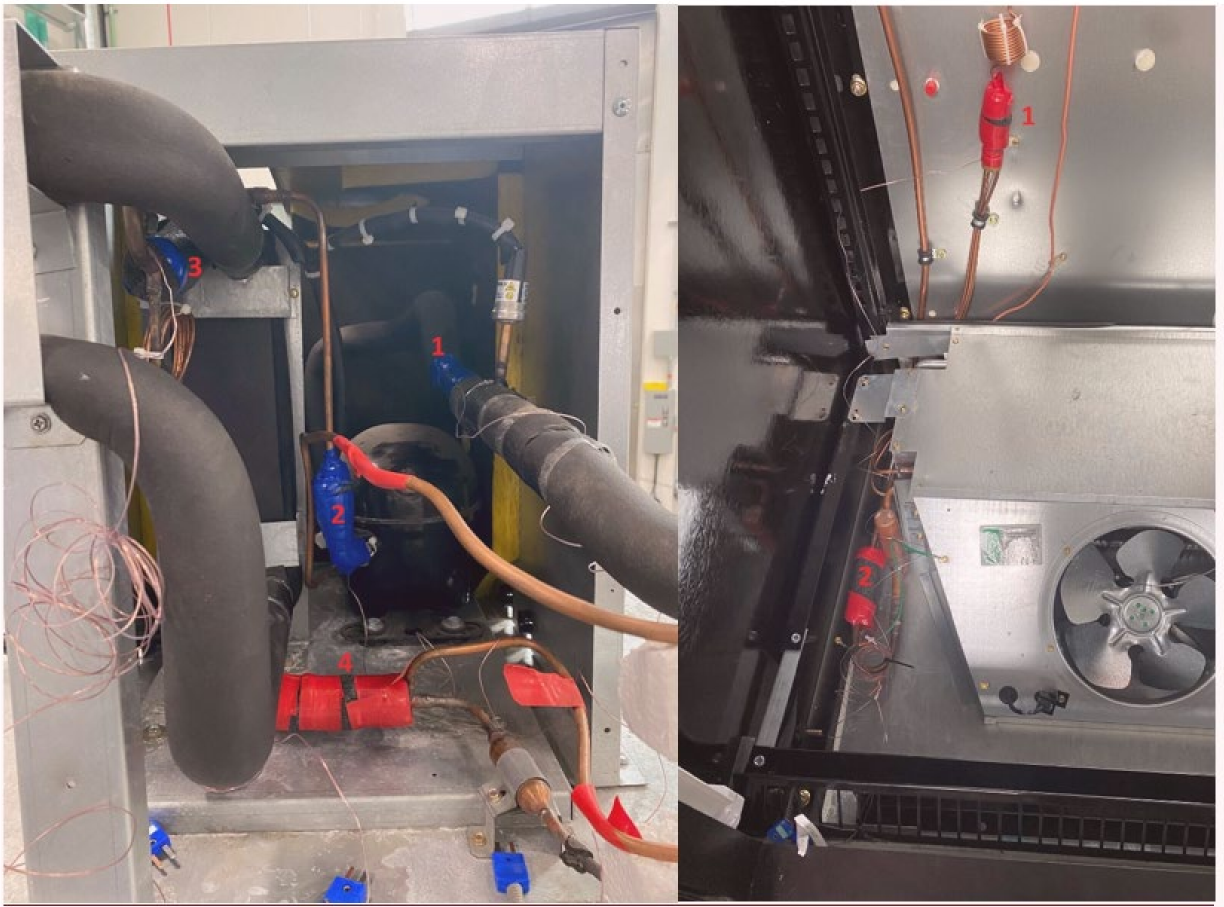


Figure 25: Refrigerant surface thermocouple locations on condensing unit (left) and evaporator panel (right).

Refrigerant measurements were taken at equivalent locations on the benchmark refrigerated cases. Typically, to calculate the dew and boiling points, pressure is measured along the liquid and vapor refrigerant lines at the condenser outlet and compressor suction in other refrigeration projects. However, that would require tapping into the refrigerant lines and altering the cases. Since the purpose of this project was to assess the energy consumption of the technology compared to the benchmark cases as they were provided commercially, it was not necessary to take those measurements and risk altering the performance.

Appendix D: Case Product Temperatures, Chamber Control Temperatures, and Condenser Inlet Water Temperatures

The mean product temperatures, chamber control temperatures, and condenser inlet water temperatures and the upper and lower limits for each are provided in Figure 26, Figure 27, Figure 28, and Figure 29, respectively, for the 55 °F, 80 °F, 95 °F, and 108 °F inlet water condition tests at ASHRAE 72 conditions. The overall product simulator temperatures for each of the inlet water conditions are provided in Figure 30, Figure 31, Figure 32, and Figure 33. Note that the case was unable to meet ASHRAE 72 product temperature requirements for the 108 °F inlet water temperature condition shown in Figure 33, despite the compressor remaining on for the duration of the experiment.

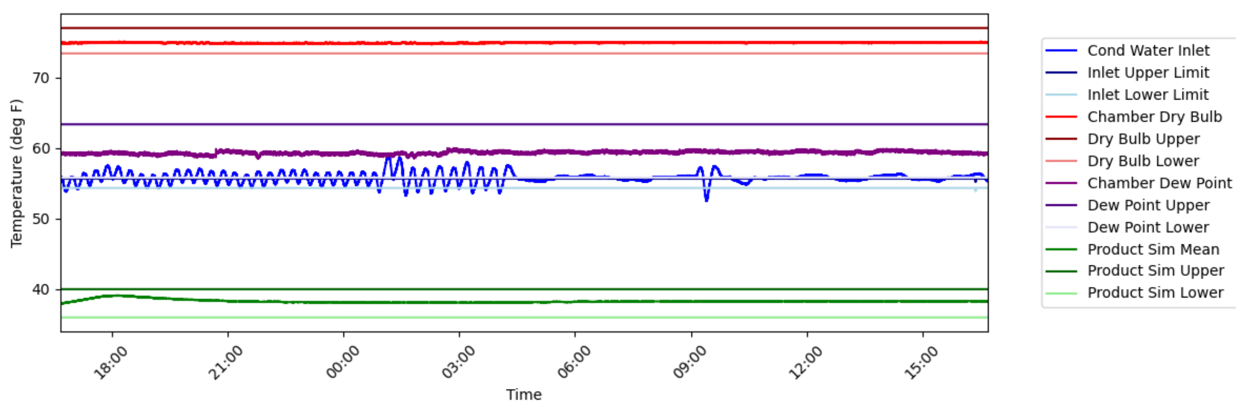


Figure 26: Mean product temperatures, chamber control temperatures, and condenser inlet water temperatures for the 55 °F inlet water test at ASHRAE 72 chamber conditions.

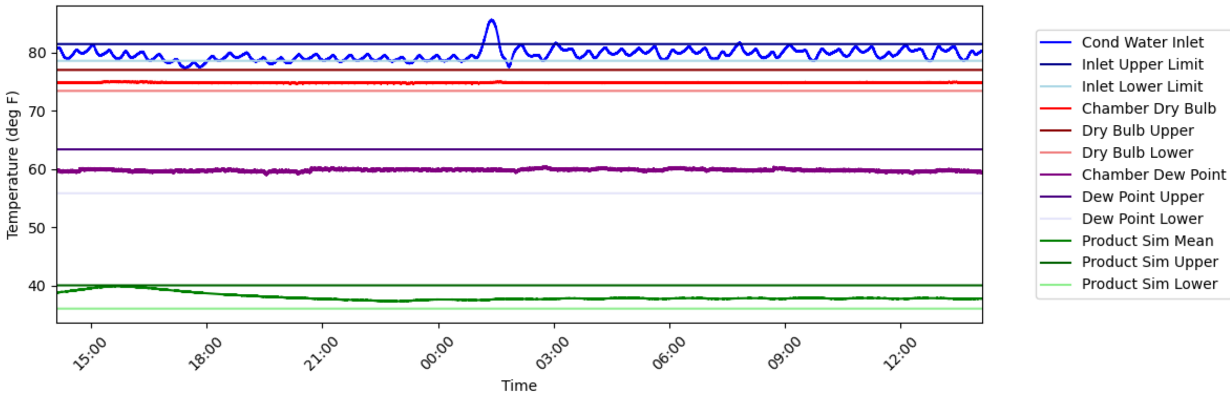


Figure 27: Mean product temperatures, chamber control temperatures, and condenser inlet water temperatures for the 80 °F inlet water test at ASHRAE 72 chamber conditions.

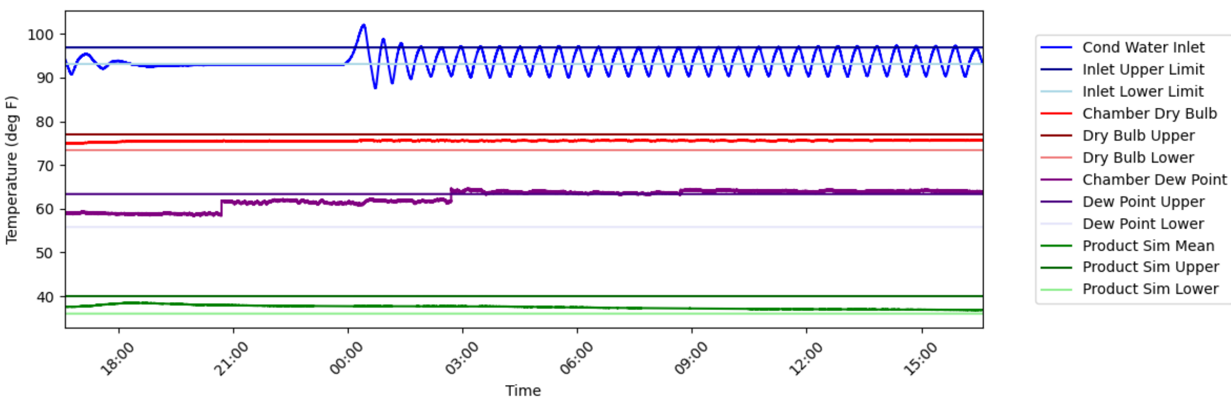


Figure 28: Mean product temperatures, chamber control temperatures, and condenser inlet water temperatures for the 95 °F inlet water test at ASHRAE 72 chamber conditions.

