FINAL PROJECT REPORT

Evaluation of Dedicated Outdoor Air System and Variable Refrigerant Flow System Controls at Nonresidential Field Sites

ET18PGE1902-5

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CREDITS

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EXECUTIVE SUMMARY

BACKGROUND

This research was performed to help those involved with the development and implementation of California's Title 24, Part 6, Building Energy Efficiency Standards ("Title 24"), better understand the real-world performance of dedicated outdoor air systems (DOAS) and variable refrigerant flow (VRF) system controls. Title 24 includes advanced control requirements for some heating, ventilation, and air conditioning (HVAC) systems, such as variable air volume (VAV) with reheat or packaged rooftop units. However, DOAS has few prescriptive requirements.

Recently, Title 24 has sought to increase building system efficiency through advanced control requirements that reduce energy consumption and peak demand. However, those requirements were based on more common HVAC system types, such as mixed-air VAV units with reheat, and the requirements may not apply to or be cost-effective for DOAS and VRF systems. Past research studies have demonstrated that decoupled HVAC systems, such as DOAS and VRF, can achieve high energy savings with high-efficiency components. However, few field demonstration research projects of DOAS and VRF controls have been performed in California. This report seeks to close this knowledge gap by evaluating the performance of DOAS and VRF controls in operational California buildings and identifying their implementation potential for Title 24, Part 6.

PROJECT DESCRIPTION

The Code Readiness Project Team (research team): Pacific Gas & Electric Company, 2050 Partners, Red Car Analytics, kW Engineering, and Evergreen Economics measured field data across five California commercial buildings for 12 to 18 months. All the buildings were built or underwent HVAC and control retrofits in the last five years. This report evaluates the performance of seven different control strategies implemented across the five sites and considers energy savings, peak electric demand impacts, and control implementation considerations. This report also analyzes current DOAS and VRF control requirements in Title 24, Part 6 and identifies code enhancement opportunities.

Sites included in the study:

Site Name	Santa Rosa	Oakland	Martinez	Sacramento	Palm Springs
Climate Zone	02	03	12	12	15
Building size (ft^2)	25,000	17,500	7,000	16,000	19,100
DOAS Unit Type	DOAS ERV (Wheel)	DX DOAS	DOAS HRV (Core)	DOAS ERV (Wheel)	DOAS ERV (Core)
Zone Heating/ Cooling System	Multi-zone VRF with heat recovery				

METHODS

The research team analyzed seven unique control strategies for DOAS and VRF systems. These control measures were selected for evaluation because they were practical to implement at existing sites, and initial analysis indicated they would have energy savings or electric demand reduction. The seven control topics are:

- DOAS heat recovery bypass control
- Zone demand control ventilation (DCV)
- Supply air temperature control
- VRF zone temperature control
- Afternoon cooling demand management
- Morning warm-up demand management
- Fan coil deadband fan speed control

Some of these strategies are currently required in Title 24 based on cost-effectiveness for non-DOAS and VRF system types.

The research team collected trend data at the five sites over 12 to 18 months from the building automation system (BAS) and additional installed sensors (e.g., individual equipment power submeters). The team cleaned and combined each site data set using Python scripts and Tableau software and conducted energy analysis and performance calculations using Tableau and Excel spreadsheets.

KEY FINDINGS AND TITLE 24 RECOMMENDATIONS

The research team identified the following key research findings and Title 24, Part 6 language recommendations; the full summary can be found in the Findings and Recommendations section of this report.

DOAS CONTROL FINDINGS

Heat recovery bypass controls had varied energy savings results depending on system setpoints and building conditions; the simpler non-integrated bypass control approach achieved more consistent savings results in operation than integrated bypass controls. The Sacramento site ERV-DOAS with DCV had modest success, achieving 0.16 kWh/sf-yr (2%) whole building energy savings. However, at the Santa Rosa site, the team determined that adding DCV controls for ventilation airflow to individual thermal zones on the ERV-DOAS was not cost-effective. The Oakland site utilizing DX-DOAS supply air temperature control experienced significant issues, despite being only five years old; the unit did not reliably control to its setpoints. Ongoing commissioning or equipment upgrades may be needed to ensure proper operation.

Additionally, the research team found that standard controllers provided by manufacturers were insufficient to implement many of the control sequences reviewed in this report. Most of the strategies evaluated would require a BAS for successful implementation and verification. There are several opportunities to leverage control measures to improve the energy and indoor air quality performance of DOAS systems. However, requiring a BAS for all DOAS installations is likely not cost-effective for all building types and sizes, and requires further analysis.

VRF CONTROL FINDINGS

The research team found that the following evaluated VRF controls were successful at achieving demand reduction and/or energy savings: VRF cooling with ceiling fan prioritization resulted in significant demand reduction and energy use, and shutting off fan coils when zones are in their deadband also saved energy for DOAS and VRF systems.

Staging the zone morning heating setpoint and 24/7 constant zone heating setpoint control are both viable control strategies to reduce morning heating electric demand. However, 24/7 operation used nearly twice as much energy as staged morning warm-up control.

Staging VRF system zone cooling setpoints by pre-cooling spaces in the early afternoon and later increasing zone cooling setpoints can significantly reduce peak cooling demand. This strategy can be implemented in all buildings with VRF. The energy and electric demand increase during pre-cooling was significant but may come with minimal cost impact to facility operators in areas with aggressive TOU rates or demand charges or in buildings where these strategies can be aligned with on-site solar energy production.

DOAS Control Title 24 Recommendations

DOAS Unit: Heat Recovery Bypass Control

Before developing code requirements for integrated heat recovery bypass controls, additional analysis is needed to establish optimal seasonal bypass control setpoints.

During the commissioning design review required in Title 24, the design documentation should be reviewed to ensure that heat recovery bypass control setpoints and control methods, with or without BAS integration, are documented in the design.

In addition, for commissioning design reviews and functional testing, the research team recommends the Title 24 Air Economizer Controls and Exhaust Air Heat Recovery Acceptance Test be updated to address integrated and non-integrated bypass controls to help ensure systems are installed to operate with heat recovery bypass functionality correctly configured.

DOAS Unit: Zone DCV

DOAS systems and mixed air VAV with reheat systems should be subject to different DCV requirements. The research team recommends that, at minimum, the 120.1(d)3 mandatory requirement for DCV ventilation zone size be larger for DOAS systems than for mixed air systems to reduce the first cost barrier to implementing DCV with DOAS.

DX-DOAS Supply Air Temperature Control

The research team recommends applying Title 24, Section 140.4(f) prescriptive requirements for supply air temperature reset control based on outside air temperature to DX-DOAS units. DX-DOAS units should also undergo acceptance testing as required in 120.5(a)15.

The research team recommends adding a mandatory requirement to 120.2 for ongoing fault detection to help ensure DX-DOAS unit supply air temperature (heating/cooling) controls maintain proper operation and achieve the designed energy savings throughout the equipment's operational lifetime.

VRF Control Title 24 Recommendations

VRF Morning Warm-up Demand Management

For buildings with electric heating systems (including VRF, hydronic heat pumps, etc.), the research team recommends adding a mandatory requirement in section 120.2 for staged morning warm-up control to reduce morning heating electric demand in peak periods. Additional modeling or field testing should be done to determine a staged morning warm-up control sequence that is cost-effective for most buildings, for incorporation into Title 24.

VRF Afternoon Cooling Demand Management

Temporary demand response and permanent dynamic demand control are tools that can be used as energy codes move toward addressing time-of-use energy use to address electric grid constraints. Staging VRF zone cooling setpoints can be used as a control strategy for demand response events to comply with 110.12(b). *However, due to occupant comfort complaints, afternoon pre-cooling should not be used as a permanent demand management controls strategy.*

VRF Fan Coil Deadband Fan Speed Control

The research team does not recommend modification for the exceptions to 2022 Title 24, section 140.0(p)2.

CONTENTS

INTRODUCTION 10
Program Background 10
Purpose 10
Objectives 10
Background 11
Methodology 11
CONTROL EVALUATION RESULTS 13
DOAS Controls 13
Heat Recovery Bypass Control 13
Zone Demand Control Ventilation (DCV) 18
DX-DOAS Supply Air Temperature Control 21
VRF System Controls 25
Zone Temperature Control 25
VRF System Morning Warm-up Demand Management 29
VRF System Afternoon Cooling Demand Management 33
VRF Cooling with Ceiling Fans 36
VRF Fan Coil Deadband Fan Speed Control 39
FINDINGS AND RECOMMENDATIONS 44
DOAS Unit: Heat Recovery Bypass Control 44
DOAS Unit: Zone DCV 44
DX-DOAS Supply Air Temperature Control 45
VRF Morning Warm-up Demand Management 45
VRF Afternoon Cooling Demand Management 45
VRF Cooling with Ceiling Fans 46
VRF Fan Coil Deadband Fan Speed Control 46
General Findings 46
REFERENCES 47
APPENDICES 48
Appendix A: Martinez Controls Setpoints and Schedule 48
Appendix B: Palm Springs Controls Setpoints and Schedule 49
Appendix C: Oakland Controls Setpoints and Schedule 50
Appendix D: Sacramento Controls Setpoints and Schedule 51
Appendix E: Santa Rosa Controls Setpoints and Schedule 52

TABLES

Table 1: Research Team 10
Table 1: Field Site DOAS and VRF System Controls Features Summary ..12
Table 2: Heat Recovery Bypass Controls Test Summary 14
Table 3: Heat Recovery Bypass Control Energy Use Comparison 18
Table 4: Sacramento DCV Zone Ventilation Design Airflow Summary 20
Table 5: Zone Temperature Schedule Control Test Summary................26
Table 6: Sacramento Morning Warm-up Controls Test Summary 30
Table 7: Santa Rosa Morning Warm-up Controls Test Summary 30
Table 8: Morning Warm-up Demand Reduction Tests: VRF Electric Energy and Demand Savings 32
Table 9: Afternoon Pre-Cooling Control Setpoints [1] 34
Table 11: Afternoon Pre-Cooling Demand Reduction Compared to Constant Setpoint: VRF Electric Energy and Demand Savings 35
Table 12: Sacramento Test 2 Summary: Ceiling Fan Prioritization Cooling Control 36
Table 13: Sacramento Ceiling Fan Cooling Prioritization Test: VRF Electric Energy and Demand Savings...38
Table 14: Average Room CO2 Levels During Occupied Hours 40

FIGURES

Figure 1: DOAS Heat Recovery Bypass Diagram: Full Heat Recovery......13
Figure 2: DOAS Heat Recovery Bypass Diagram: No Heat Recovery.......13
Figure 3: Martinez Integrated Heat Recovery Bypass Operation 15
Figure 4: Palm Springs Integrated Heat Recovery Bypass Operation (Mode C)..16
Figure 5: Sacramento Non-Integrated Heat Recovery Bypass Operation .16
Figure 6: DOAS Variable Air Volume System Diagram 19
Figure 7: Sacramento ERV-DOAS Average and Peak Hourly Fan Power by Month During Occupied Hours...21
Figure 8: DX-DOAS Unit Component Diagram 22
Figure 9: Oakland DX-DOAS Unit Sensor Diagram 23
Figure 10: Oakland DX-DOAS Default Supply Air Temperature Control ...23
Figure 11: Oakland DX-DOAS Supply Air Temperature: Example Cooling (top) and Heating (bottom) Days..24

Figure 12: VRF System Average 24-Hour Weekday Power Demand Profile, Summer 27
Figure 13: VRF System Average 24-Hour Weekday Power Demand Profile, Winter 28
Figure 14: Weekly Average VRF System Electricity Use, Summer Week ..28
Figure 15: Weekly Average VRF System Electricity Use, Winter Week 29
Figure 16: Sacramento VRF System Power Demand Profiles During Morning Warm-up 31
Figure 17: Santa Rosa VRF System Power Demand Profiles During Morning Warm-up 32
Figure 18: Sacramento and Santa Rosa VRF System Power Demand Profiles During Afternoon Cooling 34
Figure 19: Sacramento Example BAS Zone Temperature Trend During Staged Afternoon Cooling Test 35
Figure 20: Sacramento VRF System Typical Summer Day Power Demand Profiles 37
Figure 21: Sacramento Average Zone Temperature During Ceiling Fan Prioritization Cooling Test 38
Figure 22: Sacramento Open Office and Huddle Room (photo courtesy of DPR Construction) 39
Figure 23: Sacramento VRF Fan Coil Total Average Power Demand During Occupied Hours: April 2021 (Fan On in Deadband) vs. October 2021 (Fan Off in Deadband) *Note the chart with FC 2-09 has a different y-axis scale than the other charts....41
Figure 24: Sacramento Monthly VRF Fan Coil Energy and Average Occupied Fan Power Density 42
Figure 25: Sacramento Occupied Monthly ERV-DOAS Fan Energy and Average Fan Power Density 43

INTRODUCTION

Energy codes are key to reducing the commercial energy use of heating, cooling, and ventilation (HVAC) systems. In most cases, high system efficiency is achieved by increasing component efficiency and then utilizing active controls to optimize component performance further and reduce energy use. In recent years, dedicated outdoor air systems (DOAS) with variable refrigerant flow (VRF) systems have become a prominent HVAC system solution in the small and medium commercial building market. However, while research studies have shown DOAS and VRF systems with high-efficiency components hold a high potential to save energy, few research projects have documented how controls can further optimize these systems (Bulger, Weitze, Kekare 2022).

This report aims to add to the DOAS and VRF knowledge developed by the Code Readiness research team ("research team") by evaluating control capabilities and functionality observed in occupied buildings.

PROGRAM BACKGROUND

PG&E's Code Readiness Program supports the development, adoption, and implementation of California's building and appliance energy codes through long-range planning and data collection. The program works from long-term climate and energy goals to identify key regulatory opportunities within California's energy codes and standards framework, then develops strategies to fill data gaps and overcome obstacles to successful adoption and implementation of those regulations. The Code Readiness Program focuses on energy performance, cost-effectiveness, feasibility, and code compliance data to support regulatory advocacy.

The Code Readiness DOAS and VRF Research Project is led by the following research team.

TABLE 1: RESEARCH TEAM

Company	Role
Pacific Gas & Electric (PG&E)	Project Sponsor, Program Administrator
2050 Partners	Project Manager
Red Car Analytics	HVAC Technical Lead
kW Engineering	Field Monitoring Equipment Lead
Evergreen Economics	Trend Data Repository
A2 Efficiency	HVAC System Specialist

PURPOSE

This report analyzes energy consumption, peak electric demand, and implementation impacts of advanced controls for decoupled DOAS and VRF systems based on field data collected through trended monitoring equipment. In addition, this report evaluates each control mechanism's potential for incorporation into Title 24, Part 6 (Title 24) and presents code language recommendations.

OBJECTIVES

The objectives of this report include the following:

1. Quantify how the following control sequences of operation impact energy use and electric demand profiles for operational decoupled DOAS and VRF systems using field data:

  - DOAS unit heat recovery bypass control
  - DOAS unit variable air volume control through CO_2 demand control ventilation
  - DX-DOAS unit supply air temperature control
  - VRF system zone temperature control: occupied and unoccupied
  - VRF system morning warm-up demand management
  - VRF system afternoon cooling demand management
  - VRF system cooling with ceiling fans
  - VRF fan coil deadband fan speed control
2. Assess the efficacy of implemented controls, including the ease of control sequence implementation and savings expectations across different deployments or system configurations.
3. Provide information to code development teams to inform future code requirements.

BACKGROUND

Dedicated outside air system (DOAS) requirements were introduced into Title 24 energy code in 2022. The new DOAS requirements are prescriptive and largely include system configuration features with a few control requirements. The Washington State Energy Code set DOAS as the primary prescriptive pathway for nonresidential buildings in 2018, with detailed criteria on DOAS unit and heating and cooling system controls. The 2015 International Energy Conservation Code (IECC) added DOAS as an enhanced energy efficiency credit to the list of additional efficiency packages. The IECC code stipulates required DOAS unit product features and control capabilities to qualify for the enhanced energy efficiency credit.

Before the introduction of DOAS in 2022, most Title 24 HVAC system requirements were developed assuming traditional system types, such as single zone package units or mixed air economizer systems with variable air volume (VAV) reheat terminal units. Therefore, cost-effectiveness for DOAS systems was not considered in developing these requirements, and the code language does not address the applicability of these requirements to DOAS systems.

Building energy efficiency codes have recently sought to increase system efficiency through advanced control requirements. However, that analysis is based on more common HVAC system types, such as mixed-air air handler units with VAV with reheat, and by simulating energy savings based on ideal system operation rather than real-world building operations, which include imperfect operation due to untuned controls or mis-sized system design.

This report addresses the need to understand implementation considerations, energy savings potential, and demand reduction potential for DOAS and VRF control requirements using control sequences implemented in nonresidential buildings constructed within the last five years.

METHODOLOGY

The research team analyzed trend data from five office buildings with DOAS and VRF systems to quantify differences in the performance of various control features. The sites were located in the following California cities: Martinez, Oakland, Palm Springs, Sacramento, and Santa Rosa, and had the key features shown in Table 2.

TABLE 2: FIELD SITE DOAS AND VRF SYSTEM CONTROLS FEATURES SUMMARY

	Martinez	Oakland [1]	Palm Springs	Sacramento	Santa Rosa
Climate Zone	12	03	15	12	02
Building size (ft^2)	7,000	17,500	19,100	16,000	25,000
DOAS Unit Heat Recovery	HRV Core	None	ERV Core	ERV Wheel	ERV Wheel
DOAS Unit Heat Recovery Bypass Control	Integrated	N/A	Integrated	Non-Integrated	None
DOAS Unit VAV Capability	Yes	Yes	Yes	Yes	No
Zone Heating/ Cooling System	Multi-zone VRF with heat recovery 3-speed fan coils	Multi-zone VRF with heat recovery 3-speed fan coils	Multi-zone VRF with heat recovery 3-speed fan coils	Multi-zone VRF with heat recovery 3-speed fan coils	Multi-zone VRF with heat recovery 3-speed fan coils
Ventilation Ducting Configuration	Ducted directly to zones	Ducted directly to 32% of zones; Ducted to fan coil return air intake in 68% of zones	Ducted directly to 50% of zones; Ducted to fan coil return air intake in 50% of zones	Ducted to fan coil return air intake	Ducted to fan coil return air plenum

[1] The Oakland site was selected to study DX-DOAS controls only; unlike the other sites, this site did not have ventilation heat recovery.

For more information on each site, refer to individual site case studies[1]. The control measures were selected for evaluation because they were practical to implement at existing sites, and initial analysis indicated they had potential energy savings or electric demand reduction, or both, compared to the current Title 24 requirements for DOAS and VRF systems. In addition, some measures were identified because they are currently required in Title 24 based on cost-effectiveness for non-DOAS and VRF systems.

Control setpoints and test schedules are included for each site in Appendices A through E. Some control features were part of the building's default control sequence. In contrast, others were operated as part of short-term tests lasting two to four weeks or due to changes made by facility operators. See the appendices for each site's control test schedules.

