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Case Study: The First Commercial Propane/Carbon Dioxide Cascade Refrigeration System in North America

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Abstract

In 2016 the Northern California Region of a prominent U.S. supermarket company opened the first and only supermarket in North America that uses a commercial R290/carbon dioxide (R290/R744 or C3H8/CO2) cascade refrigeration system. The store is located in Santa Clara, CA, and it is part of the company's strategy to pilot the full range of natural refrigerant technology options for research and development purposes.

Introduction

Supermarket operators are facing a future in California where the use of any refrigerant with a global warming potential (GWP) greater than 150 in new equipment will be illegal¹. Multiple other pressures on technology and refrigerant choice are looming (Figure 1) – not just in California, but across the nation².

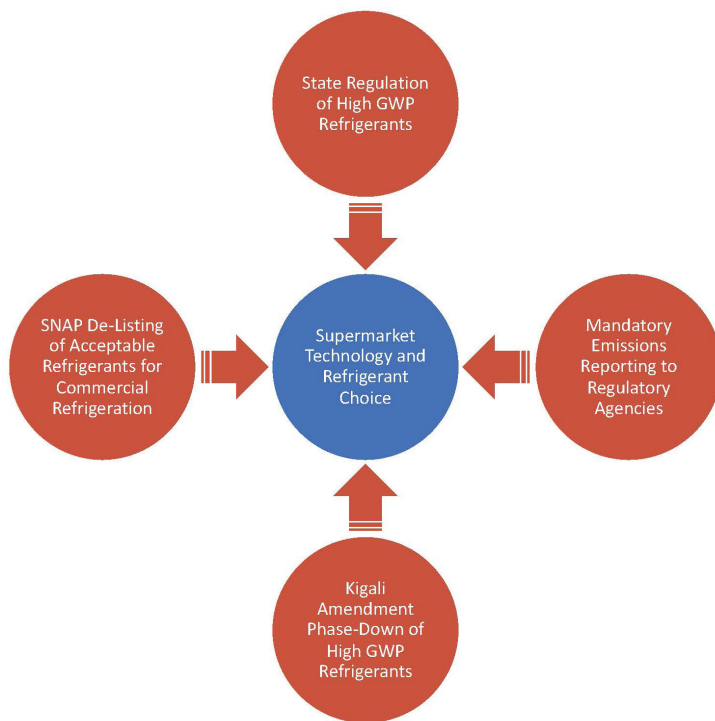


Figure 1. Factors affecting refrigerant choice.

¹ The presentation given at a California Air Resources Board (CARB) Workshop on October 24, 2018 announced CARB’s intent to pass regulations that would ban as of January 1, 2022 the “sales or installation of new systems containing a refrigerant with a GWP of 150 or greater” in systems containing more than 50 pounds of refrigerant. See <https://ww2.arb.ca.gov/sites/default/files/2018-12/HFC%20Workshop%20Presentation%20%28October%202018%29%20FINAL.pdf>. Accessed on January 15, 2019.

² As of the date of this paper, a total of 19 other U.S. states and territories (NY, MD, CT, CO, DE, HA, IL, MA, MI, MN, NJ, NC, OR, RI, VT, VA, WA, WI, and Puerto Rico) have announced that they are planning to regulate high GWP refrigerants, i.e. HFCs at the state level.

After installing multiple versions of carbon dioxide (R744) commercial refrigeration systems, this company determined that R744 is not a silver bullet for all stores in all climate zones. This resulted in the company adopting a strategy of piloting the full range of natural refrigerant commercial refrigeration systems, so that it can call on experience with the broadest range of technologies when determining the best choice for each specific store in the future. They refer to this strategy as a “silver buckshot approach,” in contrast to a “silver bullet approach.” A scattering of buckshot is more likely to hit every target than a single bullet, especially a target that is constantly moving.

Of specific concern to the company in carrying out their strategy is the failure of codes and standards organizations to keep up with the fast pace of natural refrigerant technology developments in commercial refrigeration, especially with regard to the use of hydrocarbons as refrigerants in supermarkets. The company determined that waiting on codes and standards organizations to catch up to technology developments was a strategic risk when considering the timing of future regulatory bans of hydrofluorocarbon (HFC) refrigerants. In the company’s opinion, the only way to ensure adequate preparation for future state mandates to use low-GWP refrigerants is to initiate discussions with local officials to pilot technologies that are not yet addressed by codes and standards bodies.

During a time when international standards organizations are attempting to reach consensus over raising the maximum R290 charge size in commercial self-contained cases from 150 grams to 500 grams, the Santa Clara, CA rack refrigeration system uses 231 pounds (lb.)/105 kilograms (kg) of R290 contained within 7 separate chillers.

Though the supermarket company in question normally requires the refrigeration systems for new stores to fall within certain financial and performance parameters, it also realizes that a commercial refrigeration pilot project which has been specially designed and manufactured as a one-off project will fall outside those parameters.

The supermarket industry has had several decades to achieve economies of scale and high-performance levels for traditional HFC direct expansion (DX) systems. This company has accepted that the first attempt at a new technology is unlikely to achieve the performance and cost benchmarks expected of well-established technologies.

This paper describes the Santa Clara project journey from concept to final product installation, discusses the operations and maintenance performance to date, and describes the process to get the refrigeration system approved by the Environmental Protection Agency (EPA), standards bodies, and local building code officials. This paper focuses on the primary R290 refrigeration system equipment at the Santa Clara store, as the technology used in the secondary carbon dioxide refrigeration system is commonplace.

The purposes of this paper are twofold:

1. To outline the process and parties involved in a commercial refrigeration pilot project that uses a refrigeration technology that has not yet been incorporated into industry standards and building codes in order to illustrate that the lack of codes and standards for state-of-the-art technology does not have to be a barrier to progress; and
2. To document the performance of the R290/R744 cascade system used in the pilot project.

Process from Project Concept to Equipment Installation

Project Briefing and Kick-Off

This refrigeration project differed significantly from standard projects at its most fundamental level. In order to select an equipment manufacturer for the project,

the equipment manufacturer needs information about the system that is to be built. At this point in the project, the system type was unknown. The company wanted to allow equipment manufacturers the utmost flexibility at the concept stage of the project. There was only one initial requirement for systems manufacturers: to be willing to design and manufacture a R290 refrigeration system.

The company surmised that several of the major systems manufacturers would fall out of contention for the project before it even got off the ground, due to the inability to tackle this type of project or the unwillingness to do so. Designing a new type of refrigeration system requires a lot of resources, including dedicated expert project management, research and development expertise beyond the industry norms, and a factory production line that accommodates unique features. A commercial refrigeration manufacturer must have the bandwidth across the company to handle a project of this nature.

There is also a high degree of uncertainty involved in pricing the equipment. This type of project commonly entails multiple changes to the design of the system as new properties and features become desirable. The system manufacturer has to be on solid-enough footing financially that this can be handled and treated as a longer-term investment. The benefits of this type of project can be significant for a systems manufacturer that views its brand equity as being at the forefront of new technology.

The company used a refrigerant management consultant to interview the industry's major systems manufacturers to determine the sub-segment that was interested and capable of taking on this type of project. Of the eight systems manufacturers interviewed, four fell out of contention (Figure 2). The rationale for a manufacturer's interest or lack of interest is important, because the limited number of systems manufacturers in commercial refrigeration is a major limitation to technology advances.

