# Occupancy Fan Controllers

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**ABSTRACT**

Occupancy fan controllers (OFC) monitor heating, ventilating, and air conditioning (HVAC) controls and occupancy sensor signals and automatically switch HVAC fans from ON to AUTO to save energy while allowing fans to operate during thermostat calls for cooling or heating. OFCs receive wired or wireless signals from ultrasonic or passive infrared occupancy sensors in buildings or geofencing location based services. OFCs allow fans to operate in economizer cooling mode or pre/post purge mode with an adjustable time delay of 20 to 60 minutes before switching fans from ON to AUTO and enabling fan operation for cooling or heating. OFCs work with programmable or smart thermostats and building energy management systems by overriding manual fan-on controls when spaces are unoccupied. When operating in AUTO mode, OFCs close economizer dampers to reduce unconditioned outdoor airflow and provide variable fan-off delays at the end of cooling or heating cycles to improve comfort, indoor air quality, and energy efficiency. OFCs monitor building occupancy and work with smart buildings to increase energy savings. According to the Advanced Research Projects Agency-Energy (ARPA-E), occupancy-based HVAC controls are the most cost-effective measures in residential and commercial buildings with potential savings of 30% of HVAC equivalent to 2 to 4% of total annual US energy use. The potential annual savings in California are 19% of kWh, 2% of kW, and 17% of therms. The OFC measure package is approved by the California Public Utilities Commission for incentives in California energy efficiency programs.

## Introduction

Commercial HVAC accounts for 18% of peak electricity demand and consumes about 6% of total annual energy use in the United States (US) according to the US Energy Information Administration (EIA 2019). Commercial cooling consumes 32% of total annual US commercial HVAC energy while heating uses 34% and ventilation uses 34% due to continuous or hourly fan operation (EIA 2019). About 20% of this energy is used when buildings are unoccupied or occupied below maximum occupancy (EIA 2019). Occupancy fan controllers automatically detect continuous fan-on control settings when the building is unoccupied and change fan control to only operate with a thermostat call for cooling or heating. New sensor technologies can determine number of occupants while protecting privacy and modulating ventilation and temperature. Optimized ventilation with occupant counting reduces energy use while maintaining indoor air quality and comfort (ARPA-E 2022). When operating in auto mode, OFCs provide variable fan-off delays at the end of cooling or heating cycles to improve comfort and indoor air quality, lengthen off-cycle times, and save energy.

This paper provides field tests, simulation results, and information about OFCs with potential savings of 30% of HVAC equivalent to 2% to 4% of total annual US energy use (Jacobs and Higgins 2003, CAETRM 2024).

## Code Requirements for HVAC Fan Controls

The 2022 California Building Energy Efficiency Standards (Title 24) Section 120.2(e) provides three code requirement options for HVAC fan controls (CEC 2022). Occupancy sensors are one option with various exceptions, and no code requirements are provided for supply fan heating and cooling operation during unoccupied hours (CEC 2022). For specific occupancies and conditions, each space-conditioning system must be provided with controls that can automatically shut off HVAC equipment during unoccupied hours and have one of the following: (1) An automatic time switch with manual overrides that are similar/same as lighting systems. (2) An occupancy sensor compatible with ventilation pre-purge. (3) A 4-hour timer that can be manually operated to start the system (CEC 2022). Exceptions to §120.2(e)(1) are: HVAC systems serving retail, malls, restaurants, grocery stores, churches, or theaters with 7-day programmable timers do not have to comply with above requirements (CEC 2022). Pre-K and K-12 schools are also exempt.

Most new and existing buildings do not have occupancy sensors with output signals compatible with 24 volts alternating current (VAC) for HVAC systems or dry contacts on lighting occupancy sensors to use for HVAC systems. Therefore, the OFC measure with a default 20-minute occupancy sensor delay is applicable to all existing and new buildings. The OFC will allow pre-purge with economizers since the AC Y signal is energized with pre-purge economizer outdoor air, and the OFC energizes supply fans when thermostat AC Y or heat W signals are energized even if the building is unoccupied.

