CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

INTERIM PROJECT REPORT

Improving the Performance of Wall Furnaces in California

Retrofit Wall Furnace Laboratory Test Report

Agreement Number: PIR-18-005

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Month Year | CEC-500-XXXX-XXX

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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

It is estimated that there 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 and may not have safety switches to prevent the furnaces from overheating. The oldest existing furnaces have rated thermal efficiencies of 50% while most standard replacement wall furnaces have rated thermal efficiencies of 70%.

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

This interim report documents laboratory test results for more efficient retrofit wall furnaces. Other interim reports for this project document field monitoring of these retrofit furnaces, and laboratory testing and field monitoring results of existing 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 the results of retrofit wall furnace laboratory testing to characterize the energy use, efficiency, and flue gas emissions of recently developed efficient wall furnaces. Other reports document results of field monitoring of these retrofit wall furnaces, and the laboratory testing and field monitoring results of existing baseline wall furnaces.

This project tested five retrofit wall furnaces which came directly from the manufacturer, Williams Comfort Products:

- One Williams 1753012 – direct vent, fan-type, condensing wall furnace with a hot surface igniter and a two-stage heat exchanger, rated at 17,500 Btu/hr, 94% thermal efficiency, and 93% AFUE
- Two Williams AC2030TN – top vent, fan-type, single-sided, low NOx wall furnace with an intermittent pilot, rated at 30,000 Btu/hr, 85% thermal efficiency, 82% AFUE
- One Williams AC3040TN – top vent, fan-type, double-sided low NOx wall furnace with an intermittent pilot, rated at 40,000 Btu/hr, 83% thermal efficiency, 82% AFUE

- One Williams TG2030TN – top vent, fan-type, single-sided, low NOx wall furnace with an intermittent pilot, powered by a rechargeable battery, rated at 30,000 Btu/hr, 82% thermal efficiency, 80% AFUE.

Key Results

Table 1 lists the rated and measured natural gas flows of each wall furnace, and their electrical power draw. All of these furnaces used more natural gas than their rated input, for an average 109% of rated input. None of these furnaces has a standing pilot, so their pilot gas use was zero. The Williams 1753012 condensing furnace used the most electricity during active heating and standby. The Williams AC2030TN furnaces drew about 12.5 watts only while active, and the AC3040TN furnace drew 12.5 watts all the time. The TG2030TN furnace was self-powered by a rechargeable battery, so did not draw any electrical power.

Table 1: Retrofit Wall Furnace Natural Gas Input and Electrical Power

Wall Furnace Tested		Natural Gas Input				AC Power	
Model	Field Sites	Rated Btu/hr	Tested Btu/hr	% Rated Input	Pilot Btu/hr	Active W	Standby W
1753012 (condensing direct vent)	Hayward 3 & 4	17500	19790	113%	0	100.1	0.0
AC2030TN #1 (single-sided low NOx)	LA 104-107	30000	34580	115%	0	12.5	0.0
AC2030TN #2 (single-sided low NOx)	LA 104-107	30000	31780	106%	0	12.6	0.1
AC3040TN (double-sided low NOx)	Oakland SFH	40000	41720	104%	0	12.4	0.0
TG2030TN (self-powered low NOx)	Sacto 4, 15 & 19	30000	31410	105%	0	0.0	0.0
	Average	**29500**	**31856**	**109%**	**0**	**27.5**	**0.0**

Table 2 lists the rated and test-derived thermal efficiency and AFUE for each unit. All of these furnaces exceeded the 75% minimum thermal efficiency required by the American National Standards Institute regulations (ANSI Z21.86 2016) for fan-type wall furnaces. They also exceeded the minimum AFUE required by the Code of Federal Regulations (CFR 430.32 2022), 75% and 76% for furnaces below and above 42,000 Btu/hr rated input. However, all efficiencies derived from these laboratory tests were lower than their rated efficiencies, with thermal efficiency 3.8% lower and AFUE 3.1% lower on average.

Table 2: Retrofit Wall Furnace Thermal Efficiency and AFUE

Wall Furnace Tested		Thermal Efficiency		AFUE	
Model	Field Sites	Rated TE	Tested TE	Rated AFUE	Tested AFUE
1753012 (condensing direct vent)	Hayward 3 & 4	94%	89.5%	93%	88.0%
AC2030TN #1 (single-sided low NOx)	LA 104-107	85%	81.8%	82%	80.4%
AC2030TN #2 (single-sided low NOx)	LA 104-107	85%	81.2%	82%	79.9%
AC3040TN (double-sided low NOx)	Oakland SFH	83%	79.0%	80%	77.8%
TG2030TN (self-powered low NOx)	Sacramento 4, 15 & 19	82%	78.5%	80%	77.3%
	Average Retrofit	**87.0%**	**83.0%**	**85.2%**	**81.7%**

Table 3 lists preliminary energy use and emissions for each wall furnace. This is based on a typical day of operation as found during field testing of retrofit units, where the furnace cycles 1.0 times a day for 42 minutes per cycle and remains in standby for the rest of the day.

Table 3: Retrofit Wall Furnace Energy Use and Emission Rates for a Typical Day of Operation

Wall Furnace Tested		Average Energy Use and Emission Rates				
Model	**Field Sites**	**Btu/Day**	**kWh/Day**	**CO lbm/MMBtu**	**NOx lbm/MMBtu**	**THC lbm/MMBtu**
1753012 (condensing direct vent)	Hayward 3 & 4	13853	0.070	0.021	0.086	0.001
AC2030TN #1 (single-sided low NOx)	LA 104-107	24206	0.009	0.028	0.015	0.170
AC2030TN #2 (single-sided low NOx)	LA 104-107	22246	0.011	0.127	0.012	0.010
AC3040TN (double-sided low NOx)	Oakland SFH	29204	0.009	0.270	0.039	0.018
TG2030TN (self-powered low NOx)	Sacto 4, 19	21987	0.000	0.031	0.013	0.006
	Average	**22299**	**0.020**	**0.096**	**0.033**	**0.041**

Not surprisingly, the largest capacity Williams AC3040TN furnace is estimated to use the most natural gas, and the smallest capacity Williams 1753012 furnace would use the least natural gas. The 1753012 furnace also uses the most electricity.

As for flue gas emissions:

- The Williams AC3040TN furnace had the highest CO emission rate due to relatively high CO emissions during steady state operation.
- The Williams 1753012 condensing furnace had the highest NOx emissions of these retrofit furnaces, due to high NOx emissions during steady state heating operation. The other three retrofit models were all low NOx furnaces, and substantial effort from the manufacturer appears to have gone into reducing their NOx emissions.
- The AC2030TN #1 furnace had a high total hydrocarbon emission rate, while the AC2030TN #2 furnace had low hydrocarbon emissions. The #1 furnace appears to have had a small natural gas leak which may be representative of leaks in actual installations.

There are no standards or regulations for emissions from wall furnaces. However, as detailed in Appendix A, the South Coast Air Quality Management District and the San Joaquin Valley Air Pollution Control District require central furnaces to keep nitrogen oxide emissions below 0.033 lbm/MMBtu. The AC2030TN and TG2030TN furnaces stay below this limit, while the AC3040TN furnace just exceeds the NOx limit. The 1753012 condensing furnace has an NOx emission rate that is 2.5 times the limit.

Knowledge Transfer and Next Steps

The laboratory results documented in this study will be combined with results from the field monitoring to make more detailed estimates of the energy use and emissions of these retrofit wall furnaces. Similar laboratory testing and field monitoring will be done to characterize the performance of existing baseline wall furnaces. Baseline and retrofit data will then be used to estimate the energy savings and emission reduction potential of more 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 a small number of rooms. Because they are less expensive, simpler to install, and take up less space than a central ducted furnace, they are commonly 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 Title 10 2022. (i) (1) and [CFR Title 10 2022. (i) (2)]. 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 project tested five retrofit wall furnaces which came directly from the manufacturer, Williams Comfort Products:

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- Two Williams AC2030TN – top vent, fan-type, single-sided, low NOx wall furnace with an intermittent pilot, rated at 30,000 Btu/hr, 85% thermal efficiency, 82% AFUE
- One Williams AC3040TN – top vent, fan-type, double-sided low NOx wall furnace with an intermittent pilot, rated at 40,000 Btu/hr, 83% thermal efficiency, 82% AFUE
- One Williams TG2030TN – top vent, fan-type, single-sided, low NOx wall furnace with an intermittent pilot, powered by a rechargeable battery, rated at 30,000 Btu/hr, 82% thermal efficiency, 80% AFUE.

Laboratory testing involved running the furnaces through a protocol that included standby, startup, steady state, and shutdown operation while measuring:

- Inlet, outlet, and exhaust temperatures of the wall furnaces
- Carbon monoxide, nitrogen oxide, and total hydrocarbon flue gas emissions
- Natural gas flow rates

In other project work, these test results will be applied to field monitoring data for these furnaces to estimate their energy use and emissions. Existing baseline furnaces will also be laboratory tested and field monitored as part of this project. Comparisons of baseline and retrofit energy use and emissions will be made to evaluate the savings that can be realized through the installation of more efficient retrofit furnaces.

Project Approach

Laboratory testing was conducted within the Residential and Commercial Equipment laboratory on the Des Plaines, IL GTI Energy campus. Wall furnace tests included measurement of intake, burner and exhaust temperatures, natural gas, electricity, and exhaust gas emission levels.

Furnaces Tested

This project tested a total of five retrofit wall furnaces which came directly from the manufacturer, Williams Comfort Products. The characteristics of each retrofit furnace are presented in Table 1. Additional furnace samples were also installed for monitoring at field sites (see Retrofit Wall Furnace Field Monitoring Report).

Table 1: Laboratory Tested Retrofit Wall Furnace Characteristics

Field Sites	Manufacturer	Model	Input Btu/hr	Thermal Efficiency	Rated AFUE	Features
Hayward 3 & 4	Williams	1753012	17,500	94%	93%	• Direct Vent • Condensing • Hot Surface Igniter • 2 Stage Heat Exchanger • Fan-Type w/AC Power
Los Angeles 104-107	Williams	AC2030TN #1 & #2	30,000	85%	82%	• Top Vent • Intermittent Pilot • Fan-Type w/AC Power • Low NOx emissions • Single-Sided • Traditional Form Factor
Oakland SFH	Williams	AC3040TN	40,000	83%	80%	• Top Vent • Intermittent Pilot • Fan-Type w/AC Power • Low NOx emissions • Double-Sided • Traditional Form Factor
Sacra-mento 4, 15 & 19	Williams	TG2030TN	30,000	82%	80%	• Top Vent • Intermittent Pilot • Fan-Type w/Battery • Low NOx emissions • Traditional Form Factor

The Williams AC2030TN, AC3040TN, and TG2030TN furnaces shown in Figure 1 are all top vent furnaces with traditional form factors. These furnaces are drop-in replacements for older wall furnaces and are usually installed on inside walls. They draw combustion air from the indoors then vent it through a vertical flue to the roof. They are also all "low NOx" furnaces, which means their combustion is carefully controlled to reduce nitrogen oxides emissions.

Figure 1: High Efficiency Williams Wall Furnaces Tested in this Project from left to right: 1753012, AC2030TN, AC3040TN, TG2030TN

The AC2030TN and AC3040TN furnaces must also be connected single-phase AC power to run their fans. The TG2030TN furnace is self-powered and uses a rechargeable battery to operate the fans.

The Williams 1753012 furnace, shown on the left of Figure 1, is a direct vent condensing furnace with a different form factor than the typical tall, skinny wall furnaces. It is usually installed in an outside wall for easier access to outside air for combustion, but can be installed on an inside wall if the appropriate ducting to the outside is used. It must also have access to a drain through which to channel condensate water. This furnace must also be connected to single-phase AC power to operate its fan. Note that although this condensing furnace is very efficient, it is not a "low NOx" furnace like the other retrofit furnaces being tested, so it is expected it will have higher nitrogen oxides emissions than the rest of the retrofit furnaces.

Laboratory testing included measurement of furnace natural gas flow, electricity use, operating temperatures, and concentrations of carbon monoxide (CO), nitrogen oxides (NOx), and total hydrocarbons (THC) in exhaust gases. The testing protocol covered furnace operation during standby, startup, steady state, and shutdown. Parameters derived from measurements include each furnace's input capacity and pilot gas use, efficiency, and pollutant emission rates

Measurements and Test Equipment

The following table details the measurement equipment used in the laboratory.

Table 4: Laboratory Test Equipment

Measurement	Description	Range, Accuracy
Flow-Field Temperatures	1/8″ J-type exposed bead thermocouple	32-1328ºF/0-750ºC, ±2.2ºC
Ambient Temperature	1/8″ J-type exposed bead thermocouple	32-1328ºF/0-750ºC, ±2.2ºC
Ambient Humidity	Omega OM-HL-SH-EX	0-100%RH, ±5%RH
Data Acquisition Modules	National Instruments CompactDAQ	-
Stack O_2	Horiba PG350	Span 25% O_2, ±1%
Stack CO_2	Horiba PG350	Span 25% CO_2, ±1%
Stack NO_x	Horiba PG350	Span 100 ppm, , ±1%
Stack CO	Horiba PG350	Span 500 ppm, ±1%
Stack THC	Rosemount Analytical 400A	Span 1000 ppm, 0.5ppm
Gas Flow Rate	American Meter AC250	8 pulses/ft^3

While the furnaces were not installed into a wall assembly designed to mimic a typical internal wall cavity, GTI Energy's Des Plaines laboratory technicians followed all other ANSI Z21.86 test protocols for measurement of temperatures, exhaust gas emissions, and natural gas flow.

Inlet temperatures were measured using a thermocouple in the center of the furnace inlet grill at the bottom of each furnace.

Exhaust air temperatures were measured approximately three inches from the combustion air outlet using a probe inserted into the exhaust air duct, with three thermocouples to measure temperatures across the duct span.

Burner outlet temperature measurements were recorded using an array of nine equally spaced thermocouples, following the dimensions outlined in section 11.6.1 of ANSI Z21.86 (ANSI Z21.86 2016) to ensure an average reading in the case of a heterogeneous flow field. The burner thermocouple array was attached to the center of the burner outlet to measure temperatures of the heated air leaving the furnace.

