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A Field Study of Wall Furnace Venting and Coincident Exhaust Fan Usage in 16 Northern California Apartments

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DISCLAIMER

Abstract

To inform efforts to improve combustion appliance testing in residential energy efficiency programs, we studied the frequency of coincident fan use and depressurization-induced downdrafting and spillage from atmospherically vented (i.e., natural draft) wall furnaces in airtight apartments. Indoor environmental conditions, heating appliance operation, use of exhaust fans, and cooking with stovetop or oven were monitored for approximately three weeks each in 16 apartment units in two buildings in Northern California. Apartments also were assessed using standard combustion appliance safety test methods and enhanced protocols. Monitoring occurred in February and March of 2016, with heating demand corresponding to 7.3 ± 0.5 heating degree-days at a 65ºF reference temperature. Most of the furnaces spilled combustion products when the apartments were depressurized in the "worst-case" challenge condition of all exhaust fans operating at their highest settings and all windows closed. Many also spilled under less challenging conditions (e.g., with kitchen exhaust fan on low and bathroom fan operating). On average, bathroom exhaust fans were operated 3.9% of monitored minutes (13.5% max), and cooking (burner or kitchen fan operation) occurred 4.6% of minutes (max 13.3%). Event lengths averaged 17 minutes (max 540) and 34 minutes (max 324), respectively. Their coincident operation averaged 0.34% of minutes (max 2.0%), with average event length of 13 minutes (max 92 minutes). This suggests that the operation of apartment units at or near the currently used worst-case challenge condition is quite rare. Wall furnace burners operated an average of 2.8% of minutes (max of 8.9%), with average burner cycle length of 14 minutes (max 162). Coincident bath fan use, cooking and wall furnace operation was very rare, occurring only a handful of times across all apartments. The highest rate was 0.075% of monitored minutes in one apartment, and the longest event length was 12 minutes. Exhaust fan operation in this study may have been more frequent than typical as participants were asked to use an exhaust fan whenever cooking or bathing. Consistent with the low levels of coincident operation, unambiguous spillage occurred in only 4 apartments and the longest event was 5 minutes. The frequency of partial spillage is unknown, owing to a lack of a clear signal from monitored parameters. Downdrafting during exhaust fan use occurred in all 13 of the apartments with relevant data, and 9 of these units had 10 or more events. Exhaust fans also sometimes led to weakened draft, even if downdrafting did not occur. Each unambiguous spillage event identified in the study was immediately preceded by downdrafting. The observed occurrence of downdrafting and spillage may have been impacted in those apartments with the most severe drafting problems (i.e., appliances spilled combustion pollutants under 'natural' test conditions), because occupants in these units were instructed to open windows whenever using the kitchen exhaust fan.

Acknowledgements

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Executive Summary

OBJECTIVE

The goal of this research was to inform efforts to improve combustion appliance safety testing to identify true hazards that require remediation, leading to a larger fraction of program dollars being spent on efficiency while also reducing risk. To this end, we studied the frequency of coincident fan use and depressurization-induced downdrafting and spillage from atmospherically vented wall furnaces in airtight apartments.

METHOD

Indoor environmental conditions, heating appliance operation, use of exhaust fans, and cooking with stovetop or oven were monitored for approximately three weeks each in 16 apartment units in two buildings in Northern California. The apartments were airtight and all had natural draft wall furnaces. These units were also assessed for combustion appliance safety (CAS) using standard test methods and enhanced protocols. Monitoring occurred in February and March of 2016, with heating demand corresponding to 7.3 ± 0.5 heating degree-days (65ºF reference temperature)

RESULTS

Most of the studied apartments failed a key test of many CAS protocols, as their wall furnaces spilled combustion gases to varying degrees under "worst-case" depressurization conditions of all exhaust fans being operated at their highest settings and all windows closed. In many apartments, the wall furnaces also spilled under less challenging conditions, e.g. with kitchen exhaust fan on low and bathroom fan operating. Other hazards were identified by natural condition appliance tests including high burner CO (>1,000 ppm) in one unit and repeated tripping of spill switches under as-found conditions. All readily correctable hazards were addressed prior to monitoring.

Post-hoc review of temperature measurements in the vent and draft diverter, suggest that technician assessments of venting may not always identify conditions of partial spillage. Alternatively, it could be that using measurements of vent and draft diverter temperatures is not sufficient for identification of partial spillage observed visually with a smoke stick.

On average, bathroom exhaust fans were operated 3.9% of monitored minutes (13.5% max), and cooking (burner or kitchen fan operation) occurred 4.6% of minutes (max 13.3%). Event lengths averaged 17 minutes (max 540) and 34 minutes (max 324), respectively. Their coincident operation averaged 0.34% of minutes (max 2.0%), with average event length of 13 minutes (max 92 minutes). We included cooking burner use in the coincident operation analysis to be consistent with healthy homes guidance that the kitchen exhaust fan should be used whenever the cooking burners are used. The calculated operating frequency of the kitchen fan or cooking metric provides an upper bound estimate for the frequency of the worst-case conditions used in current CAS testing.

Wall furnace burners operated an average of 2.8% of minutes (max of 8.9%), with average burner cycle length of 14 minutes (max 162). Coincident bath fan use, cooking and wall furnace operation was very rare, occurring only a handful of times across all apartments. The highest rate was 0.075% of monitored minutes in one apartment, and the longest event

length was 12 minutes. The coincidence of wall furnace operation with all exhaust fans would increase somewhat with furnace runtime during colder weather, but still be bounded by exhaust fan coincidence. Coincident operation of any two appliances (e.g., heating and bath fan, or kitchen range hood and bath fan, etc.) was generally at least an order of magnitude less frequent than solo operation of either appliance.

Despite the low frequency of worst-case exhaust fan coincidence, wall furnace downdrafting was quite common and in some cases occurred for periods of several hours. Downdrafting was more common in apartments with continuous bathroom exhaust fans. Downdrafting is of concern as it creates a condition that makes spillage more likely. Each unambiguous spillage event identified and visually reviewed during this study was immediately preceded by downdrafting.

Unambiguous spillage occurred in only four of sixteen apartments. The longest spillage event was five minutes. The frequency of partial spillage or imperfect venting of wall furnace exhaust is uncertain, as the monitored parameters did not provide a clear signal to identify weak draft and partial spillage, as was observed and recorded in some cases by the technician conducting the CAS challenge tests.

IMPLICATIONS AND RECOMMENDATIONS

The finding that coincident fan usage was infrequent and typically not of long duration supports the idea that the challenge condition for combustion safety testing should not entail operating all available exhaust fans at their highest settings. An alternative could entail operating the two largest exhaust fans or possibly only the single largest exhaust fan. The findings of somewhat frequent downdraft, and very few spillage events – with none lasting longer than 5 min – were subject to potential biases that leave questions about the potential for extended spillage unresolved. Exhaust fan operation during the study may have been more frequent than a typical home since the residents were asked to use the bath fan during all bathing and the kitchen fan during all cooking. In the other direction, the frequency of downdrafting and spillage may have been reduced by residents of particularly vulnerable apartments following the guidance to open a window when using the kitchen exhaust fan. Window operation was not monitored. Also, since the study was conducted under relatively mild weather conditions, the frequency of furnace burner firing may not have been representative of mid-winter conditions.

As direct follow-up to this study, we recommend targeted additional research to understand the frequency of downdrafting and spillage of atmospherically vented, natural gas wall furnaces in airtight apartments that have baseline mechanical ventilation meeting the ASHRAE 62.2 standard, and that are operated entirely at the discretion of residents (i.e., with no instructions about exhaust fan or window use.) Wall furnaces may be more vulnerable than central furnaces because their smaller burners produce a smaller volume of hot exhaust gases to establish upward draft when the vent is in a downdraft condition. We recommend specific focus on smaller volume apartments that can be more easily depressurized with one or two exhaust fans operating coincidentally.

Research into the safety of natural gas appliances in California homes, would be most cost-effectively accomplished if data that are already being collected during CAS tests could be efficiently compiled and organized, allowing the implementers to record supplemental information with minimal additional effort for research purposes. This would require CAS data recording in digital formats that could be compiled into databases for analysis. We recommend that CAS procedures continue to emphasize carbon monoxide measurements in the flue or vent to identify improperly functioning burners, and careful visual inspection to identify improper venting and combustion ventilation air supply.

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1 Introduction

The assessment of combustion appliance safety (CAS) is a cornerstone of the health and safety provisions embedded in nearly all of the residential energy retrofit programs in the United States (US). Although no specific risk reduction objectives are identified, the general understanding is that testing is designed to protect residents against exposures to air pollutants that can be generated in the combustion process, to keep excess moisture from being introduced into the residence, and of course to identify gas leaks.

Combustion products are primarily composed of carbon dioxide (CO_2) and water vapor; the large quantities of moisture that get introduced into the residence when larger combustion appliances are not venting can degrade materials and increase risk of dampness and mold-related illness. Combustion also produces nitrogen oxides (NO_x), including some in the form of the respiratory irritant nitrogen dioxide (NO_2), and can produce carbon monoxide (CO) and "ultrafine" particles at levels that present hazards to occupants.

All combustion safety testing protocols allow a brief period of spillage during cold start-up at the beginning of a heating cycle, but the time within which venting must begin varies from one to five minutes. Likewise, the requirements for assessing venting robustness vary, both programmatically and in practice. Starting with a smoke pencil placed adjacent to the draft diverter, some implementers consider venting acceptable when the majority of the smoke is pulled up into the vent, even if it meanders and some escapes. Others require that all of the smoke be pulled into the vent directly. The quantitative connection between these standards and the fraction of combustion gases that will spill in practice is not known.