## Experimental Methods and Models

Laboratory experimental tests were performed at Intertek®, an Air-Conditioning, Heating, and Refrigeration Institute (AHRI) certified laboratory, located in the United States. The laboratory is used by manufacturers to certify air conditioners and heat pumps for AHRI equipment efficiency testing for the U.S. Department of Energy (DOE) compliance and enforcement program to meet energy conservation standards required by the Energy Policy and Conservation Act of 1975 as amended (GAO 1975). The test facility consists of climate-controlled indoor and outdoor chambers where ducts, evaporator, condenser, furnace or hydronic heating equipment and forced air units are located. HVAC systems and test equipment were assembled and installed in the test chambers by laboratory technicians. Cooling verification tests were performed according to the AHRI Standard 340/360 2019 (AHRI 2019). Economizer airflow tests were performed according to American National Standards Institute (ANSI) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE) 41.2-1987 Standard Methods for Laboratory Airflow Measurement (ANSI/ASHRAE 1987). Thermal efficiency tests were performed according to ANSI Z21.47-5th Edition 2006/CSA 2.3-5th Edition 2006 (ANSI/CSA 2006). Laboratory test equipment was calibrated per International Organization for Standardization (ISO) 17025 by an accredited provider per the International Laboratory Accreditation Cooperation (ILAC) (ISO 2017).

### Tested HVAC Units

**Table 1** describes three packaged HVAC roof top units (RTUs) tested at Intertek® and one packaged RTU (unit #4) tested in the field. Intertek is an ISO-certified laboratory used by manufacturers and USDOE to test HVAC equipment for compliance with Federal energy efficiency standards. The following RTUs were tested at Intertek: 1) 3-ton DX AC gas furnace unit #1, 2) 4-ton heat pump unit #2, and 3) 7.5-ton two-compressor DX AC gas furnace unit #3. Field tests were performed on a 10-ton two-compressor DX AC gas furnace unit #4 installed on a commercial office building in Reno, Nevada.[1] Equipment was set up in two chambers at the laboratory to emulate indoor and outdoor conditions per AHRI 340/360 (AHRI 2019). Test conditions differ from rated conditions to match typical installations in California.[2]

**Table 1** provides a description of laboratory and field test units and measured economizer outdoor air flow (OAF) rates for closed, minimum, and fully open damper positions. ASHRAE 62.1, Ventilation for Acceptable Indoor Air Quality specifies minimum outdoor air flow (OAF) rates for commercial buildings to dilute contaminants from people, equipment, and other sources (ANSI/ASHRAE/IES 2019). The standard recommends fresh air OAF rates in cubic feet per minute per person (cfm/person), with a general rule of 10 to 15 cfm/person for occupied buildings. Building codes in California require economizers on HVAC systems greater than or equal to 36 kBtuh (CEC 2022). Existing economizers generally allow 20% to 35% OAF at 3.6 volts (V) ($0.2*8V_{range} + 2V_{offset} = 3.6V$) or "one finger open" for minimum ventilation per **Table 1** (pp.18-19 Mowris 2016, DNVGL 2014, DNVGL 2016, Jacobs and Higgens 2003). With unsealed supply and return damper perimeter gap, economizers provide 61% to 78% OAF with fully open dampers at 10V and 16% to 28% OAF with closed dampers at 2V per **Table 1** (Ibid).

Table 1: Description of laboratory and field test Units #1, #2, #3, and #4

| **Description** | **Unit #1: 3-ton DX AC Furn** | **Unit #2: 4-ton Heat Pump** | **Unit #3: 7.5-ton DX AC Furnace** | **Unit #4: 10-ton DX AC Furnace** |
|---|---|---|---|---|
| Model | 48HJM004 | 50HJQ005 | 48HJF008-541 | RKMB-A120M2 |
| Rated SEER/EER | 13 SEER/11 EER | 13 SEER/10.5 EER | 11 EER | 9 EER |
| Rated heating eff. | 81% Efficiency | 7.8 HSPF | 82% Efficiency | 81% Efficiency |
| Rated cooling capacity, airflow, static pressure (IWC) | 36 kBtuh total, 25 kBtuh sensible, 1050 cfm at 0.5" | 49 kBtuh total, 36 kBtuh sensible, 1600 cfm at 0.5" | 93 kBtuh total, 67 kBtuh sensible, 3000 cfm at 0.5" | 120 kBtuh total, 90 kBtuh sensible, 4000 cfm at 0.3" |
| Refrigerant charge | R410A 102 oz | R22 192 oz | R22 105/105 oz. | R410A 80/80 oz |
| Economizer OAF (closed, minimum, fully open) | Unsealed 23%, 31%, 66% | Unsealed 28%, 31%, 64%. Sealed 15%, 19%, 94% | Unsealed 16%, 24%, 61% | Unsealed 16%, 35%, 68%. Sealed 4%, 20%, 96% |
| Rated heating capacity, airflow, static pressure | 40,087/49,985 Btu/hr, 1,050 scfm @ 0.4 IWC | 46,500 Btu/hr 1600 scfm at 0.5 IWC | 72,900/102,500 Btu/hr 3000 scfm at 0.5 IWC | 112,000/225,000 Btuh 4,000 scfm at 0.8 IWC |
| Fan-off delay default | Fixed 30 sec. cool | 0 seconds heat/cool | 0 seconds heat/cool | Fixed 90 sec. heat |

