Residential VC Space Conditioning-Buildings III: Sub-Project A

ET13SCE1220/DR13.06.00

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Customer Service
Southern California Edison

September 2016

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Acknowledgments

Southern California Edison's Emerging Products (EP) group is responsible for this project. It was developed as part of Southern California Edison's Emerging Technologies Program under internal project numbers ET13SCE1220 and DR13.06.00. The Electric Power Research Institute with Principal Investigators of Walt Hunt and Ron Domitrovic conducted this technology evaluation with overall guidance and management from Sean Gouw and Jerine Ahmed of Southern California Edison. Contact sean.gouw@sce.com for more information on this project.

EXECUTIVE SUMMARY

Central air conditioning (AC) is the primary heating, ventilation, and air conditioning (HVAC) configuration throughout California residences. In California Climate Zone 10, located within southern California, central air-conditioning accounts for approximately 17% of the total energy consumption of a residence, at 1.1 kWh per square foot of cooled space [1, 2]. Utility programs aimed at reducing air conditioning energy use in California Climate Zone 10 include efficiency programs for air-conditioning equipment rated at 15 seasonal energy efficiency ratio (SEER) or higher and demand response (DR) programs, which cycle air-conditioning equipment at predetermined intervals.

Because residential variable capacity (VC) AC may be a potential enhancement or additional resource for utility programs, this research study investigated VCAC for energy efficiency and DR programs for residential space conditioning. The investigation included a technical survey of available equipment, a laboratory assessment of three VC air conditioners of varying SEER, and a field study of the three VC systems over a California cooling season. The study demonstrates the potential efficiency and DR capabilities of the VC equipment for California residences and utility programs.

The team explored three research areas in the laboratory and in the field: potential energy and demand savings of VCAC, correlation of VC equipment with SEER, and system effects of VC equipment.

Based on survey findings and lab capabilities, the team selected three 2-ton VC systems for inclusion in the laboratory testing. In the laboratory evaluation, VCACs of 18, 19.5, and 22 SEER were evaluated under field design operating conditions for the California climate. All three systems demonstrated improved efficiency at part-load operation for a specific indoor and outdoor condition. When compared to a baseline 14 SEER air conditioner, an energy model for California Climate Zone 10 determined energy savings of 12%, 26%, and 30% for the 18, 19.5, and 22 SEER equipment, respectively. Compared to the current utility program level of 15 SEER, VC equipment of 18, 19.5, and 22 SEER demonstrated potential energy savings of 7%, 22%, and 26% respectively for California Climate Zone 10. The VC-to-baseline comparisons demonstrated increasing energy savings with increasing SEER, as well as a potential efficiency enhancement for utility programs. The 18, 19.5, and 22 SEER VC equipment consisted of 11, 13, and 15.5 EER respectively. At 105°F outdoor temperature, the 13 and 15.5 EER VC equipment decrease power demand by approximately 5%, and 10% respectively over a baseline 12.2 EER air conditioner. In contrast, the 11 EER VC unit had a 10% increase in power demand over a baseline 12.2 EER air conditioner at 105°F outdoor temperature.

In the field, VC equipment was installed with SEERs of 20, 17.5, and 21 at three occupied residences within California Climate Zone 10; the field-selected VC equipment were similar to the lab-selected equipment, but were larger in capacity, sized to the needs of each field site. The 20 SEER system was oversized for the monitored cooling season and predominately operated at the unit's minimum cooling level. Based on the laboratory data for each of the three selected VC systems and each field site's operational characteristics, an expected seasonal cooling efficiency was determined for each field site. For both units appropriately sized for their field sites, the expected seasonal cooling efficiency compared well to the measured seasonal cooling efficiency based on field data. The baseline air conditioning equipment previously installed was estimated to be 12, 11, and 10 SEER for Sites 1, 2, and 3, respectively. This VC retrofit was accompanied by enhanced quality installation practices that improved field conditions: the duct leakage, external static

pressure, and duct insulation. Based on utility billing data and field monitoring data, the VC equipment and quality installation retrofit resulted in cooling season energy savings of approximately 30%, 18%, and 30% for the 20, 17.5, and 21 SEER equipment, respectively.

Field monitoring also included a light investigation of sensible duct losses with variable airflow in VC equipment. At one of the VC field sites that contained supply ductwork in the attic, 4 supply air temperature sensors were placed in 10-foot increments along the primary supply air duct of the distribution system. The estimated sensible duct loss along the supply duct was determined by assessing the difference between the supply air temperature reading at the unit outlet and the sensor located approximately 30 feet down the supply duct. Over the range of recorded outdoor conditions, the estimated sensible duct loss approximately doubled from high airflow to low airflow. For example at an outdoor temperature of 95°F, the measured sensible duct loss at the site was approximately 12% for maximum airflow and approximately 21% for minimum output.

To consider VC equipment as a resource for utility DR programs, the project team examined DR unit setup and DR operation of selected VC equipment in laboratory and field evaluations. DR operation consisted of OFF-cycle controls. VC system 2 claimed to have OFF-cycle and low stage capacity modulation controls. To enable DR operation, the VC equipment in this investigation required manual adjustments of dry-contacts in the outdoor units. VC systems 2 and 3 also required further adjustment of controls/thermostat settings in combination with dry-contact adjustment to enable DR operation. None of the equipment investigated was readily able to receive and act upon utility DR event signals.

During the laboratory evaluation, it was discovered that the low stage DR capacity modulation controls of VC system 2 were not functioning. The manufacturer identified that a software update would have to be developed, and the issue was not resolved at the time of the investigation. During several DR tests of the VC equipment, the indoor blower continued to operate during the active DR time frame. In a field situation, continued operation of the indoor blower may circulate warm air throughout the air.

Continued investigation into certain aspects of residential VC space conditioning could better define and quantify their potential performance for California residences and utility programs. Ongoing industry research is further investigating the impact of duct losses for VC systems. Integrating the expected duct performance of a variable speed blower would assist in quantifying the overall VC HVAC system performance with respect to a baseline system. Also, utility billing data was used to quantify the energy usage of the baseline field equipment in this study. Simple utility billing data is limited in the information provided, and a more robust baseline-to-VC monitoring package could potentially provide better quantification of energy savings with VC equipment.

ABBREVIATIONS AND ACRONYMS

AC	Air Conditioner
ACCA	Air Conditioning Contractors of America
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
DR	Demand Response
ECM	Electronically Commutated Motor
EER	Energy Efficiency Ratio
ESP	External Static Pressure
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilation, and Air Conditioning
MERV	Minimum Efficiency Reporting Value
QI	Quality Installation
RH	Relative Humidity
SEER	Seasonal Energy Efficiency Ratio
TMY	Typical Meteorological Year
VC	Variable Capacity
VCS	Variable Capacity System
VCAC	Variable Capacity Air Conditioner
VS	Variable Speed
WC	Water Column

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FIGURES

TABLES

INTRODUCTION

In recent years, variable capacity (VC) technology has been implemented into common U.S. configurations of heating, ventilation, and air conditioning (HVAC) equipment. VC refers to the ability to modulate a system's cooling or heating output in response to the actual loads of the conditioned space. An HVAC system typically achieves VC by incorporating a variable speed (VS) compressor and indoor blower into the design, as well as a control system to allow for intelligent modulation of the unit's cooling or heating output in response to thermal loads and user input. In residential space conditioning, VC technology has been incorporated into central or ducted split HVAC equipment. In general, residential VC systems offer the highest rated efficiency of a given manufacturer's product offering.

Understanding the performance of residential VC systems is key for utilities that aim to utilize these systems as energy efficiency or demand response (DR) resources. To this end, this research study investigated a range of residential VC air conditioners (ACs) for California's climate and applications by conducting a technical survey of available equipment, a laboratory assessment under realistic operating conditions, and a field study which recorded VC equipment operation over an entire cooling season. The study also included a laboratory and field demand response (DR) assessment on the selected VC systems.

In this study, the technical survey explored the HVAC market for available products and held discussions with HVAC manufacturers that produce residential VC equipment. Based on survey findings and lab capabilities, the team selected three 2-ton VC systems for inclusion in the laboratory testing: an 18 seasonal energy efficiency ratio (SEER) five-speed system, a 19.5 SEER fully VC system, and a 22 SEER fully VC system. In the field evaluation, the three VC air conditioners with SEERs of 20, 17.5, and 21 were installed at occupied residences within California's Climate Zone 10, located in central southern California, and monitored under normal operating conditions for an entire cooling season. The field-selected VC equipment were similar to the lab-selected equipment, but were larger in capacity, sized to the needs of each field site. In both the laboratory and field evaluation, comparisons were made to baseline equipment.

The results of this research study demonstrate the efficiency and performance of residential VC air conditioners of varying design and SEER. The laboratory findings may be utilized to determine a VC system's equipment efficiency for a given California application. The field results demonstrate three different applications with residential VC equipment and provide an investigation of the equipment performance and of system effects at the selected sites.

BACKGROUND

VARIABLE CAPACITY TECHNOLOGY

Variable capacity refers to the ability of a space conditioning system to modulate cooling or heating output in response to the thermal loads of the conditioned space and user input of the occupants. VC equipment is typically offers highest or near the highest rated efficiency for any HVAC configuration. VC systems are produced for residential ducted split equipment by the majority of leading U.S. HVAC manufacturers. This study explored the performance and efficiency of multiple VC systems applicable for the California residential market.

CURRENT UTILITY PROGRAMS

Utilities offer energy efficiency and DR programs for residential space conditioning as a resource for managing the load of the electrical grid. Southern California Edison (SCE) offers a residential space conditioning program that provides a fixed incentive to customers who install a packaged or split air conditioner with a SEER of 15 or higher [3] and a DR air conditioner program that provides two options (see Table 1) and various incentive levels. The DR program also offers the ability to override a limited number of DR events.

TABLE 1. SUMMARY OF SCE DR PROGRAM

OPTION	DESCRIPTION OF DR EVENT
1	AC may be shut off for up to 6 hours a day
2	AC may be shut off for 15 minutes each half hour for up to 6 hours a day

CALIFORNIA RESIDENTIAL SPACE CONDITIONING

Utilizing the Residential Energy Consumption Survey [1] and the Residential Appliance Saturation Study [2], the project team investigated space cooling for residences within the SCE service area. Figure 1 provides a breakdown of the type of space cooling equipment at different types of residences throughout the SCE area [2]. As shown, central AC equipment is the largest single type of space cooling equipment utilized for each type of residence. In single-family homes, central space cooling equipment is utilized in more than 50% of the residences in SCE territory, while central space cooling is near 40% in other residential structures. Notably, many area residences lack space cooling equipment.

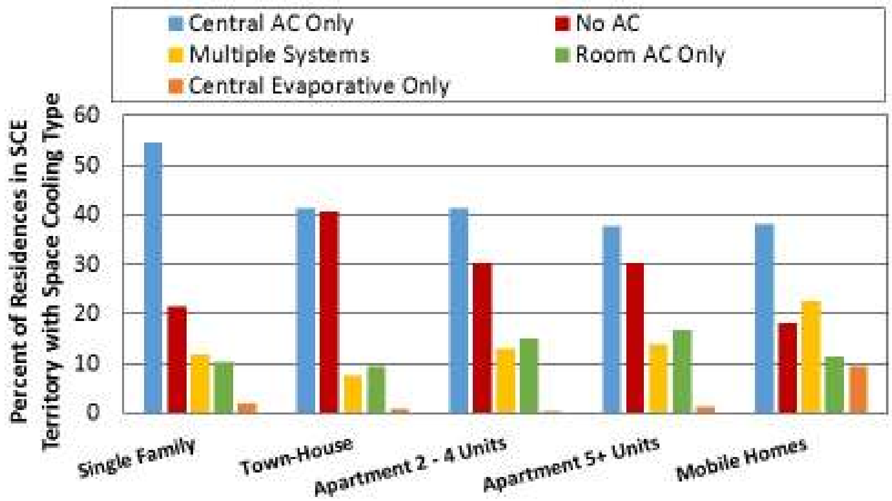

FIGURE 1. BREAKDOWN OF SPACE COOLING EQUIPMENT TYPE FOR SCE TERRITORY [2]

Research shows that California Climate Zone 10 in the SCE service area is a primary region utilizing space cooling, with about 1,300 to 1,900 annual cooling degree days.

Utilizing the Residential Energy Consumption Survey dataset, the team determined the following total home and space cooling energy usage for single-family residences in climates comparable to California Climate Zone 10 [1]:

- Total home average annual electricity consumption of 10,241 kilowatt-hours (kWh)
- Annual space cooling electric consumption of 1,736 kWh, or 17% of total consumption
- Average area of space cooled of 1,589 ft²
- Electricity consumption for space cooling of 1.1 kWh per square foot of space cooled [1].

This information helped the team select residential equipment and field sites for the investigation of VC air conditioning that were comparable to typical space cooling applications in the SCE territory.

EFFICIENCY OF RESIDENTIAL AIR CONDITIONING EQUIPMENT

Over the past few decades, the federal government has mandated specific levels of efficiency in space conditioning equipment. Table 2 provides the past three federal minimum efficiency requirements for residential split air conditioning equipment. In 2015, the federal government required a SEER of 14 for residential air conditioners installed in the south and southwest United States, including in California. Also for California, a rated energy efficiency ratio (EER) requirement of 12.2 was imposed for air conditioners with rated capacity under 45,000 Btu/h. Air conditioners in the field are assumed to be near the federal minimum efficiency at the time of installation. For instance, air conditioners installed between 2006 and 2015 are commonly 13 SEER, while air conditioners installed 15 to 20 years ago may be near 12 or 11 SEER.

TABLE 2. HISTORY OF FEDERAL AC REQUIREMENTS

ADOPTION YEAR	FEDERAL MINIMUM SEER FOR AIR CONDITIONERS	TERRITORY COVERED
1992	10	Entire U.S.
2006	13	Entire U.S.
2015	15	South and southwest U.S.

OBJECTIVES

The project team identified two high-level objectives for this project, along with research questions and a plan to address the research questions for each objective, as outlined below:

The first objective is to determine if SCE's current Residential HVAC Program may be enhanced with VC equipment.

- **Research question:** What is the expected performance (energy savings, power demand reduction) of variable capacity equipment in SCE territory?
- **Plan:**
    - Develop laboratory data to provide a detailed performance map for each VC system that allows for an equipment efficiency comparison to a baseline system (e.g., a 14 SEER air conditioner).
    - Select field sites at actual residences in the SCE territory to provide multiple demonstrations of the VC equipment efficiency and quality installation- (QI)-based system improvements (potential improvements in duct leakage and external static pressure). Based on pre- and post-installation QI data, estimate system-efficiency only and equipment-efficiency only.
    - Assess field data to provide operational characteristics of VC equipment, exploring such areas as the following:
        - How do the systems operate (minimum, intermediate, and maximum) during their operation and as a function of outdoor air and indoor air?
        - Is the VC system properly sized? Does the system operate near maximum output at the designed outdoor temperature condition?
        - What is the power profile of the VC equipment for a typical day?
- **Research Question:** How do efficiency metrics (SEER, EER) of the VC equipment compare to or track with actual performance in SCE territory?
- **Plan:**
    - Develop laboratory data to provide VC performance at conditions representative of SCE climate, outside of the SEER test matrix. Test three VC systems in the laboratory with differing SEER values. How does the actual system performance and efficiency change with increasing SEER?
- **Research Question:** What are additional insights or recommendations for a potential VC equipment program?
- **Plan:**
    - Conduct a field test to investigate thermal losses with VS blowers.
    - Document and potentially investigate insights or recommendations as discovered throughout the laboratory and field evaluation process.

The second objective is to determine how VC equipment may be incorporated with SCE's current Residential HVAC DR Program.

- **Research Question:** What steps are necessary to activate DR operation in VC equipment?
- **Plan:** Gain understanding of DR operation of VC equipment in lab and field.
- **Research Question:** How do VC systems operate during and after DR modes of operation?
- **Plan:** Demonstrate DR operation of VC equipment in both lab and field settings.

APPROACH

This research study included a technical survey, a laboratory assessment, and a field evaluation of residential VC equipment. The following sections provide details on these activities.

SURVEY

This section provides a survey—developed through discussions with manufacturers and a review of product literature—of the currently available residential VC space conditioning systems. The survey focused on systems built in the American style, ducted split configuration. At the conclusion of the survey, the project team selected three products for the laboratory and field evaluations for the project. Two manufacturer surveys were conducted and included as part of the overall technical survey (see Appendix A for informal notes). Based on survey findings and lab capabilities, the team selected three 2-ton VC systems for inclusion in the laboratory testing. The field-selected VC equipment were similar to the lab-selected equipment, but were larger in capacity, sized to the needs of each field site.

CHARACTERISTICS OF AVAILABLE VC SYSTEMS

The project team identified and compared available residential VC ducted split products and made the observations summarized below.

MARKET OVERVIEW

The majority of the major U.S. HVAC manufacturers are producing VC ducted split systems in both air conditioner–only and heat pump models and in standard residential sizes from 2–5 tons. Some manufacturers with multiple HVAC brands are releasing similar products under different brand names. VC products fall largely within one of two design categories: high end, higher efficiency product and cost-competitive product. For a given manufacturer, the SEER is the most noticeable feature for distinguishing between the two categories. When considering a manufacturer with only one available VC product or comparing products between manufacturers, it can be more difficult to determine a product’s category.

EFFICIENCY RATINGS

The nominal efficiency of the available VC products ranges from 18–24.5 SEER and 10–13 heating seasonal performance factor (HSPF). The nominal cooling efficiency typically decreases slightly in heat pump models for manufacturers that produce both air conditioner and heat pump equipment. Manufacturer discussions revealed that adding VC technology to a system significantly increases SEER but has little effect on EER (a system design efficiency based on the nominal efficiency of the components used in a system). EER values vary within the available VC products; the typical EER for an available VC product is 11–15.

Capacity Control

The majority of the VC products reviewed contain inverter-driven compressors and are able to achieve a broad array of capacity values that range from approximately 40% to 100% of nominal output. One manufacturer's VC product type contains a five-stage compressor, which allows for a similar capacity range (~40–100%) with decreased incremental steps. The capacity control for a given VC system may vary depending upon the outdoor temperature, mode of operation, and thermal load on the system. Most VC products are designed to match the load of the conditioned space, and the control strategy may involve elapsed time and learning ability.

Demand Response

VC manufacturers emphasized that VC equipment is a flexible technology that could respond in many ways to a DR signal. However, at the time of this investigation, DR options were limited due to the lack of specific industry-established protocols for DR operation of VC equipment. DR operation is typically limited to OFF-cycle controls. One of the VC products investigated claimed to have OFF-cycle and low capacity modulation controls.

To enable DR operation, the VC equipment in this investigation required manual adjustments of dry-contacts in the outdoor units. Some equipment also required further adjustment of controls/thermostat settings in combination with dry-contact adjustment to enable DR operation. None of the equipment investigated was readily able to receive and act upon utility DR event signals.

Unit Controller

All of the available VC products must be operated with a specific unit controller designed for the VC equipment. Manufacturers prefer use of a proprietary controller, because such a controller ensures that the system operates appropriately under a specific condition. Most VC unit controllers offer high end features, such as setpoint programming, connectivity, and detailed modes of operation (e.g., comfort vs. efficiency mode).

Indoor Unit Compatibility

A manufacturer may be able to couple numerous indoor units—either fan coils (air conditioner or heat pump) or a combined fan coil and gas furnace system—to the VC system. The size of an indoor unit matched to a particular size outdoor unit may be variable. Typically, an oversized indoor unit may provide higher efficiency and decreased dehumidification, which may be advantageous for hot, dry climates. Indoor units compatible with VC outdoor units are typically variable speed, rather than multi-speed.

Humidity Control

Most VC products have humidity control options within the system. Humidity control may include a humidity setpoint, overcool options, and specific dehumidification modes of operation. A unit's response to an increase in humidity will vary the performance of the unit. VC products can be configured (matching of an indoor and outdoor unit size) to provide an increased level of dehumidification in standard operation.

APPLICABILITY

Most of the VC products are suitable for either retrofit or new construction applications. The current standard refrigerant used in residential VC products is R410a. The refrigerant piping size for the available VC products is typically similar that for comparable fixed-speed equipment.

POWER QUALITY

In discussion, manufacturers noted that power factor correction is often implemented into the design of the VC equipment. Split VC equipment typically contains a variable-frequency drive to modulate the operation of the compressor, which could lead to electrical grid issues if not considered in the design of the VC equipment.

LABORATORY TEST PLAN

This section details the laboratory testing strategy of the selected VC split systems for the efficiency and DR assessments: an 18 SEER system five-speed system, a 19.5 SEER fully VC system, and a 22 SEER fully VC system.

Testing was conducted according to a modified psychrometric method based on the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) 210/240 rating method for unitary air conditioners and heat pumps. However, the laboratory tests examined a more extensive range of conditions than that required by the 210/240 standard. The team developed a laboratory performance map for each system to assist in the efficiency evaluation of VC products and documented each unit's DR functionality to demonstrate its DR capabilities.

EXPERIMENTAL SETUP

The three VC systems were laboratory tested in cooling operation in steady-state operation at specified air conditions. Performance maps were constructed based on measured performance. DR testing was also conducted for the VC units.

The experimental setup consisted of a thermal chamber that served as the simulated outdoor air and an indoor ducted setup. According to Proctor et al, external static pressures of ducted split equipment in the field are near 0.5 inch water column (WC) [4]. In contrast, AHRI 210/240 imposes a minimal external static pressure on the indoor fan coil of 0.1 inch WC for nominal two ton equipment [5]. Within the experimental setup, laboratory conditions were selected based on documented field studies or field design conditions, as opposed to utilizing standard AHRI 210/240 conditions.

The relationship between airflow and duct resistance (or external static pressure) is based on fan laws. The following equation represents the relationship of airflow and duct resistance along a system curve based on a known airflow and external static pressure [6].

$$R = P\left(\frac{cfm^{A}}{cfm^{B}}\right)^{2}$$

R = Duct resistance (inch water column) at airflow of test unit
P = External static pressure at known point
cfmA = Airflow at known point
cfmB = Airflow as adjusted by test unit

In the experimental setup, the airflow of the test unit was adjusted by the unit's control strategy or set parameters. Based on the test unit's nominal size of 2 tons and field design external static pressures, the known airflow and external static pressure for the experimental setup's system curve was selected to be 750 cfm and 0.5 inch WC. During the laboratory testing as the test unit modulated airflow, external static pressure was adjusted accordingly to fit the system curve for these known values.

Figure 2 illustrates the laboratory setup for the selected ducted VC systems. The numerical indicators shown represent the location of the instrumentation used within the laboratory setup and correspond with the instrumentation description provided in Table 3.

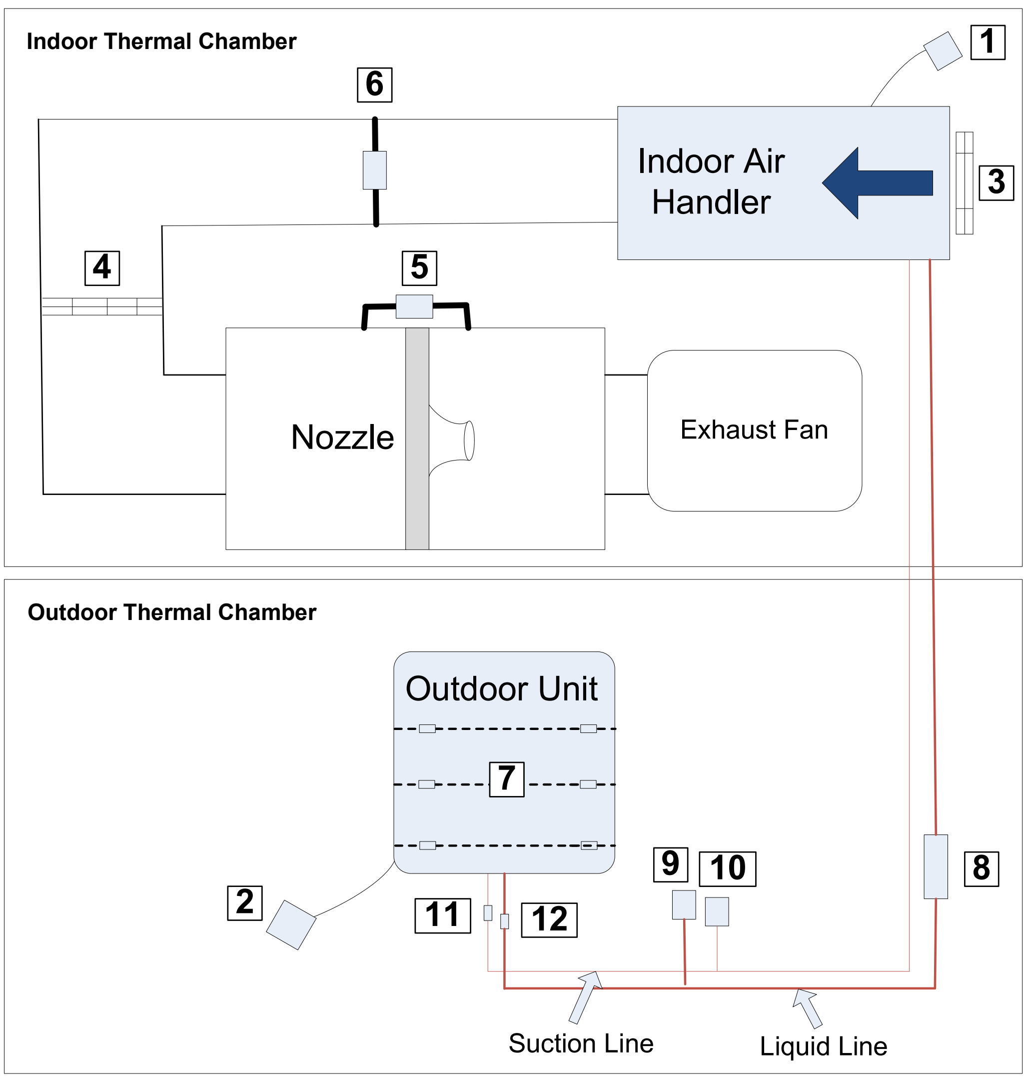

FIGURE 2. SCHEMATIC OF LABORATORY TEST SET-UP

Table 3 lists the laboratory measurements and corresponding instrumentation used in the test setup. Recorded measurements included supply air temperature and humidity, return air temperature and humidity, outdoor air temperature and humidity, indoor unit airflow, refrigerant line temperature and pressure, refrigerant mass flow, and unit power consumption. The accuracy of the instrumentation used is comparable to industry standards.

TABLE 3. INSTRUMENTATION DESCRIPTION OF EXPERIMENTAL SET-UP

LOCATION	MEASUREMENT(S)	INSTRUMENTATION (ACCURACY)
1	Indoor Unit Power	Shark Meter 200T (±0.2%)
2	Outdoor Unit Power	Shark Meter 200T (±0.2%)
3	Return Air Temperature	9 Point Omega T-Type Thermocouple Grid (±0.5°C)
3	Return Air Humidity	GE Chilled Mirror Hygrometer (±0.2°C dewpoint)
4	Supply Air Temperature	9 Point Omega T-Type Thermocouple Grid (±0.5°C)
4	Supply Air Humidity	GE Chilled Mirror Hygrometer (±0.2°C dewpoint)
5	Pressure Drop Across Nozzle	Dwyer Series 2000 (±2%)
6	Indoor External Static Pressure	Dwyer Series 2000 (±2%)
7	Outdoor Air Temperature	10 Point Omega T-Type Thermocouple Grid (±0.5°C)
		1 Point Vaisala HMT333 (±0.2°C)
8	Refrigerant Mass Flow	MicroMotion Coriolis (±0.1% Liquid; ±0.35% Gas)
9	Liquid Line Pressure	Setra 207 Pressure Transducer (±0.13%)
10	Suction Line Pressure	Setra 207 Pressure Transducer (±0.13%)
11	Suction Line Temperature	Omega T-Type Thermocouple (±0.5°C)
12	Liquid Line Temperature	Omega T-Type Thermocouple (±0.5°C)

The laboratory measurements allowed for both an air-side and refrigerant-side capacity and system efficiency calculation. Cooling capacity and efficiency (presented as the EER) were calculated based on the following equations:

$$Capacity\ (Air)\left(\frac{Btu}{h}\right) = Air\ Mass\ Flow\left(\frac{lbm}{h}\right) x\ (Return\ Air\ Enthaply - Supply\ Air\ Enthalpy)\ (\frac{Btu}{lbm})$$

$$Capacity\ (Ref.)\left(\frac{Btu}{h}\right) = Ref. Mass\ Flow\left(\frac{lbm}{h}\right) x\ (Enthalpy\ Difference\ across\ Evaporator)\ (\frac{Btu}{lbm})$$

$$Energy\ Efficiency\ Ratio\left(\frac{Btu}{Wh}\right) = \frac{Cooling\ Capacity\ (\frac{Btu}{h})}{Total\ Power\ Consumption\ (W)}$$

The testing monitored the outdoor air temperature distribution around the outdoor coil at the return air inlet and at the supply air exit. For the outdoor coil, a 10-point thermocouple grid surrounded the unit. Within the return and supply ductwork, the instrumentation for temperature and humidity measurement consisted of a 9-point thermocouple grid for dry-bulb measurement and a 9-point air sample that connected to a chilled mirror hygrometer for dewpoint measurement. Figure 3 illustrates the instrumentation within the supply and return air of the experimental setup.

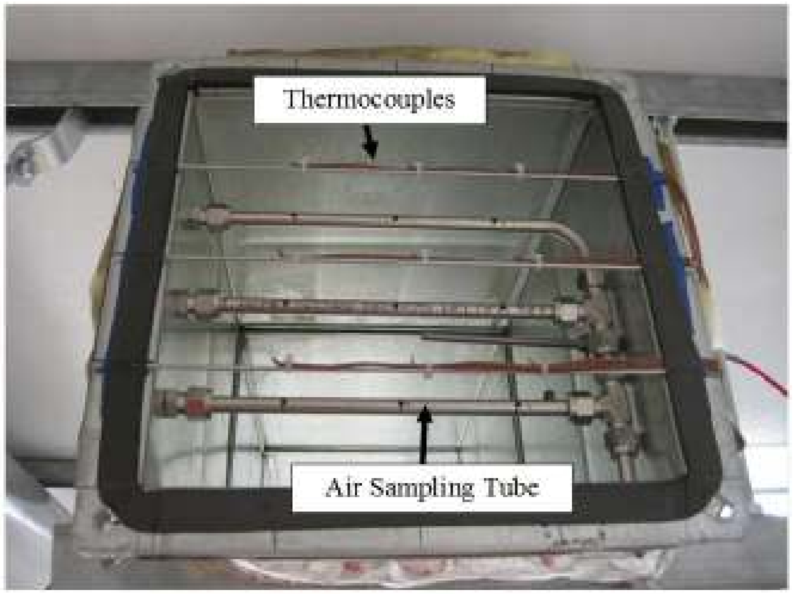

FIGURE 3. INSTRUMENTATION FOR THE SUPPLY AND RETURN AIR MEASUREMENT

LABORATORY-TESTED EQUIPMENT

Table 4 provides details of the three VC systems evaluated in the laboratory tests. The rated EER of the tested VC systems increased with the SEER of the equipment. Each of the VC units was a nominal 2-ton system. The selected VC systems were produced by three different HVAC manufacturers.

TABLE 4. DETAILS OF THE 3 VC SYSTEMS EVALUATED IN THE LABORATORY

VC SYSTEM IDENTIFIER	PRODUCT DESCRIPTION	SEER (BTU/WH)	EER (BTU/WH)	NOMINAL SIZE (TONS)
1	Fully Variable	22.0	15.5	2
2	Five Speed	18.0	11.0	2
3	Fully Variable	19.5	13.0	2

METHOD OF TEST

EFFICIENCY ASSESSMENT

The steady-state laboratory test plan consisted of a primary test matrix, representative of the California climate, and a test point for comparison to AHRI 210/240. The primary test matrix consisted of one indoor temperature, six outdoor temperatures, and three levels of operation, as summarized in Table 5.

The testing used the indoor design conditions of 75°F dry bulb and 63°F wet bulb, as set by Air Conditioning Contractors of America (ACCA) Manual J: Residential Load Calculation [7], rather than the 80°F dry bulb and 67°F wet bulb conditions set by AHRI 210/240 [2,4].The outdoor temperature range encompassed the Southern California climate. Each of the selected VC systems can operate at maximum and minimum operation and potentially at an intermediate level of operation through the standard unit controller.