System Manufacturer	Interested?	Reason why/why not
1	Yes	Company's brand equity was tied to R&D expertise
2	Yes	Company's brand equity was tied to being at the forefront of advances in natural refrigerants
3	Yes	Company with expertise in propane refrigerant use in other countries
4	Yes	Company trying to establish expertise in natural refrigerants
5	No	Company was only interested in pursuing ammonia refrigeration in the supermarket sector
6	No	Recent cooperative agreement with another systems manufacturer for natural refrigerant projects prevented this company from pursuing this project on its own
7	No	Propane too dangerous
8	No	Company could not dedicate the necessary resources, uncertain about propane

Figure 2. Results of manufacturer interviews.

The four manufacturers who declared their interest were subsequently invited for an in-person meeting with the team to discuss the project and their capabilities. The company devoted one week to this process. The in-person meetings were a key step in this process to verify the manufacturers truly understood the vision, dedication, skillsets, and capabilities required. This was a qualifying step, with the possibility that a company would not be selected to advance further in the process.

One item specifically covered in-depth in these discussions with each manufacturer was the need to get approval for the equipment from the EPA's Significant New Alternatives Policy Program (SNAP Program). The amount of work was described, as well as the process for submitting the application. It was explicitly conveyed that if the SNAP Program did not approve using R290 in a supermarket rack system,

this pilot project would have to be cancelled. The equipment manufacturer would also need to take responsibility for obtaining UL approval or its equivalent. The supermarket company would take responsibility for the local building codes and permitting.

At this early stage in the project, the supermarket company was open to any type of refrigeration equipment that used R290, whether a central DX (i.e. “rack”) system, self-contained R290 units, or R290 chillers. During initial discussions with a manufacturer that was interested in offering a system made up of self-contained R290 units, it became clear that this type of system was not yet “ripe” enough for the company. The charge limit of 150 grams of R290 in these units was a very limiting factor, but not necessarily determinative. The larger issue was that case design was not where it needed to be for all of the case styles required by this company. Each of this supermarket company’s stores is unique, and the stores often require very specialized cases. As with most supermarket companies, a refrigeration system that limits merchandisers’ flexibility and/or cannot meet the store’s need for specific case styles is a non-starter.

After these meetings, two of the four manufacturers were deemed sufficiently qualified, capable, and vested in the project’s intentions and were invited to submit proposals. Both manufacturers submitted qualified proposals. One of the manufacturers was more progressive and specific in their proposal, and it was selected as the right partner with which to proceed.

Design Proposals

The selected manufacturer had significant experience in natural refrigerant systems, and a review of a wide variety of system choices was undertaken. The systems evaluated included:

1. Transcritical CO₂ (Tc) systems with air-cooled gas cooler (this was used as a baseline comparison only, as it did not meet the project criteria);
2. Transcritical CO₂ with desuperheating R290 modules, utilized in conjunction with a gas cooler, to keep system in subcritical operation;
3. Cascade R744/R290 system – DX R744 for low temperature applications and liquid overfeed R744 for medium temperature; and
4. Separate Low Temperature & Medium Temperature systems to add redundancy and avoid the potential for total store loss of refrigeration.

The prerequisites for all of these designs were that they be energy efficient; safe; encompass reliable monitoring, alarming, and control of the mechanical systems; and be able to qualify for SNAP test marketing and UL (or equivalent) approval.

The overall goal of evaluating these different system architectures was to find an appropriate balance point which would minimize the overall ownership expenses, while also contributing significantly to the company's advanced use of natural refrigerants.

Design Decision

An independent refrigeration engineering consultant was employed at this point to help evaluate the proposals against the project-specific needs. The company contracted with a firm that fully understood their operational requirements, had experience with natural refrigerant solutions, had the appropriate technical expertise, and also had the resources available for a project of this type.

The following table of evaluation criteria was developed to help compare the system features (Figure 3). The scale used ratings that were sufficient to allow visibility into the best possible system choice, without requiring significant technical development of each solution.

Equipment configurations	Location	Complexity	Cost	Use of Propane	Experience w/ the technology in other countries
Transcritical CO2 w/ air-cooled gas cooler	Roof/mezzanine	Baseline	Baseline	None	Significant
Transcritical CO2 with desuperheater R-290 modules	Roof/mezzanine	More complex	More expensive	Not really a propane system	Limited
Cascade CO2/R-290 system	Roof/mezzanine	Less complex	More expensive	200-300 pounds	R-290 chillers used successfully in other countries
Separate low temp and medium temp systems	Roof/mezzanine	Less complex	More expensive	200-300 pounds	R-290 chillers used successfully in other countries

Figure 3. Evaluation criteria for proposal selection process.

The systems manufacturer used weather data to calculate the projected energy performance for the site's specific ambient conditions. Based upon the results of the energy review and the features summarized above, the system selections were narrowed to the Cascade R744/R290 system and the Cascade system with separate low and medium temperature systems. The company decided on the option with the separate low and medium temperature systems. This system not only met all the original requirements of the project, but also provided a level of redundancy which surpasses that of most Transcritical CO2 systems.

System Design

The process for the propane system design began with initial schematic designs exchanged between the systems manufacturer and the consulting engineer. This also included a detailed cost estimate. This was compared against the project requirements and the scope of work of other parties. Revisions for features and inclusions were generated, as well as a revised schematic and proposal. These steps were repeated multiple times as the design progressed. Some of the requirements for unique features included compliance with the California Fire Code (CFC) and NFPA 704, automatic high-to-low bypass for overpressure conditions, automatic shutdown, as well as responses to anticipated field agency inspections and required certifications.

Because of the iterative process, good faith negotiation between the parties was necessary for the pricing of the equipment, with detailed breakdowns required for modifications beyond the original estimate. The company was able to use this method of modifying the original proposal in helping to evaluate the various options encountered through the design phase, as well as helping to justify features that had an impact on the long-term operation and efficiency.

The systems manufacturer was required to provide and maintain a detailed specification for the equipment requirements as well as an Owner's Project Requirements (OPR). This provides clarity about the expectations and reduces frustrations for all parties. One key part of the requirement for this project was for the systems manufacturer to provide on-site start-up service until the time that the system operated optimally. The systems manufacturer was required to provide an operation and maintenance manual and to train the service contractor on the operation of the system.

There were multiple challenges in moving from concept to contract. As the project progressed, the number of parties involved increased. The refrigeration installation

specification was modified for the bid set release to include a section specific to this project. One of the unique requirements included the need for qualified on-site personnel who were fully trained in propane and carbon dioxide refrigeration systems. Even with careful planning and execution, there will be some things that can't be fully anticipated, and having trusted entities involved throughout the process is extremely beneficial to the overall execution. With this in mind, the contractors invited to provide proposals for the installation were those with whom Whole Foods had prior relationships and those that demonstrated a specific willingness and dedication to the training required.