The OFC saves HVAC energy by setting fans to AUTO and closing economizer dampers when unoccupied to reduce unconditioned outdoor airflow by about 10%. **Figure 1** shows

[1] One ton of cooling equals 12,000 British thermal units per hour (Btu/hr) equivalent to energy removed from 2,000 pounds (lbs) of water over 24 hours to make one ton of ice at 32°F (0°C) based on 144 Btu/lb (heat of fusion) times 2,000 lbs water or 288,000 Btu. One Btu equals energy to raise one pound (lb) of water one degree Fahrenheit (F).
[2] Cooling tests were performed at 82°F, 95F, 105F, and 115F dry bulb (DB) OAT and 75F DB and 62F wet bulb (WB) return temperature. Gas heating tests were performed at 47F OAT and 72F DB and 53°F WB (AHRI 2019).

laboratory tests of average outdoor air fractions (OAF) (y) versus economizer damper actuator control voltage (x) for base and sealed supply/return economizer perimeter gap for the four units in **Table 1** (Mowris et al. 2016). Conventional building energy models assume economizer OAF (y) is proportional to economizer actuator voltage (x) where closed position provides 0% OAF and fully open provides 100% OAF for economizing. Sealing the economizer supply/return perimeter gap between the economizer frame and HVAC system cabinet reduces outdoor airflow from 21% to 10% at the 2V closed damper position and increases outdoor airflow from 65% to 95% at the 10V fully open economizer position (Mowris et al. 2016). The base economizer provides 31% OAF at 3.6V, and economizer with sealed perimeter gap provides 20% OAF at 3.6V. Potential peak capacity savings are 10%. Sealing economizer supply/return perimeter gaps brings economizer OAF values closer to conventional building energy model assumptions.