The manufacturer of each VC system was consulted to ensure the test plan offered an acceptable method of assessing the performance of the equipment.

TABLE 5. STEADY-STATE EFFICIENCY TEST MATRIX

VARIABLE	PRIMARY TEST MATRIX	TEST POINT FOR COMPARISON TO AHRI 210/240
Indoor Conditions (dry bulb/wet bulb) (°F)	75/63	80/67
Outdoor Temperature (°F)	65, 75, 85, 95, 105, 115	95
System Operating Level	Maximum Output Intermediate Output Minimum Output	Maximum Output

DR ASSESSMENT

The laboratory DR assessment called for several steps:

- Document the mechanism for activating DR in the test unit
- Document the DR functionality of the unit
- Demonstrate the DR operation of the test unit
- Determine potential power reduction of equipment in DR operation
- Determine the response time of the unit to reduce power upon DR activation
- Determine the response time of the unit to regain cooling output after DR event

Based on the survey of VC systems, two responses to a DR signal are currently available: cycle OFF or operate at the minimum level of unit operation. The DR test matrix consisted of activating these two DR strategies at one indoor condition and the three outdoor temperature conditions. A summary of the DR test matrix is provided in Table 6.

TABLE 6. DR TEST MATRIX

VARIABLE	TEST MATRIX
Indoor Conditions (dry bulb/wet bulb) (°F)	75/63

Outdoor Temperature (°F)	95, 105, 115
DR Response	• Cycle OFF • Operate at Minimum Level of Operation

The test protocol for the DR lab assessment was as follows:

- Operate the unit at maximum output under the described indoor and outdoor conditions
- Allow unit to achieve and operate at steady-state conditions between 10 and 30 minutes
- Activate a selected DR mode for the unit for a period of 10 to 30 minutes
- Measure the response time of the unit to achieve power reduction
- Deactivate the DR mode for the unit
- Measure the response time of the unit to regain cooling output
- Assess the power reduction capabilities of the DR mode

Experimental Procedures

For steady-state efficiency testing, measurement tolerances assisted in determining the validity of a given test, similar to AHRI 210/240. The tolerances for the laboratory measurements are summarized in Table 7. For the steady-state evaluation, an acceptable laboratory test consists of steady-state operation for approximately 30 minutes within the specified tolerances. An operating tolerance refers to the maximum range that a metric can modulate over the test period, while the condition tolerance refers to the average deviation of the metric from the intended test point.

Table 7. Steady-state Laboratory Testing Tolerances

Measurement	Operating Tolerance	Condition Tolerance
Return/Supply Dry Bulb Temperature	2°F	0.5°F
Return/Supply Dew Point Temperature	2°F	1°F
Outdoor Dry Bulb Temperature	2°F	0.5°F

Field Test Plan

The project team conducted field monitoring of VC systems at residences within the Southern California Edison service area. This section describes the field test plan, covering field site selection criteria and the monitoring plan. This section also describes the field sites, the strategy for field monitoring, measurements and instrumentation at the field sites, and the instrumentation layout.

FIELD SITE SELECTION CRITERIA

Table 8 shows the **required** and **desired** criteria for residential field site selection and for each, a measure that further defines and indicates how the criterion will be satisfied. See Appendix B for details on the field site surveys.

TABLE 8. FIELD SITE SECTION CRITERIA AND MEASURES

CRITERION FOR SITES AND OCCUPANTS	MEASURE FOR SATISFYING CRITERION
REQUIRED CRITERIA	
Site is representative of the housing stock within SCE territory in size and age.	Size should be similar to the average size of a California housing unit, approximately 1,600 ft^2 [4], and be within the age of the majority of the existing housing in California, which was constructed between 1950 and 1989 [4]. Confirmation of site size and age.
Site is detached single family housing.	Approximately 58% of the California housing is detached single family [1]. Confirmation obtained during site visit.
Residence contains single HVAC zone.	Single-story homes are commonly single-HVAC zone houses. Confirmation obtained during site visit.
Homeowner intends to remain at the site throughout data collection (1+ year).	Confirmation from homeowner obtained during site visit.
Site occupancy uniform throughout data collection.	Confirmation from homeowner obtained during site visit.
Site has adequate cellular connection.	Cellular connection confirmed through website of selected carrier.
Homeowner can allow access to site during working hours.	Confirmation from homeowner obtained during site visit.
Homeowner willing to participate in simulated DR events.	Confirmation from homeowner obtained during site visit.
Baseline HVAC unit operational during year prior to installation of VC equipment.	Confirmation obtained from homeowner and through inspection performed by the installing HVAC contractor.
DESIRED CRITERIA	
Occupants remain on same rate plan throughout the data collection.	Confirmation obtained from utility
Minor modifications made to HVAC infrastructure from baseline to VC equipment.	Confirmation obtained through contractor's site survey.

DESCRIPTION OF SELECTED FIELD SITES

The selected residential field sites contained the infrastructure for a split forced air system. The baseline and VC equipment for the field sites were air conditioners with gas heat. All sites were located in the California Climate Zone 10. Table 9 provides further description of the field sites, which provide variation in construction year, home size, and location.

TABLE 9. FIELD SITE DESCRIPTIONS

FIELD SITE IDENTIFIER	LOCATION	EQUIPMENT TYPE	APPROXIMATE CONSTRUCTION DATE	APPROXIMATE SIZE (FT^2)
Site 1	Redlands, CA	Air Conditioner with Gas Heat	1967	1,730
Site 2	Mentone, CA		1989	1,484
Site 3	Yucaipa, CA		1960	1,598

For each site, the project team conducted a residential load calculation (ACCA Manual J). See Table 10 for the nominal size of the air conditioning equipment selected based on the load calculation. At each site, the baseline and VC equipment was identical in nominal size.

A different VC product was selected for each of the three field sites. Each VC product selected for the field evaluation was also examined in the laboratory assessment.

TABLE 10. NOMINAL SIZE OF THE AIR CONDITIONING EQUIPMENT SELECTED

FIELD SITE IDENTIFIER	AIR CONDITIONER NOMINAL SIZE (TONS)	VC PRODUCT DESCRIPTION	VC SYSTEM IDENTIFIER
Site 1	4	Variable Speed, 20 SEER	VC System 1
Site 2	3	5 Speed, 17.5 SEER	VC System 2
Site 3	3	Variable Speed, 21 SEER	VC System 3

STRATEGY FOR FIELD EVALUATION

The two primary purposes of the field evaluation were to evaluate the energy efficiency and identify operational characteristics of the selected VC equipment. The evaluation of the VC equipment focused on the air conditioning equipment or cooling operation only. Each VC system and site was instrumented to monitor the operation of the unit over a cooling season for Southern California. Due to the project schedule, robust baseline monitoring of the site’s existing system was not conducted. Rather, historic energy consumption data for the baseline systems at the field sites was used to compare the energy consumption of the baseline equipment to that of the VC equipment.

Information collected through an SCE quality installation and laboratory testing data complemented the field data to completely characterize the operation and performance of the selected VC equipment. Each data source provided unique information regarding the performance or installation of the equipment. For example, the QI report formulated for each of the baseline and VC systems provided details of unit external static pressure, duct leakage, refrigerant charge, and unit performance under full-load operation, allowing for equipment-to-equipment comparison between the baseline and VC systems at the field sites.

MEASUREMENTS AND INSTRUMENTATION

Monitoring of the VC equipment over the cooling season measure the following:

- Power: Power, voltage, current, and power factor measurements.
- Temperature and humidity: The air temperature and humidity were taken at the unit return air, indoor unit supply air, outdoor air, attic air, and air locations within the inside of the home. Instrumentation was placed away from potential disturbances and such that surrounding air was well mixed and representative of the intended variable. Supply air temperature was measured at multiple locations (approximately 5 feet apart beginning from the outlet of the indoor unit) to investigate the thermal losses from the ductwork at varying airflows and attic temperatures.
- Refrigerant line temperature: This measurement helped ensure the valid operation of the VC equipment over the data collection period.

Table 11 lists the measurements and instrumentation at each field site. The field measurements were recorded with one-minute resolution. The location identifier for each measurement/instrumentation refers to the schematics in the Field Monitoring Layout section below.

TABLE 11. MEASUREMENTS AND INSTRUMENTATION AT EACH FIELD SITE

LOCATION IDENTIFIER	MEASUREMENTS	INSTRUMENTATION
1	Indoor Unit Power	Elkor 1100 (±0.2%)
	Outdoor Unit Power	
2	Return Air Temperature	Dwyer RHP-2D11 (±0.2°C; ±2% RH)
	Return Air Humidity	
3	Supply Air Temperature	Dwyer RHP-2D11 (±0.2°C; ±2% RH)
	Supply Air Humidity	
4	Outdoor Air Temperature	Dwyer RHP-2D11 (±0.2°C; ±2% RH)
	Outdoor Air Humidity	
5	Attic/Crawl Space Temperature	Dwyer RHT-R016 (±0.2°C; ±2% RH)
	Attic/Crawl Space Air Humidity	
6	Home Air (Central Location) Temperature	BAPI Stat 4 – Room (±0.2%°C; ±2% RH)
	Home Air (Central Location) Humidity	
7	Liquid Line Temperature	Omega Thermistor

8	Suction Line Temperature	(±0.2%°C)

FIELD MONITORING LAYOUT

The following schematics and photographs illustrate the monitoring layout of each of the field sites. The primary differences in the layouts are the locations of the indoor units and ductwork. The indoor units for two of the field sites (Sites 1 and 3) were inside an interior closet, while the indoor unit for the other field site (Site 2) was within the attic space. For Field Sites 1 and 2, the location of the supply and return ductwork was within the attic, while for Field Site 3 the supply ductwork was underneath the home, with one centrally located return within the conditioned space. Due to ductwork locations, Field Sites 1 and 2 contained an attic air measurement, while Field Site 3 contained a crawl space air measurement. The numerical indicators within the schematics refer to the instrumentation in within Table 11. Photographs for each of the field sites capture the instrumentation at the field site.

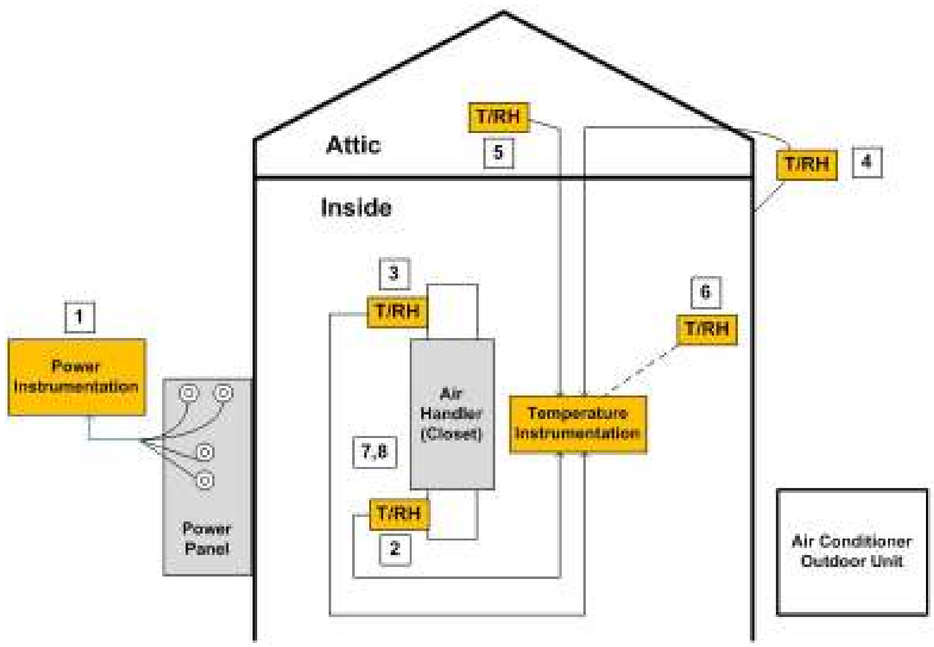

FIGURE 4. INSTRUMENTATION LAYOUT OF FIELD SITE 1

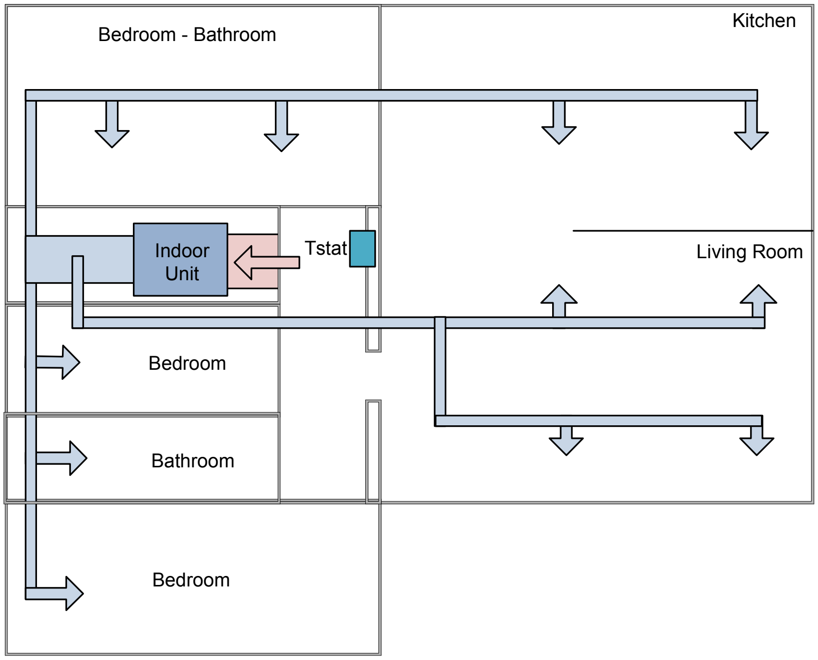

FIGURE 5. HOME LAYOUT AND DUCTWORK DISTRIBUTION OF FIELD SITE 1

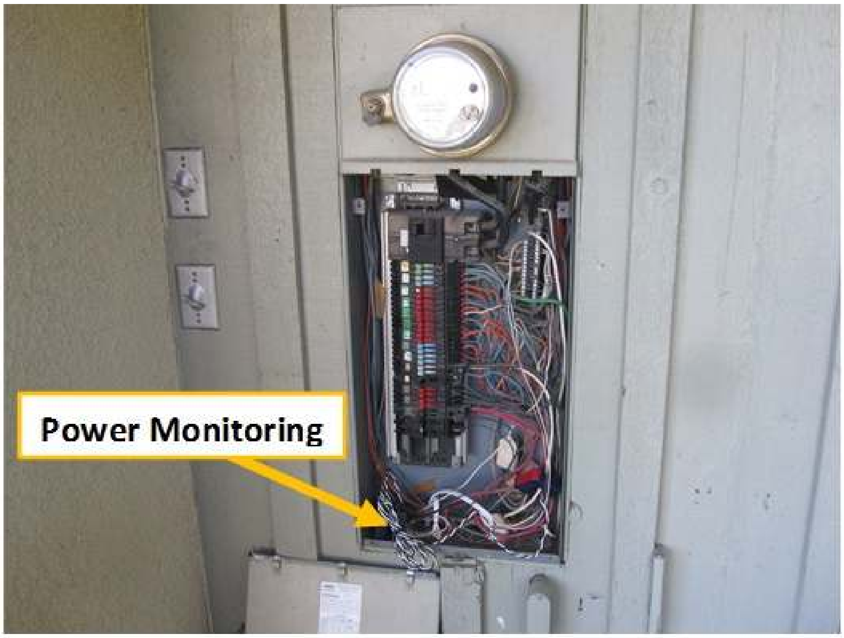

FIGURE 6. BREAKER PANEL AND POWER MONITORING AT FIELD SITE 1

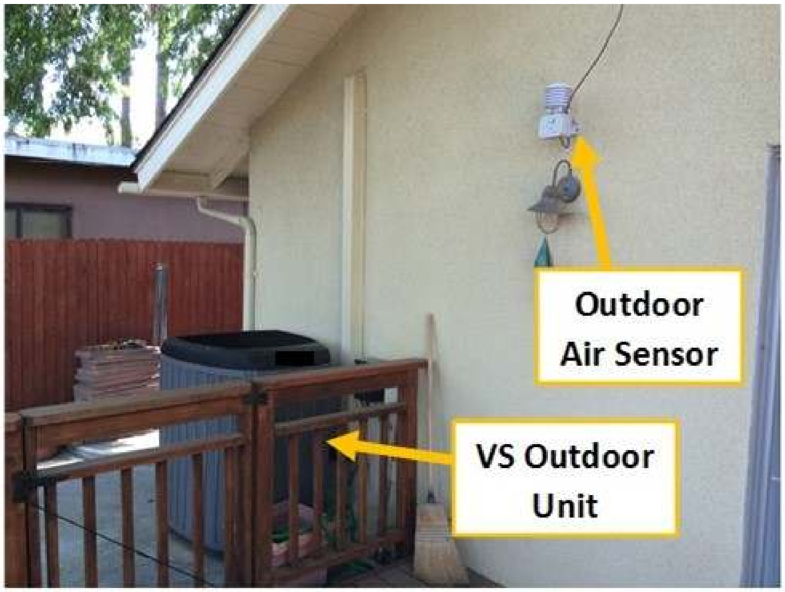

Figure 7. Outdoor Unit and Outdoor Temperature Sensor at Field Site 1

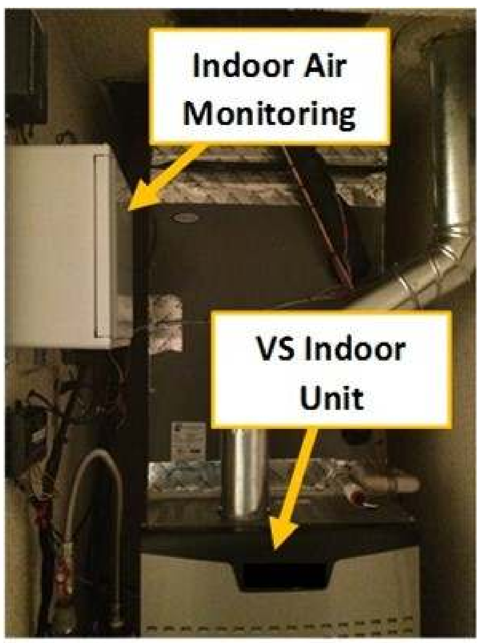

Figure 8. Indoor Unit and Indoor Air Monitoring at Field Site 1

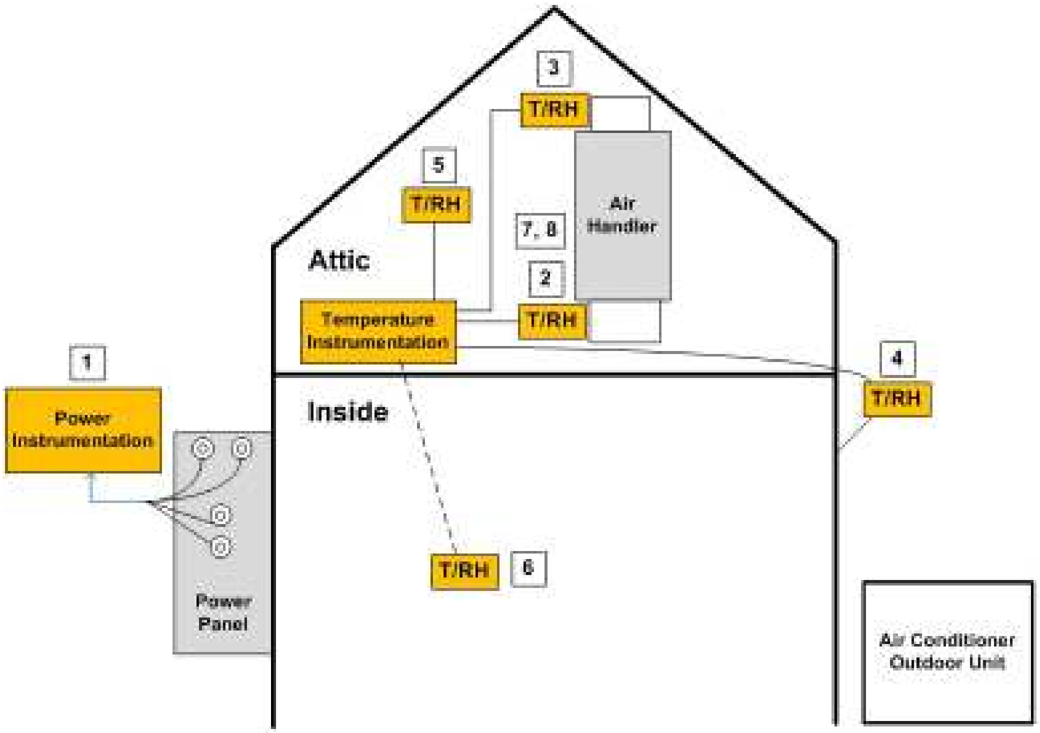

FIGURE 9. INSTRUMENTATION LAYOUT AT FIELD SITE 2

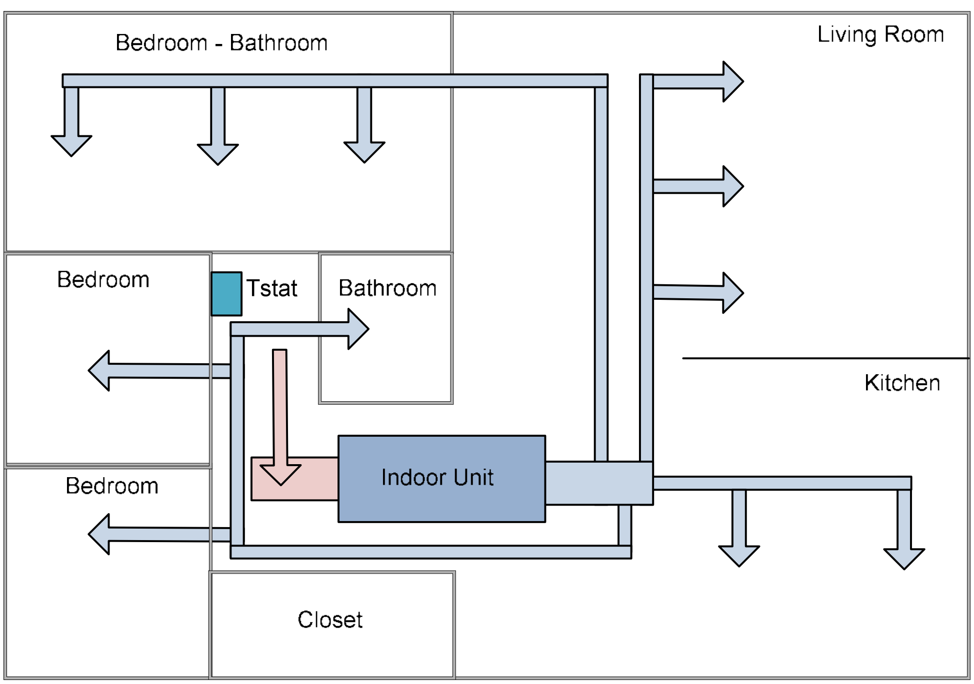

FIGURE 10. HOME LAYOUT AND DUCTWORK DISTRIBUTION OF FIELD SITE 2

FIGURE 11. POWER MONITORING AT FIELD SITE 2

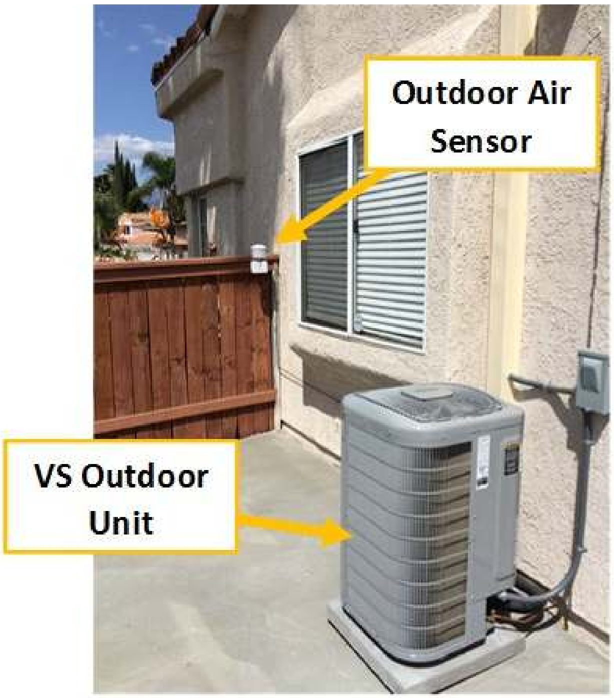

FIGURE 12. OUTDOOR UNIT AND OUTDOOR TEMPERATURE SENSOR AT FIELD SITE 2

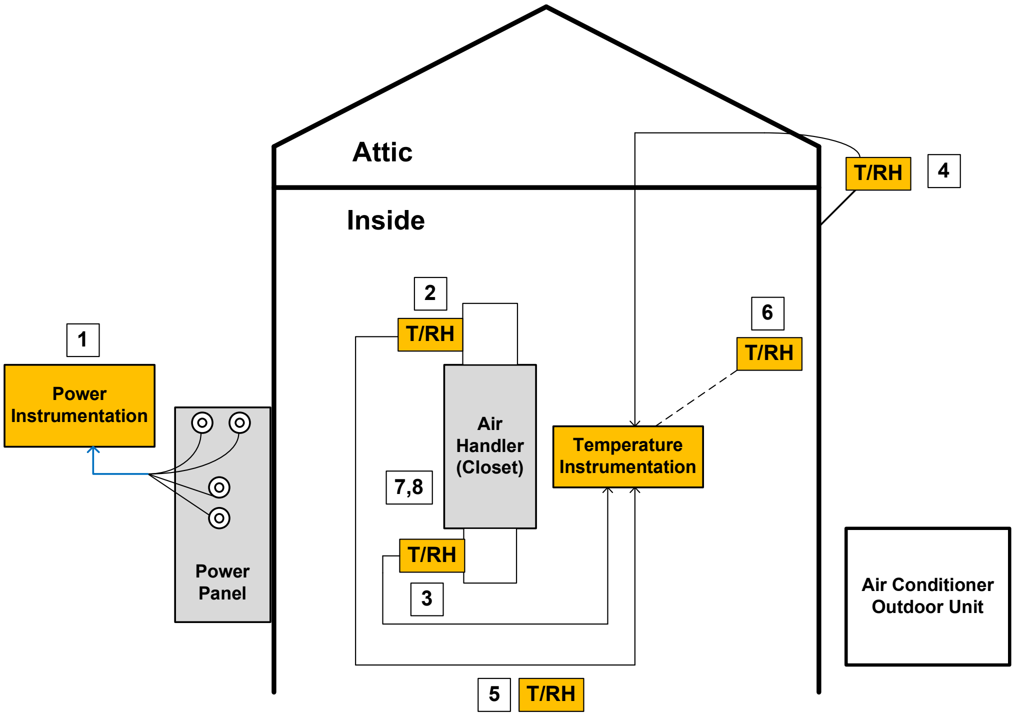

FIGURE 13. INSTRUMENTATION LAYOUT OF FIELD SITE 3

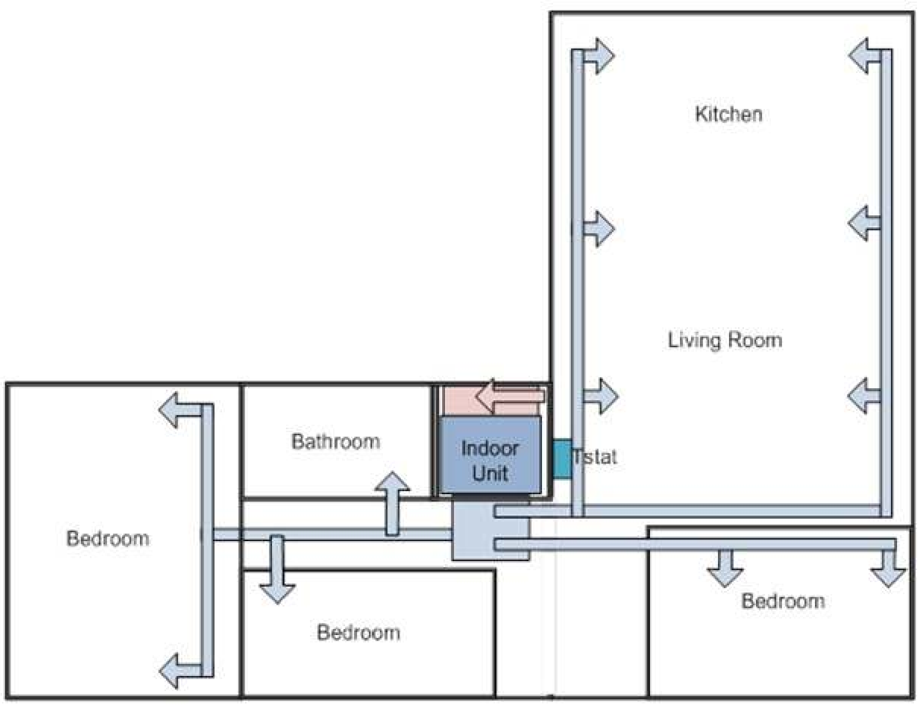

FIGURE 14. HOME LAYOUT AND DUCTWORK DISTRIBUTION OF FIELD SITE 3

FIGURE 15. BREAKER PANEL AND POWER MONITORING AT FIELD SITE 3

FIGURE 16. OUTDOOR UNIT AND OUTDOOR TEMPERATURE SENSOR AT FIELD SITE 3

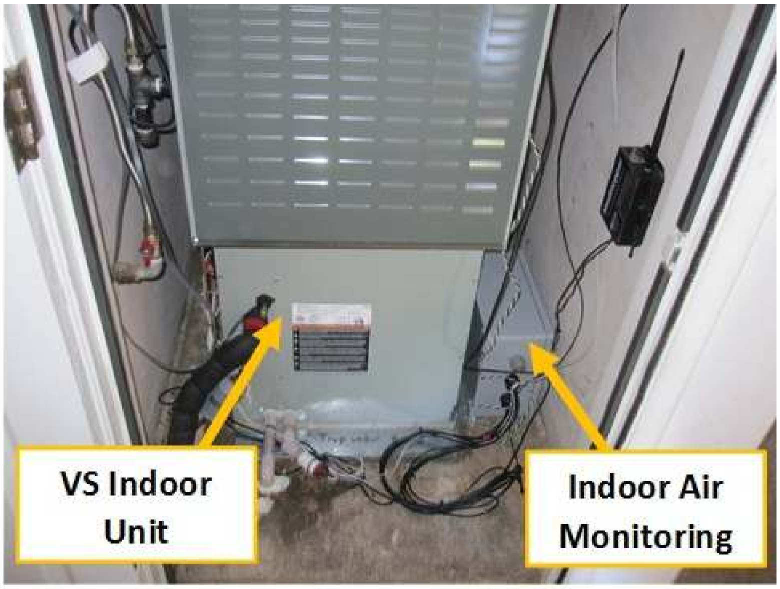

FIGURE 17. INDOOR UNIT AND INDOOR AIR MONITORING AT FIELD SITE 3

FIELD DR ASSESSMENT

The field DR assessment called for simulating an SCE DR event at each of the three VC field sites. SCE currently offers two residential DR programs: 100% cycling (continuously OFF during DR event) and 50% cycling (15 minutes OFF for each 30 minutes of DR event) [8]. The field DR assessment was intended to capture the indoor and outdoor conditions, unit operation, and equipment power consumption before, during, and after the DR event. As highlighted in the section on *Survey of Available Technologies*, one of the installed VC systems was designed to either cycle OFF or operate at minimum output when DR is activated. The other two systems are limited to cycling OFF in response to a DR signal.

The field DR assessment occurred on consecutive afternoons in early September 2015. For the locations of the three VC field sites, average daily high temperatures during early September are approximately 90°F.

The protocol for the field DR assessment at each site was set as follows; actual data collection differed from this protocol for various reasons, as described in the *Results* section:

- Login into field site's data acquisition to view real-time data collection.
- Setup DR mechanism for the site's VC equipment.
- Evaluate DR mode on VC equipment based on SCE DR Program structure.
    - For Field Sites 1 and 3, the only option for DR mode is to cycle OFF. For the Field Site 2 unit, the DR option of minimum output plans to be examined if operational (Note: The laboratory DR assessment revealed that the functionality of DR with minimum output was not operating correctly. The manufacturer is working on a software solution to the issue.)