After selection of the Refrigeration Contractor, the number of parties involved were numerous: The Facility Manager, the Construction Manager, Operations, the refrigerant management consultant, the Architect, the refrigeration engineer of record, the structural engineer, the electrical engineer, the general contractor, the refrigeration contractor, the commissioning agent, the systems manufacturer, and the controls company. The communication of project status, needs, revisions, and current challenges became correspondingly difficult, and it was critical that each party's specific role and responsibility be clearly defined.

There were overlapping engineering skillsets within the systems manufacturer and the engineer of record. The designation of specific engineering responsibilities was important, especially given that historically within the supermarket industry much of the refrigeration system design has been handled entirely by the systems manufacturer. Manufacturer expectations regarding information sharing need to be explicit. Non-disclosure-agreements (NDAs) between the manufacturer and the engineer of record are often necessary to allow the engineer of record access to sensitive information for the installation drawings so that change orders can be minimized. The manufacturer also needs to appreciate and understand that the timeliness of their information is critical to the overall successful execution. It is generally expected that at time of permit application, the design is essentially complete, and the contractors can submit accurate pricing. Any changes in

information past this point can result in pricing requests that can impact the owner's project financial status. It should be explicitly understood by all parties that transparent communication about the status of the project be maintained, so that appropriate contingencies can be included as a way to mitigate incompletions.

The systems manufacturer's role generally is to provide an engineered refrigeration system that operates as specified, and to provide the details necessary to install and service it. This requires information regarding all external coordination, including wiring, servicing clearances, structural needs, and start-up and operating procedures. The engineer of record's role typically is to develop and coordinate all mechanical, electrical, plumbing, and refrigeration system drawings, verify and document the obligations of the installing contractors, coordinate the overall installation to code requirements, and verify the design meets the owner's intentions. The more information the systems manufacturer can provide early, the less the need for design and installation revisions later in the process.

All parties must recognize that the overall development lifecycle of a project of this nature is usually longer than a standard project. With the degree of communication required, all parties should commit to a consistency of personnel devoted to the project. Staff re-assignments can be extremely difficult to fully accommodate with the high degree of cooperation required, and ultimately create a hardship for the other parties.

Through the iterative design process, learnings needed to be documented in the installation and equipment specifications. Drawings were released in stages of percent completion, with the need for the new information to be highlighted and reviewed by the owner, architect, manufacturer, the contractors, and all the engineering disciplines. Their feedback then needed to be compiled and possible further clarifications or revisions issued.

Significant attention was paid to the Fire Code compliance in design, refrigerant disclosure notices, signage, and the requirements for periodic testing and record keeping. The installation contractor was a key part of the process at this point, so the construction schedule could move forward as expeditiously as possible, with minimal budget impacts.

The final product design of the refrigeration system at the Santa Clara store is an advanced, all-natural refrigerant system, made up of a R744 cascade system with low-temperature and medium temperature fixture applications, with R290 as the primary refrigerant. The R744 is circulated through piping within the store to accomplish the refrigeration; three R290 units cool the R744 of the low temperature receiver, and the other four cool the medium temperature receiver. The seven R290 units are independent compressor systems that operate in parallel, isolated from each other and the R744 system (Figure 4). This keeps the refrigerant charge in each unit quite low; 25 pounds (11.3 Kg) in the three low temperature units and 39 pounds (17.7 Kg) in the four medium temperature units (Figure 5). The R290 is kept entirely on the roof, outside of the store. The modularized construction of the R290 units provides a high level of operation redundancy.



Figure 4. The seven propane units on the roof of the Santa Clara store

Equipment	Refrigerant Type	Final Charge Size ³ lb (Kg)
Low-temp chiller unit 1	R290	25 (11.3)
Low-temp chiller unit 2	R290	25 (11.3)
Low-temp chiller unit 3	R290	25 (11.3)
Medium-temp chiller unit 4	R290	39 (17.7)
Medium-temp chiller unit 5	R290	39 (17.7)
Medium-temp chiller unit 6	R290	39 (17.7)
Medium-temp chiller unit 7	R290	39 (17.7)
Cascade rack	R744	1,730 (785)

Figure 5. Refrigerant type/charge employed in the Santa Clara refrigeration system.

The design schematic below displays the independent R-290 chillers coupled via a heat exchanger to the CO₂ system (Figure 6). The R-290 refrigerant is used in a “chiller,” and there are seven independent chillers located on the roof. Each chiller is a sealed system. This sustainable design optimizes efficiency and improves refrigeration performance. The red lines represent the propane lines, and the blue lines represent the CO₂ lines going through the roof to the R-290 units.

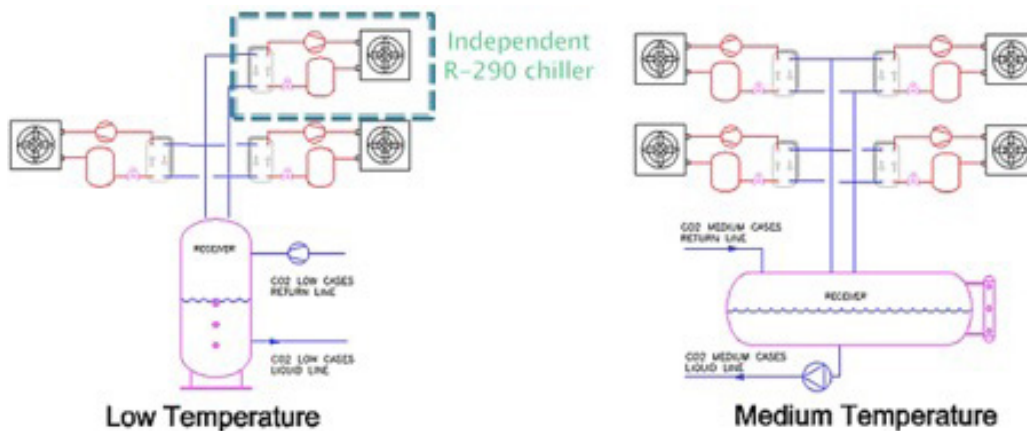


Figure 6. R-290 chillers coupled via a heat exchanger to a CO₂ system.

³ Figure 5 shows the final charge size of the individual propane chiller units. The charge size of each unit as originally designed was higher. See the section titled “Installation and Start-Up Challenges” for details.

There are two different R-290 unit models; they share the same types of components and only differ by parts sized by capacity. The three R-290 units cooling the CO₂ of the low temperature cases are smaller in capacity. The parts are smaller, and the refrigerant charge is slightly lower than the four units cooling the CO₂ of the medium temperature cases. Figure 7 shows the rooftop unit.



Figure 7. Rooftop refrigeration unit with detail.

Propane Safety Features

The full range of redundant levels of safety features of the propane units go into action only if propane leaks from one of the units. The design of each unit is such that the chance⁴ of a propane leak is very small. Nevertheless, the safety features were put in place to account for the worst-case scenario.

Passive safety features were incorporated into the propane system design wherever possible. The built-in passive ventilation features prevent any leaked R-290 from accumulating. There are four open, oversized side grills, two on the left and two on

⁴ The risk-assessment study performed by an independent third-party risk assessment firm estimated probability of a propane leak to be 0.000548.

the right of the cabinet. Since R-290 is heavier than air there is no bottom enclosure to the cabinets, but rather a mesh screen, which allows leaked propane to escape out of the bottom of the unit (Figure 8).



Figure 8. Passive safety features included in the Santa Clara installation.