The majority of combustion appliances in U.S. residences vent properly (i.e., no prolonged spillage of combustion by-products) during "natural" condition tests[1]. For appliances that use indoor air for combustion – in contrast to "direct vent" appliances that draw combustion air directly from outdoors – depressurization of the combustion appliance zone (CAZ) can weaken or reverse flow in the vent pipe, resulting in spillage of combustion products. The CAZ is the interior space that contains the combustion appliance and in many cases can be limited or expanded by opening or closing interior doors. Depressurization can be impacted by weather, exhaust fan usage, use of vented clothes dryers, interior door positions and forced air system operation. Accordingly, all CAS procedures include some sort of challenge test, in which the house is intentionally set up to depressurize the CAS with respect to outdoors and venting / spillage is evaluated. The current standard is to set up a "worst-case" depressurization (WCD) challenge condition in which all exhaust devices that can "communicate" with the appliance by being in a continuous airflow path are turned to their highest settings. Some test protocols require the implementer to find the condition of maximum depressurization between the CAZ and outdoors by operating all exhaust fans on highest settings then opening and closing interior doors and operating and

[1] Appliances failing natural condition tests often have clear defects, in that they violate code requirements for combustion ventilation air, flue pipe design, etc. or they have developed defects in use, such as clogged flue vent pipes, due to bird nests or the like.

not operating the forced air system. Other tests prescribe door position and whether the forced air system is used to set up a “worst-case” challenge.

In the past several years, some consensus has developed around the belief that worst-case testing is overly conservative and that it may result in many “safe” residences failing CAS inspections (Rapp, Less, Singer, Stratton, & Wray, 2015). These purported false-positives lead to reductions in the efficacy of energy retrofit programs, either through diversion of program funds towards remediation of perceived (but not real) combustion hazards, or by limiting energy-saving air-sealing in apartments deemed to be at risk of failing a CAS test. Many multifamily energy retrofit programs require that initial testing and remediation be performed before any energy retrofit work can commence; however, these programs do not provide the funding for the remediation work. As a result, it is not uncommon for otherwise strong energy retrofit candidate projects to drop out of these programs because they cannot, or do not want to incur the remediation costs.

National consensus standards for CAS testing (e.g., BPI Standard 1100, ACCA BSR/ACCA 12 QH -201x) have recently eliminated depressurization thresholds for the CAZ, such that appliances only fail worst-case tests if they actually spill combustion products during depressurization testing or fail based on other criteria (e.g., flue CO concentration). This is a large improvement, as the depressurization thresholds were not robust predictors of appliance spillage: some appliances spilled below the threshold while others continued to draft when the CAZ was depressurized beyond the threshold. Other improvements to test procedures are being considered and adopted in standards and being practiced by energy retrofit implementers.

California energy efficiency programs employ a variety of CAS tests and procedures. The programs vary in scope and scale, from providing a basic, prescribed package of efficiency measures to low-income residences to energy-savings-based rebate programs for homeowners. The Department of Community Services and Development (CSD) is the primary agency responsible for low-income weatherization programs in California. These include State of California weatherization programs—the Low-Income Heating Energy Assistance Program (LIHEAP)[2] and the Low-Income Weatherization Program (LIWP)[3]—as well as federal weatherization funded by the U.S. Department of Energy (USDOE). Weatherization programs administered by CSD use the Combustion Appliance Safety Inspection Form (CASIF) and instructional supplements in its CAS testing. This includes a revised Combustion Appliance Safety Protocol released in April of 2015. These California low-income weatherization programs touch approximately 2,000 (USDOE Wx), 12,000 (LIHEAP) and 11,100 (LIWP) residences per year. The Energy Savings Assistance (ESA)[4] program also serves low-income residences throughout the state. This program is administered by the investor-owned utilities (IOUs), and touches an order of magnitude more residences (i.e., more than 364,000 in 2014 and 2 million residences from 2009 to

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[2] Funded by the California Department of Health and Human Services.

[3] Funded by proceeds from the California cap and trade program administered by the California Air Resources Board (CARB).

[4] Funded by the California Public Utilities Commission (CPUC).

2014). The ESA programs have lower per-house budgets, and they use the Natural Gas Appliance Test (NGAT) procedures for ensuring combustion appliance safety. Market-rate programs retrofitting residences in the state include the Advanced Home Upgrade[5] program (formally Energy Upgrade California) administered by the investor-owned utilities. CAS testing protocols used by these programs in the state include the Natural Gas Appliance Test (NGAT) and the Building Performance Institute (BPI) CAS protocols, with specific details of testing and implementation varying by utility.

Multifamily energy retrofit programs in California that have CAS testing requirements include all of the investor-owned utility, Regional Energy Network, and community choice aggregator administered Multifamily Energy Upgrade Programs, as well the CSD administered Low Income Weatherization Program – Large Multifamily (LIWP-LMF. These are all "whole building" retrofit programs, and most of them provide funding to offset some portion of the energy efficiency work, including the initial energy assessments and CAS testing, but they do not provide funding for any remediation work that emanates from that testing.

In considering combustion safety, it is important to recognize that spillage hazards have both physical and statistical features. The physical aspect is the suite of home and appliance operational conditions, combined with weather, that produce sustained (as opposed to brief or intermittent) combustion product spillage when an appliance is operated under these conditions. The statistical consideration is in the frequency and duration of the conditions occurring. The overall hazard in a home is the confluence of these aspects. For example, if an appliance – e.g. a wall furnace – is vulnerable to spillage only when the kitchen range hood is used on the highest speed and the dryer is running and the bath fans are operating and outdoor temperatures are not too cold, it is exceedingly unlikely that those conditions will persist for a long-enough period to allow hazardous levels of combustion products to build up in the home. By contrast, if spillage would occur whenever any two exhaust fans are used irrespective of weather, the statistical likelihood is that this will occur much more frequently and the hazard is greater. To date, no research has documented the frequency of worst-case equipment operation conditions across a population of homes under actual occupancy patterns.

The goal of this research study was to inform efforts to improve CAS testing to identify truly hazardous situations that require remediation, leading to a larger fraction of program dollars being spent on efficiency while also reducing risk. A guiding premise of this research was that CAS testing based on worst-case conditions is an inefficient approach to assessing hazard. There are two bases for this premise. First is that the occurrence of WC conditions is extremely infrequent in most homes. Second is the assessment that the equipment operational conditions that create a hazard of depressurization-induced spillage typically involve high rates of outdoor air ventilation that serve to dilute the concentrations of any pollutants emitted in the spilling combustion products, thus providing protection against the hazard of high pollutant concentrations and exposures. We therefore reason that the most important hazards to identify are appliances that spill under less challenging conditions, certainly including when a single, commonly used exhaust fan operates and

[5] Managed by the California Energy Commission (CEC).

potentially including combinations of fans that are commonly used at the same time. Appliances spilling under natural or reduced challenge conditions are likely to spill much more frequently and with much lower rates of outdoor air dilution, leading to increased hazard and risk for occupants.

In place of worst-case testing, we favor the use of a more commonly occurring challenge condition to identify appliances that will spill with enough frequency and/or duration to present a true health hazard. Such a test will produce many fewer “false-positives” that fail appliances that will rarely if every spill in practice.

The approach of straightforward combustion safety testing with less than “worst-case” challenge conditions has been demonstrated in a field study of eleven homes in the Midwest US (Brand et al., 2015). The study found that even for those homes that failed under much less challenging conditions, there were only two cases presenting prolonged and excessive spillage in practice. And in both of these residences, the venting (ducting) was out of compliance with the National Fuel Gas Code. Spillage in other homes was either non-existent or occurred only briefly after some burner starts. The results reinforced that visual inspection of appliances and vent ducting is a crucial aspect of any CAS assessment.

In this study we sought to identify and characterize venting issues with wall furnaces and track the operation of exhaust fans in apartment units that fail worst-case testing, but pass a less extreme challenge condition. Equipment performance assessments included monitoring of exhaust fans to determine statistics of coincident use, monitoring of wall furnaces to quantify usage and coincidence with exhaust fan usage, and identification and recording of downdraft and spillage events. We also monitored cooking activity, so that we could assess the impacts of operating range hood exhaust fans whenever cooking occurs, as is recommended. The equipment usage data allows an estimation of how common it is for the households to be operated at various challenge conditions. The study focused on wall furnaces as one of the more hazardous natural draft appliances in California apartments. The collected data can be used to generate frequency distributions of coincident exhaust device operation. With these distributions in hand, researchers can begin to estimate how combustion spillage and hazard are affected by a variety of house parameters, including envelope airtightness, exhaust airflow capacity, and use of venting range hoods.

2 Methods

2.1 Building and Participant Recruitment

The study plan, described below, was reviewed and approved by LBNL’s Human Subjects Committee (Institutional Review Board). The plan included the following elements, which are provided in Appendix 7:

- Recruitment Flyer
- Recruitment Script
- Apartment Characterization Form
- Study Consent Form
- Daily Log Sheet

- Occupant Survey Form
- Incentive Payment Schedule
- Sequence of Events

Potential study sites were identified by AEA using their large database of past and present clients who have participated in one or more of the whole building multifamily energy efficiency programs that AEA has implemented in California. It was decided that candidate properties should have apartments with wall furnaces and kitchen exhaust fans that, based on previous testing of selected apartments as part of the efficiency program, were unlikely to not pass the worst-case combustion venting test. Wall furnaces were all located in the living rooms of the apartment units, and they used the room air volume for combustion air. As such, no permanent combustion ventilation air (CVA) openings were required.