A continuous measurement of exhaust constituents, including oxygen (O_2), carbon dioxide (CO_2) carbon monoxide (CO), nitrogen oxides (NO_X), and unburned total hydrocarbons (THC) were measured and reported on a dry basis. Emission measurements were made through a system of three 0.25-inch stainless steel inserts in a manifold arrangement in the stack downstream of the flue temperature and pressure measurements. The emission sample points were arranged to account for exhaust streams that are non-homogenous. Combustion products were drawn through a vacuum pump and passed through a series of desiccants to provide a dry sample to a bank of analyzers located within the laboratory. Each analyzer was calibrated before each test run against a "zero" gas of pure nitrogen and then against a span gas measured in an independent analyzer.

GTI's laboratory measures the composition of the natural gas used for testing every two weeks. Samples of the natural gas being used for combustion are analyzed through a calorimeter. Although variations in gas characteristics tend to be small, the latest available house gas data was used for analysis of each tested wall furnace.

Natural gas for all wall furnace tests was delivered at a pressure of 6.8 inches water column, at the high end of the recommended 5 to 7 inches water column range for each furnace.

Test Procedure

The following operating procedure was followed for wall furnace tests:

- Start up all test measurement equipment
- Calibrate all sensors following equipment manufacturer procedures
- Adjust gas supply pressure to 6.8 inches water column
- Begin recording measurements
- Light furnace pilot
- Leave furnace on standby with the pilot lit for 30 minutes to record any pilot and/or electrical energy use
- Cold start – start up furnace and allow it to run for 45 minutes (steady state operation from cold start is usually reached in less than 30 minutes)
- Turn off furnace and let it sit in standby with the pilot lit for 1.5 minutes
- Hot start – start up furnace again and let it run for 30 minutes (steady state operation from a hot start is usually reached in less than 20 minutes)
- Turn off furnace and leave on standby with pilot lit for 15 minutes
- End test

This entire procedure took about two hours and allowed for the measurement of the furnace in standby, startup, steady state, and shutdown operating modes. For retrofit furnaces without pilot lights, standby operating times at the beginning and end of the test were reduced since this time was not needed to measure pilot light natural gas use.

Some problems were encountered on three retrofit furnaces when following this procedure:

- The double-sided Williams AC3040TN furnace shut itself off after reaching steady state during the cold start portion of the test
- Both the Williams AC2030TN furnaces were difficult to restart on the hot start portion of the test, with one shutting off after the first restart and needing to be started again

Despite these problems, which were adjusted for during post-processing of the test data, all the pertinent information was captured for all furnaces.

Data Corrections

The gas analyzer and burner data acquisition system are separate pieces of equipment operating on slightly different time stamps. In addition, the flow of exhaust gases to the analyzer added a time delay. Data from the gas analyzer was synchronized with burner temperatures by lining up changes in O_2 and CO_2 concentrations with exhaust temperature changes over time.

The following corrections were made to the collected data:

- O_2 concentration maximum was adjusted to 20.9%, down from as much as 21.3% within +/- 1% measurement accuracy
- CO_2 concentration was adjusted to match the corrected O2 concentration during combustion based on the house natural gas characteristics
- CO and NOx minimum concentrations were adjusted to 0.0% (up from -0.13 ppm which is within +/- 1% measurement accuracy)

CO, NOx, and THC concentrations are reported as absolute values, and not corrected to a standard O_2% concentration as is sometimes done with furnace and boiler emissions. While the retrofit furnaces all ran with an exhaust gas O_2% of about 14%, O_2% varied from 10% to 19% for the baseline furnaces due to their no longer being well-tuned. To report actual emissions from these furnaces in their existing condition, emission concentrations were not standardized.

Analysis of Test Data

The fuel input capacity of the pilot light and during active combustion is operating was calculated from the measured gas flow rate as follows:

Qin = Fuel input capacity Btu/hr = 60 x Active Gas Flow Rate x Heating Value/Timestep

Qp= Pilot Btu/hr = 60 x Standby Gas Flow Rate x Heating Value / Timestep

Active Gas Flow Rate, ft^3 = measured value during active combustion

Standby Gas Flow Rate, ft^3 = measured during standby conditions

Heating value, Btu/ft^3 = from house natural gas used during testing

Timestep = time between measurements in minutes

Emission mass flow rates are normalized to the gas input rate from their absolute measured concentrations as follows:

Equation 1. Converting Emission Concentration to Emission Rate

$$\text{Emission Rate, lbm/MMBtu} = \frac{\text{Concentration x Molecular Weight x Fd x 20.9}}{(20.9 - O_2\%) \text{ x Molar Volume}}$$

Concentration, ppm = absolute measured pollutant concentration

Molecular weight, lbm/lbmole = 28.0097 for CO, 46.0047 for NOx as NO2, and 16.04206 for Total Hydrocarbons (THC) as methane

Fd, lbm/MMBtu = 10^6 x (3.64 x %H + 1.53 x %C + 0.57 x %S + 0.14 x %N – 0.46 x %O)/HHV, using dry weight percentages of each element in the house natural gas used for testing

O_2% = adjusted oxygen percentage in exhaust stream

HHV, Btu/lbm = higher heating value of house natural gas used for testing

Molar Volume, dry ft^3/lbmole = 385.3 at 68°F and 1 atmosphere

Estimated test thermal efficiency and AFUE are calculated for steady state operation based on Title 10 of the Code of Federal Regulations, Appendix O, Subpart B, Part 430 (CFR 430.32 2022), using the following equations:

Test η_{SS-WT} automatic $= 100 - \mathrm{Ls\ ss} - \mathrm{L\ la}$

Test η_{SS-WT} manual $= \eta_{SS-WT} - \mathrm{L\ i\ on}$

Overall Test η_{SS-WT} = (η_{SS-WT} automatic + η_{SS-WT} manual) / 2

Test $\mathrm{AFUE\ automatic} = [0.968 \times \eta_{SS-WT}] - 1.78D_f - 1.89D_s - 129P_f - 2.8L_J + 1.81$

Test AFUE manual = [2950 x $\eta_{ss\text{-}wt}$ x $\eta_{part\ load}$ x Qin] / [2950 x Qin + 2.083 x 4600 x $\eta_{part\ load}$ x Qp]

Overall Test AFUE = (Test AFUE automatic + Test AFUE manual) / 2

η_{SS-WT} = weighted-average steady state efficiency $= 100 - L_{L,A} - L_{s,SS}$

$L_{L,A}$ = latent heat loss = 9.55 for natural gas fueled furnaces

$L_{S,SS}$ = sensible heat loss at steady state $= C(R_{T,S} + D)(T_{S,SS} - T_{RA})$
where $C = 0.0175$, $D = 0.171$

$R_{T,S}$ = actual to stoichiometric air mass flow rate = A + B/X_{co2}
where $A = 0.0919$, $B = 10.96$, and X_{co2} is the concentration of carbon dioxide present in dry stack gas

$T_{S,SS}$ =steady state flue gas temperature

T_{RA} = ambient room temperature

D_f = off-cycle flue gas factor $= 1$ for atmospheric burner type furnaces

D_s = off-cycle stack gas factor and is equal to zero for direct vent furnaces

P_f = pilot fraction = Q_p/Q_{in}

L_j = jacket loss for floor furnaces, which is zero in this study

$\eta_{part\ load}$ = part load utilization efficiency $= \eta_{SS-WT} - L_{I\ ON}$

$L_{i\ ON}$ = on cycle infiltration heat loss = (70-45) x (100 x Cp x S/F) x (1+ Rts x (A/F) / HHV

Cp = specific heat of air, 0.24 Btu/lbm R

S/F = stack/mass flow ratio = 1.0

A/F = stoichiometric air-fuel ratio = 14.45 for natural gas

Note that the test apparatus was not installed in a fabricated wall assembly as designated in ANSI Z21.86 2016, therefore this report's efficiencies are not official rating tests and are for informational and comparative purposes only.

Unlike central furnaces which are most often allowed to cycle automatically to meet a thermostat setting, wall furnaces are much more likely to be turned on and off manually when occupants want heating. To reflect this operation, thermal efficiency and AFUE were found as the average of the efficiency for heaters that are automatically controlled and the efficiency for heaters with manual controls.

Results

Laboratory test results are presented here for each retrofit wall furnace. Data for each furnace is presented in standardized plots that show their operation during testing. Two pages of test result plots are shown for each of the five retrofit furnaces:

- Cold start operation including five minutes of standby operation beforehand
- Hot start operation plus a summary of steady state conditions

Each page of test results includes the following information:

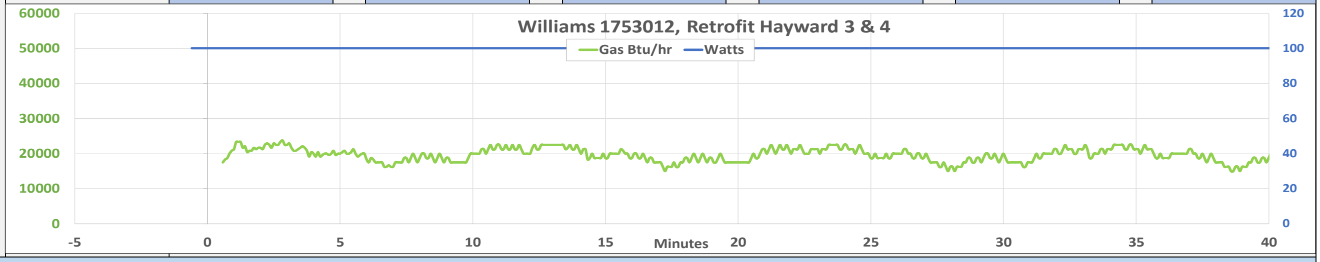
- Time to reach steady state and measured values at time intervals of 0%, 20%, 40%, 60%, 80% and 100% of steady state for the cold start, and values at time intervals of 0%, 33%, 67%, and 100% of steady state time for the hot start
- Fuel use, including both natural gas use and electrical power draw
- Exhaust, burner, inlet, and room temperatures
- Exhaust gas concentrations including O_2%, CO_2%, and CO, NO_x, and THC concentrations in parts per million
- Note that vertical scales vary on emissions plots to show their values more clearly

Figure 2: Williams 1753012 (Hayward 3 & 4), Cold Start

Williams 1753012, Retrofit Hayward 3 & 4, Rated Input 17500 Btu/hr, Thermal Efficiency 94%

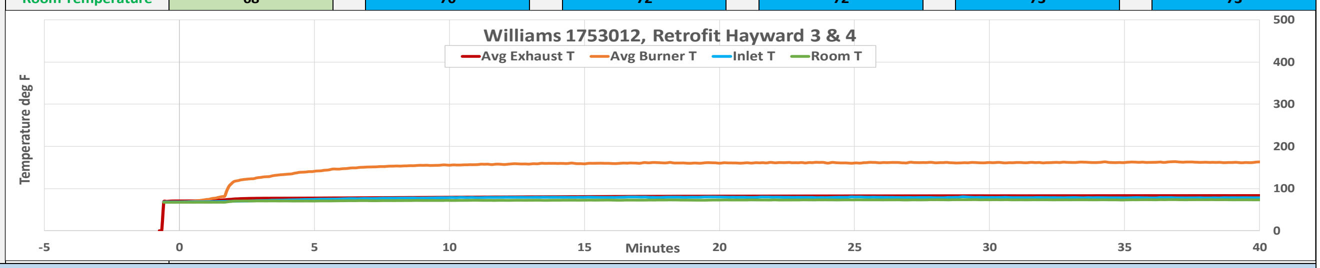
COLD START

TIME	% of Steady State	0%	20%	40%	60%	80%	100%
TIME	Minutes On	0.0	4.7	9.4	14.2	18.9	23.6
FUELS	Gas Input Btu/hr	0	21930	18970	21010	18410	19740
FUELS	Watts	100.1	100.1	100.1	100.1	100.1	100.1



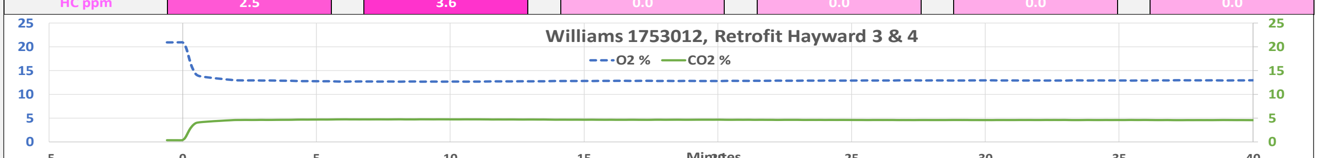
COLD START

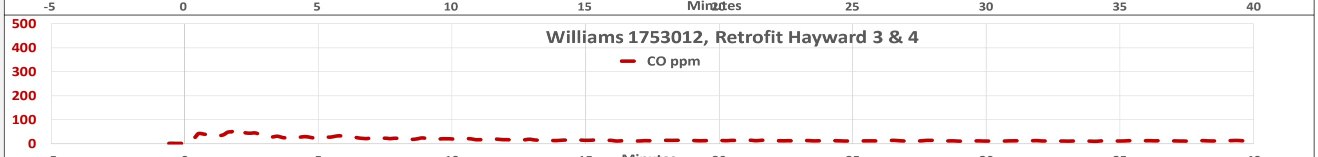
TIME	% of Steady State	0%					20%					40%					60%					80%					100%				
TIME	Minutes On	0.0					4.7					9.4					14.2					18.9					23.6				
TEMPERATURES	Exhaust Temperature	70	70	71	70	70	73	74	76	76	75	76	78	80	79	79	78	80	82	81	81	79	81	83	82	82	80	82	84	83	83
TEMPERATURES	Burner Temperatures	68	68	68	68	68	96	101	101	101	94	129	138	139	141	130	137	146	147	148	137	141	148	150	151	141	141	149	151	152	142
		68	69	68	68	68	104	99	109	101	102	143	132	153	140	143	151	140	160	147	150	154	143	162	150	154	155	144	164	151	155
		68	68	68	68	68	110	116	126	112	107	153	167	187	161	152	162	175	192	167	159	165	178	194	170	162	165	179	197	172	163
		68	68	68	69	68	116	123	120	110	111	164	181	175	157	160	173	193	183	163	168	176	196	185	166	170	176	197	187	167	171
		68	68	68	68	69	110	118	115	111	105	145	167	163	160	148	152	176	172	168	157	153	178	174	170	159	152	179	175	171	159
TEMPERATURES	Avg Burner Temperature	68					107					150					158					160					161				
TEMPERATURES	Inlet Temperature	69					71					77					79					80					80				
TEMPERATURES	Room Temperature	68					70					72					72					73					73				