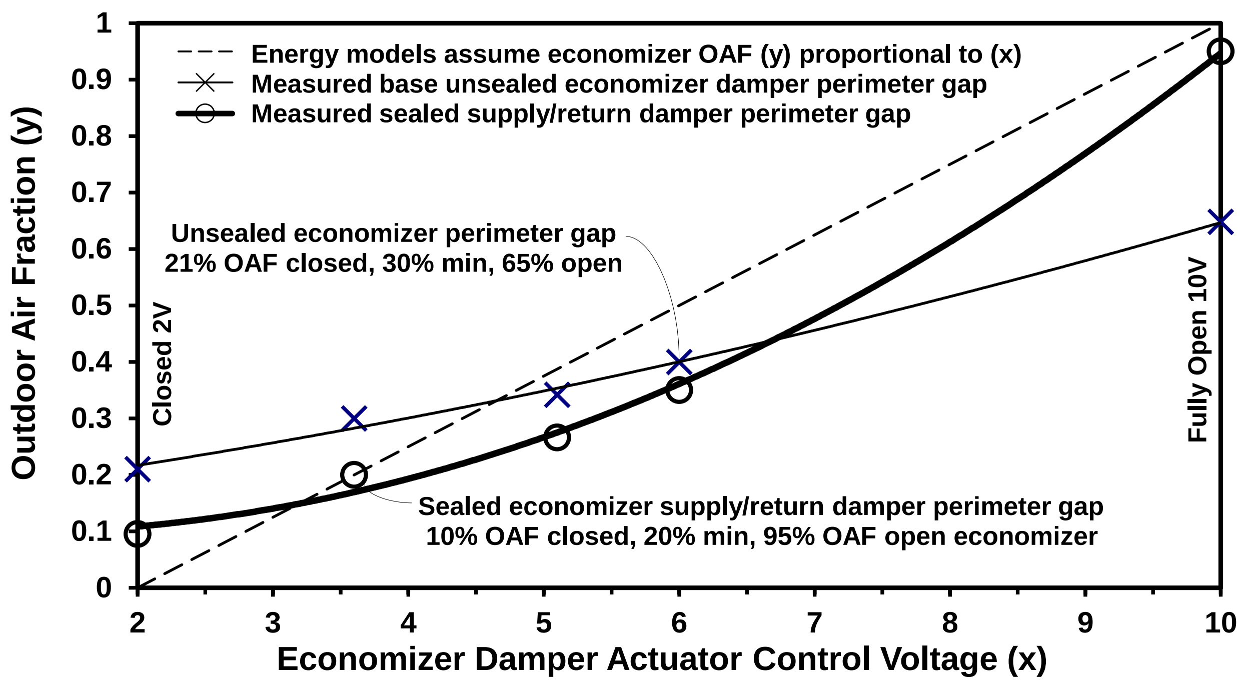


Figure 1. Laboratory tests of average economizer OAF for base and sealed supply/return economizer damper perimeter gap. *Source: Mowris et al. 2016.*

## Building Energy Simulation Models

Building energy simulation models (Energy Plus) are used to calculate energy use and energy savings (Crawley et al. 2000, Mowris Larson 2020, Mowris Jacobs 2022, Mowris et al. 2016, LBNL 2014). The base case is modeled in EnergyPlus with a supply fan schedule operating continuously 24 hours per day and 7 days per week (24x7). The OFC measure is modeled by only operating fan during thermostat calls for cooling or heating during unoccupied periods and setting NIGHT-CYCLE-CTRL to “CYCLE-ON-ANY” (Mowris Larson 2020). The OFC variable fan-off delays for cooling and heating are modeled in a post processor with energy savings versus PLR curves (CAETRM 2024). When operating in AUTO mode, the OFC provides variable fan-off delays at the end of cooling or heating cycles to improve comfort and indoor air quality, lengthen off-cycle times, and save energy.

Four HVAC types were modeled: 1) AC only, 2) AC with gas heat, 3) heat pump, and 4) variable volume AC unit with gas heat. The following twenty (20) commercial building prototypes were modeled: Assembly, Big Box Retail, Bio/Tech Manufacturing, Community College, Conditioned Storage, Department Store, Fast-Food Restaurant, Grocery, Hotel, Large Office, Light Industrial Manufacturing, Primary School, Refrigerated Warehouse, Relocatable Classroom, Secondary School, Sit-Down Restaurant, Small Office, Small Retail, University, Multifamily Common Area (CAETRM 2024).

Economizer outdoor airflow was modeled based on laboratory and field tests of packaged unit economizer OAF values from **Table 1**. Building energy simulations of 20 commercial building prototypes in sixteen (16) California climate zones are used to develop cooling, heating, and fan energy use intensities (EUIs) per unit floor area ($ft^2$) by HVAC type for the base case and the OFC measure (CAETRM 2024).

## Occupancy Fan Controller

The OFC comprises one or more sensor technologies to detect when a conditioned space is unoccupied, detect continuous fan operation, set fan control to auto, close economizer dampers, and only operate fan during calls for cooling or heating. OFC sensor technologies can determine the number of occupants while protecting privacy and modulating ventilation and temperature (Sun et al. 2020, Zhao 2022). OFC returns control to continuous fan ON during occupied periods per building occupancy for minimum outdoor airflow per ASHRAE 62.1. OFC may lower fan speed based on occupancy to save energy and maintain air quality and comfort.

**Figure 2** shows the base continuous fan ON uses 47.2 kWh over 24 hours. **Figure 2** shows OFC uses 33.1 kWh over 24 hours or 30% less energy than the base (CAETRM 2024, Mowris et al. 2020, 2021, 2021a, 2024). OFC saves energy by setting fan to AUTO with variable fan-off delays and closing economizer dampers when unoccupied from 10PM to 8AM.