The research team collected trend data in 1, 5, or 15-minute intervals for 12-18 months at each site via sensors installed by the research team and supplemental trend data from the building automation system (BAS), as available. Trend data was then cleaned and synchronized to 5-minute timestamps for analysis using Tableau and Excel.

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[1] Links to the Code Readiness Published Case Study: Martinez, Santa Rosa, Sacramento, Palm Springs. The case studies are also included in this report's References section. The Oakland site does not have a case study.

CONTROL EVALUATION RESULTS

DOAS CONTROLS

This section discusses results for three DOAS control categories: exhaust air heat recovery bypass control, demand control ventilation (DCV), and DX-DOAS supply air temperature control. For each item, a summary of the sequence of operation, related requirements in 2022 Title 24, and results are presented.

HEAT RECOVERY BYPASS CONTROL

Heat recovery bypass allows the DOAS unit heat recovery exchanger to be bypassed to provide unconditioned outside air during cool conditions, similar to an airside economizer.

Figure 1 shows a DOAS unit operating in full heat recovery mode. In this operating scenario, the heat recovery bypass dampers are fully closed; all outside air and all return air pass through the heat recovery heat exchanger where heat is transferred between the two airstreams to temper the outside air before it is supplied into the building.

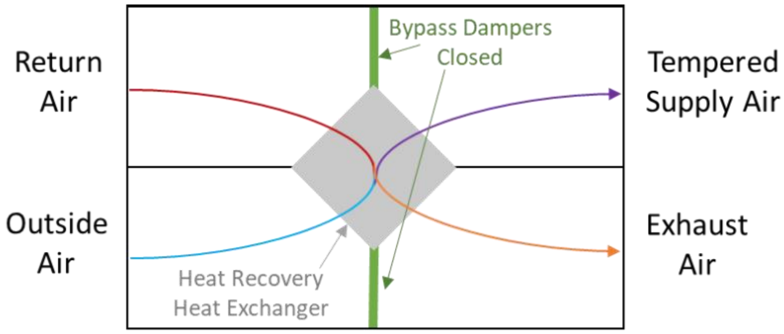

FIGURE 1: DOAS HEAT RECOVERY BYPASS DIAGRAM: FULL HEAT RECOVERY

Figure 2 shows a DOAS unit operating in full heat recovery bypass mode. In this operating scenario, the heat recovery bypass dampers are open, allowing the outside air and return air to bypass the heat recovery heat exchanger. When bypass dampers are fully open, no heat is transferred between the outside air and return airstreams. For DOAS units with integrated heat recovery bypass control, the bypass damper's position modulates from 0 to 100% open to vary the amount of air passing through the heat recovery heat exchanger and vary the heat transferred between the outside and return airstreams. For DOAS units with non-integrated heat recovery bypass control, the unit only operates in full heat recovery or no heat recovery mode (bypass dampers fully open or fully closed).

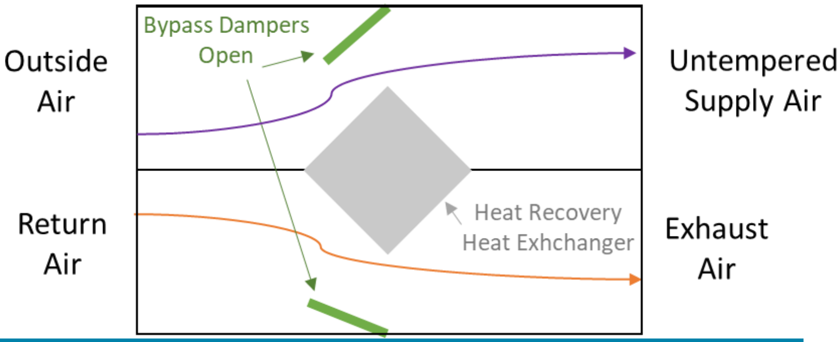

FIGURE 2: DOAS HEAT RECOVERY BYPASS DIAGRAM: NO HEAT RECOVERY

The evaluation below aims to assess whether requiring integrated heat recovery bypass control could be cost-effective as a Title 24 requirement for DOAS units.

CONTROL SEQUENCE OVERVIEW

Heat recovery bypass control intends to avoid heat recovery when outside air conditions are favorable to provide free cooling from the ventilation air. Two types of heat recovery bypass control were evaluated for this test: integrated and non-integrated bypass control.

- Non-integrated control does not recover heat when the outside air dry-bulb temperature is between a minimum and maximum setpoint.
- Integrated control allows the heat recovery bypass device to continuously modulate the amount of heat recovered from the exhaust airstream (0% to 100%) by controlling to a DOAS unit supply air (or return air) temperature setpoint. Theoretically, this control sequence can save more energy by dynamically changing the outdoor and return air temperature ratio, similar to a mixed air economizer.

2022 TITLE 24 REQUIREMENTS

Section 140.4(q) prescriptively requires that DOAS units in some climate zones have heat recovery bypass controls with a maximum temperature shut-off.[2] However, title 24 does not specify whether the heat recovery bypass control must be integrated or non-integrated.

CONTROLS EVALUATION METHOD

This test examines the performance of this control feature at three field sites: two with integrated heat recovery bypass control (Martinez and Palm Springs) and the other with non-integrated heat recovery bypass control (Sacramento). Table 3 provides an overview of each site's type of heat recovery bypass control, control setpoints, and period of trend data used in the analysis.

The research team reviewed trends of DOAS unit temperatures and bypass control device status (when available) to understand how consistently the system met its intended setpoint. The research team also evaluated each control type's operating temperatures and energy use implications.

TABLE 3: HEAT RECOVERY BYPASS CONTROLS TEST SUMMARY

Site	Test Mode	Heat Recovery Bypass Control Type	Heat Recovery Bypass Control Method	Heat Recovery Bypass Setpoint Temperature	Trend Data Period
Martinez	Mode A	Integrated	Dampers bypass airflow	59°F supply air dry-bulb	11/1/2020 – 1/14/2021
	Mode B	Integrated	Dampers bypass airflow	75°F supply air dry-bulb	1/15/2021 – 10/31/2021

[2] For the climate zone specified in Title 24, Part 6, Table 140.4-G.

Palm Springs	Mode C	Integrated	Dampers bypass airflow	62°F & 63°F supply air dry-bulb	8/20/2021 – 9/30/2022
Sacramento	Mode D	Non-Integrated	Energy wheel stops	Heat recovery disabled when outside dry-bulb 70-77°F	12/2020 – 09/2021, 11/2021, 12/2021
	Mode E	Non-Integrated	Energy wheel stops	Heat recovery disabled when outside dry-bulb 65-75°F	10/2021, 01/2022 – 03/2022

RESULTS AND OBSERVATIONS

Figure 3, Figure 4, and Figure 5 show heat recovery bypass operation for Martinez, Palm Springs, and Sacramento, respectively. Martinez and Palm Springs have integrated heat recovery bypass control. Their DOAS unit's heat recovery bypass damper is modulated from 0 to 100% open to control a supply air dry-bulb temperature setpoint.

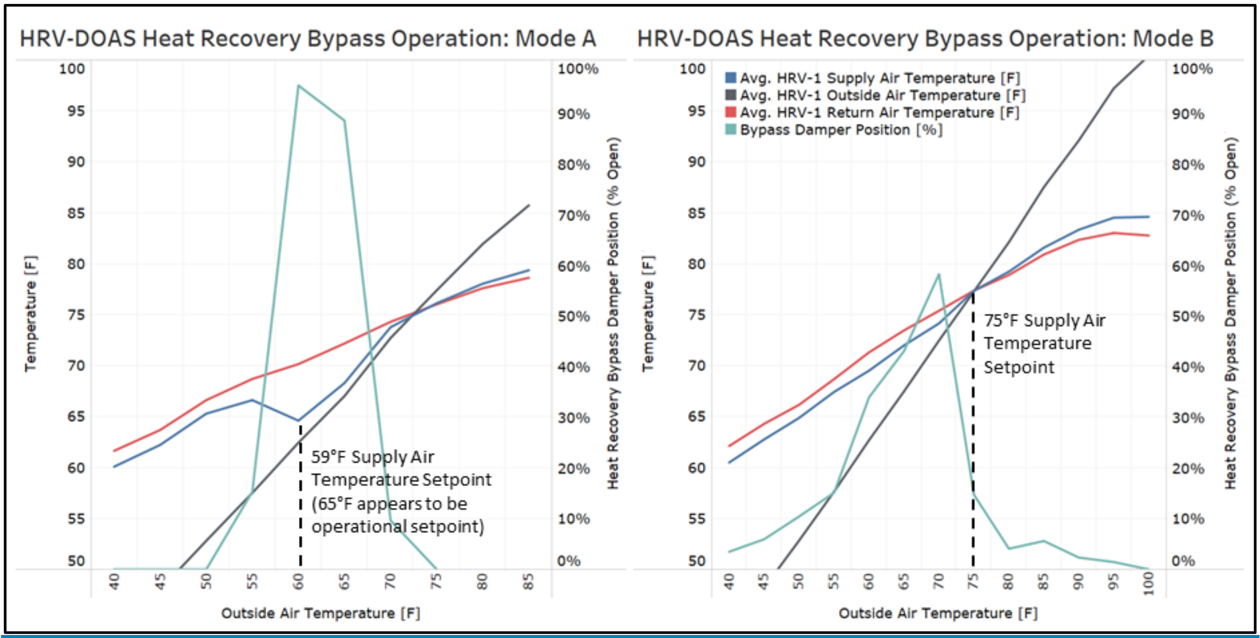

FIGURE 3: MARTINEZ INTEGRATED HEAT RECOVERY BYPASS OPERATION

The Martinez site contact indicated that from November 1, 2020, to January 14, 2021, the heat recovery bypass supply air temperature setpoint was 59°F, but starting January 15, 2021, the heat recovery bypass supply air setpoint was 75°F. However, trends for the first mode indicate the unit was controlled closer to a supply air temperature setpoint of 65°F instead of 59°F. The research team does not know if the discrepancy is due to an error in the controller or if the setpoint was incorrectly reported. Because the system had limited remote trending capability and there was limited access to manufacturer controller setpoints, the research team was unable to determine the source of the discrepancy.

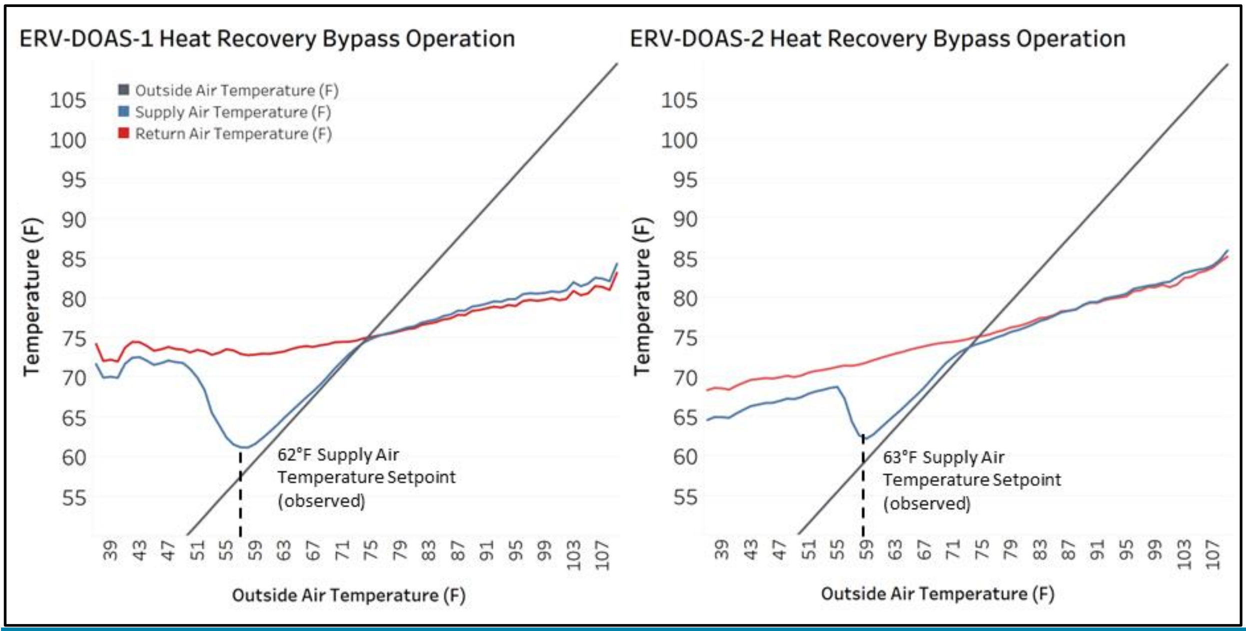

FIGURE 4: PALM SPRINGS INTEGRATED HEAT RECOVERY BYPASS OPERATION (MODE C)

Though installed by different contractors, the Palm Springs DOAS units were produced by the same manufacturer as Martinez, and both sites relied on the manufacturer's onboard controller's sequence for controlling the DOAS units. The Palm Springs site contact did not provide the heat recovery bypass damper setpoints for its DOAS units, but trends indicate that the units were controlled to a supply air temperature of 62°F and 63°F year-round, as shown in Figure 4.

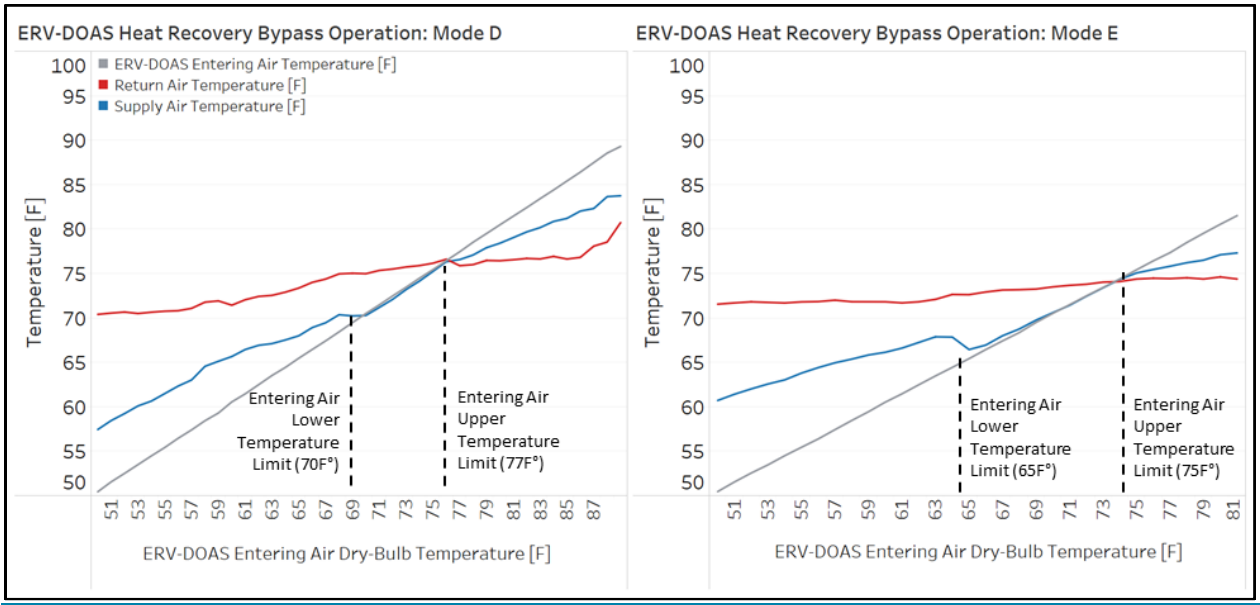

FIGURE 5: SACRAMENTO NON-INTEGRATED HEAT RECOVERY BYPASS OPERATION

Sacramento's DOAS unit utilized non-integrated heat recovery bypass control and the unit operated with two heat recovery bypass mode control sequences during the monitoring period. Mode D was the default design sequence of operation and locked out the heat recovery wheel when the outside air dry-bulb temperature was between 70°F and 77°F. The second mode (Mode E) included heat recovery bypass when the outside air dry-bulb temperature was between 65°F and 75°F; this mode was developed with input from the research team with the goal of providing more free cooling from the DOAS unit. Figure 5 shows the unit consistently operating with these setpoints: the supply air temperature equals outside air temperature at the specified minimum and maximum outside air temperatures.

Energy Impacts

The Martinez site stated they increased the heat recovery bypass setpoint from 59°F to 75°F because 59°F was sub-optimal for energy efficiency and comfort during winter. However, the heat recovery bypass setpoint could have been adjusted to a cooler setpoint like 59°F during summer to provide more free cooling and save VRF compressor energy.

While non-integrated heat recovery bypass control can theoretically provide more energy savings than non-integrated bypass control, the system must operate properly for greater energy savings. Complex control algorithms maintained by a proprietary controller made it difficult to validate integrated heat recovery bypass operation, troubleshoot issues, and adjust system setpoints to optimize energy use. In contrast, the simpler control of the non-integrated heat recovery bypass system could be verified and achieved savings in practice. The energy analysis also compares savings to a site without heat recovery bypass control (Santa Rosa).

To understand heat recovery bypass control strategies' impacts on energy use, the percent of the VRF heat pump's energy use occurring during potential economizer hours[3] and the percent of all operating hours that were potential economizer hours were calculated. Then the ratio of these two percentages was calculated. Table 4 summarizes these findings. A lower ratio of the percentage of energy use to the percentage of hours occurring during economizer hours indicates greater energy savings for the heat recovery bypass control method achieved in the field. The two sites with integrated heat recovery bypass control (Martinez and Palm Springs) performed about as well as the site without heat recovery bypass control (Santa Rosa). The lowest energy use site had non-integrated bypass control, which was unexpected, as integrated heat recovery bypass control should theoretically provide the greatest energy savings.

There are a number of other variables at each site that impact this analysis, including heat recovery bypass control setpoint, ventilation airflow rate, VRF system efficiency, and the presence of a pre-conditioning thermal labyrinth at Sacramento[4]. The energy savings benefit of heat recovery bypass control is a complex issue impacted by many HVAC system variables, which should be considered in analysis to develop code requirements.

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[3] Potential economizer conditions were assumed to be when the VRF system was operating and outside air temperatures were between 55°F and 75°F, with 50% of energy and hours occurring between 55-65°F outdoor dry-bulb temperature assumed to be cooling mode operation (the other 50% of operation during 55-65°F outdoor dry-bulb temperature was assumed to be heating mode operation).

[4] The Sacramento site had a concrete basement thermal labyrinth, through which ventilation air passed for pre-cooling or pre-heating when conditions were favorable before passing through the ERV-DOAS and into the building. See the published Sacramento Case Study for more detail. By pre-conditioning the outside air, the labyrinth brought the ventilation air temperature closer to the building temperature and reduced the potential heat recovery the ERV-DOAS could provide.