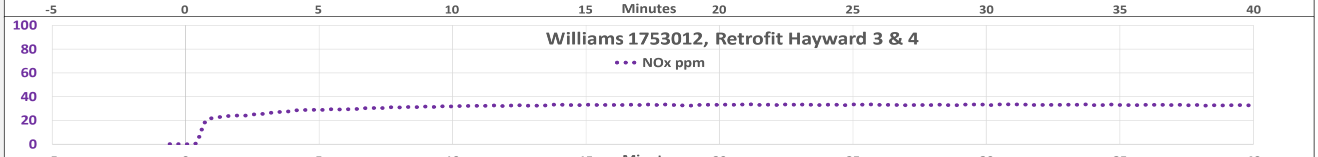


COLD START

TIME	% of Steady State	0%	20%	40%	60%	80%	100%
TIME	Minutes On	0.0	4.7	9.4	14.2	18.9	23.6
EMISSIONS	O2 %	20.9	13.6	12.7	12.7	12.8	12.9
EMISSIONS	CO2 %	0.3	4.2	4.7	4.7	4.6	4.6
EMISSIONS	CO ppm	0.5	33.6	23.3	16.1	12.7	12.0
EMISSIONS	NOx ppm	0.1	22.0	30.3	32.5	33.2	33.3
EMISSIONS	HC ppm	2.5	3.6	0.0	0.0	0.0	0.0







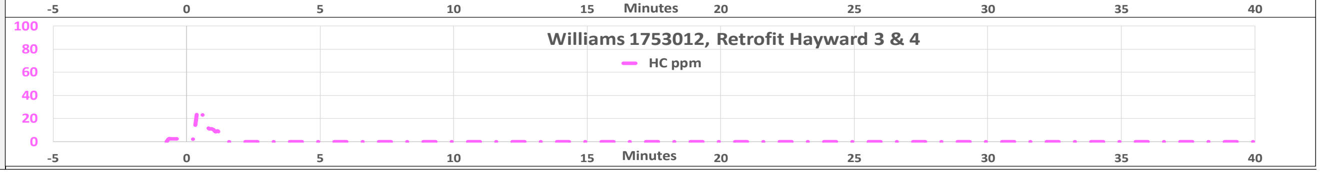
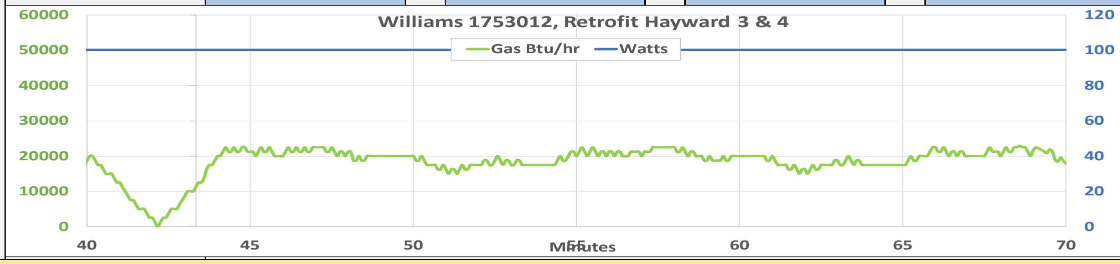


Figure 3: Williams 1753012 (Hayward 3 & 4), Hot Start & Steady State

Williams 1753012, Retrofit Hayward 3 & 4, Rated Input 17500 Btu/hr, Thermal Efficiency 94%

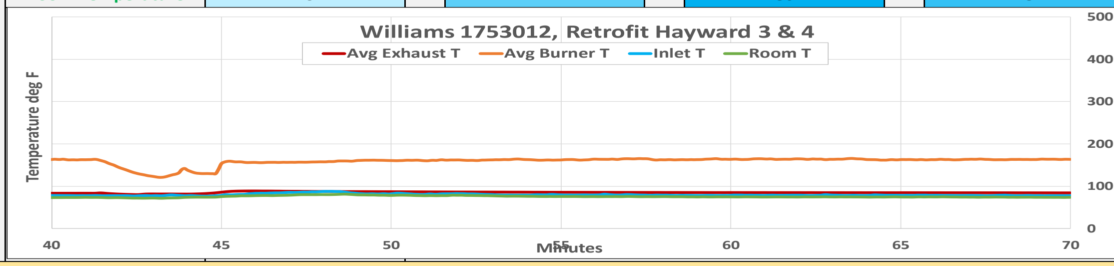
		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
	Minutes On	0.0 (43.7)	3.3 (47)	6.7 (50.4)	10.0 (53.7)	
FUELS	Gas Input Btu/hr	0	22650	19530	17190	19560
	Watts	100.1	100.1	100.1	100.1	100.1



Pilot Light
0 Btu/hr

Standby Power
100.1 W

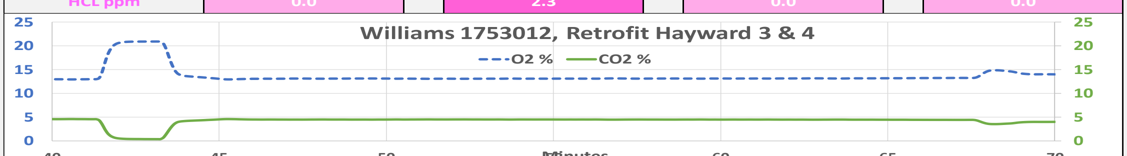
		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
	Minutes On	0.0 (43.7)	3.3 (47)	6.7 (50.4)	10.0 (53.7)	
TEMPERATURES	Exhaust Temperature	79 81 83 82 82	82 85 89 88 87	85 87 89 88 88	84 86 88 87 87	84
	Burner Temperatures	115 118 120 122 118	135 138 139 140 133	140 147 149 150 142	143 150 151 152 143	163
		122 113 127 121 124	141 131 149 139 143	152 141 159 150 153	156 145 162 151 154	
		131 139 147 134 130	150 159 176 156 149	164 175 187 167 161	167 179 190 169 163	
		139 158 146 133 136	159 168 166 152 155	175 196 183 165 169	179 201 186 166 171	
		121 142 139 136 128	150 161 158 155 147	154 178 173 169 159	157 181 176 171 160	
	Avg Burner Temperature	128	148	159	162	
	Inlet Temperature	79	81	85	81	79
	Room Temperature	73	77	80	78	75

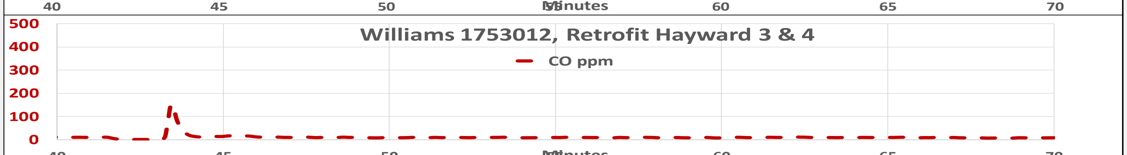


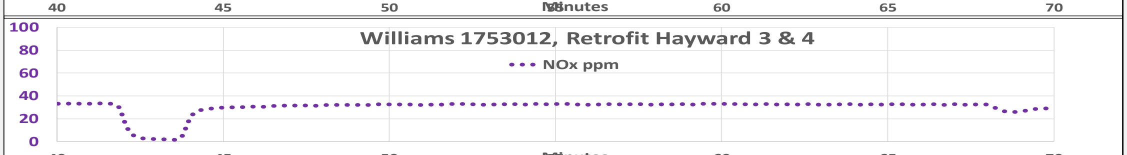
Test Thermal Efficiency
89.5%

Test AFUE
88.0%

		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
	Minutes On	0.0 (43.7)	3.3 (47)	6.7 (50.4)	10.0 (53.7)	
EMISSIONS	O2 %	15.6	13.2	13.1	13.1	13.1
	CO2 %	3.3	4.4	4.5	4.5	4.5
	CO ppm	77.9	14.6	9.5	9.5	10.0
	NOx ppm	1.7	28.0	32.0	32.5	32.6
	HCL ppm	0.0	2.3	0.0	0.0	0.0







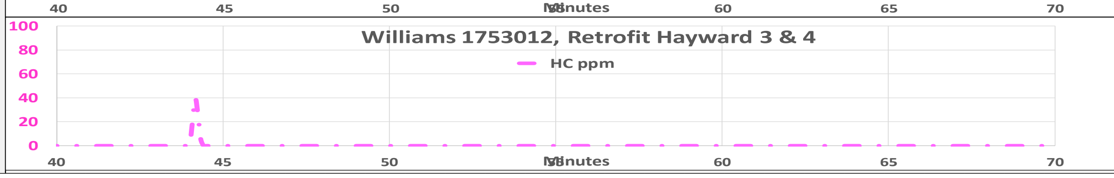
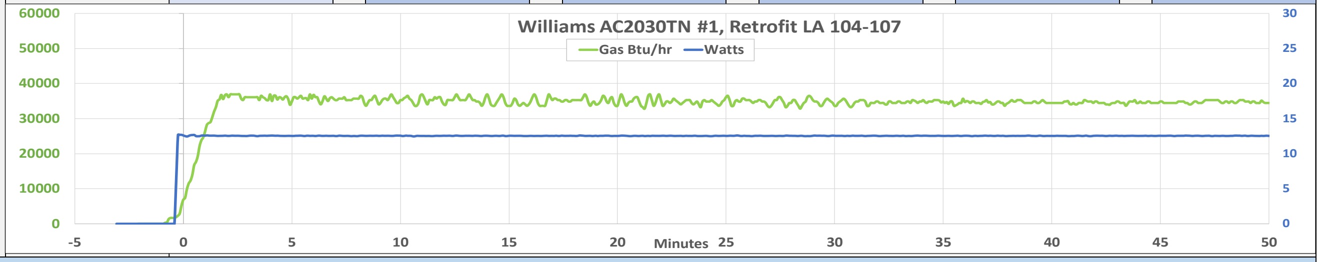


Figure 4: Williams AC2030TN #1 (Los Angeles 104-107), Cold Start

Williams AC2030TN #1, Retrofit LA 104-107, Rated Input 30000 Btu/hr, Thermal Efficiency 85%

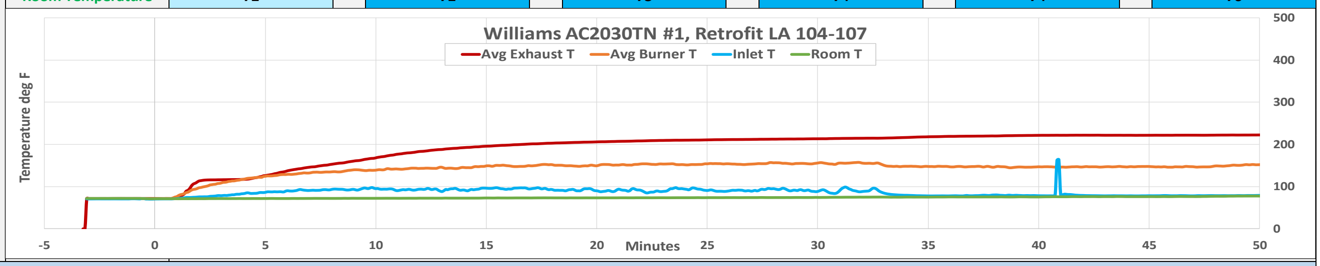
COLD START

TIME	% of Steady State	0%	20%	40%	60%	80%	100%
	Minutes On	0.0	7.5	15.1	22.6	30.2	37.7
FUELS	Gas Input Btu/hr	0	33050	34920	34990	34810	34780
	Watts	3.7	12.5	12.5	12.5	12.5	12.5



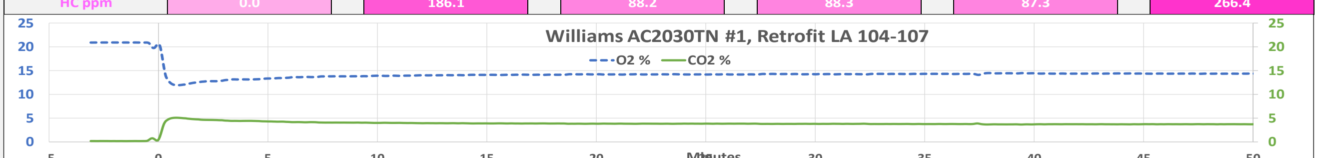
COLD START

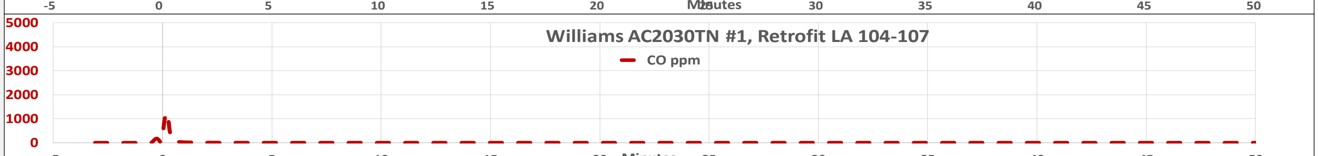
TIME	% of Steady State	0%	20%	40%	60%	80%	100%
	Minutes On	0.0	7.5	15.1	22.6	30.2	37.7
TEMPERATURES	Exhaust Temperature	72 72 72 72 72	114 115 117 116 116	171 176 181 179 177	200 204 208 206 204	208 212 216 214 212	214 217 220 218 217
	Burner Temperatures	72 72 72 71 72	132 115 111 107 124	177 150 144 139 163	185 158 153 148 172	188 161 156 152 176	183 156 152 149 176
		72 72 71 72 71	114 112 102 95 105	148 141 132 123 137	157 148 142 130 146	160 150 145 134 150	155 146 139 131 148
		72 71 71 71 71	108 100 98 96 105	139 128 133 125 135	148 137 147 135 144	151 141 152 140 148	147 135 141 136 146
		71 72 71 71 72	102 89 94 94 104	130 110 120 119 133	139 117 131 130 143	142 121 135 133 146	139 118 132 136 144
		72 71 71 72 72	118 100 102 104 125	153 128 130 133 161	162 137 140 143 168	166 140 143 146 170	163 138 141 144 164
	Avg Burner Temperature	72	134	150	153	157	148
	Inlet Temperature	71	82	94	93	92	83
	Room Temperature	72	72	73	74	74	76