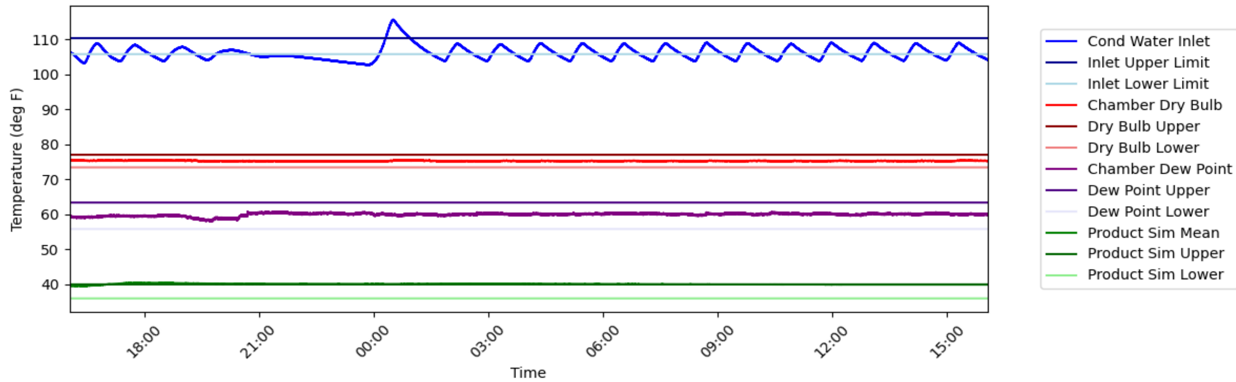


Figure 29: Mean product temperatures, chamber control temperatures, and condenser inlet water temperatures for the 108 °F inlet water test at ASHRAE 72 chamber conditions.

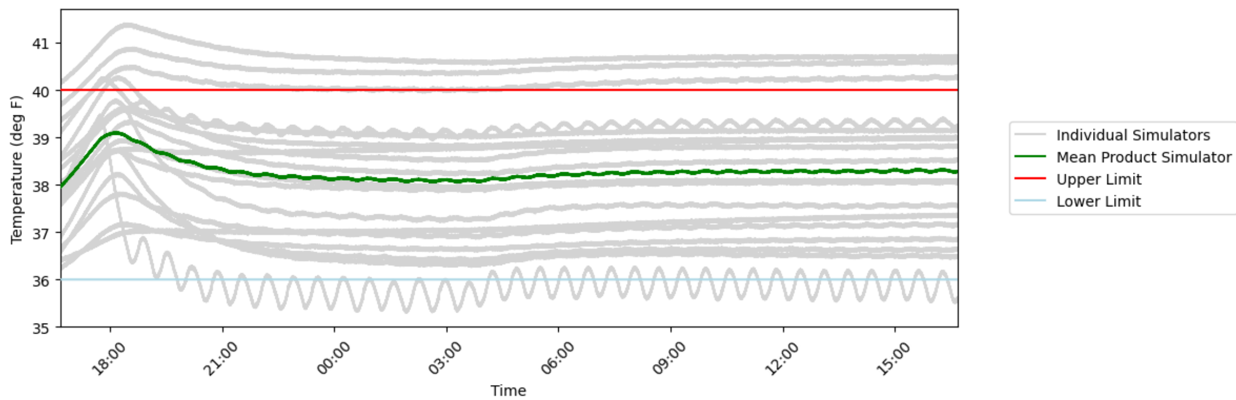


Figure 30: Product temperature distribution for the 55 °F inlet water test at ASHRAE 72 chamber conditions.

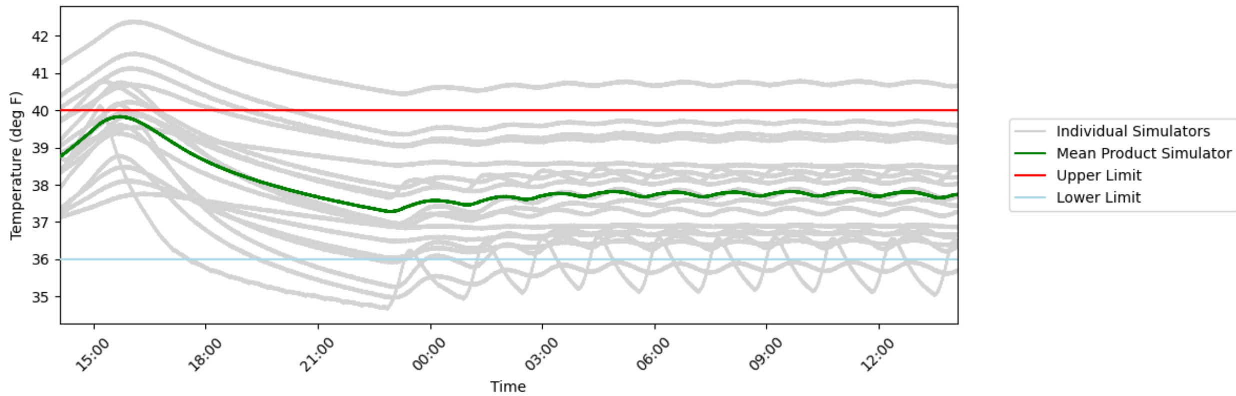


Figure 31: Product temperature distribution for the 80 °F inlet water test at ASHRAE 72 chamber conditions.

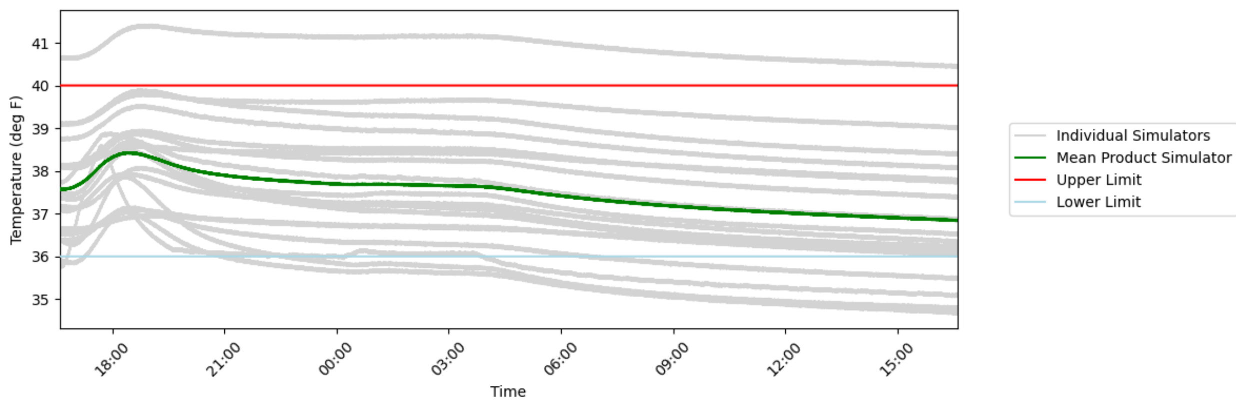


Figure 32: Product temperature distribution for the 95 °F inlet water test at ASHRAE 72 chamber conditions.

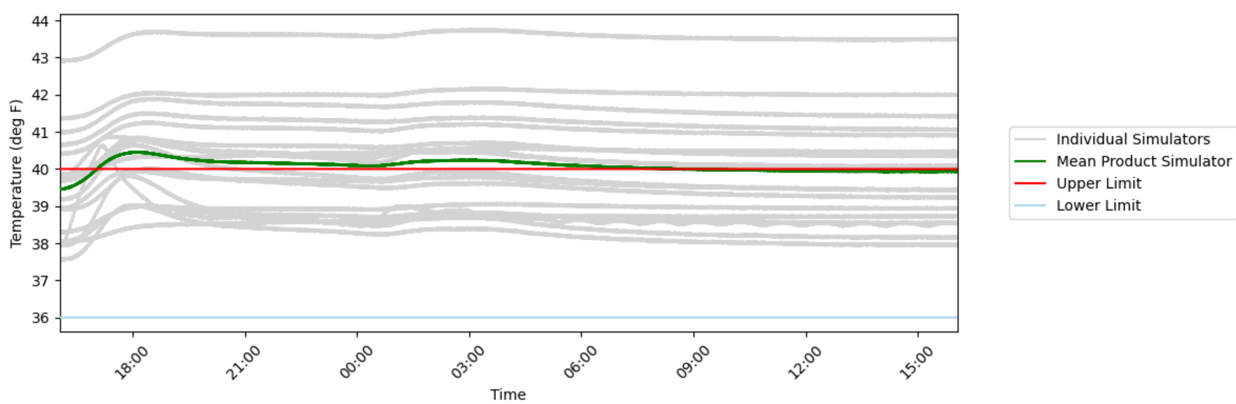


Figure 33: Product temperature distribution at the 108 °F inlet water test at ASHRAE 72 chamber conditions.

The mean product temperatures, chamber control temperatures, and condenser inlet water temperatures and the upper and lower limits for each are provided in Figure 34, Figure 35, Figure 36, and Figure 37, respectively, for the 55 °F, 80 °F, 95°F, and 108°F inlet water condition test at average store conditions. The overall product simulator temperatures for each of the inlet water conditions are provided in Figure 38, Figure 39, Figure 40, and Figure 41.

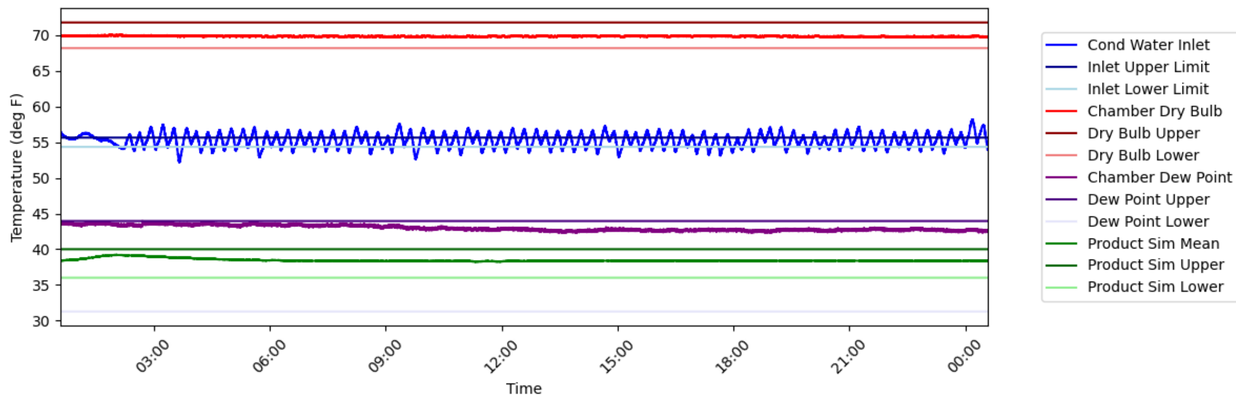


Figure 34: Mean product temperatures, chamber control temperatures, and condenser inlet water temperatures for the 55 °F inlet water test at average store chamber conditions.