Each unit is installed on 8-inch high stands to enable any propane that ventilates out of the mesh bottom to dissipate rapidly (Figure 9).



Figure 9. Refrigeration system support stands.

Venting and dissipating any leaked R290 is critical to safety, as the build-up of R290 to the lower explosive limit is one of the two necessary conditions for R290 to ignite.

The final passive safety features are restricted roof access, and the ability to shut the units off remotely.

In order to prevent the unintentional release of R290, as well as to protect the piping, receiver and equipment, additional protective devices were added to all seven units (Figure 10). The following four active safety features include a series of pressure shut-down safeties. These include compressor staging, high-to-low pressure bypass, and high-pressure alert devices. The R290 can additionally be vented from the system and flared off, either initiated through pressure relief valves, or through cross-zoned smoke and heat detectors.

1. Compressor high pressure switch (mechanical), located directly in the discharge head of the compressor. If the pressure rises, the relay starting the compressor is de-energized. The set point is 333psi (23 bar).
2. Pressure transducer programmed to activate a high-to-low bypass solenoid valve at 390 psi (26.9 bar). High pressure by-pass valves (software) are a link between the discharge side of the system to the suction side of the system. These dump the discharge pressure directly in the suction by opening the solenoid. The signal is given by the controls and is set to 390psi (26.9 bar).
3. High pressure rupture disk (mechanical) alerts the technician during service if the system pressure is near the set point of the relief valves. In the event of a ruptured disk, investigation is required to find the causes and perform preventative maintenance as required. The disk setting is 400 psi (27.6 bar).
4. Receiver pressure relief valves (mechanical) will open and vent the R290 out through the vent line, in the unlikely event that all other safety devices fail. This valve closes after a pressure drop, so that no more R290 leaks than is necessary to relieve pressure. The valve setting is 450 psi (31 bar). This was further

enhanced to meet the local authority having jurisdiction (LAHJ) requirements by venting through a flare device.



Figure 10. Close-up of additional protective devices.

The margin of the protection between the safety set points and the normal operating conditions is greater than necessary. At normal ambient temperatures (unit not operating) the pressure of the R290 is 115psi (7.9 bar). In normal operating conditions the compressor discharge pressure is at 155-165psi (10.6 – 11.4 bar). This is well below the system design pressures and the relief valve setting of 450 psi (31 bar).

The safety precautions required by Section 606 of the California Fire Code have been satisfied with several features. There are refrigerant sensors at each of the R290 units that will report out and alarm if any refrigerant leak is at or above 25% of the LFL. In addition, the unit where the leak is detected will be immediately shut down, eliminating any chance of ignition due to a spark from an electrical component. These leak detectors also report directly to the fire alarm system. Leak detectors were also installed on nearby parapet walls and the intakes of heating, ventilating and air-conditioning (HVAC) equipment.

The training of the service contractors is a critical part of any safety program, and this store is no exception. It is noted that refrigerant grade R290 is not odorized like common R290 used for fuel purposes. The service contractors must use hand-held leak detectors while on the roof servicing the equipment.

The system is equipped with a refrigerant leak detection and shutdown system intended to eliminate the risk of R290 ignition . Each unit has a leak detection module that is linked to a central system. Each leak detection module is equipped with two relays used to further reduce the risk of R290 ignition⁵. Relay #1 is normally open and changes state in the event of a power loss. This prevents anyone from disabling the module while the unit remains operational. Relay #2 is normally closed and changes state when a leak is detected, and any critical alarms are acknowledged at the central panel.

Relay #1 and Relay #2 are wired in series to cut power to components that are capable of causing ignition: the gas cooler fans, the compressor, 3-way valve motor, and the drive cooling fan. Note that four units have a 3-way valve for heat reclaim purposes and two units have a drive for control.



Figure 11. The electronic control panels on each propane unit.

The lower flammability limit (LFL) of R290 is 21,000 ppm. The leak detectors alert at 1000 ppm of R290, auditory alarm and alarm email at 2500 ppm, and critically alarm and shut down at 5000 ppm. It is at the critical level that Relay #2 changes

⁵ The risk assessment study performed by an independent third-party risk assessment firm estimated that the likelihood of leaked R290 from one of the R290 units igniting was 1.5E-07.

state. The critical concentration level setting corresponds to 25% of LFL for the R290. In addition, the central leak detection panel is configured to provide three separate signals to the Fire Alarm System in the event of a critical level leak on any channel of the system, a fault on the monitoring system, and/or a loss of power to the refrigerant leak detector.

Alarm beacon/sounder annunciators were located inside and outside the equipment room. An overpressure condition was an input to the control system, which immediately notifies the company’s facilities team and refrigeration service contractor (Figure 12).

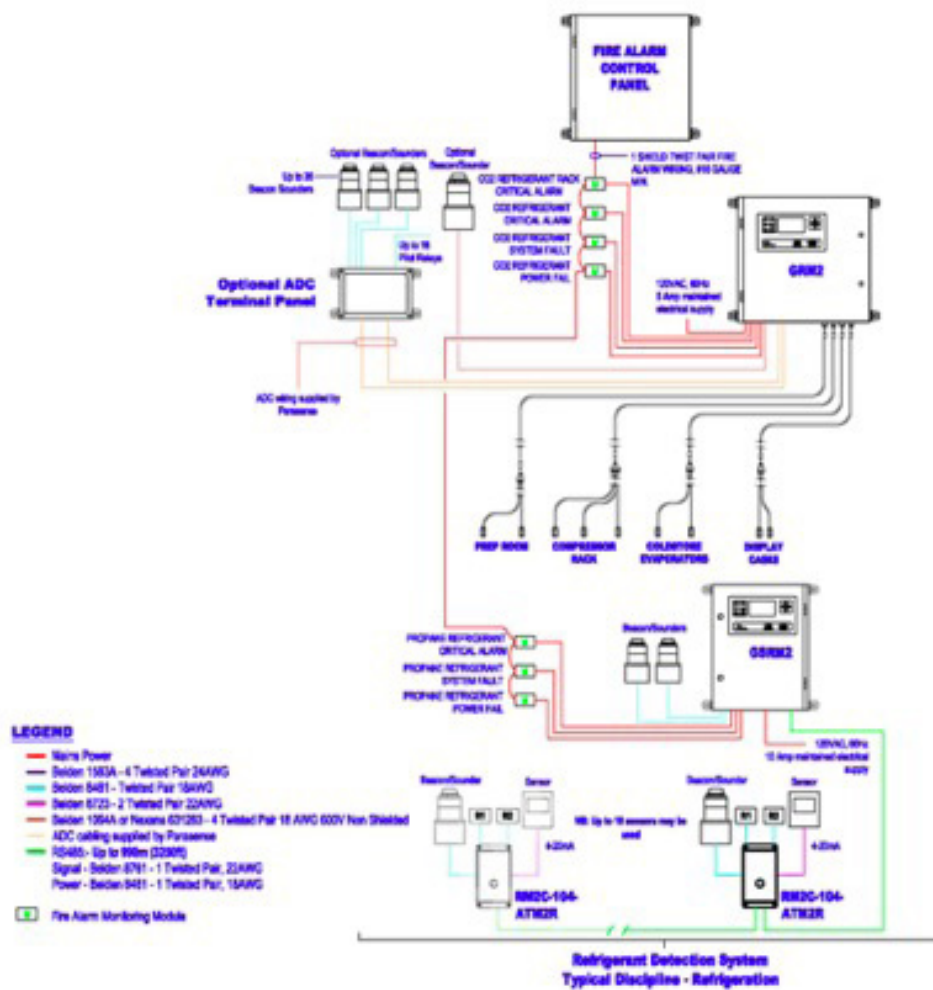


Figure 12. Schematic of alarm panel.