  - Test 1 – 50% Cycling: Activate DR for 15 minutes, Deactivate for 15 minutes (two cycles of activate/deactivate, approximately one hour total). Allow for a period of stabilization for the VC system and indoor temperature (approximately 30 minutes).
  - Test 2 – 100% Cycling: Activate DR for approximately one hour

- Monitor and track indoor conditions before, during, and after DR events.
- Monitor and track VC equipment performance and unit power consumption before and after each DR event.

RESULTS

This section provides findings from the laboratory energy and demand testing, the laboratory demand response testing, and the field testing.

LABORATORY ENERGY AND DEMAND TESTING

This section details key findings from the laboratory test data and compares energy efficiency analyses of the three VC systems to those of the baseline equipment. Results include a comparison of the laboratory test plan to AHRI conditions and ratings and a comparison of the peak power demand conducted for high ambient temperature.

COMPARISON OF LABORATORY DATA TO AHRI RATINGS

Table 12 compares the study laboratory data at AHRI conditions to AHRI rating information for unit cooling capacity and EER. For all three VC systems evaluated, the data from this study agreed reasonably well with published AHRI data. As discussed in the laboratory test plan, the AHRI condition was intended to serve as a comparison and was separate from the primary lab tests at field design conditions.

TABLE 12. COMPARISON OF AHRI EER RATINGS TO LABORATORY DATA

VC System Identifier	Data Type	Cooling Capacity (Btu/h)		Energy Efficiency Ratio (Btu/Wh)		Unit Power Consumption (W)
		Air-Side	Refrigerant-Side	Air-Side	Refrigerant-Side	
1	Laboratory	22,315	23,102	14.4	14.9	1,549.7
	AHRI	22,800		15.5		1,471.0
2	Laboratory	23,558	24,387	11.6	12.0	2,033.6
	AHRI	23,800		11.0		2,163.6
3	Laboratory	24,852	23,903	14.1	13.5	1,764.7
	AHRI	23,600		13.0		1,815.4

Table 13 compares study laboratory data for the AHRI test condition and the field design condition at 95°F outdoor temperature and maximum output. The main difference between the two conditions were external static pressure, airflow, and return temperature and humidity. Compared to the AHRI test condition, the field design conditions resulted in a reduction in capacity and efficiency of approximately 9%–15%, while maintaining similar unit power consumption.

TABLE 13. LABORATORY DATA: AHRI VS. FIELD DESIGNED 95°F, MAXIMUM OUTPUT TEST CONDITIONS

VC Lab Identifier	Lab Test Conditions	Cooling Capacity (Btu/h)	Energy Efficiency Ratio (Btu/Wh)	Unit Power Consumption (W)
1	AHRI	23,102	14.9	1,549.7
	Field	20,708	13.0	1,598.1
2	AHRI	24,387	12.0	2,033.6
	Field	21,122	10.4	2,024.3
3	AHRI	23,903	13.5	1,764.7
	Field	21,927	12.3	1,776.9

EXTERNAL STATIC PRESSURE AND INDOOR AIRFLOW

Figure 18 provides the external static pressure (ESP) curve, described in the laboratory test plan, imposed on all three VC systems evaluated. For each system and each of the 18 test conditions, ESP was controlled in accordance with the desired airflow of the system.

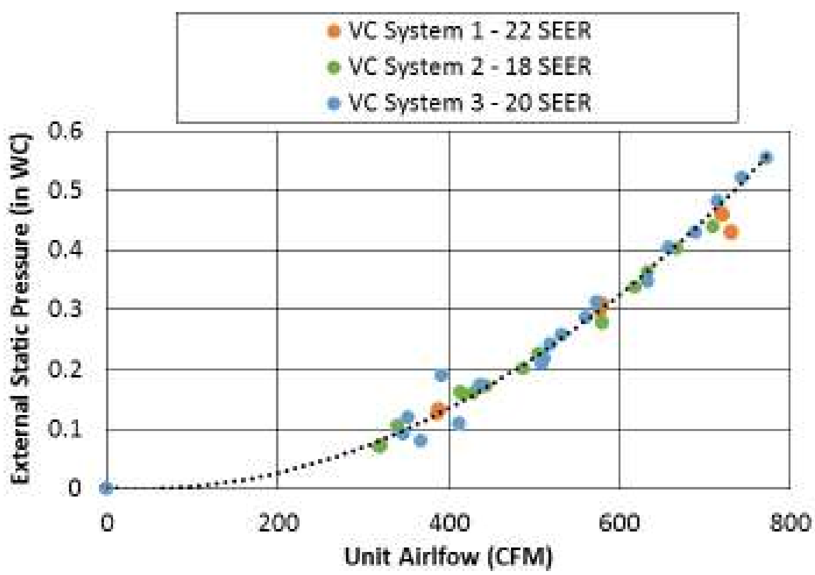

FIGURE 18. LABORATORY DATA: VC UNIT AIRFLOW VS. EXTERNAL STATIC PRESSURE

Figure 19 provides the indoor unit power consumption for each of the 18 test conditions for the three VC systems. The 18 and 20 SEER VC equipment followed a similar power consumption curve, while the 22 SEER system was slightly higher for similar airflow and external static pressure conditions.

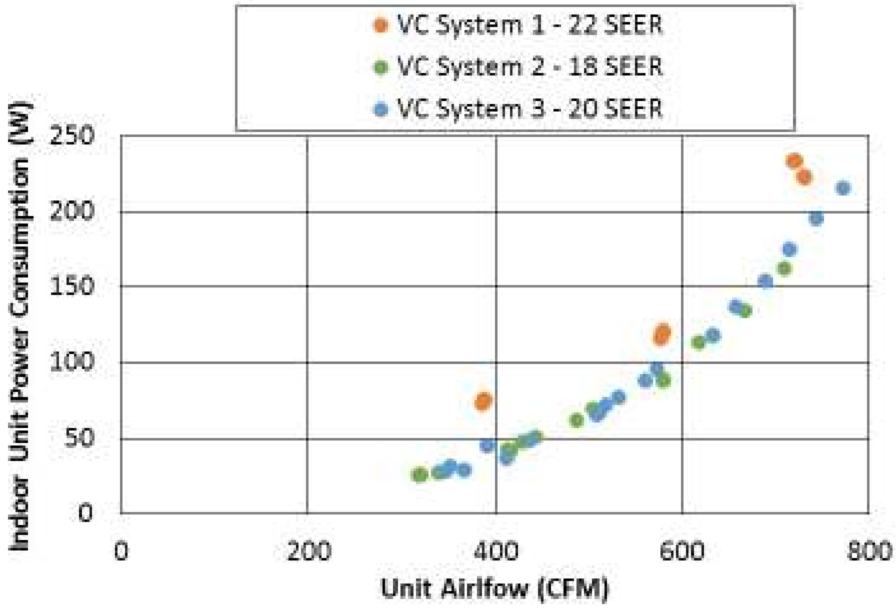

FIGURE 19. LABORATORY DATA: VC UNIT AIRFLOW VS. POWER CONSUMPTION

Table 14 shows the standby power consumption—defined as the power draw of the equipment when the unit is idle and not calling for cooling, heating, or fan operation—for the indoor and outdoor units of each VC system. The total power consumption of all three VC systems was approximately 30W. The standby power consumption for the indoor and outdoor unit for the 18 and 20 SEER equipment was approximately 10W and 20W, respectively. For the 22 SEER VC system, standby power consumption was 25W for the indoor unit and 5W for the outdoor unit. The increased standby power consumption of the equipment may account for the slightly increased power consumption of the 22 SEER indoor unit compared to the other systems for similar airflows and ESP.

TABLE 14. LABORATORY OBSERVATION: STANDBY POWER CONSUMPTION OF VC SYSTEMS

IDENTIFIER	STANDBY POWER CONSUMPTION (W)	
	INDOOR UNIT	OUTDOOR UNIT
VC System 1	25	5
VC System 2	10	20
VC System 3	10	20

In the laboratory, ESP for each system was varied higher and lower than the ESP curve used in the primary field designed test matrix to observe changes in indoor unit power consumption with ESP. Table 15 provides laboratory data for each VC system operating at the 95°F maximum output condition for three ESP levels: near the ESP testing curve (~0.5 inch WC), higher (~0.9 inch WC) than the testing curve, and lower (~0.1 inch WC) than the testing curve. Since the VC equipment was operating at different nominal airflows, data across VC equipment is not directly comparable. However, the data provides an example of power consumption variation with ESP for the VC equipment at a given condition. Higher ESP can significantly impact indoor unit power consumption and thereby the efficiency of a given VC system. All of the examined VC equipment contained an electronically commutated motor (ECM) for the variable speed indoor blower, and the units were designed to supply a specified airflow at a given level of operation.

TABLE 15. LABORATORY DATA: VC SYSTEMS AT MAXIMUM, 95°F, AIRFLOW WITH VARYING ESP

VC SYSTEM 1 - 22 SEER AIRFLOW = 720 CFM		VC SYSTEM 2 - 18 SEER AIRFLOW = 620 CFM		VC SYSTEM 3 - 20 SEER AIRFLOW = 700 CFM	
ESP (INCH WC)	INDOOR UNIT POWER (W)	ESP (INCH WC)	INDOOR UNIT POWER (W)	ESP (INCH WC)	INDOOR UNIT POWER (W)
0.2	151.4	0.1	72.7	0.1	94.5
0.5	228.4	0.5	153.6	0.5	165.8
0.8	346.0	0.9	222.0	0.9	256.9

CAPACITY CURVE COMPARISON OF LABORATORY EQUIPMENT

Figure 20 provides the maximum and minimum cooling capacity curves for each of the three evaluated VC systems. The graph illustrates the maximum capacity curves with a solid line, and the minimum capacity curves with a dashed line. The maximum capacity curves for each of the three systems are similar, as each system was designed by the respective manufacturer to be a nominal 2-ton system. For the minimum capacity curves, VC System 2 demonstrated an ability to operate at the lowest minimum capacity output, approximately 30% of the maximum output. The minimum capacity curves of VC System 1 and 3 were approximately 50% of the maximum capacity curve. At higher outdoor temperatures, namely 105°F and 115°F, the designed minimum operating level of each VC system increased. For example, with VC System 2, the minimum operating level of approximately 30% of maximum at 95°F increased to approximately 50% at 105°F.

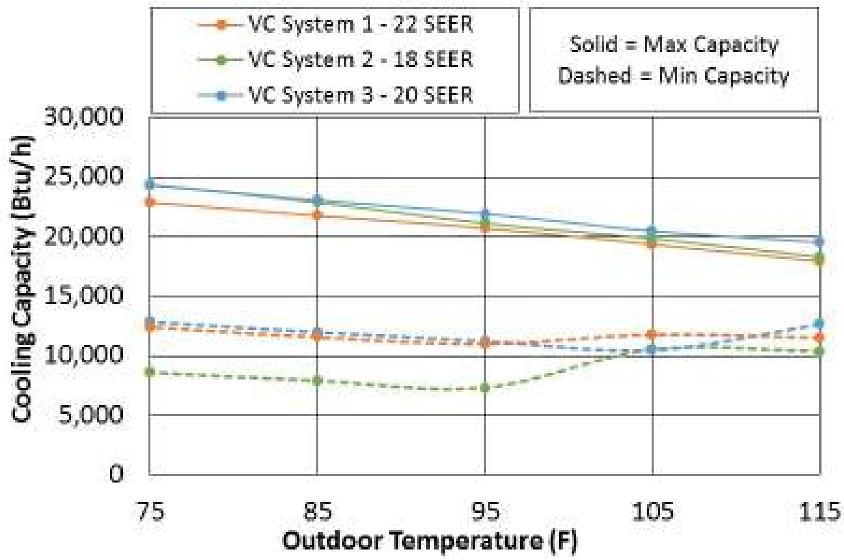

FIGURE 20. LABORATORY DATA: COOLING CAPACITY CURVES FOR THREE VC SYSTEMS

EFFICIENCY CURVE COMPARISON OF LABORATORY EQUIPMENT

Figure 21 and Figure 22 show maximum and minimum efficiency curves for the three laboratory-tested systems. For both maximum and minimum efficiency curves, the 22 SEER system demonstrated the highest efficiency at a given test point, followed by the 20 and 18 SEER systems, respectively. The efficiency difference between the 18 and 20 SEER curves is approximately 10%, while the difference between the 20 and 22 SEER curves is between 0% and 10%, depending upon the test point. For outdoor conditions above 85°F, a minimal efficiency impact was demonstrated between the 22 and 20 SEER VC equipment.

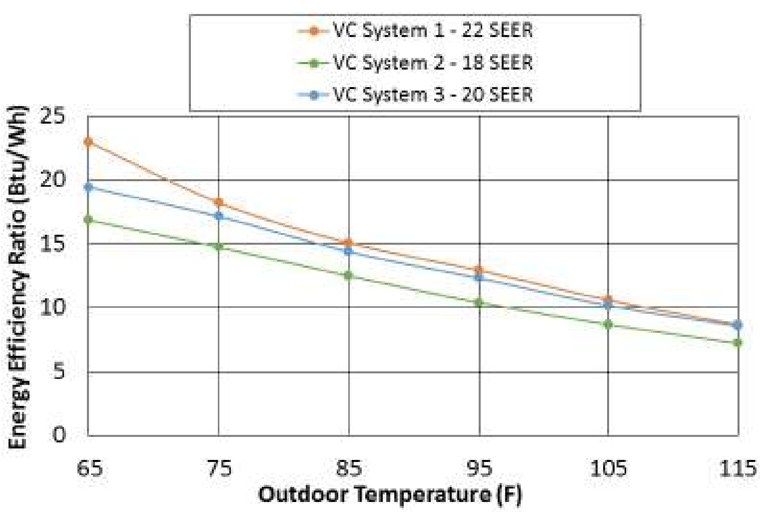

FIGURE 21. LABORATORY EFFICIENCY DATA: MAXIMUM OPERATION FOR THREE LABORATORY SYSTEMS

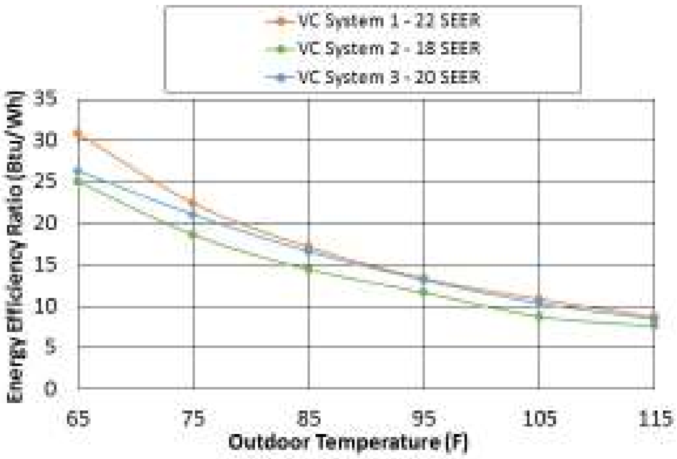

FIGURE 22. LABORATORY EFFICIENCY DATA: MINIMUM OPERATION FOR THREE LABORATORY SYSTEMS

ENERGY COMPARISON MODEL OF LABORATORY TESTED EQUIPMENT

Using previously obtained laboratory data in a similar setup to the laboratory test plan for the VC equipment, baseline efficiency curves were developed for 15, 14, and 11 SEER equipment. The SCE residential air conditioning program has set the current incentive level at 15 SEER, and 14 SEER is the current federal minimum efficiency for residential split systems in California. Based on historic federal minimums, 11 SEER is assumed representative of equipment installed in the field 15–20 years ago, which is likely to reach end of the life in the near future. Figure 23 through Figure 25 compare the VC equipment to the baseline equipment. Significantly, the 14 and 15 SEER efficiency curve is similar to the maximum output of the 18 SEER VC system, while the efficiency curves for both maximum and minimum output with the 20 and 22 SEER VC equipment exceed the 14 SEER curve by ~10%.

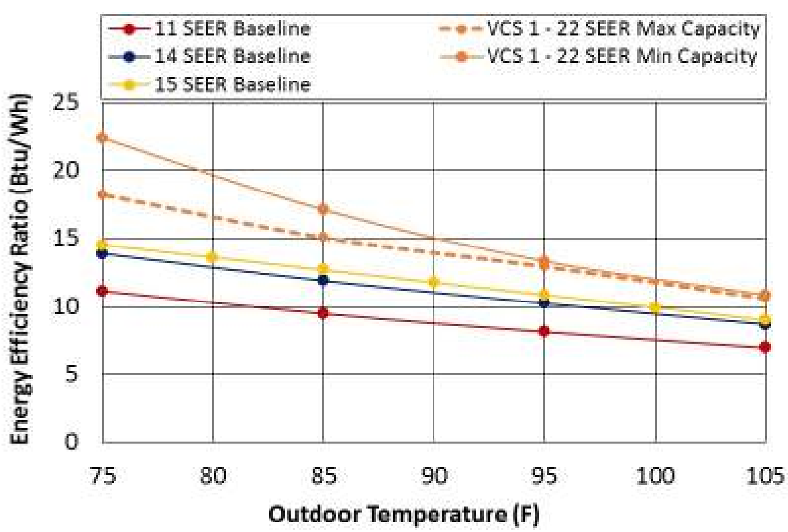

FIGURE 23. COMPARISON OF 22 SEER VC SYSTEM TO BASELINE EFFICIENCY CURVES

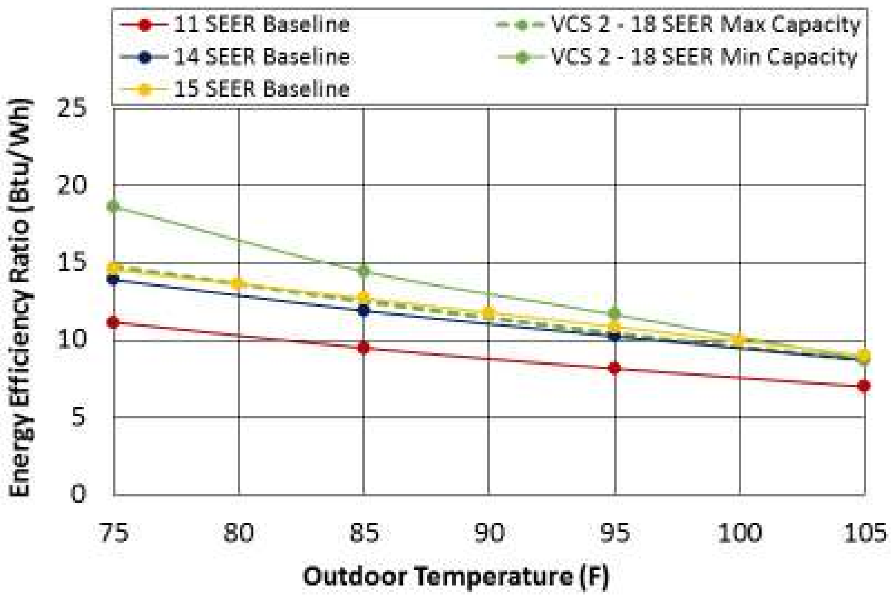

FIGURE 24. COMPARISON OF 18 SEER VC SYSTEM TO BASELINE EFFICIENCY CURVES

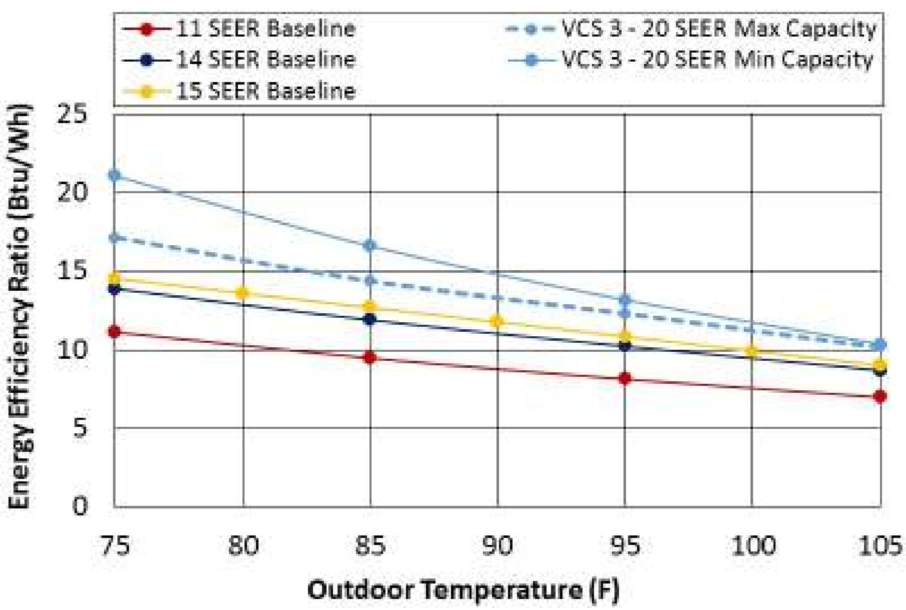

FIGURE 25. COMPARISON OF 20 SEER VC SYSTEM TO BASELINE EFFICIENCY CURVES

To evaluate the energy savings potential of each VC system, an energy model was developed to compare the VC equipment to the 14 and 11 SEER baseline cases. The energy model assumed the typical meteorological year (TMY) [9] weather profile of Redlands, CA, and a cooling load outdoor design condition of 101°F.[1] For each VC system, the cooling load design was selected to match the maximum cooling output of the unit at 101°F. This cooling load point at 101°F, along with the assumption of a balanced load (i.e., internal heat gain = heat loss) at 68°F, formed the load line for each VC system. The capacity curve of the baseline equipment was based on experimental data and set to match the cooling output of the VC unit at 101°F. In the energy model, the maximum and minimum capacity curves of the VC equipment obtained in the laboratory setup were used. Figure 26 provides an example of the capacity curves and the load line for a given VC system and energy model comparison.

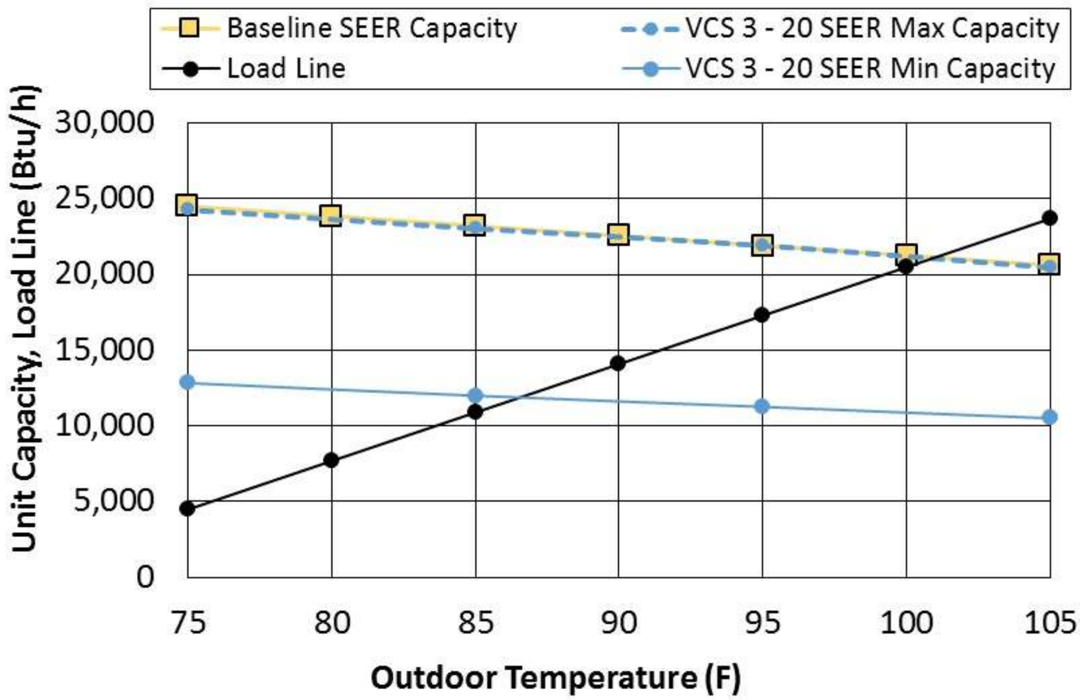

FIGURE 26. EXAMPLE OF VC CAPACITY, BASELINE CAPACITY, AND LOAD CURVES FOR EFFICIENCY MODEL

The energy model used in the comparison was based on the bin-method described in Chapter 19 of the *ASHRAE Fundamentals Handbook*. For a given outdoor temperature bin, an assumed cooling load, unit capacity, and unit power consumption were determined based on the capacity and efficiency curves. Appropriate adjustments were made for each system for unit cycling and operation time to determine the yearly energy consumption at each temperature bin for the assumed Redlands, CA, climate. An example of the bin-method is provided in Table 16.

[1] Based on the 1% design cooling condition for Redlands, Mentone, and Yucaipa, CA. [10].

Table 16. Example of Bin-Method

Row	Outdoor Temp (F)	Typical Hours in Year	Cooling Load (Btu/h)	Unit Capacity (Btu/h)	Unit Efficiency (Btu/W-h)
1	75	396	4,481	24,500	11.2
2	80	550	7,681	23,850	10.3
3	85	335	10,882	23,201	9.5
4	90	562	14,082	22,551	8.8
5	95	153	17,283	21,902	8.2
6	100	80	20,483	21,252	7.6
7	105	4	23,683	20,603	7.0

Row	Unit Power Consumption (W)	Cyclic Factor	Adjusted Capacity (Btu/h)	Operating Time	Seasonal Energy (Wh)
1	2,195	0.80	19,495	0.23	199,761
2	2,309	0.83	19,808	0.39	492,442
3	2,443	0.87	20,121	0.54	442,621
4	2,554	0.91	20,434	0.69	989,067
5	2,682	0.95	20,747	0.83	341,877
6	2,803	0.99	21,060	0.97	218,106
7	2,944	1.00	20,603	1.00	11,776

The results of the energy model comparison for each of the three VC systems are provided in Table 17, showing that the modeled energy savings of the VC equipment increase with increasing SEER, with the 22 SEER VC unit demonstrating the highest potential savings. As evident by their efficiency curves, the 20 and 22 SEER equipment provide energy savings of similar magnitude over the baseline equipment. Historically in the HVAC and energy efficiency industry, an increase in SEER is believed to correspond with an increase in unit efficiency and expected energy savings. A 2 point increase in SEER (e.g. from 18 to 20 SEER or from 20 to 22 SEER) is thought to correspond with an approximate 10% improvement in efficiency or energy savings. From the 18 to 20 SEER VC unit, the model demonstrated an energy savings improvement of approximately 10–15%, while the step from 20 to 22 SEER with the VC equipment demonstrated an approximate 3–4% improvement.

TABLE 17. ENERGY SAVINGS OF VC EQUIPMENT FROM EFFICIENCY MODEL WITH BASELINE

System Identifier		Percent Yearly Energy Savings from Baseline		
		15 SEER Baseline	14 SEER Baseline	11 SEER Baseline
VC System 1	**22 SEER**	25.6%	29.8%	47.4%
VC System 2	**18 SEER**	6.7%	12.0%	34.1%
VC System 3	**20 SEER**	21.8%	26.2%	44.7%

Figure 27 and Figure 28, which demonstrate the energy savings of each VC unit at a given outdoor temperature bin in the energy model, provide further details of the energy model comparison of the VC equipment to baseline. The first figure illustrates the baseline case of 14 SEER, while the second represents the baseline case of 11 SEER. The two figures show that the highest potential energy savings occur at milder temperatures and loads. Although the efficiency curves of the 14 SEER and the maximum output of the 18 SEER are similar, the 18 SEER system provides energy savings up to the design condition. This occurs because the 18 SEER is operating at part-load conditions below the design condition with higher levels of efficiency toward the minimum efficiency curve.

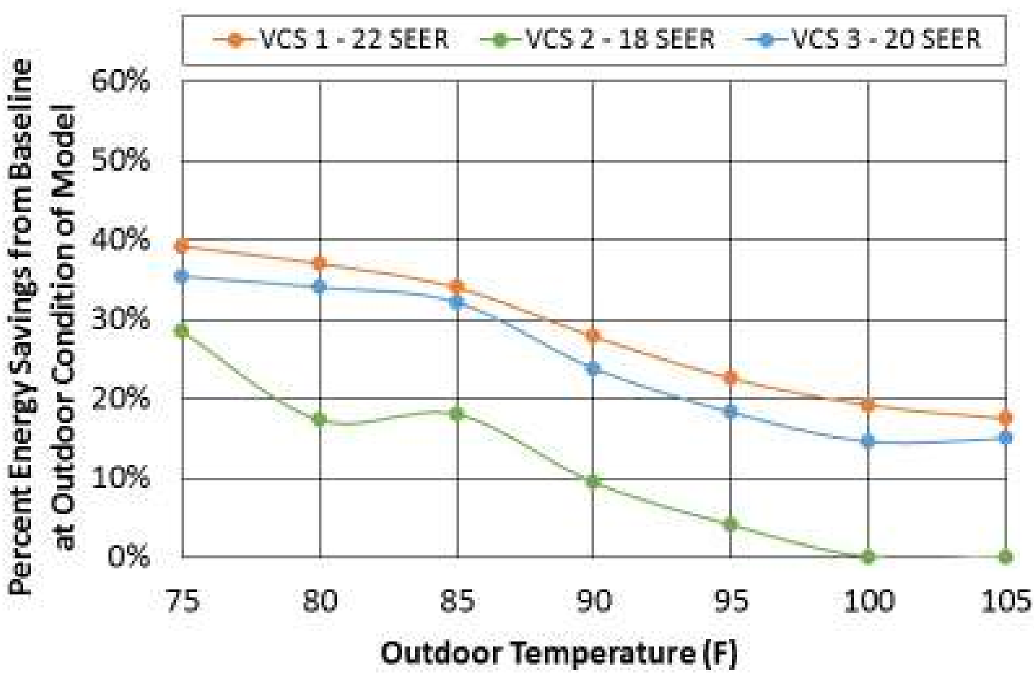

FIGURE 27. MODELED ENERGY SAVINGS OF VC EQUIPMENT COMPARED TO A BASELINE OF 14 SEER

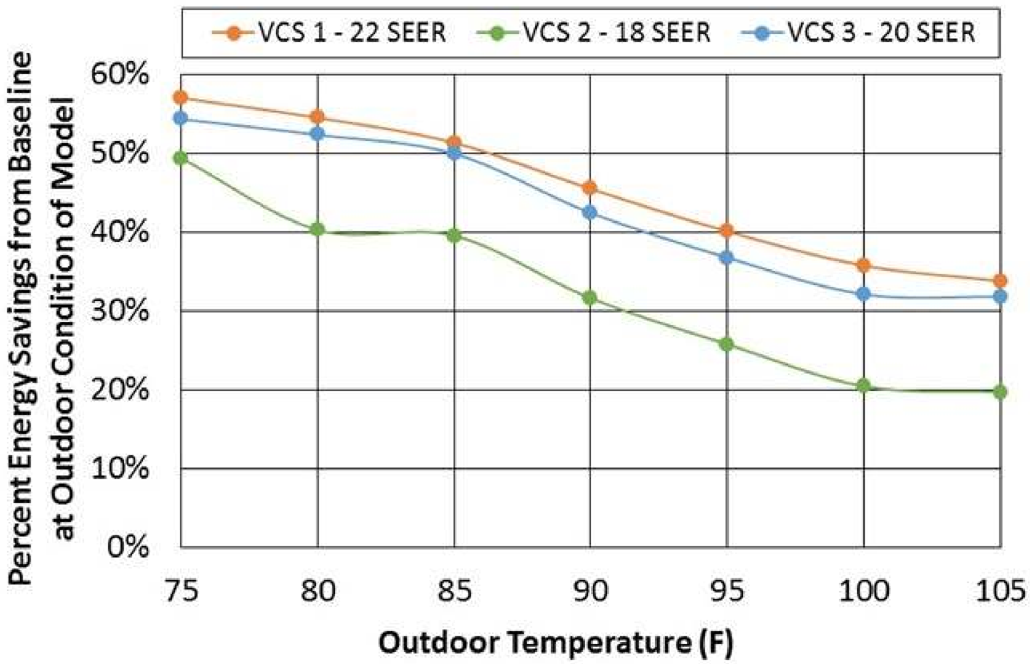

FIGURE 28. MODELED ENERGY SAVINGS OF VC EQUIPMENT COMPARED TO A BASELINE OF 11 SEER

PEAK DEMAND COMPARISON OF LABORATORY TESTED EQUIPMENT

The team compared the peak cooling demand of the three VC systems, based on the laboratory data, against a baseline 12.2-rated EER system, the current federal minimum baseline for California. The comparison used laboratory and manufacturer data to form an efficiency curve for a 12.2-rated EER system at outdoor conditions of 95°F, 105°F, and 115°F. As noted, the 18, 20, and 22 SEER VC equipment had rated EERs of 11, 13, and 15.5, respectively.