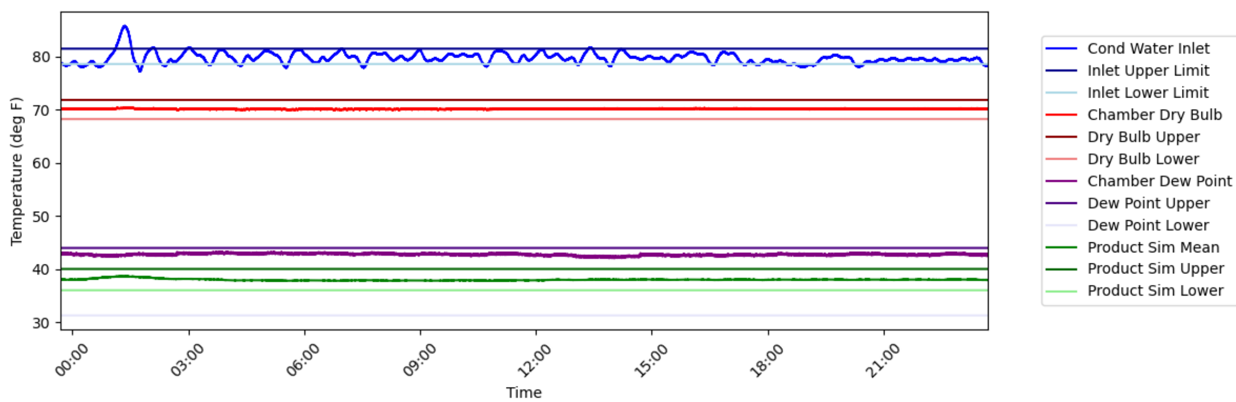


Figure 35: Mean product temperatures, chamber control temperatures, and condenser inlet water temperatures for the 80 °F inlet water test at average store chamber conditions.

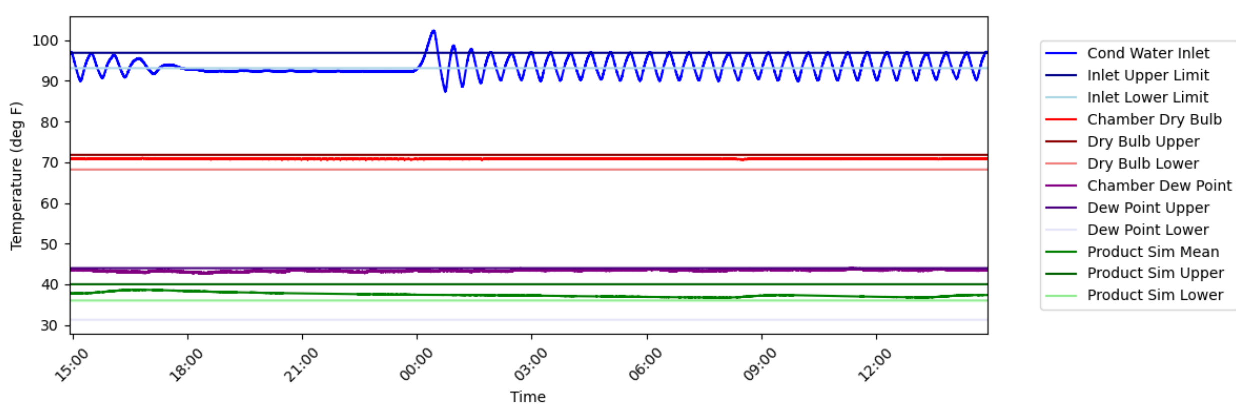


Figure 36: Mean product temperatures, chamber control temperatures, and condenser inlet water temperatures for the 95 °F inlet water test at average store chamber conditions.

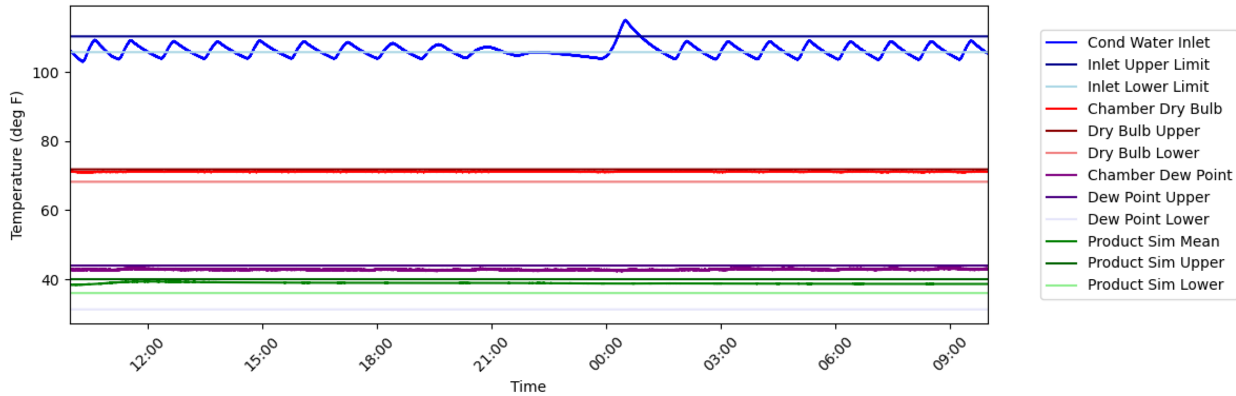


Figure 37: Mean product temperatures, chamber control temperatures, and condenser inlet water temperatures for the 108 °F inlet water test at average store chamber conditions.

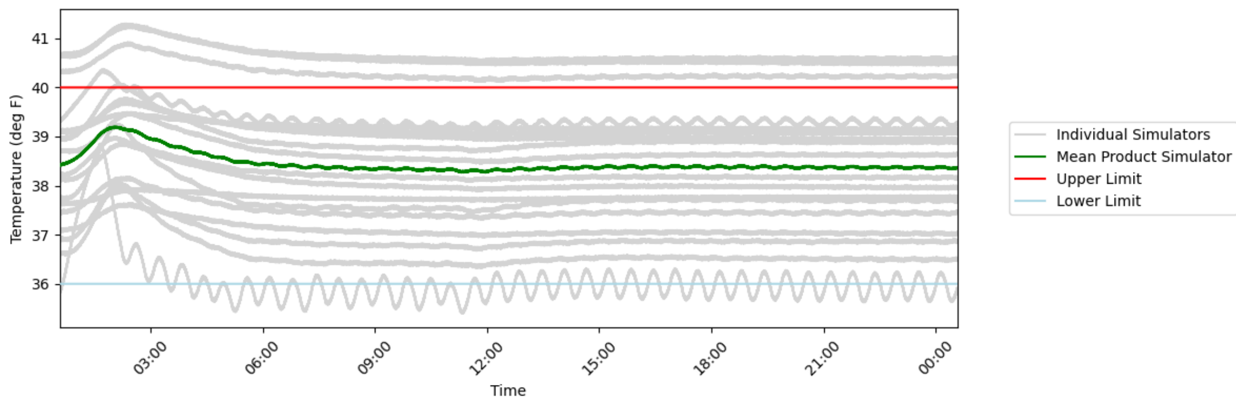


Figure 38: Product temperature distribution for the 55 °F inlet water test at average store chamber conditions.

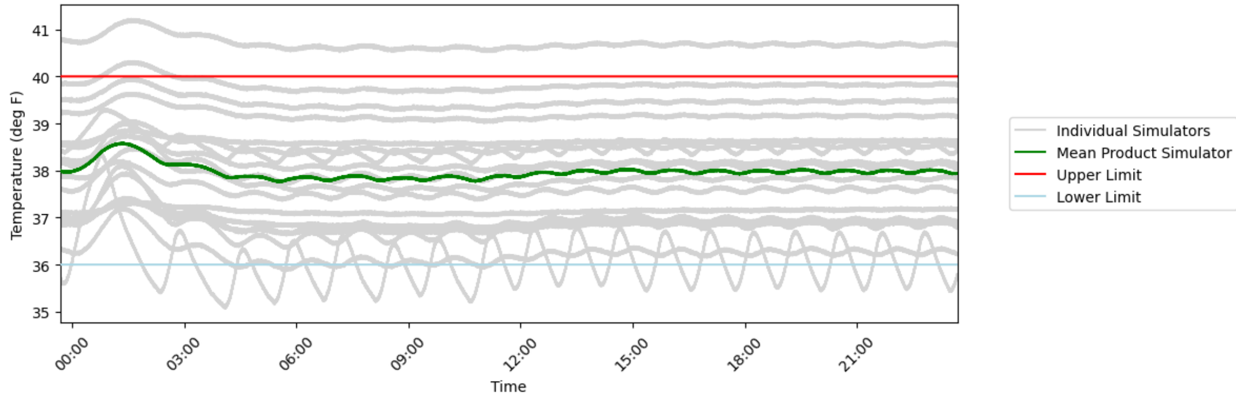


Figure 39: Product temperature distribution for the 80 °F inlet water test at average store chamber conditions.

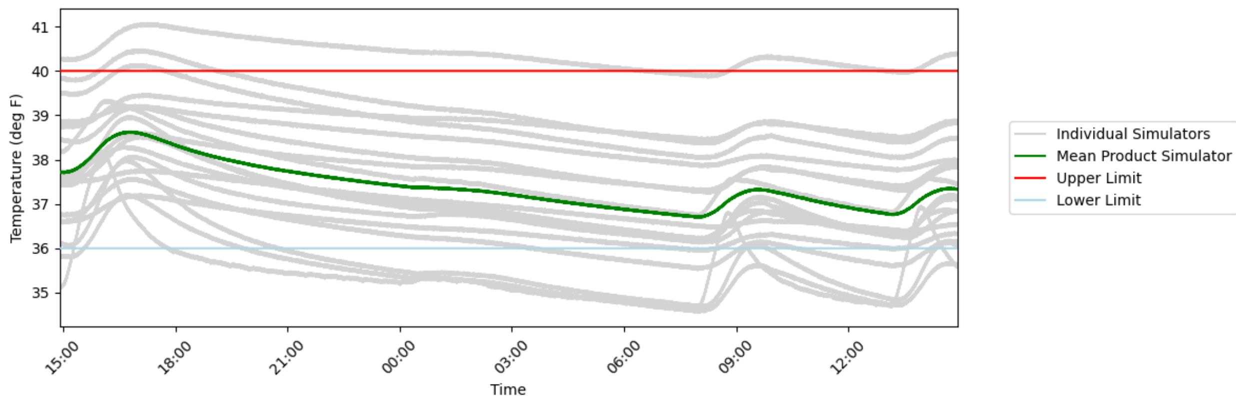


Figure 40: Product temperature distribution for the 95 °F inlet water test at average store chamber conditions.