Regulatory Approval and Permitting

The first step in the regulatory approval process involved test market approval from the US EPA's SNAP Program. The SNAP Program is part of Title VI of the Clean Air Act, enacted by Congress to ensure that substitute refrigerants for the ozone-depleting refrigerants that were being replaced under the Montreal Protocol were not more harmful to the environment than the ozone-depleting refrigerants they were replacing. The SNAP program's requirements, however, present a conundrum for end-users who are interested in piloting natural refrigerants and technologies: it is illegal to use a refrigerant that is not on SNAP's list of acceptable substitutes for a specific end-use, but the application process to obtain SNAP's "acceptable" substitute status is so time-consuming and expensive that equipment manufacturers are usually unwilling to undertake the process.

Historically, chemical manufacturers have borne the burden of obtaining SNAP approval for new refrigerants in each SNAP end-use category, because the chemical manufacturer is the entity that has the patents on the chemical, and they stand to earn enormous profits from selling their chemical refrigerant. However, a natural refrigerant like R290 cannot be patented, and the manufacturer of refrigerant-grade R290 has little financial interest in undertaking the SNAP process. The burden of obtaining SNAP approval for the use of a natural refrigerant in each separate end-use category falls to the equipment manufacturer.

The SNAP Program's acceptability determinations only apply to the particular end-use category that is applied for. For instance, the acceptability determination for the use of up to 150 grams of R290 in commercial self-contained equipment is only valid for the end-use category called stand-alone equipment. The SNAP Program has not come to a determination about the use of any amount of R290 in the end-use categories of remote condensing units and supermarket systems.

Recognizing that manufacturers often need to gain field experience with refrigerants and technologies in the field before deciding whether to begin the SNAP application process, the SNAP Program has a test market provision that allows manufacturers to pilot new technology and refrigerant options. The test market approval process is short and simple for the most part, the main difficulty being that a company must apply for and receive approval at a stage of the project where the design of a system is not yet finalized. The R290/R744 system manufacturer for the Santa Clara project applied for and received SNAP test market approval for the project.

The next step was to obtain UL approval or the equivalent. The R290 units obtained a Canadian Standards Association (CSA) field evaluation label, which, while not equivalent to a field certification, “assists code enforcing authorities and others involved in judging acceptance of the device for use in their area of jurisdiction.”⁶ The Canadian Standards Association (CSA) granted approval for the R290 chiller units.

The equipment specification required that the systems be designed to comply with ASHRAE 15, the 2013 California Mechanical Code (CMC), CFC, NFPA, and any additional LAHJ requirements. The R744 system was CSA & UL listed.

A key consideration for any project which is unique in nature and not necessarily fully described in the codes is the section for Alternate Designs in the Scope Section of the Building Codes. Section 1.2.2 of the California Mechanical Code states:

The provisions of this code are not intended to prevent the installation of any material or to prohibit any design or method of construction not specifically prescribed by this code, provided that any such alternative has been approved. An alternative material, design, or method of construction shall be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions

⁶ CSA Field Evaluation Report number 70074809-002, issued August 8, 2016 by The Canadian Standards Association.

of the code, and that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability and safety.

The engagement and communication with the local authority about the project intentions, construction, and safety features are thus extremely critical.

The authority having jurisdiction (AHJ) over permitting for the Santa Clara store did not raise any concerns about the R290 system up until the store opening. It turned out that the initial permitting had been handled by the Building Division of the AHJ, and the plans were not shared with the Fire Prevention and Hazardous Materials Division of the Plans Examiner and Code Enforcement Group (Fire Marshall) until right before the store opening. The company was notified at that time that the Fire Marshall did not approve the R290 refrigeration system. The Fire Marshall's concerns resulted in numerous design changes for control, leak detection and response, and over-pressure safety measures.

The Fire Marshall referred to CFC 6104.9, which does not allow fixed R290 storage on the roof of a structure, regardless of size. The project team's position was that CFC 6104.9 refers to LP-gas containers. The CFC Definitions chapter states that a container is "...used for transporting or storing hazardous materials. Pipes, piping systems, engines and engine fuel tanks are not considered to be containers." While the R290 in the Santa Clara R290 units is circulated in each refrigeration system on the roof, it is not intended as storage of R290. The project team requested an official International Code Council (ICC) interpretation, and the ICC found that the units were HVAC appliances and not storage containers. However, the ICC also stated that the final decision belongs to the LAHJ.

An Alternate Materials and Methods Application (AMMA) was submitted to the Fire Marshall, identifying all safety measures designed into the system. It was rejected. During several meetings, the Fire Marshall suggested various changes to the system

and/or the system's safety features. Some of these suggestions, that the R290 units be enclosed in a building on top of the roof for example, were rejected by the project team as safety risks themselves.

The Fire Marshall requested that any R290 release be flared off. With regard to a flaring system for leaked R290, the following sections of the CFC are relevant:

- CFC, 606.12.1 Flammable refrigerants. Systems containing flammable refrigerants having a density equal to or greater than the density of air shall discharge vapor to the atmosphere only through an approved treatment system in accordance with Section 606.12.4 or a flaring system in accordance with Section 606.12.5.
- CFC, 606.12.4 Treatment systems. Treatment systems shall be designed to reduce the allowable discharge concentration of the refrigerant gas to not more than 50 percent of the IDLH at the point of exhaust. Treatment systems shall be in accordance with Chapter 60.
- CFC, 606.12.5 Flaring systems. Flaring systems for incineration of flammable refrigerants shall be designed to incinerate the entire discharge. The products of refrigerant incineration shall not pose health or environmental hazards. Incineration shall be automatic upon initiation of discharge, shall be designed to prevent blowback and shall not expose structures or materials to threat of fire. Standby fuel, such as LP gas, and standby power shall have the capacity to operate for one and one-half the required time for complete incineration of refrigerant in the system.

A flaring device for any high-pressure gas release, or a gas release in the event of a fire was added to the system. To accomplish this, the pressure relief valves were piped to a common header and to a flare device. Heat and smoke sensors were added to the ceiling area of the building under the area where the R290 units were installed. The system was designed such that if a fire is detected, solenoid valves at each unit would open, releasing the refrigerant to the piping to the flare device. A slight pressure increase would initiate the flaring process. Another AMMA was submitted and accepted by the Fire Marshall.

The entire process leading to the acceptance by the Fire Marshall of the final AMMA involved numerous site inspections, with a different inspector for each site visit, and each inspector needed to be briefed on the project from the beginning. Inspectors often duplicated the requests for information of previous inspectors and sometimes renewed objections that had already been put to rest with other inspectors.