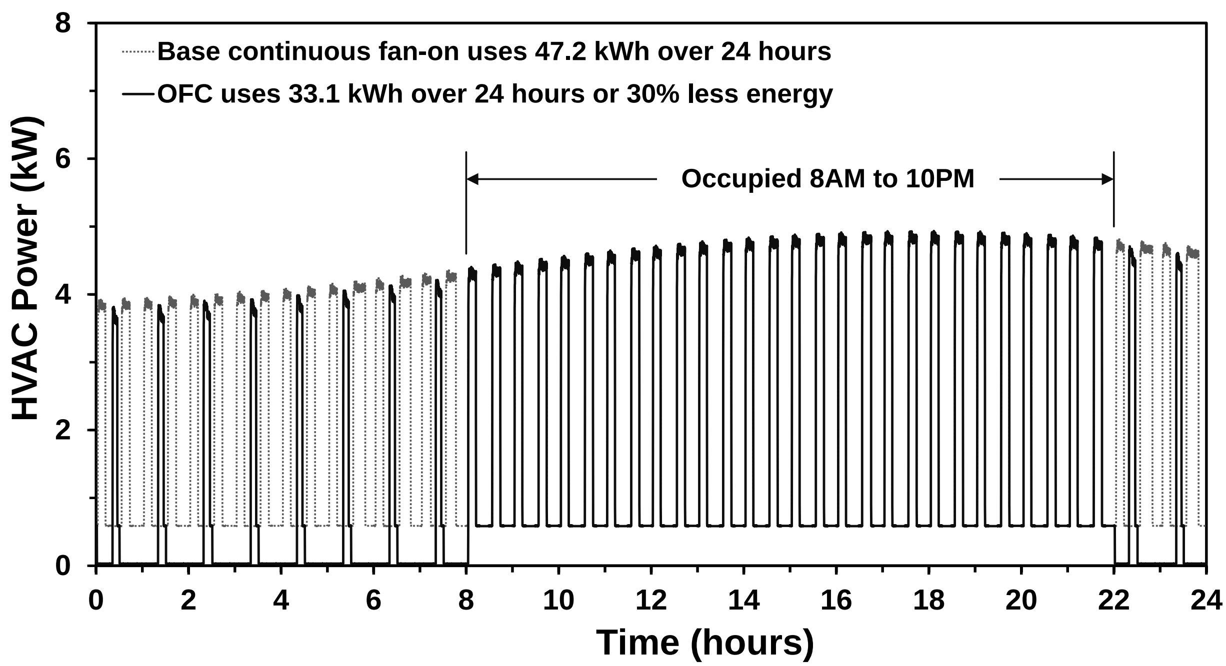


Figure 2: OFC detects continuous fan ON, sets fan to AUTO, closes economizer dampers, and uses 30% less HVAC energy. *Source: CAETRM 2024, Mowris Larson 2020, Mowris Walsh 2021, 2021a, 2024.*

The base uses 30% more energy due to continuous fan ON plus economizer dampers open at minimum position (20 to 30% OAF) which introduces more unconditioned outdoor air causing more frequent cooling or heating cycles. The base has 20 longer HVAC cycles (11.6 minutes average) when unoccupied versus 10 shorter HVAC cycles (7.2 minutes average) for OFC. The OFC has shorter, less frequent HVAC cycles when unoccupied due to fan AUTO (i.e., off unless call for cooling or heating), closed economizer dampers, and variable fan-off delays.

The OFC detects continuous fan-on settings when building is unoccupied or marginally occupied and changes fan control to operate with a thermostat call for cooling or heating or reduces fan speed based on occupant count to maintain minimum outdoor airflow and save energy. According to ARPA-E, occupancy-based HVAC controls are the most cost-effective measures in residential and commercial buildings with potential savings of 30% of HVAC equivalent to 2 to 4% of total annual US energy use (ARPA-E 2022).

When unoccupied, the OFC sets fan to AUTO and provides variable fan-off delays after each cooling or heating cycle to improve energy efficiency and indoor air quality. Cooling variable fan-off delays improve comfort and indoor air quality by removing 0.6 to 0.8 pounds (lbs) of water from evaporator coils after each cooling cycle preventing biofilms (bacteria, viruses, fungi, mold), and maintaining proper airflow (Bakker et al. 2019, Montana State University 2024). Biofilms on cooling evaporator coils can significantly reduce heat transfer efficiency and may lead to aerosolization of microbes into occupied spaces of a building causing diseases and allergies (Ibid.).

## OFC Variable Fan Off Delay

Laboratory tests of the OFC cooling variable fan-off delay for unit #1 and #2 versus base are shown in **Table 2** and **Figure 3** (CAETRM 2024). Test results show weighted average cooling savings versus part load ratio (PLR) based on Intertek® tests. The cooling PLR is based on delivered sensible cooling capacity in British thermal units (Btu) for an AC over an operating time period less than one hour divided by the AC or heat pump sensible cooling capacity delivered for one hour.

**Eq. 1** Cooling PLR = sensible cooling load (Btu/hr) / sensible AC cooling capacity (Btu/hr)

**Table 2** summarizes Intertek tests of 3-ton unit #1 operating for 30 minutes and 4-ton unit #2 operating for 2 to 50 minutes at 82F, 95F, 105F, and 115F OAT (CALETRM 2024). Savings are weighted based on 77% no delay, 11.9% 45-second delay, and 11.1% 60-second delay based on a sample of 5582 AC units where 4298 units or 77% had no fan-off delay (Ibid).