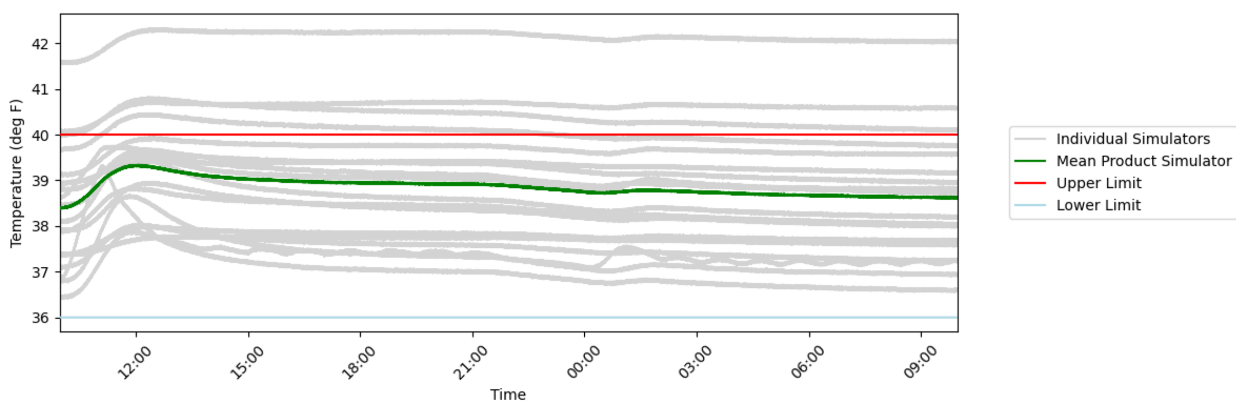


Figure 41: Product temperature distribution for the 108 °F inlet water test at average store chamber conditions.

Raw Data: Case Power Consumption

The component and total power consumption of the refrigerated case at ASHRAE 72 conditions are shown in Figure 42, Figure 43, Figure 44, and Figure 45, for each of the water inlet temperatures at 55 °F, 80 °F, 95 °F, and 108 °F, respectively. Here, the total power consumption shown is the sum of the components.

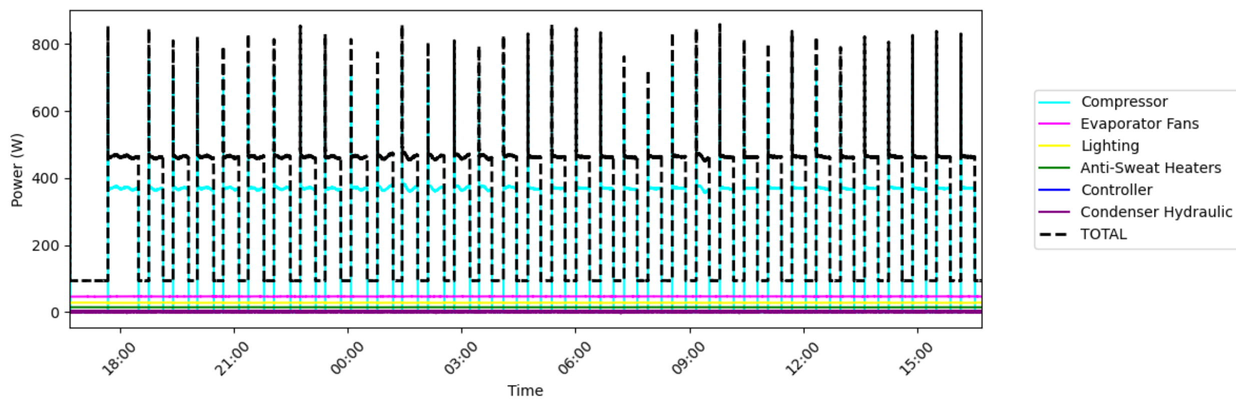


Figure 42: Case total and component power consumption for the 55 °F inlet water test at ASHRAE 72 chamber conditions.

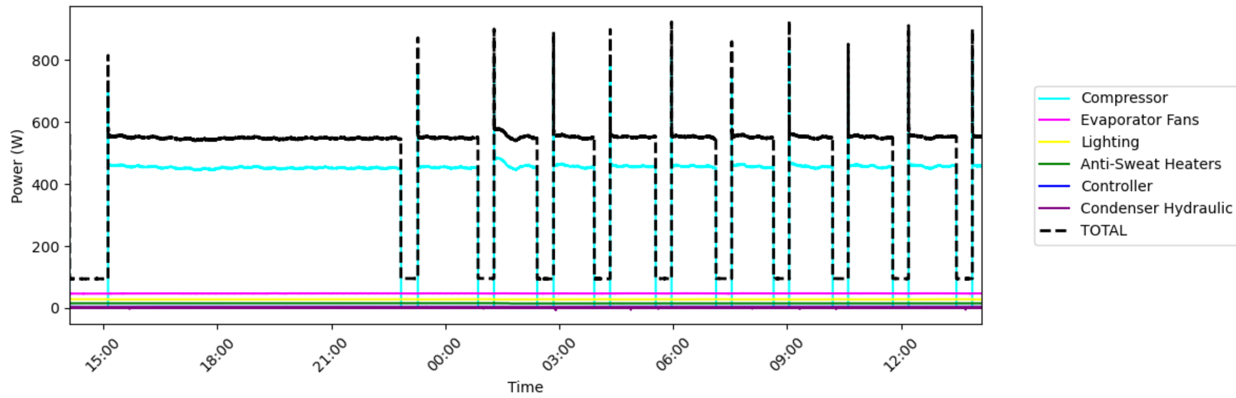


Figure 43: Case total and component power consumption for the 80 °F inlet water test at ASHRAE 72 chamber conditions.

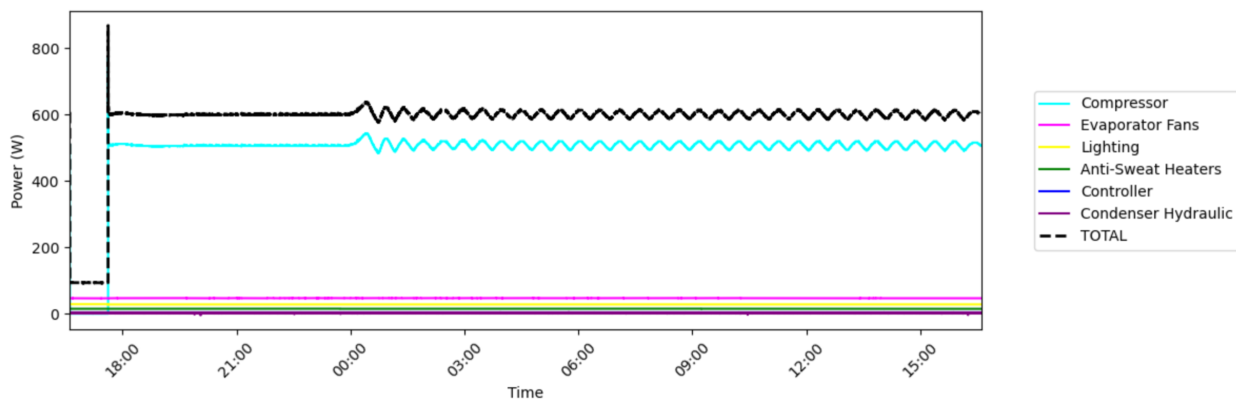


Figure 44: Case total and component power consumption for the 95 °F inlet water test at ASHRAE 72 chamber conditions.

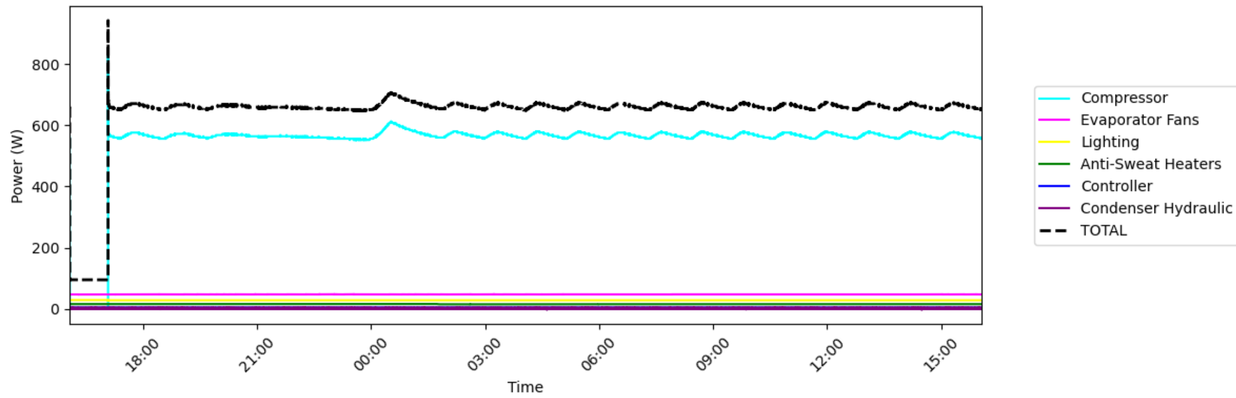


Figure 45: Case total and component power consumption for the 108 °F inlet water test at ASHRAE 72 chamber conditions.

The component and total power consumption of the refrigerated case at average store conditions are shown in Figure 46, Figure 47, Figure 48, and Figure 49 for each of the water inlet temperatures at 55 °F, 80 °F, 95 °F, and 108 °F, respectively.

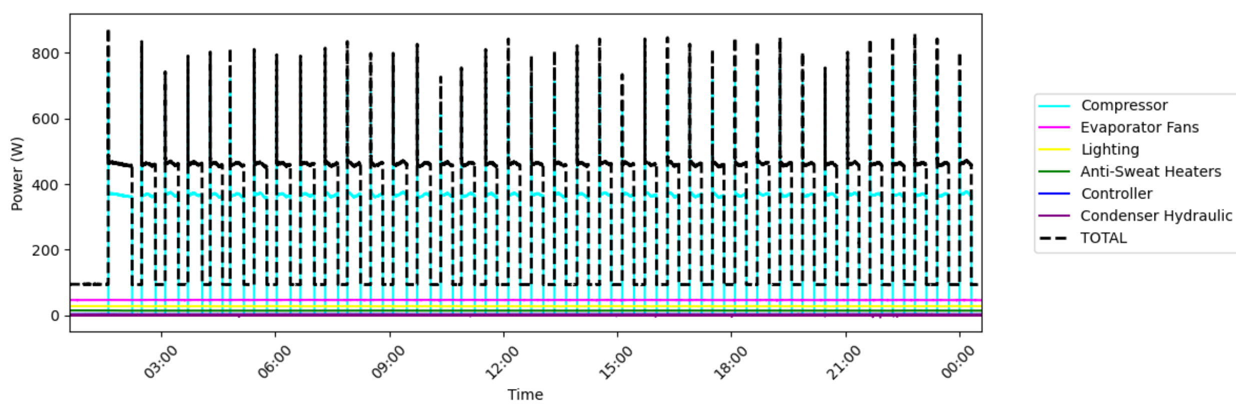


Figure 46: Case total and component power consumption for the 55 °F inlet water test at average store conditions.