Rated EER values for residential split air conditioners are determined based on the procedures of AHRI 210/240 at 95°F outdoor temperature. The laboratory results were conducted at field design conditions, which resulted in lower efficiency values at peak outdoor conditions. The laboratory field design test conditions were also utilized to develop the baseline comparison.

Rated EERs were used as system identifiers. Actual EERs from laboratory efficiency data at field design conditions were used in the peak demand comparisons.

Figure 29 provides results of the peak demand comparison. The 18 SEER VC system, with an EER below the current federal minimum, demonstrated increased demand, while the 20 and 22 SEER equipment demonstrated demand savings between 5% and 15% at 95°F, 105°F, and 115°F test cases.

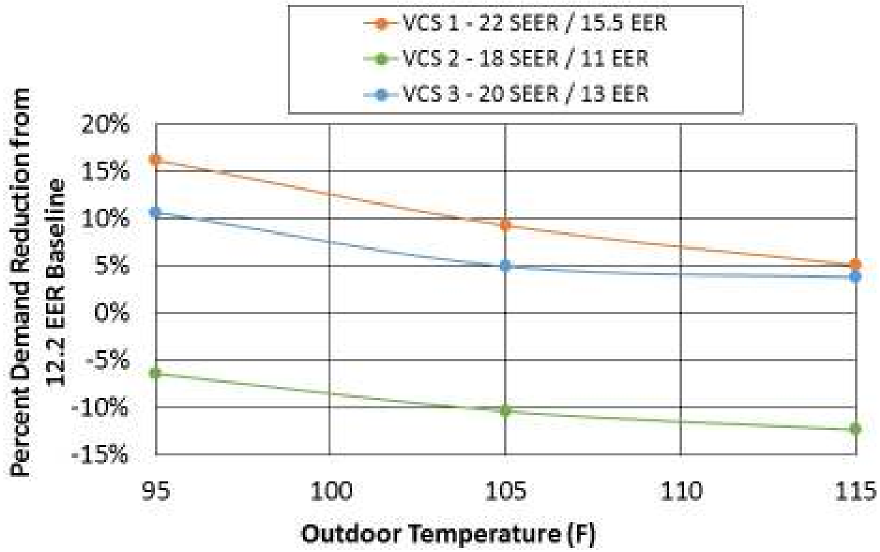

FIGURE 29. MODELED DEMAND REDUCTION OF VC EQUIPMENT COMPARED TO A BASELINE OF 12.2 EER

LABORATORY DR ASSESSMENT

Table 18 summarizes findings from the laboratory DR assessment, highlighting the elements of the laboratory DR test plan used to investigate the DR capabilities of the three VC systems. Results for each of the VC systems are discussed separately below.

TABLE 18. DETAILS FOR LABORATORY DR ASSESSMENT

CHARACTERISTIC	VC SYSTEM 1	VC SYSTEM 2	VC SYSTEM 3
DR Functionality	ON/OFF	Min Operation* ON/OFF	ON/OFF
Adjustment Required to Default Settings for DR Operation	No	Yes	Yes
DR Mechanism	Closed Electrical Contacts	Open Electrical Contacts	Open Electrical Contacts
Message Displayed on User Interface	Load Shedding	Utility Curtailment Active	Load Shedding
Indoor Blower Continued to Operate during DR Operation	No	Yes	Yes
Average Response Time to Reduced Power (sec)	9	98	24
Average Response Time to Resume Cooling Operation (sec)	28	63	80

*Minimum operation DR function was built in to system hardware, but not functional during assessment.

LABORATORY DR ASSESSMENT – VC SYSTEM 1

DOCUMENT THE MECHANISM FOR ACTIVATING DR IN THE TEST UNIT

The mechanism for activating DR mode in VC System 1 is use of electrical contacts, termed "L" and "C" by the manufacturer, within the outdoor unit control panel. If the "L" and "C" contacts complete a closed circuit, then the unit will perform DR operation. If the "L" and "C" contacts are open, then the unit will be under normal operation. No unit settings have to be adjusted within the unit for DR operation to occur.

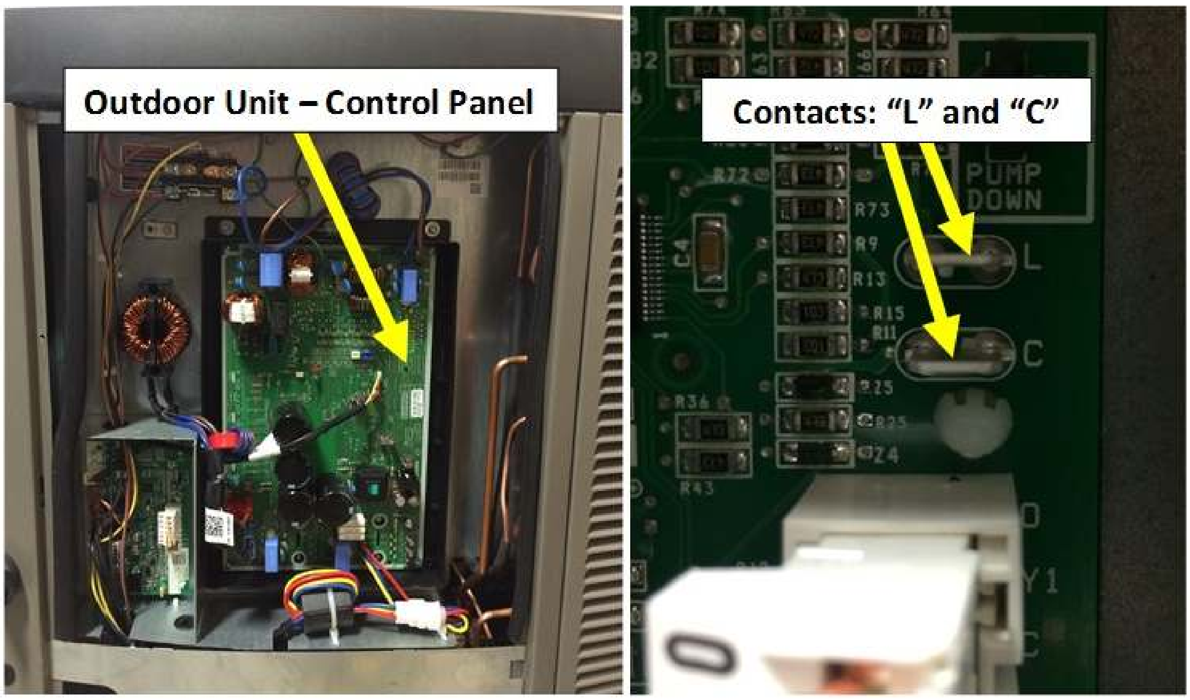

FIGURE 30. LABORATORY DR ASSESSMENT: LOCATION OF DR ACTIVATION MECHANISM – VC SYSTEM 1

DOCUMENT THE DR FUNCTIONALITY OF THE UNIT

The only DR functionality of this unit was to turn the system OFF in response to the DR signal. No unit settings need to be adjusted to allow for DR functionality. Completing a circuit between the aforementioned contacts allows for DR operation of the unit. During DR operation, an active alert—"Load Shedding"—was displayed on the user and technician interface. Figure 31 is an image of the user interface when the active "Load Shedding" alert is provided.

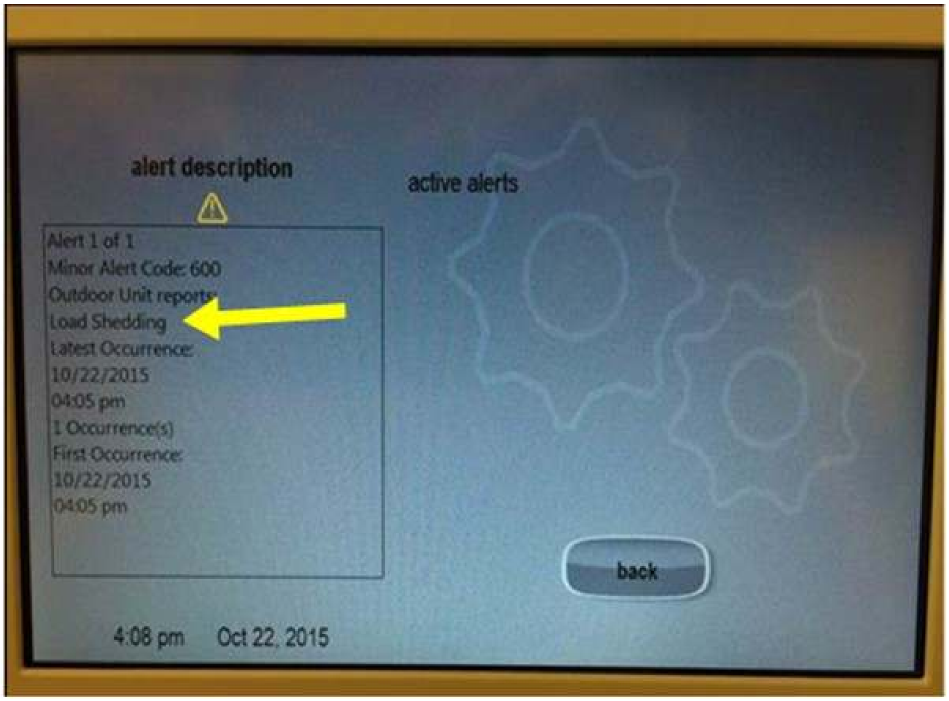

FIGURE 31. LABORATORY DR ASSESSMENT: UNIT CONTROLLER CONFIRMATION OF DR EVENT – VC SYSTEM 1

DEMONSTRATE THE DR OPERATION OF THE TEST UNIT

Figure 32 through Figure 34 provide laboratory data of the DR assessment for the test points as described in the laboratory test plan. Each graph provides the total unit power over the test case. Red marks on the graph illustrate the initiation and termination of the DR event.

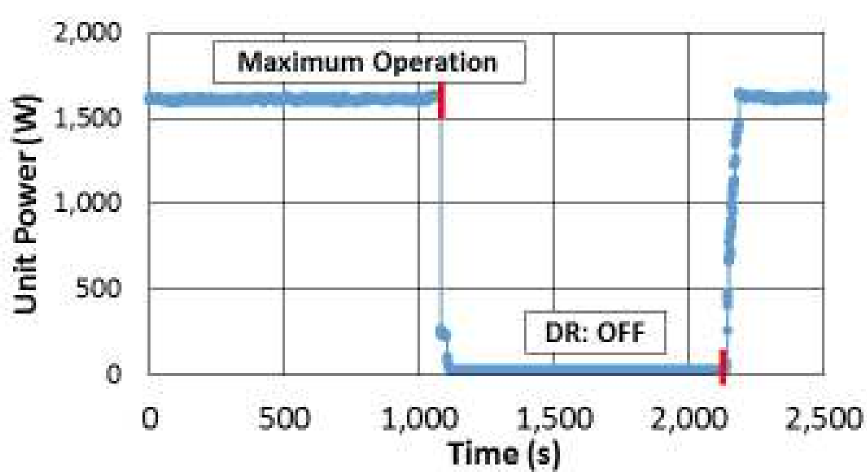

FIGURE 32. LABORATORY DATA OF DR TEST: 95°F, OFF – VC SYSTEM 1

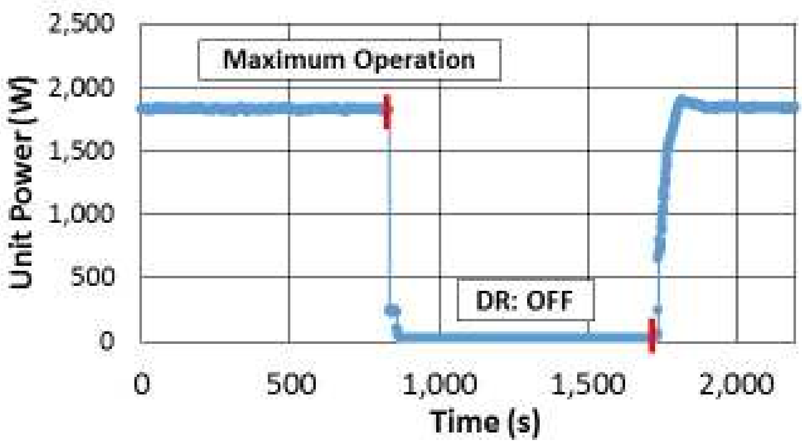

FIGURE 33. LABORATORY DATA OF DR TEST: 105°F, OFF – VC SYSTEM 1

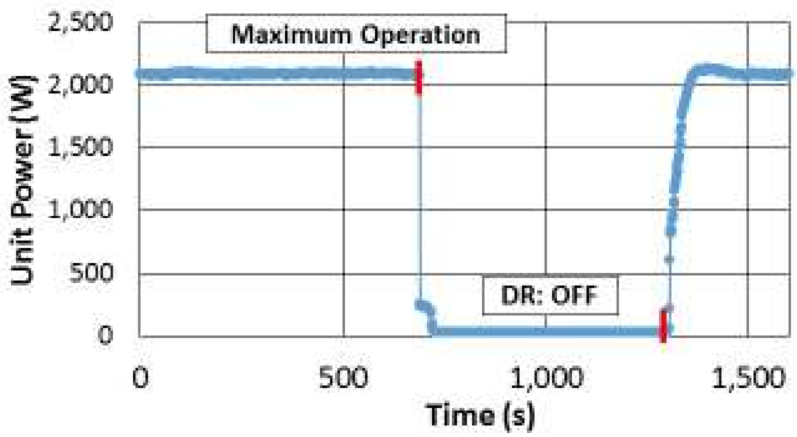

FIGURE 34. LABORATORY DATA OF DR TEST: 115°F, OFF – VC SYSTEM 1

DETERMINE POWER REDUCTION OF EQUIPMENT IN DR OPERATION

This section provides numerical data for the laboratory DR assessment test cases. Table 19 provides total unit power consumption before and after DR mode was activated. The power reduction for the DR assessment was approximately 1,600 W–2,000 W for the test cases.

TABLE 19. TOTAL UNIT POWER CONSUMPTION BEFORE AND AFTER DR MODE ACTIVATED – VC SYSTEM 1

DR Response	Outdoor Condition (F)	Unit Power before DR Event (W)	Unit Power during DR Event (W)	Unit Power Reduction (W) from DR Event
OFF	95	1,625	31	1,594
	105	1,830	29	1,801
	115	2,090	29	2,061

DETERMINE DR RESPONSE TIMES

Table 20 provides the response time of the unit to decrease unit power upon DR activation. This time is measured from the initial switch of the DR contact at the outdoor unit to the point when power reduction of the outdoor unit was at standby levels.

TABLE 20. UNIT RESPONSE TIME TO DECREASE UNIT POWER UPON DR ACTIVATION – VC SYSTEM 1

DR RESPONSE	OUTDOOR CONDITION (F)	RESPONSE TIME (S)
OFF	95	9
	105	9
	115	8

Table 21 below provides the response time of the unit to regain cooling capacity after the DR mode was deactivated. This time is measured from the initial switch of the DR contact at the outdoor unit to when the system exhibited cooling output within the laboratory data acquisition system.

TABLE 21. UNIT RESPONSE TIME TO REGAIN COOLING CAPACITY AFTER DR MODE DEACTIVATED – VC SYSTEM 1

DR RESPONSE	OUTDOOR CONDITION (F)	RESPONSE TIME (S) OF VC UNIT TO RETURN TO COOLING OPERATION
OFF	95	29
	105	27
	115	28

LABORATORY DR ASSESSMENT – VC SYSTEM 2

DOCUMENT THE MECHANISM FOR ACTIVATING DR IN THE TEST UNIT

The mechanism for activating DR mode in VC System 2 was use of electric contacts, termed “24V” and “UTIL” by the manufacturer, within the outdoor unit control panel. When DR mode is set to active on the controller, the contacts have the ability to control DR operation. If the “24V” and “UTIL” contacts complete a closed circuit and the DR setting on the unit controller is set, then the unit will operate in normal operation. If the “24V” and “UTIL” circuit is opened or disconnected and the DR setting on the unit controller is set, then DR mode will become active. Figure 30 highlights the location of the DR contacts within the outdoor unit.

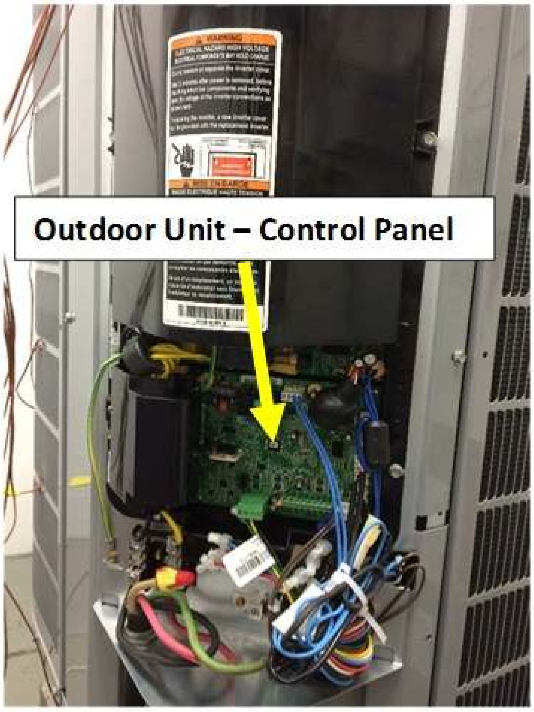

FIGURE 35. LABORATORY DR ASSESSMENT: LOCATION OF DR ACTIVATION MECHANISM – VC SYSTEM 2

The unit controller must be set to allow DR operation and to enable the “24V” and “UTIL” contacts to be operational. The setup feature is located under “setup” and “utility curtailment” within the controller. Under “utility curtailment,” the unit controller provides three options: “Disabled,” “Cooling Low Stage,” and “Cooling Turn OFF.” The default setting for utility curtailment is disabled, and thus the unit setting must be adjusted to allow for DR operation. Figure 36 provides the setup screen displaying the “utility curtailment” setting.

FIGURE 36. LABORATORY DR ASSESSMENT: DR SETUP ON UNIT CONTROLLER – VC SYSTEM 2

Document the DR functionality of the unit

The project team evaluated the ability of the VC system to operate in its two DR functionality modes: either “Turn OFF” or operate at “LOW STAGE” when DR mode is activated within the unit (Figure 37). The laboratory assessment revealed that would “Turn OFF” rather than operate in “Low Stage” when the unit was setup for “Low Stage” DR mode. Upon learning of the problem, the manufacturer identified an issue in the software for this procedure and stated that a software update would be developed to correct this issue.

During the laboratory DR assessment, the unit was operated under a pseudo-DR evaluation for “Low Stage” DR mode by operating the unit at maximum output and then adjusting to minimum output during system operation. The “Low Stage” DR assessment did not include operating the “24V” and “UTIL” contacts in the outdoor control panel. The “Turn OFF” DR assessment utilized the “24V” and “UTIL” contacts in the standard DR format as designed by the manufacturer.

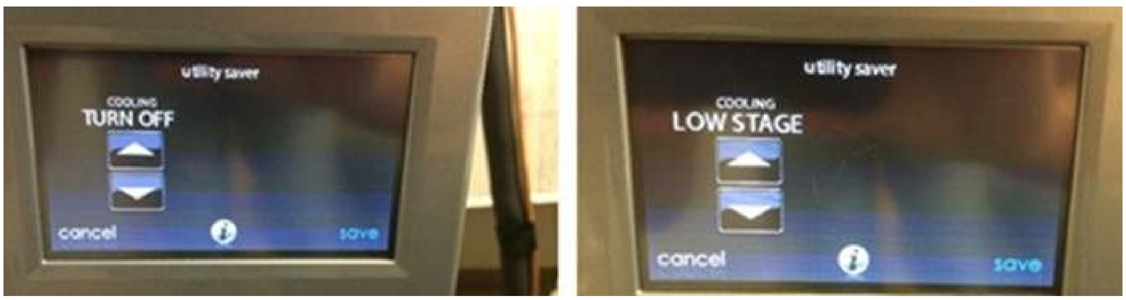

Figure 37. Laboratory DR Assessment: Options on Setup of DR Operation – VC System 2

During DR operation, a message is displayed on the unit controller stating “Utility Curtailment Active.” Figure 38 displays an example of this occurrence.

Figure 38. Laboratory DR Assessment: Unit Controller Confirmation of DR Event – VC System 2

DEMONSTRATE THE DR OPERATION OF THE TEST UNIT

Figure 39 through Figure 44 provide laboratory data of the DR assessment for the test points as described in the laboratory test plan. Each graph provides the total unit power over the DR assessment. As previously described, the "MIN Operation" or "Low Stage" DR assessment did not utilize the DR contacts at the outdoor unit due to software issues. The "Turn Off" DR assessment did utilize the contacts within the outdoor control panel. During the "Turn Off" DR assessment, the indoor blower continued to operate, and thus the total unit power consumption was between 136W and 195W during DR operation. Red marks on the graph illustrate the initiation and termination of the DR event.

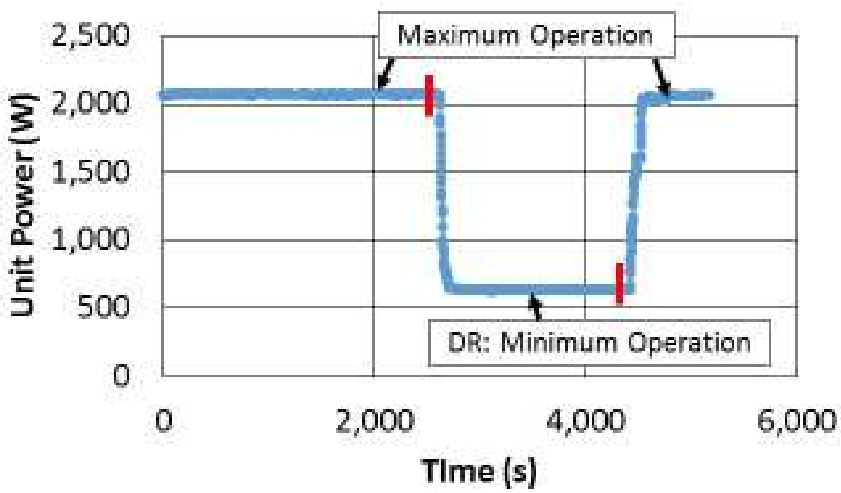

FIGURE 39. LABORATORY DATA OF DR TEST: 95°F, MINIMUM OPERATION – VC SYSTEM 2

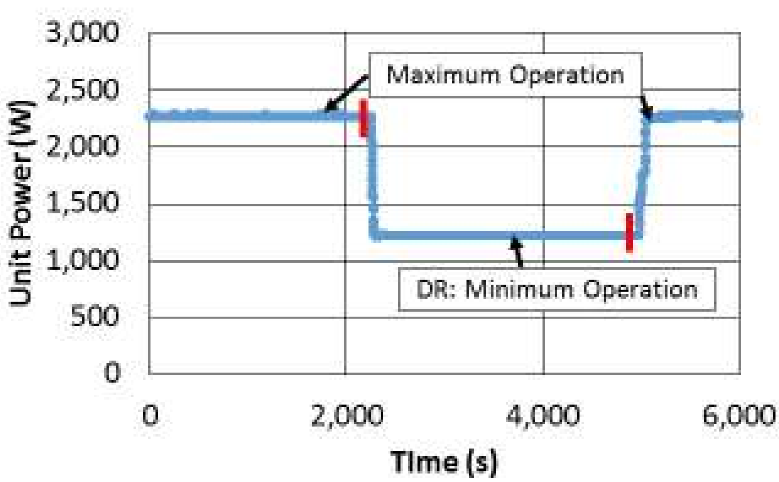

FIGURE 40. LABORATORY DATA OF DR TEST: 105°F, MINIMUM OPERATION – VC SYSTEM 2

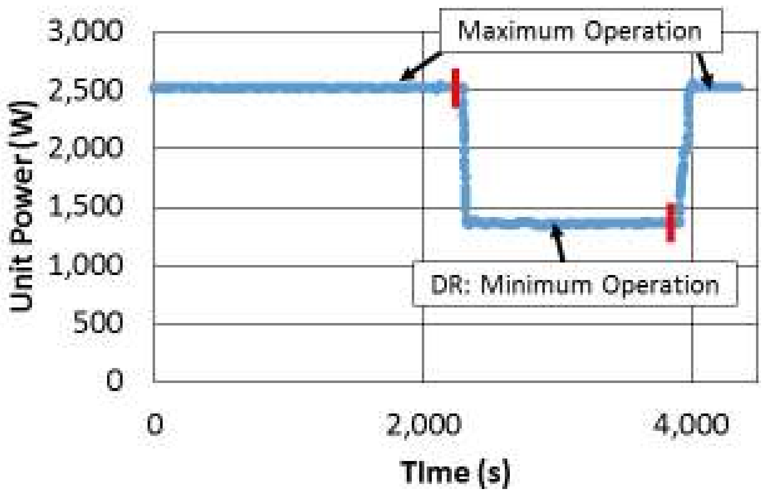

FIGURE 41. LABORATORY DATA OF DR TEST: 115°F, MINIMUM OPERATION – VC SYSTEM 2

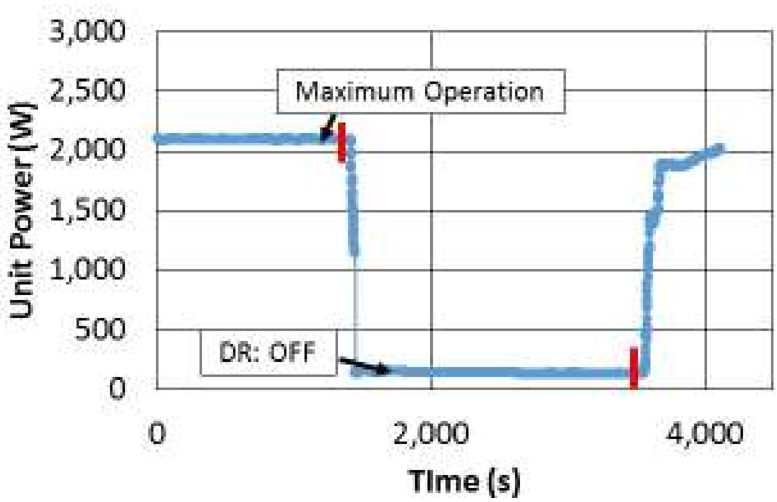

FIGURE 42. LABORATORY DATA OF DR TEST: 95°F, OFF – VC SYSTEM 2

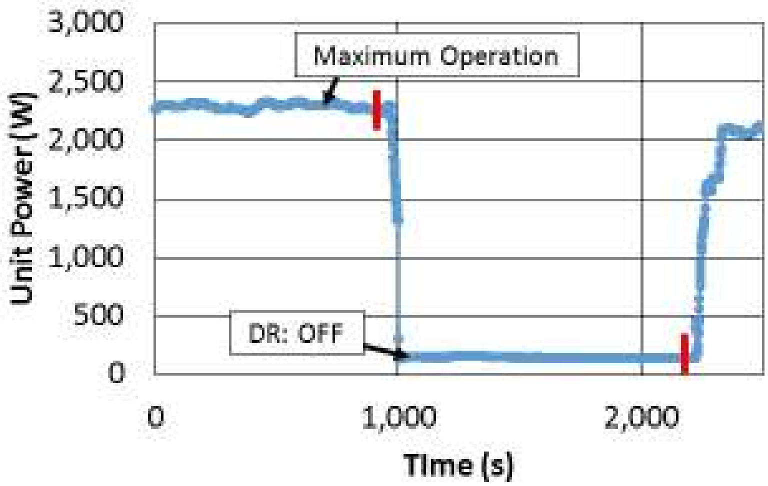

FIGURE 43. LABORATORY DATA OF DR TEST: 105°F, OFF – VC SYSTEM 2

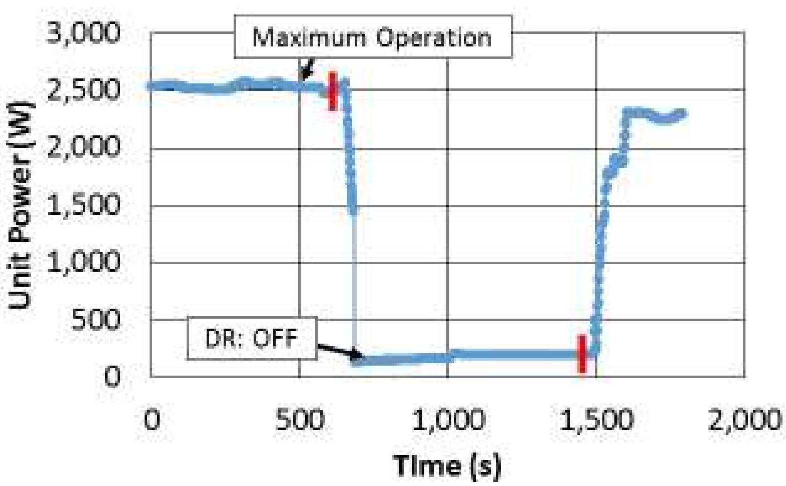

FIGURE 44. LABORATORY DATA OF DR TEST: 115°F, OFF – VC SYSTEM 2

DETERMINE POWER REDUCTION OF EQUIPMENT IN DR OPERATION

This section provides numerical data for the laboratory DR assessment test cases. Table 22 provides total unit power consumption before and after DR mode was activated. The approximate power reduction for the DR assessment was 1,000W to 1,400W for the "MIN Operation" and 2,000W to 2,300W for the "Turn OFF" cases.

TABLE 22. TOTAL UNIT POWER CONSUMPTION BEFORE AND AFTER DR MODE – VC SYSTEM 2

DR Response	Outdoor Condition (F)	Unit Power before DR Event (W)	Unit Power during DR Event (W)	Unit Power Reduction (W) from DR Event
MIN Operation	95	2,067	628	1,439
	105	2,263	1,219	1,044
	115	2,520	1,348	1,172
OFF	95	2,090	136	1,954
	105	2,216	142	2,074
	115	2,520	195	2,325

During the “OFF” DR events, the indoor blower remained operational at a level specified by the unit controls. The indoor power consumption and airflow during the “OFF” DR tests varied, due to the variation in the outdoor temperature.

DETERMINE DR RESPONSE TIMES

For the “OFF” DR test cases where the actual DR mechanism was used to control the system, response times of DR operation were recorded. Table 23 provides the response time of the unit to decrease unit power upon DR activation. This time is measured from the initial switch of the DR contact at the outdoor unit to the point when power reduction of the outdoor unit was at standby levels.

TABLE 23. UNIT RESPONSE TIME TO DECREASE UNIT POWER UPON DR ACTIVATION – VC SYSTEM 2

DR Response	Outdoor Condition (F)	Response Time (s)
OFF	95	96
	105	91
	115	106

For the “OFF” DR test cases where the actual DR mechanism was used to control the system, response times of DR operation were recorded. Table 24 provides the response time of the unit to regain cooling capacity after the DR mode was deactivated. This time is measured from the initial switch of the DR contact at the outdoor unit to when the system exhibited cooling output within the laboratory data acquisition system.

TABLE 24. UNIT RESPONSE TIME TO REGAIN COOLING CAPACITY AFTER DR MODE DEACTIVATED – VC SYSTEM 2

DR Response	Outdoor Condition (F)	Response Time (s) of VC unit to Return to Cooling Operation
OFF	95	65
	105	53
	115	72

LABORATORY DR ASSESSMENT – VC SYSTEM 3

DOCUMENT THE MECHANISM FOR ACTIVATING DR IN THE TEST UNIT

The mechanism for activating DR mode in VC System 3 involves adjusting unit DR settings and open electrical contacts within the outdoor unit control panel. On the outdoor control display, the setting of "EXT SWITCH" under the "CONFIGURATION MENU" must be adjusted to "ACTIVE" (Figure 45). The two electrical contacts of interest for DR mode were termed "T3" and "T4" by the manufacturer and are located in the outdoor control panel (Figure 46). Once the aforementioned unit DR setting is adjusted, if the "T3" and "T3" contacts are open, then the unit will perform DR operation. If the "T3" and "T4" contacts complete a closed circuit, then the unit will be under normal operation.