TABLE 4: HEAT RECOVERY BYPASS CONTROL ENERGY USE COMPARISON

Heat Recovery Bypass Control Method	Site	% Energy Use During Potential Economizer Hours	Potential Economizer Hours % of Total Hours	Energy Use / Hours Ratio
Integrated	Martinez	40%	36%	1.1
	Palm Springs	25%	34%	0.8
Non-Integrated	Sacramento	13%	28%	0.5
None	Santa Rosa	28%	31%	0.9

Implementation Considerations

Each DOAS manufacturer's proprietary controller provided the integrated bypass control. This limited the visibility to building operators, making it difficult to troubleshoot operations. It is unknown why the Martinez unit appeared to be controlling to a supply air temperature setpoint of 65°F during Mode A when the setpoint was set to 59°F. Though some of the temperature difference may be explained by supply fan waste heat; however, optimal controls would control to a supply air temperature leaving the unit after fan waste heat is added. Neither of the two sites with integrated heat recovery bypass control had a BAS to allow for automatic seasonal setpoint changes and therefore had a single heat recovery bypass temperature setpoint year-round. A more efficient control sequence would vary the heat recovery bypass temperature setpoint to be lower in summer weather and higher in winter.

While simpler than an integrated control, Sacramento's non-integrated heat recovery bypass control consistently operated as intended and achieved its energy efficiency performance target. The Sacramento site also had a BAS, which controlled the upper and lower outside air temperatures for heat recovery bypass operation. In addition, the BAS allowed for easy system operational trend review and confirmation of system operation and changes to system setpoints.

The larger ERV-DOAS units at the Santa Rosa site also had non-integrated heat recovery capability via the DOAS unit's onboard controller. However, the controller was never configured because the unit could not receive a heat recovery bypass control signal from the BAS, so the heat recovery bypass functionality was not used at this site.

ZONE DEMAND CONTROL VENTILATION (DCV)

DOAS systems are commonly operated as constant air volume systems, but varying airflow can provide energy savings through reduced fan power and reduced ventilation air heating and cooling. The analysis in this section assesses the energy savings potential of VAV DOAS unit controls based on zone CO_2 levels.

CONTROL SEQUENCE OVERVIEW

One method of DOAS unit VAV control is using zone occupancy detection (either occupancy sensors or CO_2 sensors) to modulate a damper at the zone to vary the amount of ventilation airflow. The controller also signals the DOAS unit supply fan to modulate its airflow to meet the new ventilation airflow requirement. This can be done by controlling the DOAS unit supply fan speed to meet a duct static pressure setpoint or by controlling the DOAS unit supply fan speed to meet a supply airflow setpoint. The changes in zone ventilation damper positions result in DOAS unit fan speed reduction when zones have no occupancy (in the case of occupancy sensor control as in occupied standby controls) or low occupancy (in the case of DCV controls). Figure 6 shows a diagram of a DOAS unit serving a zone that uses CO_2 DCV control. A DOAS system without DCV would typically not have a VAV damper located at the zone, and the only zone control would be for temperature by the fan coil.

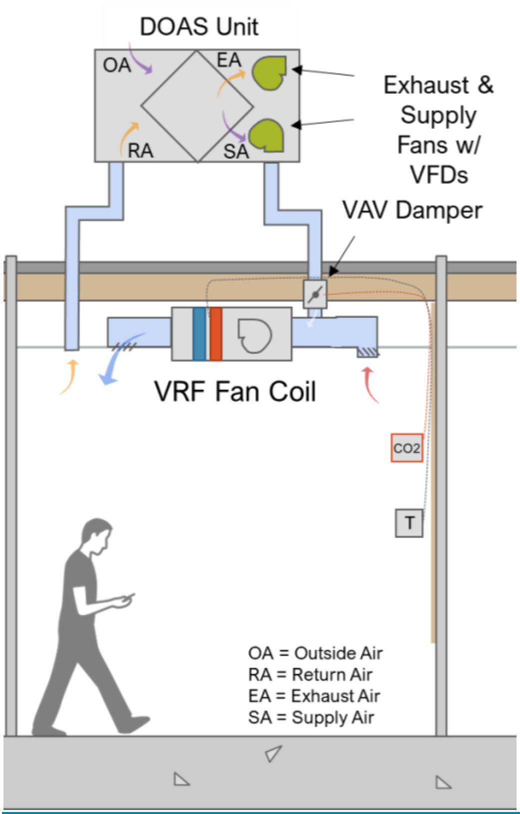

FIGURE 6: DOAS VARIABLE AIR VOLUME SYSTEM DIAGRAM

2022 TITLE 24 REQUIREMENTS

Section 120.1(d)3 has a mandatory requirement for DOAS units with a design airflow rate greater than 3,000 cfm to employ DCV using zone CO_2 sensors for any space with a maximum occupant density greater than or equal to 25 people per 1,000 sf.

Section 120.1(d)5, occupied-standby controls, has a mandatory requirement that the ventilation airflow is reduced to zero when there are no occupants for certain space types with required lighting occupancy controls.[5]

The occupied-standby requirement was introduced in 2019 Title 24, and the cost-effectiveness analysis assumed a VAV with a reheat system where each zone already had a dedicated VAV damper (Brannon et al. 2017). Therefore, cost-effectiveness was not

[5] The spaces where occupied-standby controls are required are post-secondary classrooms, lecture halls, conference, meeting rooms, training rooms, multipurpose rooms < 1,000 sf, breakrooms, enclosed offices and open plan office areas, corridors, and stairwells.

evaluated for DOAS systems which might not otherwise have zone control dampers installed. ASHRAE 90.1-2019 section 6.5.3.8 exempts multi-zone systems without automatic zone flow control dampers from having occupied standby control requirements.

CONTROLS EVALUATION METHOD

This analysis examines the DOAS unit fan energy savings of implementing DCV in conference rooms as required by Title 24 at the Sacramento site. The default control sequence included varying the ventilation airflow to four conference room zones based on each zone's CO_2 sensor reading. A constant air volume (CAV) control mode, where conference room zones each served their design maximum ventilation airflow while the DOAS unit operated, was tested in November 2021 to evaluate energy savings. Table 5 summarizes the four zones with DCV control at Sacramento. Per the design schedules, the four zones could vary the total building ventilation airflow by 835 cfm, 21% of the DOAS unit design supply airflow of 3,910 cfm.

Occupied standby was not tested but is noted in this section because it has similar zone damper control requirements and involves similar implementation costs in DOAS systems as DCV, and therefore may have similar cost-effectiveness results as DCV in DOAS systems.

The research team reviewed trends of DOAS unit fan power and airflow to evaluate energy savings between DCV and CAV DOAS unit control.

TABLE 5: SACRAMENTO DCV ZONE VENTILATION DESIGN AIRFLOW SUMMARY[6]

Zone Served	Training Room	Large Conf Room	South Med Conf Room	West Med Conf Room	DCV Zones, Total
Floor Area (sf)	1,310	634	328	438	2,710
Fan Coil Number	FC 2-05	FC 2-12	FC 2-06	FC-2-08	-
Ventilation Control Damper Number	VCD 2-01	VCD 2-02	VCD 2-03	VCD 2-04	-
Maximum Ventilation Airflow (cfm)	560	310	160	165	1,195
Minimum Ventilation Airflow (cfm)	170	95	45	50	360

RESULTS AND OBSERVATIONS

Figure 7 shows Sacramento's average and peak hourly ERV-DOAS fan power profile during occupied hours for each month in 2021 (excluding months where other tests significantly impacted fan power: September and October). In November, when the DOAS unit operated in CAV mode, the average and maximum fan powers were consistently higher than in all other months. The peak energy consumption data indicates that the ERV-DOAS unit operates with diversity for all months when not in CAV mode (i.e., not all conference rooms are fully occupied, and the maximum airflow is not used), except for December.

[6] Refer to Sacramento case study report for more detail, available at: https://www.etcc-ca.com/reports/code-readiness-case-study-energy-recovery-dedicated-outdoor-air-system-and-heat-recovery

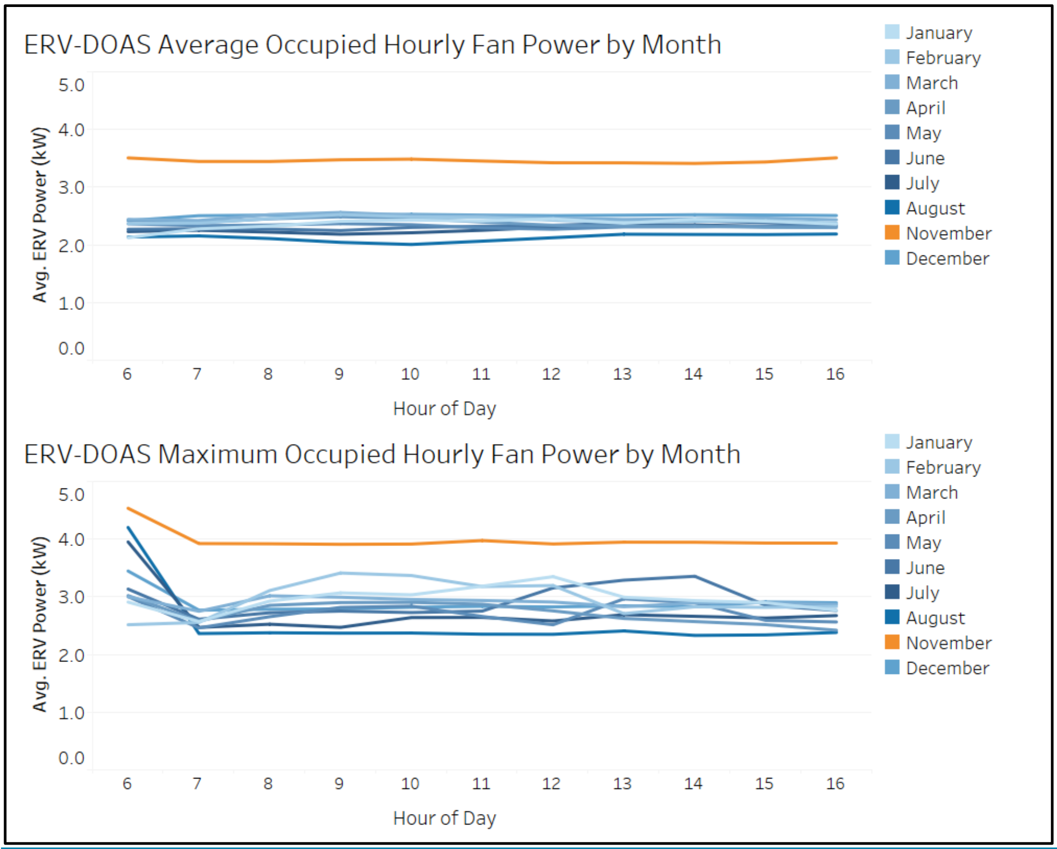

Figure 7: Sacramento ERV-DOAS Average and Peak Hourly Fan Power by Month During Occupied Hours

Energy Impacts

Further analysis found that the average ERV-DOAS fan power during months with DCV implemented and without DCV implemented was 2.5 kW (0.15 W/sf) and 3.5 kW (0.22 W/sf), respectively. Assuming 10 hours per weekday of DOAS operation, this 1.0 kW (30%) demand reduction correlates to 2,600 kWh/yr (0.16 kWh/yr-sf) annual DOAS fan energy savings (2% whole building energy savings).

However, these energy savings may not be sufficient to support the requirement of ventilation airflow controls per thermal zone in systems that otherwise do not have zone ventilation control dampers. Implementing DCV was not found to be cost-effective when analyzed at the Santa Rosa site (Weitze, Bulger, and Stober 2022).

Implementation Considerations

Demand control ventilation required a BAS to integrate the ERV-DOAS fan speed, zone ventilation damper position, and zone CO_2 sensor controls. DCV would not have been practical to implement when utilizing the DOAS and VRF system manufacturers' controllers alone.

DX-DOAS Supply Air Temperature Control

The analysis below aims to document manufacturer default controls for DX-DOAS units and assess whether DX-DOAS units should have unique Title 24 supply air temperature control requirements.

Control Sequence Overview

DX-DOAS units provide ventilation air that is cooled via a DX coil and compressor or heated, typically using a natural gas furnace. An outside air dry-bulb temperature sensor determines when and how much to heat or cool the ventilation air. Figure 8 shows a diagram of the components in a DX-DOAS unit.

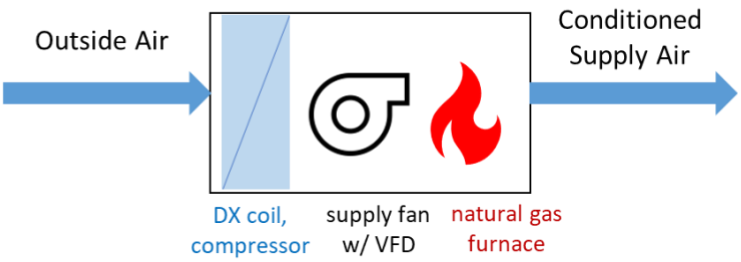

Figure 8: DX-DOAS Unit Component Diagram

2022 Title 24 Requirements

Section 140.4(f) prescriptively requires space-conditioning systems that provide heated or cooled air to multiple zones have controls that automatically reset the supply air temperature in response to building loads or outdoor air temperature. Further, the supply air temperature must increase by at least 25% of the difference between the design supply air temperature and design room air temperature.

Finally, section 140.4(p)4 prescriptively requires that DOAS units with mechanical cooling shall not heat supply air above 60°F when the majority of zones require cooling.

Controls Evaluation Method

Supply air temperature setpoint controls for a DX-DOAS unit with DX cooling and natural gas furnace heating were reviewed in an Oakland office building. The site did not have a BAS. The following features of the default onboard supply air temperature control were reviewed:

- Supply air temperature setpoint reset in heating and cooling
- External variable(s) determining when the unit should provide heating, cooling, or unconditioned outside air
- Reheat during dehumidification

Figure 9 provides a diagram of the DX-DOAS unit and sensors used to trend its performance. The research team reviewed 5-min temperature trends to understand these aspects of the DX-DOAS unit supply air temperature control and energy use implications.

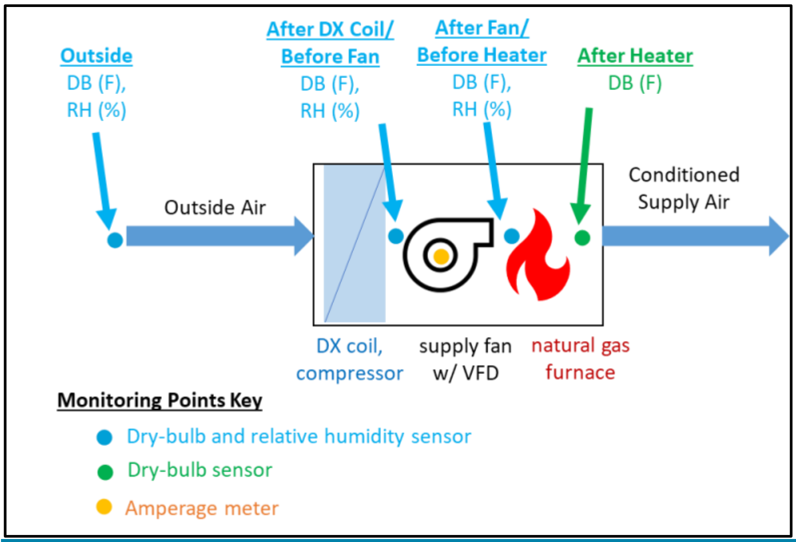

FIGURE 9: OAKLAND DX-DOAS UNIT SENSOR DIAGRAM

RESULTS AND OBSERVATIONS

The onboard controller allowed for an upper outdoor dry-bulb temperature threshold during cooling and a lower outdoor dry-bulb temperature threshold during heating. In the deadband between the two temperatures, the DOAS unit provided unconditioned outside air. As the building's default sequence of operation, the upper and lower outside air temperature thresholds were set to 55°F and 85°F, respectively. This wide deadband range was set as an energy savings strategy while the building was lightly occupied due to COVID-19. Figure 10 shows the intended control.

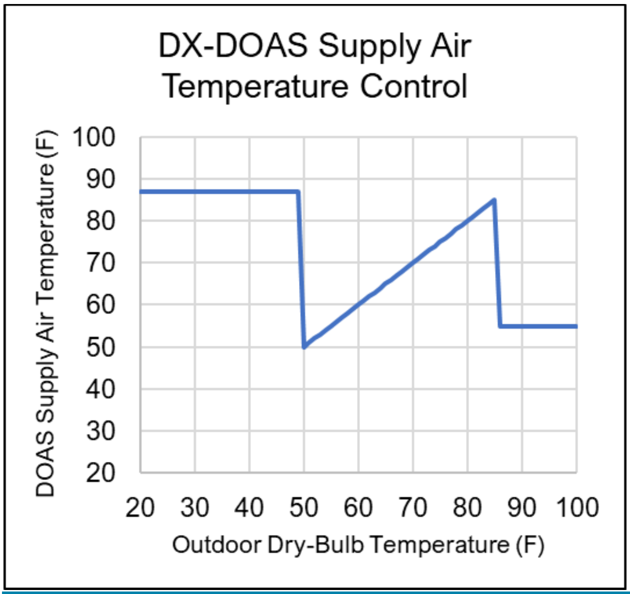

FIGURE 10: OAKLAND DX-DOAS DEFAULT SUPPLY AIR TEMPERATURE CONTROL

According to the research team's temperature sensors, the unit provided heating below 50°F outdoor temperature. The unit's DX cooling element did not consistently turn on, but a few days of cooling data was captured in August 2022.

When actively cooling, the DX coil cooled the outside air to 55°F, and the unit did not reheat the air. Fan waste heat increased the ventilation air temperature by around 1°F. When actively heating, the DOAS unit heated the outside air to 86-89°F. Figure 11 shows this control.