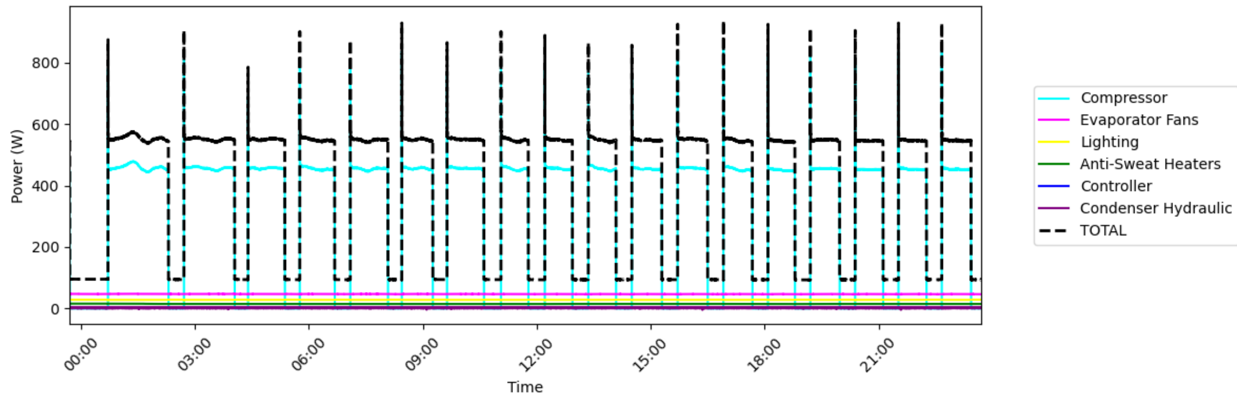


Figure 47: Case total and component power consumption for the 80 °F inlet water test at average store conditions.

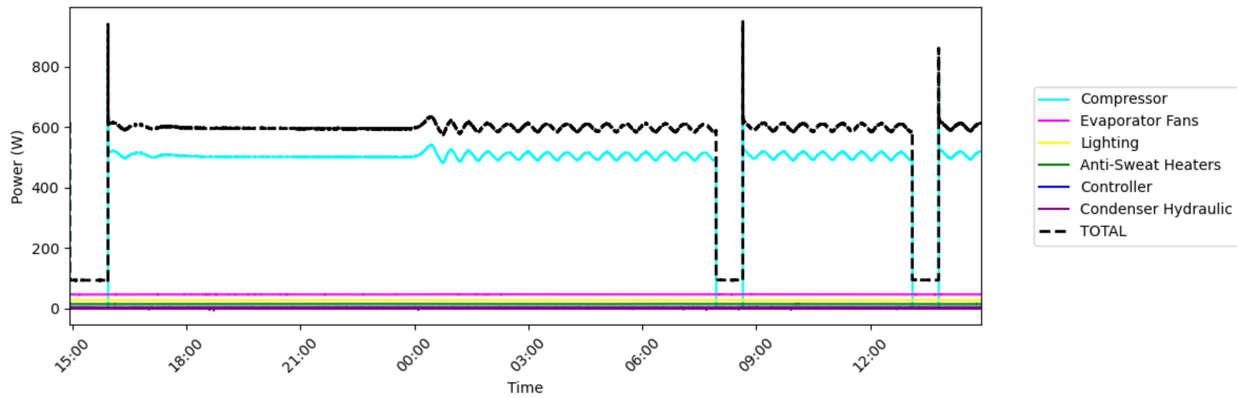


Figure 48: Case total and component power consumption for the 95 °F inlet water test at average store conditions.

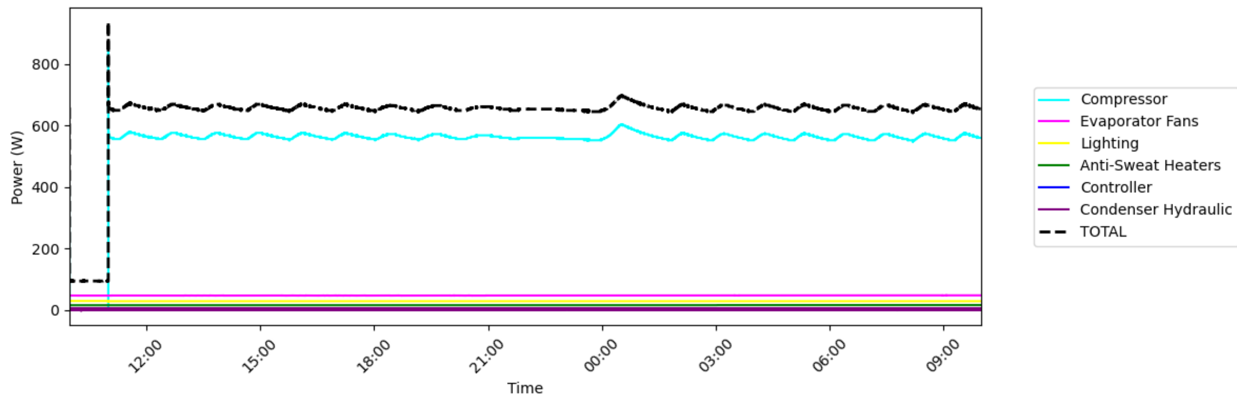


Figure 49: Case total and component power consumption for the 108 °F inlet water test at average store conditions.

Raw Data: Case Air Temperatures

The air temperatures measured within the refrigerated case at ASHRAE 72 conditions is shown in Figure 50, Figure 51, Figure 52, and Figure 53 for each of the water inlet temperatures at 55 °F, 80 °F, 95 °F, and 108 °F, respectively. The air temperatures at each location are averaged from a combination of three probes aligned laterally with the location of each evaporator fan, except for the probe located at the centroid of the interior of the case.

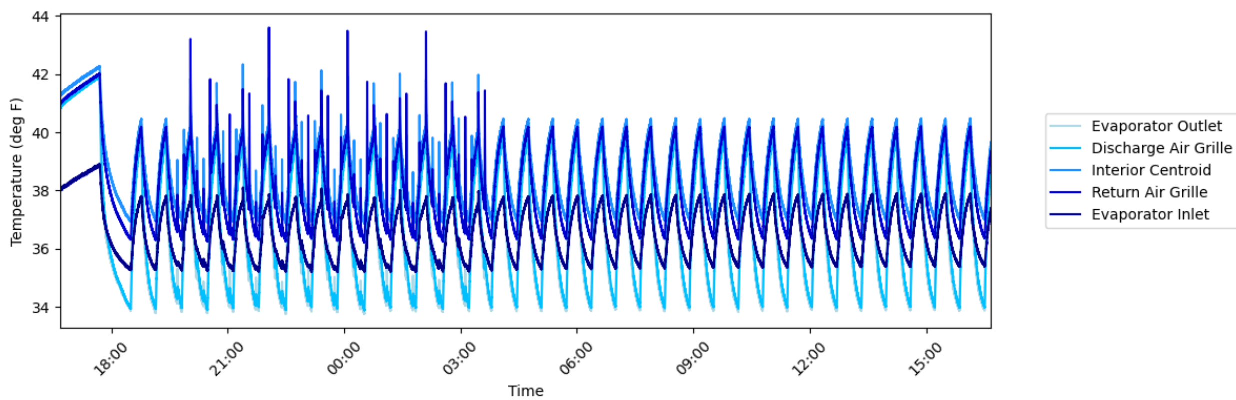


Figure 50: Interior case air temperatures for the 55 °F inlet water test at ASHRAE 72 chamber conditions.

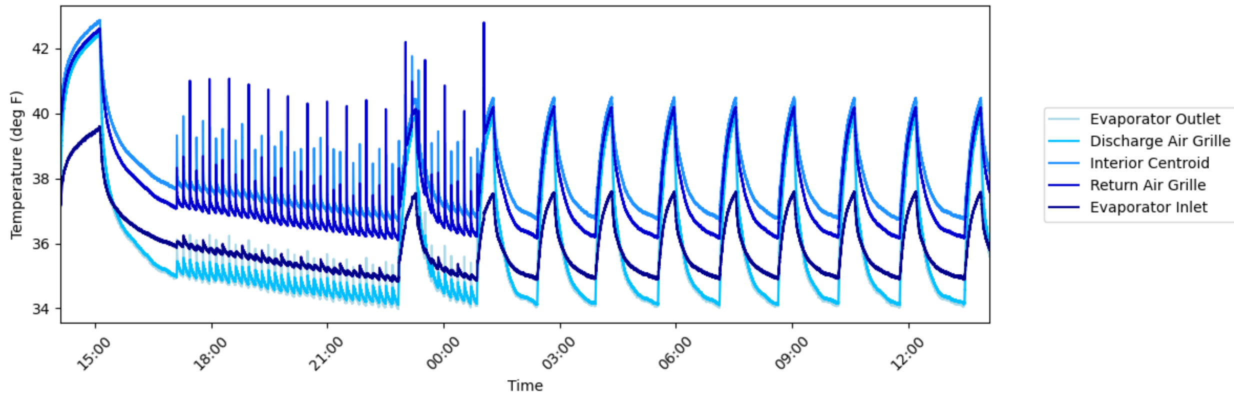


Figure 51: Interior case air temperatures for the 80 °F inlet water test at ASHRAE 72 chamber conditions.

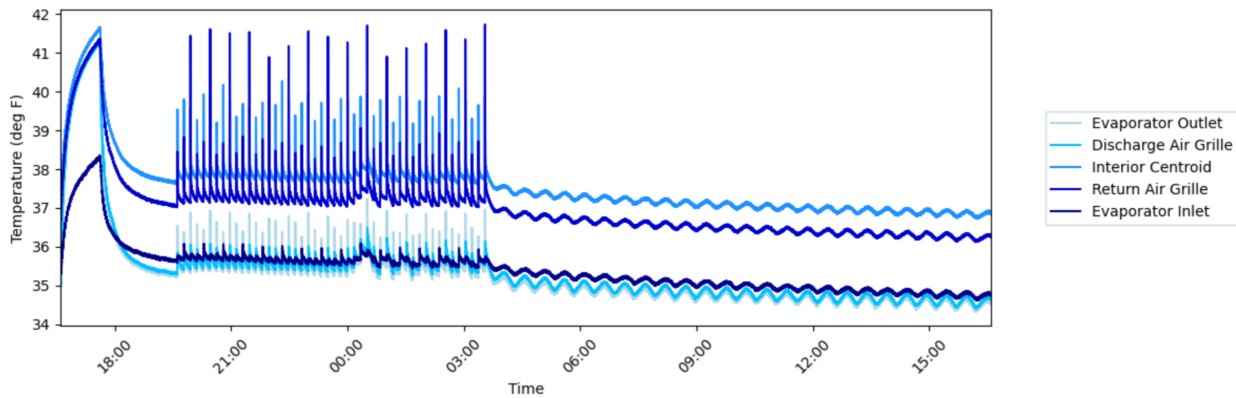


Figure 52: Interior case air temperatures for the 95 °F inlet water test at ASHRAE 72 chamber conditions.