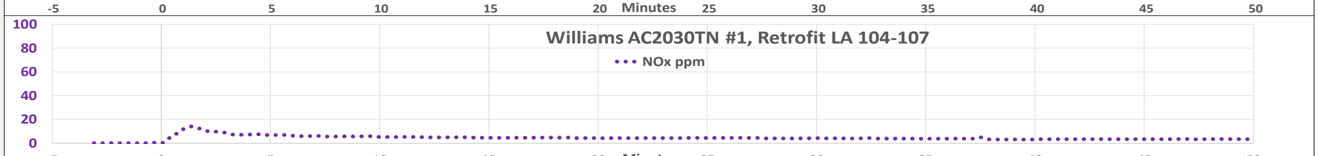


COLD START

TIME	% of Steady State	0%	20%	40%	60%	80%	100%
	Minutes On	0.0	7.5	15.1	22.6	30.2	37.7
EMISSIONS	O2 %	20.5	13.3	13.9	14.1	14.2	14.2
	CO2 %	0.3	4.3	3.9	3.8	3.8	3.7
	CO ppm	46.4	50.9	0.8	0.6	0.6	0.5
	NOx ppm	0.3	7.8	5.2	4.5	4.3	4.0
	HC ppm	0.0	186.1	88.2	88.3	87.3	266.4







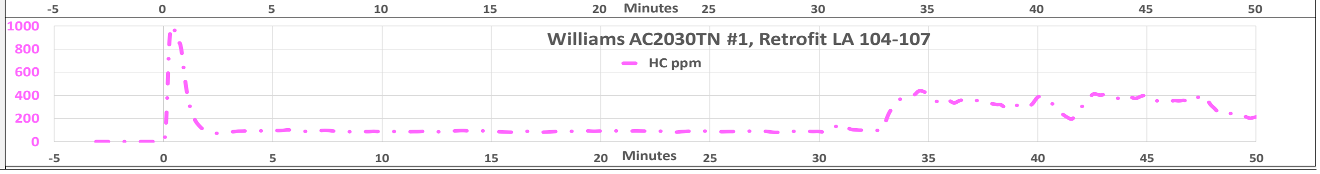
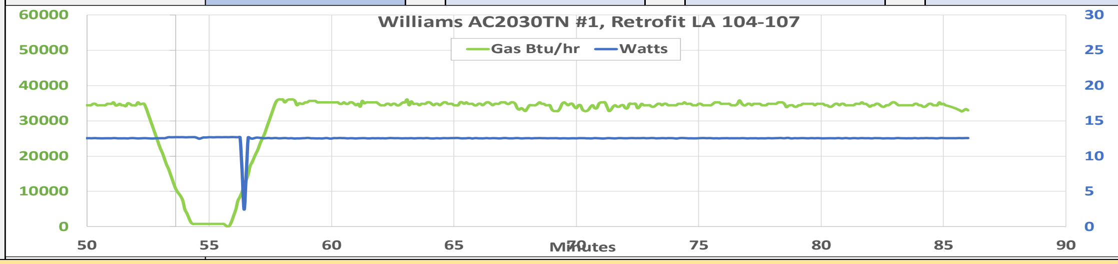


Figure 5: Williams AC2030TN #1 (Los Angeles 104-107), Hot Start & Steady state

Williams AC2030TN #1, Retrofit LA 104-107, Rated Input 30000 Btu/hr, Thermal Efficiency 85%

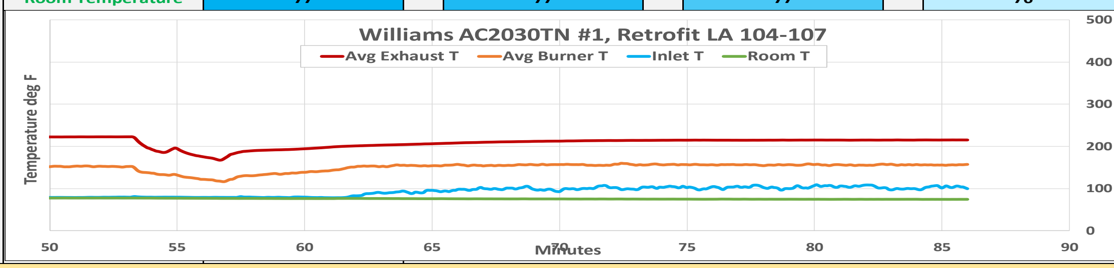
		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
	Minutes On	0.0 (56.7)	4.7 (61.4)	9.5 (66.2)	14.2 (70.9)	
FUELS	Gas Input Btu/hr	0	35020	34950	33840	*34610*
	Watts	12.6	12.5	12.5	12.5	*12.5*



Pilot Light
0 Btu/hr

Standby Power
0 W

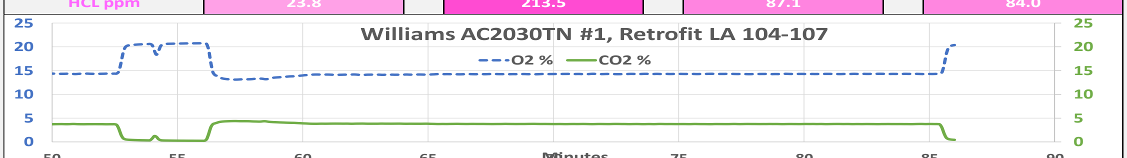
		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
	Minutes On	0.0 (56.7)	4.7 (61.4)	9.5 (66.2)	14.2 (70.9)	
TEMPERATURES	Exhaust Temperature	168 166 164 168 172	189 190 192 192 192	201 204 207 206 205	207 211 215 214 212	*218*
	Burner Temperatures	120 119 119 118 120	159 139 136 133 157	189 162 156 151 176	191 164 159 155 179	*152*
		119 119 120 113 117	138 132 127 116 132	160 152 144 132 148	162 155 147 139 152	
		118 118 128 117 116	131 123 132 123 130	151 140 147 137 147	154 142 146 139 149	
		117 109 115 109 116	124 106 119 120 128	141 119 133 133 146	145 124 134 131 146	
		123 116 116 116 124	144 123 126 128 145	165 139 143 146 173	169 142 144 146 173	
	Avg Burner Temperature	118	135	154	156	
	Inlet Temperature	80	80	90	99	*91*
	Room Temperature	77	77	77	76	*76*

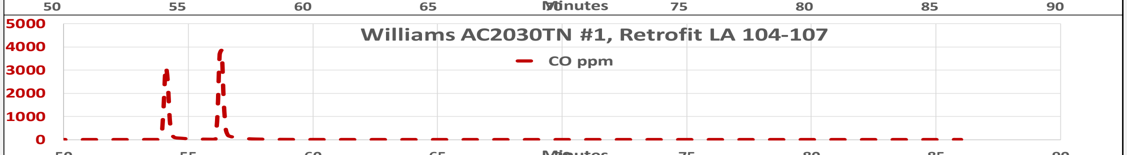


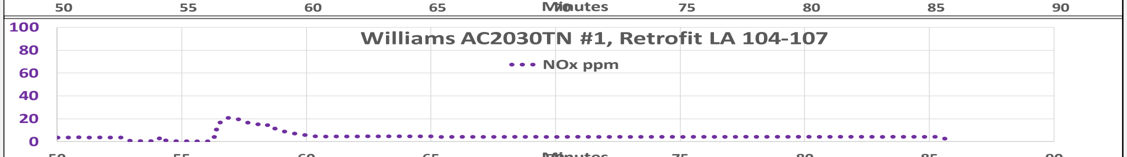
Test Thermal Efficiency
81.8%

Test AFUE
80.4%

		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
	Minutes On	0.0 (56.7)	4.7 (61.4)	9.5 (66.2)	14.2 (70.9)	
EMISSIONS	O2 %	13.7	13.6	14.1	14.2	*14.3*
	CO2 %	4.0	4.0	3.8	3.7	*3.7*
	CO ppm	162.8	16.0	0.8	0.5	*0.4*
	NOx ppm	18.0	10.9	4.4	4.1	*3.7*
	HCL ppm	23.8	213.5	87.1	84.0	*206.2*







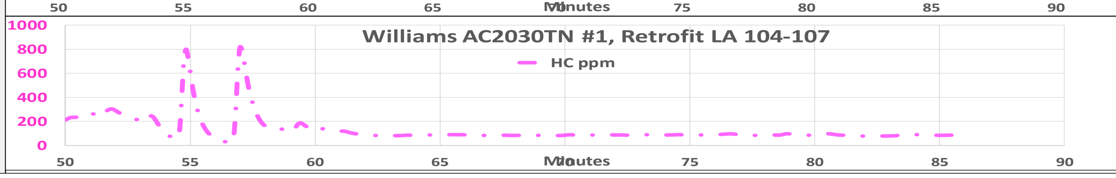
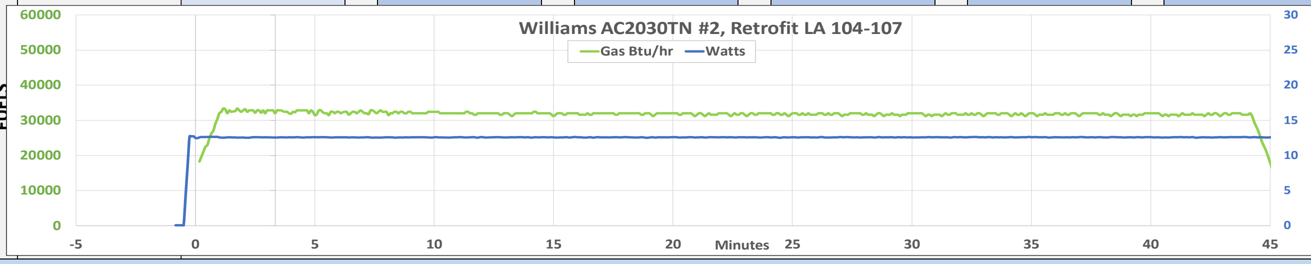


Figure 6: Williams AC2030TN #2 (Los Angeles 104-107), Cold Start

Williams AC2030TN #2, Retrofit LA 104-107, Rated Input 30000 Btu/hr, Thermal Efficiency 85%

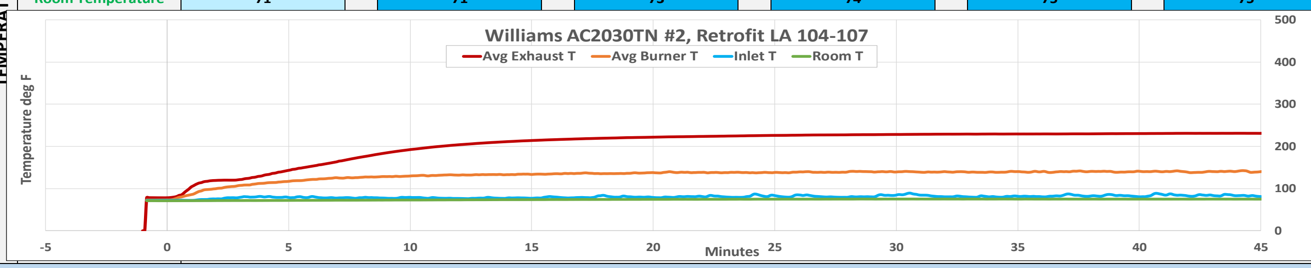
COLD START

TIME	% of Steady State	0%	20%	40%	60%	80%	100%
TIME	Minutes On	0.0	6.5	13.1	19.6	26.2	32.7
FUELS	Gas Input Btu/hr	0	31980	31980	31790	31980	31670
FUELS	Watts	5.7	12.6	12.6	12.6	12.6	12.6



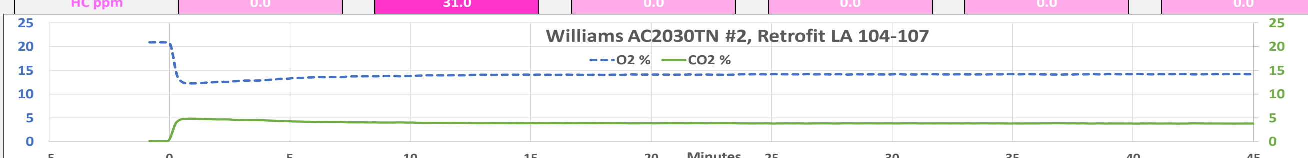
COLD START

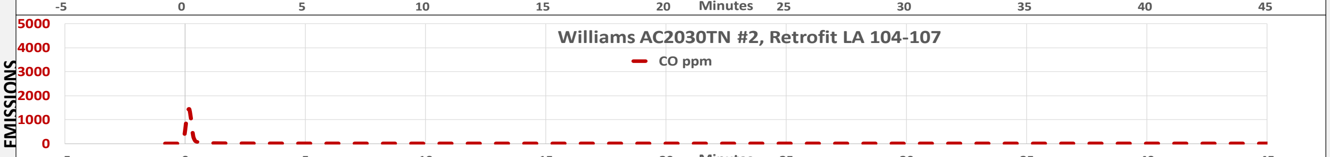
TIME	% of Steady State	0%	20%	40%	60%	80%	100%
TIME	Minutes On	0.0	6.5	13.1	19.6	26.2	32.7
TEMPERATURES	Exhaust Temperature	79 78 78 78 78	121 124 127 126 125	179 187 195 193 191	208 215 222 220 218	217 223 230 228 226	220 227 234 232 230
TEMPERATURES	Burner Temperatures	73 73 73 73 75	127 108 106 104 126	155 133 131 128 159	160 139 137 135 166	162 141 140 138 169	162 143 141 140 170
		73 73 73 72 73	107 102 95 90 102	132 127 118 109 127	137 133 123 116 133	140 135 127 119 136	142 139 128 122 137
		73 72 72 73 73	103 93 94 92 100	127 114 118 113 123	133 119 120 117 128	136 123 126 121 131	138 124 124 120 132
		73 72 72 73 73	99 83 90 91 98	122 98 109 111 119	129 105 113 114 123	132 108 117 117 126	135 111 117 115 126
		74 73 73 73 73	120 98 98 98 112	155 121 120 119 136	164 127 125 123 142	167 130 128 126 144	170 132 129 126 147
TEMPERATURES	Avg Burner Temperature	73	105	130	135	139	140
TEMPERATURES	Inlet Temperature	72	77	78	79	81	82
TEMPERATURES	Room Temperature	71	71	73	74	75	75