A supermarket company that needs to obtain the final permit for a unique refrigeration system is in a difficult position. On the one hand, all correspondence and interaction with the AHJ for the majority of the new store construction project indicated that everything was fine with the refrigeration system. There was no way for the company to know that the Building Division of the AHJ did not share the plans with the Fire Marshall throughout the permitting process. On the other hand, it was universally recognized within the project team that complaining to the AHJ about the breakdown of the process within their organization would not help solve the issue. There was an enormous amount of money at stake, had the AHJ determined that the R290 system had to be removed. The notification that the Fire Marshall had issues with the R290 system came so close to the date of the store opening that there was no chance to solve the issues by the store opening date.

The Fire Marshall allowed the store to open with the R290 system as long as the company continued to demonstrate a good faith effort to find solutions to the issues raised by the Fire Marshall. The company and the rest of the project team met with the Fire Department multiple times to explore options.

The team spent considerable time documenting the environmental benefits of the all-natural refrigeration system; explaining California's Short-Lived Climate Pollutant Strategy, which made clear that the State planned to ban refrigerants with a GWP greater than 150; outlining the need for codes and standards to be updated so that supermarkets could prepare for the planned bans of high-GWP refrigerants; and summarizing the results of several expensive, independent third-party risk assessment studies that showed that the overall safety risk presented by

the R290 system was very, very small. However, it eventually became clear that the environmental justification for the refrigeration system was irrelevant to a group of people whose responsibilities did not include the environment. Other than the risk analysis and dispersion modeling, the majority of the material provided by the team initially was “nice to know,” but it did not change the status of the project in any way.

Discussions became more productive once they focused on the Fire Department’s priorities: fire prevention, hazardous material, and the safety of first responders. The ICC opinion that stated the R290 units were not considered R290 storage tanks under CFC 6104.9 was a major turning point. The descriptions of the system’s redundant passive and active safety features, a demonstration of the leak detection and alarm system, and an independent third-party inspection of the alarm system helped overcome many of the safety concerns. The addition of the flaring mechanism resolved the last issue, and the refrigeration system was approved.

Installation and start-up challenges

Any unique system may require additional start-up time. However, the company and the service contractor were very familiar with the R744 cascade system, and the R290 modules were simple in design. The team expected the start-up to proceed relatively smoothly.

However, relatively simple issues, which may or may not even be directly related to the system design choice, can have an impact on the start-up. One surprise encountered was when the R290 charge of each unit was much higher than expected. The custom horizontal receivers built for this application did not have a dip tube on the outlet connection of the receiver. This was corrected by slanting the receivers and installing the correct tubes, thereby bringing the amount of R290 in each unit back to the originally expected levels.

Equipment	Refrigerant Type	Original Charge Size (lb./Kg)	Final Charge Size (lb./Kg)
Low-temp chiller unit 1	R290	35 (15.9)	25 (11.3)
Low-temp chiller unit 2	R290	35 (15.9)	25 (11.3)
Low-temp chiller unit 3	R290	35 (15.9)	25 (11.3)
Medium-temp chiller unit 4	R290	40 (18.1)	39 (17.7)
Medium-temp chiller unit 5	R290	40 (18.1)	39 (17.7)
Medium-temp chiller unit 6	R290	40 (18.1)	39 (17.7)
Medium-temp chiller unit 7	R290	40 (18.1)	39 (17.7)
Cascade rack	R744	not applicable	1,730 (785)

Figure 13. Santa Clara propane charge comparison.

Another issue that was unrelated to the system design choice was the decision by the property owner to have the R290 units painted the same color as the roof of the building. Unfortunately, the person who painted the units covered the sensors with rust-colored paint, and they all had to be replaced.

Given the overall simplicity and size of the R290 units, Whole Foods would have preferred to have each unit to be factory charged, saving field time and challenges. The equipment manufacturer pushed back on the idea due to perceived complexities with shipping pre-charged R290 units internationally and across US state lines. Additionally, given the moderate climate for this application, as well as the microchannel condensing surface, it is possible that the receivers could have been eliminated entirely and the systems critically charged.

Operations and Maintenance: Year 1 (2016-2017)

The following tables and graphs describe the operations and maintenance of the Santa Clara store. When comparing the Santa Clara store to other stores, every effort was made to select stores for comparison that are as similar as possible within a

company that does not use standard store designs. Though all of the stores used in comparisons are in northern California, the variety of climate zones within the state can make it difficult to even compare stores that are located close to each other.

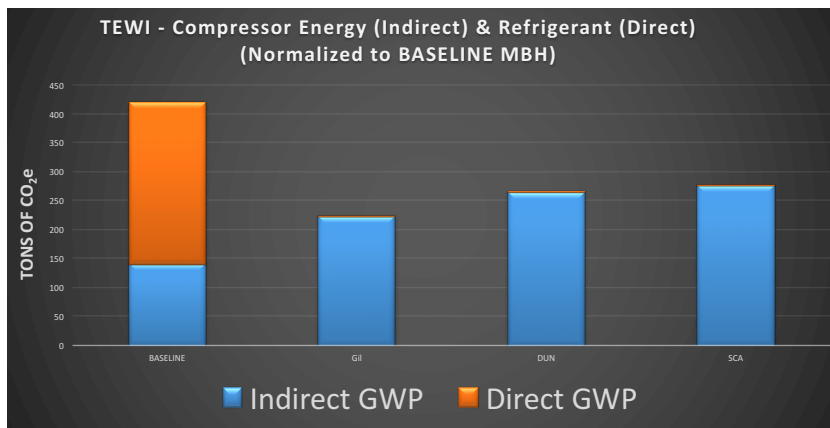
Figure 14 gives the statistics for all four stores. The baseline store, made up of data from multiple stores and serve to represent a high efficiency but traditionally designed HFC centralized DX system. The comparable stores were selected because they are among the top performing stores within the company’s northern California region.

Store ID	Size (Ft ² /m ²)	Refrigeration Load (MBH/kW)	Refrigerant Charge (LBS/kg)	System Type
BASELINE	39,029 / 3,626	847 / 248	R407A (1,225/556)	Distributed 407A scroll units, hybrid condensers
GIL	47,805 / 4,441	650 / 190	CO ₂ (1,200/545)	CO ₂ Transcritical, Gas Cooler (air cooled)
DUN	40,072 / 3,723	605 / 177	CO ₂ (1,440/654) NH ₃ (250/114)	Low-Temp DX CO ₂ /Medium temp liquid overfeed CO ₂ , cascaded to R717 (NH ₃) system, hybrid condensers
SCA	50,198 / 4,663	750 / 220	CO ₂ (1,730/785) Propane (231/105)	Low-Temp DX CO ₂ /Medium temp liquid overfeed CO ₂ , cascaded to R290 (Propane C ₃ H ₈) system, air cooled condensers

Figure 14. Comparison of baseline store and comparable facilities.

Total Equivalent Warming Impact (TEWI)

The TEWI of a refrigeration system measures the direct greenhouse gas emissions from refrigerant leaks, plus the indirect greenhouse gas emissions from energy use. Some supermarket companies use TEWI as a measure to be sure that reducing greenhouse gas emissions from one source does not lead to increased emissions from the other source.