FIGURE 45. DR SETTING ADJUSTMENT ON OUTDOOR UNIT – CONTROL DISPLAY – VC SYSTEM 3

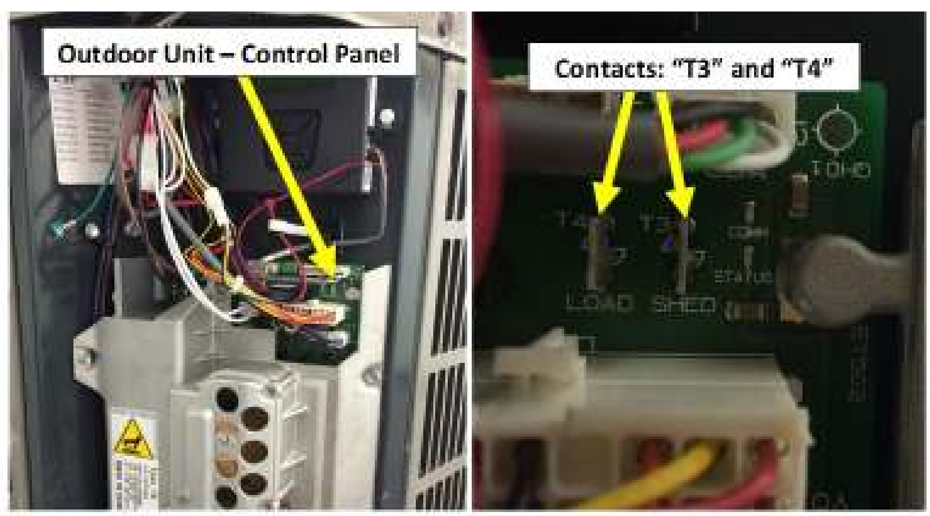

FIGURE 46. LABORATORY DR ASSESSMENT: LOCATION OF DR ACTIVATION MECHANISM – VC SYSTEM 3

DOCUMENT THE DR FUNCTIONALITY OF THE UNIT

For this VC system, the only DR functionality of the unit was to turn the system OFF in response to the DR signal. The appropriate unit settings need to be adjusted to allow for DR functionality. Adjusting the appropriate unit DR settings and opening the circuit between the aforementioned contacts allows for DR operation of the unit. During DR operation, the unit controller displayed "Load Shed" on the user interface, as shown in Figure 47.

FIGURE 47. LABORATORY DR ASSESSMENT: UNIT CONTROLLER CONFIRMATION OF DR EVENT – VC SYSTEM 3

DEMONSTRATE THE DR OPERATION OF THE TEST UNIT

Figure 48 through Figure 50 provide laboratory data of the DR assessment for the test points as described in the laboratory test plan. Each graph provides the total unit power over the test case. Red marks on the graph illustrate the initiation and termination of the DR event.

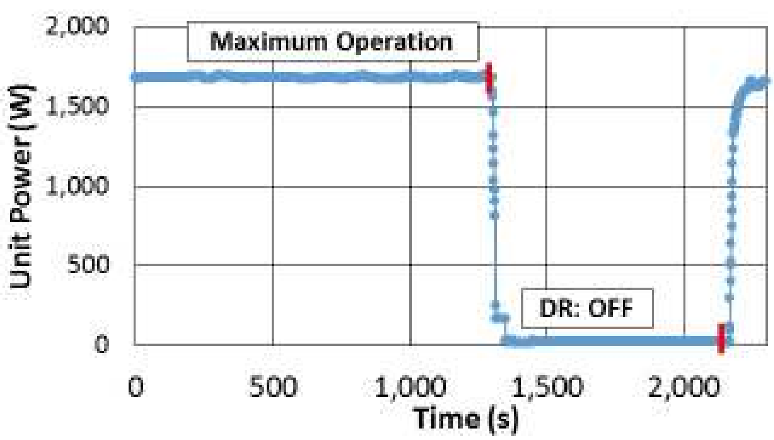

FIGURE 48. LABORATORY DATA OF DR TEST: 95°F, OFF – VC SYSTEM 3

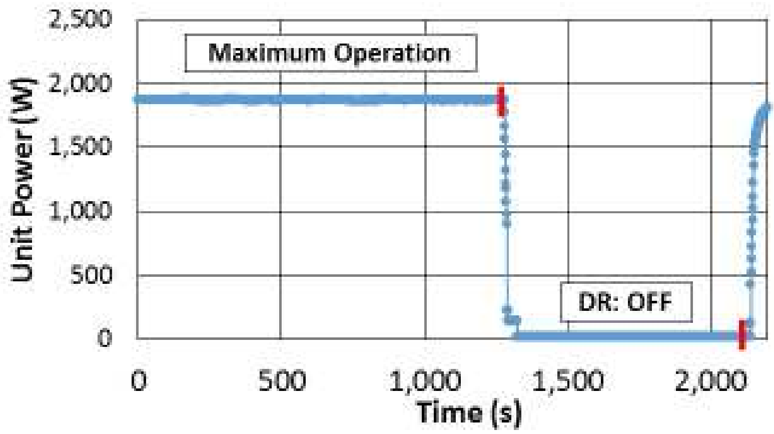

FIGURE 49. LABORATORY DATA OF DR TEST: 105°F, OFF – VC SYSTEM 3

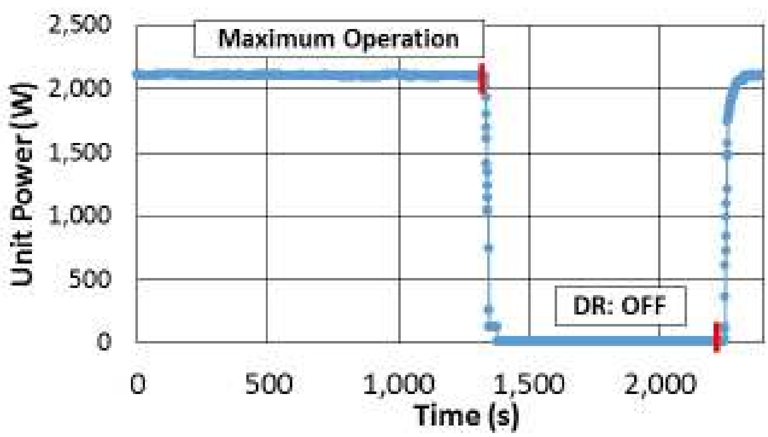

FIGURE 50. LABORATORY DATA OF DR TEST: 115°F, OFF – VC SYSTEM 3

DETERMINE POWER REDUCTION OF EQUIPMENT IN DR OPERATION

This section provides numerical data for the laboratory DR assessment test cases. Table 25 provides total unit power consumption before and after DR mode was activated. The approximate power reduction for the DR assessment was 1,600 W to 2,200 W for the test cases. During the DR events, the indoor blower remained operational at a level specified by the unit controls. The indoor power consumption and airflow during the "OFF" DR tests varied, due to the variation in the outdoor temperature.

Table 25. Total Unit Power Consumption Before and After DR Mode Activated – VC System 3

DR Response	Outdoor Condition (F)	Unit Power before DR Event (W)	Unit Power during DR Event (W)	Unit Power Reduction (W) from DR Event
OFF	95	1,789	157	1,632
	105	2,050	165	1,885
	115	2,306	122	2,184

Determine DR response times

Table 26 provides the response time of the unit to decrease unit power upon DR activation. This time is measured from the initial switch of the DR contact at the outdoor unit to the point when power reduction of the outdoor unit was at standby levels.

Table 26. Unit Response Time to Decrease Unit Power Upon DR Activation – VC System 3

DR Response	Outdoor Condition (F)	Response Time (s)
OFF	95	25
	105	20
	115	27

Determine the response time of the unit to regain cooing output after DR mode is deactivated

Table 27 provides the response time of the unit to regain cooling capacity after the DR mode was deactivated. This time is measured from the initial switch of the DR contact at the outdoor unit to when the system exhibited cooling output within the laboratory data acquisition system.

Table 27. Unit Response Time to Regain Cooling Capacity After DR Mode Deactivated – VC System 3

DR Response	Outdoor Condition (F)	Response Time (s) of VC unit to Return to Cooling Operation
OFF	95	83
	105	72
	115	84

Field Testing

This section provides analysis of data collected for the three VC field sites, described in the *Field Site Selection*. The analyses presented examined the operational characteristics of each VC field site, explored duct loss effects of VC equipment, and compared the energy efficiency of the baseline and the VC equipment. Data collection for the three sites occurred from first quarter to the fourth quarter of 2015, capturing the cooling season for the region. Details of the field data collection methodology and instrumentation are contained within the *Field Monitoring Plan* section.

Field Equipment Summary

Table 28 summarizes the baseline and VC equipment at the selected field sites. Each baseline and VC system consisted of an air conditioner with gas heating. The VC equipment selected for the three field sites: a 17.5 SEER system was a five-speed VC unit, and 20.0 and 21.0 SEER systems with fully variable speed equipment. For each of the three field sites, a QI report was conducted for both the baseline and VC equipment. The SEER of the baseline equipment was estimated based on the power consumption and performance measurements of the QI report. The SEERs of baseline equipment at the three Sites 1, 2, and 3 were determined to be 12.0, 11.0, and 10.0, respectively.

Table 28. Summary of Baseline and VC Equipment at Selected Field Sites

	Field Site 1		Field Site 2		Field Site 3	
	Baseline	VC	Baseline	VC	Baseline	VC
Equipment SEER	12.0	20.0	11.0	17.5	10.0	21.0
Nominal Size (tons)	4		3		3	
Corresponding Lab System	VC System 1		VC System 2		VC System 3	
Product Description	Fully Variable		5 Speed		Fully Variable	

Quality Installation Report of Field Sites

Table 29 summarizes the QI measurements determined for each baseline and VC system. The baseline equipment and ductwork for each field site were fully operational during the QI measurements and prior to the retrofit of the VC equipment. To correct inefficiencies, the baseline ducting system at each site was replaced or repaired during the installation of the VC equipment.

The primary ductwork for the baseline equipment was R4 insulation, while the VC equipment ductwork was upgraded to R8 duct insulation. QI measurements—taken with duct blaster testing—capture differences in the baseline and VC ducting system. The difference in external static pressure between the baseline to VC system was determined to be 0.29, 0.23, and 0.01 inch WC for Sites 1, 2, and 3, respectively.

Each of the three sites observed improvements in the duct air leakage with the VC ductwork. Along with the QI measurements, an ACCA Manual J equipment sizing calculation was performed to confirm the appropriate equipment size for each field site and application. The design conditions for the load calculation were 75°F indoor dry-bulb, 63°F indoor wet-bulb, and 101°F outdoor dry-bulb temperature.[2]

TABLE 29. SUMMARY OF QI MEASUREMENTS FOR BASELINE AND VC EQUIPMENT AND DUCT SYSTEM

		SITE 1		SITE 2		SITE 3	
		BASELINE	VC	BASELINE	VC	BASELINE	VC
ESP Measurements	Return Side ESP (inch WC)	0.62	0.33	0.49	0.48	0.48	0.57
	Supply Side ESP (inch WC)	0.44	0.44	0.61	0.39	0.38	0.30
	Total External Static Pressure (IN WC)	1.06	0.77	1.10	0.87	0.86	0.87
Airflow Measurements	Maximum Airflow (CFM)	1,367	1,627	1,407	1,305	1,169	1,247
	Duct Leakage (CFM)	489	68	264	57	333	125
Power Measurements	Indoor Unit Power at Max Airflow (W)	738	497	1,248	439	869	374
	Outdoor Unit Power (W) at Max Speed	3,815	2,126	3,542	2,289	2,720	2,445
	Outdoor Temp (F) during Outdoor Power Measurement	60	66	60	73	75	87
Manual J Calculation	Sensible Load (Btu/h)	37,198		26,667		31,346	
	Latent Load (Btu/h)	1,463		1,466		1,054	
	Total Cooling Load (Btu/h)	38,661		28,133		32,400	

SUMMARY OF VC FIELD DATA COLLECTION

Table 30 summarizes the field data collection of the three VC systems for the monitored cooling season of April to October 2015. All three sites were within the geographic area of Redlands and San Bernardino and within California Climate Zone 10. Data collection demonstrated similar outdoor conditions across the three sites over the course of the 2015 cooling season. Significant findings follow:

[2] Based on the 1% design cooling condition for Redlands, Mentone, and Yucaipa, CA. [10].

- Sites 1 and 2 contained ductwork within the attic of the residence, and an attic temperature was recorded for these sites. Site 1 demonstrated an attic temperature approximately 7°F higher than the average outdoor temperature, while Site 2 demonstrated similar outdoor and attic temperatures.
- Across the three sites, similar indoor or return dry-bulb temperatures were recorded with an approximate average of 75°F. The indoor or return humidity varied across the three sites from 41% to 55% relative humidity (RH). The varied humidity levels are likely attributed to the usage or runtime of the space conditioning equipment. Site 2 with the highest energy usage, demonstrated the lowest humidity, while Site 1, with the lowest energy usage, demonstrated the highest humidity.
- Although the three field sites were similar in home size, design load, and VC equipment efficiency, the overall cooling season energy usage varied from 800 to 2,800 kWh.

TABLE 30. SUMMARY OF VC EQUIPMENT DATA COLLECTION FOR 2015 COOLING SEASON

	Site 1	Site 2	Site 3
Average Outdoor Temp (F)	79.5	80.0	80.5
Average Outdoor Humidity (%RH)	48.6	47.2	45.1
Average Temp (F) of Duct Location	86.7 (Attic)	80.3 (Attic)	74.6 (Crawlspace)
Average Return Temp (F)	75.1	74.4	75.7
Average Return Humidity (%RH)	55.5	41.0	46.5
HVAC Energy Usage (kWh)	800.6	2,839.6	1,918.6
Outdoor Unit Energy Usage (kWh)	555.2	2,626.5	1,669.3
Indoor Unit Energy Usage (kWh)	245.4	213.1	249.3
Peak HVAC Power (kW)	3.7	3.6	3.0

Figure 51 provides an average daily profile of Field Sites 1, 2, and 3 for the month of August 2015, selected as a representative warm period with significant space conditioning usage at the field sites (see Appendix C for additional detail). The trends observed for the month of August are consistent throughout the cooling season. The figure shows average daily indoor temperature, outdoor temperature, and HVAC power consumption over the 24 hours of a day. By examining the three graphs, trends in indoor temperature and HVAC usage can be observed over the course of the day:

- The indoor temperature at Field Sites 1 and 2 remained relatively constant over the course of a day. For August 2015, the average indoor temperature was approximately 76°F and 73°F for Field Sites 1 and 2, respectively.

- As seen in the figure, the indoor temperature profile of Field Site 3 increases later in the day toward afternoon-evening hours, and then decreases in the late evening-morning hours. This trend in is attributed to an indoor temperature profile programmed into the user interface at Field Site 3. The indoor temperature profile for Site 3 was approximately 73°F during the morning hours and peaked at 78°F during the late afternoon.

Also shown in the figure is the HVAC power demand of the VC equipment, highlighting these findings:

- The power profile of Field Sites 1 and 2 is consistent with the outdoor temperature profile. As the outdoor temperature and load increases at the residence, the power consumption and cooling output of the VC unit increases.
- The HVAC power consumption profile for Field Sites 1 and 2 tracks along with the outdoor temperature profile.
- The power consumption profile for Field Site 3 lags behind the outdoor temperature profile because of the temperature setpoint schedule for the VC system, which shifts the power consumption profile and daily maximum peak power demand to later in the day.

Continued investigation of the three field sites throughout this document will further examine the operation and usage of the VC systems.

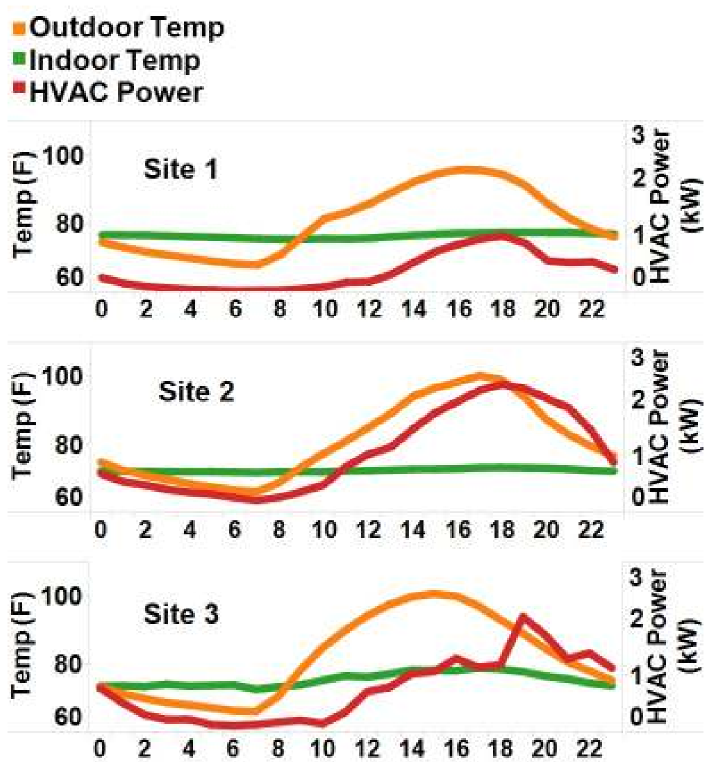

FIGURE 51. FIELD SITE 1, 2, AND 3 AVERAGE PROFILE – AUGUST 2015

OPERATIONAL CHARACTERISTICS OF VC FIELD SITES

Figure 52 through Figure 60 illustrate the operation of the VC equipment over the course of the monitored cooling season. The figures are grouped in sets by Field Site 1, 2, and 3, respectively. Each set includes three figures illustrating the usage and operation of the VC equipment for a selected timeframe or view of field data:

- The first two figures of each set include two daily profiles of operation: one extreme and one mild day based on average and peak outdoor temperature. The extreme day (August 15, 2015) consisted of an average outdoor temperature of ~90°F and a high of ~105°F, while the mild day (June 16, 2015) consisted of an average outdoor temperature of ~80°F and a high of ~95°F. The two daily profiles provide data on a one-minute timeframe for multiple field measurements, including outdoor temperature, attic temperature (when applicable), indoor temperature (when available), HVAC power consumption, unit cooling capacity, return temperature, and supply temperature.
- The third figure of each set provides operation of the VC equipment over the entire cooling season as a function of site outdoor temperature. This figure consists of unit power consumption, unit capacity, and EER for each minute of cooling operation for each VC system during cooling season data collection (i.e., each dot represents one minute of unit operation). Projected VC unit performance curves based on laboratory data for each system are overlaid on the field data. The projected performance curves are shown for maximum and minimum operation, shown visually as dashed lines on the figures.

The Figure 52, Figure 53, and Figure 54 for Field Site 1 suggest that the VC system was oversized for the home's typical loads. The VC system at Site 1 was sized at 4 tons, according to the ACCA Manual J calculation. The baseline system at Site 1 was also a nominal size of 4 tons. During the extreme outdoor temperature daily profile when outdoor temperatures were near 105°F, the VC system was operating near minimum cooling output and even cycled off to maintain the indoor temperature setpoint. For the mild outdoor temperature daily profile, the unit cycled frequently to maintain indoor conditions. Figure 54 demonstrates that throughout the monitored cooling season, the VC unit typically operated near minimum cooling output and well below the maximum capabilities of the system and below the design load of 38,000 Btu/h.

The heavy trees shading the residence provide a potential explanation for the equipment oversizing. A Manual J calculation typically does not account for the impact of heavy tree shading on the solar gain and design load of a residence. In locations where heavy tree shading is prevalent, additional calculations or assumptions may improve the accuracy of the Manual J design load. As seen in the laboratory assessment and Field Sites 2 and 3, VC equipment offers significant efficiency improvement at part-load operation. Properly sizing a VC system is key in order to achieve the designed efficiency.

The figures for Field Site 2 and 3 demonstrate that the VC equipment at these sites were sized appropriately. Field Site 2 contained the five-stage system, while Field Site 3 contained a fully variable unit. The figures for Field Site 2 enable observation of the five steps of unit operation. Over the range of outdoor temperatures, the system at Site 2 operated at the various levels of output to satisfy the loads of the residence. That is, the VC unit at Site 2 rarely operated at the minimum level of operation (step 1) and typically adjusted to step 2 quickly upon unit start-up.

Field Site 3 demonstrated variable cooling output over the daily profiles and cooling season data shown. The VC unit at Site 3 demonstrated a significant amount of operation at the maximum and minimum levels of output. Minimum output would occur during part-load or unit-cycling situations. Maximum output is known to occur in VC equipment when the difference in the indoor temperature and setpoint is 2°F or greater. The indoor schedule imposed at Site 3 regularly forced the VC unit to maximum operation to respond to the difference in indoor temperature and setpoint.

For Field Sites 1, 2, and 3, all of the power consumption, cooling capacity, and efficiency curves for the entire cooling season were agreed well with the expected performance based on collected field data and the field characteristics at each site.