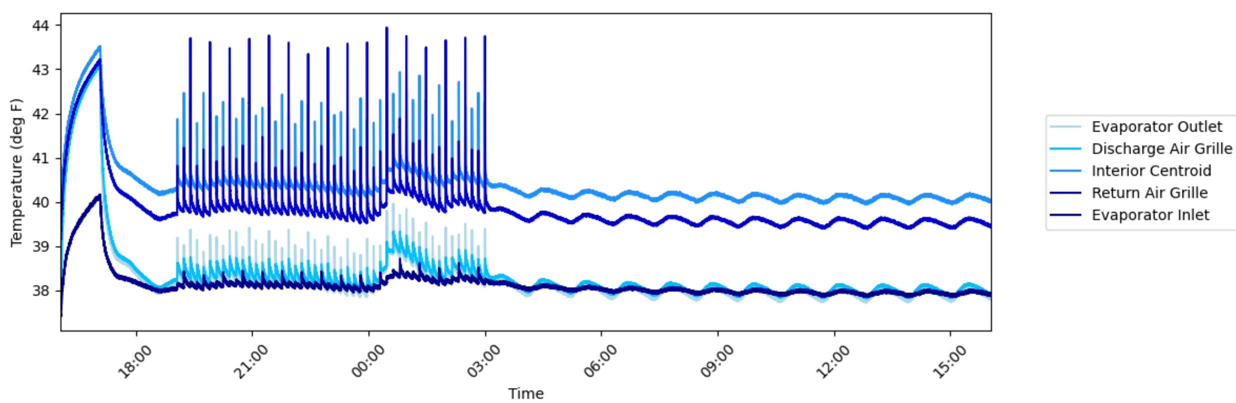


Figure 53: Interior case air temperatures for the 108 °F inlet water test at ASHRAE 72 chamber conditions.

The air temperatures measured within the refrigerated case at average store conditions are shown in Figure 54, Figure 55, Figure 56, and Figure 57 for each of the water inlet temperatures at 55 °F, 80 °F, 95 °F, and 108 °F, respectively.

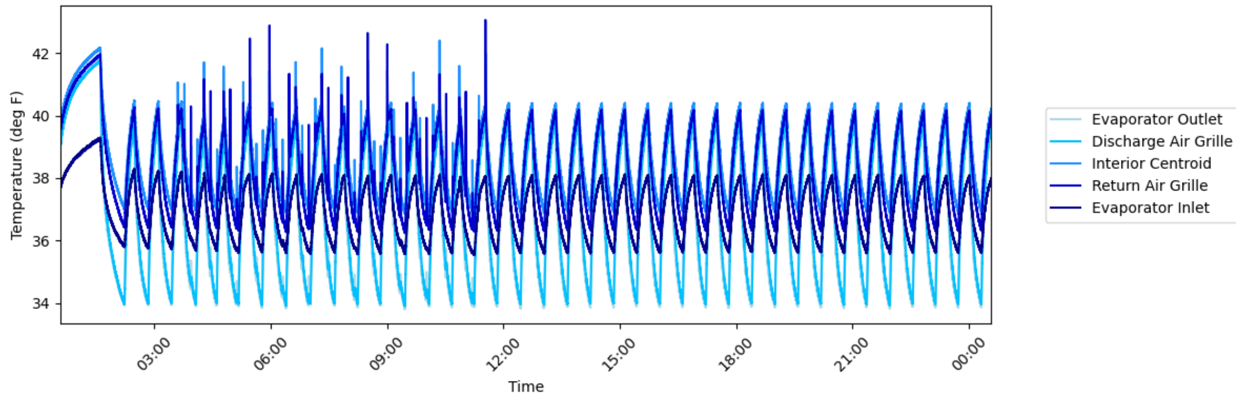


Figure 54: Interior case air temperatures for the 55 °F inlet water test at average store conditions.

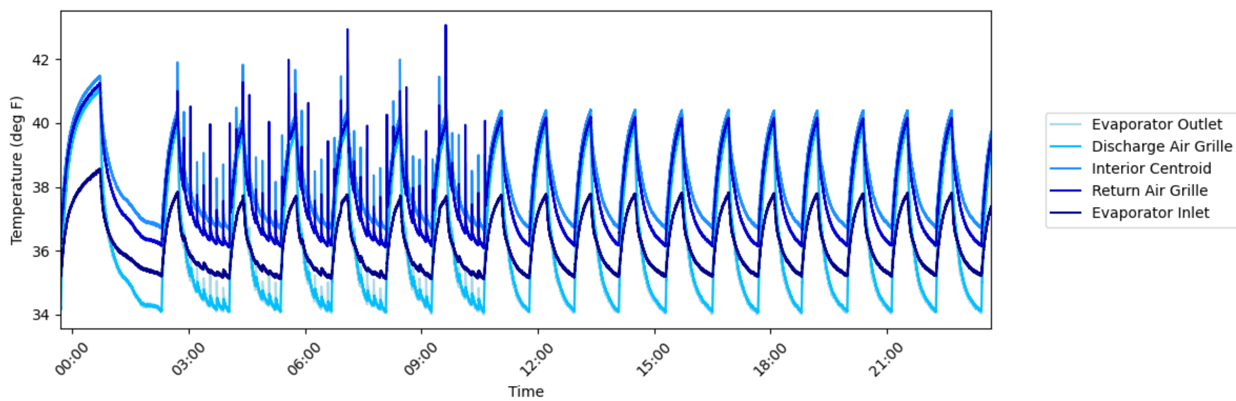


Figure 55: Interior case air temperatures for the 80 °F inlet water test at average store conditions.

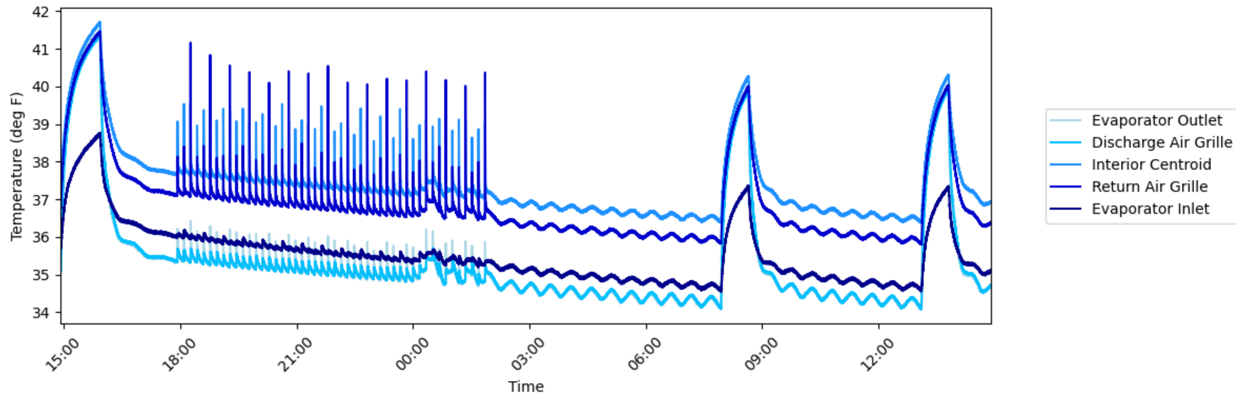


Figure 56: Interior case air temperatures for the 95 °F inlet water test at average store conditions.

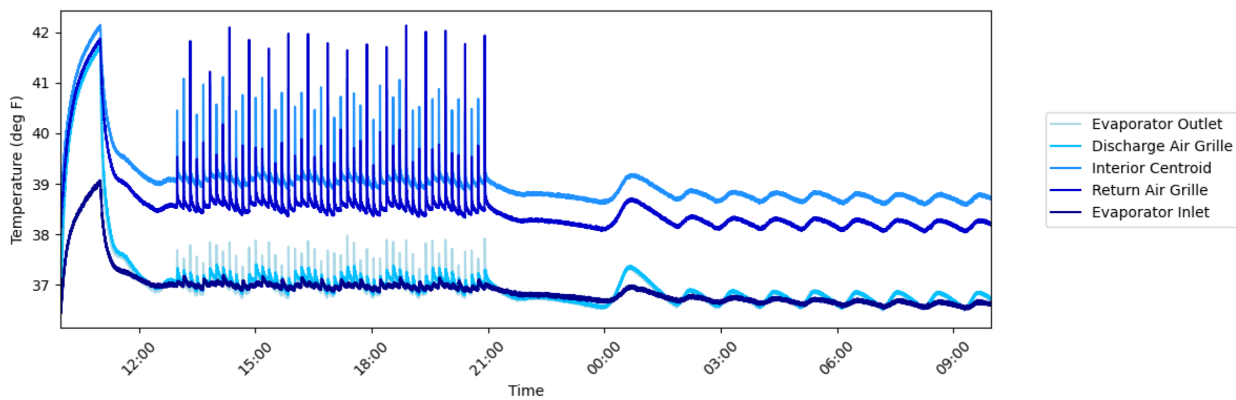


Figure 57: Interior case air temperatures for the 108 °F inlet water test at average store conditions.

Raw Data: Refrigerant Temperatures

The measured refrigerant temperatures for the refrigerated case at ASHRAE 72 conditions are shown in Figure 58, Figure 59, Figure 60, and Figure 61 for each of the water inlet temperatures at 55 °F, 80 °F, 95 °F, and 108 °F, respectively. The refrigerant temperatures are not from probes tapped to within the refrigerant lines, but rather surface thermocouples attached on the outside of the (heavily insulated) pipes. It should be noted that the evaporator saturation temperature shown here is not calculated from refrigerant pressures but is estimated by a surface thermocouple placed at the half-coil position within the evaporator coil.

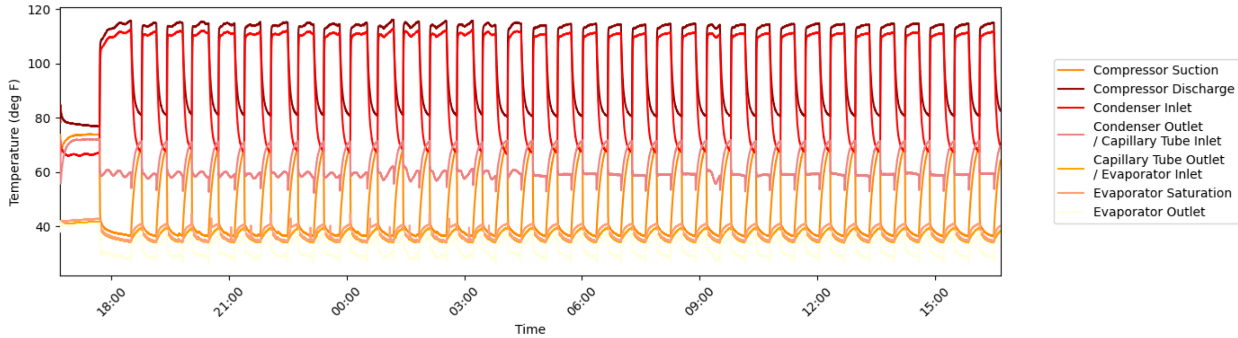


Figure 58: Refrigerant piping surface temperatures for the 55 °F inlet water test at ASHRAE 72 chamber conditions.