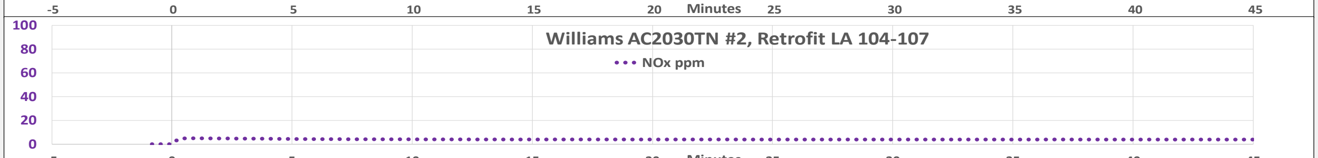


COLD START

TIME	% of Steady State	0%	20%	40%	60%	80%	100%
TIME	Minutes On	0.0	6.5	13.1	19.6	26.2	32.7
EMISSIONS	O2 %	20.9	13.2	13.8	14.1	14.1	14.2
EMISSIONS	CO2 %	0.1	4.3	4.0	3.8	3.8	3.8
EMISSIONS	CO ppm	3.7	66.1	1.2	1.1	1.2	1.2
EMISSIONS	NOx ppm	0.0	4.3	3.9	3.8	3.8	3.7
EMISSIONS	HC ppm	0.0	31.0	0.0	0.0	0.0	0.0







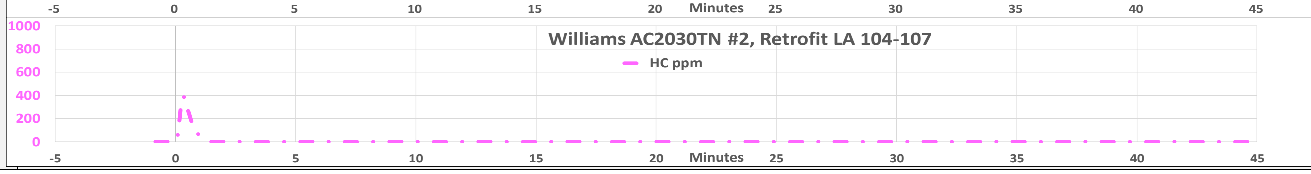
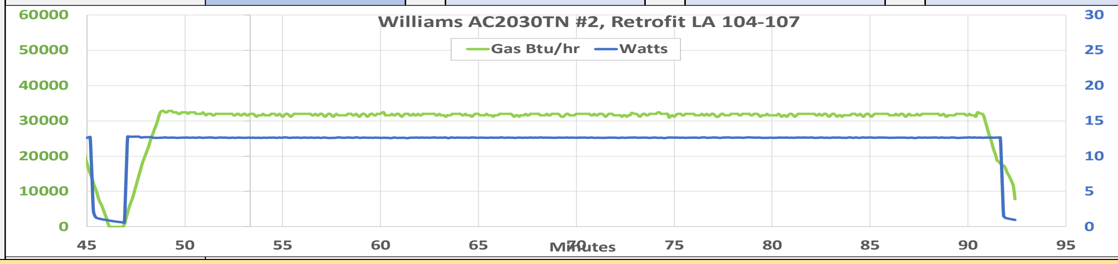


Figure 7: Williams AC2030TN #2 (Los Angeles 104-107), Hot Start & Steady State

Williams AC2030TN #2, Retrofit LA 104-107, Rated Input 30000 Btu/hr, Thermal Efficiency 85%

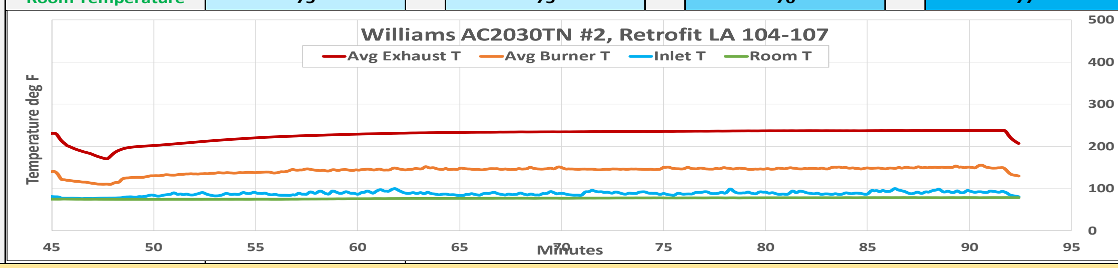
		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
TIME	Minutes On	0.0 (47.7)	8.4 (56.1)	17.1 (64.8)	25.5 (73.2)	
FUELS	Gas Input Btu/hr	0	31740	31910	31460	*31760*
FUELS	Watts	12.7	12.6	12.6	12.6	*12.6*



Pilot Light
0 Btu/hr

Standby Power
0.1 W

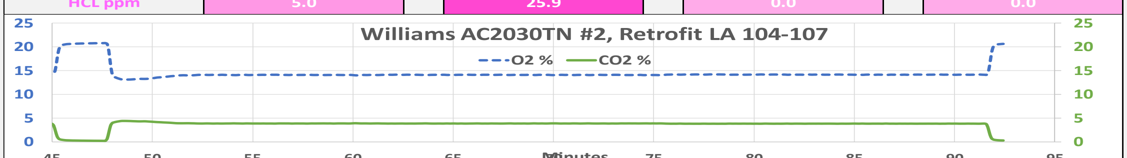
		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
TIME	Minutes On	0.0 (47.7)	8.4 (56.1)	17.1 (64.8)	25.5 (73.2)	
TEMPERATURES	Exhaust Temperature	170 169 169 171 173	202 207 212 211 210	221 228 234 233 231	227 233 240 238 236	*233*
TEMPERATURES	Burner Temperatures	108 111 111 111 108	157 136 134 132 159	173 150 148 147 174	172 150 148 147 177	*144*
		110 111 113 112 111	135 131 121 117 130	148 143 134 132 144	149 143 135 129 145	
		110 111 117 112 111	131 118 116 114 125	143 129 126 126 138	144 131 134 129 140	
		110 106 110 108 111	127 107 110 109 120	139 118 121 120 131	140 117 125 125 135	
		112 109 110 111 115	156 124 122 120 141	169 136 134 131 154	172 138 136 135 153	
TEMPERATURES	Avg Burner Temperature	111	133	145	147	
TEMPERATURES	Inlet Temperature	77	85	90	88	*86*
TEMPERATURES	Room Temperature	75	75	76	77	*77*

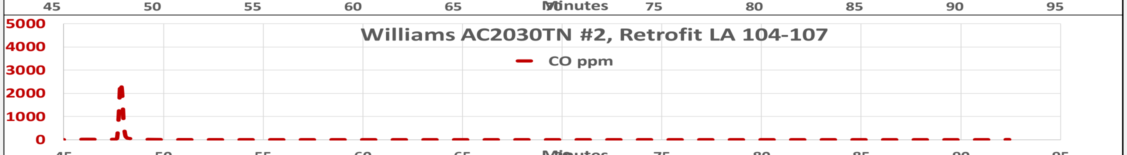


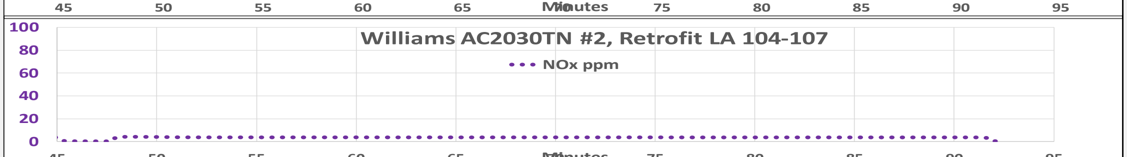
Test Thermal Efficiency
81.2%

Test AFUE
79.9%

		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
TIME	Minutes On	0.0 (47.7)	8.4 (56.1)	17.1 (64.8)	25.5 (73.2)	
EMISSIONS	O2 %	20.8	14.0	14.1	14.1	*14.1*
EMISSIONS	CO2 %	0.2	3.9	3.8	3.8	*3.8*
EMISSIONS	CO ppm	41.0	69.8	1.1	1.0	*1.0*
EMISSIONS	NOx ppm	0.1	3.9	3.8	3.8	*3.7*
EMISSIONS	HCL ppm	5.0	25.9	0.0	0.0	*0.0*







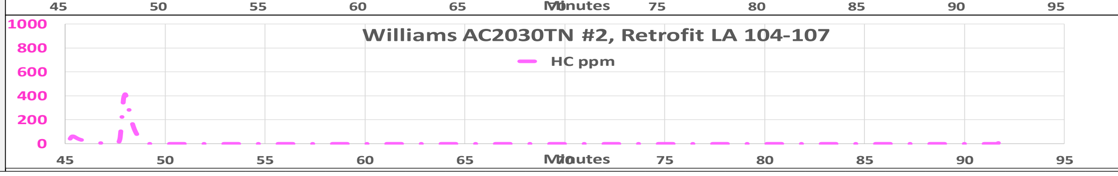


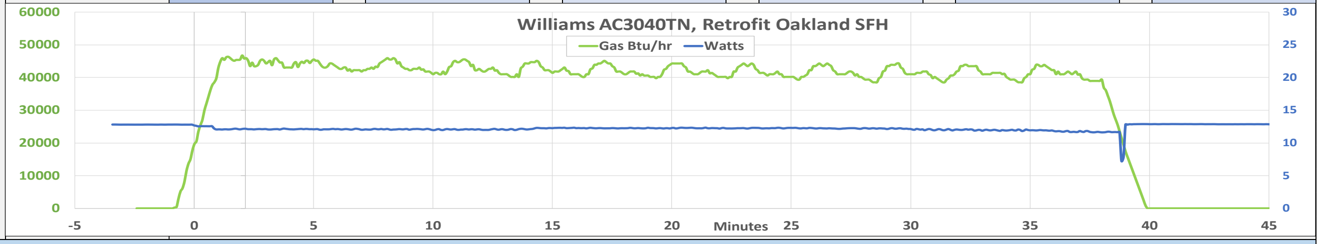
Figure 8: Williams AC3040TN (Oakland SFH), Cold Start

Williams AC3040TN, Retrofit Oakland SFH, Rated Input 40000 Btu/hr, Thermal Efficiency 83%

COLD START

TIME	0%	20%	40%	60%	80%	100%
% of Steady State	0%	20%	40%	60%	80%	100%
Minutes On	0.0	4.7	9.4	14.2	18.9	23.6
Gas Input Btu/hr	0	42840	44280	41940	42090	42010
Watts	12.8	12.2	12.1	12.1	12.3	12.3

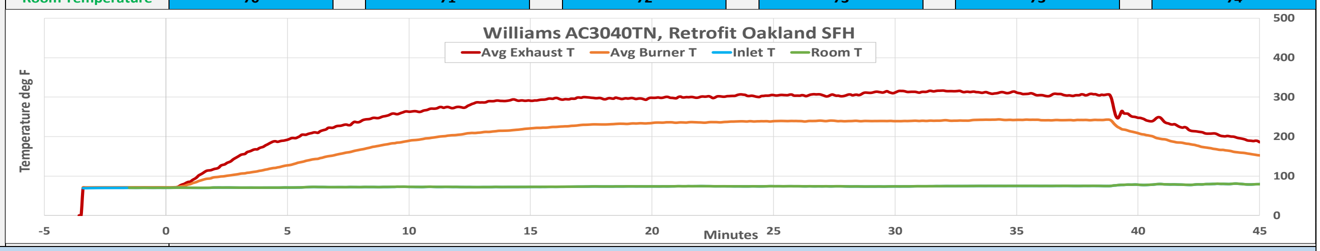
FUELS



COLD START

TIME	0%	20%	40%	60%	80%	100%
% of Steady State	0%	20%	40%	60%	80%	100%
Minutes On	0.0	4.7	9.4	14.2	18.9	23.6
Exhaust Temperature	71 71 71 71 71	141 139 138 122 107	232 239 246 220 195	279 285 291 274 257	296 298 299 295 291	300 301 301 299 297
Burner Temperatures Front Side	71 71 71 71 71	97 95 96 96 91	131 148 154 160 141	151 186 195 204 175	161 205 216 227 192	165 213 224 236 199
	71 71 71 71 71	94 95 94 104 95	146 156 158 183 158	185 200 206 232 201	204 223 230 258 224	214 233 242 267 232
	71 71 71 71 71	94 91 83 91 94	150 153 136 150 153	194 205 188 197 195	216 229 210 221 217	228 244 226 230 225
	71 71 71 71 71	93 96 88 86 93	154 167 145 133 148	203 226 195 172 189	227 254 220 195 210	242 273 232 198 218
	71 71 71 71 71	92 92 92 93 105	143 152 150 148 165	179 200 195 189 199	198 224 217 210 216	208 238 228 218 223
Burner Temperatures Back Side	71 71 71 71 72	108 103 96 89 89	174 168 160 151 157	225 227 219 212 213	245 254 246 239 236	250 263 256 250 243
	71 71 71 72 72	106 105 97 81 89	169 175 155 143 149	227 240 215 207 208	254 271 245 236 235	263 281 257 250 247
	71 72 72 72 72	103 105 104 97 98	163 158 147 148 153	219 215 198 205 207	247 246 227 234 235	257 258 241 248 246
	72 72 72 72 72	100 106 105 107 108	156 152 151 155 156	211 207 205 210 206	240 239 236 240 235	251 253 250 254 245
	71 72 72 72 71	88 100 104 108 111	158 154 155 156 163	211 208 207 206 202	235 236 236 235 228	241 248 246 245 231
Avg Burner Temperature	71	97	154	202	226	235
Inlet Temperature	70	71	72	73	73	74
Room Temperature	70	71	72	73	73	74