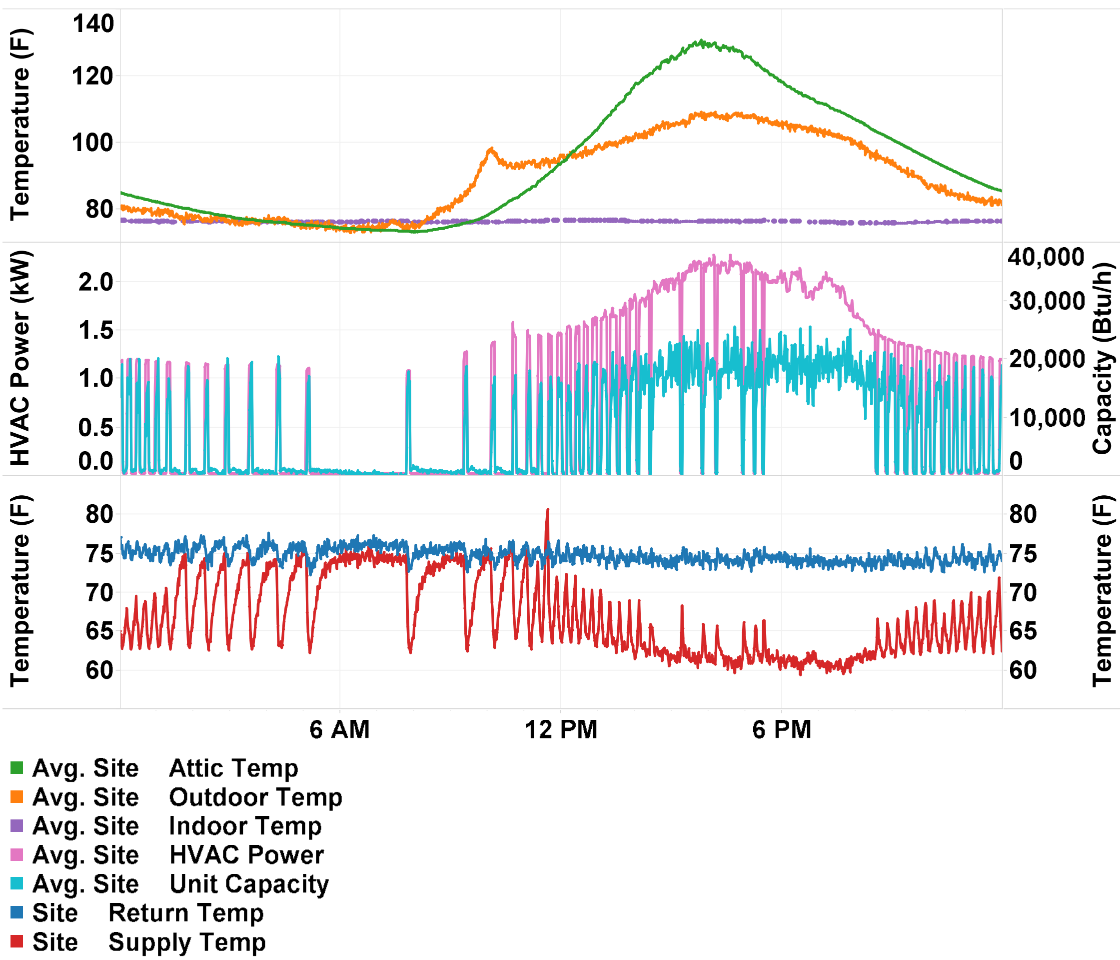

FIGURE 52. FIELD SITE 1 PROFILE – AUGUST 15TH 2015 – EXTREME OUTDOOR TEMPERATURE DAY

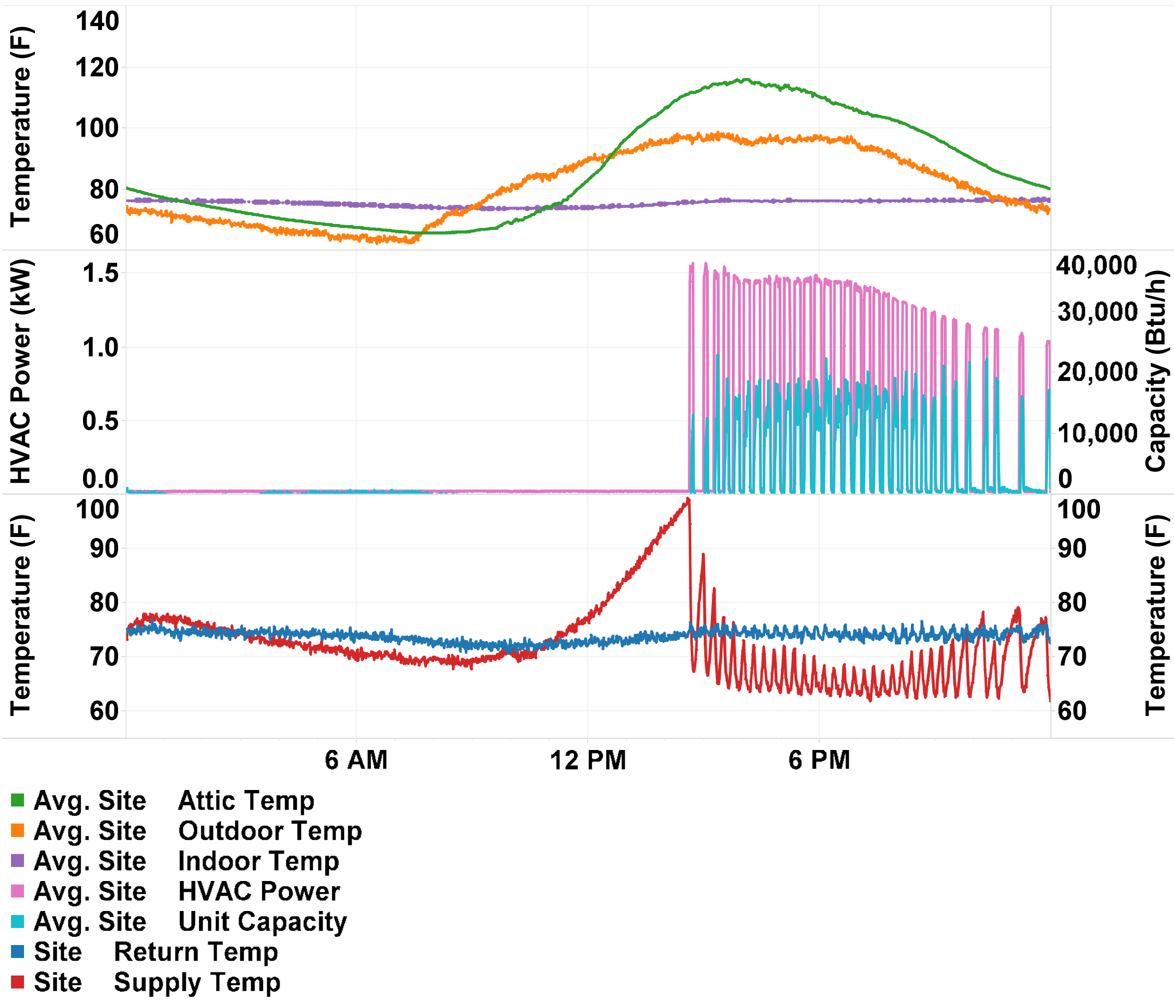

FIGURE 53. FIELD SITE 1 PROFILE – JUNE 16TH 2015 – MILD OUTDOOR TEMPERATURE DAY

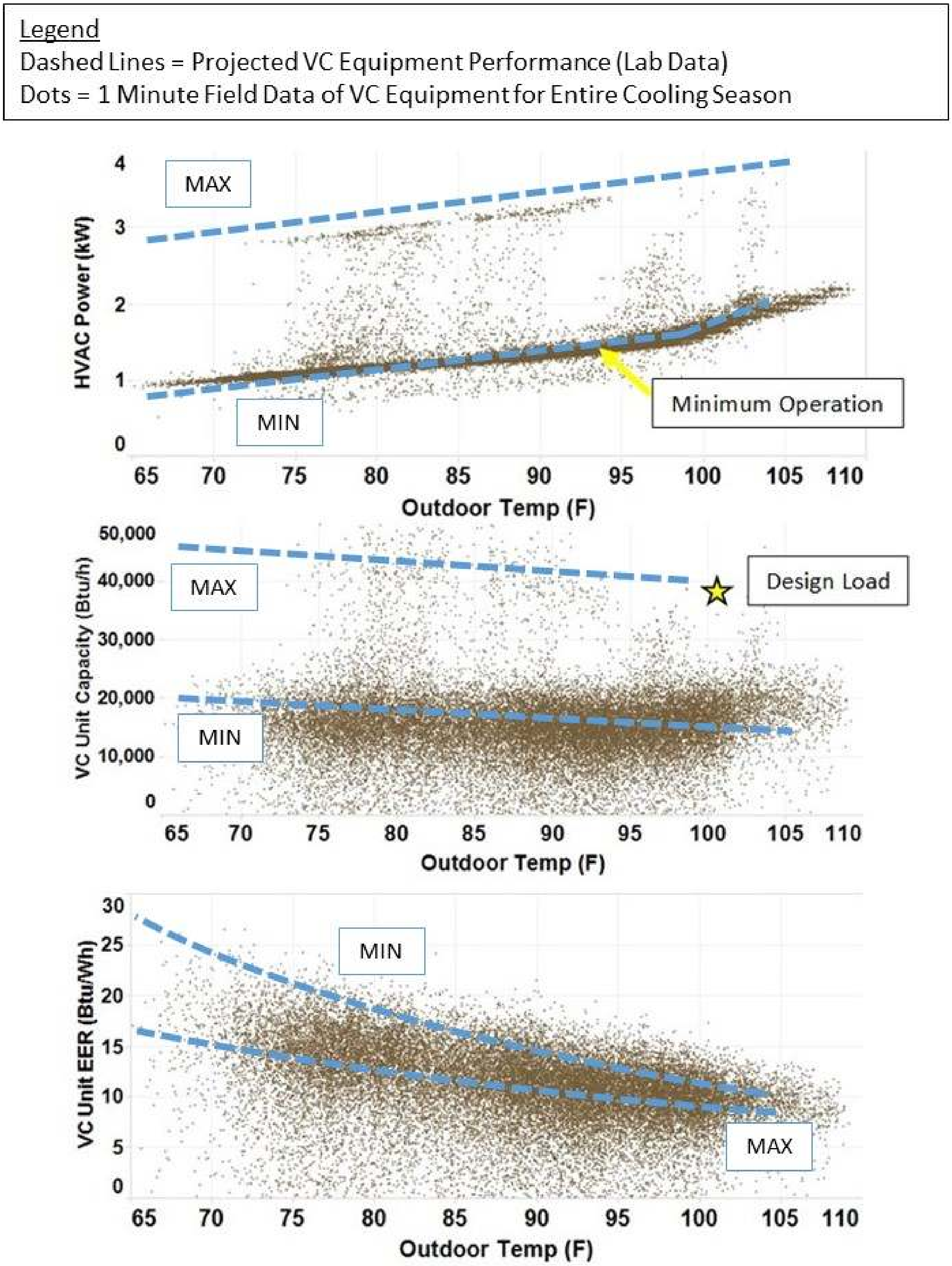

FIGURE 54. VC OPERATION AT FIELD SITE 1: HVAC POWER CONSUMPTION, CAPACITY, AND EFFICIENCY

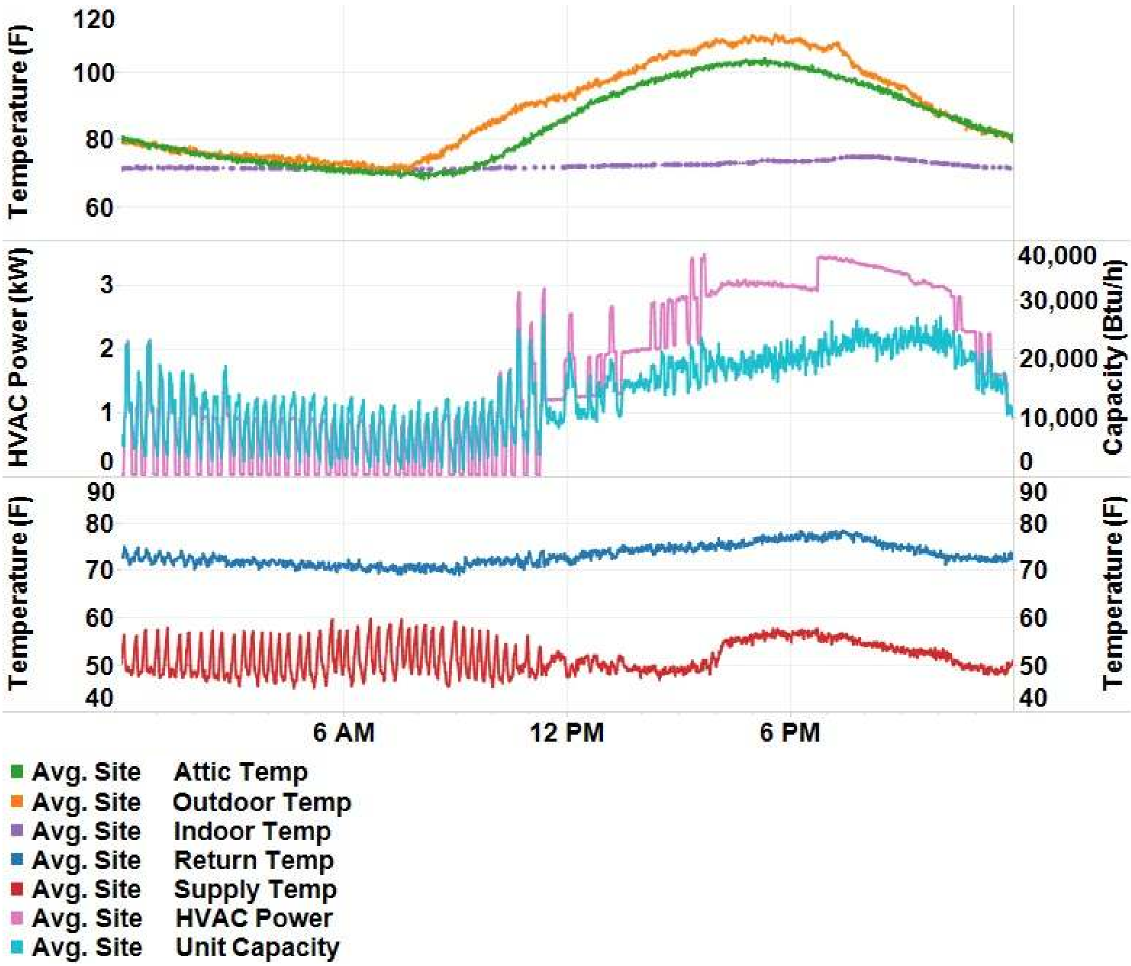

FIGURE 55. FIELD SITE 2 PROFILE – AUGUST 15TH 2015 – EXTREME OUTDOOR TEMPERATURE DAY

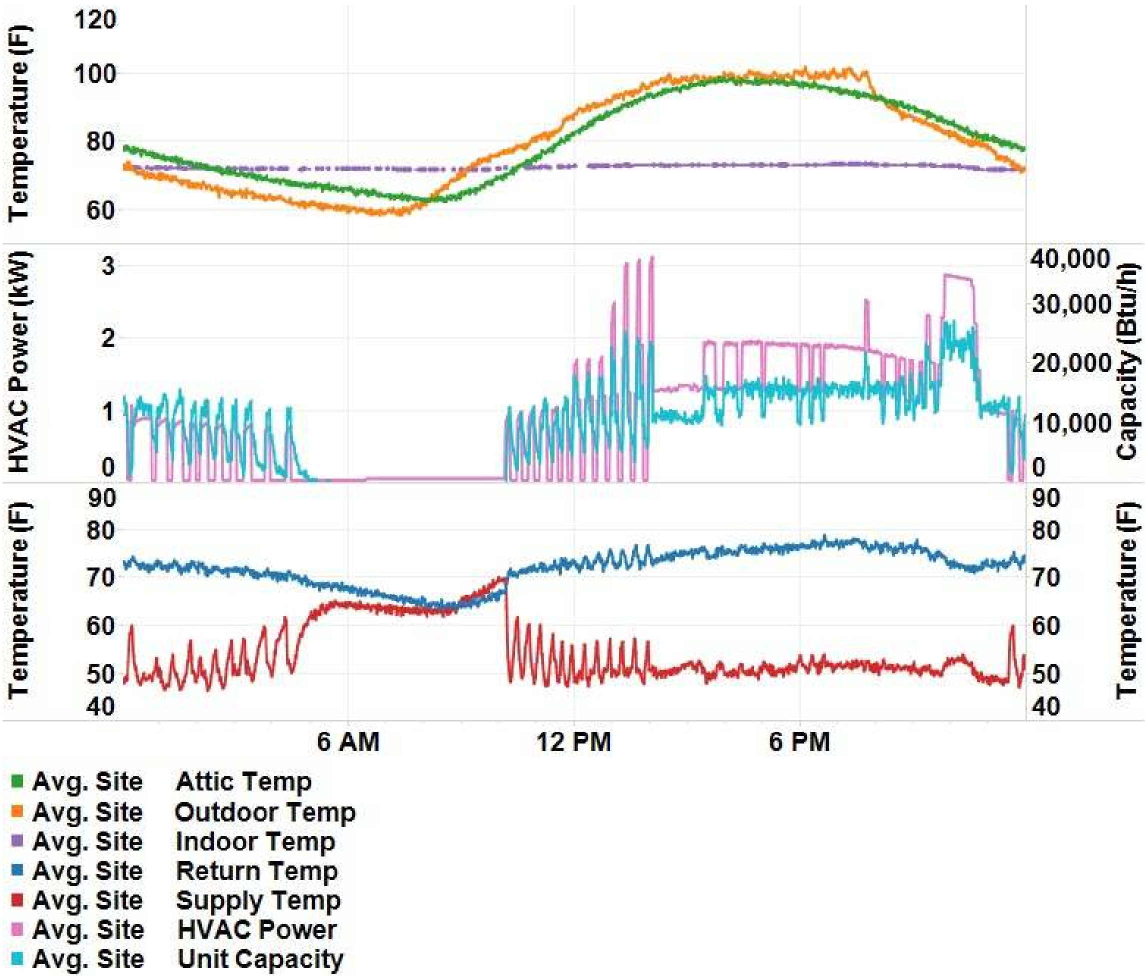

FIGURE 56. FIELD SITE 2 PROFILE – JUNE 16TH 2015 – MILD OUTDOOR TEMPERATURE DAY

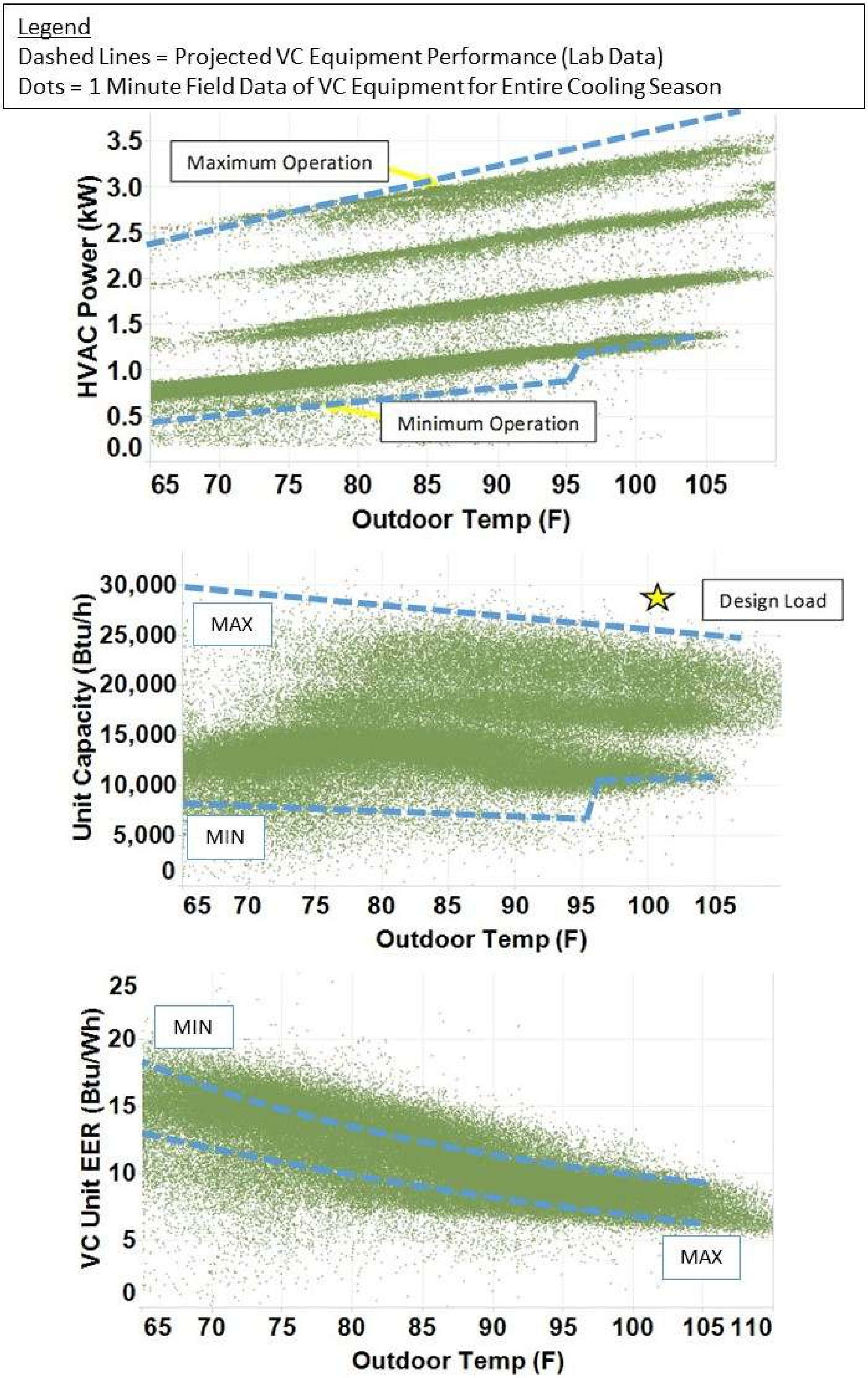

FIGURE 57. VC OPERATION AT FIELD SITE 2: HVAC POWER CONSUMPTION, CAPACITY, AND EFFICIENCY

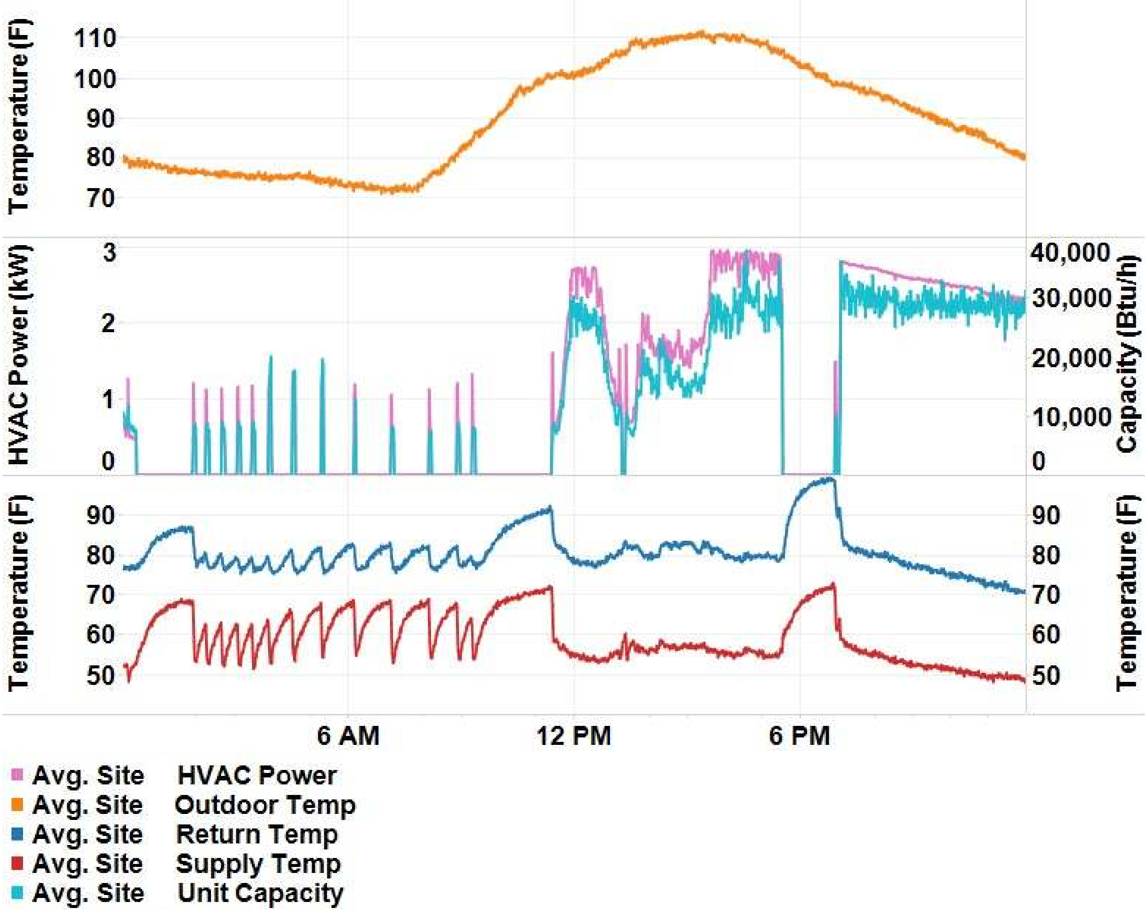

FIGURE 58. FIELD SITE 3 PROFILE – AUGUST 15TH 2015 – EXTREME OUTDOOR TEMPERATURE DAY

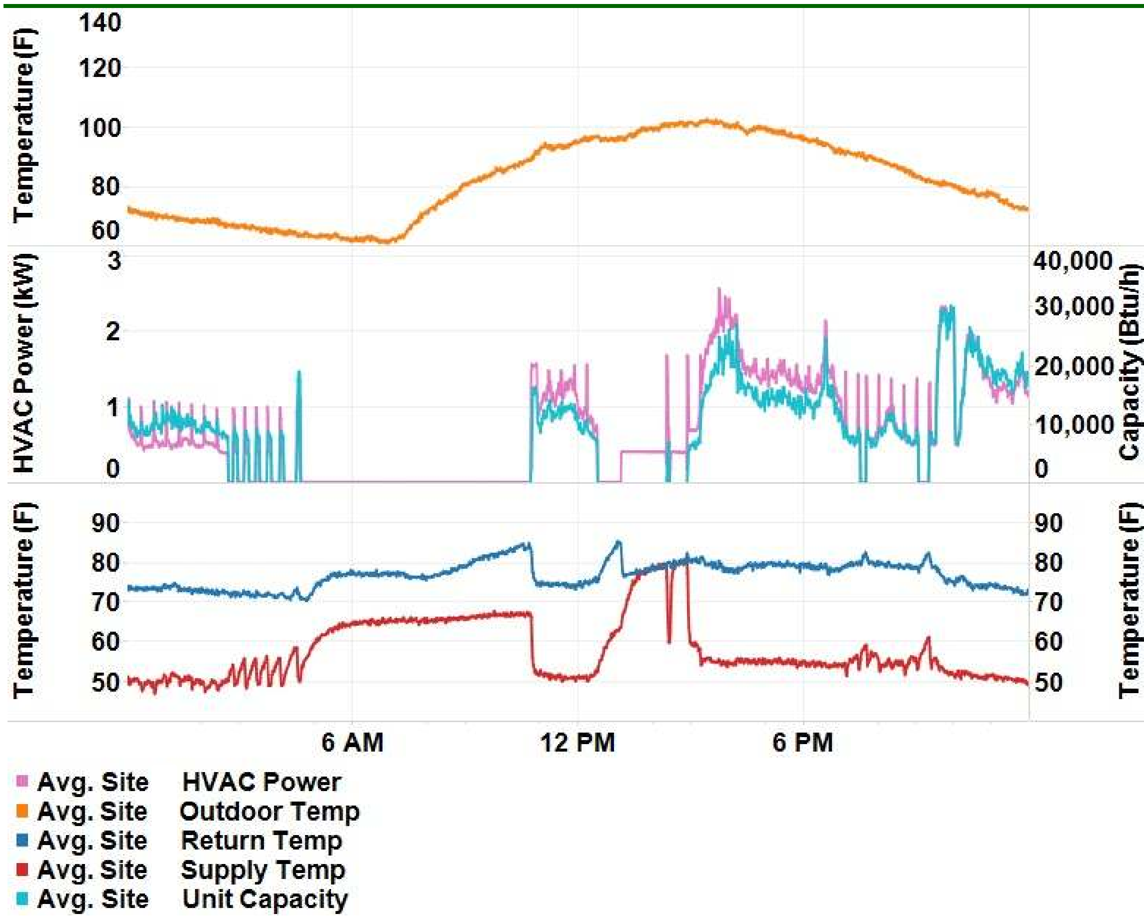

FIGURE 59. FIELD SITE 3 PROFILE – JUNE 16TH 2015 – MILD OUTDOOR TEMPERATURE DAY

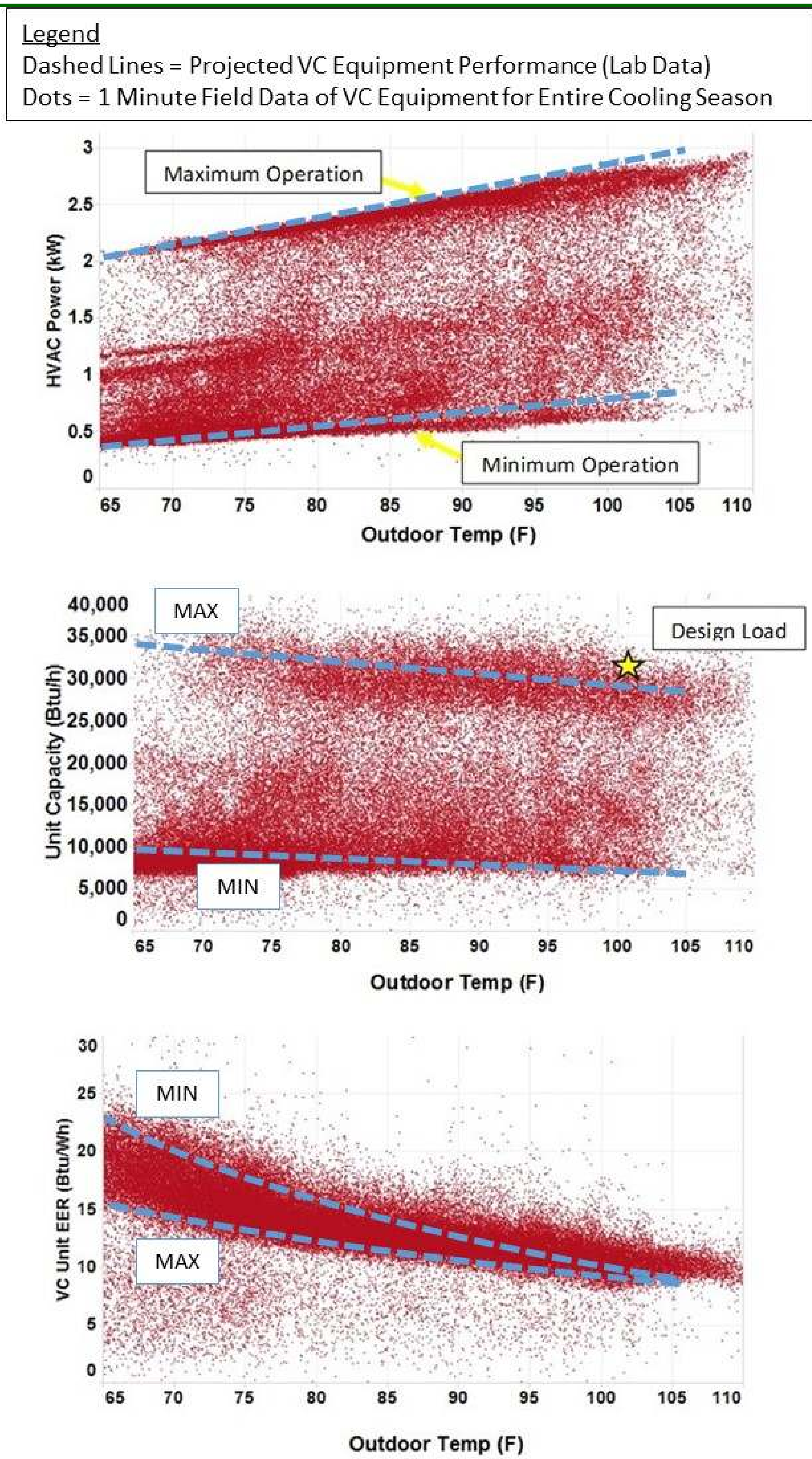

FIGURE 60. VC OPERATION AT FIELD SITE 3: HVAC POWER CONSUMPTION, CAPACITY, AND EFFICIENCY

VC Equipment Field Efficiency

Using the collected laboratory data for the three systems, energy modeling was conducted for an assumed outdoor temperature profile, indoor condition, and external static pressure curve. Details of this modeling and results are obtained in the *Lab Analysis* section. The laboratory evaluation assumed indoor conditions of 75°F dry-bulb temperature, 50% RH, an external static pressure curve of 0.5 inch WC at nominal airflow, and typical climate data for California Climate Zone 10. To examine the equipment of the field VC systems, the laboratory modeling results are presented in Table 31.

Table 31. Modeled Annual Efficiency of Laboratory Equipment

	Lab VC System 1	Lab VC System 2	Lab VC System 3
Rated SEER (Btu/Wh)	22.0	18.0	19.5
Modeled Annual Equipment Cooling Efficiency (Btu/Wh)*	15.5	12.3	14.7

**Based on Lab Data, Lab Assumptions of Indoor Air and Static Pressure, and California Climate Zone 10*

Using the laboratory data and adjusting for the characteristics of each field site, a similar estimation was made of the predicted performance of the VC field equipment. Operating characteristics at each field site differed slightly from the laboratory assumptions. The field sites had external static pressure curves near 0.9 inch WC at nominal airflow and varying indoor humidity levels during equipment operation.

The study also determined the actual efficiency based on field data was determined over the cooling season. Both annual efficiency values are shown in Table 32. Field Sites 2 and 3 demonstrated strong agreement between the estimated and actual annual equipment efficiency. Field Site 1 did not demonstrate good agreement between the annual efficiencies, as the actual efficiency was significantly lower than the predicted equipment efficiency, possibly due to equipment oversizing. The laboratory data and testing capabilities did not allow for an assessment of unit cycling and equipment oversizing. The industry assumption for cycling losses is typically between 12% and 25%.

Table 32. Estimated and Actual Annual Efficiency of Field Equipment

	Field Site 1	Field Site 2	Field Site 3
Rated SEER (Btu/Wh)	20.0	17.5	21.0
Estimated Annual Equipment Cooling Efficiency (Btu/Wh)*	13.3	11.3	13.9
Annual Equipment Cooling Efficiency (Btu/h) - Field Data	10.4	11.3	13.7

**Based on lab data, field site characteristics of indoor air and static pressure, and local climate*

ENERGY ANALYSIS BASED ON UTILITY BILLING DATA

This section compares the energy consumption of the baseline and VC equipment at each of the three field sites. For the baseline system, utility billing data for each of the three residences served as the basis for the energy consumption comparison. For the VC systems, the field monitoring data from 2015 served as the basis for the energy consumption comparison. The primary metric used to compare energy usage between the baseline and VC systems is daily average outdoor temperature, as taken from a weather station in California Climate Zone 10 for both 2014 and 2015.

To explore the premise of the relationship between billing data and HVAC power consumption for each field site, the team collected and compared field data and utility billing data for the month of July 2015. Figure 61 through Figure 63 provide an hourly average profile for July 2015 for the billing data (whole home) and collected field data (HVAC only). For all field sites, a strong correlation existed between the July 2015 billing data and field data of HVAC power consumption. Thus, the billing data comparison may be assumed to be a fair representation of the HVAC power consumption for each of the field sites.

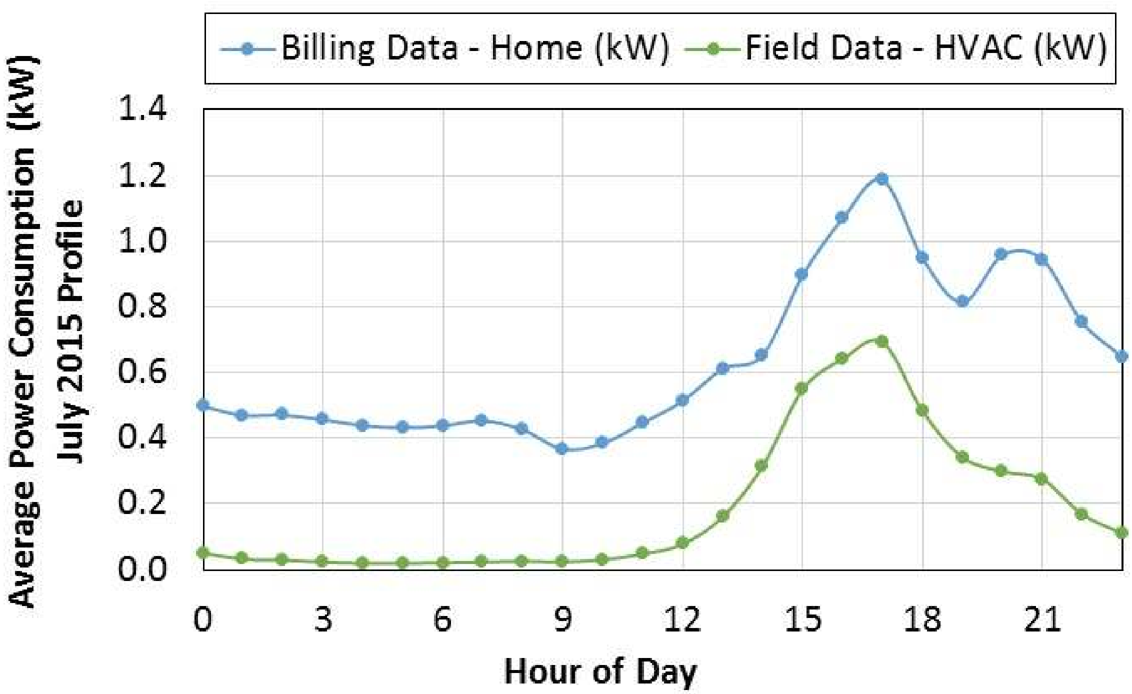

FIGURE 61. SITE 1: JULY 2015 BILLING DATA VS. JULY 2015 FIELD DATA HVAC PROFILE

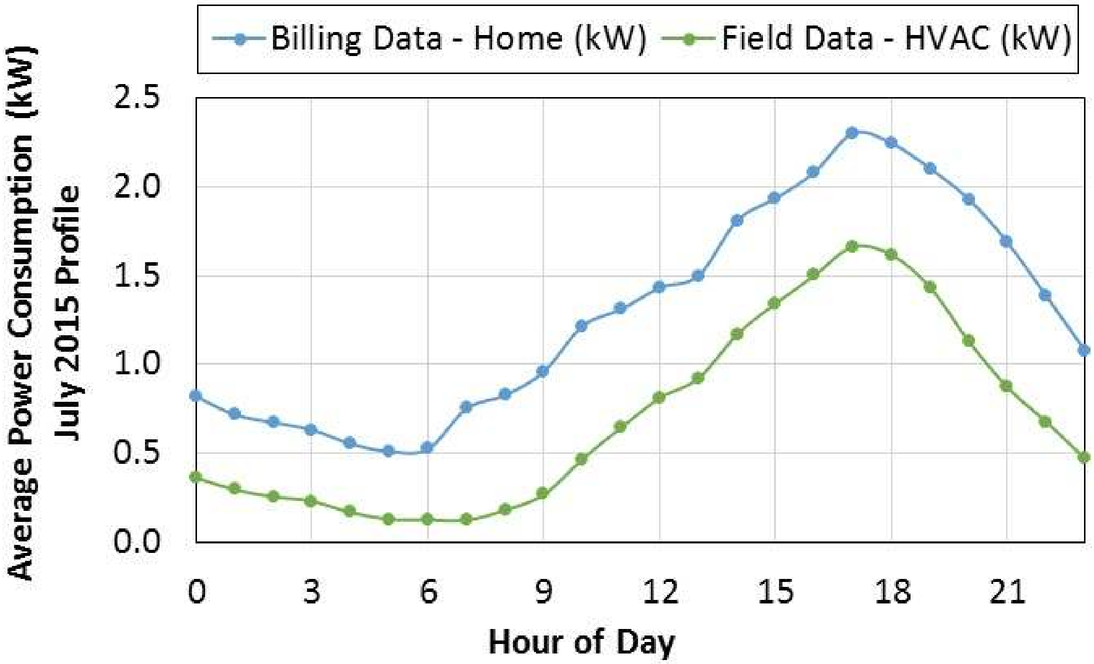

FIGURE 62. SITE 2: JULY 2015 BILLING DATA VS. JULY 2015 FIELD DATA HVAC PROFILE

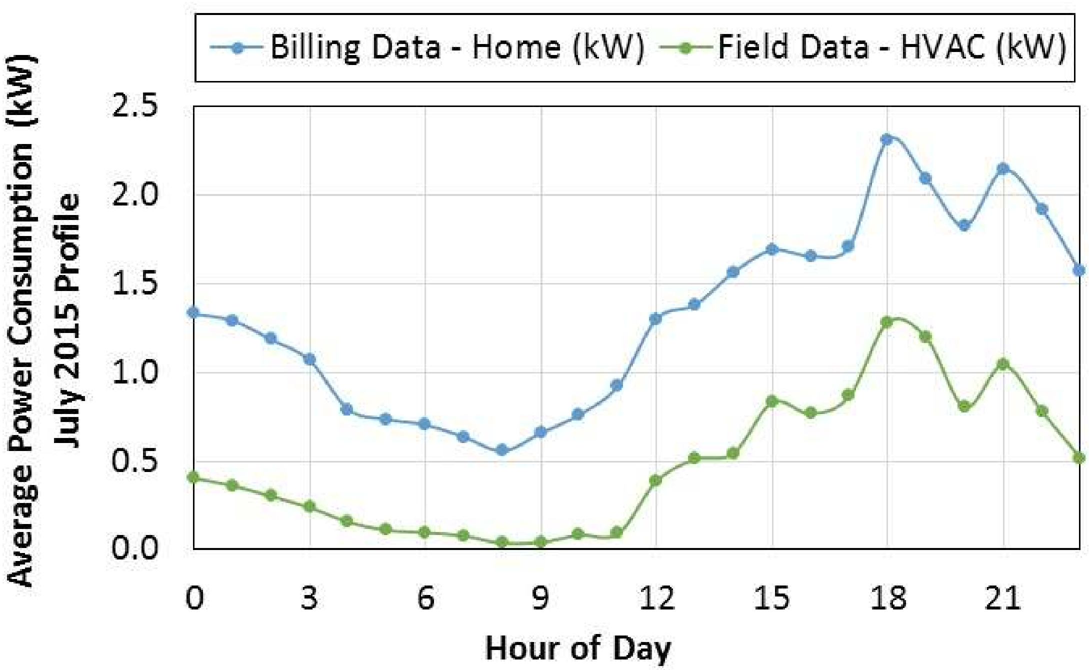

FIGURE 63. SITE 3: JULY 2015 BILLING DATA VS. JULY 2015 FIELD DATA HVAC PROFILE

To explore the validity of the baseline to VC energy consumption comparison, one month (July) of billing data from each cooling season (2014 and 2015) was selected for comparison. Figure 64 shows the average outdoor temperature profile for

California Climate Zone 10 for the selected months. Although the outdoor temperature profile for July 2014 is slightly warmer on average, the two selected months show similar trends in the outdoor temperature. It would be expected that two similar outdoor temperature profiles would result in similar loads and similar billing data (or HVAC power consumption) profiles for each residence.