TEWI of the Santa Clara store compared to the Fremont 407-A store, the Gillman CO₂ transcritical store, and the Dublin ammonia/CO₂ cascade store. Measured in Tons of CO₂ equivalent emissions. Assumes 621 Lbs. CO₂e/MWH for California (source: Environmental Investigative Agency). GWP of R-407A = 2,107.

Because the global warming potential of the high-GWP refrigerants commonly used in supermarket systems and the high leak rates that are typical in the industry, even large increases in energy use are unlikely to outweigh the greenhouse gas improvement from low-GWP refrigerant choices.⁷ The greenhouse gas impact of the refrigerant leaks of a typical US supermarket is greater than the entire annual electricity consumption of that supermarket.⁸

⁷ GWPs of typical refrigerants used in supermarket refrigeration rack systems: R-404A = 3,920; R-507A = 3,990; R-407A = 2,110; R-22 = 1,810. <https://www.epa.gov/snap/substitutes-typical-supermarket-systems#self>.

⁸ GreenChill Climate Impact Calculator for Supermarkets, Keilly Witman, US EPA, <https://www.epa.gov/greenchill/greenchill-resources-and-reports>.

Effect on Climate

Electricity Use vs. Refrigerant Emissions

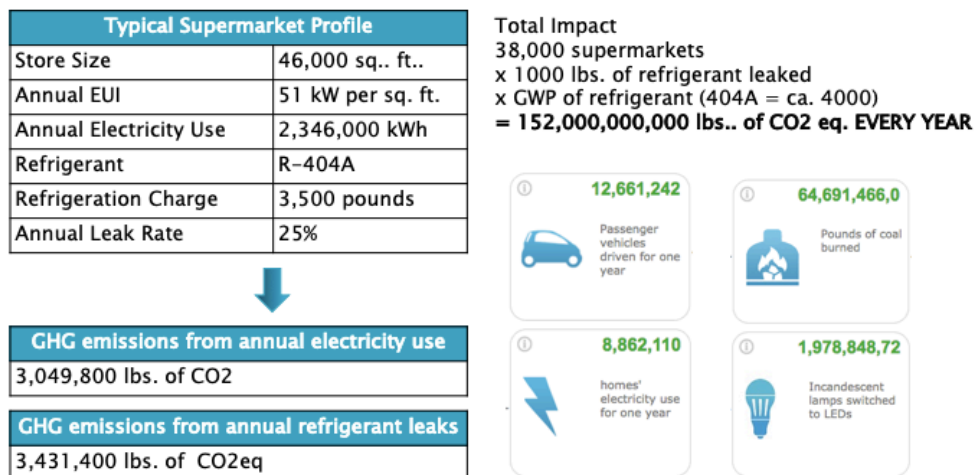


Figure 16. GreenChill Climate Impact Calculator for Supermarkets.
 EUI = Energy Use Intensity, a metric to measure to energy demand per square foot.
 Grocery stores have one of the highest EUIs.

Refrigerant Leaks

There were no refrigerant leaks from the R290 units or the R744 system in year one of operation. The seven R290 units also did not leak any refrigerant in 2018. Unfortunately, the heat exchanger on the low temperature unit #1 condensing unit cracked internally, so R744 refrigerant bled into the R290 refrigerant in the unit. To install the new heat exchanger, the service contractor had to remove the contaminated R290 from the unit. The full amount of the R290 contained in the unit was recovered and none was leaked.

The R744 system leaked 120 lbs. (54 Kg) of refrigerant in 2018.

Energy Use

Figure 17 shows the energy performance of the four stores, normalized to case design load. Each store's daily kilowatt hour use is divided by design case load. The numbers are plotted vs Ambient temperature. The crossroads for the Santa Clara R290/R744 cascade system to achieve better energy efficiency than both the Transcritical CO₂ system (GIL) and the ammonia/R744 cascade system is 66° (18.9 C).

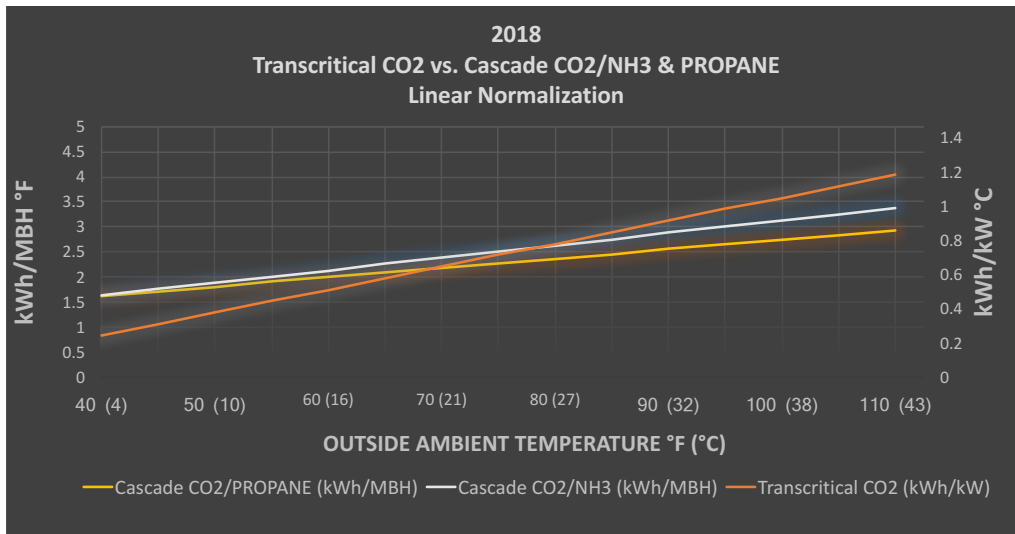


Figure 17. Energy performance normalized to case design load.

Figure 18 shows refrigeration compressors energy usage for each system sorted against ambient temperature, which was then used to develop a first-degree curve fit. The values generated by the normalized curve were then divided by the refrigeration design load to create a normalization by design load as well.

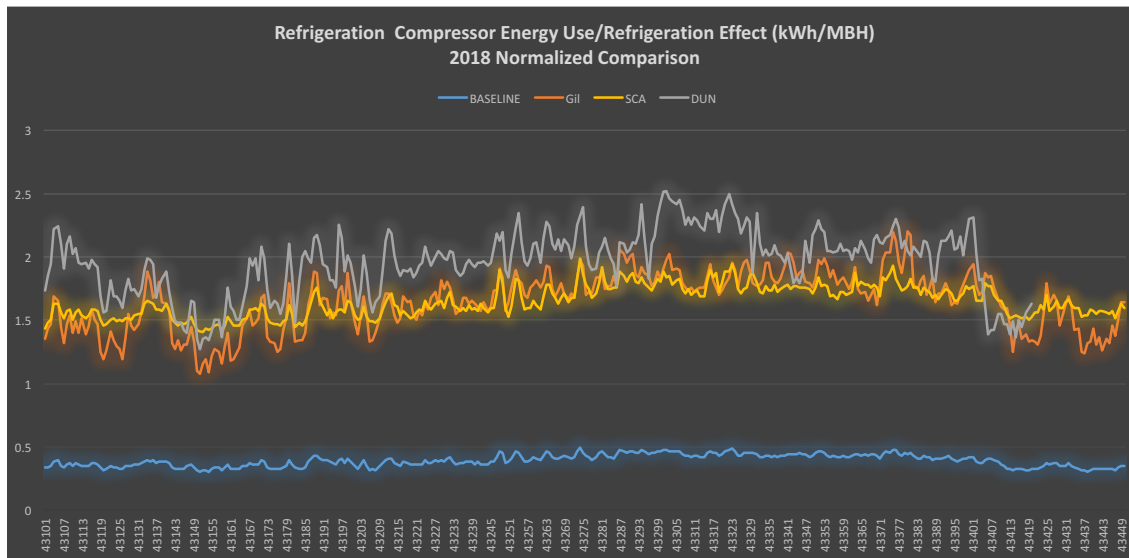


Figure 18. Energy performance: 2018 compressor energy use.