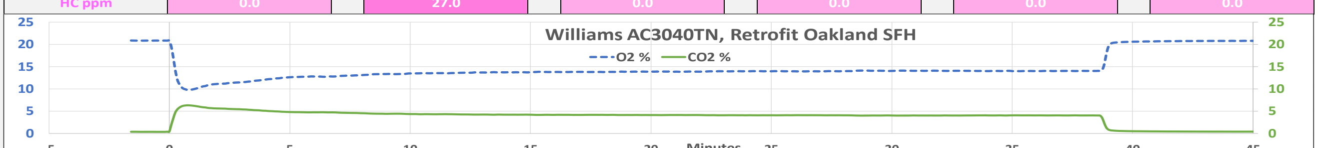
TEMPERATURES

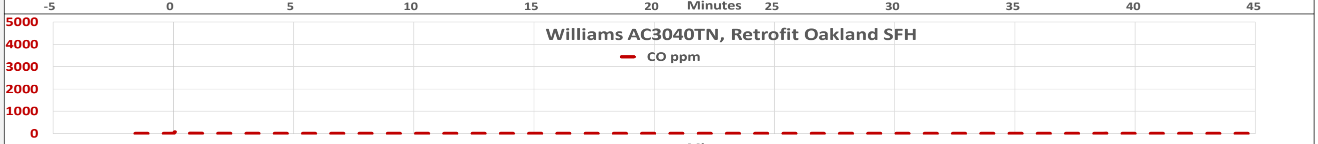


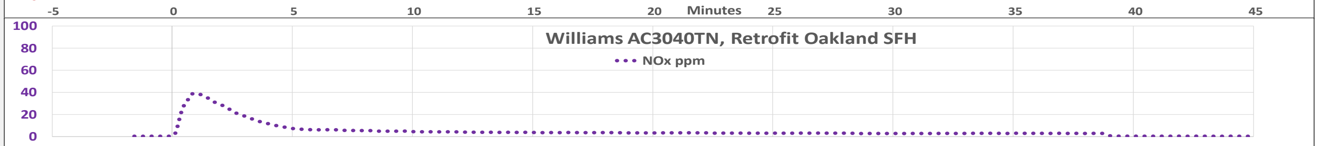
COLD START

TIME	0%	20%	40%	60%	80%	100%
% of Steady State	0%	20%	40%	60%	80%	100%
Minutes On	0.0	4.7	9.4	14.2	18.9	23.6
O2 %	20.9	11.7	12.9	13.6	13.8	13.9
CO2 %	0.4	5.3	4.6	4.3	4.2	4.1
CO ppm	0.8	8.7	0.9	0.6	0.5	0.5
NOx ppm	0.1	21.7	5.7	4.0	3.5	3.1
HC ppm	0.0	27.0	0.0	0.0	0.0	0.0

EMISSIONS







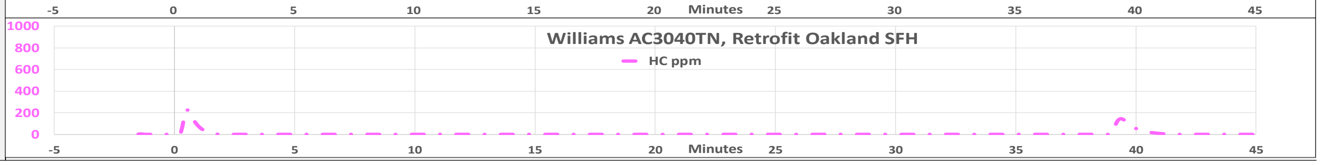
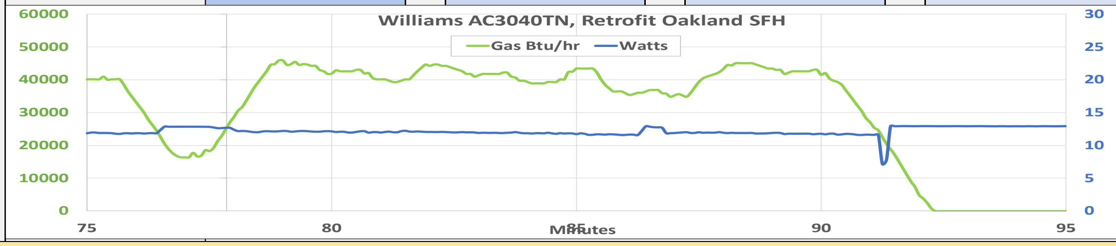


Figure 9: Williams AC3040TN (Oakland SFH), Hot Start & Steady State

Williams AC3040TN, Retrofit Oakland SFH, Rated Input 40000 Btu/hr, Thermal Efficiency 83%

FUELS

		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
TIME	Minutes On	0.0 (77.6)	2.8 (80.4)	5.6 (83.2)	8.4 (86)	
FUELS	Gas Input Btu/hr	0	43430	42150	41040	*40352*
FUELS	Watts	12.8	12.2	12.0	11.8	*12.0*

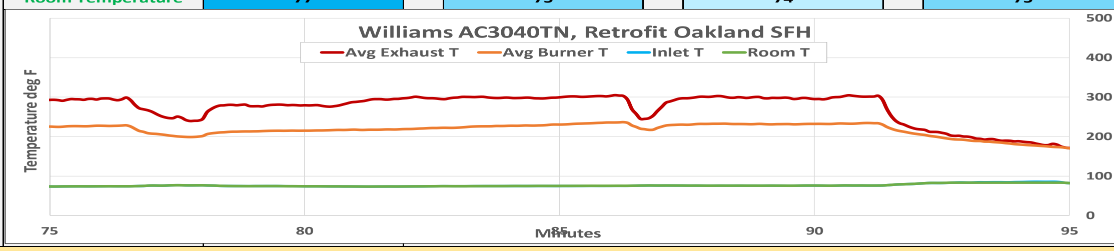


Pilot Light
0 Btu/hr

Standby Power
12.6 W

TEMPERATURES

		HOT START																				Steady-State
TIME	% of Steady State	0%					33%					67%					100%					
TIME	Minutes On	0.0 (77.6)					2.8 (80.4)					5.6 (83.2)					8.4 (86)					
TEMPERATURES	Exhaust Temperature	264	269	275	242	209	277	282	287	271	254	294	298	302	292	281	301	302	303	299	295	*300*
TEMPERATURES	Burner Temperatures Front Side	160	199	210	220	166	157	197	208	218	184	160	201	211	221	188	164	209	220	232	197	*224*
		197	207	232	264	218	197	211	223	247	215	200	217	224	250	217	208	226	235	263	228	
		208	226	225	226	207	208	222	212	215	208	210	222	206	213	210	220	234	217	225	221	
		218	245	220	191	196	219	244	214	186	200	220	244	211	184	202	232	259	224	196	213	
		183	216	206	196	176	191	216	208	200	201	193	216	209	202	212	202	228	221	213	221	
TEMPERATURES	Burner Temperatures Back Side	176	208	204	201	189	221	231	224	216	210	240	247	240	233	230	248	257	250	244	241	*252*
		207	237	210	203	196	232	249	224	214	213	247	263	237	230	229	257	275	249	242	240	
		205	207	189	196	194	227	227	210	215	213	239	236	218	225	226	250	248	229	237	238	
		204	195	194	197	193	222	222	217	219	213	231	228	225	228	224	242	240	236	240	236	
		208	199	196	193	187	217	219	216	213	204	229	227	226	224	219	239	238	237	236	231	
TEMPERATURES	Avg Burner Temperature	200					211					219					229					*235*
TEMPERATURES	Inlet Temperature	77					75					74					75					*75*
TEMPERATURES	Room Temperature	77					75					74					75					*75*

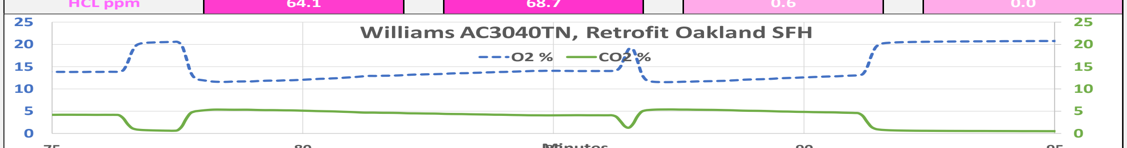


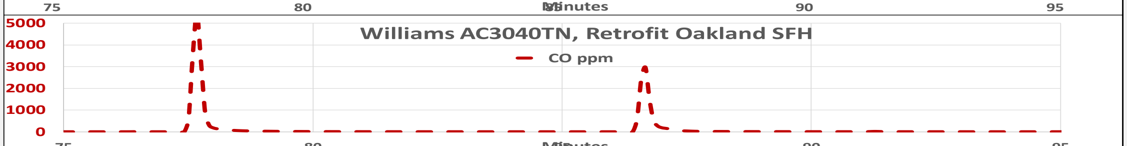
Test Thermal Efficiency
79.0%

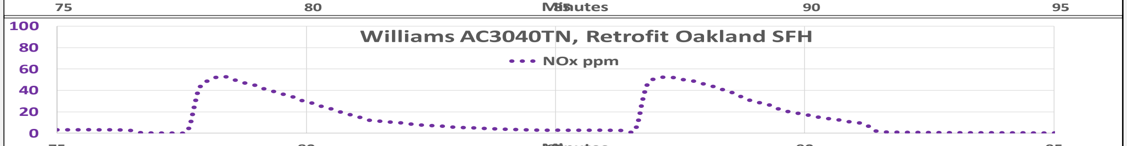
Test AFUE
77.8%

EMISSIONS

		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
TIME	Minutes On	0.0 (77.6)	2.8 (80.4)	5.6 (83.2)	8.4 (86)	
EMISSIONS	O2 %	20.1	12.1	13.0	13.9	*13.4*
EMISSIONS	CO2 %	1.1	5.1	4.6	4.1	*4.4*
EMISSIONS	CO ppm	2021.2	330.0	3.2	0.9	*96.0*
EMISSIONS	NOx ppm	0.4	39.4	11.5	3.5	*17.3*
EMISSIONS	HCL ppm	64.1	68.7	0.6	0.0	*25.6*







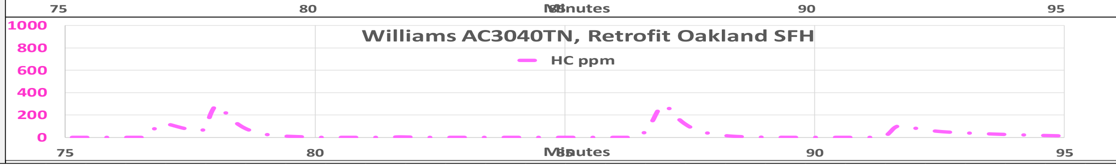
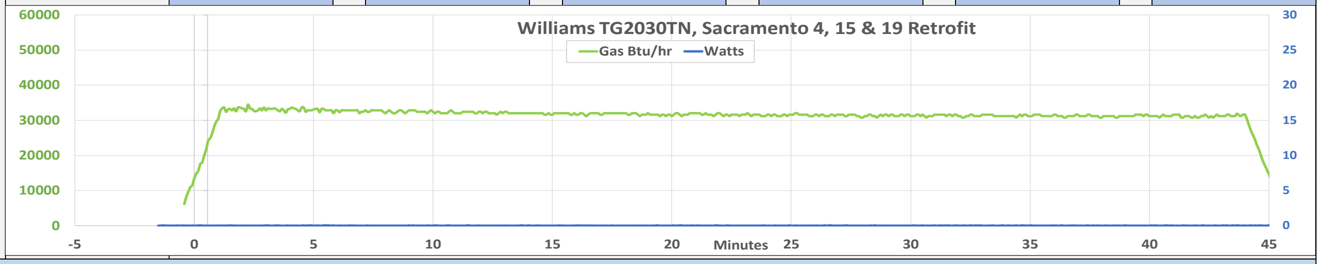


Figure 10: Williams TG2030TN (Sacramento 4, 15 & 19), Cold Start

Williams TG2030TN, Sacramento 4, 15 & 19 Retrofit, Rated Input 30000 Btu/hr, Thermal Efficiency 82%

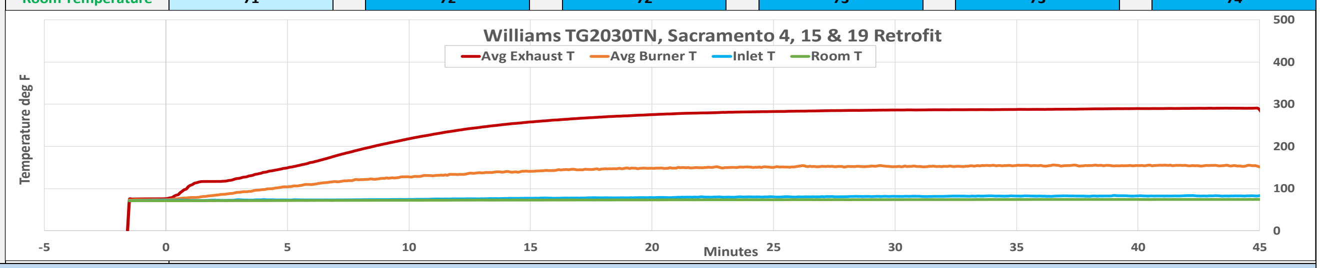
COLD START

TIME	% of Steady State	0%	20%	40%	60%	80%	100%
	Minutes On	0.0	7.6	15.2	22.8	30.4	38.0
FUELS	Gas Input Btu/hr	0	31970	32120	31700	31390	31460
	Watts	0.0	0.0	0.0	0.0	0.0	0.0



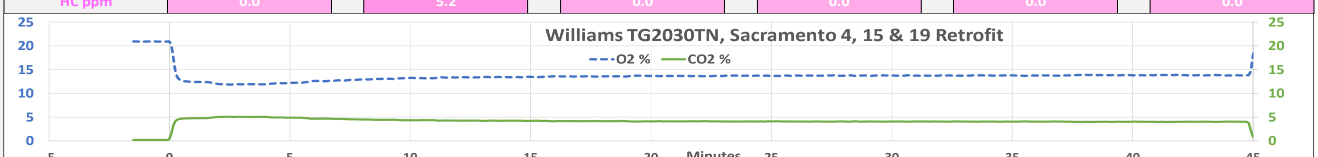
COLD START

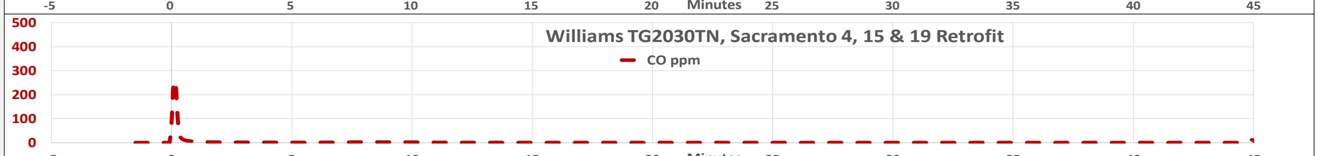
TIME	% of Steady State	0%	20%	40%	60%	80%	100%
	Minutes On	0.0	7.6	15.2	22.8	30.4	38.0
TEMPERATURES	Exhaust Temperature	76 76 75 76 76	137 135 133 135 136	231 227 224 228 233	273 269 265 271 277	285 281 277 283 289	288 284 280 286 293
	Burner Temperatures	75 74 74 74 76	118 99 97 96 118	160 133 133 133 192	175 148 148 149 219	181 153 153 154 227	183 155 156 156 230
		74 74 73 73 74	98 93 86 83 95	133 131 109 97 130	147 148 121 107 145	152 153 125 110 150	155 155 127 111 152
		74 73 74 73 74	95 84 81 83 92	127 108 100 101 123	142 120 109 110 137	146 123 112 112 141	148 125 113 114 143
		74 73 73 73 74	92 80 82 85 89	122 92 99 105 116	136 102 108 113 129	140 105 111 116 132	142 107 113 117 134
		75 74 74 74 75	111 91 90 89 100	167 119 118 116 144	186 132 130 129 165	191 136 134 132 171	193 138 136 134 174
	Avg Burner Temperature	74	96	132	147	152	154
	Inlet Temperature	73	73	75	79	81	82
	Room Temperature	71	72	72	73	73	74