Table 2: Cooling Weighted Average Savings vs. PLR at 82, 95, 105, and 115F OAT (Intertek)

| AC Run Time (Minutes) | PLR | OFC Savings vs. No delay (%) | OFC Savings vs. 45-sec delay (%) | OFC Savings vs 60-sec delay (%) | Weighted Ave. Savings |
|---|---|---|---|---|---|
| 2 | 0.01 | 40.0% | 10.8% | 8.3% | 33.0% |
| 5 | 0.04 | 30.8% | 14.6% | 10.5% | 26.6% |
| 10 | 0.13 | 14.9% | 8.4% | 6.8% | 13.2% |
| 20 | 0.32 | 7.8% | 4.8% | 4.1% | 7.0% |
| 30 | 0.48 | 5.7% | 3.6% | 3.1% | 5.1% |
| 50 | 0.83 | 3.3% | 2.1% | 1.8% | 3.0% |
| **Ave. cool savings** | | | | | **14.7%** |

A cooling PLR regression equation curve fit is shown in **Figure 3**. The weighted average savings are based on fixed fan-off delays of 0, 45, 60, and 90 seconds for the base case at 82F, 95F, 105F, and 115F outdoor air temperature (OAT). Intertek tests were also performed with 18% to 30% economizer outdoor airflow which provided similar savings. The cooling variable fan-off delay savings are modeled using a post processor and the following equation.

**Eq. 2** $y_{cool} = 0.0327\ x^{(-0.601)}$

Where, $y_{cool}$ = cooling energy savings (dimensionless), and
x = PLR cooling capacity divided by total cooling capacity (dimensionless).

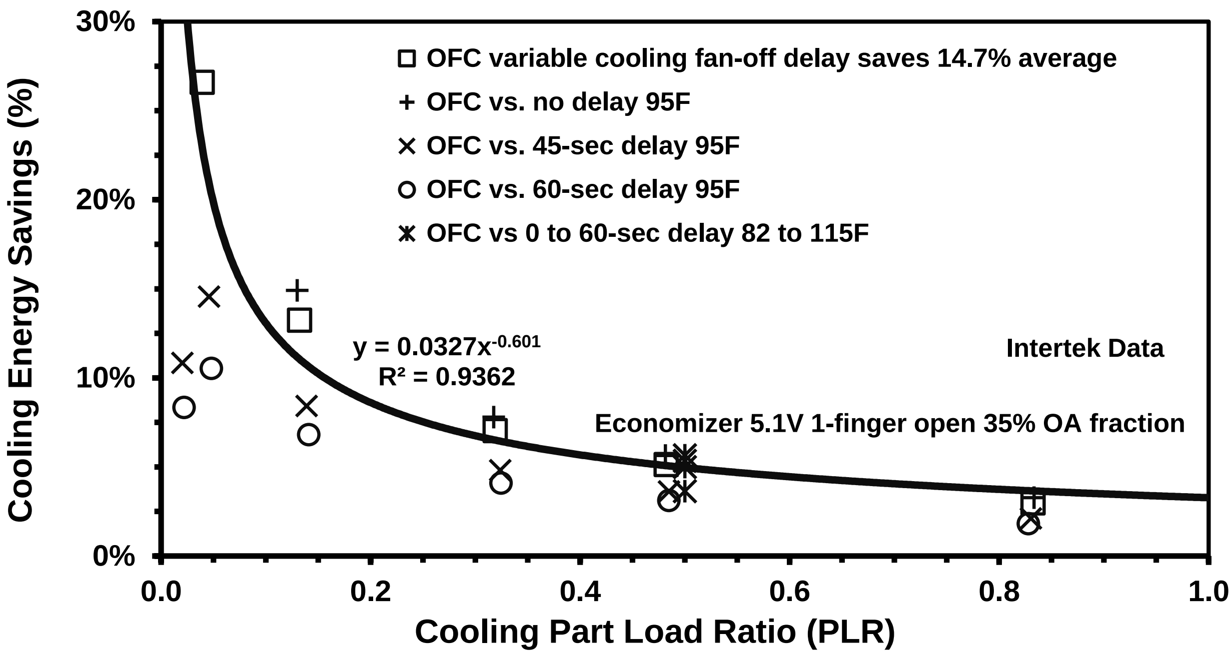

Figure 3. Laboratory tests Unit #2 (cooling) variable fan-off delay vs. base. *Source: CAETRM 2024.*

Laboratory tests of the OFC heating variable fan-off delay for unit #1 versus base are shown in **Table 3** and **Figure 4** (CAETRM 2024). Test results show weighted average heating savings versus PLR based on Intertek® tests. The heating PLR is calculated based on delivered heating capacity in Btus) for a gas furnace or heat pump over an operating time period of less than one hour divided by the gas furnace or heat pump heating capacity delivered for one hour.