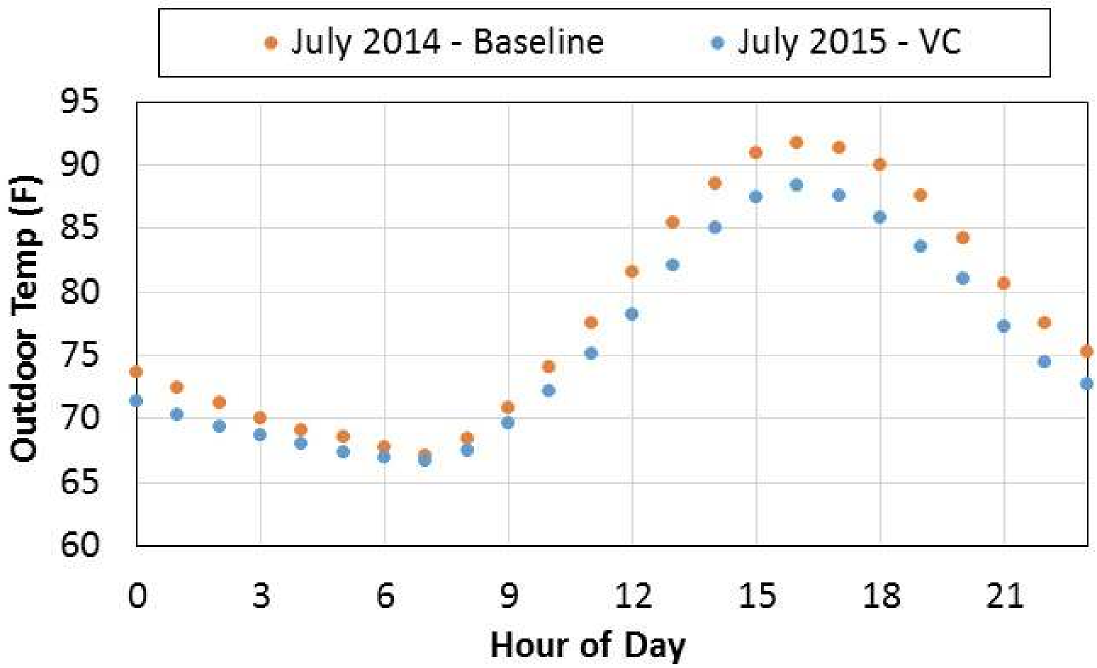

FIGURE 64. JULY 2014 VS. JULY 2015 OUTDOOR TEMPERATURE PROFILE FOR FIELD SITES

For months under consideration (July 2014 and 2015), the team constructed hourly average power consumption profiles from utility billing data. Figure 65 through Figure 67 show the utility billing data profile for July 2014 (baseline equipment) and July 2015 (VC equipment) for the three sites. The power consumption profile trends for 2014 are highly similar to Field Sites 1 and 3 between July 2014 and 2015. For instance at Field Site 1, the July 2014 and 2015 billing data curves are relatively flat until early afternoon and then rise and peak in similar manners. Due to these similar profiles, similar usage of the baseline and VC HVAC equipment usage at these sites might be assumed. Field Site 2 demonstrated slightly different profile trends between the 2014 and 2015 billing data, suggesting slightly different usage between the baseline and VC HVAC equipment operation at Field Site 2.

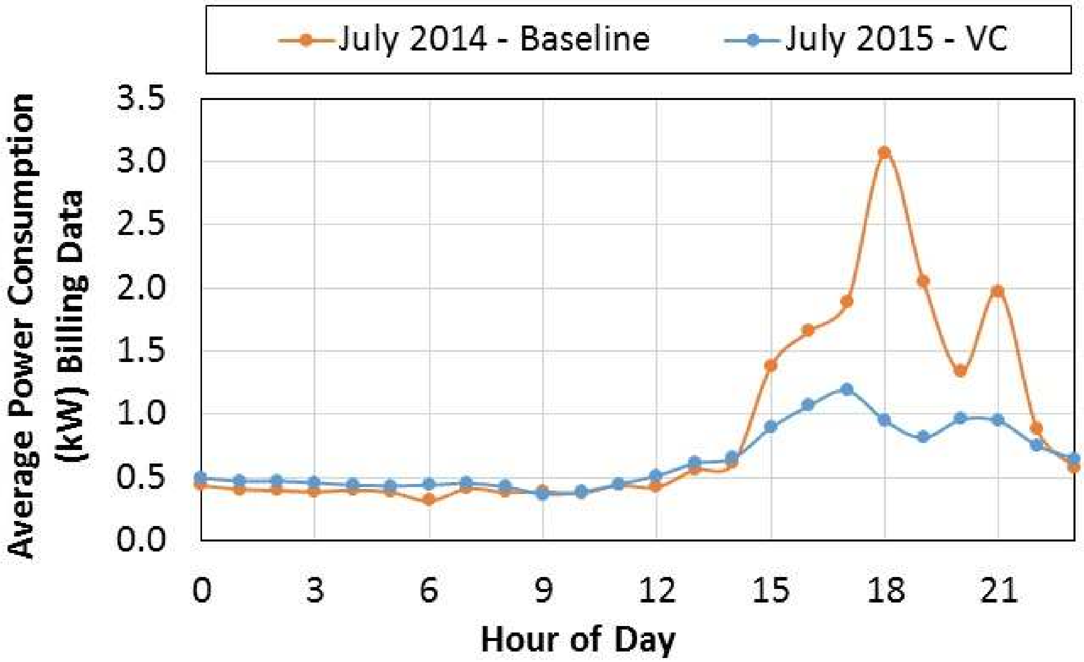

FIGURE 65. FIELD SITE 1: JULY 2014 VS. JULY 2015 BILLING DATA PROFILE

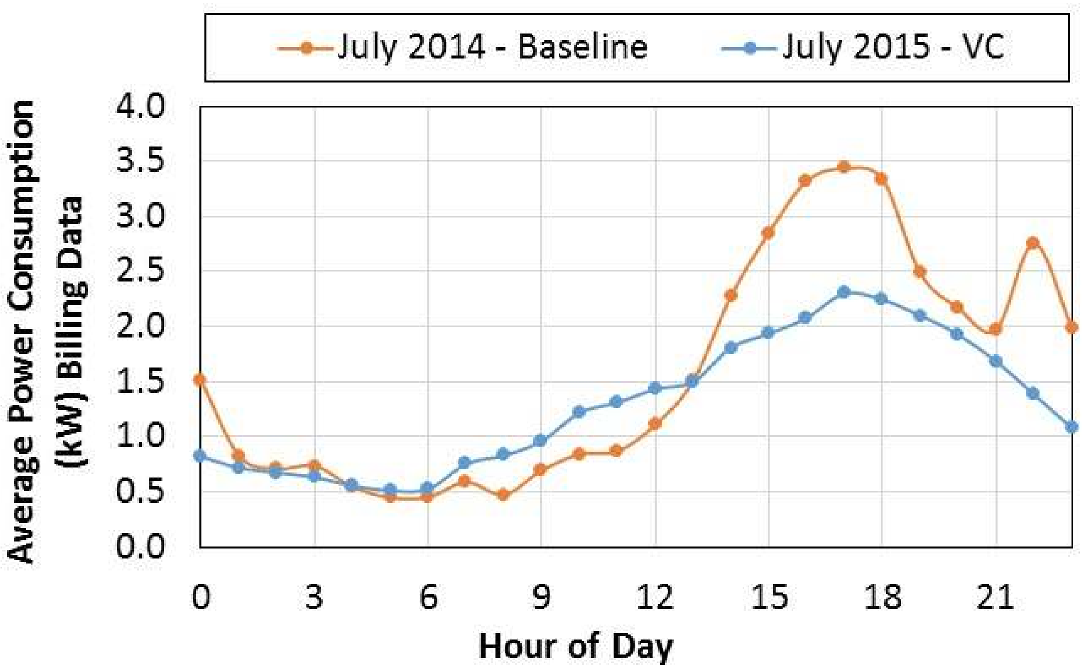

FIGURE 66. SITE 2: JULY 2014 VS. JULY 2015 BILLING DATA PROFILE

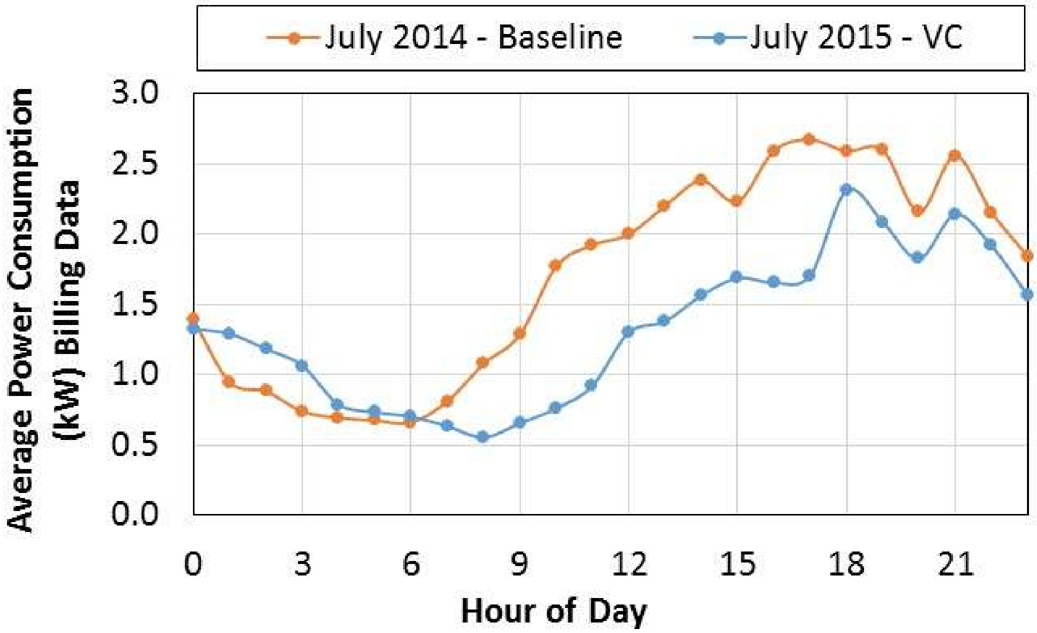

FIGURE 67. SITE 3: JULY 2014 VS. JULY 2015 BILLING DATA PROFILE

For each of the three field sites, utility billing data and collected field data were used to determine the baseline and VC HVAC energy consumption based on average daily outdoor temperature. The comparison used outdoor temperature data from a weather station within California Climate Zone 10. The results of the analysis for each of the three field sites are provided in the Table 33. Average daily HVAC energy usage was determined for average outdoor temperatures from 70°F to 90°F in 5°F increments. The estimated percent energy savings from the baseline to VC system for each outdoor temperature bin is provided on the right side of the table. Based on TMY data for Climate Zone 10, the typical weighting of a daily outdoor temperature bin over a cooling season is as follows:

- 59% for 70°F to 74°F
- 28% for 75°F to 79°F
- 11% for 80°F to 84°F
- 2% for 85°F to 89°F

These weighted values were used to determine the potential energy savings of each VC field site for a typical year.

TABLE 33. ENERGY USAGE COMPARISON BETWEEN BASELINE AND VC SYSTEMS AT FIELD SITES

Field Site 1			
Average Daily Outdoor Temperature Range (F)	Daily HVAC Energy (kWh)		Energy Savings from Baseline to VCAC
	Baseline - Billing Data	VCAC - Field Data	
70 - 74	2.3	2.1	9.4%
75 - 79	6.8	4.7	31.5%
80 - 84	13.8	7.7	44.0%
85 - 89	19.8	13.0	34.2%

Field Site 2			
Average Daily Outdoor Temperature Range (F)	Daily HVAC Energy (kWh)		Energy Savings from Baseline to VCAC
	Baseline - Billing Data	VCAC - Field Data	
70 - 74	15.4	12.8	17.4%
75 - 79	21.3	17.6	17.1%
80 - 84	29.1	23.2	20.2%
85 - 89	35.0	30.9	11.8%

Field Site 3			
Average Daily Outdoor Temperature Range (F)	Daily HVAC Energy (kWh)		Energy Savings from Baseline to VCAC
	Baseline - Billing Data	VCAC - Field Data	
70 - 74	8.5	7.1	16.3%
75 - 79	18.9	13.2	29.8%
80 - 84	31.1	16.9	45.6%
85 - 89	43.9	21.5	51.0%

Based on TMY data for California Climate Zone 10, the expected energy savings for each field site was determined for a typical cooling season. Table 34 provides the estimated yearly HVAC energy usage for baseline and VC systems, the energy savings, and the percent savings. The estimated percent savings from the baseline to VC systems was 29.6%, 17.6%, and 30.0% for Field Sites 1, 2, and 3, respectively.

TABLE 34. ESTIMATED ENERGY SAVINGS FOR FIELD SITES DURING TYPICAL COOLING SEASON

Field Site	Typical Yearly HVAC Cooling Energy (kWh)		Energy Savings from Baseline to VCAC (%)	Energy Savings from Baseline to VCAC (kWh)
	Baseline	VCAC		
1	878	619	29.6%	260
2	3,239	2,670	17.6%	570
3	2,486	1,740	30.0%	746

The outdoor temperature profile for the period of field data collection (2015) for the field sites was comparable to a TMY. The actual VC HVAC energy usage and the estimated savings for 2015 is provided in Table 35. Site energy savings for 2015 ranged from 337 kWh to 821 kWh.

TABLE 35. ESTIMATED ENERGY SAVINGS FOR FIELD SITES DURING 2015 COOLING SEASON

Field Site	2015 VCAC Field Data HVAC Cooling Energy (kWh)	2015 Estimated Energy Savings from Baseline to VCAC (kWh)
1	801	337
2	2,840	605
3	1,919	821

SYSTEM EFFECTS AT VC FIELD SITES

This section presents analysis and results of two system effects—thermal duct loss and the addition of MERV 16 filters—that were identified for examination. Specifically, the team evaluated how thermal duct losses varied with varying airflow of the VC unit and how much external static pressure the MERV 16 filters added to duct system.

THERMAL DUCT LOSSES

To investigate thermal duct losses, additional supply air temperature instrumentation was added to selected field sites. During the field monitoring setup at Field Site 1 and 2, four temperature sensors were placed in approximately 10-foot increments along a run of supply ductwork, beginning at the unit outlet. These additional supply temperature readings could not be installed at Site 3, due to the limited moveable space for the installers because of the underfloor distribution and ductwork layout and fear of damaging the ductwork. As previously highlighted, Field Site 1 operated predominately near minimum operation throughout the cooling season. Therefore, Field Site 2, with a significant usage of VC equipment at both low and high operation and airflow, was the primary site for investigating thermal duct losses.

For Field Site 2, Figure 68 provides the average thermal losses at two levels of operation (or airflows) as a function of attic temperature. Sensible thermal losses were correlated to the temperature difference between the supply unit outlet and the supply measurement at approximately 30 feet downstream of the supply ductwork. As observed in the figure, the thermal losses approximately double between low and high operation and airflow. The calculation of sensible duct loss in Figure 68 assumes that no duct air leakage was present between the unit outlet and downstream temperature measurement. Duct loads on an HVAC system may involve sensible loss, latent loss, and air leakage. The measured sensible duct loss, as expected, increased with increasing attic temperature.

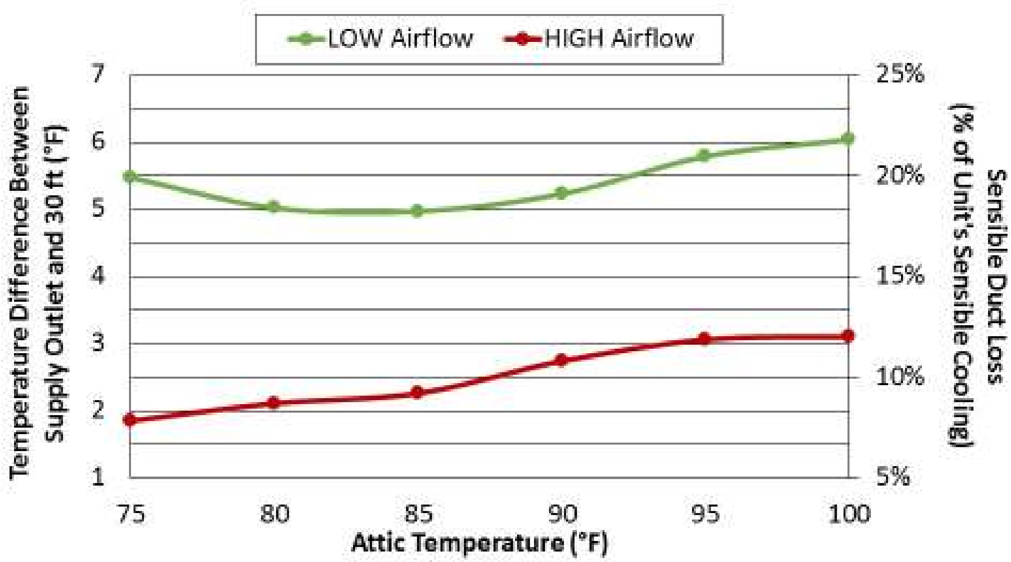

FIGURE 68. DUCT LOSS COMPARISON AT FIELD SITE 2 FOR LOW AND HIGH OPERATION

MERV 16 FILTERS

A MERV 16 filter was installed at each of the sites, based on the installing contractor's suggestion that the filter was part of a typical "high efficiency equipment" installation. For each site, external static pressure was measured at nominal and part-load airflow both with and without a MERV 16 filter. Table 36 provides the unit external static pressure measurements with and without the MERV 16 filter. At nominal airflow, the added ESP ranged from 0.1 to 0.19 inch WC. This additional static would contribute to additional energy usage in the indoor blower, as described in the *Laboratory Assessment* section and documented in Table 15.

TABLE 36. EXTERNAL STATIC PRESSURE OF VC SYSTEM WITH AND WITHOUT MERV 16 FILTER

		SITE 1	SITE 2	SITE 3
High Airflow	Approximate Airflow (CFM)	1,450	1,000	1,200
	With MERV 16 Filter (inch WC)	0.86	0.58	0.92
	Without MERV 16 Filter (inch WC)	0.76	0.41	0.73
	Difference in Static Pressure (inch WC)	0.10	0.17	0.19
Intermediate or Low Airflow	Approximate Airflow (CFM)	1,275	300	600
	With MERV 16 Filter (inch WC)	0.70	0.11	0.29
	Without MERV 16 Filter (inch WC)	0.63	0.06	0.21
	Difference in Static Pressure (inch WC)	0.07	0.05	0.08

FIELD DR EVALUATION

OVERVIEW

As documented earlier, the field DR assessment consisted of two test conditions:

- Test 1 – DR Activated at ~15 minute cycle
- Test 2 – DR Activated at ~60 minute cycle

The aim was to conduct the field DR assessment during warm outdoor temperatures (80°F or higher). Due to the nature of the field DR test and test setup, a project engineer or technician was required to physically be at each site during the DR assessment. The project engineer traveled to the sites in mid-October for the DR field setup and assessments; during this time, the outdoor temperatures ranged from approximately 60°F to 70°F. An arrangement was made with the project's local HVAC contractor to perform the field DR assessments during another period when the temperatures were appropriate for the DR evaluation. For Field Site 2 and Field Site 3, the field DR test plan was successfully performed. For Field Site 1, a successfully DR assessment was not completed due to low outdoor temperatures and the limited availability of the homeowner and contractor during the DR testing window.

EVALUATION

During the field DR assessment, the DR function of the VC equipment successfully operated at Field Sites 2 and 3. Based on manufacturer discussions and knowledge from other laboratory assessments, the team assumed that VC unit operation is heavily dependent upon the difference in the indoor condition and the unit setpoints. After a DR event was activated at the sites, the "resume operation" of the equipment depended on the conditions at the site.

As discovered in the laboratory assessment, a VC unit may continue to operate the indoor blower during DR operation, and the equipment used at Sites 2 and 3 exhibited this trend during the laboratory assessment. In the field assessment, demonstrate indoor blower operation occurred only once during DR operation. The reason for the varying operation of the indoor blower under DR operation is unknown, and the manufacturers are being asked to clarify.

For each of the DR field tests, a graph and summary table illustrate the DR activate and inactive time periods, as shown in Figure 69 through Figure 72 and Table 37 through Table 40. The graphs provide outdoor and return or indoor temperature measurements. The summary tables primarily provides the average field data during each time frame of interest.

The outdoor and return measurements were both recorded with an identical, hard-wired instrument, while the indoor temperature was recorded with a dissimilar, wireless instrument. The outdoor and return instruments provided reliable 1-minute interval data, while the indoor temperature instrument provided measurements intermittently based on connectivity to the data acquisition system. Thus, the return measurement was given precedence over the indoor measurement when appropriate. At Field Site 1, the unit return was in the attic and thus the indoor measurement was used to characterize the indoor space temperature. For Field Sites 2 and 3, the return of the unit was near the occupied space and given precedence over the indoor measurement due to reliability in data collection.

FIELD DR ASSESSMENT – VC SYSTEM 2

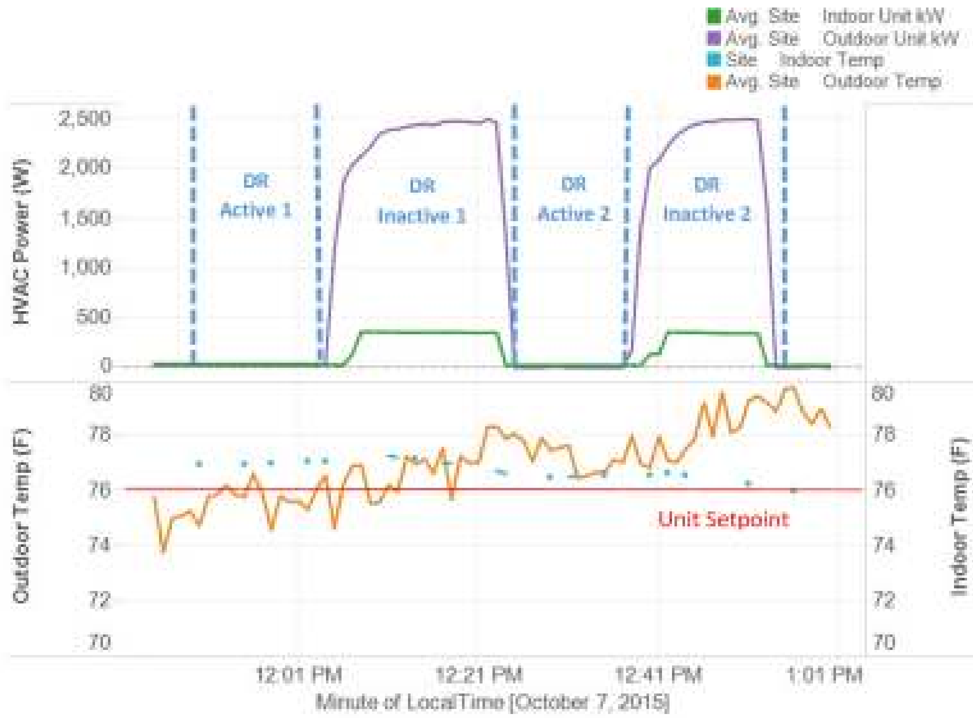

FIGURE 69. DR FIELD TEST 1 TEMPERATURES AND DR OPERATION – FIELD SITE 2

TABLE 37. DR FIELD TEST 1 SUMMARY – FIELD SITE 2

	DR ACTIVE 1	DR INACTIVE 1	DR ACTIVE 2	DR INACTIVE 2
Indoor Temperature Setpoint (°F)	76	76	76	76
Avg Outdoor Temperature (°F)	75.5	76.7	77.2	78.1
Avg Outdoor Relative Humidity (%)	50.2	47.3	45.7	46.0
Avg Attic Temperature (°F)	76.7	77.9	78.6	79.3
Avg Attic Humidity (%)	55.4	52.4	50.7	49.4
Avg Indoor Temperature (°F)	77.0	77.1	76.5	76.5
Avg Indoor Relative Humidity (%)	53.9	51.3	50.1	49.2
Avg Return Temperature (°F)	74.3	74.5	74.0	74.1
Avg Return Humidity (%)	56.5	53.4	51.4	49.8
Avg Supply Temperature (°F)	75.9	59.9	57.8	56.6
Avg Supply Humidity (%)	53.5	75.0	83.6	78.2
Avg Indoor Unit Power (W)	20.4	305.5	20.8	273.5
Avg Outdoor Unit Power (W)	34.6	2,296.5	9.1	2,166.3
Max HVAC Power (W)	55.8	2,848.5	31.0	2,842.5

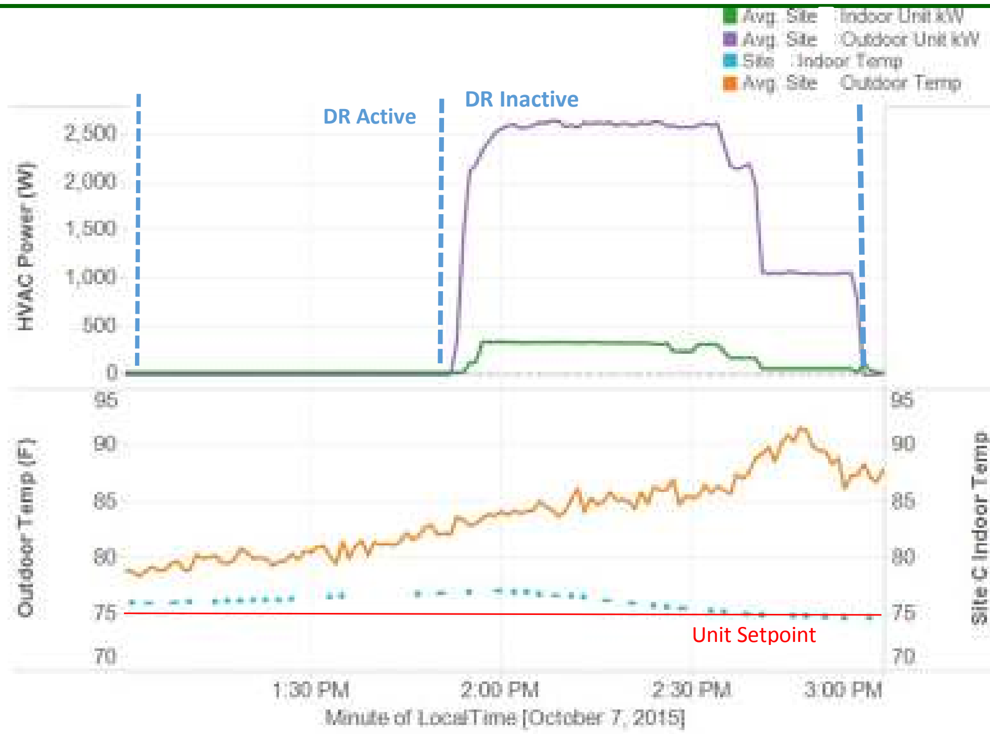

FIGURE 70. DR FIELD TEST 2 TEMPERATURES AND DR OPERATION – FIELD SITE 2

TABLE 38. DR FIELD TEST 2 SUMMARY - FIELD SITE 2

	DR ACTIVE	DR INACTIVE
Indoor Temperature Setpoint (°F)	76	76
Avg Outdoor Temperature (°F)	80.2	86.2
Avg Outdoor Relative Humidity (%)	42.7	36.6
Avg Attic Temperature (°F)	81.7	84.0
Avg Attic Humidity (%)	46.1	41.4
Avg Indoor Temperature (°F)	76.3	76.0
Avg Indoor Relative Humidity (%)	49.0	45.6
Avg Return Temperature (°F)	76.3	74.5
Avg Return Humidity (%)	48.4	47.2
Avg Supply Temperature (°F)	67.4	54.5
Avg Supply Humidity (%)	66.4	79.4
Avg Indoor Unit Power (W)	20.5	233.7
Avg Outdoor Unit Power (W)	9.8	2,179.2
Max HVAC Power (W)	30.7	2,966.4

FIELD DR ASSESSMENT – VC SYSTEM 3

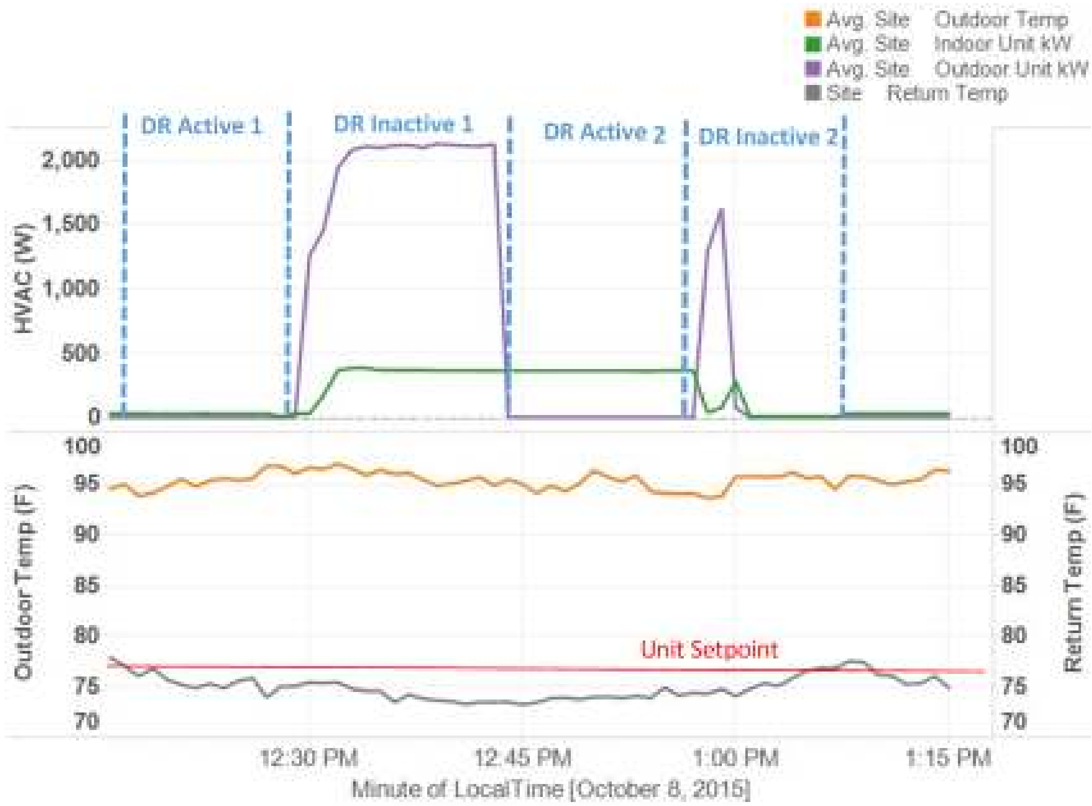

FIGURE 71. DR FIELD TEST 1 TEMPERATURES AND DR OPERATION – FIELD SITE 3

TABLE 39. DR FIELD TEST 1 SUMMARY – FIELD SITE 3

	DR ACTIVE 1	DR INACTIVE 1	DR ACTIVE 2	DR INACTIVE 2
Indoor Temperature Setpoint (°F)	77	77	77	77
Avg Outdoor Temperature (°F)	95.0	95.8	94.9	95.1
Avg Outdoor Relative Humidity (%)	22.3	20.6	19.7	19.4
Avg Return Temperature (°F)	75.9	74.3	73.9	75.6
Avg Return Humidity (%)	54.9	54.8	56.6	53.8
Avg Supply Temperature (°F)	65.7	56.0	64.3	63.7
Avg Supply Humidity (%)	90.6	89.5	90.3	90.0
Avg Indoor Unit Power (W)	34.5	314.0	364.3	85.1
Avg Outdoor Unit Power (W)	6.4	1,858.4	6.4	192.8
Max HVAC Power (W)	41.7	2,495.1	372.0	1,705.2