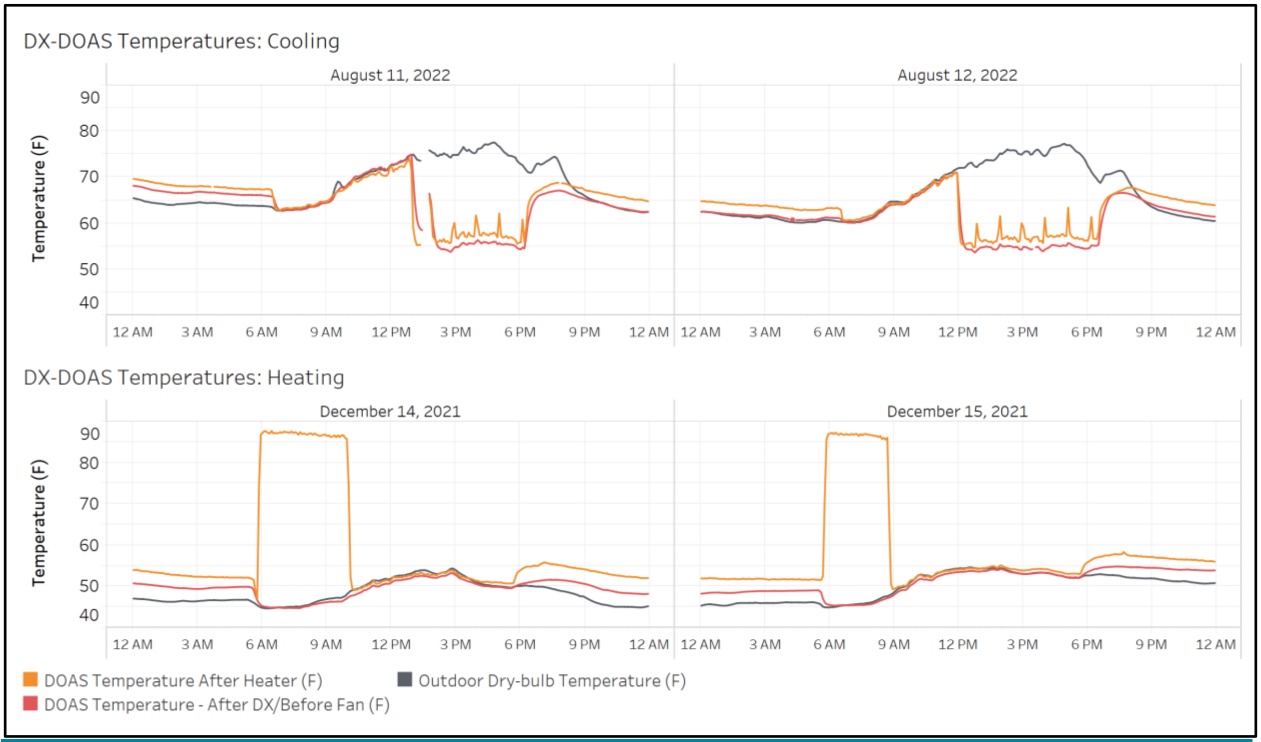

FIGURE 11: OAKLAND DX-DOAS SUPPLY AIR TEMPERATURE: EXAMPLE COOLING (TOP) AND HEATING (BOTTOM) DAYS

Energy Impacts

The DX-DOAS unit's default control of not reheating dehumidified supply air reduces heating energy use. However, it creates potential comfort issues in zones with fully decoupled ventilation air ducted directly into the space. One example is the building's basement office zones, which often require heating even when outdoor temperatures are warm enough that the DX-DOAS unit is in cooling mode. As a result, occupants may experience discomfort receiving 55°F ventilation air when they expect heat. If the DX-DOAS unit had a cooling supply air temperature reset, implemented by resetting refrigerant head pressure, this potential comfort issue could be mitigated while reducing DX compressor energy use.

Implementation Considerations

This DX-DOAS supply air temperature control proved difficult to maintain, in part due to the limitations of the simple onboard control of the DX-DOAS unit and the site not having a BAS. While initial acceptance tests or commissioning functional performance tests during construction may have addressed some of these issues, ongoing performance reviews and component calibration/upgrades are needed to keep the system operating as intended.

The research team is not aware of any occupant comfort complaints due to this method of control. However, occupant comfort issues could arise if the DOAS unit provides unconditioned hot outside air due to the temperature controller not working properly. The Oakland DOAS unit does not have heat recovery, so the air is untempered. Further, some spaces have fully decoupled zone VRF fan coils where ventilation air is provided directly to occupied spaces.

VRF System Controls

This section discusses results for five VRF system controls tests: zone temperature setpoint schedule, staged morning warm-up, afternoon pre-cooling, ceiling fan cooling prioritization, and fan coil fan speed control during zone deadband. The first three tests primarily examined the control sequence impact on peak heating and cooling demands and energy use. For each test, a summary of the control sequence, related requirements in 2022 Title 24, and results are presented.

Zone Temperature Control

Title 24 has mandatory requirements for zone thermostat controls. These requirements were evaluated for Title 24 using natural gas space heating and mixed air heating and cooling systems. The analysis below examines the impact on the VRF cooling and heating electric demand profiles using different zone temperature control schedules in winter and summer.

Control Sequence Overview

Zone thermostats measure space temperature and send a signal to the mechanical system to provide cooling if the space is above the zone temperature cooling setpoint and to provide heating if the space is below the zone temperature heating setpoint. When the space temperature is between the cooling and heating zone temperature setpoints (i.e., deadband), it calls for neither heating nor cooling.

In a VRF system, zone heating and cooling are delivered through a refrigerant fan coil in the zone. A fan blows room air across a coil, and warmed or cooled air is distributed into the room. For some VRF systems, separate heating and cooling setpoints can be programmed through a BAS; if the building does not have a BAS, the VRF thermostat may allow for a single zone temperature setpoint with a built-in deadband temperature range (e.g., ±3°F).

For comfort-driven spaces that are not occupied 24/7, such as offices, there are multiple common approaches to controlling space temperatures during scheduled unoccupied hours, including the following:

1. Running the system with constant heating/cooling setpoints (24/7). This is the simplest control method but can result in energy waste if there are many unoccupied hours.
2. Shutting off the heating/cooling system during unoccupied hours. This control method is also simple and can lead to the greatest energy savings. However, it may negatively impact occupant comfort if the building cannot reach the setpoint by the time the building is occupied. This control method also has the potential for high morning electric cooling or heating demand when the HVAC system turns on before occupancy.
3. Controlling to an unoccupied zone temperature heating setback setpoint (e.g., 60°F) and cooling setup setpoint (e.g., 80°F). This control method saves energy by allowing the system to shut off or provide minimum heating and cooling during unoccupied hours and prevents zones from becoming extremely hot or cold. However, it requires the ability to control the heating/cooling system using separate heating and cooling setpoints and different setpoints at different times of day and days of the week.

2022 Title 24 Requirements

Section 120.2(b) has the following mandatory requirements for zone thermostats:

- Capability to reduce the setpoint to 55°F or lower when used for comfort heating
- Capability to increase the setpoint to 85°F or higher when used for comfort cooling
- Capability of providing a deadband of at least 5°F where heating/cooling provided to the zone is shut off or reduced to a minimum

Section 120.2(e) has mandatory requirements for automatic shut-off and reset controls for space conditioning systems, including:

- Automatic shut-off control during periods of nonuse
- Automatic restart of the system to control to the unoccupied heating setback and unoccupied cooling setup thermostat setpoints.

Controls Evaluation Method

This test examines the performance of the three control schedule approaches at four sites. Table 6 provides an overview of the control modes evaluated for each site.

The research team reviewed trends of outside and zone temperatures, VRF fan power, and VRF heat pump power to understand how consistently the system met its intended setpoints, energy use implications, and electric demand impacts.

Table 6: Zone Temperature Schedule Control Test Summary

Site	24/7	Off During Unoccupied Hours	Setback/Setup During Unoccupied Hours
Martinez	Summer Test (7/20/21-9/4/21)	Summer Test (6/1/21-7/11/21) Winter Test (12/1/20-2/28/21)	N/A
Palm Springs	Default	N/A	N/A
Sacramento	Winter Test (3/14/22-3/25/22)	N/A	Default
Santa Rosa	Default during 2021	N/A	Default during 2022

Results and Observations

Figure 12 and Figure 13 show the average 24-hour weekday VRF system power demand profile normalized by square feet (sf) in summer and winter, respectively, for sites with different VRF operating schedules: 24/7, unoccupied setback, and off during unoccupied hours.

In summer, the sites with 24/7 operation have flatter electric demand profiles across the 24 hours compared with sites that shut off or setback their VRF system during unoccupied nighttime hours. The results can be seen in Figure 12 by comparing Santa Rosa's 24/7 (red line) and unoccupied setback (orange line) operation and by comparing Martinez's 24/7 (dark purple line) and unoccupied off (light purple line) operation. Palm Springs also operates under 24/7 control and shows a similar demand profile, though at a higher range due to the significant cooling load in climate zone 15. The peak electric demand density at all sites occurs late afternoon when outside air temperatures are usually highest. Both sites with unoccupied setback controls, Santa Rosa (orange line) and Sacramento (green line), show a morning peak demand when the system turns on to bring the system to its occupied temperature setpoints.

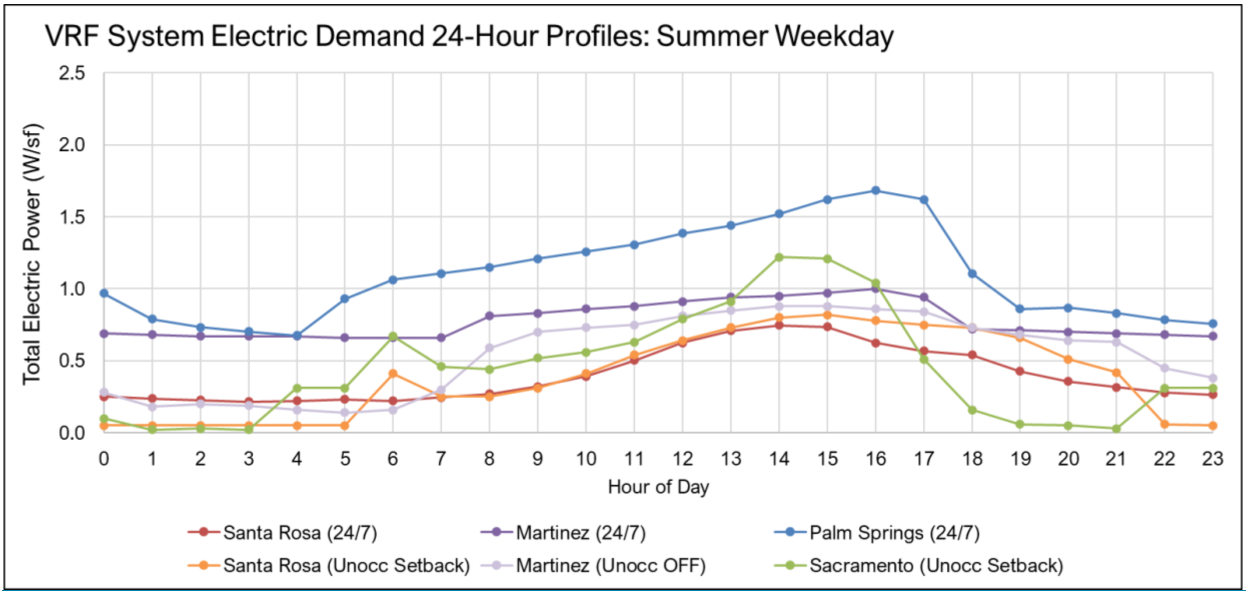

FIGURE 12: VRF SYSTEM AVERAGE 24-HOUR WEEKDAY POWER DEMAND PROFILE, SUMMER

Like in summer, in winter the sites with 24/7 operation have flatter electric demand profiles across 24 hours compared with sites that shut off or setback their VRF system during unoccupied nighttime hours. This can be seen in Figure 13 by comparing Santa Rosa's 24/7 (red line) and unoccupied setback (orange line) operation and by comparing Sacramento's 24/7 (dark green line) and unoccupied setback (light green line) operation. Palm Springs also operates under 24/7 control and shows a similar flat demand profile. The peak electric demand density at all sites occurs in the morning when outside air temperatures tend to be lowest. Two sites operating in unoccupied setback mode, Santa Rosa (orange line) and Sacramento (light green line), have a significantly greater morning peak demand than the other site operating modes.

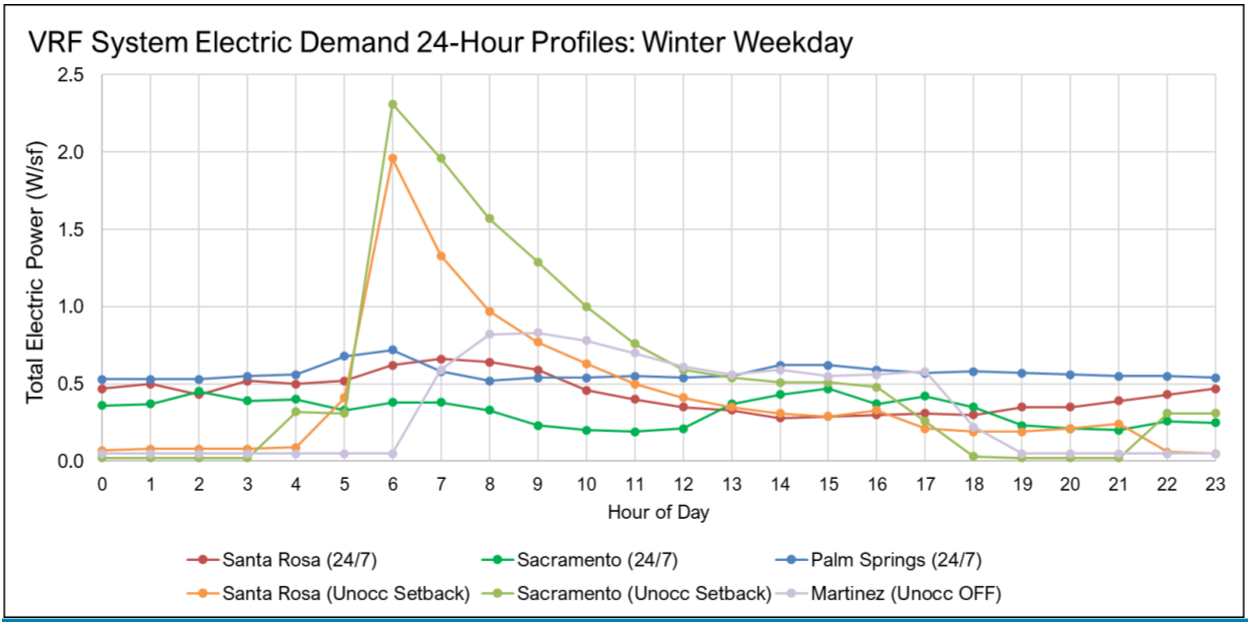

FIGURE 13: VRF SYSTEM AVERAGE 24-HOUR WEEKDAY POWER DEMAND PROFILE, WINTER

Energy Impacts

For Martinez, average weekly electricity use (in kWh/sf) was 30% lower in summer when off during unoccupied hours compared to 24/7 operation, as shown in Figure 14. Similarly, Santa Rosa's average weekly electricity use was 26% lower in winter when operating with an unoccupied setback compared to 24/7 operation, as shown in Figure 15.

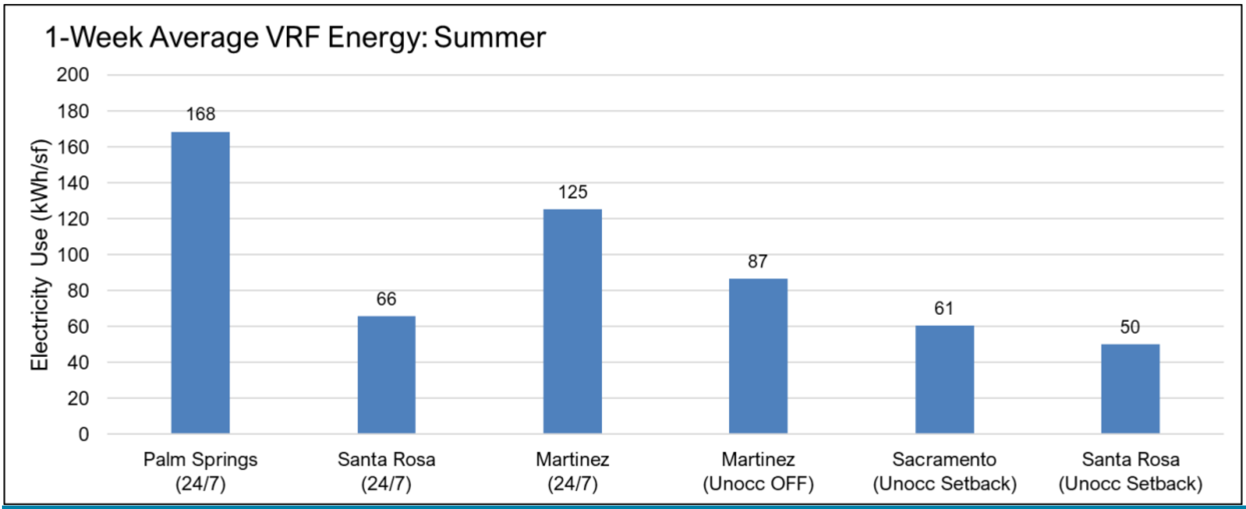

FIGURE 14: WEEKLY AVERAGE VRF SYSTEM ELECTRICITY USE, SUMMER WEEK

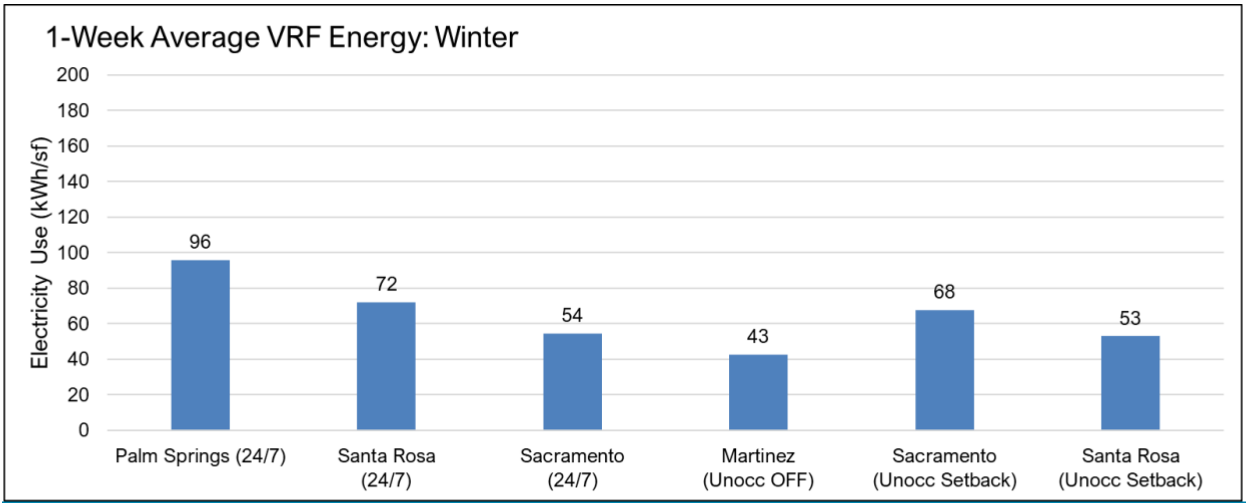

FIGURE 15: WEEKLY AVERAGE VRF SYSTEM ELECTRICITY USE, WINTER WEEK

Implementation Considerations

Palm Springs and Martinez staff indicated they operated 24/7 in summer due to concerns with occupant comfort. Santa Rosa staff stated they operated 24/7 due to issues with BAS scheduling which were eventually resolved in the second half of the monitoring period, at which point they utilized a setback control during unoccupied hours.

Martinez staff stated they could not implement an unoccupied setback because their site did not have a BAS, and the wall thermostats were incapable of dual setpoint control. The site's VRF system usually shut off during unoccupied hours, but the occupants did have the ability to control thermostats, and the VRF system was observed to operate at some times during scheduled unoccupied hours.

VRF System Morning Warm-up Demand Management

This section assesses the impacts of different thermostat heating sequences of operation on a VRF system's morning winter heating electric demand profile to help assess whether Title 24 should adopt unique requirements for all-electric buildings employing VRF systems to mitigate morning warm-up peak demand.

Control Sequence Overview

The highest heating loads and heating energy occur during cold weather mornings when outside temperatures are typically at their lowest point in the day. The heating load may be higher in cases where the building shuts off or sets back its heating system during unoccupied hours: the system uses a significant amount of energy in the morning to warm up zones that cooled down overnight to satisfy the zone occupied heating setpoint temperature. With electric heating systems, morning warm-up heating demand becomes a new electric load on the grid when renewable energy production is low. Finding strategies to reduce morning electric heating is important for California's future electric grid stability.

2022 Title 24 Requirements

Section 120.2(k) has a mandatory requirement for space conditioning systems with direct digital control (DDC) at the zone level to have optimum start/stop controls, which are a function of space temperature, occupied zone temperature setpoint, outdoor air temperature, and the amount of time before scheduled occupancy.

Section 110.12(b) has a mandatory requirement for HVAC systems with DDC to the zone level to have the capability to decrease the heating setpoint by 4°F remotely.

These requirements were evaluated using the code standard baseline system design, which uses a natural gas space heating system and mixed air heating and cooling system. The analysis below aims to evaluate the impact on electric energy use and demand for VRF systems with DOAS using different morning warm-up strategies.

CONTROLS EVALUATION METHOD

This test examines the energy and electric demand implications for implementing staged morning warm-up compared to an unoccupied setback at two sites: Sacramento and Santa Rosa. Table 7 and Table 8 provide a summary of the control sequences included in this evaluation.

The research team reviewed trends of outside and zone temperatures, VRF fan power, VRF heat pump power, and DOAS unit power to understand how consistently the system met its intended setpoints, and to evaluate the energy use implications and electric demand impacts. For Sacramento, unoccupied setback trends include January - February 2021 and January 2022, and staged morning warm-up trends cover February 1 – March 13, 2022. For Santa Rosa, unoccupied setback trends cover January – February 2022, and staged morning warm-up trends cover March 2022.

TABLE 7: SACRAMENTO MORNING WARM-UP CONTROLS TEST SUMMARY

Mode	Schedule	ERV-DOAS Status	VRF Zone Heating Setpoint (°F)	
			Unoccupied Setback (Default)	Staged Morning Warm-up (Test)
Unoccupied	Mon-Fri, 5:30 pm-2 am All day Sat/Sun	Off	40	Off
Pre-Heating	Mon-Fri, 2 am-4 am (2 Hours Before ERV Turns On)	Off	Off	65
Flush-out	Mon-Fri, 4 am-6 am	On	Off	70
Occupied	Mon-Fri, 6 am-5:30 pm	On	70	70

TABLE 8: SANTA ROSA MORNING WARM-UP CONTROLS TEST SUMMARY

Mode	Schedule	ERV-DOAS Status	VRF Zone Heating Setpoint (°F)	
			Unoccupied Setback (Default)	Staged Morning Warm-up (Test)
Unoccupied	Mon-Fri, 9 pm-4 am All day Sat/Sun	Off	Off	Off
Pre-Heating	Mon-Fri, 4 am-6 am (2 Hours Before ERV Turns On)	Off	Off	65
Occupied	Mon-Fri, 6 am-9 pm	On	70	70

RESULTS AND OBSERVATIONS

Figure 17 and Figure 17 show the average winter weekday VRF system power demand profile for the Sacramento and Santa Rosa sites for three different operating modes:

- 24/7 constant heating setpoint (dark blue line).
- Unoccupied setback (light blue line).
- Staged morning warm-up (green line).

Both 24/7 constant setpoint and staged morning warm-up provide significant morning peak demand reduction compared to unoccupied setback. Due to differences between the sites' ERV-DOAS operating schedules which impacted the start time of the VRF system turning on for staged morning warm-up, with Sacramento site starting earlier than Santa Rosa.

Although the site indicated the Santa Rosa staged morning was programmed to start at 4am per Table 8, trends indicate the VRF system turned on at 6am each morning, and stage 1 pre-heating operation occurred 6am-8am.

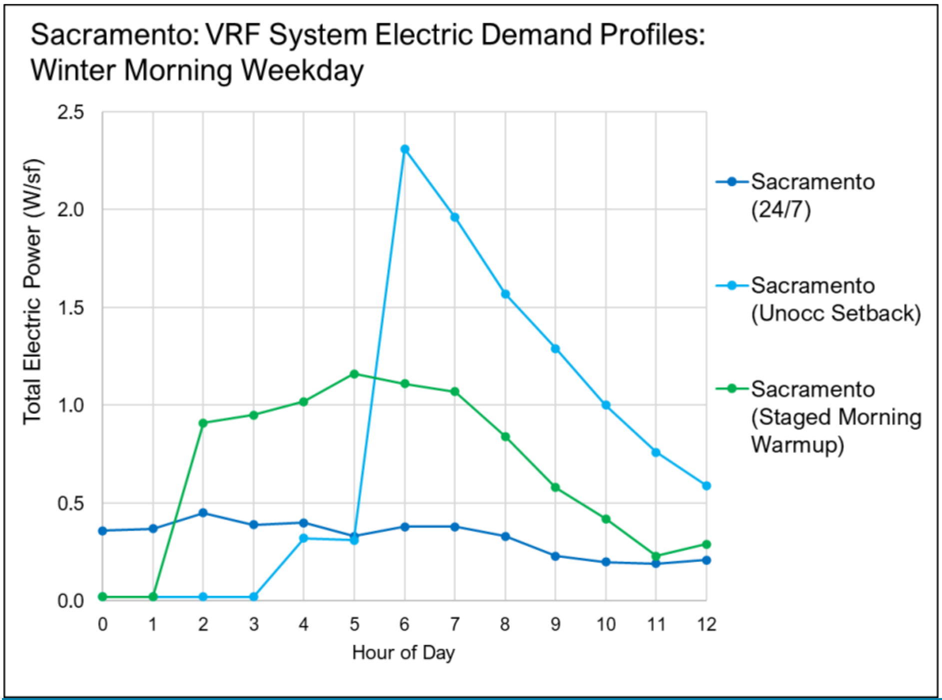

FIGURE 16: SACRAMENTO VRF SYSTEM POWER DEMAND PROFILES DURING MORNING WARM-UP

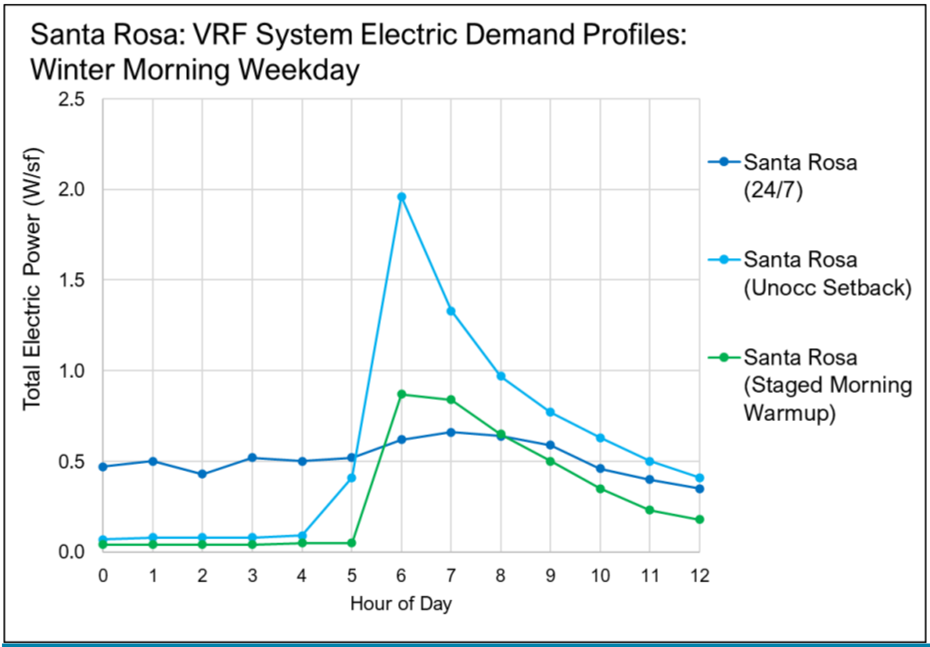

FIGURE 17: SANTA ROSA VRF SYSTEM POWER DEMAND PROFILES DURING MORNING WARM-UP

Energy Impacts

The peak VRF system power demand reduction and net energy impact for the evaluated morning warm-up strategies are presented in Table 9, in metrics of absolute demand density (W/sf) and energy use normalized by heating degree day (Wh/sf per HDD). Staging heating setpoints resulted in about 50% peak demand reduction at both sites, and 24/7 constant heating setpoints resulted in about 65-85% peak demand reduction between sites. The large demand reduction indicates both control sequences could be viable strategies to reduce electric demand in winter mornings in all-electric buildings.

When normalized by HDD, net energy impact of morning heating demand reduction strategies varied by site, as shown in Table 9. For both sites, 24/7 operation resulted in an increase in energy use. Staged morning warm-up resulted in 25% energy savings at Santa Rosa and a 10% energy increase at Sacramento. One of the factors impacting energy use is the hours of operation; Sacramento's staged morning warm-up started earlier than the VRF system's typical morning warm-up and was interrupted by an ERV-DOAS ventilation air flush-out, both resulting in increased energy use compared to Santa Rosa, which started its staged morning warm-up at the same time as its typical morning warm-up.

TABLE 9: MORNING WARM-UP DEMAND REDUCTION TESTS: VRF ELECTRIC ENERGY AND DEMAND SAVINGS

	Sacramento		Santa Rosa	
	24/7 Constant Setpoint	Staged Morning Warm-up	24/7 Constant Setpoint	Staged Morning Warm-up
Peak Demand Reduction (W/sf) [1]	1.9 (84% savings)	1.2 (50% savings)	1.3 (66% savings)	1.1 (56% savings)
Weekly Net Energy Savings (Wh/sf per HDD) [2]	-121 (110% increase)	-10 (10% increase)	-16 (25% increase)	14 (25% savings)

[1] Peak demand reduction occurred at 6:00 am.

[2] VRF system energy during unoccupied and morning hours is included. For Sacramento, this includes Mon-Fri 6:00 pm-12:00 pm and all day Sat/Sun. For Santa Rosa, this includes Mon-Fri 9pm-12pm and all day Sat/Sun.

Implementation Considerations

Both sites that implemented staged morning warm-up used a BAS that required additional programming and commissioning time to implement scheduled staged setpoints. The Sacramento site benefitted from having a controls contractor available to help review trends and controls programming to make sure the controls test was implemented correctly. However, the Santa Rosa site did not have a controls contractor available for verification support, and the research team did not have access to the BAS controls logic, thus confirming the test schedule and start time programming was not achievable.

Occupant feedback on this test was not provided. Although the Santa Rosa setback operation did not begin until 6am, classes did not start until 9am, so the building had very few occupants during the staged morning warm-up operation that would have been directly impacted.

VRF System Afternoon Cooling Demand Management

The following section assesses the impacts of different thermostat cooling sequences of operation on a VRF system's afternoon summer electric demand profile to evaluate potential strategies for permanent demand reduction and demand response.

Control Sequence Overview

Commercial building peak electric demand typically occurs in the late afternoon when cooling loads are greatest. Historically, this afternoon cooling peak demand occurred when electric utility demand cost rates were highest. However, California's electric rate structure has shifted in recent years due to increased electricity produced through renewable solar energy. As a result, the highest electric demand charges have changed to summer evenings when building cooling loads are still high, but solar energy production is low. Finding strategies to reduce early evening cooling demand while taking advantage of abundant solar energy production in the afternoon is important for California's future electric grid stability.

2022 Title 24 Requirements

In addition to Title 24's mandatory optimal start/stop requirement described in the Zone Temperature Control section above, Section 110.12(b) has a mandatory requirement for HVAC systems with DDC to the zone level to have the capability to remotely increase (setup) the cooling setpoint by 4°F for demand response control.

The analysis below aims to evaluate the impact on electric energy use and demand for VRF systems with DOAS using an afternoon pre-cooling strategy to help assess whether Title 24 should adopt unique requirements for VRF systems.

Controls Evaluation Method

This test examines the energy and electric demand implications for implementing staged afternoon zone cooling setpoints compared to a constant afternoon cooling setpoint at the Sacramento and Santa Rosa sites. Table 10 provide a summary of the control setpoints at both locations.

The research team reviewed trends of outside and zone temperatures, VRF fan power, VRF heat pump power, and DOAS unit power to understand how consistently the system met its intended setpoints, energy use implications, and electric demand impacts. For Sacramento, constant afternoon setpoint trends include August 2021, and staged afternoon cooling trends include July 2022. For Santa Rosa, constant afternoon setpoint trends include June 2022, and staged afternoon cooling trends include July 2022.

TABLE 10: AFTERNOON PRE-COOLING CONTROL SETPOINTS [1]

Mode	Schedule	VRF Zone Afternoon Cooling Setpoint (°F)	
		Constant Setpoint (Default)	Pre-Cooling Setpoint (Test)
Stage 1 (Pre-Cooling)	Mon-Fri, 2-4pm	75	70
Stage 2 (Setup Cooling)	Mon-Fri, 4-6pm	75	80

[1] During the 2-6pm Pre-Cooling Setpoint Test, the zone heating setpoint was decreased from 70°F (default) to 65°F.

RESULTS AND OBSERVATIONS

Figure 18 shows the average summer weekday VRF system power demand profile for the Sacramento and Santa Rosa sites during the staged afternoon zone cooling setpoint test (orange and light blue lines) and default constant cooling setpoint operation (red and dark blue lines).

During the staged afternoon cooling setpoint test, peak VRF cooling demand at both sites occurs at 2:00 pm (hour 14) when zone cooling setpoints decrease from 75°F to 70°F. Sacramento shows a dramatic decrease in power demand at 4:00 pm (hour 16) when zone cooling setpoints increase from 70°F to 80°F and continue to decrease until the system turns off between 5:00 and 6:00 pm. Santa Rosa's VRF power demand variation is less extreme than Sacramento's. Santa Rosa's lowest power demand occurs later than Sacramento's, between 5:00 and 6:00 pm as zone cooling setpoints are highest (80°F) and then increases slightly at 7:00 pm (hour 19) as zone cooling setpoints resume to their typical setpoint of 75°F. The system continues to operate until between 9:00 and 10:00 pm.

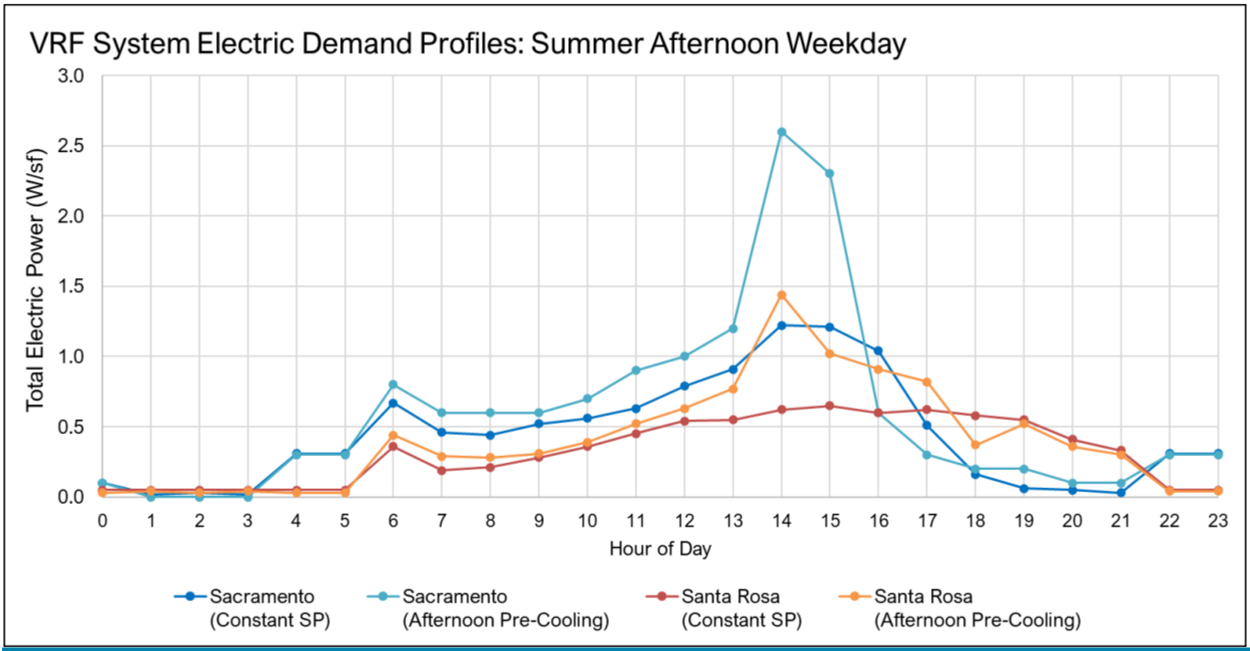

FIGURE 18: SACRAMENTO AND SANTA ROSA VRF SYSTEM POWER DEMAND PROFILES DURING AFTERNOON COOLING

Figure 19 shows a two-day BAS trend of room temperature for an example zone at Sacramento. The trend shows that at 2:00 pm, the room temperature was 75°F, then decreased to around 72°F when the cooling setpoint decreased to 70°F between 2:00 and 4:00 pm, and then increased up to around 79°F when the room temperature setpoint increased to 80°F at 4:00 pm. The room cooling setpoint remained at 80°F overnight as the unoccupied setup temperature setpoint.