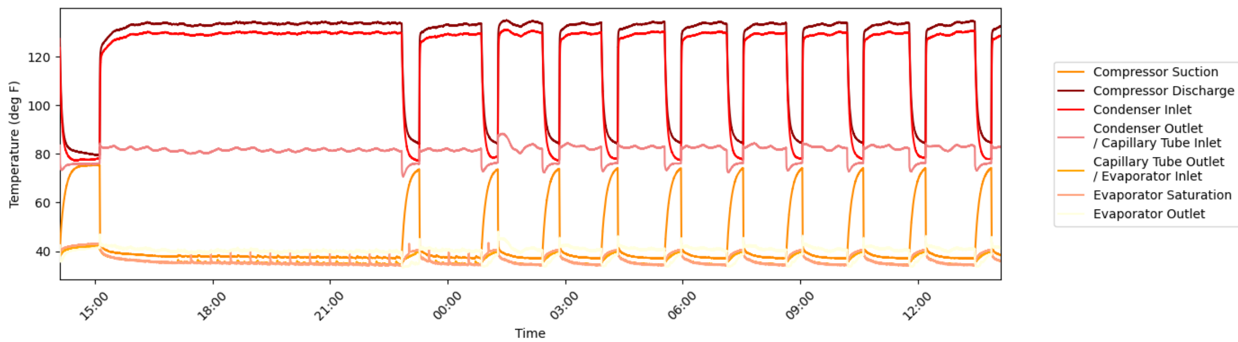


Figure 59: Refrigerant piping surface temperatures for the 80 °F inlet water test at ASHRAE 72 chamber conditions.

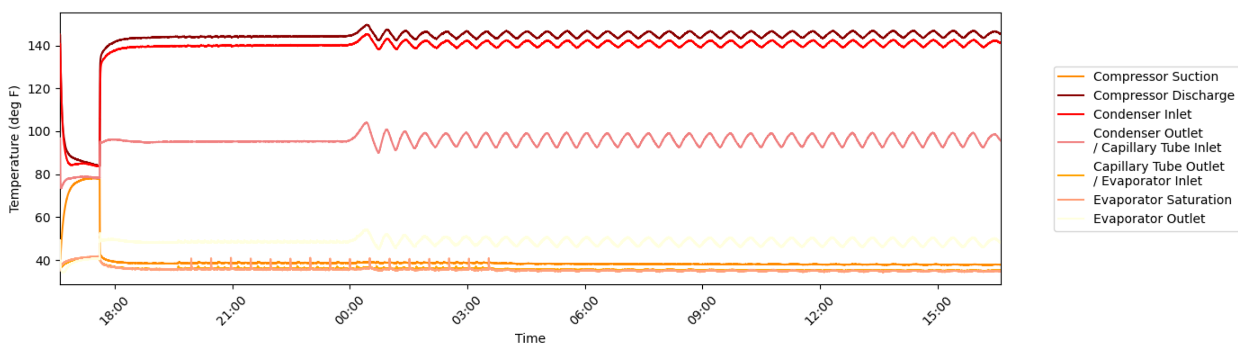


Figure 60: Refrigerant piping surface temperatures for the 95 °F inlet water test at ASHRAE 72 chamber

conditions.

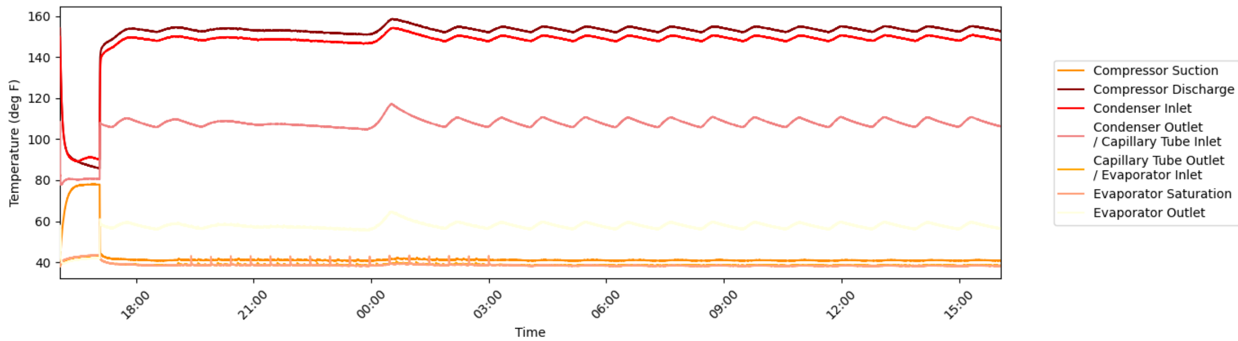


Figure 61: Refrigerant piping surface temperatures for the 108 °F inlet water test at ASHRAE 72 chamber conditions.

The measured refrigerant temperatures for the refrigerated case at average store conditions are shown in Figure 62, Figure 63, Figure 64, and Figure 65, for each of the water inlet temperatures at 55 °F, 80 °F, 95 °F, and 108 °F, respectively.

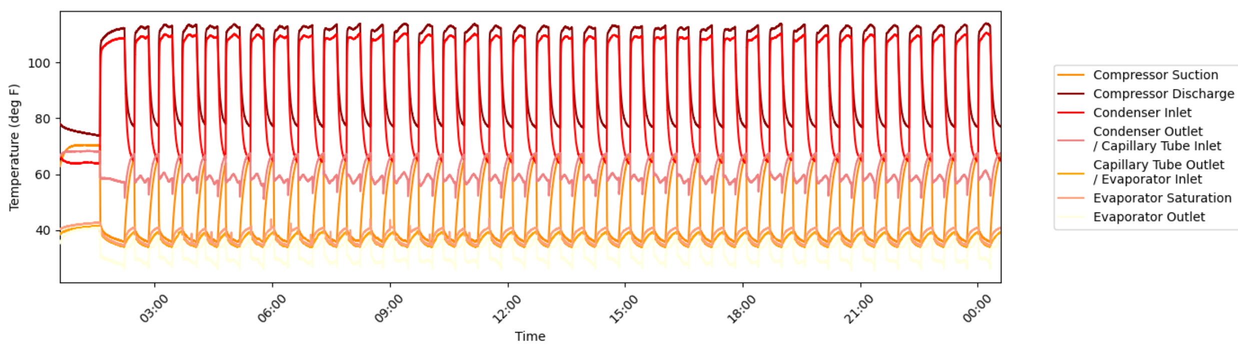


Figure 62: Refrigerant piping surface temperatures for the 55 °F inlet water test at average store conditions.

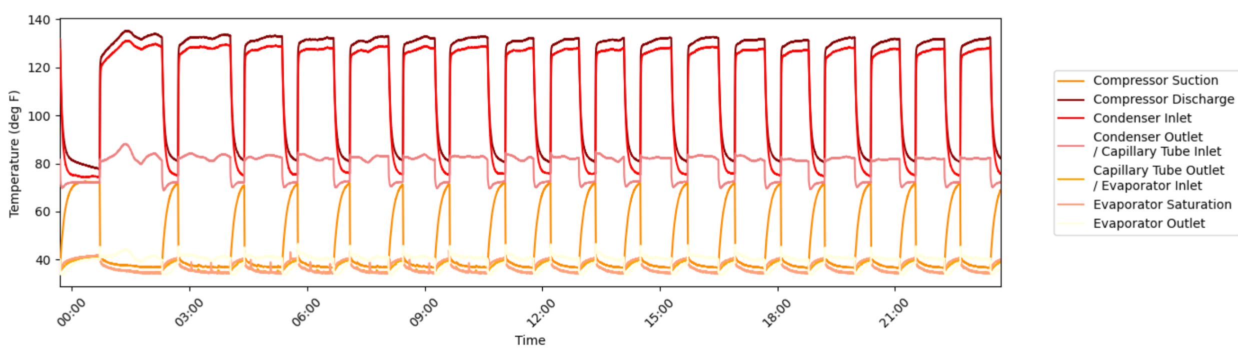


Figure 63: Refrigerant piping surface temperatures for the 80 °F inlet water test at average store conditions.

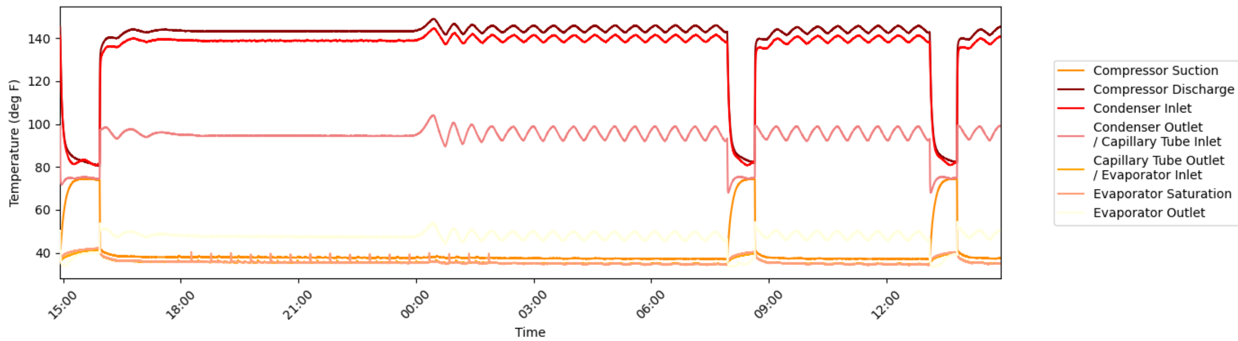


Figure 64: Refrigerant piping surface temperatures for the 95 °F inlet water test at average store conditions.