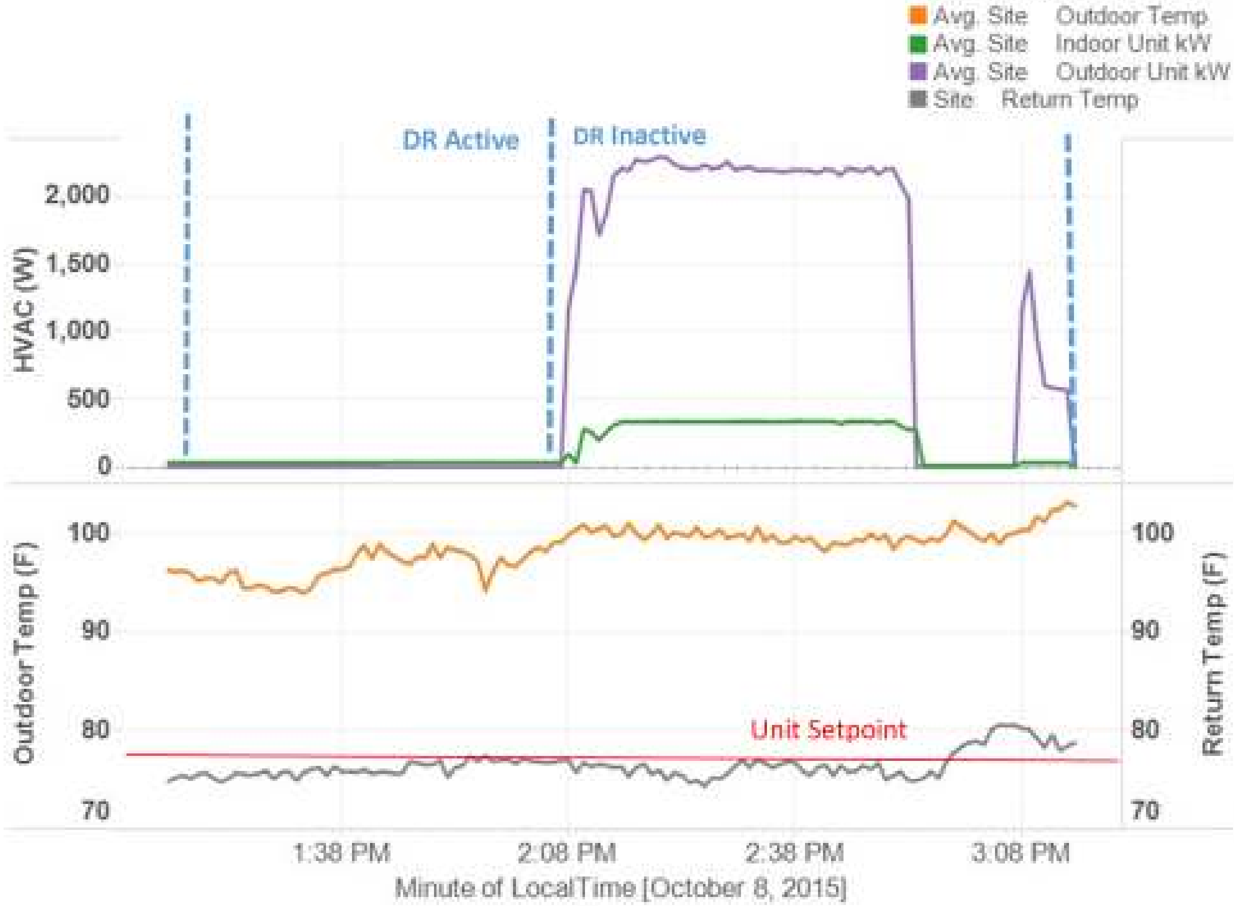

FIGURE 72. DR FIELD TEST 2 TEMPERATURES AND DR OPERATION – FIELD SITE 3

TABLE 40. DR FIELD TEST 2 SUMMARY – FIELD SITE 3

	DR Active	DR Inactive
Indoor Temperature Setpoint (°F)	77	77
Avg Outdoor Temperature (°F)	96.4	99.7
Avg Outdoor Relative Humidity (%)	18.0	17.9
Avg Return Temperature (°F)	76.0	76.5
Avg Return Humidity (%)	54.9	51.9
Avg Supply Temperature (°F)	73.2	56.4
Avg Supply Humidity (%)	67.1	91.2
Avg Indoor Unit Power (W)	35.3	245.1
Avg Outdoor Unit Power (W)	6.7	1,611.8
Max HVAC Power (W)	43.8	2,626.2

FIELD DR DISCUSSION

Due to uncontrolled and unique nature of the field evaluation, aspects of the DR field cases are not ideal. During actual DR events in a utility's service area, outdoor temperatures may often exceed 90°F. Such temperatures were present during the DR assessment at Field Site 2, when outdoor temperatures ranged from approximately 95 to 99°F. However, during the Field Site 1 DR assessment, outdoor temperatures ranged from approximately 75 to 85°F.

Also troublesome was the absence of unit operation prior to the first DR activation for DR Field Test 1. At field sites 2 and 3 for field DR testing, the units were not operating prior to the start of the DR assessment. Thus, the DR Field Test 1 case could be considered as having a single "DR Active" period instead of two "DR Active" periods. The DR operation of the unit was activated twice during each of the "DR Field Test 1" trials. However a unit power demand was not initially recorded in the field data because the unit was not in operation.

The DR field assessment produced valuable information for each of the two VC sites. The following highlights the observed takeaways for the DR field assessment:

- During DR Field Test 2 at Field Site 2, the measured indoor temperature rose by approximately 1 to 2°F during the "DR Active" time period and then fell to approach the indoor setpoint during the "DR Inactive" period. As the indoor temperature measurement approached the indoor unit setpoint, the unit power demand and thereby cooling capacity decreased to maintain the indoor temperature setpoint.
- During DR Field Test 1 at Field Site 3, the indoor blower remained in operation during the "DR Active 2" time period. The continued operation of the blower during DR operation may result in the circulation of warm air throughout the home due to the absence of cooling output.
- The observed power demand of the VC equipment during DR activation was comparable to the unit power demand observed in the laboratory DR assessment.

CONCLUSIONS

This study demonstrated the potential efficiency and DR capabilities of the VC equipment for California residences and utility programs through a survey, laboratory testing, and field testing.

The survey confirmed the market availability of high SEER (17 to 24 SEER) VC equipment in air conditioner or heat pump configurations and the typical range of residential and small commercial sizes. Available VC equipment includes fully variable speed equipment and five-speed systems. In addition, VC systems are available with DR capabilities that allow the systems to cycle OFF or potential operate at a minimum level of cooling output.

The laboratory and field tests provided information on potential energy and demand savings of VC air conditioning, correlation of VC equipment with SEER, and system effects of VC equipment that will be useful in evaluating utility energy efficiency and DR programs.

The laboratory evaluation focused on VC air conditioners of 18, 19.5, and 22 SEER. All three systems demonstrated improved efficiency at part-load operation for a specific indoor and outdoor condition. Modeling for the California Climate Zone 10 demonstrated the following:

- Compared a baseline 14 SEER air conditioner, 18, 19.5, and 22 SEER VC equipment can provide energy savings of 12%, 26%, and 30%, respectively.
- Compared to the current utility program level of 15 SEER, 18, 19.5, and 22 SEER VC equipment can provide energy savings of 7%, 22%, and 26%, respectively.

The VC-to-baseline comparisons demonstrated increasing energy savings with increasing SEER, as well as a potential efficiency enhancement for utility programs. The 18, 19.5, and 22 SEER VC equipment consisted of 11, 13, and 15.5 EER, respectively. At 105°F outdoor temperature, the 13 and 15.5 EER VC equipment resulted in a power demand savings of approximately 5%, and 10% respectively over a baseline 12.2 EER air conditioner. In contrast, the 11 EER VC unit had a 10% increase in demand over a baseline 12.2 EER air conditioner at 105°F outdoor temperature.

In the field, VC equipment with SEERs of 20, 17.5, and 21 replaced baseline ACs of 12, 11, and 10 SEER, respectively, at three occupied residences within California Climate Zone 10. This VC retrofit was accompanied by enhanced quality installation practices that improved field conditions: the duct leakage, external static pressure, and duct insulation.

The 17.5 and 21 SEER units were appropriately sized for their sites for the monitored cooling season and demonstrated modulation of the cooling output from minimum to maximum outputs over the course of the data collection. The 17.5 SEER system, a five-speed unit, demonstrated operation at the five speeds, whereas the 21 SEER system, a fully variable unit, demonstrated modulation operation between the maximum and minimum levels of cooling output. The 20 SEER system was oversized for its site for the monitored cooling season and predominately operated at the unit’s minimum cooling level.

The project team determined an expected seasonal cooling efficiency for each field site on the basis of the laboratory data for each of the three selected VC systems and each field site’s operational characteristics. For the appropriately sized units, the expected seasonal cooling efficiency compared well to the measured seasonal cooling efficiency based on field data. Based on utility billing data and field monitoring data, the VC equipment and quality installation retrofit resulted in cooling season energy savings of approximately 30%, 18%, and 30% for the 20, 17.5, and 21 SEER equipment, respectively.

Field monitoring also investigated sensible duct losses with variable airflow in VC equipment. At one of the VC field sites that contained supply ductwork in the attic, four supply air temperature sensors were placed in 10-foot increments along the primary supply air duct of the distribution system. The estimated sensible duct loss along the supply duct was determined by analyzing the difference between the supply air temperature reading at the unit outlet and the sensor located approximately 30 feet down the supply duct. Over the range of recorded outdoor conditions, the estimated sensible duct loss approximately doubled from high airflow to low airflow. For example, at an outdoor temperature of 95°F, the measured sensible duct loss at the site was approximately 12% for maximum airflow and approximately 21% for minimum output.

The project team examined DR unit setup and DR operation of selected VC equipment in laboratory and field evaluations. DR operation consisted of OFF-cycle controls. VC system 2 claimed to have OFF-cycle and low stage capacity modulation controls. To enable DR operation, the VC equipment in this investigation required manual adjustments of dry-contacts in the outdoor units. VC systems 2 and 3 also required further adjustment of controls/thermostat settings in combination with dry-contact adjustment to enable DR operation. None of the equipment investigated was readily able to receive and act upon utility DR event signals.

During the evaluation, it was discovered that the low stage DR capacity modulation controls of VC system 2 were not functioning. The manufacturer identified that a software update would have to be developed, and the issue was not resolved at the time of the investigation. During several DR tests of the VC equipment, the indoor blower continued to operate during the active DR time frame. In a field situation, continued operation of the indoor blower may circulate warm air throughout the air.

For continued investigation of residential VC space conditioning and utility programs in California, multiple areas of research could be considered: the prevalence and mitigation of oversizing of HVAC equipment; duct loss impact with variable airflow equipment; and further demonstration of field energy savings of VC equipment.

At Field Site 1, the VC field data demonstrated an oversizing of the equipment. Although VC equipment operates efficiency at part-load operation, oversized VC equipment does not likely provide the utility or the customer with the most efficient or economical solution. To operate as designed by a manufacturer, a VC system should be sized appropriately at the design condition.

A potential explanation for the equipment oversizing at Field Site 1 is heavy shading of the residence by surrounding trees. A Manual J calculation typically does not account for the effect of heavy tree shading on the solar gain and design load of a residence. In locations where heavy tree shading is prevalent, additional calculations or assumptions may improve the accuracy of the Manual J design load. Utility programs could also consider examining historical utility billing data or adding quality installation measurements to examine unit runtime or space temperature response to unit full-load operation.

A study of the sensible duct loss of the VC system at Site 2 demonstrated that lower airflow or modes of operation may result in higher sensible duct losses. A more detailed investigation of the total duct losses associated with VC equipment and variable airflow would assist in appropriately quantifying the potential field energy savings of VC equipment.

In this research study, the potential energy savings of VC equipment over baseline 10 to 12 SEER equipment was demonstrated to be higher in the laboratory (30%–50%) than in the field (18%–30%). The discrepancy in potential energy savings between the lab and field may be attributed to system effects, such as differences in duct loads between fixed-speed and variable speed equipment, or to the use of utility billing data to determine the baseline HVAC energy usage. Utility billing provides a readily available tool for exploring energy savings, but it does not directly provide valuable data on HVAC unit power consumption, indoor temperature and humidity, or unit operating air or refrigerant conditions. Such information would enable a more thorough comparison of HVAC energy usage at a residence.

APPENDIX A. INFORMAL NOTES FROM MANUFACTURER DISCUSSIONS

Manufacturer A

1) Discuss the purpose of VC product development:
    a. High end product? Feature set driven – high end – better comfort
    b. Efficiency driven? Inverter technology – highest in terms of efficiency which can leverage to improve efficiency (ratings). Brushless DC motor – compressor, indoor blower, condenser fan. SEER is driving metric for air conditioning.

2) Describe briefly the currently available VC products? Air conditioner released in March 2014. Heat pumps available early 2015. New technologies start in best category, and potentially work their way down.
    a. Heat Pump vs. Air conditioner models
        i. Differences in cooling mode efficiency? What contributes?
    b. Target SEER of the equipment 20 SEER. Two stage equipment approaches 20 SEER. Variable speed above 20 SEER. EER of VC equipment is relatively similar to single speed, two speed equipment.
    c. Compressor type Turn down ratio is ~30% on VC products. Rotary up to 4 ton. 5 ton uses Scroll.
    d. Variable Speed vs. Multi-speed All components are variable (blower, fan)
    e. High End vs. Economical Inverter systems are high end – more costly
    f. %THD considerations? Inverter systems do use power factor correction
    g. Targeted for replacement market, new construction, etc…? new building or retrofit market
    h. Special certification needed for proper install? Training course – both hands on and online training available

3) Describe the compatibility of the VC product line?
    a. E.g. for a given VC outdoor unit is there only one compatible indoor unit or multiple options (nominal size, multi-speed vs. variable speed blower) Multiple indoor units which are compatible. Indoor units could be gas furnaces, air conditioners only, etc… All indoor units are variable speed blowers.

4) Describe (high-level) the control strategy of the VC equipment? Honeywell thermostat used to control VC products
    a. Designed to match load of the space? Yes - Match load of space
    b. Does the difference between indoor temperature and setpoint factor into strategy? Yes – accounts for this factor
    c. Does "elapsed time" factor into the strategy? Maybe – learning algorithm
    d. Is there a "learning factor" within the equipment? Yes – remembers previous situations and scenarios of user interaction
    e. Does the system always operate at the "lowest level" upon start-up? No – proprietary scheme – for example oil management

f. What is the lowest % operation the system ramps down to? ~30% of maximum
g. Different modes of cooling operation? Differences in CFM/ton, SHR, etc? Dehumidification mode – blower speed run at 85% of nominal airflow. Increases dehumidification. Other modes: Normal mode. Service mode – charge mode.
h. Startup speed different than nominal speed? Is nominal speed = maximum speed? Intermediate speed upon start-up.

5) What are the DR capabilities of the VC equipment?
   a. What is the "communication" for DR events? Currently, no DR capabilities right now. Demonstrated their ability to respond to a DR events in EPRI laboratory testing.
   b. Can DR be overridden by the user?
   c. Different responses to level of criticality of signal or other considerations?

6) What are the humidity control options with the VC equipment? Improved dehumidification is an option on the unit. Humidity setpoint.

Manufacturer B

1) Discuss the purpose of VC product development:
   a. High end product? Designed for High Volume Product, High End
   b. Efficiency driven? Products intended to be a balance of efficiency and cost effectiveness – i.e. the currently available VC products are NOT the most efficient system that they could currently produce

2) Describe briefly the currently available VC products?
   a. Heat Pump vs. Air conditioner models Both HP and AC models available
   b. Target SEER of the equipment Two families of VC: 18 SEER and 20 SEER
   c. Compressor type Scroll – Fully Variable. Cooling 30 – 100% operation. Heating 20 – 100% operation. Compressor operation in heating down to -15°F. 750 steps in compressor operation.
   d. Variable Speed vs. Multi-speed Compressor and indoor blower fully variable in VC products
   e. High End vs. Economical Also addressed in Question 1. Currently available products do include power factor correction. VC products mostly intended to be for replacement market. Currently Super SEER product is being developed with higher SEER (20+ SEER). Super SEER product does not aim to have substantial improvement in EER.

3) Describe the compatibility of the VC product line?
   a. E.g. for a given VC outdoor unit is there only one compatible indoor unit or multiple options (nominal size, multi-speed vs. variable speed blower) Sizing of products is fairly 1 to 1 (identical nominal size between indoor and outdoor unit). VC products can be configured (through internal settings) to promote slightly better efficiency or dehumidification depending on the application. E.g. efficiency vs. comfort mode setting with indoor airflow.

4) Describe (high-level) the control strategy of the VC equipment?
   a. Designed to match load of the space? Yes – load matching. Increase/Decrease output in response to changing load.

b. Does the difference between indoor temperature and setpoint factor into strategy? Yes – system accounts for user input, load, and unit settings to determine operation.
c. Does "elapsed time" factor into the strategy? Yes – control strategy includes PI controller. I.e. integral factor includes time as a variable.
d. Is there a "learning factor" within the equipment? Control strategy designed to adapt to the thermal load. Defrost control within the unit is demand only.
e. Does the system allows operate at the "lowest level" upon start-up? Upon start-up, unit operates at a SET (low) speed first in order provide sufficient oil-management to the compressor. After brief period, control strategy takes over.

5) What are the DR capabilities of the VC equipment?
   a. What is the "communication" for DR events? Unit includes a dry-contact with communicates DR signal to the unit. DR must be enabled in the unit settings. The only present DR operation for the VC products are to TURN OFF. VC products must be operated with the standard proprietary controller.
   b. Can DR be overridden by the user? No – remains as long as the dry-contact is open.

6) What are the humidity control options with the VC equipment? System includes humidity settings which can provide greater dehumidification or less dehumidification (and improved efficiency) depending on the application.

APPENDIX B. FIELD CANDIDATE EVALUATION

This section contains an evaluation of the potential candidates for a VC field site. Each criteria was examined through an evaluation of the residence and based on discussions with the homeowner. When appropriate, notes expound on the criteria in the tables.

TABLE 41. CRITERIA FOR FIELD SITE 1

	Criteria Number	Satisfied Criteria	Explanation of Satisfying Criteria
Required Criteria	1	✓	Approx. Built 1967; Size 1,730 ft^2
	2	✓	Confirmed during site visit
	3	✓	Confirmed during site visit
	4	✓	Confirmed with homeowner during site visit
	5	✓	Confirmed with homeowner during site visit
	6	✓	Confirmed cellular service
	7	✓	Confirmed with homeowner during site visit
	8	✓	Confirmed with homeowner during site visit
	9	✓	Confirmed with homeowner and contractor
	10	✓	Located in Redlands, CA (Climate Zone 10)
Wish List Criteria	11	NA	Rates to be confirmed through SCE
	12	✓	Ductwork Modifications at Site

TABLE 42. CRITERIA FOR FIELD SITE 2

	Criteria Number	Satisfied Criteria	Explanation of Satisfying Criteria
Required Criteria	1	✓	Approx. Built 1989; Size 1,484 ft^2
	2	✓	Confirmed during site visit
	3	✓	Confirmed during site visit
	4	✓	Confirmed with homeowner during site visit
	5	✓	Confirmed with homeowner during site visit
	6	✓	Confirmed cellular service
	7	✓	Confirmed with homeowner during site visit
	8	✓	Confirmed with homeowner during site visit
	9	✓	Confirmed with homeowner and contractor
	10	✓	Located in Mentone, CA (Climate Zone 10)
Wish List Criteria	11	NA	Rates to be confirmed through SCE
	12	✓	Ductwork and Unit Location Modifications at Site

TABLE 43. CRITERIA FOR FIELD SITE 3

	Criteria Number	Satisfied Criteria	Explanation of Satisfying Criteria
Required Criteria	1	✓	Approx. Built 1960; Size 1,598 ft^2
	2	✓	Confirmed during site visit
	3	✓	Confirmed during site visit
	4	✓	Confirmed with homeowner during site visit
	5	✓	Confirmed with homeowner during site visit
	6	✓	Confirmed cellular service
	7	✓	Confirmed with homeowner during site visit
	8	✓	Confirmed with homeowner during site visit
	9	✓	Confirmed with homeowner and contractor
	10	✓	Located in Yucaipa, CA (Climate Zone 10)
Wish List Criteria	11	NA	Rates to be confirmed through SCE
	12	✓	Ductwork Modifications at Site

APPENDIX C. MONTHLY OPERATION OF FIELD SITES FOR COOLING SEASON

Figure 73 through Figure 76 provide the average daily profile for each of the three field sites by month. The profiles demonstrate the usage of VC or HVAC equipment at each site over the Southern California cooling season. The figures provided correspond with Figure 51, which is discussed in detail in the Field Results section.

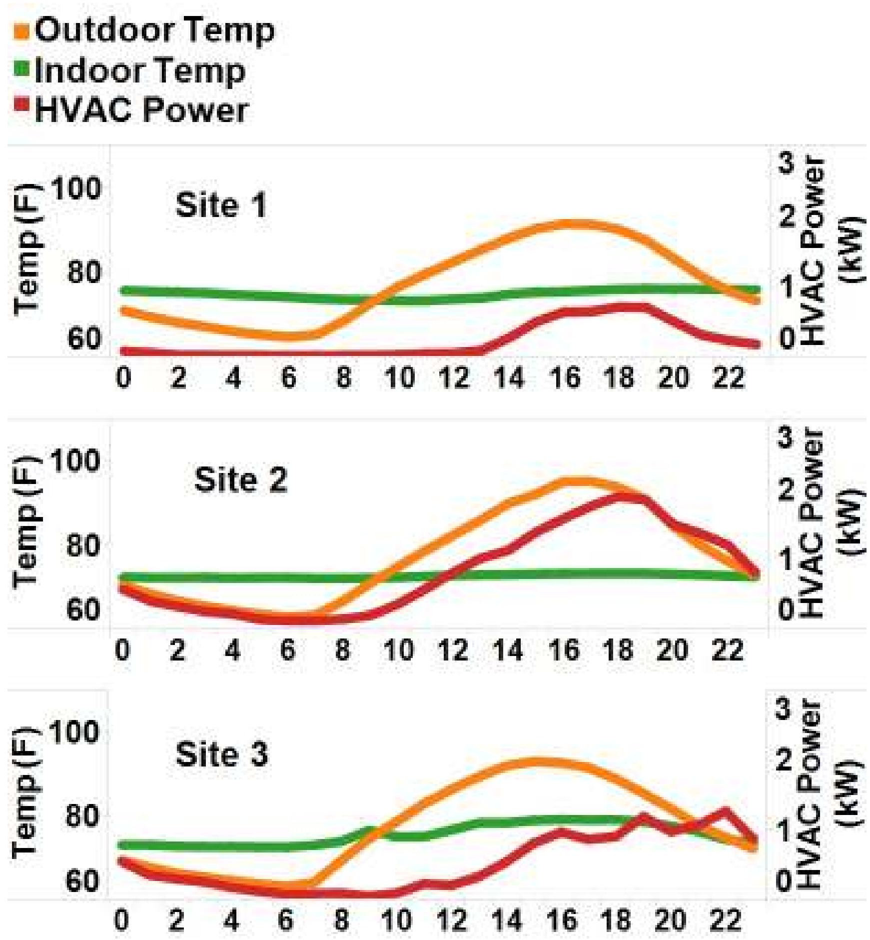

FIGURE 73. FIELD SITE 1, 2, AND 3 AVERAGE PROFILE –JUNE 2015

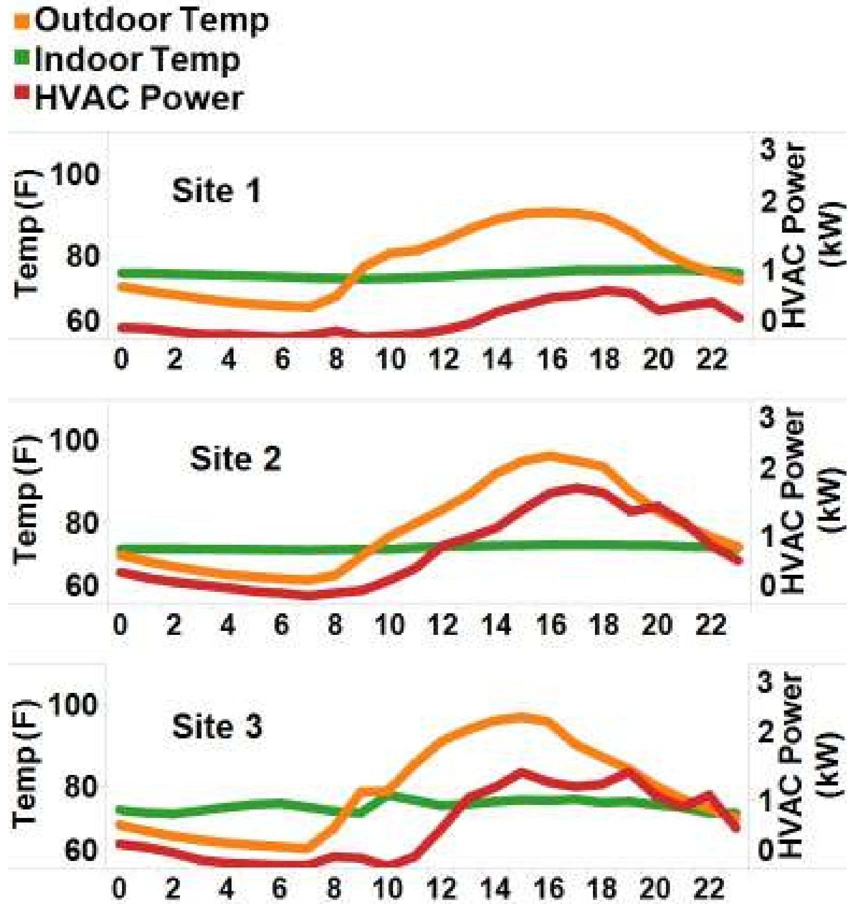

FIGURE 74. FIELD SITE 1, 2, AND 3 AVERAGE PROFILE – JULY 2015

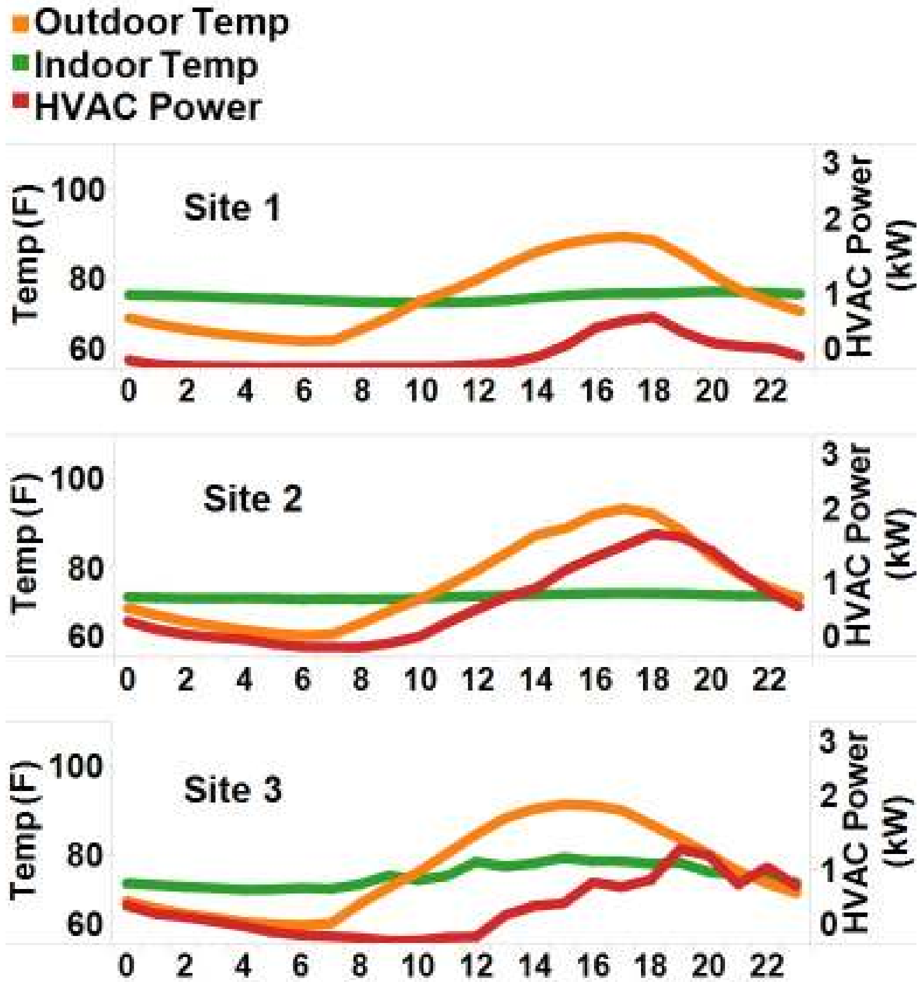

FIGURE 75. FIELD SITE 1, 2, AND 3 AVERAGE PROFILE – SEPTEMBER 2015

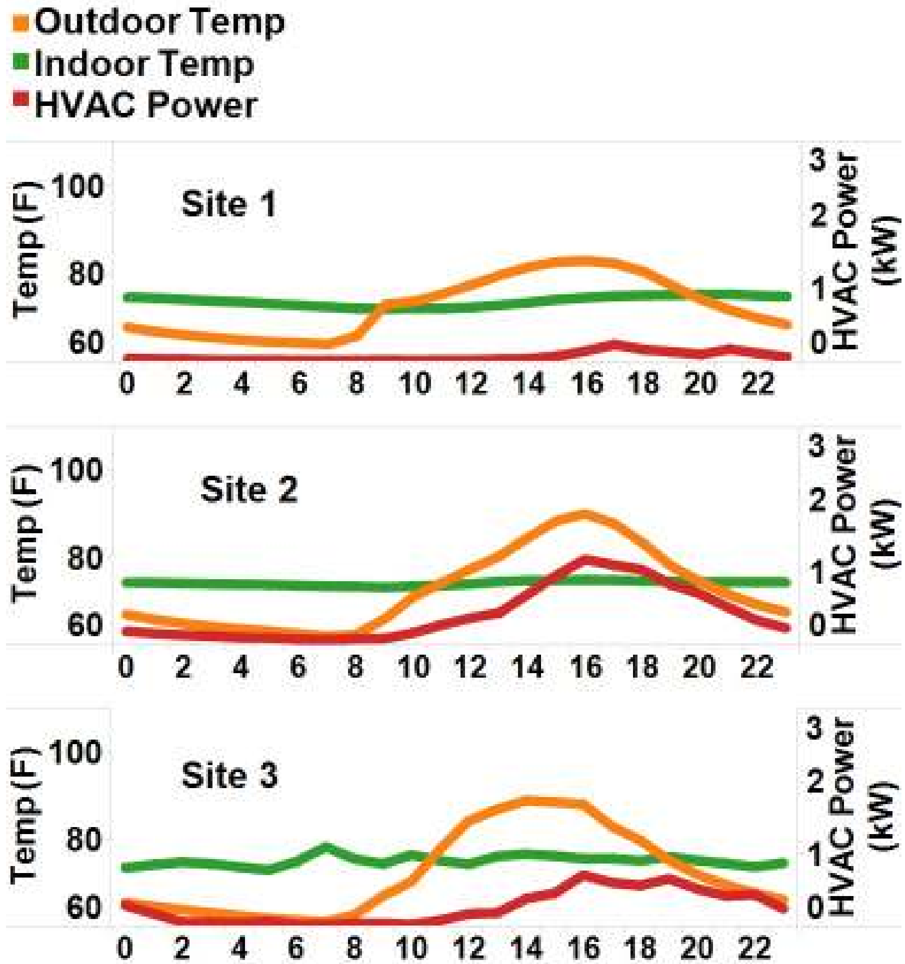

FIGURE 76. FIELD SITE 1, 2, AND 3 AVERAGE PROFILE –OCTOBER 2015

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