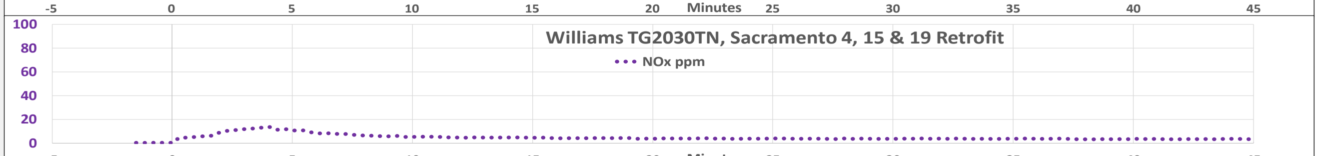


COLD START

TIME	% of Steady State	0%	20%	40%	60%	80%	100%
	Minutes On	0.0	7.6	15.2	22.8	30.4	38.0
EMISSIONS	O2 %	20.9	12.6	13.3	13.6	13.7	13.8
	CO2 %	0.2	4.7	4.3	4.1	4.1	4.0
	CO ppm	0.3	10.1	1.4	0.5	0.5	0.4
	NOx ppm	0.1	8.8	5.0	3.9	3.5	3.5
	HC ppm	0.0	5.2	0.0	0.0	0.0	0.0







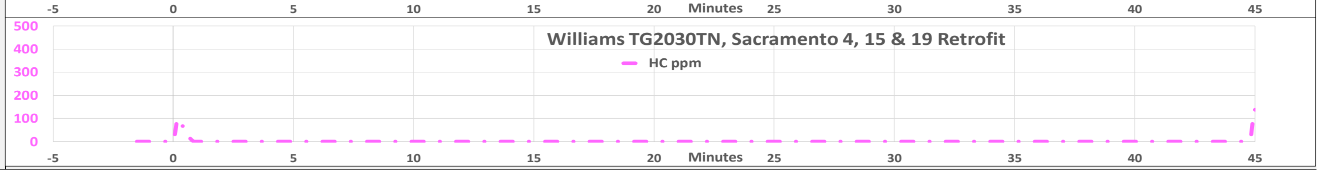
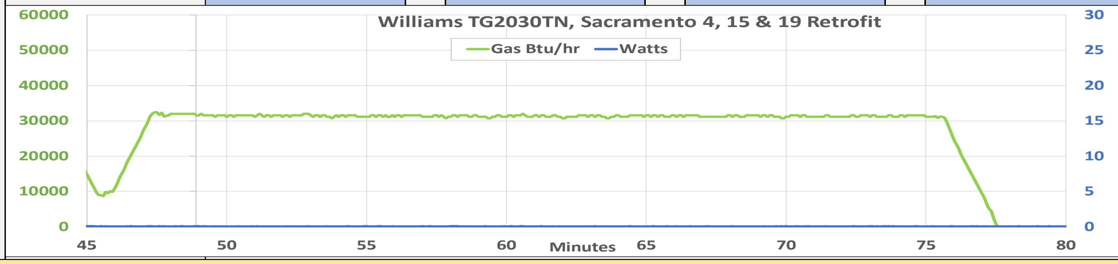


Figure 11: Williams TG2030TN (Sacramento 4, 15 & 19), Hot Start & Steady State

Williams TG2030TN, Sacramento 4, 15 & 19 Retrofit, Rated Input 30000 Btu/hr, Thermal Efficiency 82%

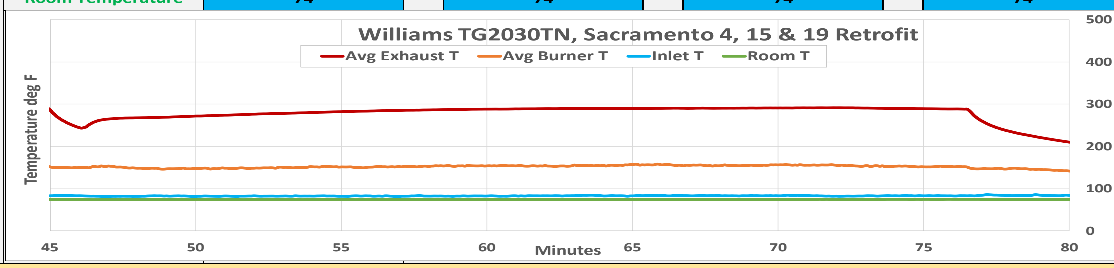
		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
TIME	Minutes On	0.0 (46.2)	5.4 (51.6)	11.0 (57.2)	16.4 (62.6)	
FUELS	Gas Input Btu/hr	0	31040	31520	31330	31210
FUELS	Watts	0.0	0.0	0.0	0.0	0.0



Pilot Light
0 Btu/hr

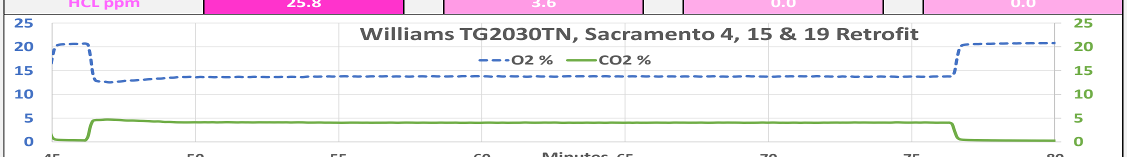
Standby Power
0 W

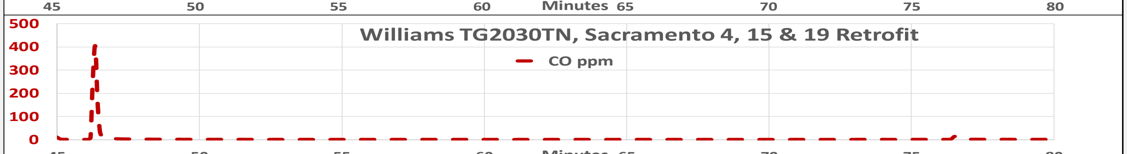
		HOT START																				Steady-State
TIME	% of Steady State	0%					33%					67%					100%					
TIME	Minutes On	0.0 (46.2)					5.4 (51.6)					11.0 (57.2)					16.4 (62.6)					
TEMPERATURES	Exhaust Temperature	243	240	238	244	250	269	265	262	268	273	282	278	274	280	286	288	285	281	287	293	289
	Burner Temperatures	162	152	152	151	200	179	151	151	151	218	179	152	152	153	224	183	155	155	156	229	155
		154	161	133	120	145	151	150	124	111	147	151	152	124	110	149	155	156	127	112	151	
		152	138	119	116	139	145	124	111	111	138	145	123	112	112	140	148	125	113	114	143	
		149	135	121	111	133	139	110	111	112	129	139	106	111	115	132	142	108	112	116	134	
		176	144	138	133	166	183	135	132	129	164	189	135	134	132	170	193	138	136	134	174	
	Avg Burner Temperature	150					149					151					154					
	Inlet Temperature	83					82					82					83					83
	Room Temperature	74					74					74					74					74

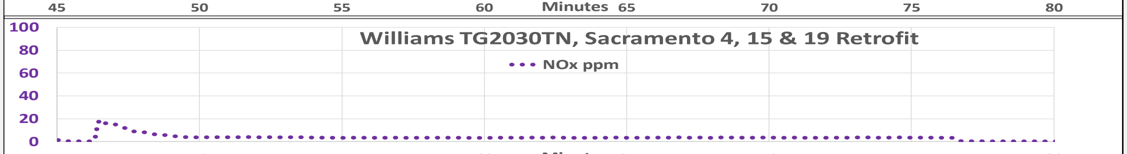


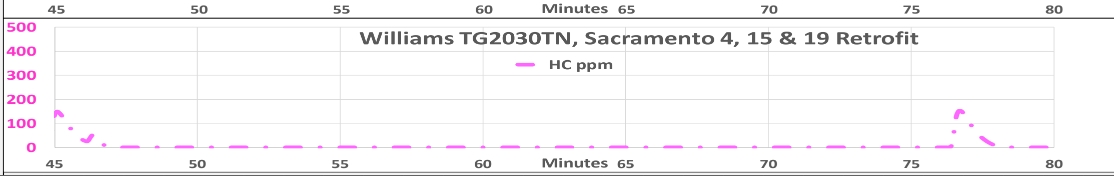
Test Thermal Efficiency
78.5%
Test Thermal Test AFUE
77.3%

		HOT START				Steady-State
TIME	% of Steady State	0%	33%	67%	100%	
TIME	Minutes On	0.0 (46.2)	5.4 (51.6)	11.0 (57.2)	16.4 (62.6)	
EMISSIONS	O2 %	20.6	13.5	13.7	13.8	13.8
EMISSIONS	CO2 %	0.4	4.2	4.1	4.0	4.0
EMISSIONS	CO ppm	4.1	14.7	0.5	0.4	0.4
EMISSIONS	NOx ppm	0.2	7.0	3.5	3.4	3.3
EMISSIONS	HCL ppm	25.8	3.6	0.0	0.0	0.0









Conclusion

Below laboratory test results for all five tested retrofit wall furnaces are compared, including their fuel use, electricity use, combustion and thermal characteristics, efficiency, and emissions.

Retrofit Wall Furnace Fuel Use

Table 5 lists the measured fuel input for all tested wall furnaces, including natural gas use during heating and electrical power draw during active heating and standby periods. Note that a gas pressure of 6.8 inches water column was used during all testing, at the high end of the recommended 5 to 7 inches water column range for each furnace.

Table 5: Retrofit Wall Furnace Natural Gas Input and Electrical Power

Wall Furnace Tested		Natural Gas Input				AC Power	
Model	Field Sites	Rated Btu/hr	Tested Btu/hr	% Rated Input	Pilot Btu/hr	Active W	Standby W
1753012 (condensing direct vent)	Hayward 3 & 4	17500	19790	113%	0	100.1	0.0
AC2030TN #1 (single-sided low NOx)	LA 104-107	30000	34580	115%	0	12.5	0.0
AC2030TN #2 (single-sided low NOx)	LA 104-107	30000	31780	106%	0	12.6	0.1
AC3040TN (double-sided low NOx)	Oakland SFH	40000	41720	104%	0	12.4	0.0
TG2030TN (self-powered low NOx)	Sacto 4, 15 & 19	30000	31410	105%	0	0.0	0.0
	Average	**29500**	**31856**	**109%**	**0**	**27.5**	**0.0**

All the retrofit furnaces used more natural gas than their rated value, from 4 to 15% more, and 9% more on average. It is not clear why test capacity was higher than rated capacity, since these tests used the same gas pressure as is used to derive rated capacity. None of these furnaces had standing pilots, so they used no pilot energy use when in standby mode.

Both tested AC2030TN furnaces drew about 12.5 W of power when active to run their fans, but that power draw dropped to essentially zero when in standby mode. The double-sided AC3040TN furnaces also used about 12.5 W of power when active, but also drew 12.5 W when in standby. The 1753012 direct vent condensing furnace drew the largest amount of power, using 100 W both while actively firing and in standby. Subsequent field monitoring of the AC3040TN and 1753012 furnaces found their power draw dropped to zero when in standby, so standby power draw in Table 5 was adjusted to zero for these furnaces. The TG2030TN furnace didn't draw any electrical power, as it's powered by a rechargeable battery.

Retrofit Wall Furnace Combustion and Thermal Characteristics

Table 6 lists the percentages of oxygen and carbon dioxide found in the exhaust gases of each wall furnace, which is an indicator of combustion efficiency. Oxygen levels around 14% and carbon dioxide around 4% indicate that the fuel-air ratio is neither too rich nor too lean for good combustion. All the retrofit furnaces have flue gas oxygen levels that indicate adequate fuel-air ratio for good combustion. There are variations of about 1% in O2 and 0.7% in CO2 between the furnaces, most likely because of differences in how manufacturers decided to operate each furnace to achieve both high efficiency and low NOx emissions.

Table 6: Combustion Exhaust Gas Oxygen and Carbon Dioxide Percentages

Wall Furnace Tested		Combustion	
Model	**Field Sites**	**% O2**	**% CO2**
1753012 (condensing direct vent)	Hayward 3 & 4	13.0	4.5
AC2030TN #1 (single-sided low NOx)	LA 104-107	14.1	3.8
AC2030TN #2 (single-sided low NOx)	LA 104-107	14.0	3.8
AC3040TN (double-sided low NOx)	Oakland SFH	13.2	4.5
TG2030TN (self-powered low NOx)	Sacto 4, 19	13.6	4.1
	Average	**13.6**	**4.2**

Table 7 lists the time to reach steady state conditions during cold and hot starts for each tested furnace. Steady state conditions were assumed to be reached when the average exhaust temperature first rose to within 3°F of the maximum temperature achieved during each respective cold or hot start.

Table 7: Retrofit Wall Furnace Steady State Conditions, deg F

Wall Furnace Tested		Startup		Avg Hot & Cold Start Steady State Conditions			
Model	**Field Sites**	**Cold Start**	**Hot Start**	**Exhaust °F**	**Burner °F**	**Inlet °F**	**Room °F**
1753012 (condensing direct vent)	Hayward 3 & 4	23.6	10.0	83.7	162.6	79.0	74.5
AC2030TN #1 (single-sided low NOx)	LA 104-107	37.7	14.2	218.2	152.4	91.4	76.0
AC2030TN #2 (single-sided low NOx)	LA 104-107	32.7	25.5	232.9	144.0	85.5	76.5
AC3040TN (double-sided low NOx)	Oakland SFH	23.6	8.4	299.8	235.0	75.0	75.0
TG2030TN (self-powered low NOx)	Sacramento 4, 15 & 19	38.0	16.4	289.4	154.6	82.8	74.2
	Average Retrofit	**31.1**	**14.9**	**224.8**	**169.7**	**82.7**	**75.2**

Steady state was reached within 23 to 38 minutes during cold starts, and within 8 to 16 minutes during hot starts. In all furnaces it took longer to reach steady state in cold starts.

Table 7 also lists the average cold and hot start steady state exhaust, burner, inlet, and room temperatures reached for each furnace. Room temperatures varied since the test facility was not isolated in a climate-controlled room. Inlet temperatures to each furnace tended to be higher than the room temperature, indicating that the furnaces entrain some of the heat they produce directly back into the unit. This entrainment may have been affected by a lack of conditioning and air circulation in the test facility.

Average exhaust temperatures in the non-condensing furnaces vary by more than 200°F, from around 220°F on the AC2030TN furnace to around 290°F on the AC3040TN and TG2030TN furnaces. Presumably exhaust temperature differences are a consequence of the adjustments made to fuel-air ratios to control nitrogen oxides emissions for these low NOx furnaces.
The exhaust temperature for the condensing furnace was much lower, at about 85°F, which is expected because a heat exchanger is used to recover heat from the exhaust air. This heat recovery is what makes the condensing furnace so efficient.

Retrofit Wall Furnace Efficiency

Table 8 lists the rated and tested thermal efficiency and Annual Fuel Utilization Efficiency (AFUE) of each wall furnace. Note that these are not official rated values since the furnaces were not installed into a fabricated wall cavity assembly as specified by the ANSI Z21.86 2016 test standard.

Table 8: Retrofit Wall Furnace Tested Thermal Efficiency and AFUE

Wall Furnace Tested		Thermal Efficiency		AFUE	
Model	**Field Sites**	**Rated TE**	**Tested TE**	**Rated AFUE**	**Tested AFUE**
1753012 (condensing direct vent)	Hayward 3 & 4	94%	89.5%	93%	88.0%
AC2030TN #1 (single-sided low NOx)	LA 104-107	85%	81.8%	82%	80.4%
AC2030TN #2 (single-sided low NOx)	LA 104-107	85%	81.2%	82%	79.9%
AC3040TN (double-sided low NOx)	Oakland SFH	83%	79.0%	80%	77.8%
TG2030TN (self-powered low NOx)	Sacramento 4, 15 & 19	82%	78.5%	80%	77.3%
	Average Retrofit	**87.0%**	**83.0%**	**85.2%**	**81.7%**

Tested values of thermal efficiency on all furnaces were 3.2% to 4.5% lower than their rated thermal efficiencies, and 3.8% lower on average. Tested AFUE values were 1.6% to 5.0% lower than rated AFUE values, and 3.1% lower on average. The two AC2030TN furnaces gave similar thermal efficiency and AFUE results.

Recall that the furnaces were not installed in fabricated wall assemblies during this laboratory testing This may have allowed more heat loss from back side of the furnaces than they would see during official rating tests, thereby lowering the test efficiency. The thermal efficiencies and AFUE values from this report's testing should therefore be used only for comparative purposes between furnaces.

According to ANSI Z21.86-2016 as listed in Table 13 of Appendix A, the minimum thermal efficiency for fan-type furnaces should be 75%. All retrofit furnaces still tested well above that minimum, even if they tested short of their ratings.

As listed in Table 14 of Appendix A, the minimum AFUE from the Code of Federal Regulations for fan-type wall furnaces is 75% for furnaces below 42,000 Btu/hr and 76% for furnaces above 42,000 Btu/hr. All tested furnaces exceeded these minimum standards, even though these test results fell short of their rated AFUE values.

Retrofit Wall Furnace Emissions

Emission concentrations for each wall furnace were measured using a gas analyzer probe inserted in the exhaust stream. Emissions were then averaged over four operating conditions:

- Pilot – while in standby with only the pilot light burning natural gas
- Startup – from the start of combustion until the average exhaust temperature reaches steady state as defined by heating up to within 2°F of the maximum temperature achieved during that test

- Steady State – after the exhaust temperature reaches steady state and before the burner shuts off
- Shutdown – for 1.5 minutes after gas flow to the burner is turned off and only the pilot light burning natural gas

Exhaust stream concentrations in parts per million are converted to emission mass flow rates in lbm per MMBtu using Equation 1. Note that this conversion uses the percentage of oxygen in the exhaust flow to account for the fuel input, not the measured natural gas flow itself. There are often brief high concentrations and mass flow rates of pollutants in the exhaust stream at startup and shutdown. These spikes get ameliorated somewhat because startup emissions get folded into the entire startup time to steady state, and because shutdown emissions are assumed to occur at the much lower pilot gas rate.

Table 9, Table 10, and Table 11 list the carbon monoxide, nitrogen oxides, and total hydrocarbon emission rates found during testing of each wall furnace.

Table 9: Baseline Wall Furnace Carbon Monoxide Emissions

Wall Furnace Tested		Carbon Monoxide, lbm/MMBtu			
Model	**Field Sites**	**Standby**	**Startup**	**Steady State**	**Shutdown**
1753012 (condensing direct vent)	Hayward 3 & 4	1.093	0.027	0.017	0.023
AC2030TN #1 (single-sided low NOx)	LA 104-107	0.620	0.045	0.001	3.106
AC2030TN #2 (single-sided low NOx)	LA 104-107	2.216	0.183	0.002	0.681
AC3040TN (double-sided low NOx)	Oakland SFH	0.230	0.145	0.348	0.048
TG2030TN (self-powered low NOx)	Sacto 4, 19	0.075	0.042	0.012	0.041
	Average	**0.846**	**0.088**	**0.076**	**0.780**

Table 10: Baseline Wall Furnace Nitrogen Oxides Emissions

Wall Furnace Tested		Nitrogen Oxides, lbm/MMBtu			
Model	**Field Sites**	**Standby**	**Startup**	**Steady State**	**Shutdown**
1753012 (condensing direct vent)	Hayward 3 & 4	0.178	0.083	0.089	0.266
AC2030TN #1 (single-sided low NOx)	LA 104-107	0.027	0.018	0.012	0.019
AC2030TN #2 (single-sided low NOx)	LA 104-107	0.030	0.012	0.012	0.015
AC3040TN (double-sided low NOx)	Oakland SFH	0.077	0.032	0.043	0.032
TG2030TN (self-powered low NOx)	Sacto 4, 19	0.039	0.014	0.013	0.016
	Average	**0.070**	**0.031**	**0.034**	**0.069**

Table 11: Baseline Wall Furnaces Total Hydrocarbon Emissions

Wall Furnace Tested		Total Hydrocarbons, lbm/MMBtu			
Model	**Field Sites**	**Standby**	**Startup**	**Steady State**	**Shutdown**
1753012 (condensing direct vent)	Hayward 3 & 4	0.004	0.003	0.000	0.000
AC2030TN #1 (single-sided low NOx)	LA 104-107	0.171	0.160	0.258	1.499
AC2030TN #2 (single-sided low NOx)	LA 104-107	0.008	0.013	0.000	0.597
AC3040TN (double-sided low NOx)	Oakland SFH	0.004	0.013	0.026	1.386
TG2030TN (self-powered low NOx)	Sacto 4, 19	0.002	0.004	0.032	1.144
	Average	**0.038**	**0.038**	**0.063**	**0.925**

As was seen in the plots of emission concentrations over time during the baseline wall furnace tests, carbon monoxide and total hydrocarbon emission rates tend to be higher during startup and especially shutdown, when combustion is not quite complete. In standard wall furnaces without control of excess air during combustion, nitrogen oxide emissions tend to be higher while heating is actively operating due to poor fuel-air ratios. However, furnaces with good combustion controls like most of these retrofit furnaces have much lower steady state nitrogen oxides emission rates.

There are some clear outliers with high emission rates:

- Both AC2030TN furnaces have high CO emission rates at startup and shutdown, and the 1753012 furnace has a high CO emission rate at startup, while the AC3040TN furnace had higher CO emission rates during steady state operation
- Nitrogen oxides emission rates for the four non-condensing furnaces are quite low, while the 1753012 condensing furnace has much a higher NOx emission rate
- All four non-condensing furnaces have high total hydrocarbon emission rates at shutdown, and the AC2030TN #1 has high hydrocarbon emission rates across the board

Although the two theoretically identical AC2030TN furnaces had similar thermal efficiency and AFUE, their emissions profiles were somewhat different from each other. Nitrogen oxides emissions were similar on both furnaces, but carbon monoxide and hydrocarbon emissions varied. CO emissions were high on both furnaces when not in steady-state, but were higher during shutdown on #1 and during standby and startup on #2. Hydrocarbon emissions were high during all operating modes on #1 and high at shutdown on #2. This indicates that both furnaces had poor fuel-air mixing as their gas valve opens and closes, and AC2030TN #1 may have had a small natural gas leak.

There are no standards or regulations for emissions from wall furnaces. However, as detailed in Appendix A: Wall Furnace Characteristics, the South Coast Air Quality Management District and the San Joaquin Valley Air Pollution Control District require central furnaces to keep nitrogen oxide emissions below 0.033 lbm/MMBtu.

From Table 10, it is seen that the two AC2030TN furnaces stay below the NOx limit for central furnaces. The AC3040TN and TG2030TN furnaces exceed the 0.033 lbm/MMBtu NOx limit in at least one of their operating modes. The 1753012 condensing furnace's NOx emission rates were at least 2.5 times the limit in all operating modes.

Wall Furnace Energy Use and Emissions during Typical Operation

To investigate energy use and emissions further, Table 12 lists preliminary estimates of fuel use and emission rates over a typical day of operation for each retrofit furnace. Field testing showed that the average retrofit furnace was operated for an average of 1.0 on-off cycles every day for 42 minutes per cycle. Natural gas use, electricity use, and flue gas emissions were summed up over pilot, startup, standby, and shutdown operations for this typical day.

Table 12: Energy Use and Emission Rates for a Typical Day of Operation

Wall Furnace Tested		Average Energy Use and Emission Rates				
Model	Field Sites	Btu/Day	kWh/Day	CO lbm/MMBtu	NOx lbm/MMBtu	THC lbm/MMBtu
1753012 (condensing direct vent)	Hayward 3 & 4	13853	0.070	0.021	0.086	0.001
AC2030TN #1 (single-sided low NOx)	LA 104-107	24206	0.009	0.028	0.015	0.170
AC2030TN #2 (single-sided low NOx)	LA 104-107	22246	0.011	0.127	0.012	0.010
AC3040TN (double-sided low NOx)	Oakland SFH	29204	0.009	0.270	0.039	0.018
TG2030TN (self-powered low NOx)	Sacto 4, 19	21987	0.000	0.031	0.013	0.006
	Average	**22299**	**0.020**	**0.096**	**0.033**	**0.041**

Not surprisingly, the largest capacity Williams AC3040TN furnace is estimated to use the most natural gas, and the smallest capacity Williams 1753012 furnace would use the least natural gas. The 1753012 furnace also uses the most electricity.

The Williams AC3040TN furnace had the highest CO emission rate due to relatively high CO emissions during steady state operation.

The Williams 1753012 condensing furnace had the highest NOx emissions of these retrofit furnaces, due to high NOx emissions during steady state heating operation. The other three retrofit models were all low NOx furnaces, and substantial effort from the manufacturer appears to have gone into reducing their NOx emissions, as seen when comparing to the 1753012 condensing furnace emissions.

The AC2030TN #1 furnace had a high total hydrocarbon emission rate, while the AC2030TN #2 furnace had low hydrocarbon emissions. The #1 furnace appears to have had a small natural gas leak which may be representative of leaks in actual installations.

There are no standards or regulations for emissions from wall furnaces. However, as detailed in Appendix A, the South Coast Air Quality Management District and the San Joaquin Valley Air Pollution Control District require central furnaces to keep nitrogen oxide emissions below 0.033 lbm/MMBtu. The AC2030TN and TG2030TN furnaces stay below this limit, while the AC3040TN furnace just exceeds the NOx limit. The 1753012 condensing furnace has an NOx emission rate that is 2.5 times the limit.

Summary and Next Steps

Tests of retrofit wall furnaces found the following:

- Average input capacity is 109% of rated capacity, with all furnaces using more natural gas than their rating indicated
- On average, the retrofit furnaces draw about 25 W of power, but there was a lot of variation in the electricity use from furnace to furnace, and during active heating and standby operations
- These tests yielded thermal efficiency and AFUE lower than rated values for all the retrofit furnaces. On average thermal efficiency was about 4% below rated efficiency and average AFUE was about 3% below rated AFUE.
- In the non-condensing retrofit furnaces, nitrogen oxide emissions were below or just slightly over the central furnace limit of 0.033 lbm/MMBtu designated by two California air quality districts.

Overall emissions from these retrofit furnace remain quite complicated to predict, as they are not just dependent upon how much natural gas is burned. Emissions also depend on how often furnaces start up and shut down, and whether their operating cycles last long enough to reach steady state conditions.

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

Acknowledgements

The authors thank the California Energy Commission for their funding and support, as well as Southern California Gas Company for their partial sponsorship of this research, and Williams Comfort Products for providing some of the retrofit furnaces.

Thanks also to the members of this project's Technical Advisory Committee:

Jeff Horn, Alan D. Leung, and Eric Kirchhoff of the Southern California Gas Company
Francois Rongere of Pacific Gas and Electric
Helcio Blum of Lawrence Berkeley National Laboratory
Nick Dirr of the Association for Energy Affordability, Inc.
Perry Glenn of the Retirement Housing Foundation
Mary Jo Gentry and Ruth Ann Davis-McElwee of Williams Comfort Company

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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 a small number of rooms. Because they are less expensive, simpler to install, and take up less space than a central ducted furnace, they are commonly 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 calls for heating are made, 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 different 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 adding 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 be handled in different 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're generally 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 13. The date 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 13: 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 2022. (i) (1)] and furnaces manufactured after 2013 [CFR 430.32 2022. (i) (2)]. Table 14 lists the current minimum AFUE requirements for new wall furnaces. AFUE minimums were raised by at least 2% for furnaces manufactured after 2013.

Table 14: Minimum AFUE Requirements for Wall Furnaces manufactured after January 1, 1990 and April 16, 2013

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

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 are required to 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 don't 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 2022, 60.5474 (b) (4)], 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 2022, 60.5474 (b) (6)].

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 15 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 15: Emissions and Indoor Air Quality Regulations, Standards and Guidelines

Rule	Equipment	CO	NOx	PM2.5 & PM10
Code of Federal Regulation	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	Central furnaces	n/a	0.033 lbm/MMBtu (14 nanograms/Joule)	n/a
US EPA reference levels of typical indoor air pollutants	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	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	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