Most of the efficiency programs in CA have combustion safety testing requirements, and as such, AEA was able to identify a number of properties that had been previously tested and had passed the spillage test under natural conditions, but failed under worst-case conditions. As enforced by most of the multifamily programs throughout the state, properties are allowed to proceed with energy retrofits when they fail worst-cases testing, but pass natural condition tests. If any efficiency measures are installed that affect the pressure dynamics of the unit, then CAS tests are repeated post-retrofit, to ensure that appliances still pass natural condition tests.

AEA used results of the industry standard worst-case venting tests conducted for the efficiency programs and considered how other units located within a site were likely to compare to the measured apartments. It should be noted that testing a sample of apartments within a building is a standard practice for multifamily energy efficient programs. The standard procedure is to test additional apartments when a high percentage of the sample apartments fail one or more tests.

AEA used phone and email to contact Property Owners or Asset Managers of two candidate sites that met the screening criteria. AEA described the research project context, objectives and methods. AEA obtained verbal consent from the owner or manager to contact and engage with the onsite Property Manager, to coordinate and assist in the resident outreach efforts, and the residents themselves. From that point on, AEA worked closely with the on-site Property Managers to engage directly with the residents.

Building A had twelve units that had already undergone combustion safety tests as part of an energy efficiency program, and all twelve units passed under natural conditions and failed at worst-case. Using this information and considering the appliances and apartment configurations in the building, AEA predicted that many of the other apartments in the building would also fail under worst-case and pass under natural draft conditions (as other apartments in the buildings failed during prior energy retrofit testing). Additionally, a number of apartments that were assessed during the rebate program process were found to have intentionally disengaged spill switches. The spill switch is a safety feature that disables furnace operation when the temperature at the draft diverter becomes too high, as this typically indicates spillage. Some rebate program participants reported during those assessments that the safety device was disabled by either building maintenance staff or the building's outside plumber in response to multiple "no heat" service calls.

For Building A, AEA was invited to attend a community meeting of residents and was given the opportunity to deliver a brief presentation about the study, the participation process, and the incentive details. Many residents of the building were seniors, who spoke English as a second language and Mandarin as a first language. The Property Manager arranged for a Mandarin translator to attend the meeting and translate as needed. A contact information sheet was circulated and residents who were interested in participating in the study were encouraged to provide their names, email addresses, phone numbers and apartment numbers.

Building B had a mix of wall furnaces and ducted FAUs in the apartments. A sampling of units had been tested as part of the rebate program's initial site assessment, and a number of failures were identified, primarily at the FAUs. Those failures, as well as the fact that new windows were being installed as part of the program, triggered a 100% test-out requirement upon project completion. At the initial test-out many of the FAUs exceeded the CO limits, and as a result ended up being replaced prior to a subsequent test-out. Some of the wall furnaces registered higher than optimal CO levels but still lower than the failure limit (between 26-100 ppm), and it was recommended these units be serviced and cleaned. All of the wall furnaces passed spillage under natural conditions, but failed under worst case. Notably, all apartments had passive air inlets, also called "trickle vents". Most of these were found to be open during the CAS inspection. These passive inlets were not permanent openings, and as such cannot be counted in combustion ventilation air (CVA) calculations. Furthermore, all of these apartments used the living room volume for combustion air, so they provided no CVA openings to outside. Consistent with this, the building analyst closed these passive air inlets during worst-case testing.

At Building B, the property owner was unable to schedule a community meeting for the purpose of introducing residents to the study. Recruitment involved posting flyers throughout the building and limited door-to-door outreach. All door-to-door recruitment was performed in coordination with the Property Manager and assisted by the on-site Maintenance Supervisor.

AEA followed up with phone calls to interested residents with apartments deemed likely to meet the study criteria. During the call, AEA answered any additional questions and scheduled the initial testing and equipment installation site visit. AEA used the approved recruitment scripts during these phone calls to provide information about the study.

At the start of the initial site visit an AEA analyst thoroughly reviewed the study consent form and obtained written consent before proceeding.

2.2 Occupant Survey and Daily Logs

After the consent form was signed, the AEA Analyst presented the occupant survey and the daily log forms to the participant, reviewed the forms, and answered any questions. The participant was asked to complete the occupant survey form while the initial testing or installation was being set up, and the form was collected prior to the completion of that initial site visit. A daily log form was provided for each planned day of the study. The participant was asked to complete the form on a daily basis, preferably at the end of the day, and to enter their best estimates for each day and time period. Participants were instructed not to list the names of any people and to ensure that all information in each table was for the same day.

The occupant survey (reproduced in-full in Appendix Section 8.2) aimed to characterize the occupant's perception of the indoor and outdoor air quality and apartment comfort by asking them to rate their satisfaction levels on a scale from "Very Dissatisfied" to "Very Satisfied". The form also asked questions about window operation, range hood and bathroom fan operation and usage patterns, bathing and moisture producing appliance operation (dishwasher, washing machine etc.), and interior door operation. The window, door, and fan operation related questions were designed to help characterize the likelihood and frequency of worst-case depressurization events occurring.

Daily log sheets (reproduced in-full in Section 8.1) were given to participants with the guidance to complete one log table for each day of the study. An example of the daily table is provided below. These logs were intended to capture information about the activities that were thought to most impact the study questions.

Very limited time was available for analysis of the survey and daily log data. As such, we do not present those results here. The survey data are compiled and presented in their raw format in Appendix Section 8.3. We provide no summary of the daily log data.

Exhibit 1. Daily Log

Instructions: Please enter your best estimates for each day and time period. Do not list the names of any people. Please make sure all information in a table is for the same day.

Day____: Date _______________ Date completed _________________

	Midnight to 7am	7am to 11am	11am to 1pm	1pm to 5 pm	5pm to 9pm	9pm to Midnight
Number of people in home						
Number of times cooktop or oven used						
Number of times kitchen exhaust fan used						
Number of baths or showers						
Number of times bath exhaust fan used						
Number of windows open more than a few minutes						

Sign and print name of person filling in table above: …………………………………………………

2.3 Guidance on Use of Windows and Exhaust Fans

The study plan included guidance to participants to keep windows closed and to use the kitchen range hood or bathroom exhaust fans whenever cooking or bathing occurred. This guidance was initially provided to the first four participants in Building A. However, after it was determined that all four of the apartments had mild spillage occur under natural conditions, it was decided that using exhaust fans in this way could cause frequent spillage and potentially result in undesirable levels of occupant exposure to pollutants. AEA staff thus returned to those four units and revised the instructions to occupants. If the unit had a wall furnace that spilled under natural conditions AEA staff instructed the participant to open their windows when cooking and/or using their range hood. If the apartment did not spill under natural conditions, AEA staff instructed the participant to operate windows as they normally do. Occupants were not instructed to open windows during wall furnace operation.

For the next 12 apartments, AEA staff used this same conditional instruction. If the apartment showed any signs of spillage under natural conditions, the participant was instructed to open their windows when operating their range hood. If the tested apartment was not spilling under natural conditions, the participant was instructed to operate their windows as they normally do. AEA made clear to participants that the incentive would be issued however they chose to operate their windows.

These instructions, which were required for safe participation in the study, meant that we were not able to study spillage and downdrafting under 'normal, as-found' occupied conditions. Rather occupants were instructed to use their exhaust fans when cooking or bathing, and some occupants were instructed to open windows during kitchen fan use. Window operation was not monitored, which makes our results inconclusive. Any time a window was opened in accordance with these instructions, it affected the potential for downdrafting and/or spillage. As a result, we also present the coincident operation assessments of exhaust fans (and cooking) with the wall furnace operation. When paired with the diagnostic testing performed by AEA, these results can serve as an imperfect proxy for spillage or downdrafting, if all windows had been closed. Specifically, we can look at the frequency of coincident operation that matches the minimum tested spillage conditions reported in Table 9.

2.4 Diagnostic Testing Protocols

Diagnostic testing was carried out in each apartment unit to determine the airflow through ventilation fans and the draft performance of the wall furnace under various levels of depressurization caused by operating varying exhaust fan and door combinations. CAS testing was conducted on the furnace to ensure that its use during the study would not present a hazard. CAS testing consists of checking natural gas lines for leaks, testing for flue gases spilling into the room at natural and worst-case conditions, and determining the concentration of carbon monoxide (CO) in the flue gases.

Leaks in the natural gas line and all connections were checked using a Leakator Jr combustible gas leak detector, made by Bacharach, Inc. The detector was zeroed outdoors at each apartment and passed along the gas lines and connectors at a rate of no more than 1 inch per second.

A Testo 310 residential combustion analyzer kit was used to test flue gases for air-free CO concentrations. Once the furnace cover was removed and the furnace had been fired, the probe of the Testo was inserted into the draft diverter. The probe was pointed down, toward the combustion chamber to ensure it was measuring only the flue gases and not a mixture of flue gas and room air. CO levels below 25 parts per million (ppm) were considered safe. For CO between 25 ppm and 100 ppm, we informed residents and the manager of the property, but proceeded with the study. Levels of CO above 100 ppm called for an immediate halt to work in that apartment unit, and the furnace was required to be repaired or replaced such that CO levels were reduced to a safe level before the apartment could participate in the study.

Testing of flue gases spilling into the living space ("spillage") involved using a "smoke stick" to determine whether gases were entering or exiting the draft diverter. In addition, indoor-outdoor pressure differences were measured to assess the magnitude of induced depressurization during exhaust fan operation. A DG-700 Pressure and Flow Gauge (made by The Energy Conservatory, www.energyconservatory.com) was used.

The procedure used to carry out the spillage test is detailed below:

1. Close all doors and windows in the apartment; ensure bathroom and kitchen fans are turned off (if possible).
2. Record the difference between outdoor (reference) and indoor (input) pressures.
3. Turn on kitchen hood and bathroom fan to highest settings to create "worst-case" conditions, record the new pressure differential.
4. Turn on furnace, use the smoke stick to measure degree to which spillage occurs, if at all. Continue to test with the smoke stick every minute for five minutes (standard CAS protocol calls for two minutes of sampling).
5. If spillage still occurs after five minutes, reduce speed of kitchen fan, note pressure differential, and retest spillage for one minute.
6. Continue to test spillage at reduced challenge conditions, as indicated in Table 1 below, until natural conditions or no spillage are achieved.
7. Characterize spillage using the criteria in Table 2.

In Building B, the apartments included a bathroom exhaust fan that operated continuously on a low setting, and it was boosted to a higher airflow setting based on a motion detector. The inspectors could not measure the low airflow, as any attempt to do so automatically boosted the fans to high speed. As such, during spillage testing, these bathroom fans operated on the high setting during all test conditions listed in Table 1, including 'natural' conditions.

Table 1 Furnace spillage order of test conditions.

<table>
<tr><td>Order number</td><td>#1</td><td>#2</td><td>#3</td><td>#4</td><td>#5</td><td>#6</td></tr>
<tr><td>Primary Condition</td><td>Kitchen fan high & Bathroom fan on</td><td>Kitchen fan high & Bathroom fan off</td><td>Kitchen fan low & Bathroom fan on</td><td>Kitchen fan low & Bathroom fan off</td><td>Kitchen fan off & Bathroom fan on</td><td>Kitchen fan off & Bathroom fan off</td></tr>
<tr><td rowspan="3">Secondary Conditions</td><td>Bathroom door: Open / Closed</td><td></td><td>Bathroom door: Open / Closed</td><td></td><td>Bathroom door: Open / Closed</td><td rowspan="3"></td></tr>
<tr><td colspan="5">Bedroom door: Open / Closed</td></tr>
<tr><td colspan="5">Passive Vent: Open / Closed</td></tr>
</table>

Table 2 Spillage Classifications

Classification	Description
Drafting (0)	Smoke travels directly up the flue, regardless of where it is placed within the diverter
No spillage (1)	Little to no air movement is present in diverter. Smoke may go up the flue, but only if the smoke pen is placed toward the back of the diverter. Near the front of the diverter there may appear to be spillage, but it is primarily eddy currents due to the heat of the furnace. Flue gases are not necessarily spilling but the furnace may fail a traditional CAS test due to the need to have the smoke pen far back within the diverter in order to have any evidence of drafting.
Light Spillage (2)	Smoke moves as though caught in eddy currents regardless of location in diverter. Some flue gases are entering room, and so the space in front of the diverter may feel somewhat warmer than usual.
Medium Spillage (3)	Smoke has a distinct direction of coming out of the diverter, regardless of placement in the diverter. At the corners of the diverter there will be additional turbulence. Air coming from the diverter is hot.
Heavy Spillage (4)	Smoke travels extremely quickly away from the diverter. A lit match or lighter will go out if moved in front of the diverter, and the heat makes it painful to keep your hand there for more than a few seconds.

Flow rates of the kitchen range hood and bathroom fans in each apartment were measured using a Retrotec (www.retrotec.com) duct blaster and a DM-2 Mark II dual-channel digital micro-anemometer and control. A cardboard transition was used to connect the duct blaster to the inlet of the range hood and a loop of soaker hose connected the space inside the transition to the DM-2 controller. With the fan turned on we were able to use the controller to drive the duct blaster to reach a speed that balanced the air being pulled up through the range hood, as evidenced by a neutral pressure in the transition. The airflow through the calibrated duct blaster was then taken as the flow through the range hood.

Wall furnaces at Building B were side-vented Williams models that had spill switches. In apartments that spilled even at low exhaust air ventilation rates, tenants commented on spill switches being tripped frequently during normal use. As expected, spill switches were tripped during AEA diagnostic tests, requiring that technicians change to air leakage tests while the spill switches cooled, before continuing with the spillage tests. At least one resident was resetting her spill switch herself every time the unit shut off. AEA informed her of the purpose of the device and why resetting it repeatedly is a bad idea. AEA also told her that she should keep her passive vent open anytime she uses her wall furnace, and that if it continues to shut off with the vent open, then she should contact property management staff. Select wall furnaces in Building A also included automatic spill switches—units A_6_1, A_8_1, A_10_1 and A_12_1.

2.5 Short-Term Monitoring Protocols

In order to monitor the patterns of combustion appliance and exhaust devices used under normal occupancy, monitoring equipment was installed for a three-week duration. Sensors were installed by AEA at the start of each monitoring period. Due to data storage limitations some of the sensors were not capable of logging data for the full three-week period; therefore, a mid-term visit was conducted at each apartment in order to download and re-launch those sensors. At the completion of the study all sensors and loggers were retrieved and data were downloaded.

The measured parameters and monitoring equipment are summarized in Table 3. Temperature sensors were placed adjacent to each stovetop burner and the middle of the stovetop to detect when any burner was used. An anemometer measured air speed at the inlet to the range hood fan to determine use and potentially to distinguish setting. Carbon monoxide, carbon dioxide, temperature, and relative humidity were monitored in the living room of each unit. Carbon dioxide and temperature were also logged at the inlet of the draft diverter for the wall furnace. Temperature also was monitored at two locations in the furnace: within the diverter, approximately 2/3 of the way toward the diverter inlet away from the flue, and within the vent approximately 2 feet up from the diverter. A sensor was placed on the bathroom exhaust fan to monitor its use and a temperature and outdoor grade humidity sensor (which functions to 100% RH) were placed in the bathroom.

Table 3 Monitoring sensor and data acquisition equipment summary.

Measurement	***Sensor/Logger***	***Sampling Frequency***	***Rated Accuracy***
Temperature/RH in bathroom[1]	HOBO U23-001	5 minutes	±0.21 °C (0-50°C) ±2.5% RH from 10–90%[2]
Bath fan operation	HOBO UX90-004	Records each state change (on/off)	
Cooking burner use	iButton DS1922L	1-minute	± 0.5 °C
Range hood operation	Digi-Sense 20250-22 Data Logging Anemometer	1-minute	± 3%
Carbon monoxide in living room	El-USB-CO	5-minute	±2 ppm
Temperature/RH in living room	HOBO U10-003	5- minute	±0.53 °C (0-50°C) ±3.5% RH (from 25 to 85%)
CO_2 in living room	Vaisala GMW115 w data logged to HOBO UX120-006M	5-minute	±2% of range +2% of reading
Furnace vent temperature	HOBO UX120-014M w/ Omega K-type Thermocouple	1-second	±1.6 °C
CO_2 in room just above draft diverter (to identify spillage)	Vaisala GMW115 w data logged to HOBO UX120-006M	1-second	±2% of range +2% of reading

[1] To detect excess moisture as indicator of times when bath fan should have been used but was not. This device is designed to withstand condensation (100% RH) conditions but the protected internal sensor has a relatively slow response time of 40 min.
[2] Maximum of ±3.5% including hysteresis

2.6 Data Processing and Analysis

All data analysis was performed using the R for Statistical Computing open source software package version 3.2.3 (2015-12-10). The following specific packages were used: *data.table* (version 1.9.4) for large data sets, *xts* (version 0.9-7) and *zoo* (version 1.7-12) for time series manipulation.

2.6.1 Stovetop Temperatures

The stovetop temperature data were processed with the goal of identifying cooking events with any active gas burner operation. We did not attempt to identify which burners were operating or how many operated coincidently. As with other measurements in this study, simply using a threshold temperature was insufficient, because of the growth-decay cycle inherent in such environmental measurements. To further complicate analysis, the five measurement locations on each stovetop influence one another, such that waste heat from the front left burner is reflected in the center measurement point and to a lesser degree at other burner locations. This makes identifying individual burner operation difficult. So, we made burner on/off predictions for each of the five burners, and then merged these results into a single cooking index.

In analyzing stove data, we first merged data from all five stovetop locations together by time index. For all five temperature locations, we calculated the differences from time-step to time-step to find the temperature change for each minute (°C/minute). These data are referred to as 'differenced' in this report. Each burner location was then assessed for either rapid positive or negative rates of change in temperate, indicating the start or end of a burner cycle, respectively. Cooking events were then assigned to the time periods between a cycle start and a cycle end signal. In general, changes of +/- 1 °C per minute were indicative of the start or end of a cooking cycle. Some customization was required in order to consistently and cleanly identify burner operation (i.e., to not miss the 'off' signal, we sometimes set the negative threshold to -0.5 °C per minute). With on/off predictions for each burner, we then created a combined cooking index that was 'on' if one or more burners were on and was otherwise 'off'. This combined index value is shaded in the plots below that show a simple stovetop burner event (Figure 1), an oven burner event (Figure 2) and a more complex event that required manual editing of the data (Figure 3). All five of the burner locations are plotted, along with the differenced series for the back right burner (color black, second y-axis), which tended to be at the highest temperature.

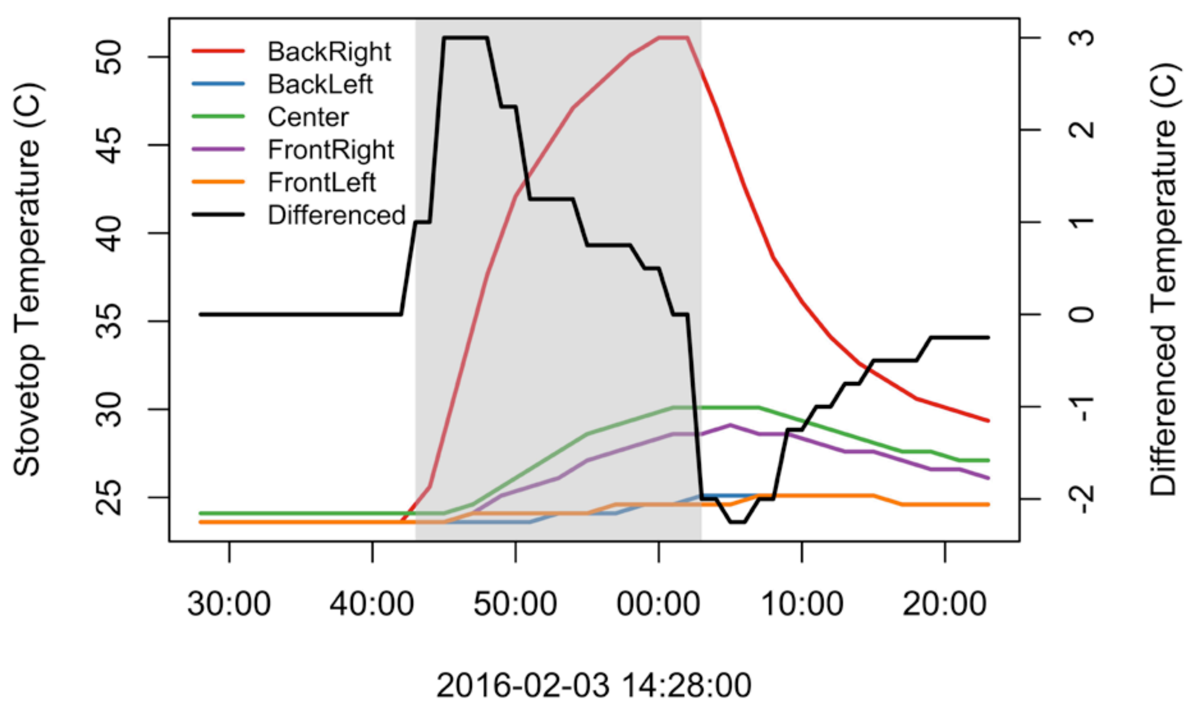

Figure 1 Example of a stovetop burner cycle, using differenced time-series to identify cycle start and stop points, Apt A_12_1.

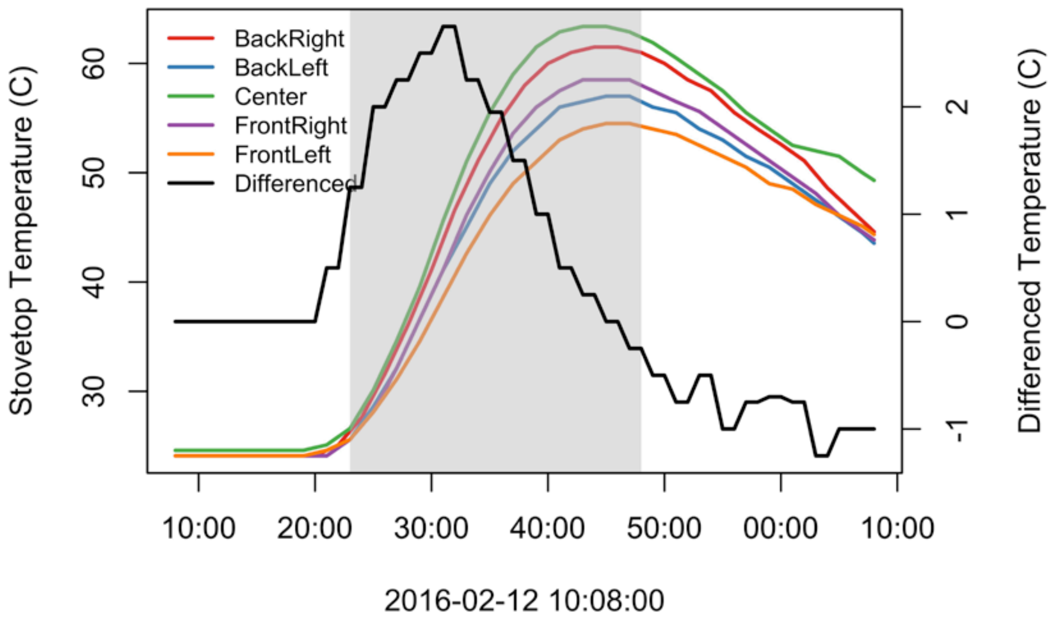

Figure 2 Example of an oven burner cycle, using differenced time-series to identify cycle start and stop points, Apt A_12_1.

Note that the cycle 'off' signal is at -0.5°C, rather than -1.0°C in this case. This more gradual temperature decay is more difficult to correctly identify.

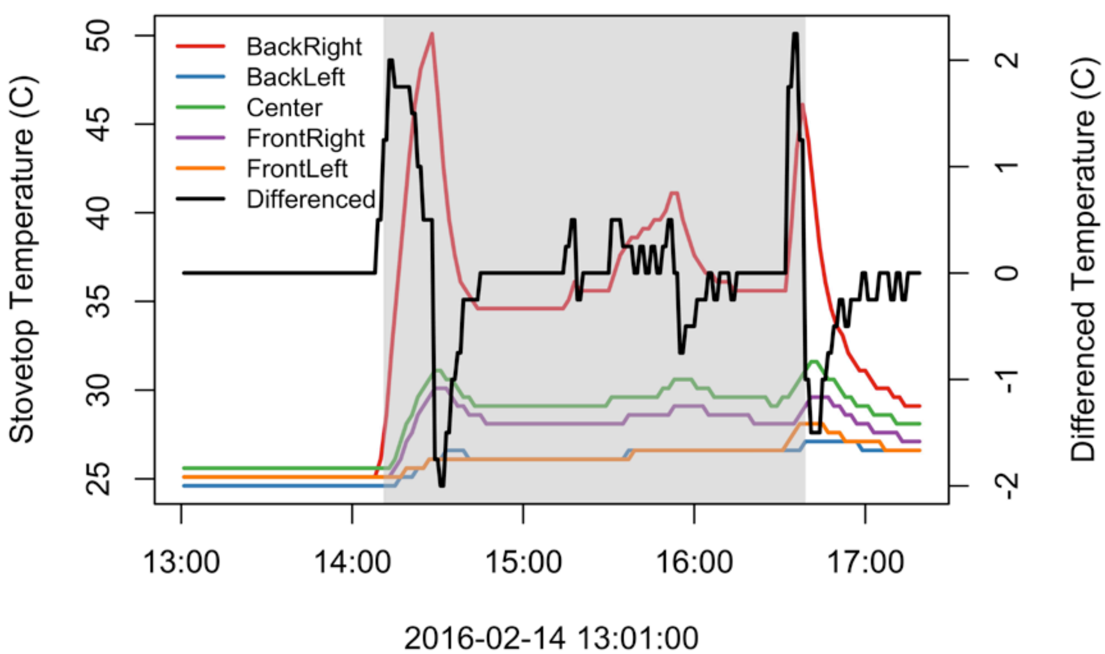

Figure 3 Example of a more complex cooking burner event that required manual editing of the burner index, Apt A_12_1.

Note that the back right burner remains at a high temperature even after its initial sharp decay around 14:20; this is assumed to be continued operation at a lower burner setting, rather than the burner being turned off.

Collection of temperature data from stoves was challenging, as a sizeable percentage of "iButton" temperature sensors read entirely 0°C for the duration of the data sampling period. At initial midpoint visits these files were not saved, although at later visits these files were saved. Additionally multiple files at Unit A_7_2 were lost due to user error. Unit A_8_1 had one sensor that was non-functional at the midpoint visit (would not download data or re-launch); so this sensor was removed and residents were asked to avoid using that burner if possible. All buttons that were found to record only zeroes at the prior deployment were checked by launching, collecting data for 5-10 minutes and reading and checking the collected data to confirm functionality before re-launching for the next deployment. Despite this precaution, multiple sensors installed in Apartments B_16_1 and B_15_1 still gave non-usable data upon collection. Nevertheless, the approach used to assess if cooking occurred may be robust against some missing sensor locations, because locations where cooking was not happening are still affected by nearby cooking (see Figure 1 and Figure 2). In particular, the center location can serve as proxy for all four burner locations. These secondary effects may still have indicated 'cooking' occurred.

2.6.2 Kitchen Range Hood Anemometer

Kitchen range hood fan data were processed to produce an on-off index based on the anemometer output. All units produced the maximum 4 m/s velocity value at almost all times that the recorded value was not 0 m/s. It is much easier to identify fan operation than burner operation, because there are no signal growth or decay periods. A threshold velocity of 2 m/s was used to identify the start and end of a fan cycle. This threshold captured fan operation but avoided identifying occasional signal noise as fan operation. The 30-second sensor data was averaged to one-minute values for merging with the other sensor data streams. The velocity and the on-off index values were averaged, as well.

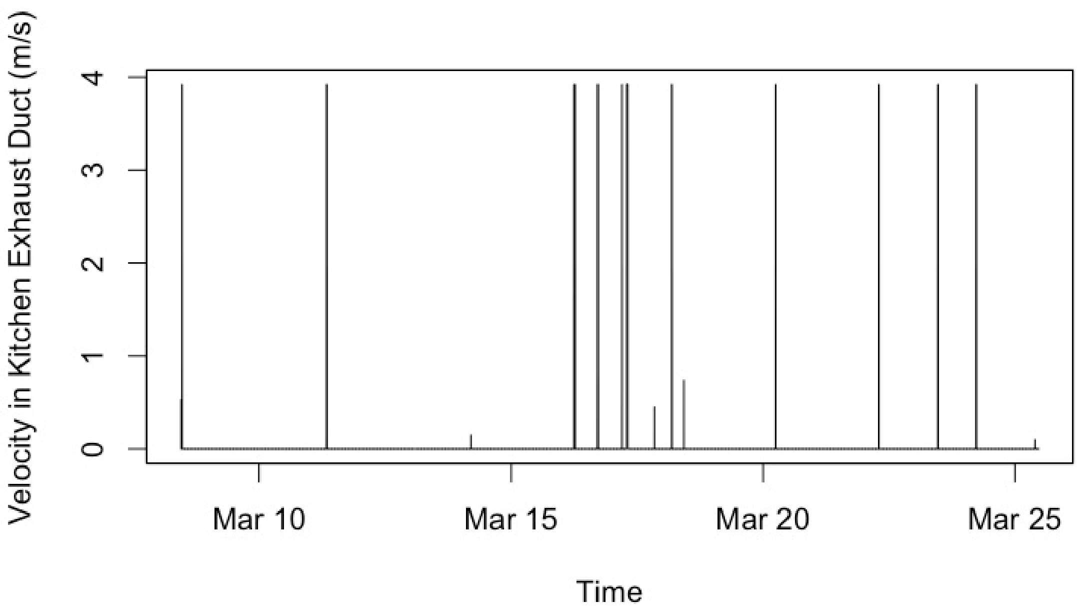

Figure 4 Example plot of kitchen range hood anemometer data from Apartment A_3_2. No growth or decay periods, simple on-off signal.

The anemometer installed in Unit A_12_1 was installed upside down after the midpoint visit, and so may return data that is negative relative to the first half of the study. Unit A_1_2 had a broken range hood that was supposed to be replaced early in the study. The anemometer used in Apartment B_15_1 was found to be non-functional on data review.

2.6.3 Bathroom Fan Motor Operation

Most participating apartments had bathroom exhaust fans monitored for operation using fan motor sensors. Bath fan data were first translated into one-minute time series values using simple averaging. Any fan motor fraction values that were greater than zero were assigned a bath fan index value of one, indicating that the fan operated that minute. This approach likely overstates bathroom fan usage, as some minutes had only fractional values, indicating runtime less than 60 seconds. Bath fan monitoring did not record useful data in the apartment units in the second building. Fans in this building were set to operate continuously at a low speed – presumably to provide baseline, dwelling unit ventilation – and they were increased to a higher airflow based on an occupancy sensor.

2.6.4 Furnace Flue Temperatures

All participating apartment units in this study used natural gas vented wall furnaces. Each appliance was instrumented with two temperature sensors, one located in the vent above the draft diverter and another on the wall adjacent to the appliance, just above the inlet to the draft diverter. The sensors were placed in this way so as to allow identification of appliance burner operation, as well as to identify spillage and downdraft events. An example of the installation is shown in Figure 5 and Figure 6. An example plot of the two temperatures is provided over a three-day period in Apartment A_8_1 in Figure 7.

Figure 5. Placement of sensors around and inside a wall furnace.

The device on top of the cover is the CO_2 sensor and logger. The device attached to the front of the cover logs the thermocouples placed at the draft diverter and up into the vent.

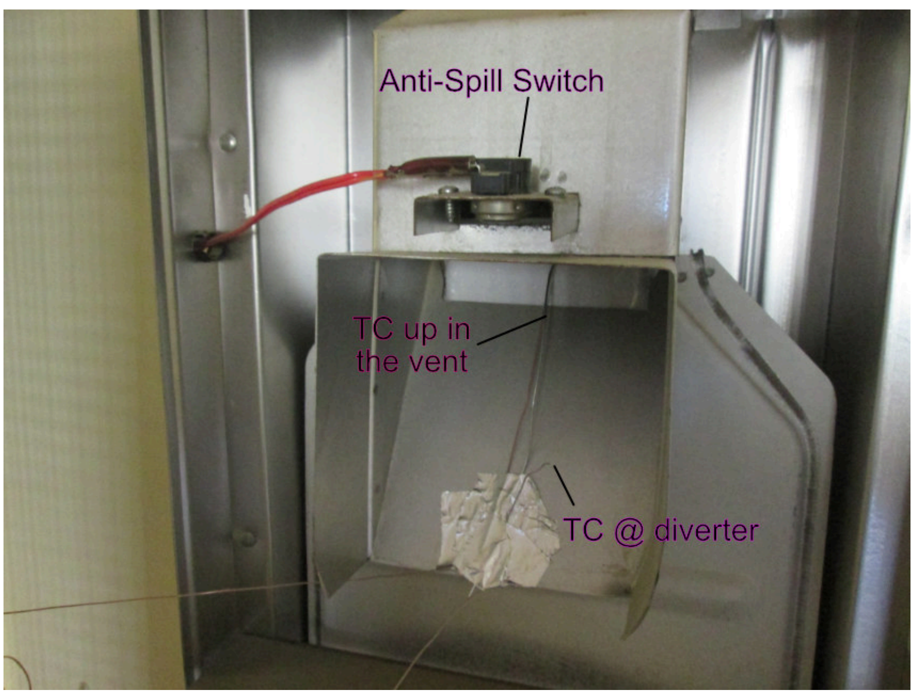

Figure 6. Placement thermocouples at draft diverter and vent.

Close-up from Figure 5.

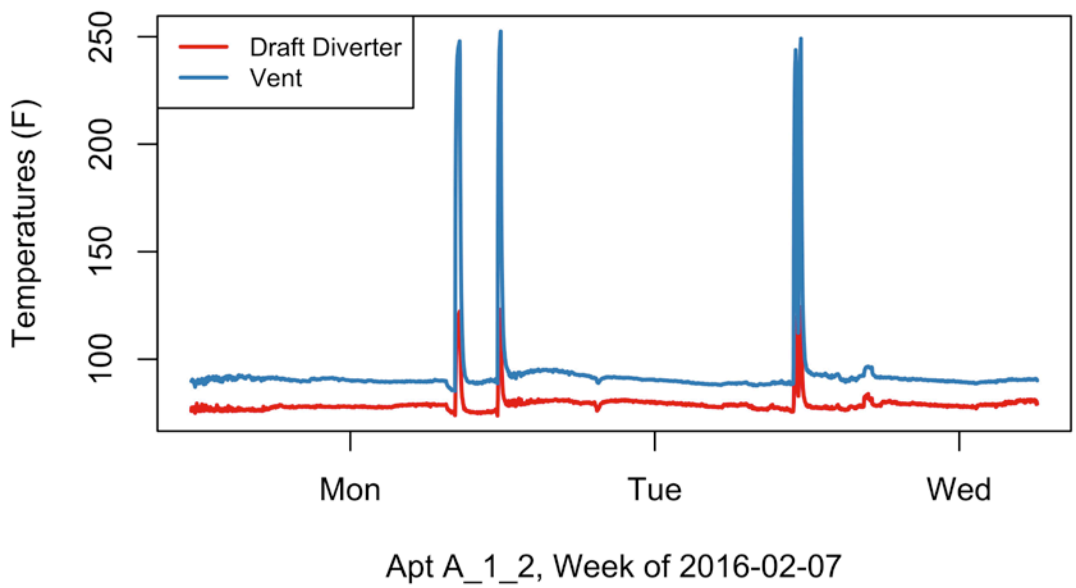

Figure 7 Characteristic plot of wall furnace temperatures in Apartment A_1_2.
The plot includes the temperature at the draft diverter (red) and in the vent (blue). The vent sensor is characterized by much higher temperatures, up to 250°F in this case.

2.6.4.1 Identification of Furnace Cycles and Burner Operation

Wall furnace burner operation occurs in cycles that appear as a rapid increase in vent temperature followed by a variable length period of elevated temperature and ending with a decay that is less steep than the rise. This clean pattern is disrupted when the exhaust gases spill into the living space instead of venting to the outdoors. Furnace burner cycles were identified using methods similar to those outlined in Section 2.6.1 for cooktop burner temperatures. Identification of a burner cycle from a wall furnace flue temperature also requires distinguishing temperature growth and steady-state periods (when the burner is on) from the decay periods (when the burner is off).

All furnace temperature data were first cleaned of obviously erroneous values (e.g., 888.88). The remaining data were then converted from one-second data to one-minute data using simple averaging. This was done to make the data analysis and processing faster and to smooth out noise in the one-second signals. With one-minute data in-hand, the time series were differenced one time-step, and five-minute rolling means were calculated to create 'smoothed, differenced' time series. A right-adjusted rolling mean (reflecting concentrations over the prior 5 min) was used to identify the cycle start point: a left-adjusted mean (reflecting concentrations over the next 5 minutes) was used to identify the cycle end point. The rolling mean approach smoothed out fast up-down spikes and ensured that cycle identification algorithms were able to identify clear and continuous burner cycles. The start and end of each cycle was identified based on positive and negative spikes in the smoothed, differenced series. An example of a burner cycle in Apartment A_1_2 is provided in Figure 8. Draft diverter and vent temperatures (red and blue) show three clear burner cycles, with burner operation highlighted in grey. The vent temperature climbs quite high, while the temperature at the draft diverter also increases due to its being secondarily heated by the furnace. Note the large positive and negative spikes in the smoothed, differenced series (green and purple lines centered around zero). Using the smoothed, differenced one-minute data, we typically identified the start and end of cycles using +/- 15°F per minute threshold values.

The ideal cycle identification algorithm would clearly identify the start and stop of contiguous, real burner cycles. It would never miss an on- or off-signal. Yet, draft diverter and vent temperatures in wall furnaces can be highly variable, both between appliances, as well as between cycles in the same appliance. In order to produce the cleanest and most believable burner cycling index, a combination of human visual review was required, along with some algorithmic fixes. In general, automatic cleaning of the cycle start and end indices was performed first. For example, for a matched pair of start and end time indices, the start index must be lower than the end index. In cases where this was not the case, the offending index was removed. Similarly, a new start index was not allowed if it was less than the end index of the prior cycle (indicating two 'starts' in a row). In addition, cycles were removed that were longer than 24-hours, because these indicated that an end index was missed. When start or end indices were missed, it generally required an adjustment of the +/-15°F per minute threshold mentioned above. Identifying a new suitable threshold involved plotting the temperatures, along with the smoothed, differenced values, and a new cut-off was chosen based on the visible patterns in the data. For example, sometimes the decay at the end of the cycle was at a slower rate, so a cut-off of 7 or 10°F per minute was required to capture the end index. With the cleaned start and end indices in-hand, the values between start and end were filled-in with ones, and all other values were set to zero, giving an on-off furnace burner signal.

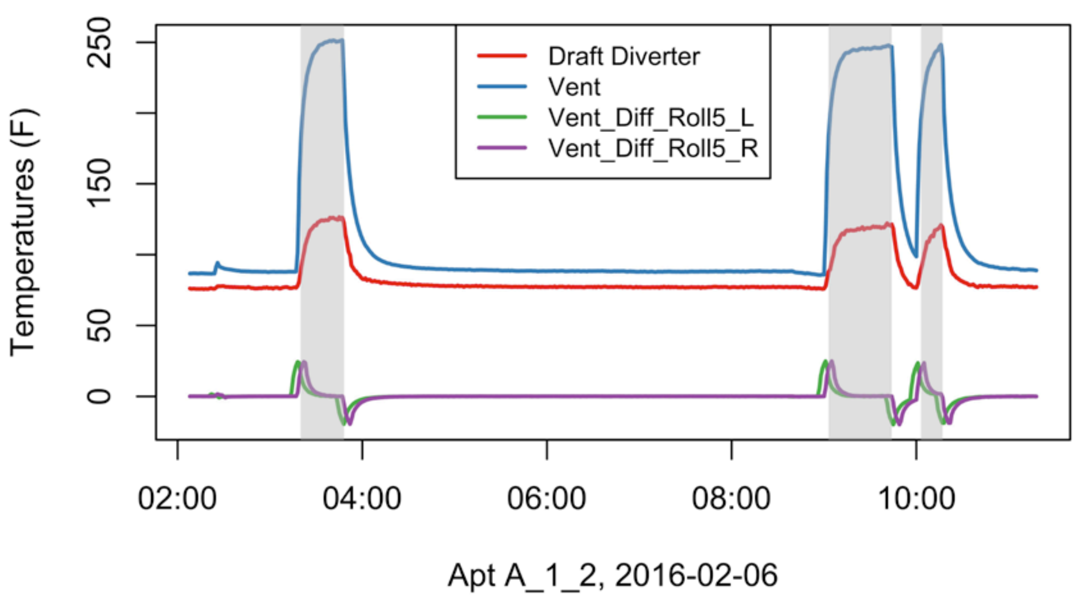

Figure 8 Example of a furnace burner cycle in Apartment A_1_2.

The beginning of a furnace cycle is characterized by rapid increases in vent and draft diverter temperatures (blue and red), and the end of the cycle by decaying temperatures. Purple and green series are right and left adjusted five-minute running means of the differenced time series used to identify cycle start and stop times. Furnace operation occurred during gray bands.

2.6.4.2 Identification of Furnace Spillage

The algorithm outlined in Section 2.6.4.1 will only identify burner cycles where the combustion products travel up the vent. Spillage can produce a very different pattern. As described in Section 2.4, AEA staff performed a sequence of appliance tests in which flue gas spillage was assessed under different exhaust fan operation and door configurations. These tests were performed after all of the sensors were installed and began logging data. These test results provide us with training data for identifying spillage events in the sensor data streams. After reviewing diagnostic testing notes from AEA, alongside visualization of the sensor data taken during diagnostic testing, we found that spillage could fall roughly into one of two categories: (1) unambiguous spillage and (2) possible but uncertain spillage.

The spillage assessments in this work involved four steps: (1) on-site diagnostic spillage testing and visual labeling and characterization of spillage events by the AEA team, (2) manual labeling of unambiguous spillage events in the sensor data taken during diagnostic tests by the LBNL team, (3) training of classification learning models on this test data, and (4) use of trained models to predict spillage in sensor data taken during normal occupancy. Each of these steps are discussed below, with the exception of the AEA diagnostic testing, which was described in Section 2.4.

2.6.4.2.1 Comparison of AEA Diagnostic Testing Notes and Sensor Data

The LBNL team first identified the periods in the sensor data during which AEA field-testing was taking place, and these values were identified with an index value of 1. We then plotted furnace temperature data from these periods for visual inspection and comparison with AEA visual inspection notes. Mostly there was agreement between the wall furnace temperature data and AEA's visual identification of spillage (by smoke pen). Unambiguous spillage events were identified in most apartments, though sensor data was available during diagnostics testing for only 10 of 16 units. Yet there were exceptions, and it was at this point that we developed the two spillage event types: unambiguous and uncertain.

We created an entirely manual index for indicating unambiguous flue gas spillage during the AEA test periods (1 for spilling and 0 for not spilling). Examples of unambiguous spillage events are provided in Figure 9 and Figure 10. These events are characterized by the draft diverter temperature doing two things: (1) increasing to an abnormally high temperature, and (2) becoming much hotter than the vent temperature. When draft is established, the vent and draft diverter temperatures flip-flop, with the vent taking the characteristically higher temperature, while the draft diverter remains only secondarily heated by the furnace. These spillage events contrast obviously with more typical non-spilling furnace burner events, such as those pictured in Figure 8. As with the furnace burner cycle identification described in Section 2.6.4.1, we took care in this manual labeling to only include periods when temperatures were increasing (decay periods not included).

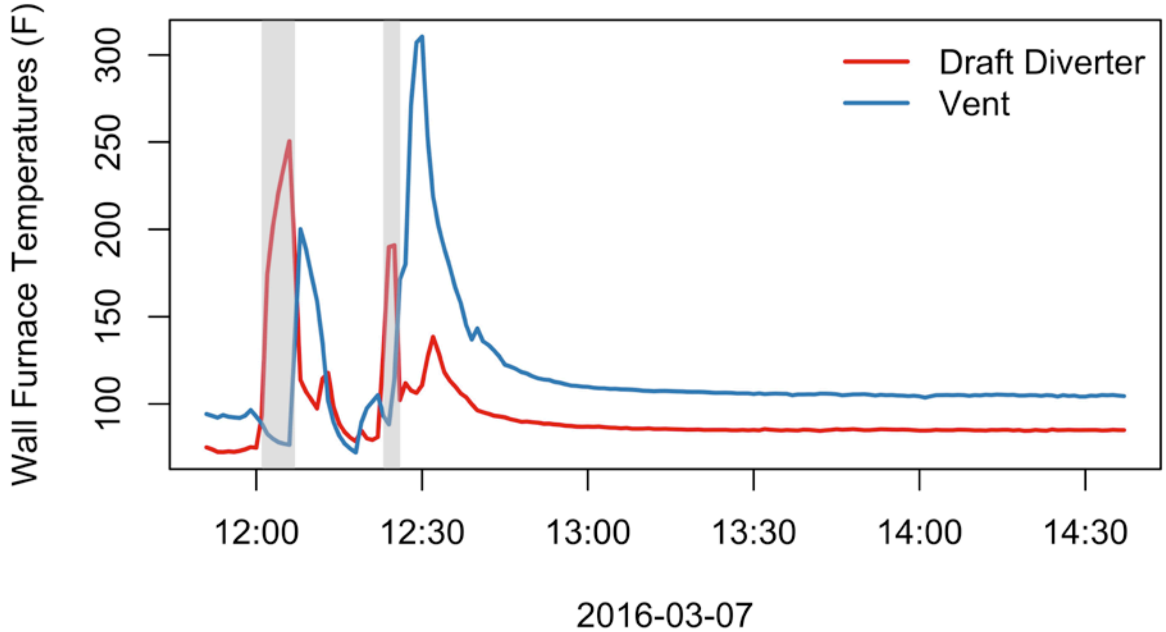

Figure 9 Example of unambiguous wall furnace spillage event during AEA diagnostic testing, Apt A_4_1. Spillage events manually identified in shaded grey regions.