**Eq. 3** Heating PLR = heating load (Btu/hr) / gas furnace heating capacity (Btu/hr)

The following table summarizes Intertek tests of the OFC gas furnace heating savings versus 45-second and 60-second fixed base delays and 17F and 47F OAT (CAETRM 2024). Average savings are based on savings for 0, 45, and 60-second delays (Ibid.).

Table 3: Heating weighted average gas savings vs. PLR at 17F and 47F OAT (Intertek)

| Furnace Run Time (minutes) | PLR | OFC Savings vs. no delay (%) | OFC Savings vs. 45-sec delay (%) | OFC Savings vs 60-sec delay (%) | Weighted Ave. Savings |
|---|---|---|---|---|---|
| 2 | 0.01 | 45.4% | 29.8% | 40.5% | 25.6% |
| 5 | 0.04 | 27.8% | 22.2% | 22.2% | 17.0% |
| 10 | 0.12 | 15.9% | 13.3% | 12.5% | 10.0% |
| 20 | 0.29 | 8.4% | 7.1% | 6.7% | 5.4% |
| 30 | 0.47 | 5.4% | 4.6% | 5.8% | 5.0% |
| 50 | 0.83 | 3.0% | 2.5% | 3.9% | 2.4% |
| **Ave. heat savings** | | | | | **14.3%** |

A heating PLR regression equation curve fit is shown in **Figure 4**. The weighted average heating savings are based on fixed fan-off delays of 0, 45, and 60 seconds for the base case at 17°F and 47°F outdoor air temperature (OAT). The heating variable fan-off delay savings are modeled using a post processor and the following equation.

**Eq. 4** $y_{heat} = 0.0357\ x^{(-0.523)}$

Where, $y_{heat}$ = gas heating energy savings (dimensionless), and
x = PLR heating capacity divided by total heating capacity (dimensionless).

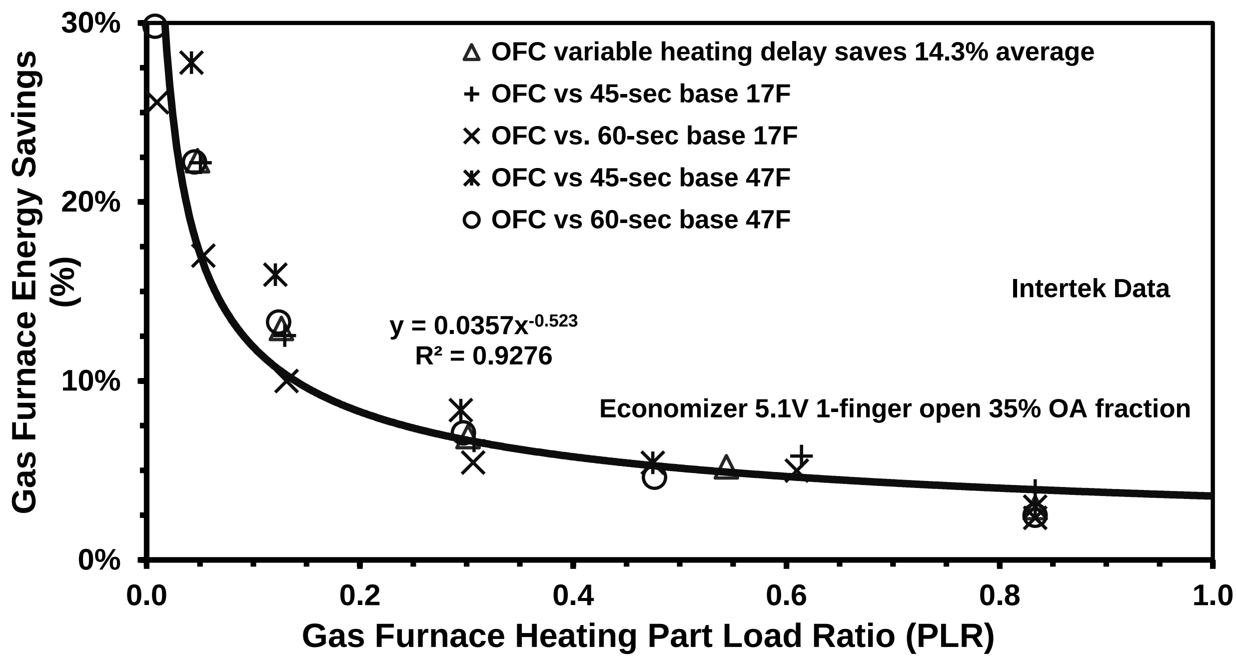


Figure 4. Laboratory tests Unit #1 heating variable fan-off delay vs. base. *Source: CAETRM 2024.*

## Energy Impacts

OFC applies to all buildings with or without continuous fan operation. OFC sensors detect occupancy and OFC sets fan control from ON to AUTO only operating fan during cooling or heating to save 10 to 12%. OFC provides variable fan-off delays after each cooling or heating cycle to save 5 to 7%. OFC closes economizer dampers to save 2 to 3%. If supply fan is not operated continuously, then OFC saves 11 to 12% on variable fan-off delays and closes economizer dampers when unoccupied to save 6 to 7% so total savings are 17 to 19%.

**Table 4** provides a summary of building energy simulation modeling results for the base and OFC energy intensity per unit floor area ($ft^2$) and percentage (%) energy savings by HVAC type for all buildings. Average savings are 19% +/- 2% of kWh/yr, 2% +/- 0.5% of kW, and 17% +/- 3% of therm/yr. Peak demand savings are about 10 times less than kWh savings due to OFC saving energy during unoccupied off-peak hours. OFC measure costs are $200 per ton for materials plus installation with an effective useful life or 5 years as an add on equipment (AOE) measure. The average total resource cost (TRC) ratio is 4.8. Based on energy savings and cost effectiveness, the OFC measure is approved by the California Public Utilities Commission (CPUC) for incentives in California energy efficiency programs (CAETRM 2024).

Table 4: Baseline and OFC energy intensity and energy savings by HVAC type for all buildings

| **HVAC type** | **Base kWh/y/ft²** | **Base kW/ft²** | **Base th/y-ft²** | **OFC kWh/y-ft²** | **OFC kW/ft²** | **OFC th/y-ft²** | **kWh Savings** | **kW savings** | **Therm Savings** |
|---|---|---|---|---|---|---|---|---|---|
| AC only | 9.040 | 0.008 | | 7.766 | 0.007 | | 14.1% | 1.3% | |
| AC Gas Heat | 9.247 | 0.008 | 0.059 | 7.958 | 0.007 | 0.051 | 13.9% | 1.3% | 12.9% |
| Heat Pump | 3.290 | 0.003 | | 2.394 | 0.003 | | 27.2% | 3.3% | |
| Var Vol. | 3.324 | 0.004 | 0.185 | 2.683 | 0.004 | 0.145 | 19.3% | 0.4% | 21.8% |
| **Average.** | **6.225** | **0.006** | **0.061** | **5.200** | **0.005** | **0.049** | **19±2%** | **2±0.5%** | **17±3%** |

## Conclusions

The OFC monitors HVAC controls and occupancy sensor signals and automatically switches HVAC fans from fan-on continuously to auto and closing economizer dampers to save energy while allowing fans to operate during thermostat calls for cooling or heating and providing variable fan-off time delays after cooling or heating cycles. OFC sensor technologies can also determine the number of occupants to reduce energy use while maintaining indoor air quality and comfort. OFCs receive wired or wireless signals from ultrasonic or passive infrared occupancy sensors in buildings, occupant counting systems, or geofencing location based services. OFCs allow fans to operate in economizer cooling mode or pre/post purge mode with an adjustable time delay of 20 to 60 minutes before switching fans from ON to AUTO and enabling fan operation for cooling or heating. OFCs work with programmable or smart thermostats and building energy management systems by overriding manual fan ON controls when spaces are unoccupied. When operating in AUTO mode, OFCs close economizer dampers to reduce unconditioned outdoor airflow and provide variable fan-off delays after cooling or heating cycles to improve comfort, indoor air quality, and energy efficiency. OFCs monitor building occupancy and work with smart buildings to increase energy savings. Simulations of 20 prototypical commercial buildings in 16 California climate zones indicate average potential annual savings are 19% of kWh, 2% of kW, and 17% of therms. The OFC measure package is approved by the CPUC for incentives in California energy efficiency programs.

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