Figure 19 shows consumption data for three natural refrigerant stores plotted vs. baseline energy usage for HFC stores. The baseline was created using compressor energy usage from 10 representative stores using an HFC as the working refrigerant. Refrigeration compressors energy usage, for each system, was sorted against ambient temperature and then used to develop a first-degree curve fit. The values generated by the normalized curve were then divided by the refrigeration design load to create a normalization by design load as well. The same methodology was used on a representative group of HFC stores to develop a baseline. Notice that at higher ambient temperatures the Santa Clara store appears to be reaching parity in terms of energy usage.

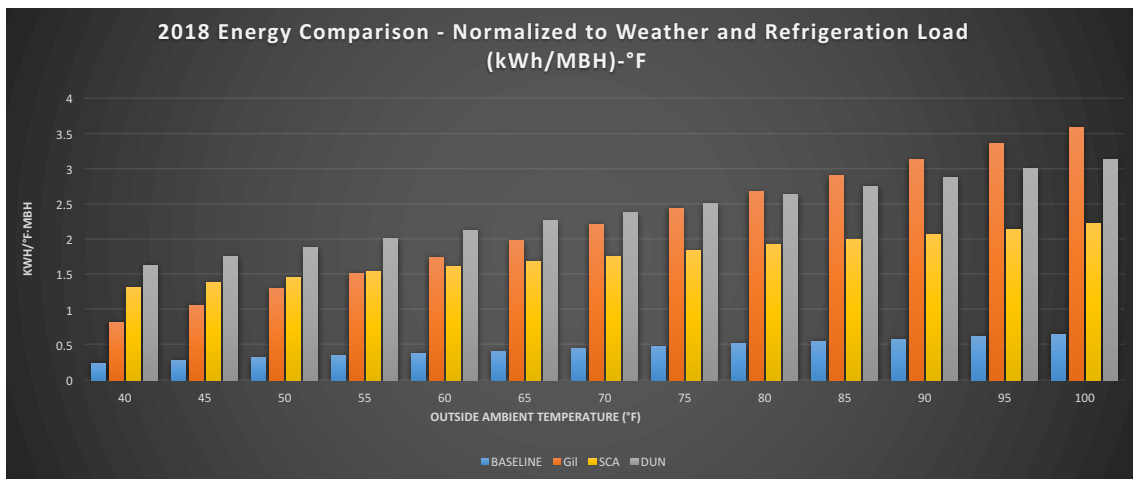


Figure 19. Energy performance normalized to weather and refrigeration load.

Safety

There were no safety issues with the Santa Clara refrigeration system. The alarm system did alarm frequently in the first weeks of operation, though no R290 leaks were detected in the R290 refrigeration system. It was later discovered that some of the leak detectors were located close enough to the exhaust from the prepared foods area of the store that the fumes from the exhaust were setting off the R290 alarms. Once the issue with the exhaust system from prepared foods triggering the R290 leak detectors was solved, the number of any type of alarm dropped to near zero. The R290 units did not leak any R290 in 2018.

Cost

Store	Type	System Cost	Install Cost	Total	Percent Increase Over Baseline
FRE	Baseline DX	1	1	2	0%
GIL	CO ₂ Transcritical	1.22	2.01	3.23	61%
DUN	Low-Temp DX CO ₂ /Medium temp liquid CO ₂ , Cascaded R717 (NH ₃) System	2.45	1.58	4.03	101%
SCA	Low-Temp DX CO ₂ /Medium temp liquid CO ₂ , Cascaded R290 (Propane C ₃ H ₈) System	2.06	2.66	4.72	136%

Figure 20. Cost comparison of baseline store and three comparable stores. (Details of the four stores compared in the cost table can be found in the energy use tables, above.)

Conclusions

Lessons Learned

- The greatest lessons learned in any project are often the hardest lessons learned. The need for earlier and closer engagement with the AHJ is without a doubt the greatest, and the hardest, lesson learned from the Santa Clara project.
- If the company decides to use a R290/R744 cascade system in another new store, they would mandate the use of pre-charged factory-sealed units vs. field-charged units.
- Custom systems, regardless of design, come at a premium, but standardization & wider adoption is driving costs down. Some of the costs of the project would automatically be eliminated if such a project were undertaken in another store. For instance, the costly risk assessment studies for the R290 technology would not need to be repeated.
- Controls collaboration and commissioning are key.

- The service technicians were comfortable with installing and servicing the R290 units. Training is very necessary, and wherever possible the same technicians should service the store to capitalize on the experience curve.

Though the energy use of the Santa Clara system is higher than the Baseline comparison stores, the company did not enter the project with the expectation that the prototype R290/R744 cascade system's energy efficiency would surpass the company's best HFC centralized DX systems. The energy use was within the range that was expected. With repetition comes improvement, as a company implements the lessons learned, makes improvements and design tweaks, and optimizes performance. It is interesting to point out, that at higher ambient temperatures above 100°F (38° C), the Santa Clara store appears to be reaching parity in terms of energy usage.

- Any technology that uses individual chiller units will entail somewhat higher energy use. In theory, with repetition, the very high energy efficiency of R290 should counteract any energy penalty inherent in individual chiller units.
- The company expects that the learning curve with future R290 systems would follow the same learning curve experienced with subsequent Transcritical CO₂ systems. Improved control strategy and system architectures should be instrumental with future R290 systems, as was the case with Transcritical CO₂ systems.

Project Satisfaction Rating

Figure 21 shows the average satisfaction rating from the values given by the members of the Santa Clara project team. The team members rated their satisfaction under the understanding that their individual ratings would remain confidential. It is notable that individual ratings varied greatly for the same performance criteria, which is probably a reflection of the different perspectives of the various functional areas within the team and their different expectations of each other.

Energy efficiency	62
Equipment cost	50
Refrigerant cost	88
Servicing cost	60
Maintenance cost	60
Installation cost	67
Installation quality	95
Servicing (after installation)	52
Leak rate	95
Compliance	100
Equipment quality	66
Equipment manufacturer performance	43
Equipment Manufacturer Selection Process	78
Coordination between parties	70
Leak detection	70
Permitting process	45

Figure 21. Average satisfaction rating for selected elements of the Santa Clara refrigeration project.⁹

The most telling indicator of satisfaction with the propane/CO₂ transcritical project is whether Whole Foods would choose to use the technology in another new store. The Northern California Regional Facilities Manager would use the technology again.

⁹ Scale is from 0-100, with 100 being the highest satisfaction rating.

Notes:
