CALIFORNIA ENERGY COMMISSION

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INTERIM PROJECT REPORT

Baseline Wall Furnace Field Monitoring Report – Improving the Performance of Wall Furnaces in California

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Executive Summary

This is an interim report for CEC-PIR-18-005, “Improving the Performance of Wall Furnaces in California”, a project designed to yield gas savings by replacing existing wall furnaces with more efficient retrofit models. This project gathers information about furnace performance, operation, emissions, and indoor air quality from laboratory testing and field monitoring of baseline and retrofit wall furnaces.

Background

There are an estimated are 1.4 million wall furnaces in California. Wall furnaces were introduced in California as early as 1930 and gained prevalence in single-family homes and low-rise multifamily residential buildings as primary or auxiliary sources of heating. Not infrequently wall furnaces are as old as the buildings they occupy. The oldest existing furnaces have thermal efficiencies of 50% while today’s standard replacement wall furnaces have thermal efficiencies of 70%.

More advanced wall furnaces achieve thermal efficiencies of 80% to 94% by eliminating pilot lights, using more efficient heat exchangers, and incorporating condensing or modulating technology. This leaves substantial savings potential for a state-wide replacement program that promotes furnaces using these efficiency advancements.

This interim report documents field monitoring results from the evaluation of ten existing baseline wall furnaces in California homes. Other interim reports for this project document field monitoring of these existing baseline furnaces, laboratory test results for more efficient retrofit furnaces, and field monitoring of retrofit furnaces that replaced the baseline furnaces.

Project Purpose and Approach

The goal of this research is to demonstrate cost-effective solutions for retrofitting existing wall furnaces in California multifamily and single-family residences. This interim report gives results of baseline wall furnace field monitoring to characterize the patterns of operation and indoor comfort and air quality. Other reports document results of laboratory tests of retrofit wall furnaces, and laboratory testing and field monitoring results for existing baseline wall furnaces.

The baseline wall furnaces studied in this project were existing furnaces that were in service in California homes. The furnaces were monitored in the field over a heating season, then were removed and shipped to Des Plaines, IL facilities for testing in GTI Energy’s Residential and Commercial Equipment laboratory (documented in the Baseline Wall Furnace Laboratory Testing Report for this project).

Ten baseline vented gravity wall furnaces were tested:

- Two in side-by-side apartments in Hayward (apartments 3 and 4)
- Four in a retirement apartment community in Los Angeles (104, 105, 106, and 107)
- One in a single-family home in Oakland (SFH)
- Three in multifamily apartments in Sacramento (4, 15, and 19)

These ten existing wall furnaces were all vented gravity non-condensing furnaces with standing pilots. They ranged in age from about 10 years to more than 40 years, with input capacities between 25,000 and 50,000 Btu/hr and thermal efficiencies from 50% to 74%. The Oakland furnace was a double-sided unit serving two rooms, while all other furnaces were single-sided units.

The field monitoring performed by the research team included:

- Physical inspection of the wall furnaces and combustion safety checks
- Heating season measurement of furnace operation
- Heating season measurement of indoor temperature and humidity
- Heating season measurement of indoor air quality (IAQ) in terms of concentrations of carbon monoxide, nitrogen oxides, and particulate matter (PM2.5 and PM10)

Key Results

The operation of existing baseline wall furnaces was monitored at ten sites. Table 1 summarizes the operating hours per day, cycles per day and minutes per cycle for these furnaces.

Table 1: Summary of Baseline Wall Furnace Operation

Site	Manufacturer	Model	Average Operating Hours per Day	Average Furnace Cycles per Day	Average Furnace Cycle Minutes
Hayward 3	Perfection Products	PW8G25SEN #1	1.36	1.77	46.1
Hayward 4	Perfection Products	PW8G25SEN #2	0.55	0.92	35.9
LA 104	Williams	25GV-A1	0.07	0.30	13.8
LA 105	Williams	35GV-C #1	0.89	1.91	28.1
LA 106	Williams	35GV-C #2	0.34	1.52	13.5
LA 107	Williams	RMG35-IN	0.07	0.25	17.3
Oak SF	Williams	5009622	0.67	1.08	37.2
Sacto 4	Holly General	35S-D #1	1.41	1.73	48.8
Sacto 15	Holly General	35S-D #2	2.18	3.77	34.6
Sacto 19	Williams	3509622	2.17	4.18	31.3
Average			**0.97**	**1.73**	**33.6**

The Los Angeles furnaces were used less often, while the Sacramento furnaces operated for the greatest number of hours per day. Furnace cycles also tended to be shortest in Los Angeles at less than 30 minutes per cycle, and over 30 minutes in Northern California On average, furnaces operated for an hour a day, cycling 1.7 times at 34 minutes per cycle.

These averages do not tell the whole story, though. Both operating hours and cycle length tend to increase when outdoor temperatures get colder. Based on the average daily outdoor temperature, wall furnace operating hours in Northern and Southern California and cycle length throughout all of California can be estimated as:

- NorCal Daily Operating Hours = 8.7 – 0.146 x Average Daily Outdoor Temperature, ^{o}F,
- SoCal Daily Operating Hours = 3.2 – 0.047 x Average Daily Outdoor Temperature, ^{o}F
- Cycle Minutes = 63.5 – 0.64 x Average Daily Outdoor Temperature, ^{o}F

Indoor pollutant levels were also measured during field monitoring, and the average and maximum indoor pollutant concentrations are listed in Table 2 and Table 3.

Table 2: Average Carbon Monoxide and Nitrogen Oxides Concentrations (top) and Average Particulate Matter PM2.5 and PM10 Concentrations (bottom) at All Sites when Furnaces are On and Off

	Regional CO ppmx10	CO Off ppmx10	CO On ppmx10	CO On-Off Difference %	Regional NOx ppb/10	NOx Off ppb/10	NOx On ppb/10	NOx On-Off Difference %
Hayward 3	4.7	23.5	23.4	0%	2.0	**32.3**	**30.9**	-4%
Hayward 4	4.7	9.8	12.4	26%	2.0	**22.0**	**23.1**	5%
LA 104	5.6	17.7	43.3	145%	4.1	**24.8**	**45.2**	83%
LA 105	5.2	24.2	23.9	-1%	3.7	2.8	3.7	31%
LA 106	5.2	17.3	16.5	-5%	3.7	1.3	2.0	51%
LA 107	5.4	31.2	31.4	1%	3.9	**26.2**	**24.5**	-7%
Oak SF	4.7	4.2	5.5	30%	2.5	5.3	3.3	-37%
Sacto 4	4.1	10.4	10.8	4%	2.4	**49.4**	**47.7**	-4%
Sacto 15	3.8	9.3	10.8	16%	2.2	**1.8**	**2.4**	30%
Sacto 19	3.9	9.1	10.9	19%	2.1	**7.9**	**7.5**	-5%
Average	**4.7**	**15.7**	**18.9**	**21%**	**2.9**	**17.4**	**19.0**	**9%**
	0-50 ppmx10 inside normal **50-150 ppmx10 inside property adjusted** 300+ ppm inside improperly adjusted				10 ppb/10 1 hour outside **5.3 ppb/10 24 hour outside**			

	Regional PM2.5 ug/m3	PM2.5 Off ug/m3	PM2.5 On ug/m3	PM2.5 On-Off Difference %	PM10 Off ug/m3	PM10 On ug/m3	PM10 On-Off Difference %
Hayward 3	9.8	6.0	3.0	-50%	6.5	0.1	-99%
Hayward 4	9.8	5.9	3.1	-48%	6.5	3.2	-51%
LA 104	13.1	10.9	5.1	-53%	9.7	4.7	-52%
LA 105	12.5	26.3	33.8	29%	29.3	36.8	25%
LA 106	12.3	15.5	21.7	40%	17.5	23.6	34%
LA 107	12.7	12.8	13.3	4%	15.0	38.0	154%
Oak SF	7.0	5.7	9.4	65%	6.2	10.1	65%
Sacto 4	16.1	33.1	28.4	-14%	37.1	31.0	-16%
Sacto 15	13.5	10.2	9.1	-11%	10.3	9.1	-11%
Sacto 19	15.0	25.5	28.0	10%	26.5	28.8	9%
Average	**12.2**	**15.2**	**15.5**	**2%**	**16.5**	**18.5**	**13%**
	35 ug/m3 24 hour outside				**150 ug/m3 24 hour outside**		

As seen in Table 2, the overall ***average*** indoor concentrations of CO, NOx, PM2.5, and PM10 increased by 21%, 9%, 2% and 13% respectively when the furnaces were operating compared to when they were off. However, there is a lot of variability in the averages from site to site. Half of the sites saw average indoor pollutants increase when the furnaces run, either due to flue gas emissions leaking into the space, pollutants being drawn into the living room from other spaces, or existing pollutants being stirred up by air circulation. The other half of the wall furnaces saw average indoor pollutant levels decrease, most likely because they draw air from the indoor space for combustion.

Table 3: Maximum Carbon Monoxide and Nitrogen Oxides Concentrations (top) and Maximum Particulate Matter PM2.5 and PM10 Concentrations (bottom) at All Sites when Furnaces are On and Off

	Regional CO ppmx10	CO Off ppmx10	CO On ppmx10	CO On-Off Difference %	Regional NOx ppb/10	NOx Off ppb/10	NOx On ppb/10	NOx On-Off Difference %
Hayward 3	6.2	49.1	34.1	-31%	3.1	**93.3**	**57.2**	-39%
Hayward 4	6.2	43.2	20.1	-53%	3.1	**61.7**	**29.6**	-52%
LA 104	7.8	84.9	47.4	-44%	7.6	**117.8**	**48.0**	-59%
LA 105	7.6	24.2	23.9	-1%	7.1	2.8	3.7	31%
LA 106	7.4	104.7	25.3	-76%	7.0	9.9	2.9	-70%
LA 107	7.6	50.9	31.4	-38%	7.3	**67.2**	**24.5**	-64%
Oak SF	7.0	12.5	7.4	-41%	5.1	**26.4**	7.5	-72%
Sacto 4	5.6	30.0	17.5	-42%	4.0	**138.5**	**74.2**	-46%
Sacto 15	5.2	29.9	19.5	-35%	3.7	6.5	4.1	-38%
Sacto 19	5.1	26.4	18.8	-29%	3.3	**24.3**	**13.3**	-45%
Average	**5.8**	**45.6**	**24.5**	**-46%**	**5.1**	**54.9**	**26.5**	**-52%**
	0-50 ppmx10 inside normal **50-150 ppmx10 inside property adjusted** 300+ ppm inside improperly adjusted				**10 ppb/10 1 hour outside** 5.3 ppb/10 24 hour outside			

	Regional PM2.5 ug/m3	PM2.5 Off ug/m3	PM2.5 On ug/m3	PM2.5 On-Off Difference %	PM10 Off ug/m3	PM10 On ug/m3	PM10 On-Off Difference %
Hayward 3	13	**106**	10	-91%	112	0	-100%
Hayward 4	13	**132**	8	-94%	**151**	8	-95%
LA 104	17	**62**	6	-91%	52	5	-90%
LA 105	15	26	34	29%	29	37	25%
LA 106	16	**197**	34	-83%	**222**	37	-83%
LA 107	16	22	13	-41%	83	38	-54%
Oak SF	9	**44**	30	-33%	49	31	-36%
Sacto 4	23	**354**	**91**	-74%	**404**	100	-75%
Sacto 15	19	**120**	25	-79%	121	25	-79%
Sacto 19	20	**278**	**108**	-61%	**306**	112	-63%
Average	**16**	**134**	**36**	**-73%**	**153**	**39**	**-74%**
	35 ug/m3 24 hour outside				**150 ug/m3 24 hour outside**		

In contrast, the ***maximum*** indoor pollutant concentrations listed in Table 3 decreased at all sites when the furnaces operated. The overall maximum indoor concentrations of CO, NOx, PM2.5, and PM10 decreased by 46%, 52%, 73% and 74% respectively when the furnaces were operating compared to when they were off. The wall furnaces significantly improve indoor air quality by reducing maximum levels of indoor air pollutants, most likely by drawing air for combustion from the indoor space.

Knowledge Transfer and Next Steps

The monitoring results documented in this study will be combined with results from laboratory testing to determine energy use and emissions from typical baseline wall furnaces. Similar field monitoring and laboratory testing will be done to characterize more efficient retrofit furnaces. Baseline and retrofit data will then be used to estimate the energy savings, emission reductions, and the effects on indoor air quality of efficient wall furnaces.

Introduction

This project's overall objective is to characterize the operation, energy, indoor air quality, and emissions of existing and retrofit wall furnaces. The goal of this research is to investigate and demonstrate efficient solutions for retrofitting existing wall furnaces in California multifamily and single-family residences.

A wall furnace is a compact device installed within a home's wall cavity and used to heat one or two rooms. Because they are less expensive, simpler to install, and take up less space than a central ducted furnace, they are used in multifamily apartment complexes and smaller single-family homes.

Wall furnaces are categorized by how they distribute heat (gravity or fan-type), where their combustion air comes from (from inside for top vent furnaces, from outside for direct vent furnaces), how they ignite the burner (standing pilot, intermittent pilot, or hot surface igniter), and whether they use condensing technology. Additionally, furnaces can be either single-sided to serve just one room, or double-sided to serve rooms on either side of the wall in which it is installed. These wall furnace technologies are described in more depth in Appendix A.

Many California low-rise multifamily buildings and smaller homes use wall furnaces for space heating. Most of these existing wall furnaces are non-condensing gravity vented furnaces that use a standing pilot to ignite the burner. Wall furnaces are usually replaced only when the original unit is irreparably broken. Anecdotal information from Williams, the predominant wall furnace manufacturer, indicates that many older furnaces are still in operation, some without safety switches and with rated thermal efficiencies as low as 50%.

Most replacement wall furnaces are non-condensing gravity vented furnaces that just meet current efficiency standards. ANSI Z21.86 for Vented Gas-Fired Space Heating Appliances (ANSI Z21.96 2016) is the federal regulating standard for wall furnaces, It currently requires gravity wall furnace thermal efficiency to be at least 70% and fan-type wall furnace efficiency to be at least 75%. In addition, Annual Fuel Utilization Efficiency (AFUE) for wall furnaces are mandated under the Code of Federal Regulations (CFR 430.32 (i) (1) 2022) and (CFR 430.32 (i) (2) 2022). AFUE must be at least 65% to 76%, depending on furnace capacity and whether it is a gravity or fan-type wall furnace. More information about wall furnace efficiency standards is included in Appendix A.

Minimum wall furnace AFUE levels are well below the 81% AFUE requirement for standard central ducted furnaces and even further below the >90% AFUE that condensing furnaces can deliver. However, wall furnaces have recently been developed with thermal efficiencies as high as 85% and AFUE up to 82%, achieved by improving burners and removing standing pilot lights. In addition, condensing wall furnaces with thermal efficiency up to 94% and AFUE as high as 93% have been developed.

As with all primary gas space heating equipment in the state of California, emissions from wall furnace combustion are required to be vented to the outside to prevent the accumulation of indoor pollutants. There are no federal or California limits for wall furnaces regarding flue gas emissions or indoor pollutants, although there are some limits on NOx emissions for natural gas-fired fan-type central furnaces in California's South Coast Air Quality Management District (SCAQMD) and the San Joaquin Valley Air Pollution Control District (SJVAPCD). See Appendix A for information about guidelines, standards, and regulations that pertain to indoor air quality and furnace emissions.

This project examines existing baseline and efficient retrofit wall furnaces in the laboratory and the field to assess their performance, ease of installation, operation, and reliability. Energy use, emissions, indoor air quality, and costs are assessed to help determine whether efficient retrofit wall furnace technologies should be promoted in California.

This interim report describes results from field monitoring of ten baseline wall furnaces in California homes:

- Two in side-by-side apartments in Hayward (apartments 3 and 4)
- Four in a retirement apartment community in Los Angeles (apartments 104, 105, 106, and 107)
- One in a single-family home in Oakland (SFH)
- Three in multifamily apartments in Sacramento (apartments 4, 15, and 19)

These field monitoring results will be combined with laboratory data for each of these furnaces to estimate their field energy use and emissions. More efficient retrofit furnaces will also be laboratory tested and field monitored as part of this project. Comparisons of baseline and retrofit energy use, emissions, and indoor air quality will be made to evaluate the benefits that can be realized through the installation of more efficient retrofit furnaces.

Project Approach

The objective of field monitoring is to characterize wall furnace operation and effects on indoor air quality. Operation of the existing baseline wall furnaces was monitored over a winter heating season. Indoor temperature and humidity and levels of indoor carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM2.5 and PM10) were also monitored in each dwelling to quantify the effects of wall furnace operation on indoor comfort and air quality. This report section describes the instrumentation and data collection procedures and the furnaces monitored in this project.

Test Equipment and Measurements

A single monitoring package from Senseware was used for this research. This package was able to automatically log all monitored data and store it in the cloud, relieving researchers of the need to manually download data and allowing for remote troubleshooting. This gave the project greater flexibility in site selection and a reduction in travel time and cost.

The Senseware package included visually unobtrusive sensors that measured furnace operation, indoor conditions, and indoor air quality. The specific Senseware equipment used in each dwelling included:

- wireless node to collect data readings
- sensor bridges to connect sensors to wireless nodes
- 0-5V sensor to monitor gas solenoid valve operation
- 0-5V sensors to monitor indoor temperature and relative humidity
- NOx sensor to monitor IAQ in ppm
- CO sensor to monitor IAQ in ppm
- PM10 and PM2.5 sensors to monitor IAQ in ug/m3
- wireless gateway to send data
- 3G cellular modem to connect to the internet

More information about the Senseware equipment, including instrumental measurement ranges and error, is included in Appendix B of this report.

A gas submeter was not included in the monitoring package because it was too large and cumbersome to fit within the wall furnace base, and its installation would be difficult to achieve without removing the furnace. Baseline wall furnaces have a single-input burner, so monitoring the signal sent to the gas solenoid valve indirectly measured its energy consumption. The baseline furnaces were removed after heating season monitoring and sent to the GTI-Des Plaines facilities for laboratory testing, where their natural input rates were measured during active heating and standby pilot-only operation. The solenoid valve signal was converted to natural gas use based on each furnace’s tested natural gas input rate.

The equipment package was installed at numerous sites to monitor wall furnace performance and indoor conditions during the heating season. In addition to tucking the solenoid valve sensor into the base of the wall furnaces, sensors measuring temperature, humidity, and pollutant concentrations were mounted to a wall within 5 ft of the wall furnace, between 4 and 6 feet above the floor. The exact placement depended on the room layout and furniture placement within each dwelling. This instrumentation and a sample wall furnace are depicted in Figure 1 and Figure 2. The cellular modem, gateway and IAQ sensors are shown in Figure 3.

Figure 1: Wireless Node, Bridge, and Wall Furnace Lead

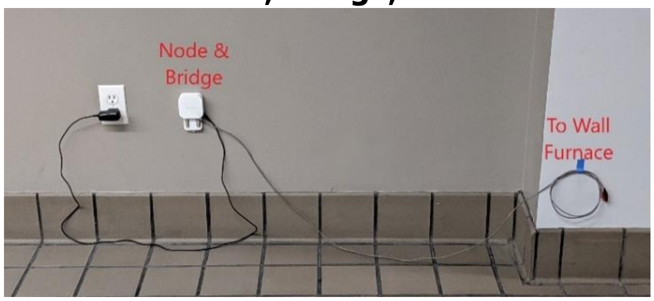
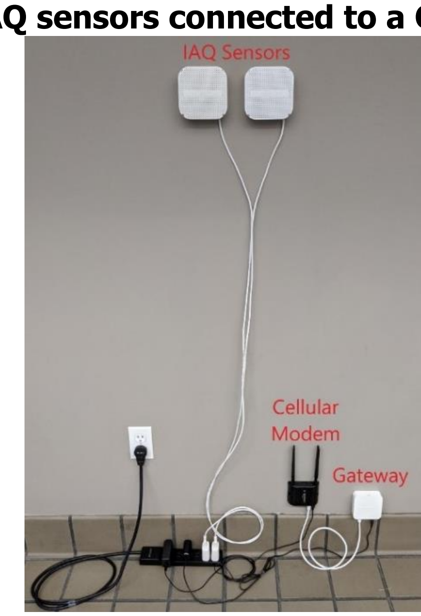


Figure 2: Sample Wall Furnace Voltage Bridge Wiring

Figure 3: Senseware IAQ sensors connected to a Cell Modem and Gateway



Before the installation technician left each site, a researcher checked the functionality of the remote system. Researchers also checked the monitoring system periodically over the heating season to watch for and quickly fix any operational or data collection problems.

During the monitoring period, data was collected every minute from each sensor and sent to the wireless node, then relayed to the cloud through the gateway at least twice a day. Each furnace was monitored over a winter heating season.

Key results from the baseline monitoring include:

- Wall furnace operating hours based on gas solenoid valve signals
- Indoor air quality measurements (CO, NOx, PM2.5, PM10)
- Indoor temperature and relative humidity
- Correlations with outdoor temperatures from local weather stations

At the end of the monitoring period, the baseline furnaces were replaced with various retrofit furnace options for monitoring during the next heating season. This retrofit field work is documented in the interim project report "Retrofit Wall Furnace Field Monitoring Report".

Regional Weather and Air Quality Data

Field monitoring data from each site was supplemented with regional weather data and air quality data. Hourly weather data including outdoor temperature, humidity, and wind speed was collected from the National Oceanic and Atmospheric Administration's Climate Data Online Tool for Local Climatological Data (NOAA 2022)., an archive of historical weather data collected by the National Climate Data Center. The weather stations used to represent each site were:

- Hayward - Hayward Air Terminal, Station ID WBAN:93228
- Oakland - Oakland International Airport, Station ID WBAN:23285
- Los Angeles - Los Angeles Downtown USC, Station ID WBAN:93134
- Sacramento – Sacramento Airport ASOS, Station ID WBAN:23232

Hourly air quality data including levels of carbon monoxide, nitrogen oxides, and particulate matter PM2.5 was collected from the California Air Resources Board Air Quality Data Query Tool (CARB 2022). Regional air stations used to represent each site's outdoor air quality were:

- Hayward - Site 3247, 9925 International Boulevard-Oakland
- Oakland - Site 3742, Oakland-West
- Los Angeles - Site 2899, Los Angeles-North Main Street
- Sacramento - Site 3011, Sacramento-T Street

Site and Wall Furnace Selection Criteria

Sites had to meet various criteria and clear various screening processes to be included in this study. First, each site needed to be either a single-family home or low-rise multifamily residence in California with an existing wall furnace. The research team also looked for sites in the climate zones of Los Angeles, the San Francisco Bay Area, and the Central Valley.

Researchers then visited each potential site to assess its feasibility. Information collected included the overall building plan, information about the wall furnaces, including their type, make and model, physical dimensions, venting, operational status, and thermostat location. They also determined whether power was available for instrumentation, looked for suitable instrumentation locations, and took note of other gas appliances in the dwellings.

Occupants at each site were also interviewed about their furnace usage patterns. Sites with higher furnace usage were prioritized over sites with low furnace usage. Some residents were unwilling to have their wall furnace replaced or unwilling to house the instrumentation package for the duration of the study.

Once potential wall furnaces were identified, an HVAC technician was sent to each location to perform combustion safety tests and make any basic repairs. The experimental design dictated that a wall furnace would be disqualified if it did not pass its safety test or needed extensive repairs, although none of the screened furnaces were disqualified in this way.

Occupants were given up to $1000 in incentives for their participation: $200 for allowing their furnace to be initially inspected, $300 for monitoring the baseline furnace over a initial heating season, and $500 for installation of a retrofit furnace and monitoring it over a second heating season. Costs of the retrofit furnaces and their installation were also covered by the project, but the project did not pay any utility costs.

Baseline Sites and Wall Furnaces

Baseline furnaces in ten sites were monitored during this project. These sites were: four apartments (104, 105, 106, and 107) in Los Angeles, a single-family home in Oakland, two apartments (3 and 4) in Hayward, and three apartments (4, 15, and 19) in Sacramento.

A summary of the characteristics of each baseline furnace is presented in Table 4. All the monitored baseline furnaces are gravity, top vent, non-condensing furnaces with standing pilots. See Appendix A for a description of each of these furnace technologies.

Table 4: Baseline Wall Furnace Characteristics, Gravity Top Vent Non-Condensing Units with Standing Pilots

Field Site	Manufacturer	Model*	ANSI Z21 Std	Age years	Input Btu/hr	Thermal Efficiency	Rated AFUE
Hayward 3	Perfection Products	PW825SEN-B-4 #1	49a.1982	~40	25,000	50%	n/a
Hayward 4	Perfection Products	PW825SEN-B-4 #2	49a.1982	~40	25,000	50%	n/a
Los Angeles 104	Williams	25GV-A1	49.1986	~35	25,000	70%	n/a
Los Angeles 105	Williams	35GV-C #1	49.1986	~35	35,000	70%	n/a
Los Angeles 106	Williams	35GV-C #2	49.1986	~35	35,000	70%	n/a
Los Angeles 107	Williams	RMG35IN	49.1986	~35	35,000	70%	n/a
Oakland SFH	Williams	5009622 (Double-sided)	86a.2005	~15	50,000	76%	74%
Sacramento 4	Holly General	Narrowall 35S-D #1	none	40+	35,000	70%	n/a
Sacramento 15	Holly General	Narrowall 35S-D #2	none	40+	35,000	70%	n/a
Sacramento 19	Williams	3509622	86.2008	~10	35,000	74%	72%

* All models are single-sided except for the double-sided Williams model 5009622.

Input capacities range from 25,000 to 50,000 Btu/hr. The 50,000 Btu/hr 5009622 furnace is a double-sided furnace installed in the wall between the living and dining rooms of the Oakland single-family home. All other furnaces are single-sided and serve the apartment living rooms.

The exact age of these furnaces could not be determined. An ANSI.Z21 standard and year is listed on most of the furnace nameplates, indicating that they range in age from about 10 to 40 years. The Holly-General furnaces installed in two Sacramento apartments have no ANSI standard included on their nameplate at all, so it is assumed they are more than 40 years old

Thermal efficiencies, defined as the output capacity divided by the input capacity, are between 50% and 76%. AFUE ratings were only available for the two youngest furnaces, since AFUE ratings were not required when the older furnaces were manufactured.

Figure 4, Figure 5, and Figure 6 show the existing baseline wall furnaces described in Table 4as they were installed in each California home

Figure 4: Existing Baseline Wall Furnaces in Hayward 3 (left), Hayward 4 (middle), and Oakland SFH (right)

Figure 5: Existing Baseline Wall Furnaces in Los Angeles Apartments 104, 105, 106, and 107 (from left to right)

Figure 6: Existing Baseline Wall Furnaces in Sacramento Apartments 4 (left), 15 (middle), and 19 (right)

The following report sections describe the four field monitoring locations and nine sites where field data was collected during the 2020-2021 and 2021-22 heating seasons: two side-by-side apartments in Hayward, four retirement apartments in Los Angeles, a single-family home in Oakland, and two apartments in a multifamily building in Sacramento.

Hayward Apartments

The Hayward apartments 3 and 4 were located side by side in a building within the Hayward, CA 94541 zip code, and the building exterior is shown in Figure 7.Two to four non-smoking tenants live in each apartment. Each unit also had a gas water heater in an internal closet and a gas range with a ventilation hood in the kitchen.

Figure 7: Hayward Apartments 3 and 4

The Hayward wall furnaces were single-sided, vented, gravity, non-condensing furnaces with a standing pilot, Perfection Products PW8G25SEN with an input rate of 25,000 Btu/hr. Their nameplates reference the ANSI Z21.49a.1982 standard so estimate these furnaces are 40 years old. The furnaces were installed in an interior wall adjacent to the living room.

Both furnaces were operational during screening checks. An HVAC technician cleaned and vacuumed the furnace internals and brushed off their burner ports, and the furnaces passed combustion safety checks.

Los Angeles Apartments 104, 105, 106, and 107

The Los Angeles multifamily site was a senior housing complex affiliated with the Retirement Housing Foundation located within the Los Angeles, CA 90015 zip code, as shown in Figure 8. Each apartment housed between two and six nonsmoking occupants. All apartments had gas ranges and water heaters. Residents in one of the apartments mentioned very frequent candle lighting, but none of the other apartments had any particulate matter indicators.

Baseline monitoring, furnace replacement, and retrofit furnace monitoring was performed in four apartments: 104, 105, 106, and 107. These were ground-floor apartments chosen for monitoring because they had lower solar gain than the top floor apartments, and because occupants noted more use of the furnaces.

Figure 8: Los Angeles Retirement Apartments Site

The Los Angeles wall furnaces were single-sided, vented, gravity, non-condensing units with a standing pilot, and installed in an interior wall in the main living/dining area of each apartment. The furnace in apartment 104 was a Williams 25GV-A1 with an input capacity of 25,000 Btu/hr. Williams 35GV-A1 furnaces were in apartments 105, 106 and a Williams RMG35-IN was in apartment 107, all with an input capacity of 35,000 Btu/hr. Nameplates indicated that all four furnaces were regulated under ANSI Z21.49.1986, so estimate they are about 35 years old.

None of these wall furnaces were functional during its initial screening. Minor physical repairs by the HVAC technician included cleaning, installing a new gas solenoid valve, and relighting the pilot. After repairs all furnaces were operational and passed combustion safety checks, and pilot relighting procedures were explained to multiple residents.

Oakland Single-Family Home

The Oakland single-family home site was located within the Oakland, CA 94610 zip code, and is shown in Figure 9. Two non-smoking, working adults live in the dwelling. The occupants light candles a few times per year, but never burn wood or incense or leave open flames indoors. There was also a gas water heater in the basement, and a gas range with a ventilation hood in the kitchen, over 15 feet from the wall furnace in the dining room.

Figure 9: Oakland Single Family Home Site

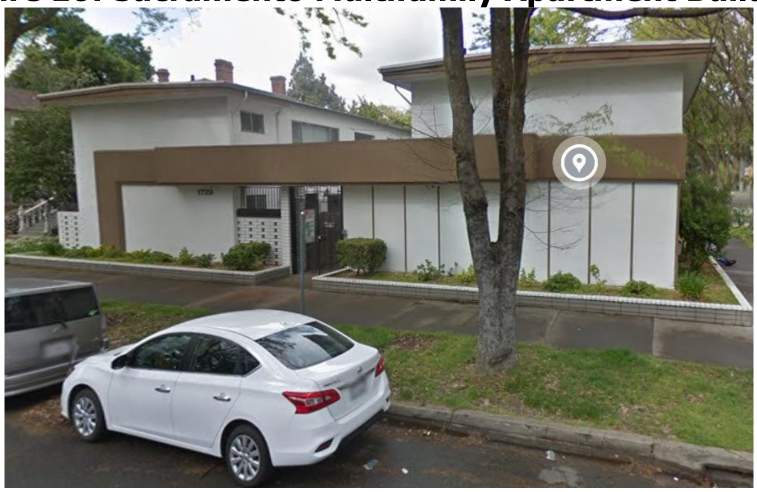
The Oakland wall furnace was a double-sided, vented, gravity, non-condensing furnace with a standing pilot, Williams 5009622 with an input rate of 50,000 Btu/hr. Its nameplate references the ANSI Z21.86a.2005 standard so estimate the age of this furnace to be about 15 years. This double-sided furnace was installed in an interior wall between the living and dining room.

This furnace was operational during screening checks. An HVAC technician cleaned and vacuumed the furnace internals and brushed off the burner ports, and the furnace passed its combustion safety check.

Sacramento Apartments 4, 15, and 19

The Sacramento apartments were in a multifamily building within the Sacramento, CA 95811 zip code, as shown in Figure 10. One to four non-smoking tenants live in each apartment. Each unit also had a gas water heater in an internal closet and a gas range with ventilation hood in the kitchen.

Figure 10: Sacramento Multifamily Apartment Building



The Sacramento wall furnaces were all single-sided, vented, gravity, non-condensing furnaces with a standing pilot with an input rate of 35,000 Btu/hr. Apartment 4 and 15 have Holly General 35S-D furnaces with no reference standard on their nameplate, indicating they were manufactured before 1982 and are at least 40 years old. Apartment 19 has a Williams 3509622 furnace with a nameplate reference to ANSI Z21.86.2008 standard, so estimate this furnace to be about 10 years old. The furnaces were installed in an interior wall adjacent to the main living area.

Despite being some of the oldest furnaces in this study, all the Sacramento furnaces were operational during screening checks. An HVAC technician cleaned and vacuumed the furnace internals and brushed off their burner ports, and the furnaces passed combustion safety checks.

Baseline field monitoring and laboratory testing was completed for the furnace in Sacramento apartment 15 and is reported here and in the baseline laboratory testing report. Note however that the retrofit furnace that was subsequently installed in Sacramento apartment 15 never worked properly and had to be removed, so no field data is reported for Sacramento 15 in the retrofit field monitoring report.

Results

Operating and indoor air quality data from field monitoring are presented here for the ten existing baseline wall furnaces.

Collected Field Data and Operating Conditions

Table 5 summarizes the data collection at each site, including the winter heating season over which data was collected, the number of days of data collected, and the average monitored outdoor temperature, indoor temperature, and operating characteristics in terms of daily hours of operation, average cycles per day, and average minutes per cycle. A cycle is defined as the time over which the furnace continually fires to heat the space.

Table 5: Baseline Wall Furnace Field Data and Temperature Condition Summary

Site	Manufacturer	Model	Heating Season	# Days Monitored	Average Outdoor Temperature, °F	Average Indoor Temperature, °F
Hayward 3	Perfection Products	PW8G25SEN #1	2020-21	105	52.7	66.2
Hayward 4	Perfection Products	PW8G25SEN #2	2020-21	105	52.7	64.7
LA 104	Williams	25GV-A1	2019-20	85	60.5	70.6
LA 105	Williams	35GV-C #1	2019-20	80	60.8	76.3
LA 106	Williams	35GV-C #2	2019-20	91	60.3	73.9
LA 107	Williams	RMG35-IN	2019-20	91	60.3	71.5
Oak SF	Williams	5009622	2019-20	77	54.5	63.3
Sacto 4	Holly General	35S-D #1	2020-21	77	48.5	67.2
Sacto 15	Holly General	35S-D #2	2020-21	77	49.0	69.1
Sacto 19	Williams	3509622	2020-21	77	49.0	71.8
Average				**87**	**54.9**	**69.8**

At least 77 days or 11 weeks of field operating data was collected for each wall furnace.

Weather during each heating season was warmest in Los Angeles at an average outdoor temperature of ~60°F and coldest in Sacramento, with an average outdoor temperature of ~49°F.

The Los Angeles apartments stayed warmest mostly because they were in a warmer and sunnier climate. The Oakland and Hayward homes had the lowest indoor temperatures due to low furnace use in a colder climate, while the Sacramento homes fell somewhere in between.

Looking more at outdoor temperatures in more detail, Figure 11 plots the average daily outdoor temperature over time of day at the Hayward, Los Angeles, Oakland, and Sacramento locations, both when the furnace is on and when the furnace is off. This figure shows again that Los Angeles weather was the warmest and Sacramento's was coldest, and Oakland is slightly warmer than Hayward. Outdoor average daily high to low temperature difference is about 15°F in Los Angeles, 12°F in Oakland, 13°F in Hayward, and 20°F in Sacramento. Furnace use is more common on colder days.

Figure 11: Average Outdoor Temperature versus Time of Day at Four Locations while Furnace is On and Off

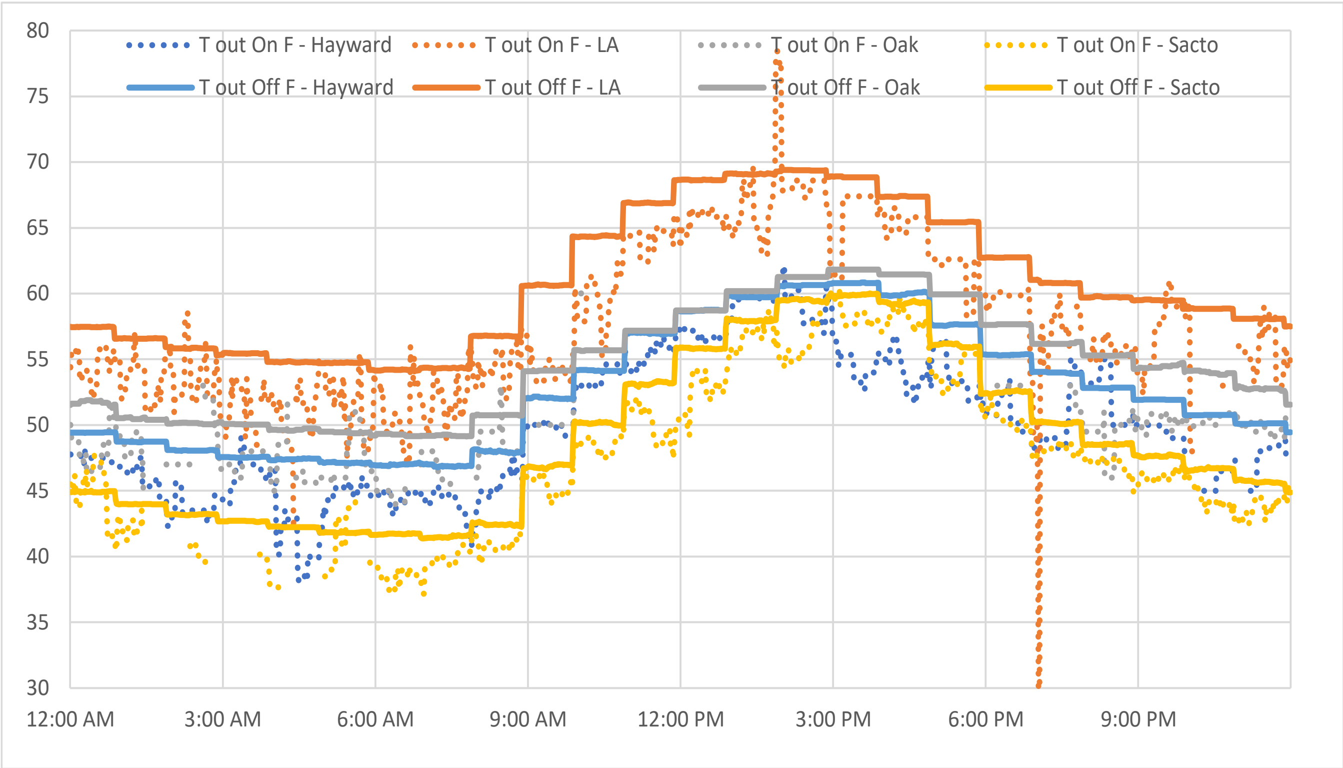
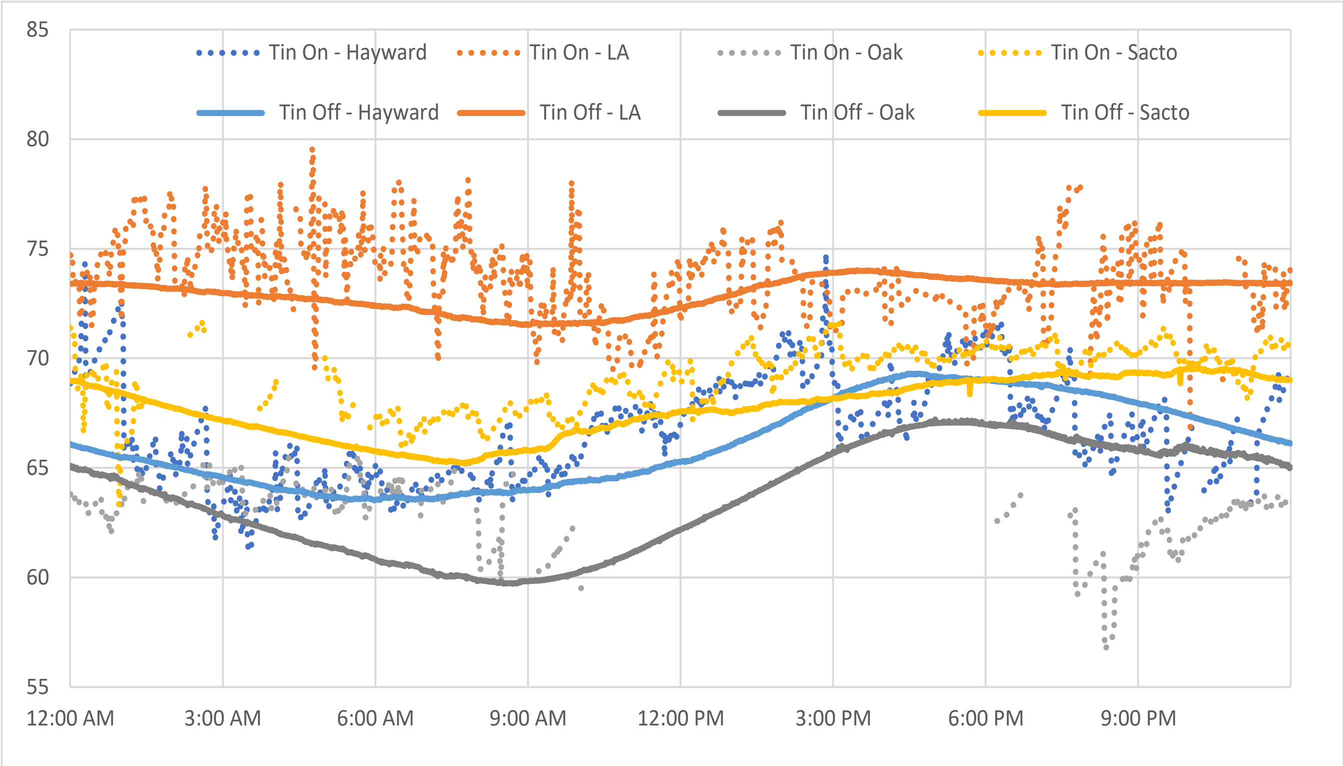


Figure 12 plots the average daily indoor temperature over time of day at each of the four locations, both when the furnace is on and when the furnace is off.

Figure 12: Average Indoor Temperature versus Time of Day at Four Locations while Furnace is On and Off



Indoor temperatures are both warmest and most constant over the day in Los Angeles, at an average of 73ºF and varying by about 2.5ºF. Here the furnace is mainly used during early morning hours, and indoor temperatures are about 2 ºF warmer when the furnace is on than when it is not in use.

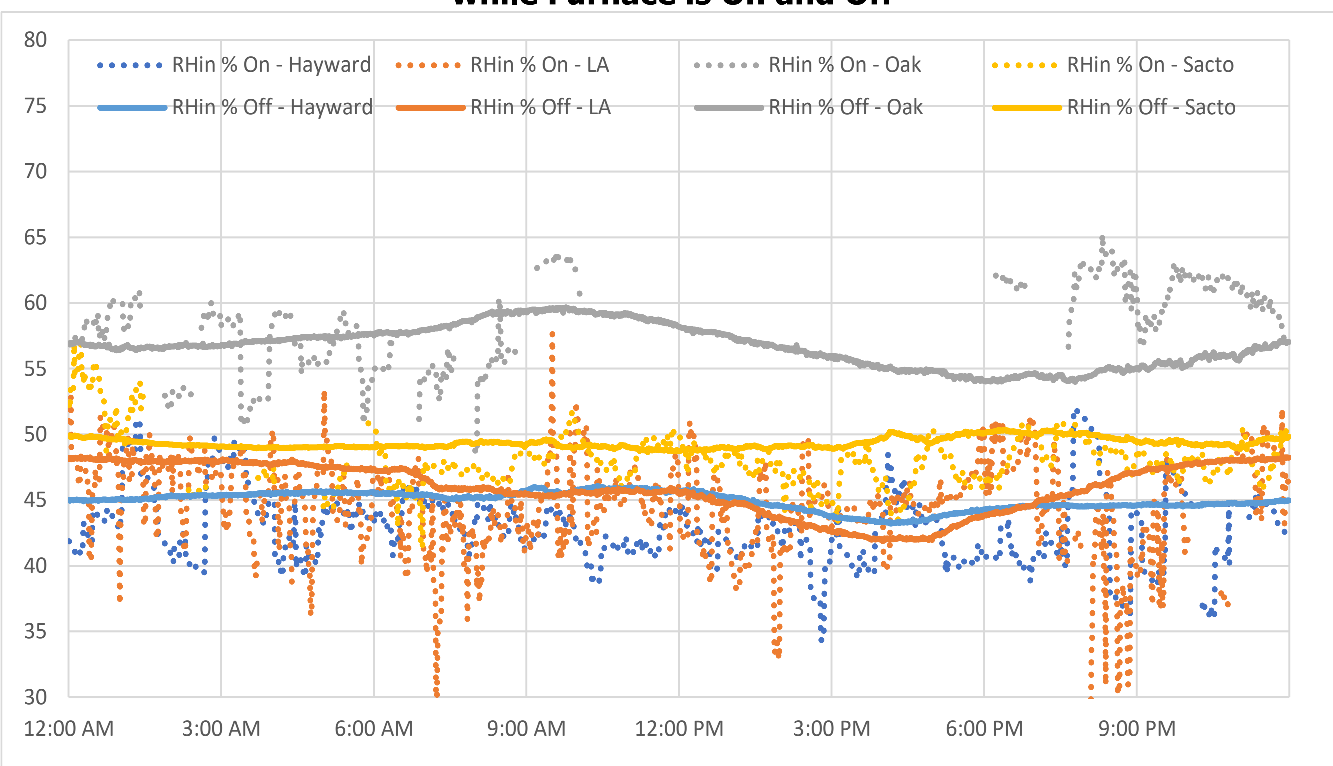
In Sacramento, average indoor temperatures are about 70ºF and vary by about 5ºF over the day. Furnace use occurred over most of the day but less frequently in the early morning before 6 am. Furnace use tends to heat the indoor space by up to 4ºF.

In Hayward, indoor temperatures are about 65ºF and vary by about 6ºF over the day. Furnace use is most common in the morning and evening, rare in the afternoon. It generally warms the space by 2 ºF in the over temperatures when the furnace is off. But furnace use in the evening keeps the space temperatures about the same as when the furnace is not used.

In Oakland, indoor temperatures are coldest at about 63ºF on average, with daily variation of about 7ºF. The furnace is only used before 9 am and after 6 pm. Furnace use before 9 am shows it warms the space by up to 4ºF compared to when the furnace isn't used. After 6 pm the furnace doesn't seem to warm the space very well, as temperatures tend to be as much as 9ºF colder when the furnace is on compared to when the furnace is off.

Figure 13 plots indoor relative humidity versus time of day at each of the four locations, both when the furnace is on and when the furnace is off. Indoor humidity was at least 5% higher in the Oakland home than in the other homes. It is not clear if this is due to lower furnace use, as heating tends to dry out the air, or if there are more sources of humidity at this home.

Figure 13: Average Indoor Relative Humidity versus Time of Day at Four Locations while Furnace is On and Off



Baseline Wall Furnace Field Monitored Data

Additional data is presented for each location in Figure 14 through Figure 33. These graphs show daily patterns of variables averaged from all collected days of data at each minute of the day. The plots also show average values while the furnace is running and when it is not.

Two graphs are shown for each of the ten baseline furnaces:

- Operational data including indoor temperature and relative humidity, outdoor temperature, and the percent of operating time
- Indoor air quality data including concentrations of carbon monoxide, nitrogen oxides, and particulate matter (PM2.5 and PM10)

Operations plots show time of day on the horizontal axis, temperature from 0 to 100 ºF on the left vertical axis, and percentage from 0 to 100% on the right vertical axis. Solid lines show averages of these variables while the furnace was off, while markers show averages while the furnace was on and actively heating. Variables included are:

- Average daily indoor temperature (ºF) in gold line when furnace is off, in gold markers when furnace is on
- Average daily outdoor temperature (ºF) in blue line when furnace in off, in blue markers when furnace is on
- Average daily indoor relative humidity (%) in green line when furnace is off, in green markers when furnace is on
- Average percentage of time the furnace was operating in solid red line

Indoor air quality plots also show time of day on the horizontal axis, and pollutant concentration on the vertical axis. Solid lines show averages of these variables while the furnace was off, while markers show averages while the furnace was on and actively heating. Variables included are:

- Average daily levels of carbon monoxide (CO ppm x 10), in blue line when furnace in off, in blue markers when furnace is on, plus regional outdoor levels of carbon monoxide in a turquoise line
- Average daily levels of nitrogen oxides (NOx ppb / 10), in purple line when furnace in off, in purple markers when furnace is on, plus regional outdoor levels of nitrogen oxides in a pink line
- Average daily level of PM2.5 particulate matter (ug/m3), in gold line when furnace in off, in gold markers when furnace is on, plus regional outdoor levels of PM2.5 in an orange line
- Average daily level of PM10 particulate matter (ug/m3), in green line when furnace in off, in green markers when furnace is on

The vertical scale on the indoor air quality graphs varies depending on the monitored values, from as small as 0 to 60 to as large as 0 to 300.

Figure 14: Hayward Apartment 3, Perfection Products PW8G25SEN-B-4 Average On and Off Operations versus Hour of Day

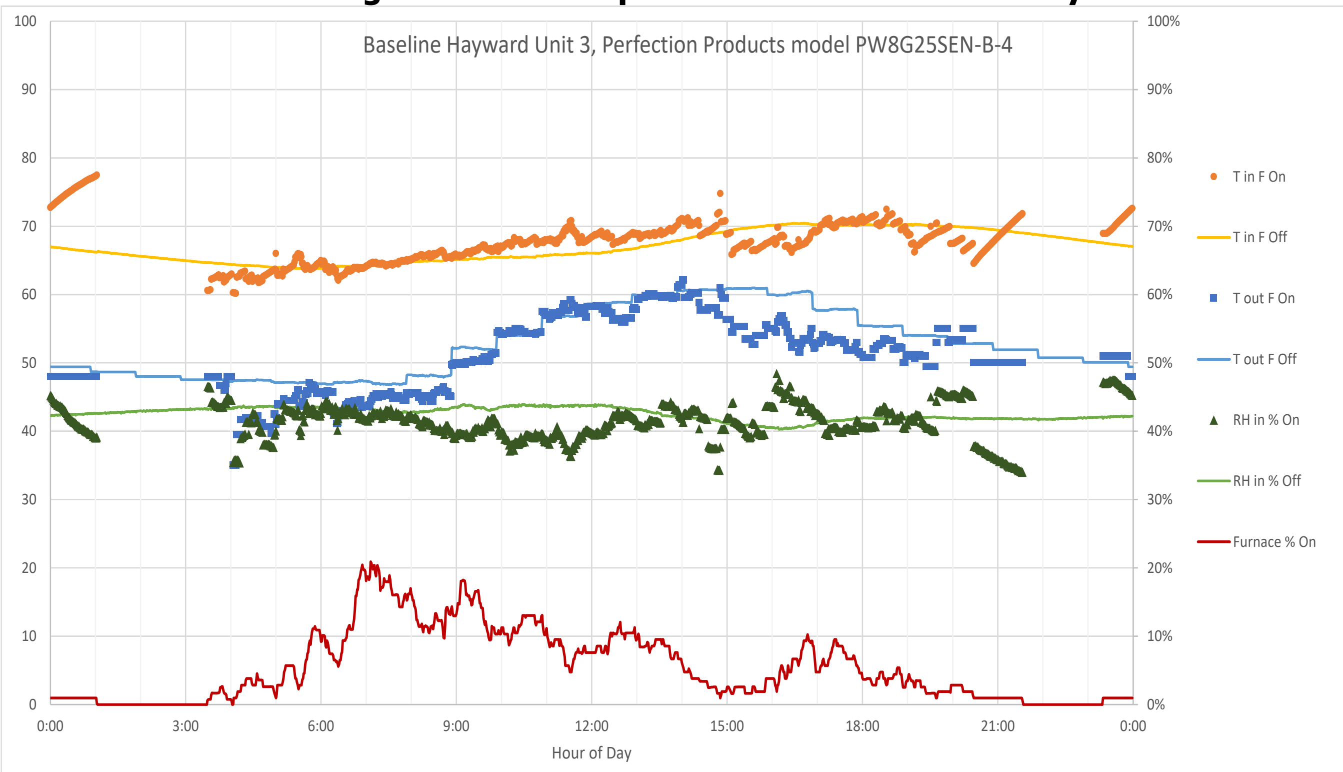


Figure 15: Hayward Apartment 3, Perfection Products PW8G25SEN-B-4 Average On and Off Indoor Air Quality versus Hour of Day

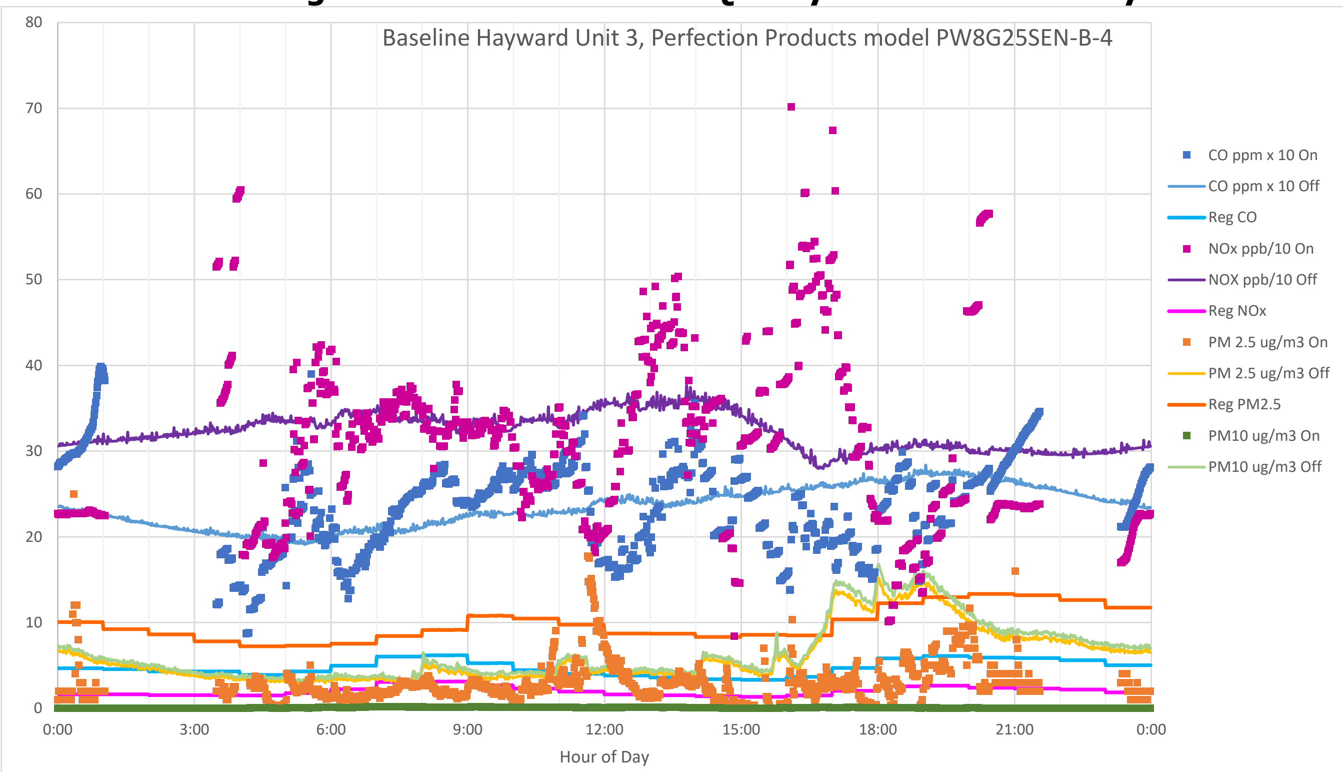


Figure 16: Hayward Apartment 4, Perfection Products PW8G25SEN-B-4 Average On and Off Operations versus Hour of Day

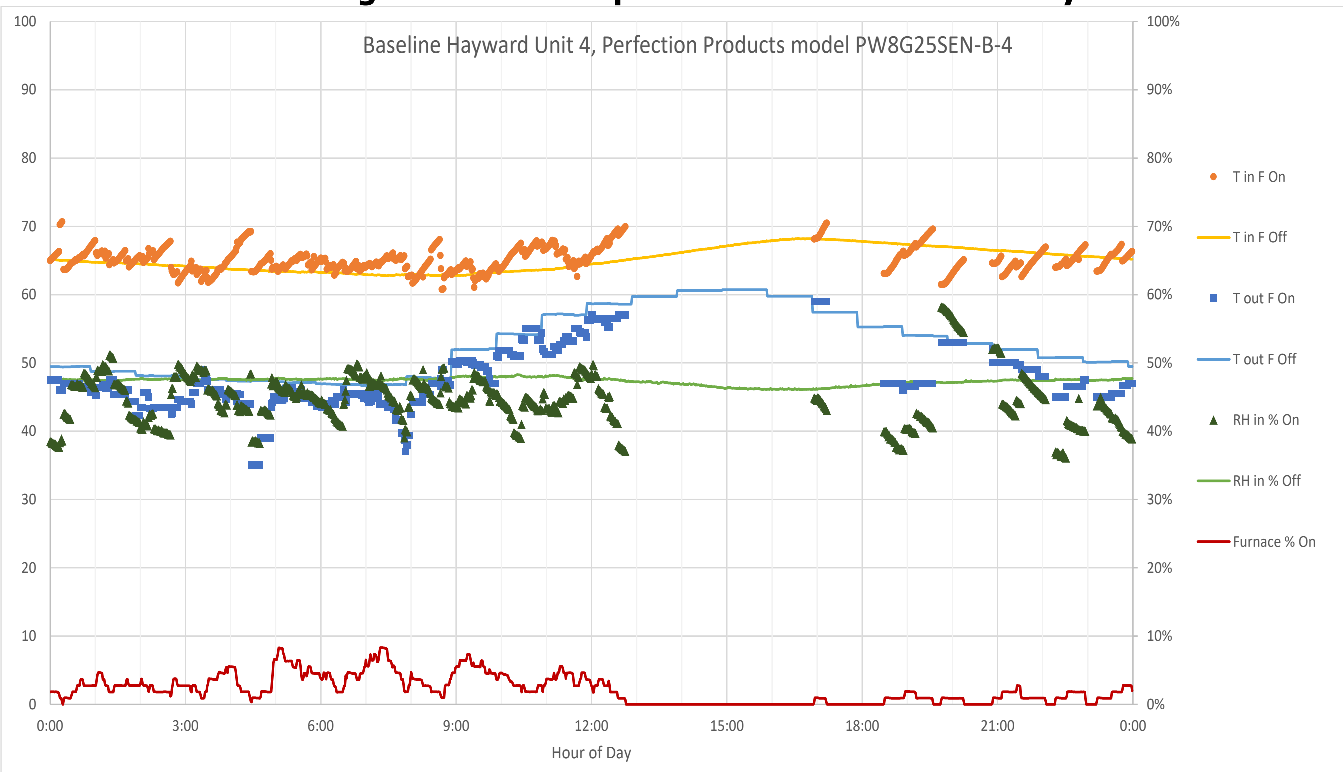


Figure 17: Hayward Apartment 4, Perfection Products PW8G25SEN-B-4 Average On and Off Indoor Air Quality versus Hour of Day

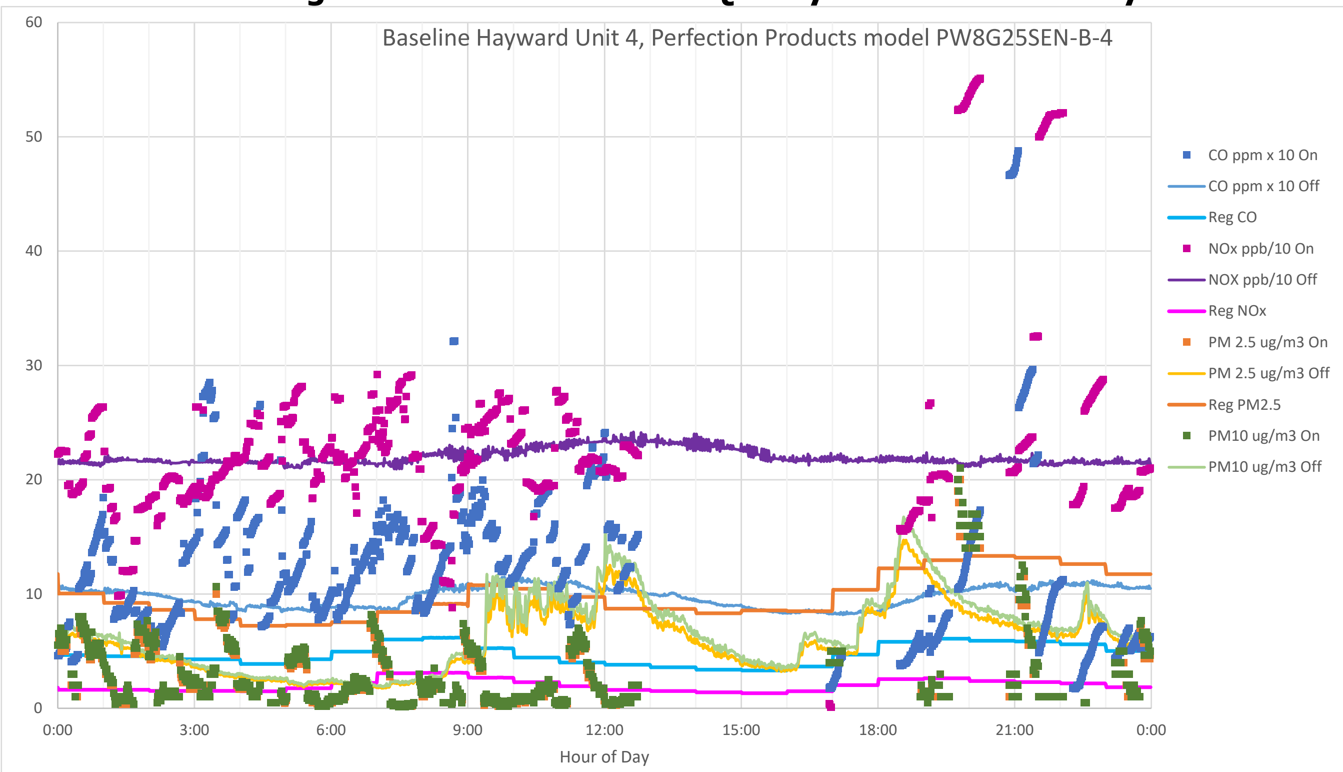


Figure 18: Los Angeles Apartment 104, Williams 25GV-A1-5 Average On and Off Operations versus Hour of Day

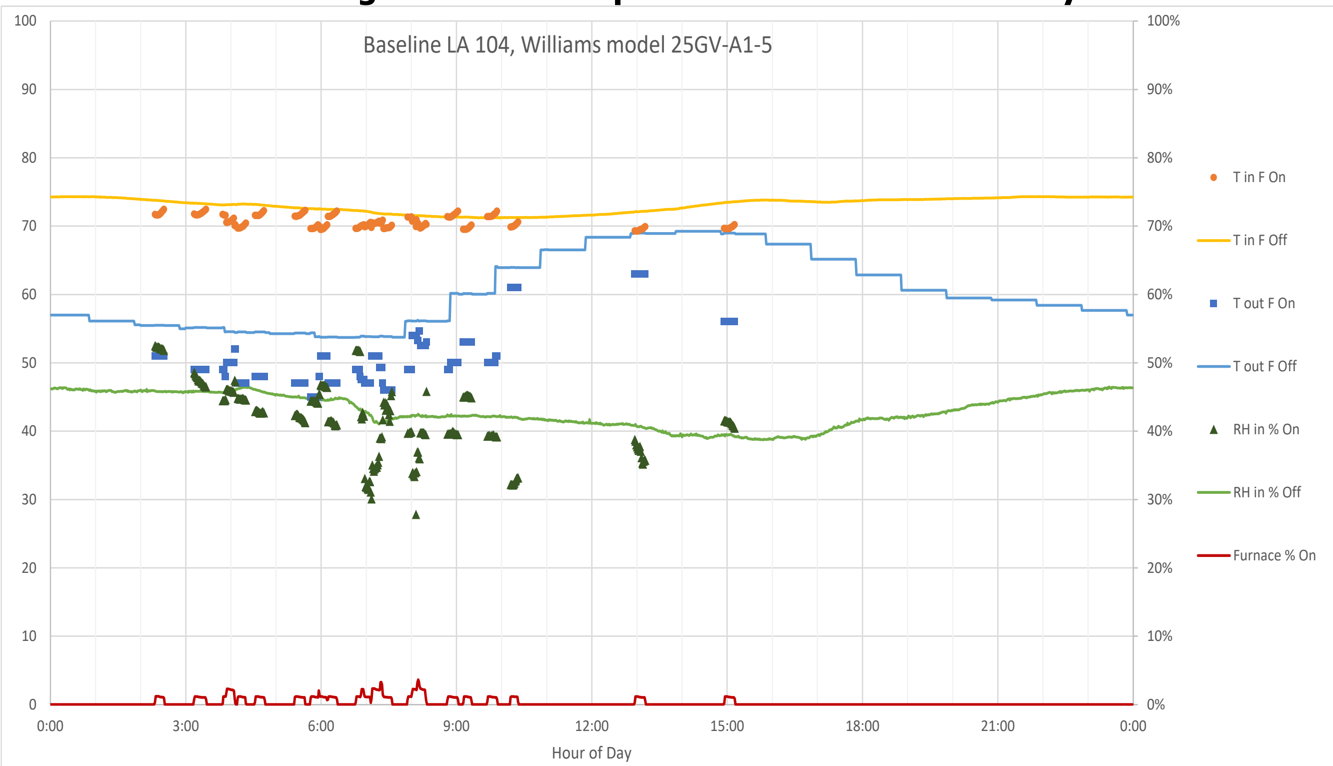


Figure 19: Los Angeles Apartment 104, Williams 25GV-A1-5 Average On and Off Indoor Air Quality versus Hour of Day

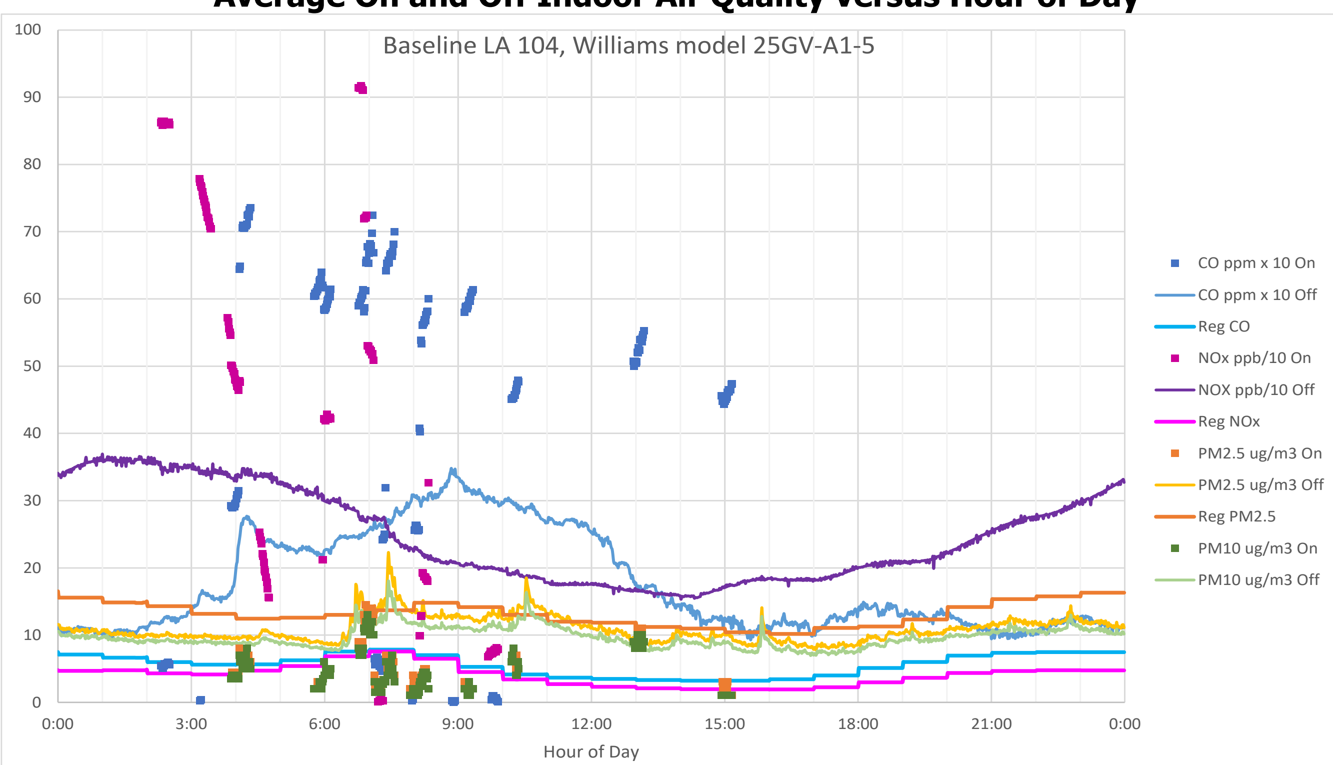


Figure 20: Los Angeles Apartment 105, Williams 35GV-C-5T Average On and Off Operations versus Hour of Day

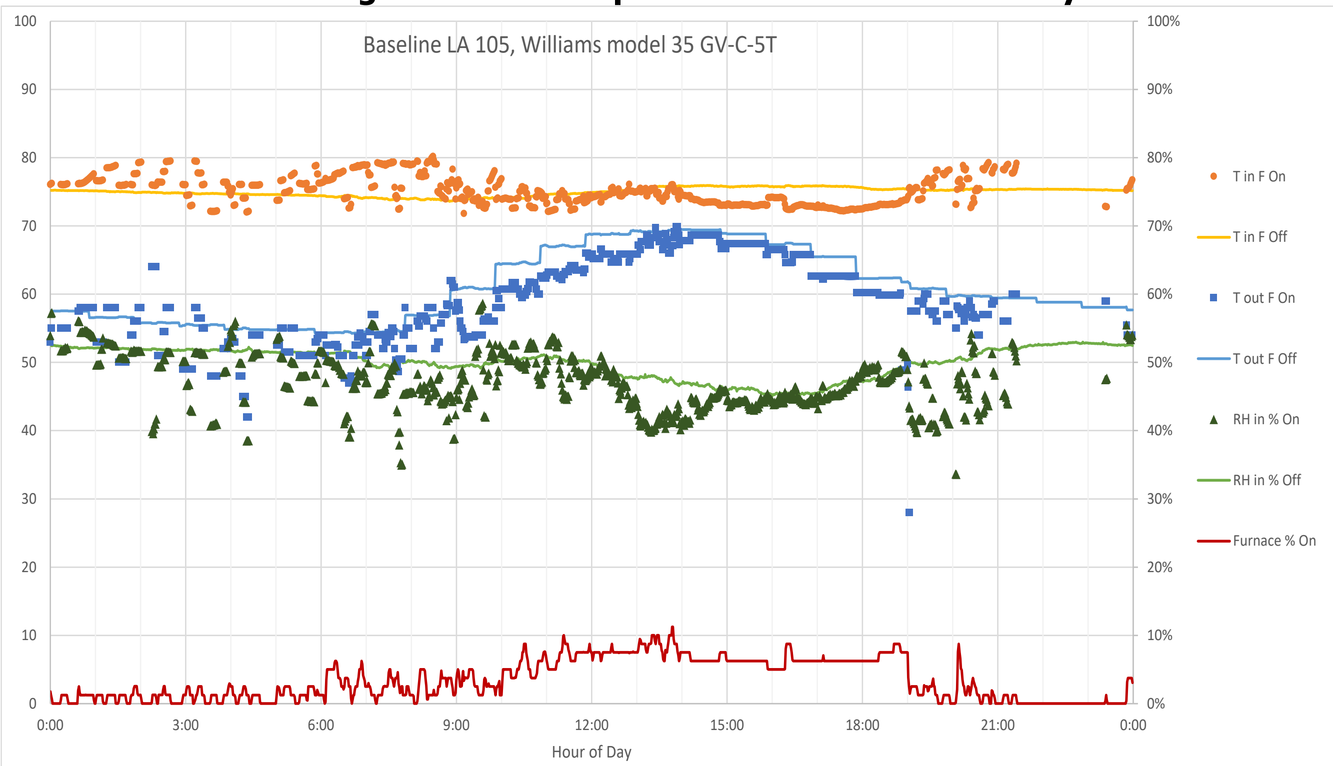


Figure 21: Los Angeles Apartment 105, Williams 35GV-C-5T Average On and Off Indoor Air Quality versus Hour of Day

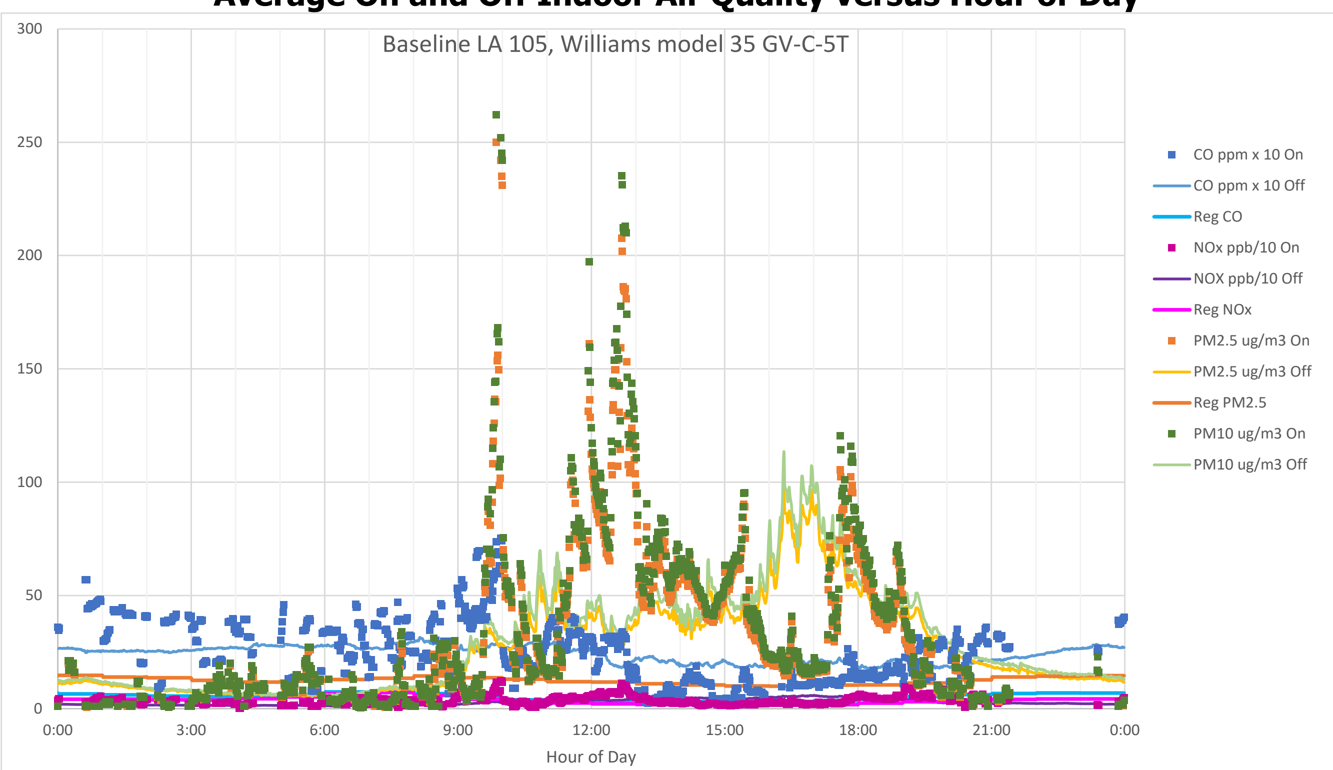


Figure 22: Los Angeles Apartment 106, Williams 35GV-C-5T Average On and Off Operations versus Hour of Day

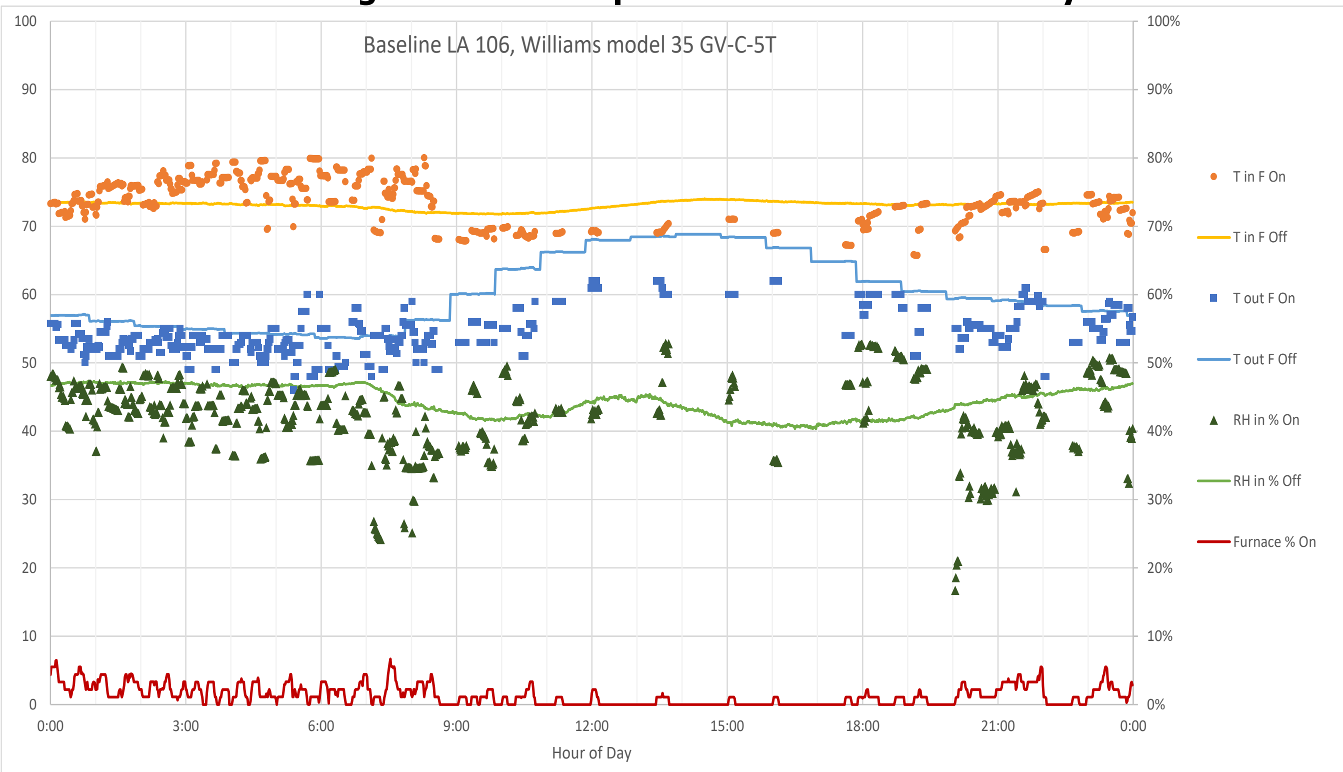


Figure 23: Los Angeles Apartment 106, Williams 35GV-C-5T Average On and Off Indoor Air Quality versus Hour of Day

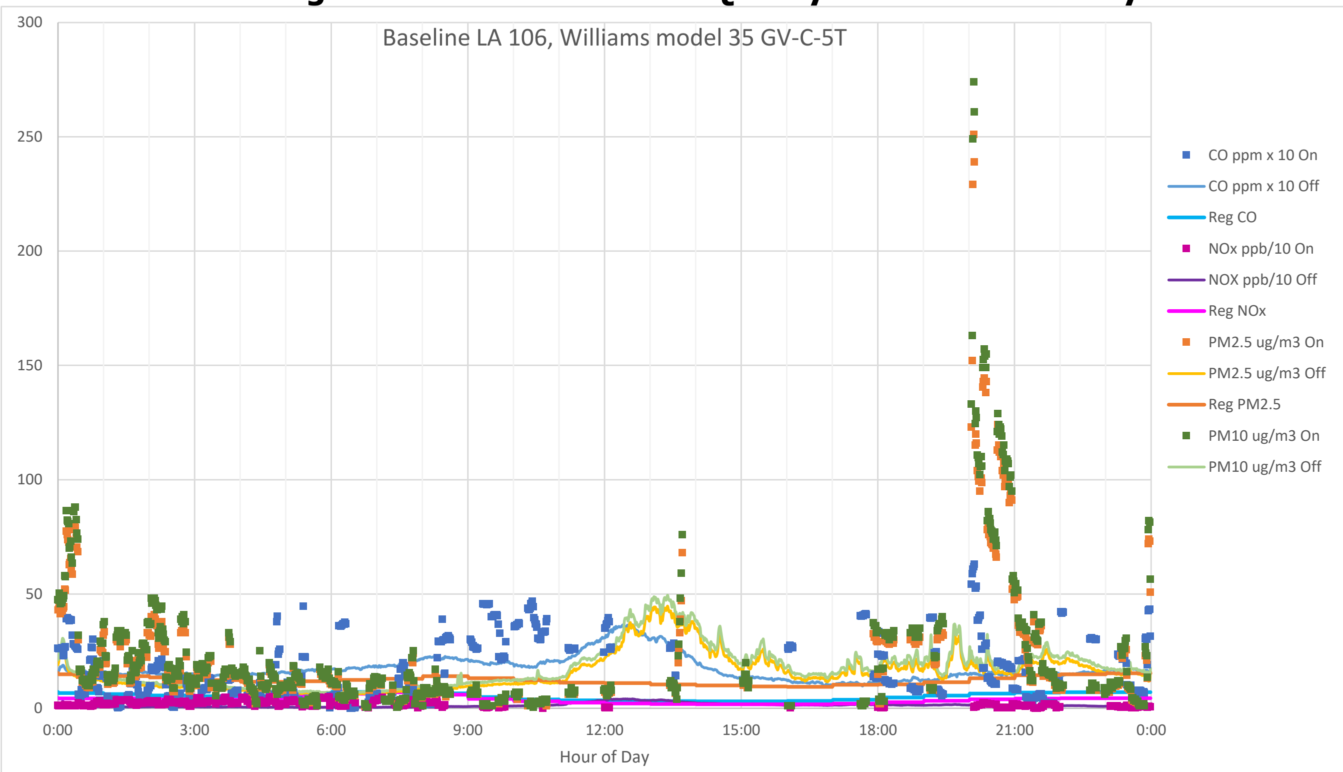


Figure 24: Los Angeles Apartment 107, Williams RMG35-IN Average On and Off Operations versus Hour of Day

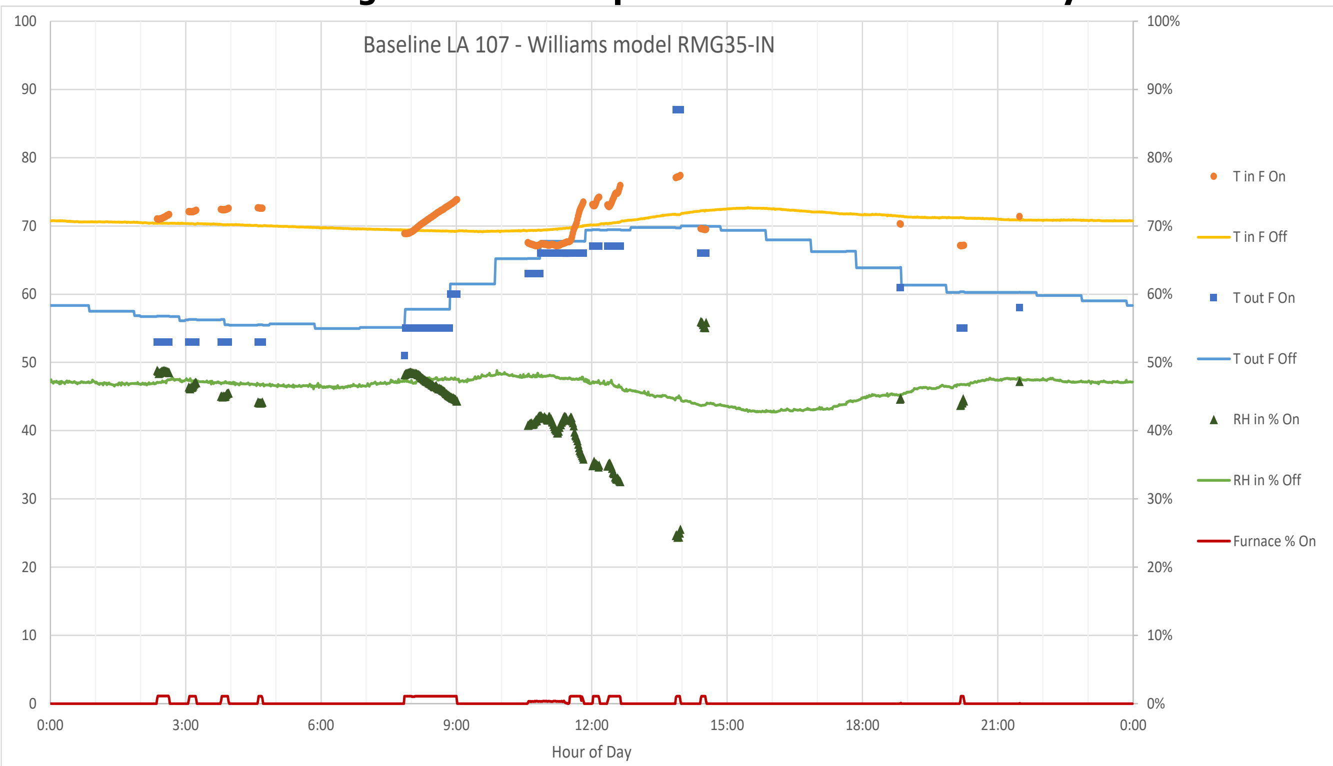


Figure 25: Los Angeles Apartment 107, Williams RMG35-IN Average On and Off Indoor Air Quality versus Hour of Day

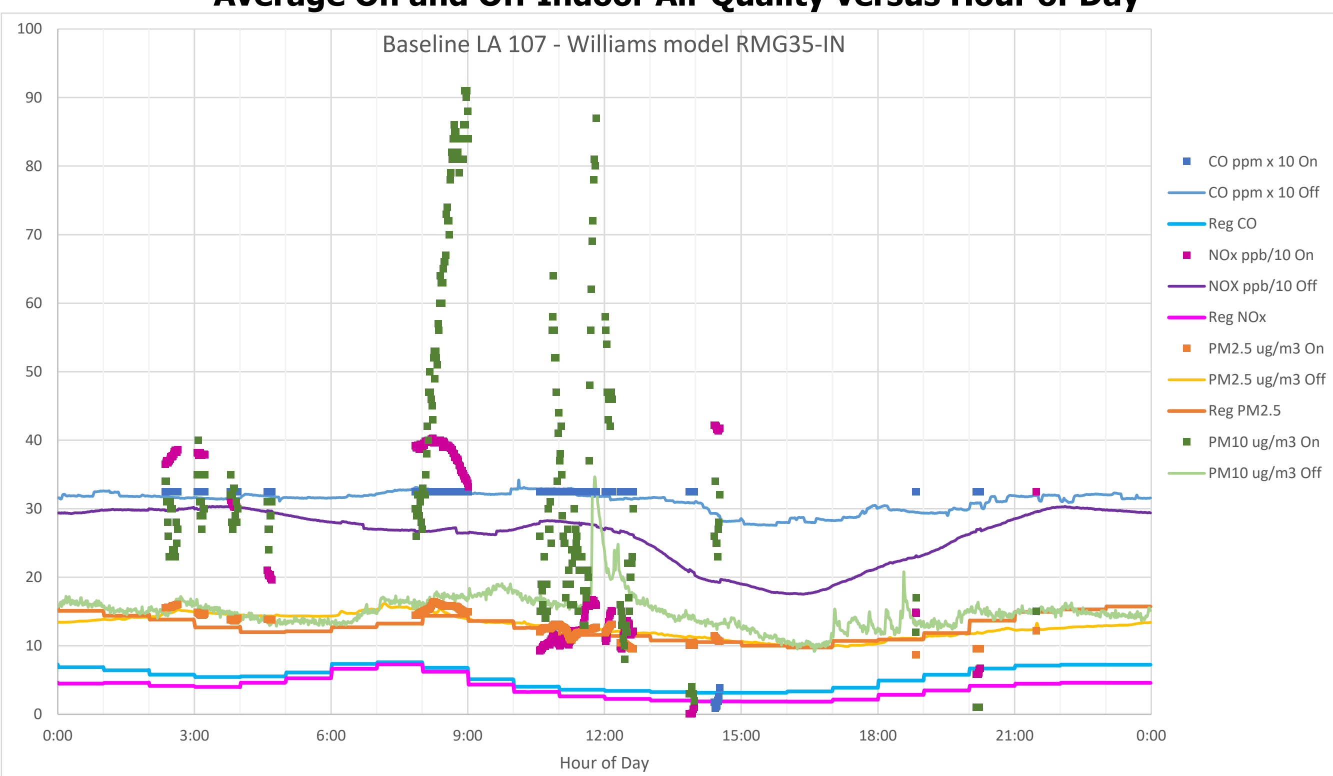


Figure 26: Oakland Single Family Home, Williams 5009622 Average On and Off Operations versus Hour of Day

Figure 27: Oakland Single Family Home, Williams 5009622 Average On and Off Indoor Air Quality versus Hour of Day

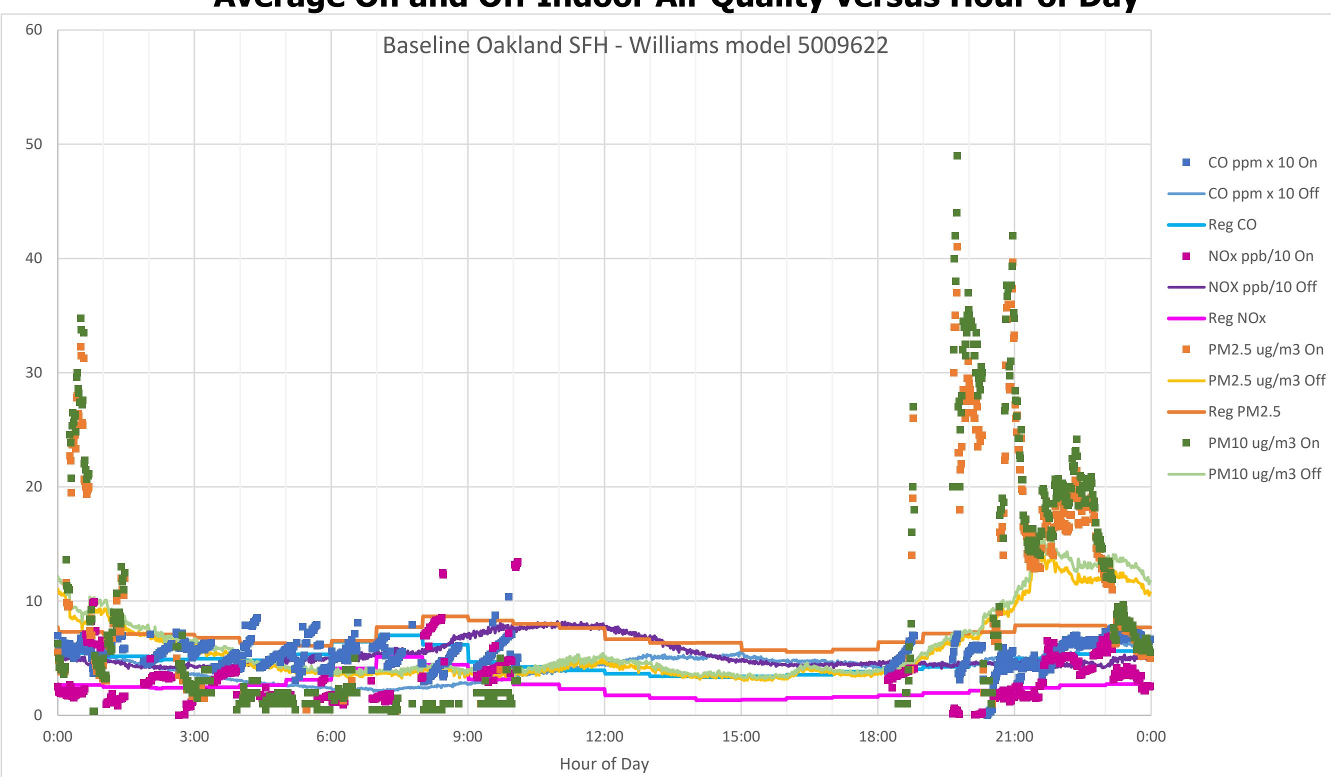


Figure 28: Sacramento Apartment 4, Holly General 35S-D #1 Average On and Off Operations versus Hour of Day

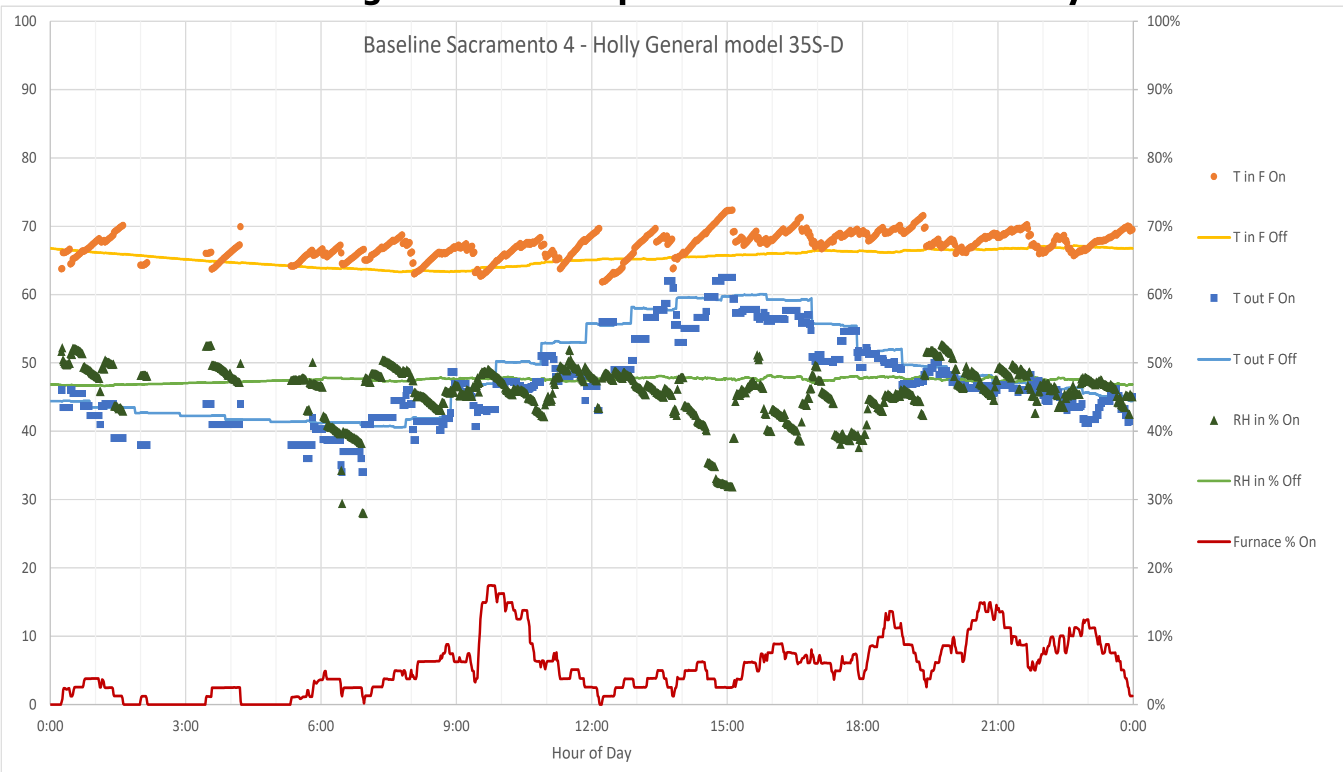


Figure 29: Sacramento Apartment 4, Holly General 35S-D #1 Average On and Off Indoor Air Quality versus Hour of Day

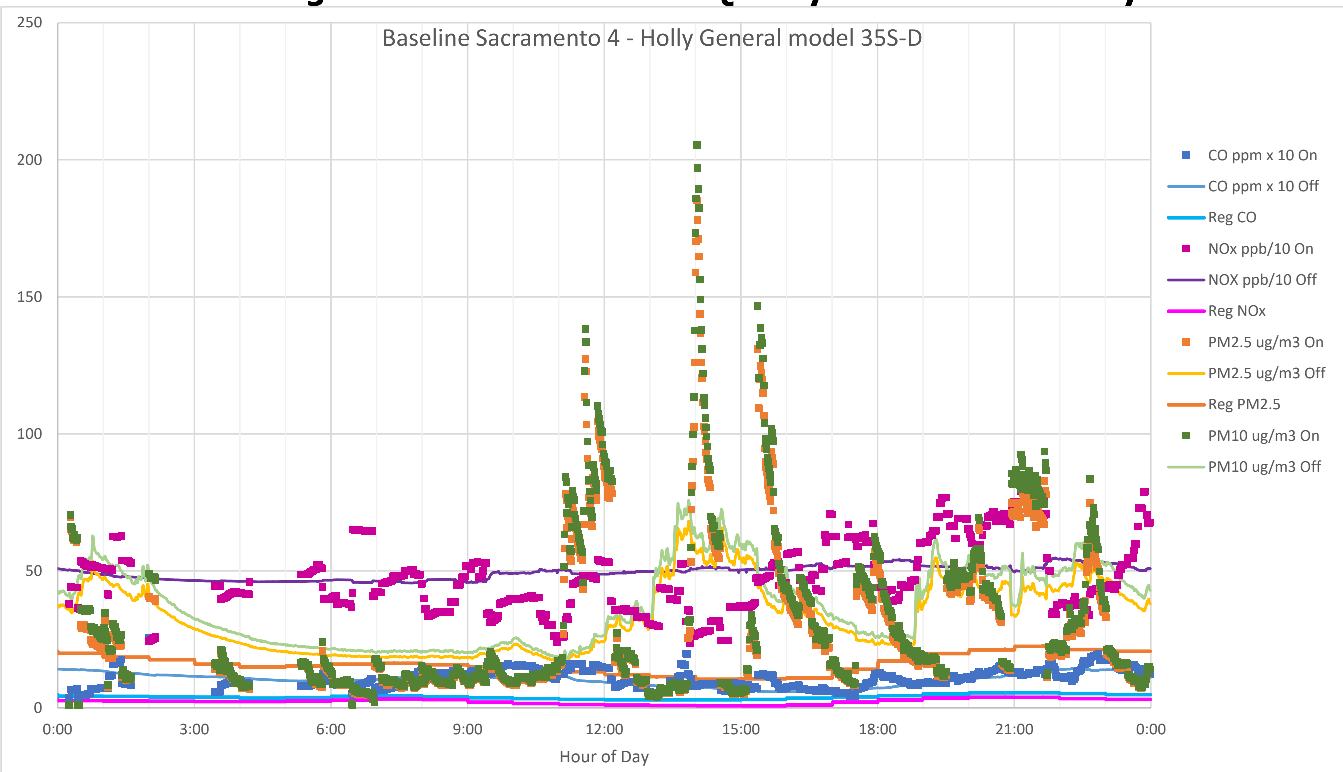


Figure 30: Sacramento Apartment 15, Holly General 35S-D #2 Average On and Off Operations versus Hour of Day

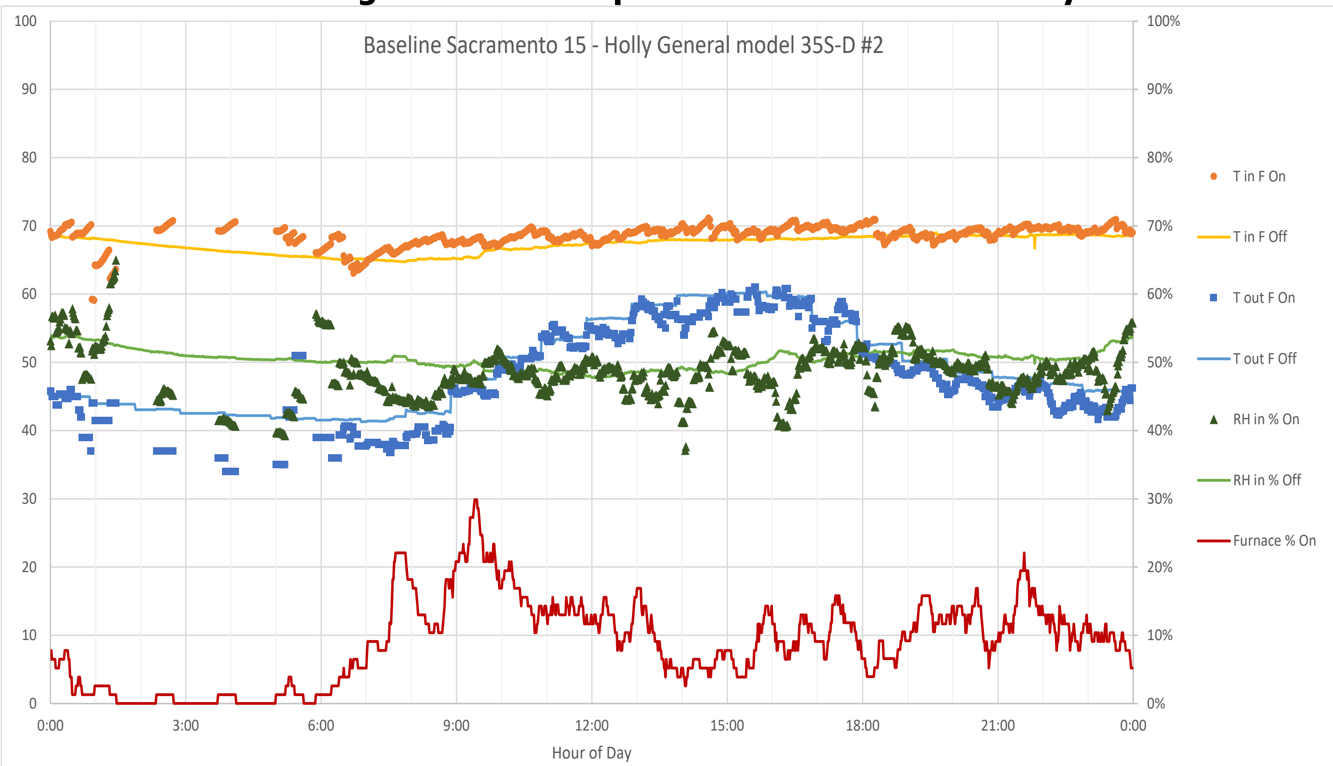


Figure 31: Sacramento Apartment 15, Holly General 35S-D #2 Average On and Off Indoor Air Quality versus Hour of Day

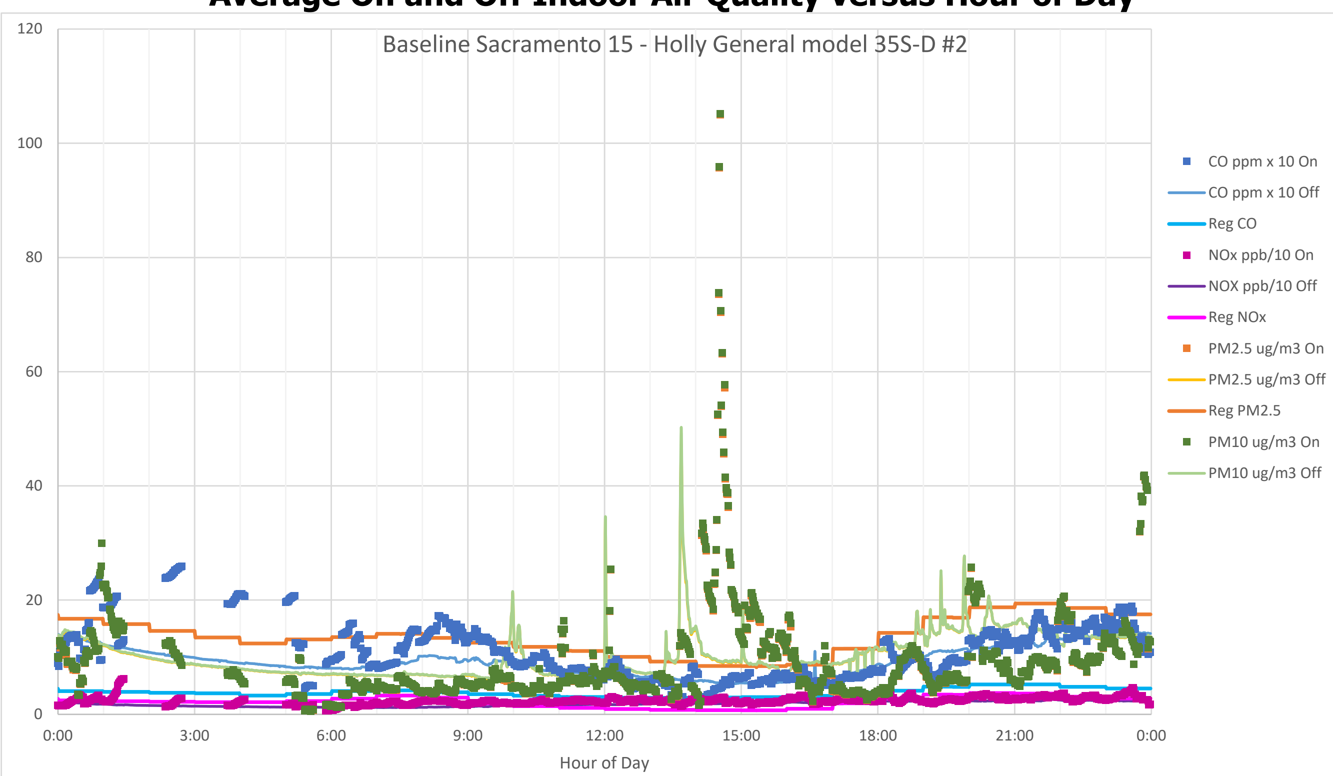


Figure 32: Sacramento Apartment 19, Williams 3509622 Average On and Off Operations versus Hour of Day

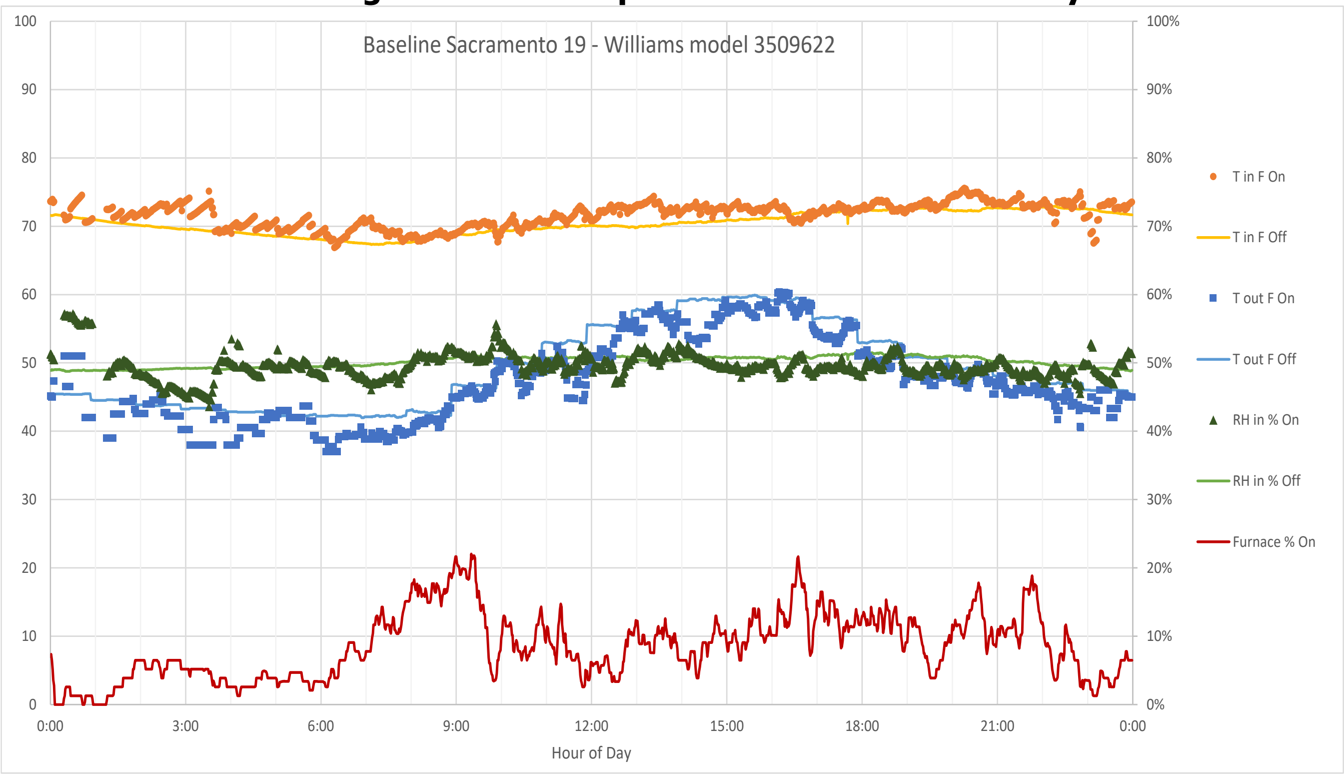
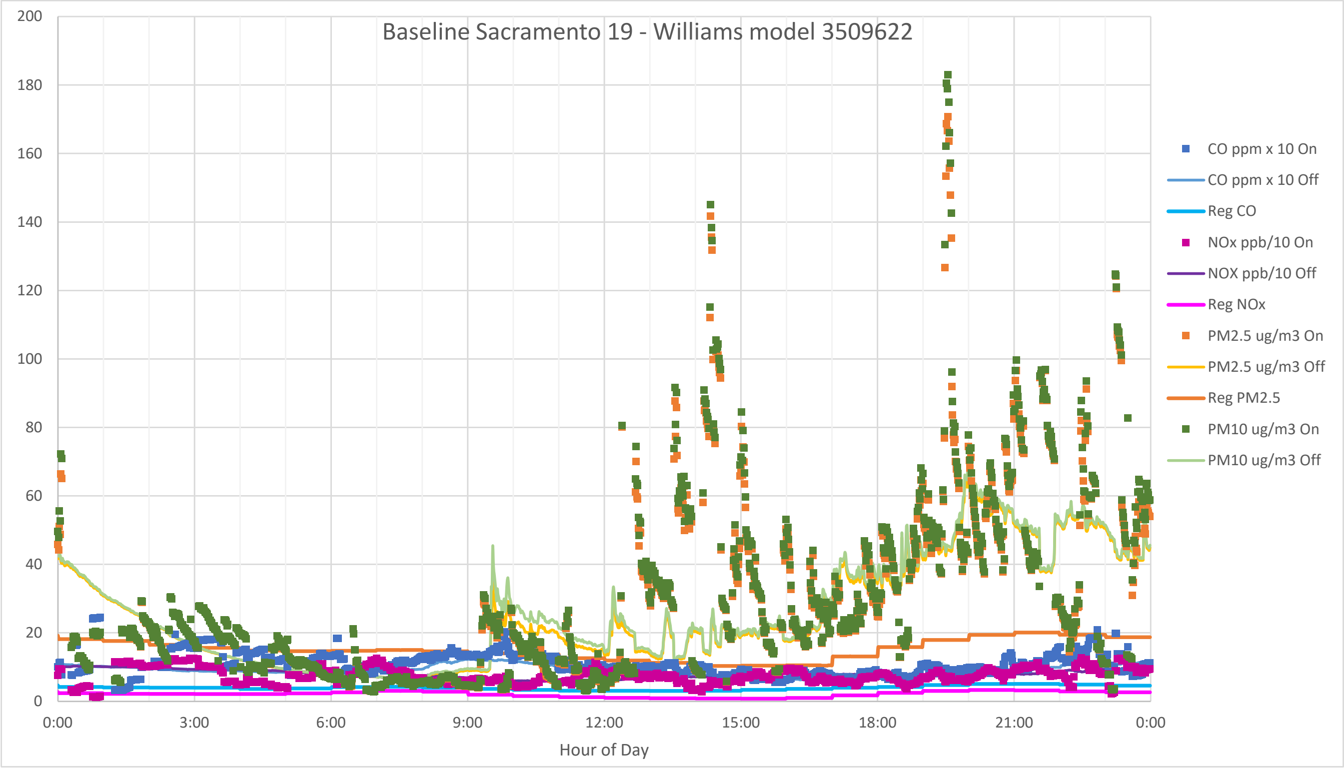


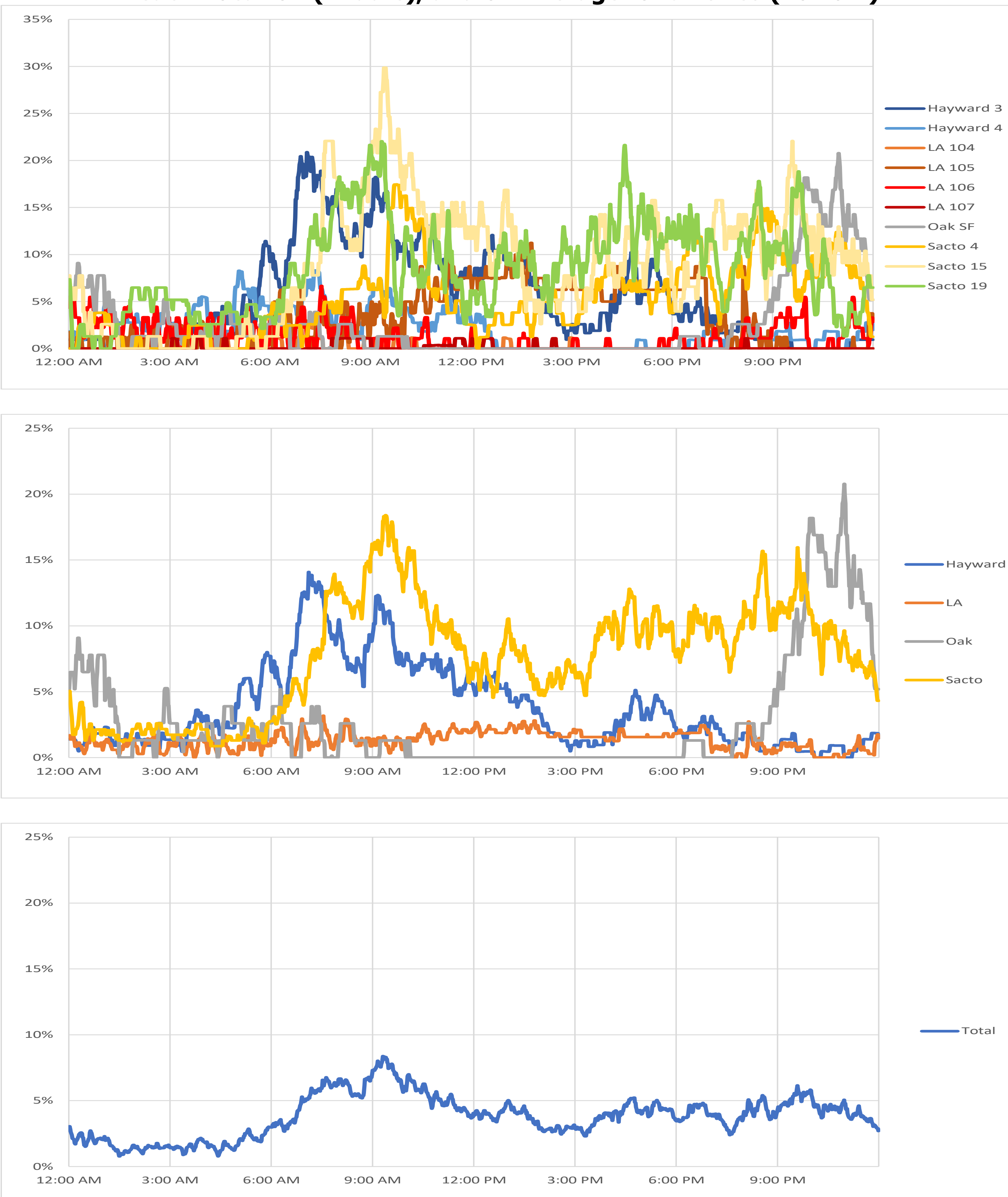
Figure 33: Sacramento Apartment 19, Williams 3509622 Average On and Off Indoor Air Quality versus Hour of Day



Analysis of Baseline Wall Furnace Operation

Figure 34 graphs how frequently the wall furnaces were operating versus time of day for each site, at each location, and for the overall average of all monitored wall furnaces.

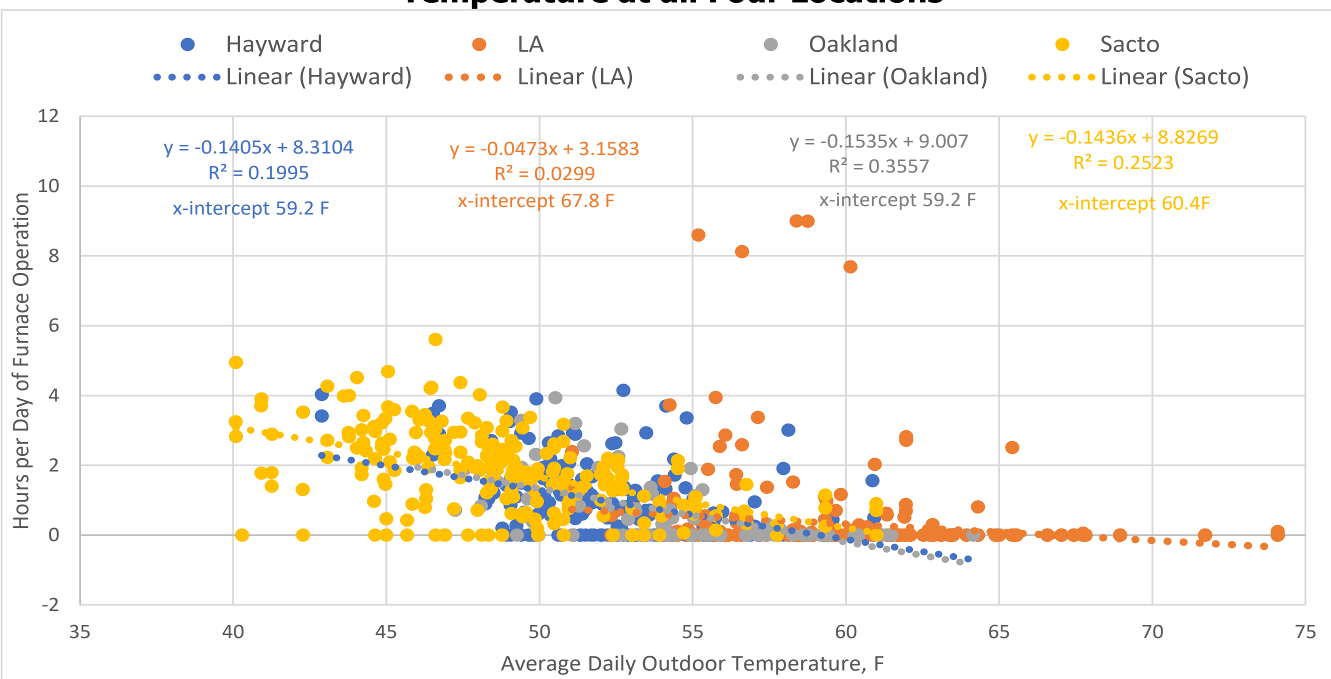
Figure 34: Furnace Operating % over Time of Day at each Site (top), each Location (middle), and on Average for all sites (bottom)



There are significant variations between household wall furnace use patterns. For example, the Sacramento furnaces were most likely to be operated during the day, while Hayward apartment 3 was usually heated in the morning, and Oakland's wall furnace was never used between 10 am and 6 pm. Furnaces were most likely to operate between 6 am and noon and after 6 pm, and least likely to operate from midnight to 6 am.

Figure 35 plots the daily hours of furnace operation versus average daily outdoor temperature, grouping each site into one of the four locations. Regression lines and equations correlate the average hours of furnace use to the average daily outside temperature. Regressions for Hayward, Oakland, and Sacramento lay almost right on top of each other, showing that average daily furnace use versus outdoor temperature is consistent in these Northern California locations.

Figure 35: Daily Hours of Furnace Operation versus Average Daily Outdoor Temperature at all Four Locations



An average regression to characterize Northern California locations is:

NorCal Daily Operating Hours = 8.7 – 0.146 x Average Daily Outdoor Temperature, ºF
Nor Cal X-Intercept = 59.6 ºF, average daily outdoor temperature above which no heat is used

The amount of heating energy used was lower in Los Angeles than in Northern California, and less dependent on outside temperature. The regression line is less steep, and heat is more likely to be used on warmer days.

The regression equation for Los Angeles, extended to all of Southern California, is:

SoCal Daily Operating Hours = 3.2 – 0.047 x Average Daily Outdoor Temperature, ºF
LA X-Intercept = 67.8 ºF, average daily outdoor temperature above which no heat is used

In addition to operating hours, the cycle length was analyzed for each monitored furnace. Figure 36 looks at the length of cycles versus outdoor temperature for all sites. This figure also shows the average cycles per hour across all sites, in the thick purple line, with the dotted purple line showing the linear regression of that average. Cycles per hour increase with colder outdoor temperatures. Cycles per hour can be characterized by the following equation:

California Cycle Length, minutes = 63.5 – 0.64 x Average Daily Outdoor Temperature, ºF

Figure 36: Wall Furnace Cycle Length versus Outdoor Temperature

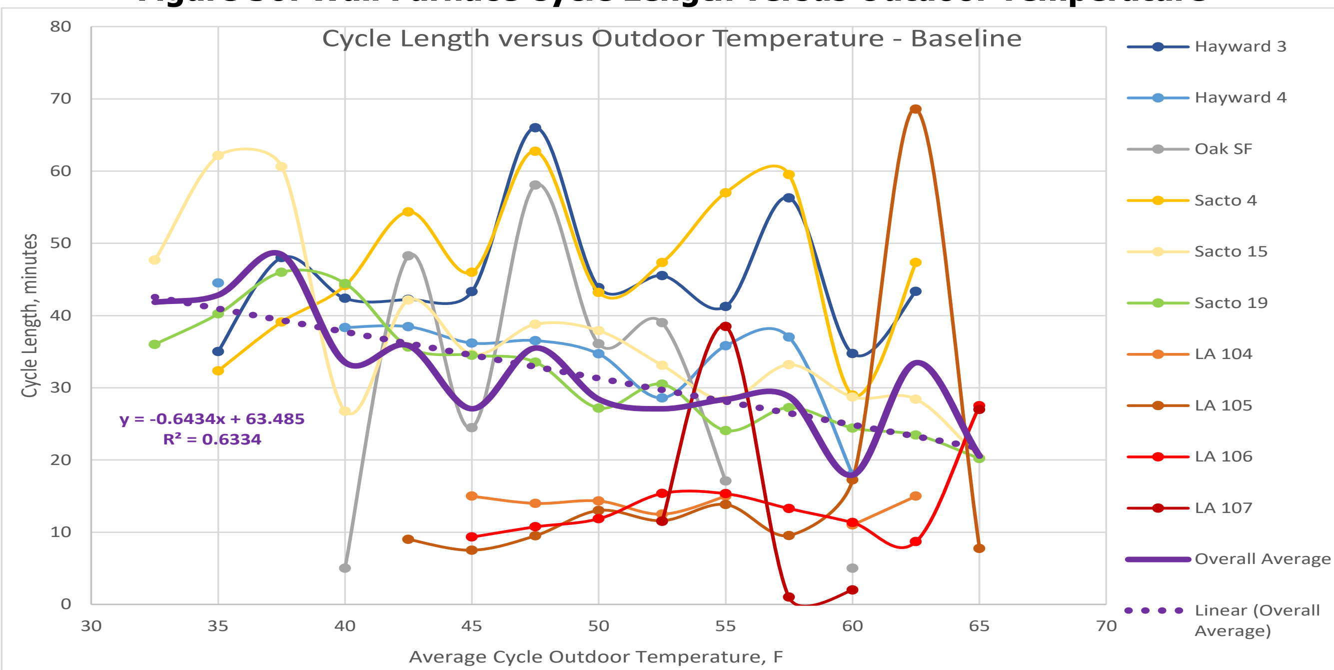


Table 6 summarizes the operating hours, cycles per day and minutes per cycle for all baseline wall furnaces. The Los Angeles furnaces were used less often, while the Sacramento furnaces operated for the greatest number of hours per day. Furnace cycles tended to be the shortest in Los Angeles at less than 30 minutes per cycle, and over 30 minutes in Northern California On average, furnaces operated for 1 hour a day, cycling 1.7 times at 34 minutes per cycle.

Table 6: Summary of Baseline Wall Furnace Field Operation

Site	Manufacturer	Model	Average Operating Hours per Day	Average Furnace Cycles per Day	Average Furnace Cycle Minutes
Hayward 3	Perfection Products	PW8G25SEN #1	1.36	1.77	46.1
Hayward 4	Perfection Products	PW8G25SEN #2	0.55	0.92	35.9
LA 104	Williams	25GV-A1	0.07	0.30	13.8
LA 105	Williams	35GV-C #1	0.89	1.91	28.1
LA 106	Williams	35GV-C #2	0.34	1.52	13.5
LA 107	Williams	RMG35-IN	0.07	0.25	17.3
Oak SF	Williams	5009622	0.67	1.08	37.2
Sacto 4	Holly General	35S-D #1	1.41	1.73	48.8
Sacto 15	Holly General	35S-D #2	2.18	3.77	34.6
Sacto 19	Williams	3509622	2.17	4.18	31.3
Average			**0.97**	**1.73**	**33.6**

Analysis of Baseline Wall Furnace Indoor Air Quality

To quantity the effects of wall furnace operation on indoor air quality, the difference between indoor pollutant concentrations when the furnace is on and when it is off was analyzed. Some caveats about the field monitoring must be noted. First, sensors were in just one location near the wall furnace. Second, there may have been a lag in the dispersion of pollutants relative to furnace on-off cycles. Third, there are other sources of pollutants at all sites, including ranges, water heaters, and general dust and dirt. It is therefore difficult to know whether furnace operation was directly responsible for pollutant level changes or if furnace operation stirs up pollutants or draws them from elsewhere in the homes.

Figure 37 and Figure 38 show the differences in levels of indoor air pollutants measured at each site from when the furnace was off and on. The values shown are differences in the minute-by-minute on and off averages in pollutant levels over all monitored days. Separate graphs are shown for CO, NOx, PM2.5 and PM10. To show these pollutants on similar scales, CO ppm values were multiplied by ten, NOx ppb values were divided by ten, and particulate matter is presented in units of ug/m3. Positive values occur when pollutants increase while the furnace operates, negative values occur when pollutants decrease with furnace operation.

Figure 37: Differences in Average Daily Levels of Carbon Monoxide (left) and Nitrogen Oxides (right) at Each Site while Furnace is On and Off

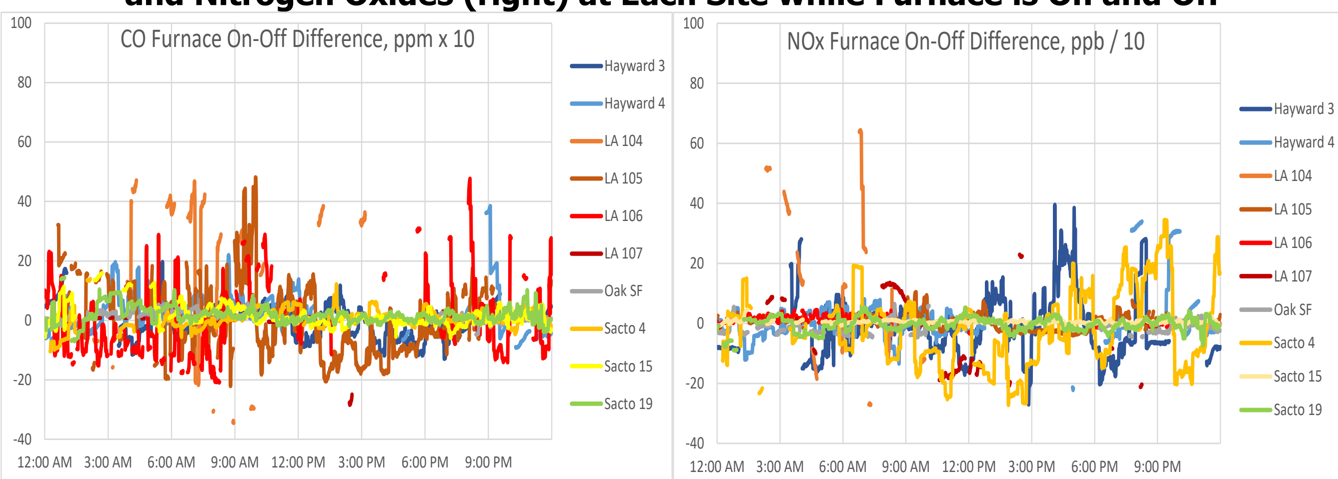


Figure 38: Difference in Average Daily Levels of PM2.5 (left) and PM10 (right) at Each Site while Furnace is On and Off

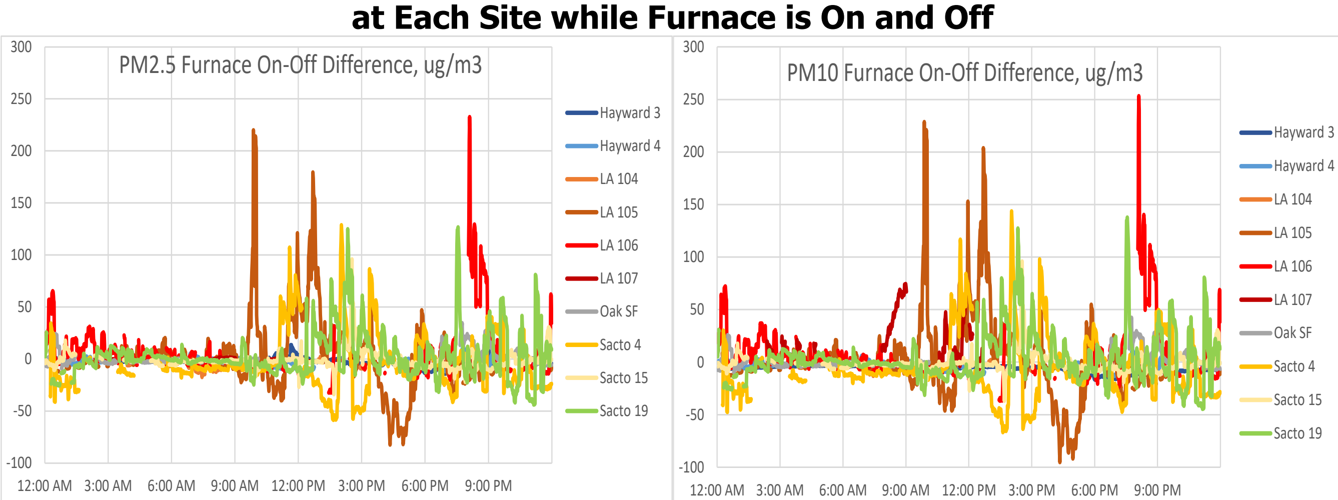
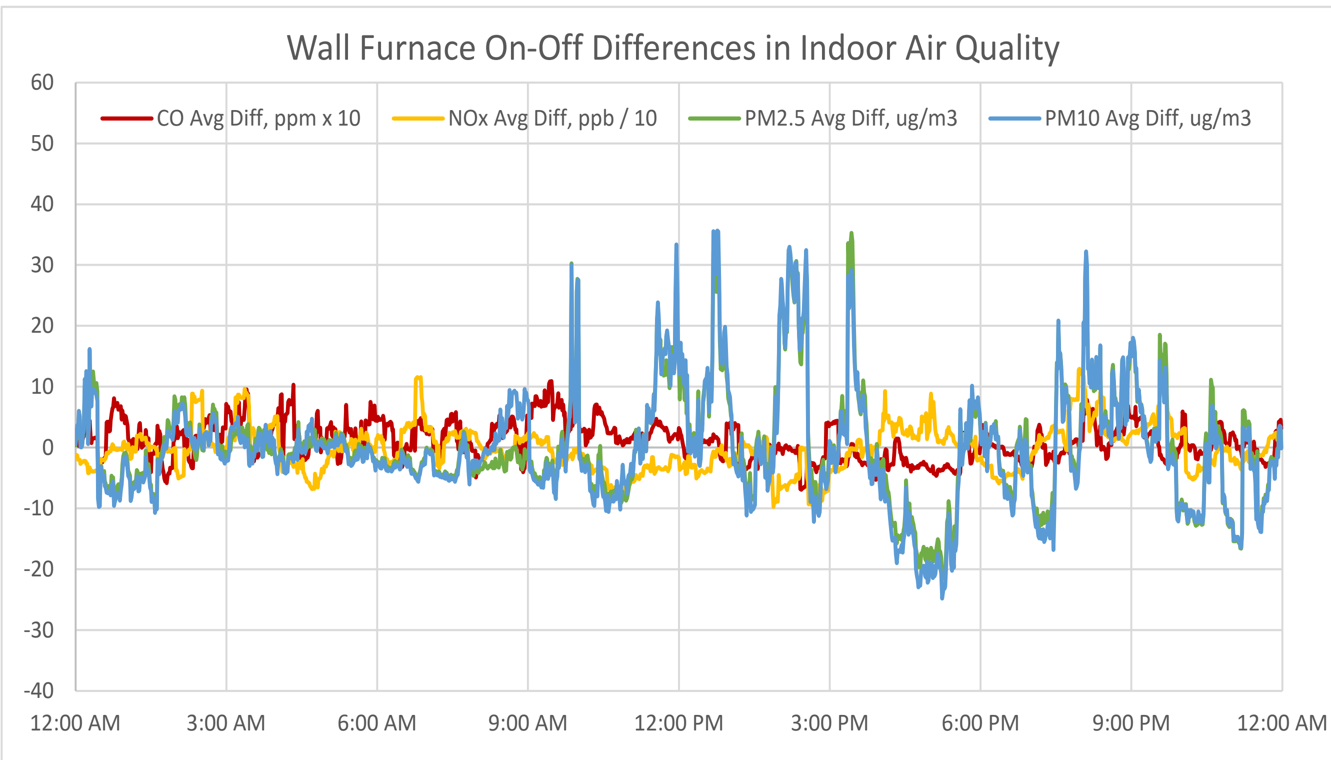


Figure 37 shows that carbon dioxide levels are more likely to decrease when the furnace runs between noon and 6 pm but may increase or decrease at other times of day. Nitrogen oxides are more likely to increase when the furnace runs between 3pm and 6 pm but may increase or decrease at other times of day. Peak increases in carbon dioxide and nitrogen oxides are greater in magnitude than peak decreases.

Figure 38 shows that differences in levels of PM2.5 and PM10 have extremely similar patterns, one must look carefully to see any differences. The magnitude of PM10 differences is slightly greater than PM2.5. Increases in particulate matter levels with furnace operation are larger from 9 am to 4 pm and 7 pm to 9 pm. Particulate matter levels tend to decrease between 4 pm and 7 pm when the furnace operates.

Figure 39 graphs the average across all sites of the differences in pollutant levels when the furnace is on and off versus time of day.

Figure 39: Daily Average Difference in IAQ Pollutants for All Sites when the Furnace is On or Off



Average carbon monoxide differences tend to be elevated when the furnace runs between midnight and 9 am, tend to decrease from 9 pm to 6 pm, and then increase again after 6 pm.

Average nitrogen oxides differences are more variable over the typical day than carbon monoxide levels, but they do tend to be higher when the furnace runs between 9 am and noon, and lower when the furnace runs between 3 pm and 6 pm.

PM2.5 and PM10 on-off differences are just about identical. They increase substantially when the furnace runs from 9 am to 4 pm, as well as from about 7:30 pm to 10 pm, but were shown to decrease on average from 4 pm to 6 pm.

Table 7 summarizes **average** indoor carbon monoxide and nitrogen oxides concentrations at each site when the furnace is on and off, as well as the percent differences between furnace on and furnace off levels. Regional average outdoor pollution levels during each site's monitoring period are also listed. Comparative concentration limits from Appendix A's Table 22 are given for context. Any values that exceed the comparative limit are in red.

Table 7: AVERAGE Carbon Monoxide and Nitrogen Oxides Concentrations at All Sites when Furnaces are On and Off

AVERAGES Field Site	Regional CO ppmx10	CO Off ppmx10	CO On ppmx10	CO On-Off Difference %	Regional NOx ppb/10	NOx Off ppb/10	NOx On ppb/10	NOx On-Off Difference %
Hayward 3	4.7	23.5	23.4	0%	2.0	**32.3**	**30.9**	-4%
Hayward 4	4.7	9.8	12.4	26%	2.0	**22.0**	**23.1**	5%
LA 104	5.6	17.7	43.3	145%	4.1	**24.8**	**45.2**	83%
LA 105	5.2	24.2	23.9	-1%	3.7	2.8	**3.7**	31%
LA 106	5.2	17.3	16.5	-5%	3.7	1.3	2.0	51%
LA 107	5.4	31.2	31.4	1%	3.9	**26.2**	**24.5**	-7%
Oak SF	4.7	4.2	5.5	30%	2.5	**5.3**	**3.3**	-37%
Sacto 4	4.1	10.4	10.8	4%	2.4	**49.4**	**47.7**	-4%
Sacto 15	3.8	9.3	10.8	16%	2.2	1.8	2.4	30%
Sacto 19	3.9	9.1	10.9	19%	2.1	**7.9**	**7.5**	-5%
Average	**4.7**	**15.7**	**18.9**	**21%**	**2.9**	**17.4**	**19.0**	**9%**
Comparative Limit	**50-150 ppmx10 inside property adjusted (US EPA)**				**3.0 ppb/10 24 hour outside (CAAQS)**			

Although indoor CO and NOx levels tend to be higher than the outdoor pollutant levels measured at the closest regional air quality station, no relationships were identified between regional and indoor levels of pollution.

As described in Appendix A, the US EPA deems indoor CO levels of 50 to 150 ppm x 10 to be typical near a properly adjusted gas appliance. By those definitions, average CO levels always fell within the normal range, both while the furnaces were operating and when they were not.

Across all sites, average indoor CO increased from 15.7 ppm x 10 to 18.9 ppm x 10 while the furnace was running, a 21% increase. CO increases were mostly close to zero or positive at all sites. CO increased much more at LA 104 than at any of the other sites. It is likely that the LA 104 furnace was improperly tuned despite being checked over and cleaned by an HVAC technician at the start of this project.

California Ambient Air Quality Standards (CAAQS) deem outdoor NOx levels below 3.0 ppb/10 to be acceptable for 24 hours. Average indoor NOx levels at seven sites did not meet the 24-hour outdoor air standard, and these high values are marked in red text.

The average indoor NOx for all sites increased from 17.4 ppb/10 to 19.0 ppb/10 while the furnaces were running. Average indoor NOx increased at four sites and decreased at six sites while the furnaces were running for a net 9% increase. Indoor NOx increased more at LA 104 during furnace operation than at any of the other sites, again indicating this furnace was improperly tuned.

Table 8 summarizes **average** indoor particulate matter PM2.5 and PM10 concentrations at each site when the furnace is on and off, as well as the percent differences between furnace on and furnace off levels. Regional **average** outdoor pollution levels are also listed for PM 2.5, although they were not available for PM10. Comparative concentration limits from Appendix A's Table 22 are given for context. Any values that exceed the comparative limit are in red.

Table 8: AVERAGE Particulate Matter PM2.5 and PM10 Concentrations at All Sites when Furnaces are On and Off

AVERAGES Field Site	Regional PM2.5 ug/m3	PM2.5 Off ug/m3	PM2.5 On ug/m3	PM2.5 On-Off Difference %	PM10 Off ug/m3	PM10 On ug/m3	PM10 On-Off Difference %
Hayward 3	9.8	6.0	3.0	-50%	6.5	0.1	-99%
Hayward 4	9.8	5.9	3.1	-48%	6.5	3.2	-51%
LA 104	13.1	10.9	5.1	-53%	9.7	4.7	-52%
LA 105	12.5	26.3	33.8	29%	29.3	36.8	25%
LA 106	12.3	15.5	21.7	40%	17.5	23.6	34%
LA 107	12.7	12.8	13.3	4%	15.0	38.0	154%
Oak SF	7.0	5.7	9.4	65%	6.2	10.1	65%
Sacto 4	16.1	33.1	28.4	-14%	37.1	31.0	-16%
Sacto 15	13.5	10.2	9.1	-11%	10.3	9.1	-11%
Sacto 19	15.0	25.5	28.0	10%	26.5	28.8	9%
Average	**12.2**	**15.2**	**15.5**	**2%**	**16.5**	**18.5**	**13%**
Comparative Limit	**35 ug/m3 24 hour outside (NAAQS)**				**50 ug/m3 24 hour outside (CAAQS)**		

National Ambient Air Quality Standards (NAAQS) deem outdoor PM2.5 levels below 35 ug/m^3 to be acceptable for 24 hours, and the California Ambient Air Quality Standards (CAAQS) deem PM10 levels below 50 ug/m^3 to be acceptable for 24 hours. All average indoor PM2.5 and PM10 concentrations meet these standards whether the furnaces were running or not.

Indoor particulate matter levels fell at five sites and rose at five sites while the furnace was on compared to when it was off. On average across all sites, indoor PM2.5 and PM10 levels increased 2% and 13% respectively while the furnace was operating. It is impossible to say whether these furnaces are stirring already-existing particulate matter into the air, exhausting dusty air through the flue, or introducing more particulates due to leakage or backflow of combustion gases during operation.

In addition to looking at overall average indoor pollutant concentrations, maximum pollutant concentrations are investigated at each site when the furnace is on and off, and the differences between on and off concentrations. This maximum is derived by finding the highest pollutant concentrations for each of the 1,440 minutes across all the days of collected data, and then averaging the minute values.

Table 9 summarizes **maximum** indoor carbon monoxide and nitrogen oxides concentrations at each site when the furnace is on and off, as well as the percent differences between furnace on and furnace off levels. Regional **maximum** outdoor pollution levels are also listed. Comparative concentration limits from Appendix A's Table 22 are given for context. Any values that exceed the comparative limit are in red.

Table 9: MAXIMUM Indoor Carbon Monoxide and Nitrogen Oxides Concentrations at All Sites when Furnace is On and Off

MAXIMUMS Field Site	Regional CO ppmx10	CO Off ppmx10	CO On ppmx10	CO On-Off Difference %	Regional NOx ppb/10	NOx Off ppb/10	NOx On ppb/10	NOx On-Off Difference %
Hayward 3	6.2	49.1	34.1	-31%	3.1	93.3	57.2	-39%
Hayward 4	6.2	43.2	20.1	-53%	3.1	61.7	29.6	-52%
LA 104	7.8	84.9	47.4	-44%	7.6	117.8	48.0	-59%
LA 105	7.6	24.2	23.9	-1%	7.1	2.8	3.7	31%
LA 106	7.4	104.7	25.3	-76%	7.0	9.9	2.9	-70%
LA 107	7.6	50.9	31.4	-38%	7.3	67.2	24.5	-64%
Oak SF	7.0	12.5	7.4	-41%	5.1	26.4	7.5	-72%
Sacto 4	5.6	30.0	17.5	-42%	4.0	138.5	74.2	-46%
Sacto 15	5.2	29.9	19.5	-35%	3.7	6.5	4.1	-38%
Sacto 19	5.1	26.4	18.8	-29%	3.3	24.3	13.3	-45%
Average	**4.9**	**45.6**	**24.5**	**-46%**	**5.1**	**54.9**	**26.5**	**-52%**
Comparative Limit	50-150 ppmx10 inside property adjusted (US EPA)				18 ppb/10 1 hour outside (CAAQS)			

As noted in Appendix B, the US EPA deems indoor CO levels of 0 to 50 ppm x 10 to be normal, levels of 50 to 150 ppm x 10 to be typical near a properly adjusted gas appliance, and levels of 300 ppmx10 or more to occur near improperly adjusted gas appliances. Maximum indoor CO levels for all ten furnaces were within the normal range when the furnace was on and off.

Across all sites, maximum indoor CO levels decreased from 45.6 ppm x 10 to 24.5 ppm x 10 while the furnace was running, a 46% decrease. Maximum indoor CO concentrations decreased when the furnace was on compared to when it was off at all sites.

California Ambient Air Quality Standards (CAAQS) deem outdoor NOx levels below 18 ppb/10 to be acceptable for 1 hour. Maximum indoor NOx levels at seven sites did not meet the 1-hour outdoor air standards, and these high values are marked with red text in Table 11.

Across all sites, maximum indoor NOx decreased from 54.9 ppb/10 to 26.5 ppb/10 while the furnaces were running for a net 52% decrease. Maximum indoor NOx decreased at nine sites and increased at the Los Angeles 105 site.

Table 10 summarizes **maximum** indoor carbon monoxide and nitrogen oxides concentrations at each site when the furnace is on and off, as well as the percent differences between furnace on and off levels. Regional **maximum** outdoor pollution levels are also listed. Comparative concentration limits from Appendix A's Table 22 are given for context. Any values that exceed the comparative limit are in red.

Table 10: Maximum Indoor Particulate Matter PM2.5 and PM10 Concentrations at All Sites when Furnace is On and Off

MAXIMUMS Field Site	Regional PM2.5 ug/m3	PM2.5 Off ug/m3	PM2.5 On ug/m3	PM2.5 On-Off Difference %	PM10 Off ug/m3	PM10 On ug/m3	PM10 On-Off Difference %
Hayward 3	13.3	106.3	9.6	-91%	112.1	0.1	-100%
Hayward 4	13.3	132.0	7.9	-94%	151.2	8.2	-95%
LA 104	16.5	62.2	5.9	-91%	52.1	5.4	-90%
LA 105	14.7	26.3	33.8	29%	29.3	36.8	25%
LA 106	15.5	197.4	33.6	-83%	221.6	36.6	-83%
LA 107	15.8	22.5	13.3	-41%	83.4	38.0	-54%
Oak SF	8.7	44.3	29.6	-33%	48.7	31.1	-36%
Sacto 4	22.8	353.7	91.2	-74%	403.6	100.3	-75%
Sacto 15	19.4	119.9	25.3	-79%	121.0	25.5	-79%
Sacto 19	20.1	277.8	108.5	-61%	306.3	112.2	-63%
Average	**16.0**	**134.2**	**35.9**	**-73%**	**152.9**	**39.4**	**-74%**
Comparative Limit	**35 ug/m3 24 hour outside (NAAQS)**				**50 ug/m3 24 hour outside (CAAQS)**		

National Ambient Air Quality Standards (NAAQS) deem outdoor PM2.5 levels below 35 ug/m^3 acceptable for 24 hours, and California Ambient Air Quality Standards (CAAQS) deem PM10 levels below 50 ug/m3 to be acceptable for 24 hours. Maximum indoor PM2.5 concentrations exceeded outdoor levels at eight sites when furnaces were off, and at two sites when furnaces were on. Maximum indoor PM10 concentrations exceeded 24-hour outdoor level at eight sites when furnaces were off and two sites when furnaces were on. Maximum indoor PM2.5 and PM10 concentrations fell at all sites, except for LA 105, for net 73% and 74% decreases.

Average indoor concentrations of CO, NOx, PM2.5, and PM10 increased by 21%, 9%, 2% and 13% respectively when the furnaces were operating compared to when they were off, as shown in Table 7 and Table 8. Half the sites see average indoor pollutant increases when the furnaces run, either due to leaking of flue gas emissions into the space, drawing pollutants into the living room from other spaces, or stirring up existing pollutants via air circulation. The other half of the wall furnaces see average indoor pollutant levels decrease most likely because they draw air for combustion from the indoor space.

Maximum indoor concentrations of CO, NOx, PM2.5, and PM10 decreased by 46%, 52%, 73% and 74% respectively when the furnaces were operating, as shown in Table 9 and Table 10. Maximum concentrations decreased at all sites except Los Angeles 105. The wall furnaces significantly improve indoor air quality most likely by drawing air for combustion from the indoor space.

Baseline Wall Furnace Energy Use and Flue Gas Emissions

Natural gas use was not measured directly during field monitoring, the activation of the gas valve was monitored instead. Emissions in the flue gases were also not measured during field testing, although indoor air quality was monitored via sensors that measured various indoor pollutant concentrations. Instead, all the existing baseline wall furnaces were removed when field monitoring was complete, then shipped to GTI's Des Plaines office for laboratory testing. Laboratory measured values of natural gas use and flue gas concentrations are used to calculate energy use and emissions from the wall furnaces during field monitoring.

To determine the amount of natural gas used during field monitoring, active and standby gas flow rates are multiplied by the operating hours and standby hours for each wall furnace.

Natural gas use, Btu/day = Tested Btu/hr x Operating Hours/day + Pilot Btu/hr x Standby Hours/day

Standby Hours/day = Total Hours/day – Operating Hours/day

Natural gas use was measured in the laboratory during active furnace operation and standby when only the pilot light was operational, with gas pressure was held constant at 6.9 inches of water. Table 11 lists the natural gas input rates found for each baseline wall furnace during laboratory testing for use in the above natural gas use calculation.

Table 11: Laboratory Measurements of Baseline Furnace Natural Gas Use

Wall Furnace Tested				Natural Gas Input				Startup
Manufacturer	**Model**	**Field Sites**	**Age years**	**Rated Btu/hr**	**Tested Btu/hr**	**% Rated Input**	**Pilot Btu/hr**	**Minutes**
Perfection Produ	PW8G25SEN #1	Hayward 3	~40	25000	20280	81%	520	19.4
Perfection Produ	PW8G25SEN #2	Hayward 4	~40	25000	20210	81%	510	21.8
Williams	25GV-A1	LA 104	~35	25000	25100	100%	750	18.0
Williams	35GV-C #1	LA 105	~35	35000	31720	91%	520	17.8
Williams	35GV-C #2	LA 106	~35	35000	31800	91%	570	16.5
Williams	RMG35-IN	LA 107	~35	35000	31810	91%	500	17.7
Williams	5009622	Oak SF	~15	50000	44500	89%	1090	19.6
Holly General	35S-D #1	Sacto 4	40+	35000	31530	90%	720	22.4
Holly General	35S-D #2	Sacto 15	40+	35000	29110	83%	710	20.0
Williams	3509622	Sacto 19	~10	35000	33800	97%	1050	15.5
		Average	**32**	**33500**	**30000**	**89%**	**690**	**18.8**

Total flue gas emissions are found from the sum of emissions during standby, startup, steady state, and shutdown operations, as follows:

Standby Emissions lbm/day = [Standby hrs/day x Pilot Btu/hr x Standby Emission lbm/MMBtu]/(1000x1000)

Startup Emissions lbm/day = [Cycles/day x minimum (Cycle minutes **or** Avg Startup minutes) x Tested Btu/hr x Startup Emission lbm/MMBtu] / (60 x 1000 x 1000)

Steady state Emissions lbm/day = [Cycles/day x maximum (Cycle min - Avg Startup min) x Tested Btu/hr x Steady state Emission lbm/MMBtu] / (60 x 1000 x 1000)

Shutdown Emissions lbm/day = [Cycles/day x (1.5 minutes/60 x Pilot Btu/hr + 2 seconds/3600 x Tested Btu/hr) x Shutdown Emission lbm/MMBtu] / (1000 x 1000)

Total Emissions, lbm/day = Standby Emissions + Startup Emissions + Steady state Emissions + Shutdown Emissions

Table 12, Table 13, and Table 14 list the laboratory tested flue gas emissions from baseline furnaces during standby, startup, steady state, and shutdown modes of operation. These values are used in calculations to estimate emissions of the wall furnaces in the field.

Table 12: Laboratory Tested Carbon Monoxide Emissions of Baseline Wall Furnaces

Wall Furnace Tested			Carbon Monoxide, lbm/MMBtu			
Manufacturer	**Model**	**Field Sites**	**Standby**	**Startup**	**Steady State**	**Shutdown**
Perfection Products	PW8G25SEN #1	Hayward 3	0.459	0.005	0.001	0.314
Perfection Products	PW8G25SEN #2	Hayward 4	0.078	0.002	0.019	0.178
Williams	25GV-A1	LA 104	0.253	0.002	0.001	0.271
Williams	35GV-C #1	LA 105	0.190	0.018	0.063	0.175
Williams	35GV-C #2	LA 106	0.105	0.010	0.001	0.057
Williams	RMG35-IN	LA 107	0.183	0.012	0.001	0.059
Williams	5009622	Oakland SF	0.809	0.008	0.002	0.261
Holly General	35S-D #1	Sacramento 4	0.166	0.004	0.002	0.072
Holly General	35S-D #2	Sacramento 15	0.000	0.880	1.194	1.065
Williams	3509622	Sacramento 19	0.122	0.006	0.001	0.064
		Average	**0.237**	**0.095**	**0.128**	**0.251**

Table 13: Laboratory Tested Nitrogen Oxides Emissions of Baseline Wall Furnaces

Wall Furnace Tested			Nitrogen Oxides, lbm/MMBtu			
Manufacturer	**Model**	**Field Sites**	**Standby**	**Startup**	**Steady State**	**Shutdown**
Perfection Products	PW8G25SEN #1	Hayward 3	0.049	0.102	0.105	0.125
Perfection Products	PW8G25SEN #2	Hayward 4	0.021	0.095	0.133	0.309
Williams	25GV-A1	LA 104	0.009	0.105	0.108	0.890
Williams	35GV-C #1	LA 105	0.038	0.073	0.113	0.414
Williams	35GV-C #2	LA 106	0.032	0.076	0.071	0.061
Williams	RMG35-IN	LA 107	0.045	0.081	0.084	0.091
Williams	5009622	Oakland SF	0.037	0.103	0.106	0.077
Holly General	35S-D #1	Sacramento 4	0.036	0.088	0.093	0.045
Holly General	35S-D #2	Sacramento 15	0.028	0.012	0.012	0.031
Williams	3509622	Sacramento 19	0.058	0.115	0.121	0.107
		Average	**0.035**	**0.085**	**0.095**	**0.215**

Table 14: Laboratory Tested Hydrocarbon Emissions of Baseline Wall Furnaces

Wall Furnace Tested			Total Hydrocarbons, lbm/MMBtu			
Manufacturer	**Model**	**Field Sites**	**Standby**	**Startup**	**Steady State**	**Shutdown**
Perfection Products	PW8G25SEN #1	Hayward 3	0.126	0.001	0.000	1.889
Perfection Products	PW8G25SEN #2	Hayward 4	0.383	0.002	0.642	6.767
Williams	25GV-A1	LA 104	0.558	0.001	0.000	0.003
Williams	35GV-C #1	LA 105	0.012	0.001	0.009	0.097
Williams	35GV-C #2	LA 106	0.000	0.000	0.000	0.140
Williams	RMG35-IN	LA 107	0.448	0.025	0.000	0.000
Williams	5009622	Oakland SF	0.000	0.014	0.004	0.586
Holly General	35S-D #1	Sacramento 4	0.000	0.009	0.004	0.161
Holly General	35S-D #2	Sacramento 15	0.000	0.047	0.075	0.140
Williams	3509622	Sacramento 19	0.287	0.023	0.007	0.939
		Average	**0.181**	**0.012**	**0.074**	**1.072**

Table 15 lists calculated values of average daily natural gas use and flue gas emissions for the baseline wall furnaces during field monitoring. These values reflect **actual** occupant use.

Table 15: Average Daily Natural Gas Use and Flue Gas Emissions of Baseline Wall Furnaces during Field Monitoring (Actual Operation)

Wall Furnace Tested			Field Operation - Actual			Actual Daily Energy Use & Emissions			
Manufacturer	Model	Field Sites	Operating Hrs/Day	Cycles/Day	Cycle Minutes	Btu/Day	CO lbm/day	NOx lbm/day	THC lbm/day
Perfection Products	PW8G25SEN #1	Hayward 3	1.36	1.77	46.1	39345	0.0055	0.0034	0.0015
Perfection Products	PW8G25SEN #2	Hayward 4	0.55	0.92	35.9	23104	0.0010	0.0015	0.0081
Williams	25GV-A1	LA 104	0.07	0.30	13.8	19674	0.0045	0.0003	0.0100
Williams	35GV-C #1	LA 105	0.89	1.91	28.1	40312	0.0033	0.0029	0.0002
Williams	35GV-C #2	LA 106	0.34	1.52	13.5	24339	0.0015	0.0013	0.0000
Williams	RMG35-IN	LA 107	0.07	0.25	17.3	14241	0.0022	0.0007	0.0054
Williams	5009622	Oakland SF	0.67	1.08	37.2	55160	0.0207	0.0040	0.0003
Holly General	35S-D #1	Sacramento 4	1.41	1.73	48.8	60728	0.0028	0.0046	0.0003
Holly General	35S-D #2	Sacramento 15	2.18	3.77	34.6	78814	0.0642	0.0012	0.0032
Williams	3509622	Sacramento 19	2.17	4.18	31.3	96420	0.0030	0.0100	0.0078
		Average	**0.97**	**1.74**	**33.4**	**45214**	**0.0109**	**0.0030**	**0.0037**

Table 15 shows that the Sacramento apartment 19 furnace used the most natural gas due to both its high hours of operation and high rate of pilot gas use at 1050 Btu/hr. The LA 104 and LA 107 furnaces used the least natural gas because their operating hours were lowest.

There was a wide range of carbon monoxide emissions, from a low of 0.0010 lbm/day from the Hayward 4 furnace to a high of 0.0642 lbm/MMBtu from Sacramento 15. As shown in Table 12, the Sacramento 15 furnace demonstrated high CO emissions during startup, steady state, and shutdown indicating that its combustion was incomplete due to low air flow or poorly controlled natural gas flow.

The range of nitrogen oxides emissions spanned from a 0.0003 lbm/day at Los Angeles 104 to a high of 0.0100 lbm/day from Sacramento 19. While the rates of nitrogen oxides emissions for the Sacramento 19 furnace are not that high as listed in Table 13, this furnace operates on average for over 2 hours a day of with more than 4 cycles a day.

Total hydrocarbons were largest from Los Angeles 104 at 0.0100 lbm/day and smallest from LA 106 at essentially zero. The large hydrocarbon emissions for the Los Angeles 104 furnace are likely due to a small gas leak from the furnace, as evidenced by the high hydrocarbon emissions during standby as listed in Table 14. There are also high hydrocarbon emissions from the furnaces in Hayward 4, Sacramento 19, and LA 107. These furnaces may also have small natural gas leaks, but also appear to have incomplete combustion during steady state operation or at shutdown. Incomplete combustion is generally due to insufficient mixing of air and fuel or insufficient air supply to the flame.

To compare each furnace's energy use and emissions on their own, without accounting for occupant patterns of use, Table 16 lists **normalized** values of average daily natural gas use and flue gas emissions for the baseline wall furnaces. These values assume each furnace ran for 0.97 hours a day over 1.73 cycles, the average field operation found for all ten baseline furnaces.

Table 16: Average Daily Natural Gas Use and Flue Gas Emissions of Baseline Wall Furnaces during Field Monitoring (Normalized Operation)

Wall Furnace Tested			Field Operation - Normalized			Normalized Daily Energy Use & Emissions			
Manufacturer	Model	Field Sites	Operating Hrs/Day	Cycles/Day	Cycle Minutes	Btu/Day	CO lbm/day	NOx lbm/day	THC lbm/day
Perfection Products	PW8G25SEN #1	Hayward 3	0.97	1.73	33.6	31671	0.0056	0.0026	0.0016
Perfection Products	PW8G25SEN #2	Hayward 4	0.97	1.73	33.6	31372	0.0011	0.0024	0.0103
Williams	25GV-A1	LA 104	0.97	1.73	33.6	41648	0.0044	0.0028	0.0097
Williams	35GV-C #1	LA 105	0.97	1.73	33.6	42781	0.0035	0.0033	0.0002
Williams	35GV-C #2	LA 106	0.97	1.73	33.6	44010	0.0015	0.0027	0.0000
Williams	RMG35-IN	LA 107	0.97	1.73	33.6	42408	0.0023	0.0031	0.0056
Williams	5009622	Oakland SF	0.97	1.73	33.6	68319	0.0205	0.0054	0.0005
Holly General	35S-D #1	Sacramento 4	0.97	1.73	33.6	47202	0.0029	0.0033	0.0002
Holly General	35S-D #2	Sacramento 15	0.97	1.73	33.6	44622	0.0285	0.0008	0.0014
Williams	3509622	Sacramento 19	0.97	1.73	33.6	57006	0.0031	0.0053	0.0075
		Average	**0.97**	**1.73**	**33.6**	**45104**	**0.0073**	**0.0032**	**0.0037**

Table 16 shows that when operating hours are the same, aka normalized, the highest capacity Oakland furnace would use the most natural gas, and the smallest capacity Hayward furnaces would use the least. High standby pilot gas use can also be significant, increasing the Sacramento apartment 19 gas use to the highest of all the 35,000 Btu/hr furnaces due to its relatively high pilot gas use of 1050 Btu/hr.

There was a wide range of normalized carbon monoxide emissions, from a low of 0.0011 lbm/day from the Hayward 4 furnace to a high of 0.0285 lbm/MMBtu from Sacramento 15. As shown in Table 12, the Sacramento 15 furnace demonstrated high CO emissions during startup, steady state, and shutdown indicating that its combustion was incomplete due to low air flow or poorly controlled natural gas flow. These emission levels are enough to keep this furnace's CO emissions highest even when furnace operations are normalized.

The normalized range of nitrogen oxides emissions spanned from 0.0008 lbm/day from Sacramento 15 to 0.00054 lbm/day from the Oakland double-sided furnace. The relatively high NOx operating emissions in Table 13 combined with the highest rate of natural gas use as in Table 11 combine to make the Oakland furnace the highest emitter of nitrogen oxides.

Four furnaces have high normalized hydrocarbon emissions. Hayward 4, LA 104, Sacramento 19, and LA 107 emit 0.0103, 0.0097, 0.0075, and 0.0056 lbm/day of hydrocarbons respectively. Looking at Table 14, furnaces emit hydrocarbons during startup, steady state, and/or shutdown operations. High standby hydrocarbon emissions indicate a small natural gas leak. High hydrocarbon emissions during steady state and shutdown mean there is incomplete combustion, either due to insufficient air-fuel mixing or insufficient air supply to the flame.

Note that the existing baseline furnaces were serviced by HVAC technicians prior to field monitoring. Services included cleaning and vacuuming out the furnace internals, brushing the burner ports, installing new solenoid valves if needed, and relighting pilots. All the furnaces passed combustion safety checks before field monitoring commenced. After field monitoring, the furnaces were shipped to GTI Energy's Des Plaines laboratory for testing. The furnaces were not serviced prior to testing, but their natural gas connections were leak-checked before testing began. The baseline furnaces therefore represent typical existing furnaces after a standard tune-up.

Conclusion

Field monitoring and laboratory testing of ten baseline wall furnaces shows that their energy use, indoor air quality, and emissions depend on many interrelated factors. Some important factors are related to the furnace's specifications:

- Rated input capacity - Standard baseline furnace sizes are 25,000 Btu/hr and 35,000 Btu/hr for single-sided furnaces, and 50,000 Btu/hr for double-sided furnaces
- Age and rated thermal efficiency - Furnaces were 10 to 40+ years with rated thermal efficiencies of 50-74% and 67% on average

Some factors have to do with existing unit performance as compared to its specifications:

- Actual input capacity - Existing baseline wall furnaces were found during laboratory testing to deliver 20,000 to 45,000 Btu/hr, or 89% of their rated input capacity
- Pilot gas rate - Pilot energy use ranged from 500 to 1090 Btu/hr and 690 Btu/hr average in laboratory testing
- Startup Time - Wall furnace delivery temperatures and NOx emissions level off once steady state conditions are reached, but this time varies from 15 to 22 minutes

Other factors are associated with occupant preferences and furnace use:

- Climate zone and weather conditions - Average daily outdoor temperature lows were ~50°F Los Angeles, ~45°F Hayward and Oakland, and ~40°F in Sacramento
- Indoor temperature preferences - Average daily indoor temperatures of 60°F to 75°F
- Furnace operation - Wall furnaces are turned on and off manually when heat is wanted
- Cycling frequency and cycle length - Wall furnaces cycle infrequently at only 0.25 to 4.2 average cycles per day, and 13 to 49 average minutes per cycle

Wall Furnace Energy Use

Furnace heating energy use was calculated from laboratory measured input capacity multiplied by each furnace's field monitored hours of use. However, since these furnaces ran less than 2.2 hours a day, their standby energy use is also important. Table 17 shows that pilot energy use is responsible for 20% to 91% of the total wall furnace energy use. On average, pilot energy use accounts for 35% of the total baseline wall furnace energy use.

Table 17: Wall Furnace Energy Use from Field Monitoring and Laboratory Testing

Manufacturer	Model	Field Sites	Operating Hrs/Day	Tested Btu/hr	Pilot Btu/hr	Avg Heating Btu/day	Avg Pilot Btu/day	Heating %	Pilot %
Perfection Products	PW8G25SEN #1	Hayward 3	1.36	20,280	520	27,572	11,773	70%	30%
Perfection Products	PW8G25SEN #2	Hayward 4	0.55	20,210	510	11,146	11,959	48%	52%
Williams	25GV-A1	LA 104	0.07	25,100	750	1,725	17,948	9%	91%
Williams	35GV-C #1	LA 105	0.89	31,720	520	28,296	12,016	70%	30%
Williams	35GV-C #2	LA 106	0.34	31,800	570	10,854	13,485	45%	55%
Williams	RMG35-IN	LA 107	0.07	31,810	500	2,277	11,964	16%	84%
Williams	5009622	Oakland SF	0.67	44,500	1090	29,728	25,432	54%	46%
Holly General	35S-D #1	Sacramento 4	1.41	31,530	720	44,463	16,265	73%	27%
Holly General	35S-D #2	Sacramento 15	2.18	29,110	710	63,318	15,496	80%	20%
Williams	3509622	Sacramento 19	2.17	33,800	1050	73,503	22,917	76%	24%
		Average	**0.97**	**30,000**	**690**	**29,138**	**15,890**	**65%**	**35%**

Wall Furnace Effects on Indoor Air Quality

Before determining how much wall furnaces contribute to indoor air pollution, it is important to make three notes. First, monitoring included a single set of sensors near the wall furnace, not multiple sets throughout the indoor space. Second, dispersion of pollutants may lag furnace operation. Third, there are other sources of pollutants at all sites, including ranges and water heaters for CO and NOx plus general dust and dirt for PM2.5 and PM10. It is therefore difficult to know whether furnace operation is directly responsible for indoor pollutant level changes.

Indoor air quality was compared when the furnaces were off and on. Table 18 shows that **average** indoor concentrations of CO, NOx, PM2.5, and PM10 increased by 21%, 9%, 2% and 13% respectively when the furnaces were on compared to off. About half the sites saw average pollutant increases when the furnaces ran, the other half saw average indoor pollutant levels decrease. Conversely, **maximum** indoor concentrations of CO, NOx, PM2.5, and PM10 decreased by 46%, 52%, 73% and 74% respectively when the furnaces operated. Maximum concentrations decreased at all sites except Los Angeles 105.

Table 18: Average (top) and Maximum (bottom) Indoor Pollutants while Wall Furnaces Were in Standby/Off and Actively Heating/On

AVERAGES Field Site	CO Off ppmx10	CO On ppmx10	NOx Off ppb/10	NOx On ppb/10	PM2.5 Off ug/m3	PM2.5 On ug/m3	PM10 Off ug/m3	PM10 On ug/m3
Hayward 3	23.5	23.4	**32.3**	**30.9**	6.0	3.0	6.5	0.1
Hayward 4	9.8	12.4	**22.0**	**23.1**	5.9	3.1	6.5	3.2
LA 104	17.7	43.3	**24.8**	**45.2**	10.9	5.1	9.7	4.7
LA 105	24.2	23.9	2.8	**3.7**	26.3	33.8	29.3	36.8
LA 106	17.3	16.5	1.3	2.0	15.5	21.7	17.5	23.6
LA 107	31.2	31.4	**26.2**	**24.5**	12.8	13.3	15.0	38.0
Oak SF	4.2	5.5	**5.3**	**3.3**	5.7	9.4	6.2	10.1
Sacto 4	10.4	10.8	**49.4**	**47.7**	33.1	28.4	37.1	31.0
Sacto 15	9.3	10.8	1.8	2.4	10.2	9.1	10.3	9.1
Sacto 19	9.1	10.9	**7.9**	**7.5**	25.5	28.0	26.5	28.8
Average	**15.7**	**18.9**	**17.4**	**19.0**	**15.2**	**15.5**	**16.5**	**18.5**
Difference	--	**21%**	--	**9%**	--	**2%**	--	**13%**
Comparative Limit	**50-150 ppmx10 inside property adjusted (US EPA)**		**3.0 ppb/10 24 hour outside (CAAQS)**		**35 ug/m3 24 hour outside (NAAQS)**		**50 ug/m3 24 hour outside (CAAQS)**	

MAXIMUMS Field Site	CO Off ppmx10	CO On ppmx10	NOx Off ppb/10	NOx On ppb/10	PM2.5 Off ug/m3	PM2.5 On ug/m3	PM10 Off ug/m3	PM10 On ug/m3
Hayward 3	49.1	34.1	**93.3**	**57.2**	**106.3**	9.6	**112.1**	0.1
Hayward 4	43.2	20.1	**61.7**	**29.6**	**132.0**	7.9	**151.2**	8.2
LA 104	84.9	47.4	**117.8**	**48.0**	**62.2**	5.9	**52.1**	5.4
LA 105	24.2	23.9	2.8	3.7	26.3	33.8	29.3	36.8
LA 106	104.7	25.3	9.9	2.9	**197.4**	33.6	**221.6**	36.6
LA 107	50.9	31.4	**67.2**	**24.5**	22.5	13.3	**83.4**	38.0
Oak SF	12.5	7.4	**26.4**	7.5	**44.3**	29.6	48.7	31.1
Sacto 4	30.0	17.5	**138.5**	**74.2**	**353.7**	**91.2**	**403.6**	**100.3**
Sacto 15	29.9	19.5	6.5	4.1	**119.9**	25.3	**121.0**	25.5
Sacto 19	26.4	18.8	**24.3**	**13.3**	**277.8**	**108.5**	**306.3**	**112.2**
Average	**45.6**	**24.5**	**54.9**	**26.5**	**134.2**	**35.9**	**152.9**	**39.4**
Comparative Limit	**50-150 ppmx10 inside properly adjusted (US EPA)**		**18 ppb/10 1 hour outside (CAAQS)**		**35 ug/m3 24 hour outside (NAAQS)**		**50 ug/m3 24 hour outside (CAAQS)**	

The conclusion is that wall furnaces both worsen and ameliorate indoor air quality. Increases in average pollutant levels are likely because of some leaking of flue gas emissions but could also be due to the furnaces drawing pollutants from other spaces or stirring existing pollutants into the air. Decreases of indoor pollutants while the furnaces operate is most likely because these gravity furnaces draw air for combustion from the indoor space. Gravity wall furnace operation seems to help reduce maximum indoor pollutant concentrations, in particular.

Flue Gas Emissions of Wall Furnaces

Emission rates of carbon monoxide, nitrogen oxides, and hydrocarbons are highly variable from furnace to furnace, and have very different emission rates during standby, startup, steady state, or shutdown as listed in Table 12, Table 13, and Table 14. Summing up emissions during different operating modes, Table 19 lists the overall flue gas emission rates of the baseline wall furnaces. These were calculated from laboratory test results for the actual operation at each site, as well as for normalized operation of 0.97 hours and 1.74 cycles a day.

Table 19: Overall Flue Gas Emission Rates of Baseline Wall Furnaces during Actual and Normalized Operation

Wall Furnace Tested			Actual Emission Rates			Normalized Emission Rates		
Manufacturer	Model	Field Sites	CO lbm/MMBtu	NOx lbm/MMBtu	THC lbm/MMBtu	CO lbm/MMBtu	NOx lbm/MMBtu	THC lbm/MMBtu
Perfection Products	PW8G25SEN #1	Hayward 3	0.139	0.087	0.039	0.176	0.083	0.049
Perfection Products	PW8G25SEN #2	Hayward 4	0.045	0.064	0.351	0.034	0.076	0.327
Williams	25GV-A1	LA 104	0.231	0.018	0.509	0.106	0.067	0.232
Williams	35GV-C #1	LA 105	0.081	0.073	0.005	0.081	0.077	0.006
Williams	35GV-C #2	LA 106	0.063	0.051	0.000	0.035	0.061	0.000
Williams	RMG35-IN	LA 107	0.156	0.051	0.380	0.055	0.072	0.132
Williams	5009622	Oakland SF	0.376	0.073	0.005	0.301	0.079	0.007
Holly General	35S-D #1	Sacramento 4	0.047	0.076	0.005	0.061	0.071	0.005
Holly General	35S-D #2	Sacramento 15	0.814	0.015	0.040	0.639	0.018	0.031
Williams	3509622	Sacramento 19	0.032	0.104	0.081	0.054	0.093	0.131
		Average	**0.241**	**0.066**	**0.082**	**0.163**	**0.070**	**0.082**

It is interesting to note that no single furnace had the highest emission rates for all three pollutants. Conversely, no furnace had the lowest emission rates across all three pollutants.

Five furnaces had high to moderate CO emission rates: Sacramento 15, Oakland SF, LA 104, LA 107, and Hayward 3 had actual CO emissions of 0.814, 0.376, 0.231, 0.156, and 0.138 lbm/MMBtu respectively. The five remaining furnaces had actual emission rates below about 0.8 lbm/MMBtu. Normalized CO emissions were still above ~0.8 lbm/MMBtu on four furnaces, Sacramento 15, Oakland SF, Hayward 3, and LA 104. This reflects the complicated effects that operating hours and cycle lengths have on furnace emissions. There are no standards or limits on CO emission rates for comparison.

Almost all the baseline furnaces have relatively high nitrogen oxides emissions, about double the 0.033 lbm/MMBtu NOx limit for central furnace emissions being enforced by SCAQMD and SJVAPCD (see Appendix B). Only the Sacramento 15 furnace stays below this limit during both actual and normalized operation. The LA 104 furnace stays below this limit during actual operating conditions only because it was used so infrequently.

Three furnaces had high to moderate hydrocarbon emission rates: LA 104, LA 107, and Hayward 4 had actual HC emissions of 0.509, 0.380, and 0.351 lbm/MMBtu respectively. The seven remaining furnaces had actual emission rates below about 0.8 lbm/MMBtu. Normalized HC emissions were also moderately high for Sacramento 19 due higher standby HC emissions.

Summary and Next Steps

These field monitoring results show how complicated it is to estimate baseline wall furnace energy use, indoor air quality, and flue gas emissions. From this sample of ten furnaces, the average existing baseline furnace in California has the following characteristics:

- Actual input capacity: 30,000 Btu/hr
- Pilot energy use: 690 Btu/hr
- Operation: 1 hour a day, 1.75 cycles a day for 34 minutes per cycle
- Daily energy use: 45,000 Btu, 35% of which is from standby pilot gas use
- Indoor air quality: increases average indoor pollution levels by about 10%; decreases maximum indoor pollution levels by about 60%
- Flue gas emission rates: 0.20 lbm/MMBtu of carbon monoxide, 0.07 lbm/MMBtu of nitrogen oxides (twice the 0.033 lbm/MMBtu SCAQMD limit for central furnaces), and 0.08 lbm/MMBtu of total hydrocarbons

In next steps associated with the project, the field monitoring results documented in this study are used together with laboratory testing results to perform additional estimates of energy use and emissions for this sample of baseline wall furnaces. Comparisons will be made with retrofit wall furnace laboratory testing and field monitoring to estimate energy savings, indoor air quality improvements, and emissions reductions of more efficient wall furnaces.

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References

ANSI Z21.49 1995. ANSI Z21.49 – Gas-Fired Gravity and Fan Type Vented Wall Furnaces. https://standards.globalspec.com/std/119007/ansi-z21-49. American National Standards Institute.

ANSI Z21.86 2016. ANSI Z21.86-2016/CSA 2.32-2016 - Vented Gas-Fired Space Heating Appliances. https://webstore.ansi.org/Standards/CSA/ANSIZ21862016CSA32. American National Standards Institute.

CARB 2022. Air Quality Data (PST) Query Tool, Special Reports Tab. https://www.arb.ca.gov/aqmis2/aqdselect.php?tab=specialrpt.

CARB CO 2022. Carbon Monoxide & Health. https://ww2.arb.ca.gov/resources/carbon-monoxide-and-health. California Air Resources Board.

CARB NOx 2022. Nitrogen Dioxide & Health. https://ww2.arb.ca.gov/resources/nitrogen-dioxide-and-health. California Air Resources Board.

CARB PM 2022. Inhalable Particulate Matter and Health (PM2.5 and PM10). https://ww2.arb.ca.gov/resources/inhalable-particulate-matter-and-health. California Air Resources Board.

CFR 430.32 (i)(1) 2022. Code of Federal Regulations Title 10 Chapter II Subchapter D part 430 Subpart C Section 430.32 (i) (1) Energy and water conservation standards and their compliance dates, Vented home heating equipment manufactured on or after January 1, 1990 and before April 16, 2013. https://www.ecfr.gov/current/title-10/chapter-II/subchapter-D/part-430/subpart-C/section-430.32. National Archives.

CFR 430.32 (i)(2) 2022. Code of Federal Regulations Title 10 Chapter II Subchapter D part 430 Subpart C Section 430.32 (i) (2) Energy and water conservation standards and their compliance dates, Vented home heating equipment manufactured on or after April 16, 2013. https://www.ecfr.gov/current/title-10/chapter-II/subchapter-D/part-430/subpart-C/section-430.32. National Archives.

CFR 60.5474 (b)(4) 2022. Code of Federal Regulations Title 40 Chapter I Subchapter C Part 60 Subpart QQQQ 60.5474 (b) (4) What standards and requirements must I meet and by when? 2016 small forced-air furnace particulate matter emission limit. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-60/subpart-QQQQ. National Archives.

CFR 60.5474 (b)(6) 2022. Code of Federal Regulations Title 40 Chapter I Subchapter C Part 60 Subpart QQQQ 60.5474 (b) (6) What standards and requirements must I meet and by when? 2020 forced-air furnace particulate matter emission limit. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-60/subpart-QQQQ. National Archives.

NOAA 2022. Data Tools: Local Climatological Data (LCD). https://www.ncdc.noaa.gov/cdo-web/datatools/lcd. National Oceanic and Atmospheric Administration.

SCAQMD 2021. Rule 1111. Reduction of NOx Emissions from Natural-Gas Fired, Fan-Type Central Furnaces, http://www.aqmd.gov/docs/default-source/rule-book/reg-xi/rule-1111.pdf. South Coast Air Quality Management District.

SJVAPCD 2020. Rule 4905 Natural Gas-Fired, Fan-Type Central Furnaces. https://www.valleyair.org/rules/currntrules/Rule4905.pdf. San Joaquin Valley Air Pollution Control District.

US EPA CO 2022. Carbon Monoxide's Impact on Indoor Air Quality. https://www.epa.gov/indoor-air-quality-iaq/carbon-monoxides-impact-indoor-air-quality. US Environmental Protection Agency.

US EPA Indoor PM 2022. Indoor Particulate Matter. https://www.epa.gov/indoor-air-quality-iaq/indoor-particulate-matter. US Environmental Protection Agency.

US EPA NAAQS 2022. National Ambient Air Quality Standards Tables. https://www.epa.gov/criteria-air-pollutants/naaqs-table, US Environmental Protection Agency.

US EPA NOx 2022. Nitrogen Dioxide's Impact on Indoor Air Quality. https://www.epa.gov/indoor-air-quality-iaq/nitrogen-dioxides-impact-indoor-air-quality. US Environmental Protection Agency.

Project Deliverables

The following project deliverables, including interim project reports, are available upon request by submitting an email to ERDDpubs@energy.ca.gov:

- Baseline Wall Furnace Laboratory Test Report – Improving the Performance of Wall Furnaces in California
- Retrofit Wall Furnace Laboratory Test Report – Improving the Performance of Wall Furnaces in California
- Baseline Wall Furnace Field Monitoring Report – Improving the Performance of Wall Furnaces in California
- Retrofit Wall Furnace Field Monitoring Report – Improving the Performance of Wall Furnaces in California
- Wall Furnace Technology Transfer Report – Improving the Performance of Wall Furnaces in California
- Final Wall Furnace Report – Improving the Performance of Wall Furnaces in California

Appendix A:
Related Efficiency, Emissions, and Indoor Air Quality Information

Wall Furnace Characteristics

A wall furnace is a compact device used to heat one or two rooms. Because they are less expensive, simpler to install, and take up less space than a central ducted furnace, they are used in multifamily apartment complexes and smaller single-family homes.
Wall furnaces are typically installed within the stud cavity of an interior wall. They exhaust combustion gases through a flue stack running vertically up to a roof penetration. They use continuously operating pilot lights to fire the main burner when there is a call for heating, and usually do not even need an electrical connection.

Wall furnaces are categorized by how they distribute heat, where their combustion air comes from, how they ignite the burner, and whether they use condensing technology.
Heated air from wall furnaces can be distributed in two ways. **Gravity** furnaces heat the air around the furnace, causing it to rise and distribute itself throughout a space naturally. This gravity-induced air flow can be supplemented by a booster fan, with the fan separately connected to AC power. **Fan-type** wall furnaces integrate a fan directly into the wall furnace unit to distribute heated air. The energy used by these fans can vary from 0.8 to 5 amps of single-phase AC current at 120 V depending on the capacity of the wall furnace and the efficiency of the fan.

Wall furnace combustion air is also handled in two ways. A **vented** or **top vent furnace** draws combustion air from inside the house, then exhausts combustion gases directly to the outside. This furnace is located between the studs of an interior wall, and exhaust gases are sent through a flue of six or eight inches in diameter that travels vertically through the wall cavity to the roof. In contrast, **direct vent** furnaces draw combustion air from outside. They are placed in an outside wall to keep their intake ducts short, although they can be installed in an inside wall by using the proper duct extensions. Exhaust gases can also be sent outside horizontally through the wall or vertically through the wall cavity to the roof.

Three different technologies exist to ignite wall furnaces. The oldest and least efficient ignition technology is a **standing pilot**. This device uses a small burner that stays lit continually, ready to ignite the main burner whenever there is a call for heating. The standing pilot stays on by heating a thermopile which sends current to keep the pilot gas valve open. If the pilot goes out the thermopile cools off and stops sending current, and the pilot gas will stop flowing. An **intermittent pilot**, developed after the oil crisis of the 1970s, is lit only when a call for heating is made. The intermittent pilot uses an electronic spark to first light a pilot flame and then the pilot flame lights the main burner. Use of an intermittent pilot is said to reduce furnace energy use by about 5% on average. A **hot surface igniter** also uses electricity to light the furnace, but it lights the burner directly by heating a silicon nitride ceramic probe to 2000-2500°F. While heating up, the hot surface igniter draws 2 to 4 amps of current at 120 V.

While standard furnaces vent hot combustion gases outside, **condensing** furnaces run combustion air through a heat exchanger to heat incoming air. This cools the exhaust to temperatures under 100°F so that its water vapor condenses into a liquid. Condensing furnaces must be connected to drains so the condensate water is removed from the building. Additionally, furnaces can be either **single-sided** to serve just one room, or **double-sided** to serve rooms on either side of the wall in which it is installed.

Wall Furnace Efficiency Standards

From 1982 through 1995, wall furnaces were regulated under ANSI Z21.49 for Gas-Fired Gravity and Fan Type Vented Wall Furnaces (ANSI Z21.49 1995). In 1996, ANSI Z21.49 was made inactive and ANSI Z21.86 for Vented Gas-Fired Space Heating Appliances (ANSI Z21.86 2016) became the regulating standard for wall furnaces. This standard was most recently updated in 2016.

Both the Z21.49 and Z21.86 standards mandated that wall furnace nameplates list their input and output capacity based on standard test methods. The latest Z21.86 standard mandates for thermal efficiency (output capacity divided by input capacity) are listed in Table 20. The date when when these minimum thermal efficiency standards were first introduced was unable to be confirmed, but they were probably part of the ANZI Z21.49-1986 update.

Table 20: Minimum Wall Furnace Thermal Efficiency Requirement from ANSI Z21.86-2016

	Gravity Wall Furnaces	**Fan-Type Wall Furnaces**
Minimum Thermal Efficiency	70%	75%

In addition, minimum Annual Fuel Utilization Efficiency (AFUE) levels for wall furnaces are mandated under the Code of Federal Regulations for furnaces manufactured after 1990 (CFR 430.32 (i) (1) 2022) and furnaces manufactured after 2013 (CFR 430.32 (i) (2) 2022). Table 21 lists the current minimum AFUE requirements for new wall furnaces. AFUE minimums were raised by at least 2% for furnaces manufactured after 2013.

Table 21: Minimum AFUE Requirements for Wall Furnaces manufactured after January 1, 1990 and April 16, 2013

<table>
<tr><th>Furnace Type</th><th>Input Capacity</th><th>AFUE 1990</th><th>AFUE 2013</th></tr>
<tr><td>Gas Wall Gravity</td><td>up to 10,000 Btu/hr</td><td>59%</td><td rowspan="5">65%</td></tr>
<tr><td>Gas Wall Gravity</td><td>over 10,000 up to 12,000 Btu/hr</td><td>60%</td></tr>
<tr><td>Gas Wall Gravity</td><td>over 12,000 up to 15,000 Btu/hr</td><td>61%</td></tr>
<tr><td>Gas Wall Gravity</td><td>over 15,000 up to 19,000 Btu/hr</td><td>62%</td></tr>
<tr><td>Gas Wall Gravity</td><td>over 19,000 up to 27,000 Btu/hr</td><td>63%</td></tr>
<tr><td>Gas Wall Gravity</td><td>over 27,000 up to 46,000 Btu/hr</td><td>64%</td><td>66%</td></tr>
<tr><td>Gas Wall Gravity</td><td>over 46,000 Btu/hr</td><td>65%</td><td>67%</td></tr>
<tr><td>Gas Wall Fan-Type</td><td>up to 42,000 Btu/hr</td><td>73%</td><td>75%</td></tr>
<tr><td>Gas Wall Fan-Type</td><td>over 42,000 Btu/hr</td><td>74%</td><td>76%</td></tr>
</table>

Thermal efficiency and AFUE are both measures of a furnace's efficiency, but they represent different furnace operations. Thermal efficiency represents the full-load performance of a system, while AFUE represents the performance over a typical range of operating conditions. Many of the baseline furnaces in this study were manufactured before AFUE ratings were required. While all rated and tested AFUE values are reported, furnace efficiency comparisons rely mostly on thermal efficiency values.

Wall furnaces are located inside the building envelope, and all top vent furnaces use indoor air for combustion. This means that their performance tends to stay relatively constant under different weather conditions as compared to furnaces that sit in unconditioned or semi-conditioned spaces. It also means that laboratory-measured efficiencies should be fairly good job of predicting actual efficiency of wall furnaces as they operate in the field.

Related Emissions and Indoor Air Quality Guidelines

Like all gas burning equipment, even properly operating wall furnaces produce low levels of CO, NOx, and particulate matter emissions. As with all primary gas space heating equipment in the state of California, emissions must be vented to the outside to prevent the accumulation of indoor pollutants.

There are no federal or California limits on flue gas emissions or indoor pollutants generated by wall furnaces. However, the Code of Federal Regulations limits particulate matter emissions from wood-burning residential forced-air furnaces. Residential forced-air furnaces are defined for this standard as fuel burning devices designed to burn wood or wood pellet fuel that warms a space other than the space where the furnace is located. Wall furnaces do not meet this definition because they burn natural gas, and because heat the space where they are installed.

For reference, forced-air furnaces manufactured after May 16, 2015 were required to emit no more than 0.93 lbm/MMBtu of particulate matter (CFR 60.5474 (b) (4) 2022), defined as the total of PM2.5 and PM10 particles. This limit was lowered to 0.15 lbm/MMBtu in total particulate matter for forced-air furnaces manufactured after May 15, 2020 (CFR 60.5474 (b) (6) 2022).

In California, the South Coast Air Quality Management District (SCAQMD) and the San Joaquin Valley Air Pollution Control District (SJVAPCD) limit NOx emissions from natural gas-fired fan-type central furnaces distributed or sold in their territories. These standards do not specifically define a central furnace. It is typically a furnace that heats air in one place and circulates it through ducts to other places, so these rules do not apply to wall furnaces. For reference, both the SCAQMD Rule 1111 (SCAQMD 2021) and SJVAPCD Rule 4905 (SJVAPCD 2020) require furnaces to keep NOx emissions, on a basis of NO2, below 14 ng/Joule (0.033 lbm/MMBtu).

The US Environmental Protection Agency does not regulate indoor air quality, but they have characterized typical levels of carbon monoxide found in homes (US EPA CO 2022). They have not agreed upon standards for nitrogen oxides (US EPA NOx 2022) or particulate matter (US EPA PM 2022) within homes but have laid out acceptable levels for these pollutants in outside air over different time periods.

The US Environmental Protection Agency has developed guidelines for outdoor air quality, the National Ambient Air Quality Standards (US EPA NAAQS 2022), with acceptable limits of outdoor air pollutants in terms of averages over different time periods. The California Air Resources Board has also developed standards for outdoor air quality that are sometimes more stringent than federal standards, the California Ambient Air Quality Standards (CARB CO 2022, CARB NOx 2022, CARB PM 2022).

Table 22 summarizes the regulations, standards, and guidelines for residential furnaces and indoor air quality, as well as some outdoor air pollution standards. Although none of these standards applies to wall furnaces, they serve as reference values for this project's emissions and indoor air quality analyses. Note that no regulations, standards, or guidelines were identified that help characterize hydrocarbon emissions.

Table 22: Emissions and Indoor Air Quality Regulations, Standards and Guidelines

Rule	Equipment	CO	NOx	PM2.5 & PM10
Code of Federal Regulation (CFR)	Residential forced-air furnaces, wood-burning	n/a	n/a	0.93 lbm/MMBtu, 2015 0.15 lbm/MMBtu, 2020
SCAQMD Rule 1111 & SJVAPCD Rule 4905 (SCAQMD)	Central furnaces	n/a	0.033 lbm/MMBtu (14 nanograms/Joule)	n/a
US EPA reference levels of typical indoor air pollutants (US EPA)	Indoor air quality in homes	0 - 5 ppm normal 5 - 15 ppm near properly adjusted gas stove 30 ppm or more near improperly adjusted gas stoves	n/a	n/a
National Ambient Air Quality Standards (NAAQS)	Outside air	9 ppm 8 hours 35 ppm 1 hour	100 ppb 1 hour 53 ppb 24 hours	PM2.5 35 ug/m^3 24 hours PM10 150 ug/m^3 24 hours
California Ambient Air Quality Standards (CAAQS)	Outside air	9 ppm 8 hours 20 ppm 1 hour	180 ppb I hour 30 ppb 24 hours	PM2.5 none 24 hours PM10 50 ug/m3 24 hours