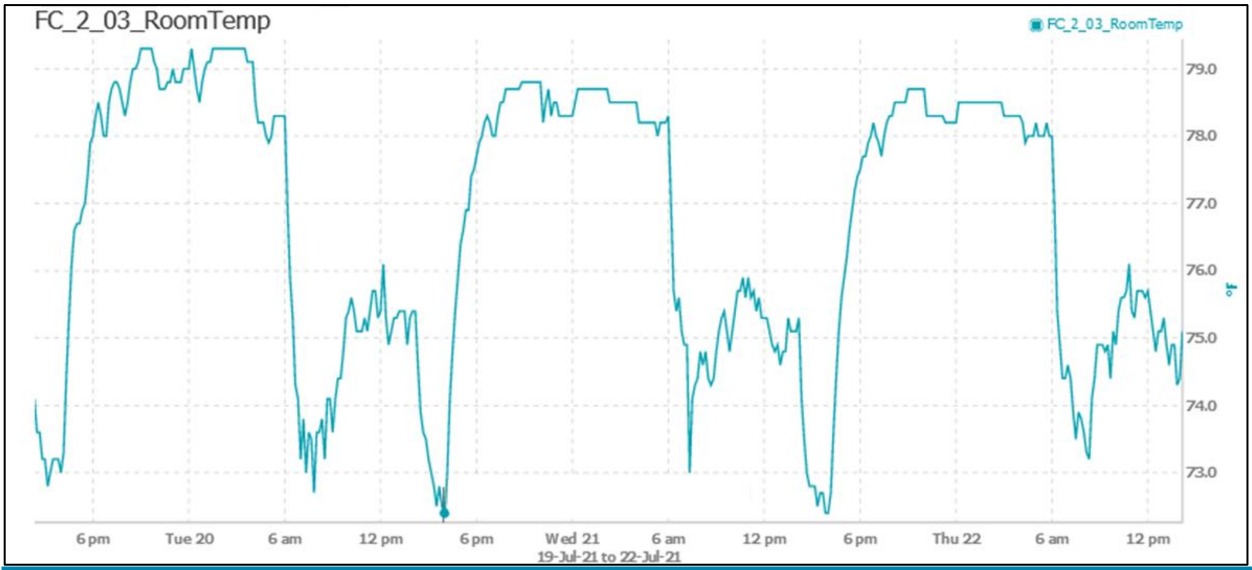

FIGURE 19: SACRAMENTO EXAMPLE BAS ZONE TEMPERATURE TREND DURING STAGED AFTERNOON COOLING TEST

Energy Impacts

Table 11 presents the peak VRF system power demand reduction and net energy impact for afternoon pre-cooling compared to a constant zone cooling temperature setpoint. Absolute demand density (W/sf) and energy use are normalized by cooling degree day (Wh/sf per cooling degree day (CDD)). Both sites experienced about 40% peak demand reduction. However, the demand reduction came with a significant energy increase.

TABLE 11: AFTERNOON PRE-COOLING DEMAND REDUCTION COMPARED TO CONSTANT SETPOINT: VRF ELECTRIC ENERGY AND DEMAND SAVINGS

	Sacramento	Santa Rosa
	Afternoon Pre-Cooling	**Afternoon Pre-Cooling**
Peak Demand Reduction (W/sf) [1]	0.44 (42% savings)	0.21 (36% savings)
Afternoon Net Energy Savings (Wh/sf per CDD) [2]	-1.6 (26% increase)	-4.4 (96% increase)
Average Weekday Room Temperature (12-5pm)	76.3	76.2

[1] Sacramento's peak demand reduction occurred at 4:00 pm. Santa Rosa's peak demand reduction occurred at 6:00 pm.
[2] VRF system energy from 2:00 to 6:00 pm is included.

Implementation Considerations

Both sites that implemented afternoon pre-cooling used a BAS for control and required additional programming and commissioning to implement scheduled staged setpoints. The

Sacramento site benefitted from having a controls contractor available to help review trends and controls programming to ensure the controls test was implemented correctly. However, the Santa Rosa site did not have controls contractor available for verification support, and the research team did not have access to BAS controls logic, so underlying controls logic issues may have prevented this test from being optimally implemented.

Occupants at the Sacramento site reported they were too cold during the 2:00 to 4:00 pm pre-cooling period, where the cooling setpoint was 70°F. However, occupants did not report discomfort with the 80°F setpoint from 4:00 to 6:00 pm, likely due to many leaving by 5:00 pm.

The Santa Rosa site did not report occupant comfort complaints with the temperature setpoints other than one occupant complained about their lack of ability to adjust their thermostat during the test period.

VRF Cooling with Ceiling Fans

One of the sites (Sacramento) had ceiling fans. The research team performed tests to assess the impacts of prioritizing ceiling fans as the first stage of cooling ahead of the VRF fan coils during all occupied hours. The following section assesses these impacts on a VRF system's afternoon summer electric demand profile to evaluate potential strategies for permanent demand reduction and demand response.

Control Sequence Overview

See VRF System Afternoon Cooling Demand Management section above.

2022 Title 24 Requirements

See VRF System Afternoon Cooling Demand Management section above.

Controls Evaluation Method

This test examines the energy and electric demand implications for implementing a control strategy that prioritized ceiling fans as the first stage of cooling and the VRF system as the second stage of cooling compared to a typical system without ceiling fans. During the test that used cooling fans, the ceiling fans were programmed to turn on at a typical zone cooling temperature setpoint (75°F) and automatically increase speed as the room temperature increased. Then the VRF fan coil provided cooling if the zone reached an increased cooling temperature (78°F), as shown in Table 12.

Table 12: Sacramento Test 2 Summary: Ceiling Fan Prioritization Cooling Control

Parameter	Constant Setpoint (Default)	Ceiling Fan Priority (Test)
Occupied Hours	Monday - Friday 6 am - 5:30 pm	
Cooling Setpoint (°F)	75	78
Ceiling Fan Speed Control	0-90% via BAS as room temperature increases above 75ºF (with manual user override)	0-100% [1] via BAS as room temperature increases from 74ºF to 78ºF (no user override)
Ceiling Fan Rotation Direction	Counter-clockwise (down)	

[1] The maximum fan speed setpoint was adjusted during the test based on occupant feedback. See Implementation Considerations for details.

Results and Observations

Figure 20 shows the average summer weekday VRF system power demand profile for the Sacramento site during the ceiling fan prioritization test (dashed blue line), afternoon pre-cooling test (light blue line), and default constant cooling setpoint operation (dark blue line).

During the ceiling fan prioritization test, the VRF system power demand was lower than during default constant setpoint operation for all hours when the test was enabled (daytime, occupied hours). During peak demand hours (4:00 pm to 6:00 pm), the ceiling fan priority operation resulted in less demand reduction than the afternoon pre-cooling test but still lower demand than constant setpoint operation.

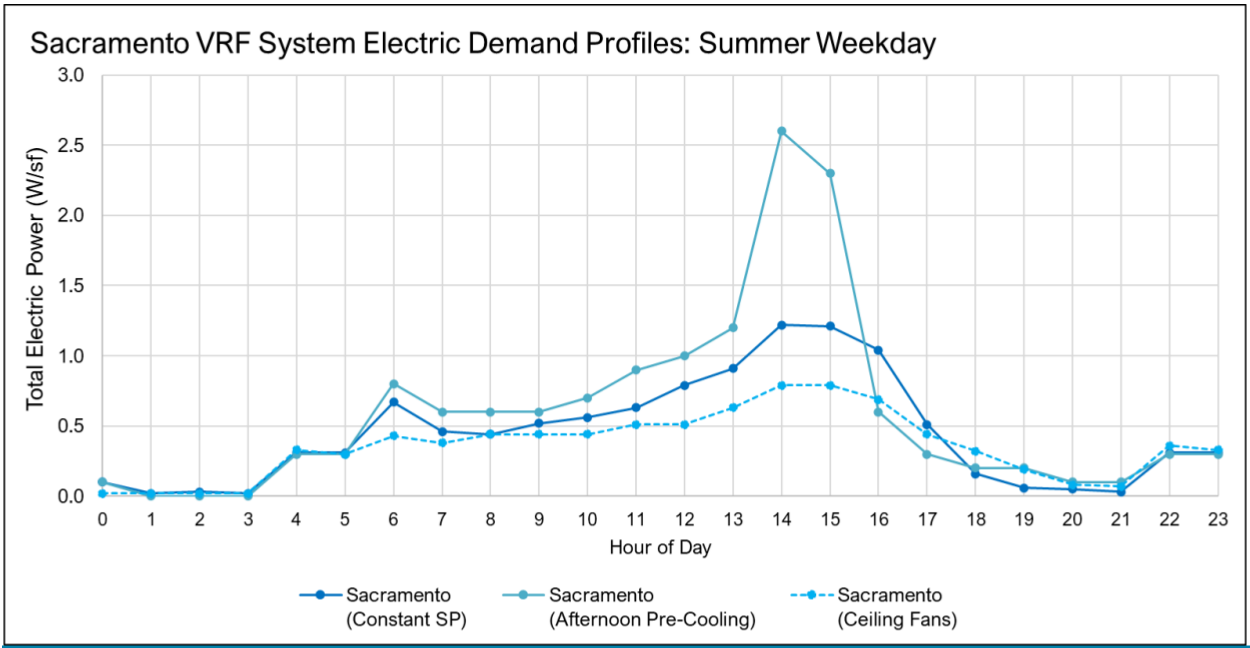

Figure 20: Sacramento VRF System Typical Summer Day Power Demand Profiles

Figure 21 shows the average zone temperature during the ceiling fan prioritization cooling test (blue line) compared to summer afternoon space temperature using default control (green line) and staged afternoon cooling setpoint test (orange line). In the afternoon, the average zone temperature was 1-2°F warmer during the ceiling fan prioritization test when ceiling fans were prioritized for cooling and the VRF zone cooling setpoint temperature was increased to 78°F.

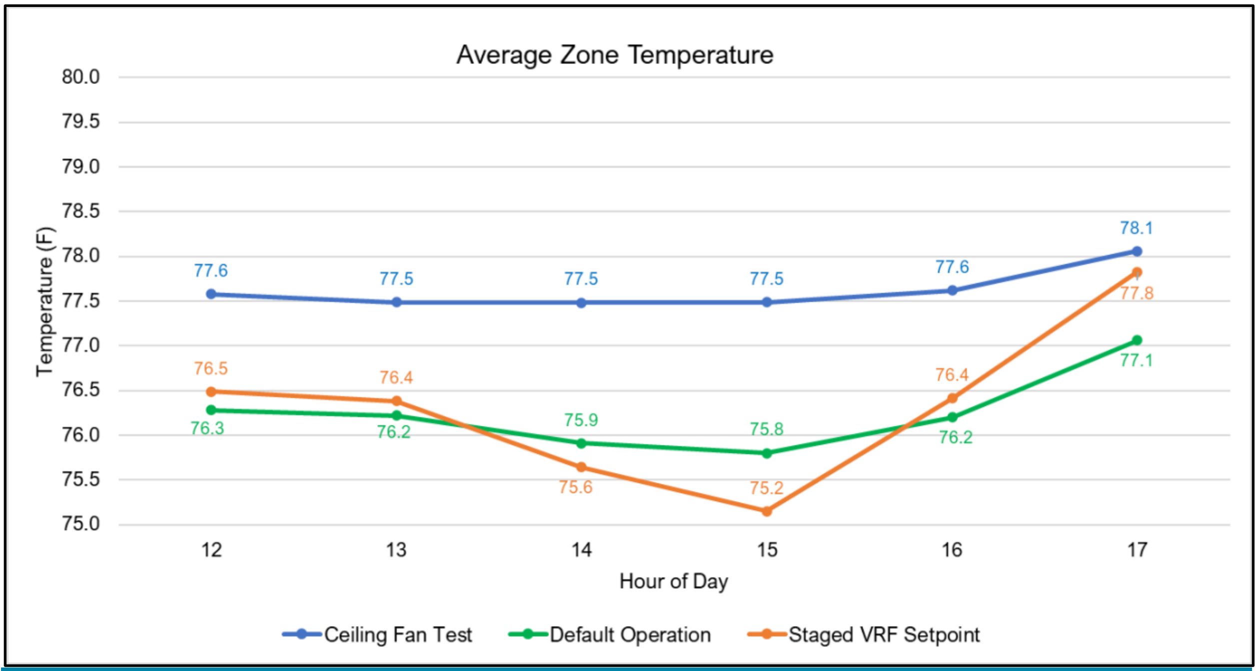

FIGURE 21: SACRAMENTO AVERAGE ZONE TEMPERATURE DURING CEILING FAN PRIORITIZATION COOLING TEST

Energy Impacts

Table 13 presents the peak VRF system power demand reduction and net energy impact for the ceiling fan prioritization test compared to a constant zone cooling temperature setpoint. Absolute demand density (W/sf) and energy use are normalized by cooling degree day (Wh/sf per CDD). Like the afternoon pre-cooling test, ceiling fan prioritization resulted in close to 40% peak demand reduction. However, while afternoon pre-cooling can be implemented with any VRF system, buildings with VRF systems and ceiling fans installed can achieve similar peak demand reduction while also decreasing cooling energy use by automating ceiling fans as the first stage of cooling and increasing VRF zone cooling setpoints. This strategy reduced energy use by around 40%, whereas simply staging VRF afternoon zone cooling setpoints without ceiling fans increased energy by 25 to 100%.

TABLE 13: SACRAMENTO CEILING FAN COOLING PRIORITIZATION TEST: VRF ELECTRIC ENERGY AND DEMAND SAVINGS

Peak Demand Reduction (W/sf) [1]	0.35 (34% savings)
Afternoon Net Energy Savings (Wh/sf per CDD) [2]	2.5 (41% savings) [1]
Average Weekday Room Temperature (12-5pm)	77.6

[1] Ceiling fan energy use is about 0.1 Wh/sf per CDD, resulting in a net energy savings of 2.4 Wh/sf per CDD (40% savings).

Implementation Considerations

Initially, the control sequence intent was to increase ceiling fan speed from 0% to 100% as zone temperature increased from 74°F to 78°F. However, when the control sequence was first implemented, occupants working in the open office area complained that the 100% ceiling fan speed was too high due to the low ceiling height and resulting high airflow velocity experienced at workstations. Consequently, the maximum ceiling fan speed was adjusted to 35% at the BAS.

Another challenge during this test resulted from the floor plan layout and thermal zoning. The VRF fan coils serving the open office area also served three small huddle rooms, which did not have ceiling fans, unlike the open office. As a result, when zone cooling setpoints were increased, the huddle rooms did not gain the comfort benefit of air movement from ceiling fans, resulting in occupant discomfort.

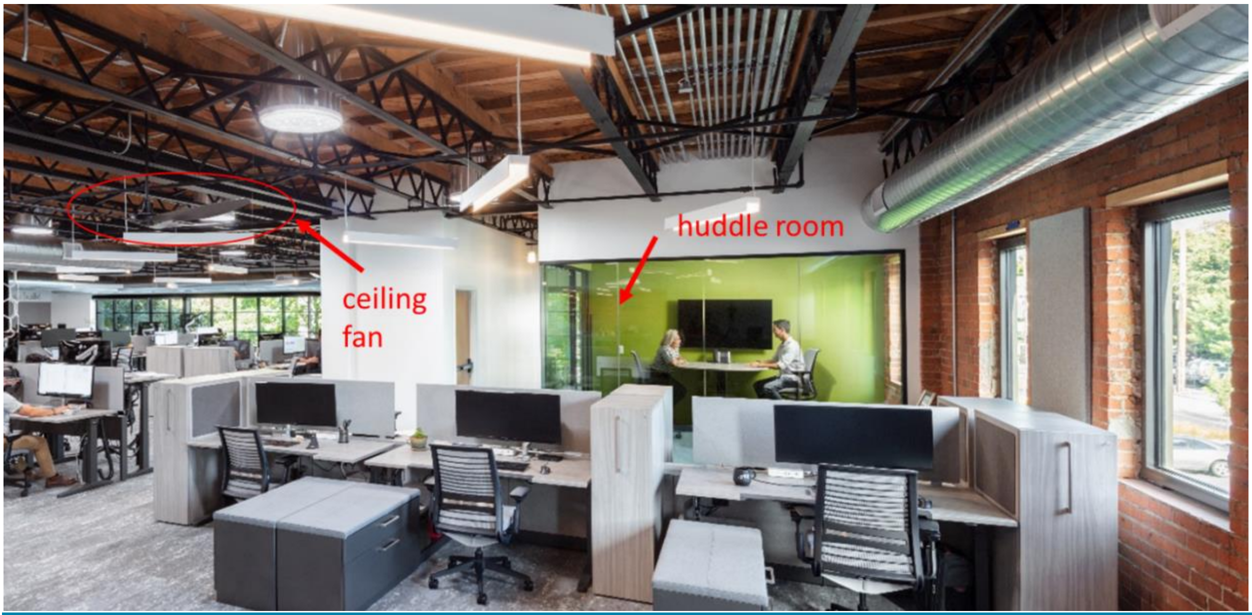

FIGURE 22: SACRAMENTO OPEN OFFICE AND HUDDLE ROOM (PHOTO COURTESY OF DPR CONSTRUCTION)

VRF FAN COIL DEADBAND FAN SPEED CONTROL

2022 Title 24 includes prescriptive requirements for DOAS airflow configurations and zone terminal unit fan and pump power. The analysis below aims to compare the field-measured energy use of the Title 24 compliance pathway and its exception to shut off zone fan/pump power when the zone is not in heating or cooling to inform whether the 2022 Title 24 requirement should be revised.

CONTROL SEQUENCE OVERVIEW

VRF fan coils at all sites had three speeds. When a zone was within its heating and cooling temperature deadband, the most common control sequence observed was fan coil fans remaining on. An alternative control method is for the fan coil fan to turn off when the zone is within in deadband.

2022 TITLE 24 REQUIREMENTS

Section 140.4(p)2 prescriptively requires that DOAS ventilation air be delivered directly to a space or downstream of zone heating/cooling coils and that zone heating and cooling equipment (fans, pumps) cycle off when the zone is in its temperature deadband, unless the zone fan power is no greater than 0.12 W/cfm when the zone is in its temperature deadband, in which case DOAS ventilation air may be provided upstream of zone heating/cooling units.

CONTROLS EVALUATION METHOD

This test examines the performance of VRF fan coil fan speed control at the Sacramento field site. The research team used two deadband control sequences of operation to compare fan energy use and electric demand when zones were in their deadband:

1. Default operation: When a zone was within its temperature deadband; fan coil remains on at a speed determined by the fan coil's manufacturer controller.
2. Controls test implemented in October 2021: When a zone was within its temperature deadband, fan coil turns off (provided the ERV-DOAS supply air temperature into the building was between 45°F and 73°F to avoid potential occupant comfort issues in extreme weather).

At Sacramento, the ERV-DOAS ventilation air was ducted directly to the return air intake of each zone fan coil and mixed with room air before passing over the fan coil and being distributed into the space.

The research team reviewed zone temperature and individual fan coil power trends. The team also reviewed zone CO_2 trends to evaluate indoor air quality impacts. Occupant feedback was also solicited to assess occupant comfort impacts.

RESULTS AND OBSERVATIONS

Figure 23 shows the average weekday 24-hour power demand profile of four sample fan coils at Sacramento for two months with similar weather data: April 2021 where fan coil fans operated with their default control sequence of keeping fan coils on when zones were in their temperature deadband and October 2021 where fan coil fans shut off when zones were in their temperature deadband. Fan coil fan power was largely the same during the two ventilation "flush-out" periods (4:00 am-6:00 am and 10:00 pm-12:00 am); however, there is a significant reduction in energy use during occupied hours (6:00 am-4:00 pm) in October compared to April. This was largely driven by one fan coil (FC 2-09). This fan coil was the largest fan coil (6 tons) and served an open office area at the West perimeter of the building. This fan coil was able to significantly reduce its energy use (30% reduction) by turning off when in its temperature deadband.

Because ventilation air is ducted through the fan coils at Sacramento, room CO_2 levels were also compared to understand if shutting off fan coil fans when zones were in their temperature deadband impacted indoor air quality. Table 14 compares room CO_2 data from August 2021 (when fans stayed on in their deadband) and October 2021 (when fans shut-off in their deadband). Overall, the impact on indoor CO_2 levels was negligible (1% lower in October 2021), with individual rooms ranging from 9% lower to 5% higher CO_2 levels during the deadband shut-off test in October, still within a safe and normal range.

TABLE 14: AVERAGE ROOM CO2 LEVELS DURING OCCUPIED HOURS

Room	Default: April 2021 (ppm)	Test: October 2021 (ppm)	Difference (ppm)	% Difference
Small Conference Rooms (FC 2-07)	558	510	-48	-9%
Medium Conference Room (FC 2-06)	581	536	-45	-8%
Corridor (N) (FC 1-02)	502	483	-19	-4%
Library (N) (FC 2-13)	527	508	-18	-4%
Huddle/Wellness (FC 2-02)	490	479	-12	-2%

Reception (FC 2 -03)	506	495	-11	-2%
Corridor (FC 2-04)	495	486	-10	-2%
Open Workspace & Huddle (FC 2-09)	523	527	4	1%
Open Workspace (FC 2-10)	526	535	9	2%
Large Conference Room (FC 2-12)	612	626	14	2%
Classroom (FC 2-05)	510	522	12	2%
Medium Conference Room (FC 2-08)	542	572	30	5%
Overall Average	**531**	**523**	**-8**	**-1%**

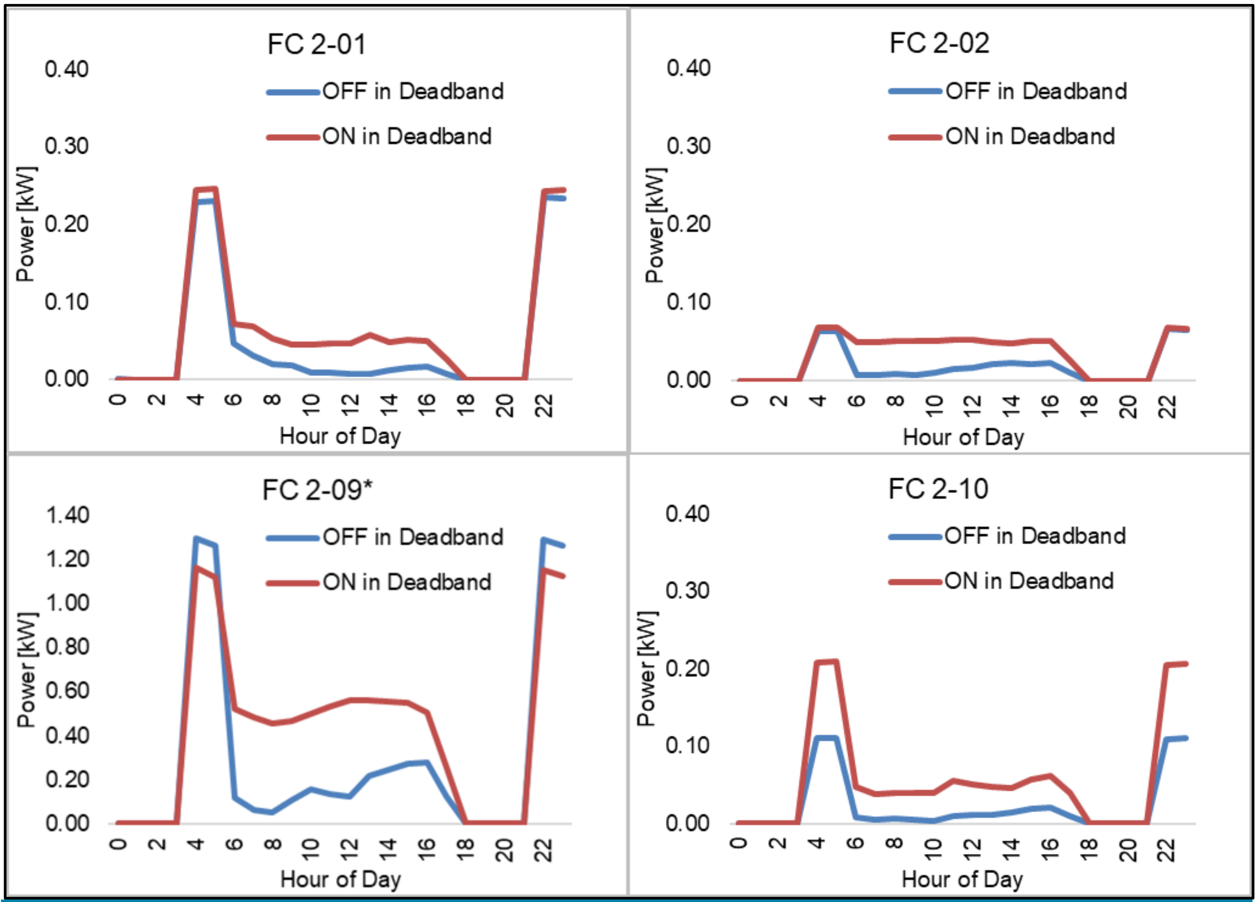

FIGURE 23: SACRAMENTO VRF FAN COIL TOTAL AVERAGE POWER DEMAND DURING OCCUPIED HOURS: APRIL 2021 (FAN ON IN DEADBAND) VS. OCTOBER 2021 (FAN OFF IN DEADBAND) *NOTE THE CHART WITH FC 2-09 HAS A DIFFERENT Y-AXIS SCALE THAN THE OTHER CHARTS.

Energy Impacts

As shown in Figure 24, shutting off fan coils when zones are in their temperature deadband in October 2021 saved approximately 12 Wh/sf-month (23%) of fan coil fan energy compared to a similar weather month (April 2021). The average fan coil demand reduction during occupied hours (6:00 am-4:00 pm) was around 55% compared to April 2021, with negligible (1%) fan coil peak demand reduction.

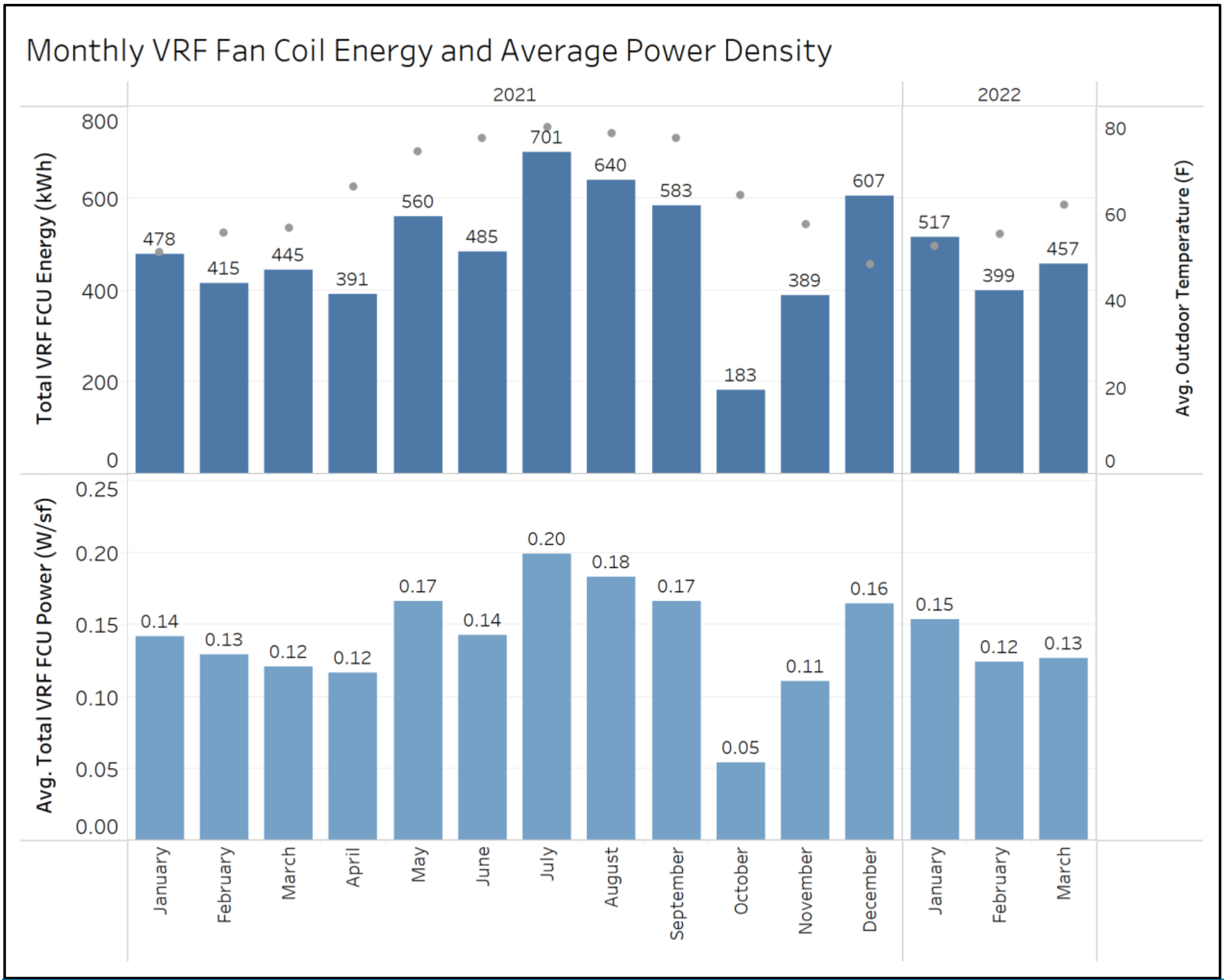

FIGURE 24: SACRAMENTO MONTHLY VRF FAN COIL ENERGY AND AVERAGE OCCUPIED FAN POWER DENSITY

However, because this site had ERV-DOAS ventilation air ducted to VRF fan coil return air intakes, when the VRF fan coils shut off, the ERV-DOAS unit fans had to increase speed to overcome the pressure drop of the fan coils. This increased DOAS fan power and energy use can be seen in the October 2021 data in Figure 25; October 2021 ERV-DOAS fan energy and average power was noticeably higher than all other months[7]. This was an increase of 8 Wh/sf-month (23% increase) in October compared to average DOAS occupied-hour energy. Therefore, subtracting the 8 Wh/sf ERV-DOAS fan energy increase from the 12 Wh/sf fan coil energy savings, the net energy savings for this site was just 4 Wh/sf-month due to its coupled DOAS and VRF airflow configuration.

[7] Except November 2021, when the ERV-DOAS unit operated in CAV mode at full airflow as part of another controls test.

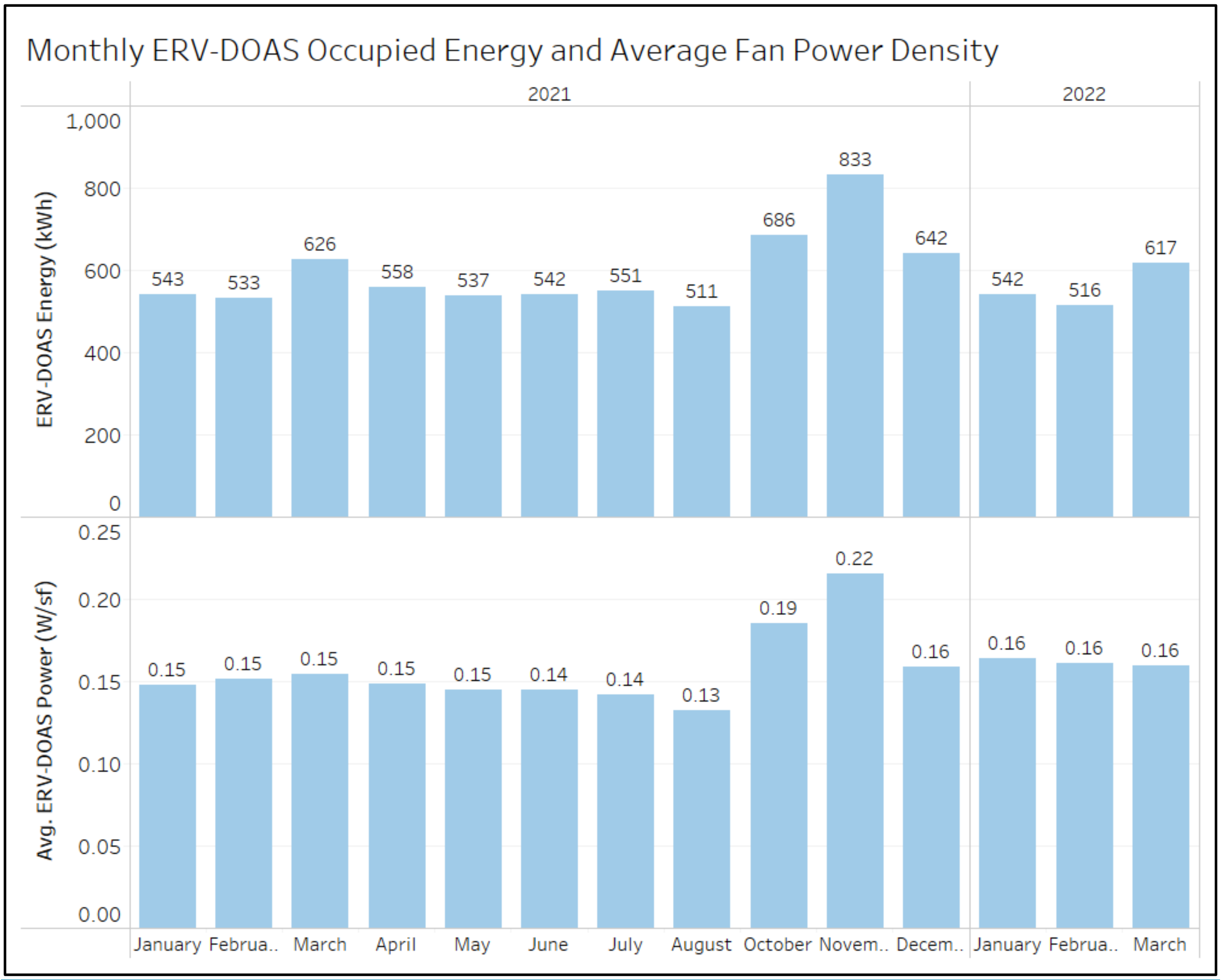

Figure 25: Sacramento Occupied Monthly ERV-DOAS Fan Energy and Average Fan Power Density

Implementation Considerations

This measure required additional control programming in the BAS by the building's controls contractor to be implemented and would have been difficult, if not impossible, to implement with the VRF manufacturer's controls alone.

Occupants did not provide feedback, negative or positive, on this measure, indicating that most occupants likely did not notice the change in operation while energy savings was achieved.

The original design intent was to integrate the lighting occupancy sensors into the BAS to be able to shut off ventilation air for zones with VAV dampers and zone fan coils when the zone was unoccupied. However, due to extensive issues configuring the lighting control system that lasted beyond construction and well into building occupancy, this control was not implemented.

For VRF systems using A2L refrigerants, it may be desirable to operate zone fans continuously to comply with ASHRAE 15-2022 section 7.6.1.1 as a simpler compliance path than installing a refrigerant detection system.

FINDINGS AND RECOMMENDATIONS

DOAS UNIT: HEAT RECOVERY BYPASS CONTROL

FINDINGS

Many factors impact the energy savings achieved with DOAS heat recovery bypass control, including setpoint, ventilation rate, zone heating/cooling system efficiency, and control integration. This interaction makes it difficult to establish a strong correlation between any single factor and energy savings observed in the field.

While DOAS-integrated heat recovery bypass control theoretically provides more energy savings than non-integrated control, the observed energy savings for integrated bypass control varied based on the bypass temperature setpoint(s) used at the sites. Due to the difficulty in validating the proper integrated bypass control in the field, the simpler non-integrated bypass control approaches achieved more consistent results in operation.

ENERGY CODE RECOMMENDATIONS

Before developing code requirements for integrated heat recovery bypass controls, additional analysis is needed to establish optimal seasonal bypass control setpoints. The lowest energy setpoint may vary depending on the season, climate zone, and building characteristics, including building type, hours of operation, internal load profiles, and thermal zone configuration. Each of these items should be included in an energy analysis.

During the commissioning design review required in Title 24, the design documentation should be reviewed to ensure that heat recovery bypass control setpoints and control methods, with or without BAS integration, are documented in the design. In addition, for commissioning design reviews and functional testing, the research team recommends the Title 24 Air Economizer Controls and Exhaust Air Heat Recovery Acceptance Test be updated to address integrated and non-integrated bypass controls to help ensure systems are installed to operate with heat recovery bypass functionality correctly configured.

DOAS UNIT: ZONE DCV

FINDINGS

The Sacramento site implemented DCV in spaces where required by Title 24. Testing showed modest ERV-DOAS fan energy savings from DCV (0.16 kWh/sf-yr, 2% whole building energy savings). However, the research team determined that adding DCV controls for ventilation airflow to individual thermal zones on the Santa Rosa ERV-DOAS system was not cost-effective.

ENERGY CODE RECOMMENDATIONS

Due to poor cost-effectiveness and relatively low energy savings experienced at field sites, DOAS systems and mixed air VAV with reheat systems should be subject to different DCV requirements. The research team recommends that, at minimum, the 120.1(d)3 mandatory requirement for DCV ventilation zone size be larger for DOAS systems than for mixed air systems to reduce the first cost barrier to implementing DCV with DOAS.

DX-DOAS Supply Air Temperature Control

Findings

The findings for this control strategy are based on a single site; however, the research team believes that they apply to all sites that do not have a BAS and rely solely on the onboard DX-DOAS controller for supply air temperature control. Despite being only five years old, significant issues were found with the Oakland site DX-DOAS unit's onboard supply air temperature controller; the unit did not reliably control to its setpoints. Ongoing commissioning or equipment upgrades may be needed to ensure proper operation.

Energy Code Recommendations

The research team recommends applying Title 24, Section 140.4(f) prescriptive requirements for supply air temperature reset control based on outside air temperature to DX-DOAS units. DX-DOAS units should also undergo acceptance testing as required in 120.5(a)15.

The research team recommends adding a mandatory requirement to 120.2 for ongoing fault detection to help ensure DX-DOAS unit supply air temperature (heating/cooling) controls maintain proper operation and achieve the designed energy savings throughout the equipment's operational lifetime.

VRF Morning Warm-up Demand Management

Findings

Staging the zone morning heating setpoint and 24/7 constant zone heating setpoint control are both viable control strategies to reduce morning heating electric demand. However, 24/7 operation uses nearly twice as much energy as staged morning warm-up control.