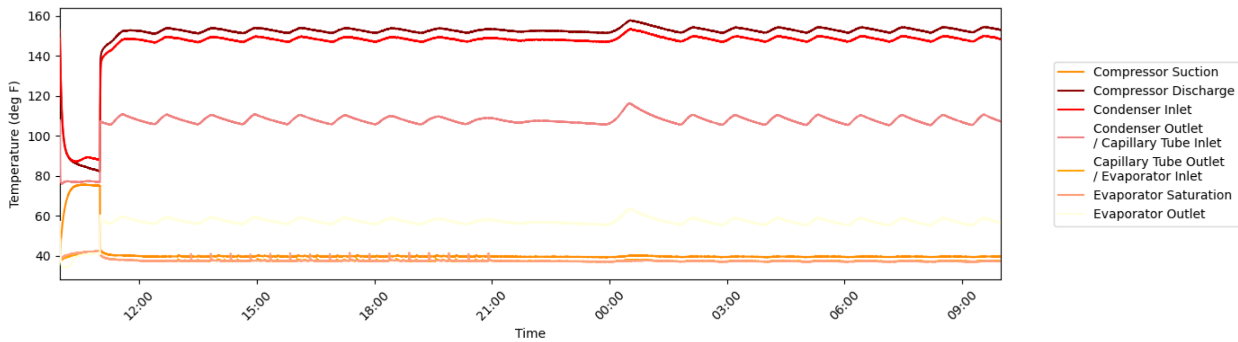
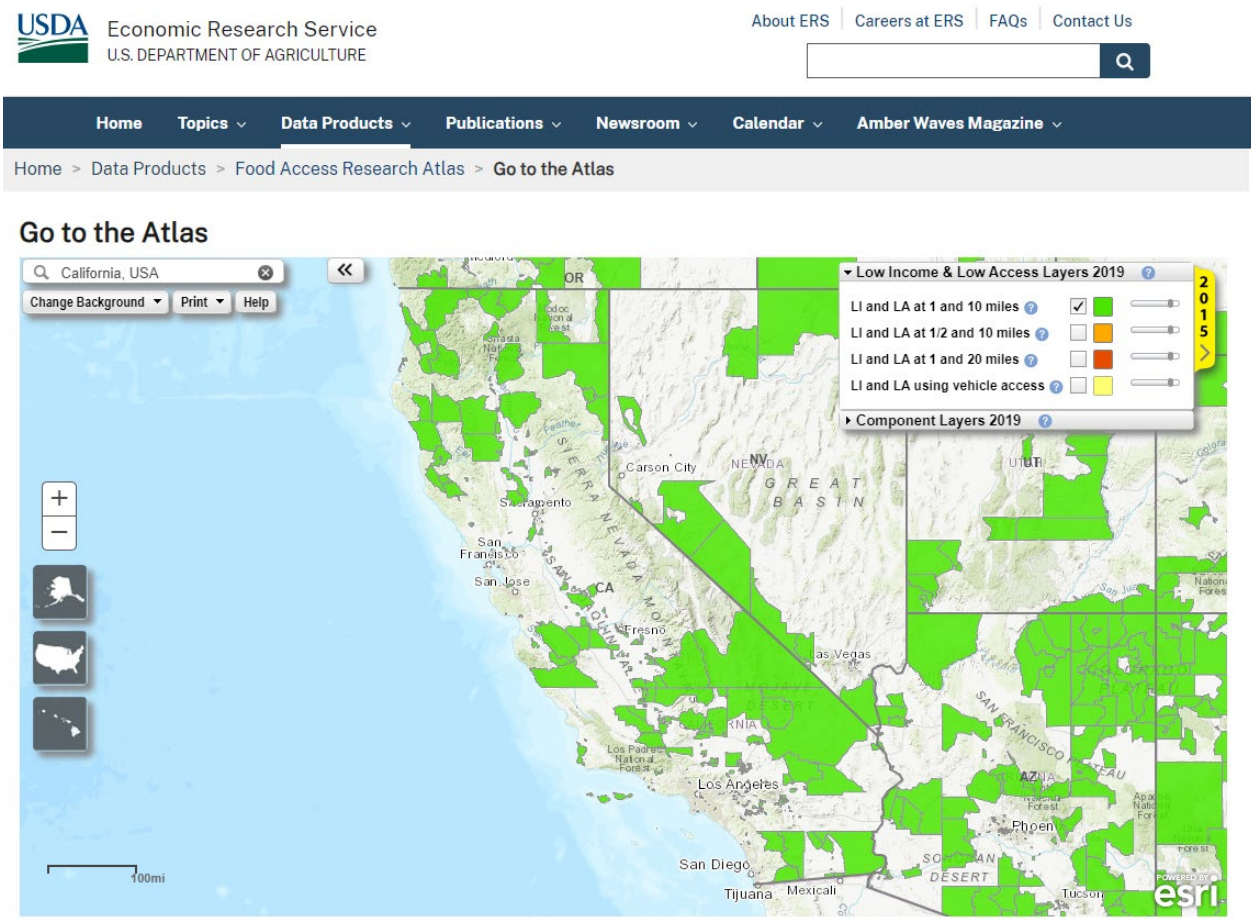


Figure 65: Refrigerant piping surface temperatures for the 108 °F inlet water test at average store conditions.

Appendix E: USDA Food Access Research Atlas Map

https://www.ers.usda.gov/data-products/food-access-research-atlas/go-to-the-atlas/



Appendix F: Climate-Friendly Supermarkets

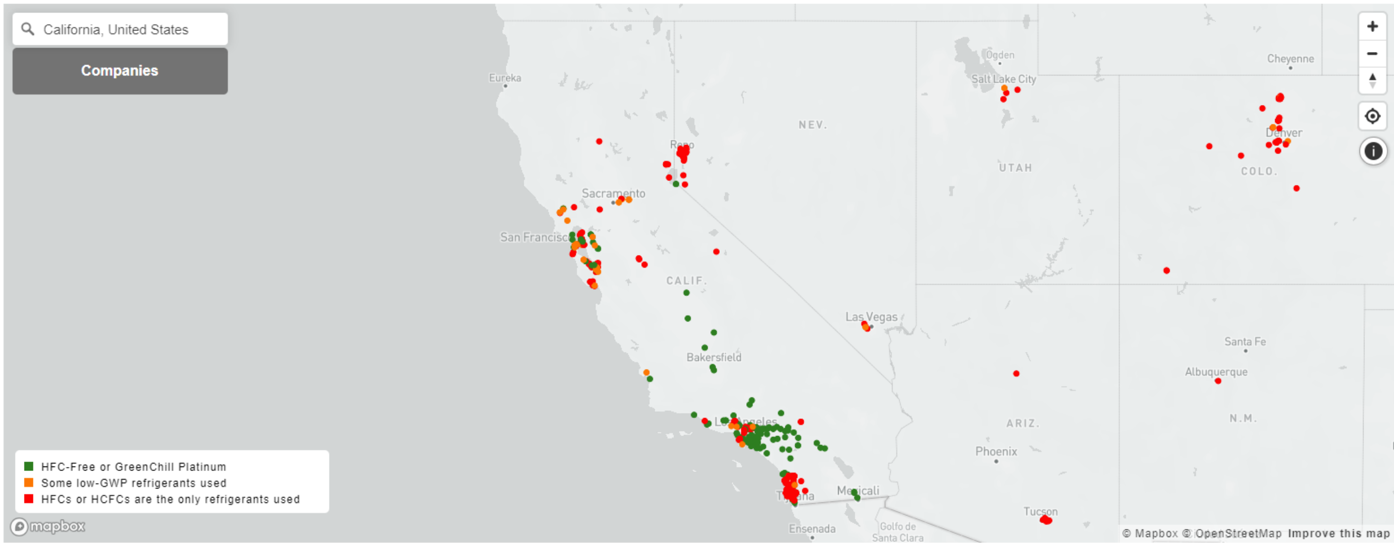
https://www.climatefriendlysupermarkets.org/map

CLIMATE-FRIENDLY SUPERMARKETS Facts on HFCs | Actions | Map | Reports | Scorecard | Media

< Home

What's in your supermarket?

Investigate your store and request a climate-friendly supermarket near you.



Appendix G: Technical Specifications

HUSSMANN®

Hussmann Corporation
12999 St Charles Rock Road
Bridgeton, MO 63044

Sold To:	NREL 525 S Hewitt St Los Angeles, CA 90013 United States	**Job:**	NREL - Golden, CO 15013 Denver West Parkway Golden, CO 80401 United States
Sales Representative:	Lauren Martyn	**Date:**	04/02/2024
Quote Number:	198901-01	**Revision Number:**	1

QUOTATION SUMMARY:

Department	Qty	Options	Description
01: 3 DRS RMN-W			
	1	**RMN3W**	**RMN3W - REACH-IN MED TEMP 290 - Pos: 10 - ID: 18-1-1**
	1	R290	REFRIGERANT - PROPANE
	1	EC	EXT COLOR - EC, Color: Y701
	1	IC	INT COLOR - IC, Color: 701
	0	701	SHADOW BLACK
	1	Y701	CASE COLOR - EXT-COLOR SHADOW BLACK, Color: Y701
	1	UG73	LAMP - LED-S 3DR 4000K RL
	1	VW00	FACADE - FACADE 20IN O/C RLN3W, Color: Y701
	1	BB49	BUMPER - BMPR-701 SHDW BLK 3 DR
	1	DE58	SPLASHGUARD - SPLASHGUARD O/C EXPRT 3DR, Color: Y701
	1	IC701-3N	INTERIOR OPTIONAL COLOR KITS - INTERIOR COLOR 701, Color: 701
	0	701	SHADOW BLACK
	3	BC30-701	PTM FOR BOTTOM WIRE RACK - PTM 1.5 BTM RACK BLACK, Color: 701
	0	701	SHADOW BLACK
	15	FX5400	SHELVES UNLIT - SHELF-22 RL 2 POS BLACK, Color: Y701
	0	701	SHADOW BLACK
	15	BC43-701	PRICE TAG MOLDING FOR SHELVES - PTM 1.5 N/L SHELF BLACK, Color: 701
	1	TH99	OTHER KITS - CONDENSING UNIT SOUND INSUL
	1	UE13	OTHER KITS - CORELINK ADPTR USB TO ETHERNET
	1	WG41	SWITCH KITS (REMOVAL,DUAL TEMP,ETC) - REMOVE SWITCH BLACK FRAME
	3	XE43	HOSES KITS - HOSE-WATER HOSE KIT
	1	VZ46	LABEL KITS - LABEL-MICRO DS
	1	FM16	LH END REACH IN - END-LH RECT TEX OC EXT/BLK INT RLN, Color: Y701
	1	VW05	LH FACADE SIDE - FACADE SIDE 20IN O/C RLNW, Color: Y701
	1	KKT150	SPLASHGUARD END LH - SPLASHGUARD END LH O/C, Color: Y701
	1	FM17	RH END REACH IN - END-RH RECT TEX OC EXT/BLK INT RLN, Color: Y701
	1	KKT160	SPLASHGUARD END RH - SPLASHGUARD END RH O/C, Color: Y701
		Department Total	**7,772.00**

Total Price: $7,772.00 (USD)

Notes:

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