Energy Code Recommendations

For buildings with electric heating systems (including VRF, hydronic heat pumps, etc.), the research team recommends adding a mandatory requirement in section 120.2 for staged morning warm-up control to reduce morning heating electric demand in peak periods. Additional modeling or field testing should be done to determine a staged morning warm-up control sequence that is cost-effective for most buildings, for incorporation into Title 24.

VRF Afternoon Cooling Demand Management

Findings

Staging VRF system zone cooling setpoints by pre-cooling spaces in the early afternoon and later increasing zone cooling setpoints can significantly reduce peak cooling demand. This strategy can be implemented in all buildings with VRF. The energy and electric demand increase during pre-cooling are significant but may come with minimal cost impact to facility operators in areas with aggressive TOU rates or demand charges or if aligned with on-site solar energy production.

Energy Code Recommendations

Temporary demand response and permanent dynamic demand control are tools that can be used as energy codes move toward addressing time-of-use energy use to address electric grid constraints. Staging VRF zone cooling setpoints can be used as a control strategy for demand response events to comply with 110.12(b). *However, due to occupant comfort complaints, afternoon pre-cooling should not be used as a permanent demand management controls strategy.*

VRF Cooling with Ceiling Fans

Findings

Prioritizing ceiling fans as the first stage of cooling before active VRF cooling resulted in significant demand reduction and energy savings for all operating hours. Occupants expressed discomfort from the high air velocity when fans operated at maximum speed due to the low fan ceiling height, which should be considered when developing ceiling fan control sequences.

Energy Code Recommendations

Prioritizing ceiling fans as the first cooling stage before the VRF system operates is a good permanent control strategy to flatten cooling demand as a demand management method without increasing energy use. However, findings are based on only a single building; further research is recommended to determine if ceiling fan requirements should be included in the energy code as a prescriptive requirement in section 140.4.

VRF Fan Coil Deadband Fan Speed Control

Findings

In DOAS and VRF systems where ventilation airflow is ducted to the return air of the zone VRF fan coil, shutting off fan coils when zones are in their deadband saves energy, even when accounting for increased ERV-DOAS fan energy consumption due to increased pressure drop through the fan coil when the fan coil fan is not running.

Energy Code Recommendations

The research team does not recommend modification for the exceptions to 2022 Title 24, section 140.0(p)2.

General Findings

Afternoon Pre-Cooling

As a best practice, when this measure is implemented, the research team advises that occupants are educated on the intent of this temporary demand management control strategy to mitigate potential occupant comfort complaints.

BAS Control

Manufacturer controllers were insufficient to implement many of the control sequences reviewed in this report, most of which require a BAS for successful implementation and verification. There are several opportunities to leverage control measures to improve the energy and indoor air quality performance of DOAS systems. However, requiring a BAS for all DOAS systems is likely not cost-effective and further analysis is needed to determine if there is a building size threshold where requiring a BAS would be cost-effective in future code cycles.

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APPENDICES

APPENDIX A: MARTINEZ CONTROLS SETPOINTS AND SCHEDULE

		Test Number	**Test 1**	**Test 2**	**Test 3**
		Test Name	**Initial Operation**	**Default Operation**	**24/7 Summer VRF**
		Test Description	**DOAS CAV,** **DOAS 24/7,** **Cold DOAS HR Bypass Temp,** **VRF OFF when Unoccupied**	**DOAS CAV,** **DOAS Night Flush,** **Neutral DOAS HR Bypass Temp,** **VRF OFF when Unoccupied**	**DOAS CAV,** **DOAS Night Flush,** **Neutral DOAS HR Bypass Temp,** **VRF 24/7**
		Test Time Period	**Nov 2020 - Jan 14, 2021**	**Jan 15, 2021 - October 2021 (except Test 3)**	**July 20, 2021 - September 4, 2021**
VRF	Heat Pump		Unit modulates per manufacturer's default control sequence to serve heating and cooling loads in building.		
VRF	Fan Coils	Fan Speed	Fan automatically modulates between low, medium, and high speeds to meet room temperature setpoint	Fan automatically modulates between low, medium, and high speeds to meet room temperature setpoint	Fan automatically modulates between low, medium, and high speeds to meet room temperature setpoint
VRF	Fan Coils	Fan ON/OFF	Fan operates automatically during Occupied Hours. Fan speed control to be documented, based on trend observations	Fan operates automatically during Occupied Hours. Fan speed control to be documented, based on trend observations	Fan operates automatically during Occupied Hours. Fan speed control to be documented, based on trend observations
VRF	Fan Coils	Hours of Operation	Mon-Fri 7am-7pm	Mon-Fri 7am-7pm	**24/7**
VRF	Fan Coils	Room Temperature Setpoint - Occupied	Setpoint sent from controller (default = 72F). Setpoint can be adjusted by users.	Setpoint sent from controller (default = 72F). Setpoint can be adjusted by users.	Setpoint sent from controller (default = 72F). Setpoint can be adjusted by users.
VRF	Fan Coils	Room Temperature Setpoint - Unoccupied	n/a	n/a	**Setpoint sent from controller (default = 72F). Setpoint can be adjusted by users.**
DOAS	Occupied Mode	Mode	Constant Air Volume (CAV)	Constant Air Volume (CAV)	Constant Air Volume (CAV)
DOAS	Occupied Mode	DCV Sensor Location(s)	n/a	n/a	n/a
DOAS	Occupied Mode	HRV Bypass Damper Control	modulates to temperature setpoint	modulates to temperature setpoint	modulates to temperature setpoint
DOAS	Occupied Mode	HRV Bypass Damper Control Temperature Sensor	supply air temperature	supply air temperature	supply air temperature
DOAS	Occupied Mode	HRV Bypass Damper Control Temperature Setpoint	**59F**	75F	75F
DOAS	Occupied Mode	Minimum Outside Air Bypass Temperature	not provided	61F	61F
DOAS	Occupied Mode	Hours of Operation	**24/7**	Monday - Friday 7:30am - 6:30pm	Monday - Friday 7:30am - 6:30pm
DOAS	Unoccupied Mode	Mode	**same as occupied**	Free Cooling (Night Flush)	Free Cooling (Night Flush)
DOAS	Unoccupied Mode	HRV Bypass Damper Control		100% bypassed (no heat recovery)	100% bypassed (no heat recovery)
DOAS	Unoccupied Mode	HRV Bypass Damper Control Temperature Sensor		65F	65F
DOAS	Unoccupied Mode	Minimum Outside Air Bypass Temperature		61F	61F
DOAS	Unoccupied Mode	Hours of Operation		Monday - Friday 10pm - 12am. Weekend schedule varies.	Monday - Friday 10pm-12am. Weekend schedule varies.

Note: **Bold red** text indicates changes from default control sequence (Test 2).

APPENDIX B: PALM SPRINGS CONTROLS SETPOINTS AND SCHEDULE

		Test Number	**Test 1**
		Test Name	**Default**
		Test Description	**Default**
		Test Time Period	**August 2021 - September 2022**
VRF	Heat Pump		Unit modulates per manufacturer's default control sequence to serve heating and cooling loads in building.
VRF	Fan Coils	Fan Speed	Fan automatically modulates between low, medium, and high speeds to meet room temperature setpoint
VRF	Fan Coils	Fan ON/OFF	Fan operates automatically during Occupied Hours. Fan speed control to be documented, based on trend observations
VRF	Fan Coils	Hours of Operation	24/7
VRF	Fan Coils	Room Temperature Setpoint - Occupied	72F-75F
VRF	Fan Coils	Room Temperature Setpoint - Unoccupied	72F-75F
DOAS	Occupied Mode	Mode	Constant Air Volume (CAV)
DOAS	Occupied Mode	DCV Sensor Location(s)	n/a
DOAS	Occupied Mode	HRV Bypass Damper Control	modulates to temperature setpoint
DOAS	Occupied Mode	HRV Bypass Damper Control Temperature Sensor	supply air temperature
DOAS	Occupied Mode	HRV Bypass Damper Control Temperature Setpoint	not provided
DOAS	Occupied Mode	Minimum Outside Air Bypass Temperature	not provided
DOAS	Occupied Mode	DX Coil Supply Air Temperature	68F
DOAS	Occupied Mode	Hours of Operation	24/7

APPENDIX C: OAKLAND CONTROLS SETPOINTS AND SCHEDULE

		Test Number	**Test 1**
		Test Name	**Default**
		Test Description	**Default**
		Test Time Period	**October 2021 - September 2022**
VRF		Heat Pump	Unit modulates per manufacturer's default control sequence to serve heating and cooling loads in building.
	Fan Coils	Fan Speed	Fan automatically modulates speed to meet room temperature setpoint.
		Fan ON/OFF	Fan operates automatically during Occupied and Unoccupied hours.
		Occupied Hours	Monday - Friday 4am - 8pm
		Room Temperature Setpoint - Occupied	Heating: 69F Cooling: 72F
		Room Temperature Setpoint - Unoccupied	n/a
DOAS	DX	Mode	Constant Air Volume (CAV)
		Occupied Hours	Monday - Friday 5am - 7pm.
		Cooling Setpoint - Occupied	Outside air temperature > 85F
		Heating Setpoint - Occupied	Outside air temperature < 55F
		Cooling Setpoint - Unoccupied	n/a
		Heating Setpoint - Unoccupied	n/a

APPENDIX D: SACRAMENTO CONTROLS SETPOINTS AND SCHEDULE

		Test Number	Test 1	Test 2	Test 3a	Test 3b	Test 4	Test 5a	Test 5b	Test 6	Test 7	Test 8	Test 9
		Test Name	Default Operation	Energy Recovery Bypass Disabled	Staged Ceiling Fans & VRF Cooling	Staged Ceiling Fans & VRF Cooling	Staged VRF Afternoon Cooling Setpoints	DCV Disabled (Min. Ventilation)	DCV Disabled (Max. Ventilation)	VRF Fan Coil Decoupling	Winter Ceiling Fans Speed Optimization	Staged VRF Morning Heating Setpoints	VRF Constant Temperature Setpoints
		Test Description	Zone DCV, DOAS w/ heat recovery bypass, VRF w/ unoccupied setback &setup, Default ceiling fan SOO	Zone DCV, **DOAS w/o heat recovery bypass,** VRF w/ unoccupied setback & setup, Default ceiling fan SOO	Zone DCV, DOAS w/ heat recovery bypass, **VRF OFF during unoccupied hours,** **Ceiling Fan Summer Test 1 (2 weeks)**	Zone DCV, DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, **Ceiling Fan Summer Test 2 (2 weeks)**	Zone DCV, DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, Default ceiling fan SOO, **VRF afternoon cooling setpoint staging**	**No DCV,** DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, Default ceiling fan SOO	**No DCV,** DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, Default ceiling fan SOO	Zone DCV, DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, Default ceiling fan SOO, **VRF fan coil decoupling with optimized economizer controls**	Zone DCV, DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, **Ceiling Fan Winter Test**	Zone DCV, DOAS w/ heat recovery bypass, **VRF OFF during unoccupied hours,** Default ceiling fan SOO, **VRF morning heating setpoint staging**	Zone DCV, DOAS w/ heat recovery bypass, **VRF w/ constant setpoints,** Default ceiling fan SOO
		Test Time Period	January - March 2021, August 2021, December 16-31, 2021, January 2022	April - May 2021	June 1-17, 2021	June 17-24, 2021	July 2021	September 2021	November 2021	October 2021	December 1-15, 2021	February 1 - March 13, 2022	March 14-25, 2022
VRF	Heat Pump		Unit modulates per manufacturer's default control sequence to serve heating and cooling loads in building.										
VRF	Fan Coils	Fan Speed	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.
VRF	Fan Coils	Fan ON/OFF	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied hours. **Fan is off during Unoccupied hours.**	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied and Unoccupied hours.	Fans shut off when room is in deadband.	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied hours. **Fan is off during Unoccupied hours.**	Fan operates automatically during Occupied and Unoccupied hours.
VRF	Fan Coils	Occupied Hours	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	**Monday - Friday 2am - 5:30pm.**	**24/7**
VRF	Fan Coils	Room Temperature Setpoint - Occupied	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	**Heating: 70F** **Cooling: 78F**	**Heating: 70F** **Cooling: 80F**	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	**When ERV turns on (4am):** **Heating: 70F** **Cooling: 75F**	Heating: 70F Cooling: 75F
VRF	Fan Coils	Room Temperature Setpoint - Stage 1					**Weekdays 2-4pm:** **Heating: 65F** **Cooling: 70F**					**Weekdays 2 hours before ERV turns on (2am):** **Heating: 65F** **Cooling: 75F**	
VRF	Fan Coils	Room Temperature Setpoint - Stage 2					**Weekdays 4-6pm:** **Heating: 65F** **Cooling: 80F**					n/a	
VRF	Fan Coils	Room Temperature Setpoint - Unoccupied	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	**n/a**	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	**Heating: 40F** **Cooling: 80F**	**Heating: 70F** **Cooling: 75F**
Ceiling Fans		Fan Speed	0-90% (with manual override)	0-90% (with manual override)	**0-100% as room temperature increases from 74F to 78F**	**0-100% as room temperature increases from 74F to 78F**	0-90% (with manual override)	0-90% (with manual override)	0-90% (with manual override)	0-90% (with manual override)	**10% (constant)**	0-90% (with manual override)	0-90% (with manual override)
Ceiling Fans		Fan Direction	Counter-clockwise (down)	Counter-clockwise (down)	**Counter-clockwise (down)**	**Counter-clockwise (down)**	Counter-clockwise (down)	Counter-clockwise (down)	Counter-clockwise (down)	Counter-clockwise (down)	Counter-clockwise (down)	Counter-clockwise (down)	Counter-clockwise (down)
DOAS	ERV	Mode	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	**Minimum Ventilation**	**Maximum Ventilation**	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)
DOAS	ERV	DCV Sensor Location(s)	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 232	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 235	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 236	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 237	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 237	**n/a**	**n/a**	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 233	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 233	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 237	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 232
DOAS	ERV	Airflow Rate	Variable, controlled based on zone air CO_2.	Variable, controlled based on zone air CO_2.	Variable, controlled based on zone air CO_2.	Variable, controlled based on zone air CO_2.	Variable, controlled based on zone air CO_2.	**Constant.**	**Constant.**	Variable, controlled based on zone air CO_2.	Variable, controlled based on zone air CO_2.	Variable, controlled based on zone air CO_2.	Variable, controlled based on zone air CO_2.
DOAS	ERV	ERV Wheel Bypass Control	Enabled.	**Disabled (wheel always rotates to recover energy when ERV is on).**	Enabled.	Enabled.	Enabled.	Enabled.	Enabled.	Enabled.	Enabled.	Enabled.	Enabled.
DOAS	ERV	Control Conditions for ERV Heat Recovery Wheel Bypass Operation (No Heat Recovery)	If quantity of FCUs in active heating mode is less than 8, quantity of FCUs in active cooling mode is less than 8, and OAT = 70-77F	**n/a**	If quantity of FCUs in active heating mode is less than 8, quantity of FCUs in active cooling mode is less than 8, and OAT = 70-77F	If quantity of FCUs in active heating mode is less than 8, quantity of FCUs in active cooling mode is less than 8, and OAT = 70-77F	If quantity of FCUs in active heating mode is less than 8, quantity of FCUs in active cooling mode is less than 8, and OAT = 70-77F	If quantity of FCUs in active heating mode is less than 8, quantity of FCUs in active cooling mode is less than 8, and OAT = 70-77F	**Delta between quantity of FCUs in active heating or cooling is less than 3 and OAT = 65-75F**	**Delta between quantity of FCUs in active heating or cooling is less than 3 and OAT = 65-75F**	**Delta between quantity of FCUs in active heating or cooling is less than 3 and OAT = 65-75F**	**Delta between quantity of FCUs in active heating or cooling is less than 3 and OAT = 65-75F**	**Delta between quantity of FCUs in active heating or cooling is less than 3 and OAT = 65-75F**
DOAS	ERV	Occupied Hours	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.
DOAS	ERV	COVID Safety Night Purge Hours	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.
DOAS	Thermal Labyrinth	Mode - Occupied	Auto - per SOO	Auto - per SOO	Auto - per SOO	Auto - per SOO	Auto - per SOO	Auto - per SOO		Auto - per SOO	Auto - per SOO	Auto - per SOO	Auto - per SOO
DOAS	Thermal Labyrinth	Mode - Unoccupied	Preheating/precooling	Preheating/precooling	Preheating/precooling	Preheating/precooling	Preheating/precooling	Preheating/precooling		Preheating/precooling	Preheating/precooling	Preheating/precooling	Preheating/precooling

Note: **Bold red** text indicates changes from default control sequence (Test 1).

APPENDIX E: SANTA ROSA CONTROLS SETPOINTS AND SCHEDULE

		Test Number	Test 1	Test 2	Test 3	Test 4
		Test Name	**Default 24/7 Operation**	**Default Unoccupied Setback**	**Staged VRF Afternoon Cooling Setpoints**	**Staged VRF Morning Heating Setpoints**
		Test Description	**VRF 24/7 constant setpoints**	**VRF w/ unoccupied setback & setup**	**RF w/ unoccupied setback & setup,** **VRF afternoon cooling setpoint staging**	**VRF OFF during unoccupied hours,** **VRF morning heating setpoint staging**
		Test Time Period	**May - December 2021**	**January - September 2022 (except Test 3 and 4)**	**July 18, 2022 - August 19, 2022**	**February 25 - March 31, 2022**
VRF	Heat Pump		Unit modulates per manufacturer's default control sequence to serve heating and cooling loads in building.			
VRF	Fan Coils	Fan Speed	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.
VRF	Fan Coils	Fan ON/OFF	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied hours. **Fan is off during Unoccupied hours.**
VRF	Fan Coils	Occupied Hours	24/7	**Monday - Friday 6am - 10pm.**	**Monday - Friday 6am - 10pm.**	**Monday - Friday 6am - 10pm.**
VRF	Fan Coils	Room Temperature Setpoint - Occupied	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	**When ERV turns on (6am):** **Heating: 70F** **Cooling: 75F**
VRF	Fan Coils	Room Temperature Setpoint - Stage 1			**Weekdays 2-4pm:** **Heating: 65F** **Cooling: 70F**	**Weekdays 2 hours before ERV turns on (4am):** **Heating: 65F** **Cooling: 75F**
VRF	Fan Coils	Room Temperature Setpoint - Stage 2			**Weekdays 4-6pm:** **Heating: 65F** **Cooling: 80F**	n/a
VRF	Fan Coils	Room Temperature Setpoint - Unoccupied	n/a	**Heating: 60F** **Cooling: 80F**	**Heating: 60F** **Cooling: 80F**	n/a
DOAS	ERV	Mode	Constant Air Volume (CAV)	Constant Air Volume (CAV)	Constant Air Volume (CAV)	Constant Air Volume (CAV)
DOAS	ERV	Occupied Hours	Monday - Friday 5am - 3pm.	**Monday - Friday 6am - 9pm.**	**Monday - Friday 6am - 9pm.**	**Monday - Friday 6am - 9pm.**

Note: **Bold red** text indicates changes from default control sequence (Test 1).