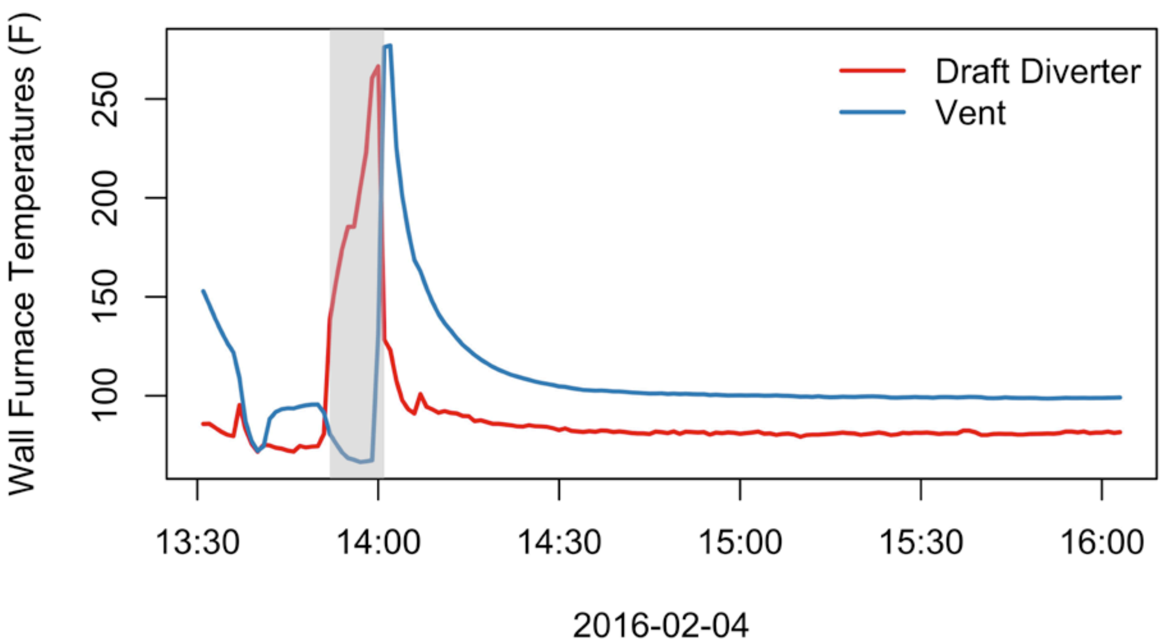

Figure 10 Example of unambiguous wall furnace spillage event during AEA diagnostic testing, Apt A_11_1. Spillage event manually identified in shaded grey region.

However, as noted above, possible but uncertain spillage events were also found in the sensor data taken during diagnostic testing. These events were characterized generally by: (1) AEA reporting 'light' or 'barely' spilling (though not always), and (2) furnace temperature data that was visually indistinguishable from behavior during non-spilling burner cycles, often with the exception of a brief one- or two-minute draft diverter temperature spike at the beginning of the cycle. These events are difficult to categorize as spillage, but they may represent periods of non-robust draft, lacking strong flow of combustion products up the vent. We discuss some examples below.

In Apt B_15_1 wall furnace temperature data would suggest that draft is fully established and strong, while AEA continued to report spillage as being 'light' or 'medium' (see notes in Table 2). The test period data are plotted for this apartment in Figure 11. Draft appears strong in the first and third burner cycles, but AEA reported 'light' or 'medium' spillage up to the point where the vent temperature was 320°F in the third event.

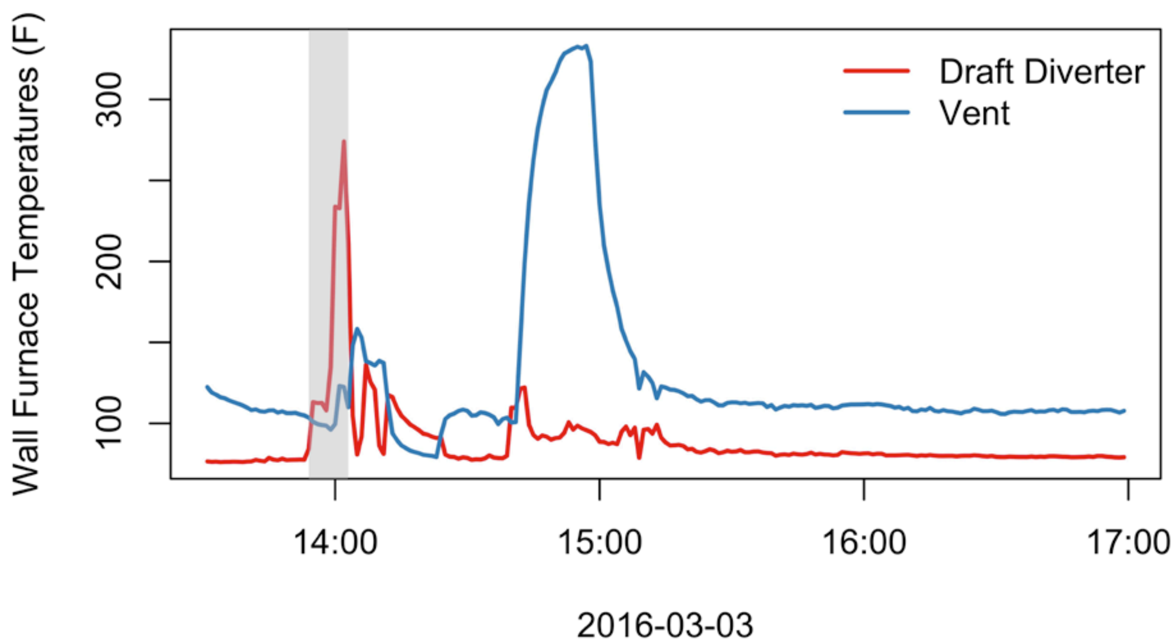

Figure 11 Example of disagreement between furnace temperature sensor data and reports of visually identified spillage by AEA during diagnostic testing in Apt B_15_1.

AEA reported 'light' or 'medium' spillage well into the second burner cycle. Brief spillage is probable at the start of the second cycle, but strong draft appears to be established within minutes. Light grey highlights period identified as unambiguous spillage.

In apartments A_8_1 and A_9_1 we see similar issues (plotted in Figure 12 and Figure 13, respectively). In A_8_1, the second burner cycle was identified as 'barely spilling' or 'minor spillage' up until the second decay period after the initial peak at >500°F. In A_9_1, the third burner cycle represents AEA testing, and they indicated 'barely spilling' or 'minor spillage' during the 3rd cycle up until the tiny divot in the peak around 350°F. Visually, all of these events are nearly indistinguishable from 'normal' burner cycles.

In this work, we report only unambiguous spillage events, as these are the only ones we can reliably identify in the sensor data. For a secondary indication of when unclear spillage might be occurring, we have provided reports of periods of coincident operation of cooking, bath fan use and wall furnace operation, and these values would represent the maximum incidence of even unclear spillage in the apartments. The appropriate coincident condition could be determined using the data in Table 9. For example, in Apt A_11_1, the minimum exhaust fan condition required to spill the appliance was the kitchen fan on low. So, coincident heating and cooking would represent the maximum incidence of unclear spillage in this unit. In fact, this would represent an over-estimate even of unclear spillage, as any window open during cooking would alleviate depressurization and facilitate stronger wall furnace draft.

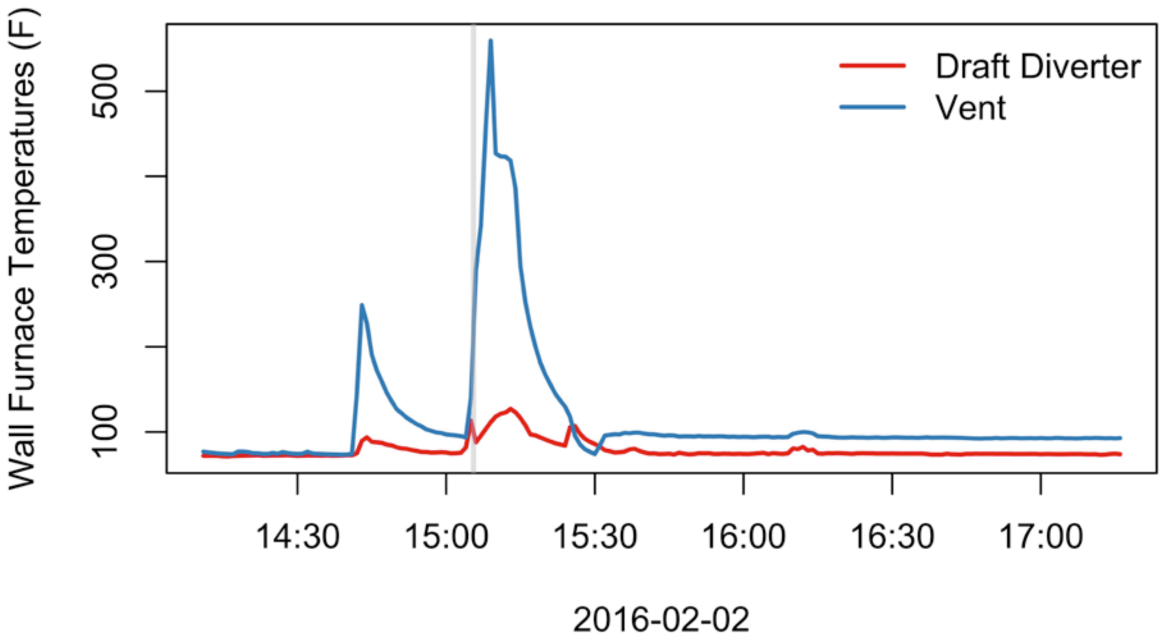

Figure 12 Example of apparent disagreement between furnace temperature sensor data and spillage indicated by AEA during diagnostic testing in Apt A_8_1.

The second burner cycle was identified as 'barely spilling' or 'minor spillage' up until the second decay period after the initial peak at >500°F. Light grey highlights the time period we identified as unambiguous spillage.

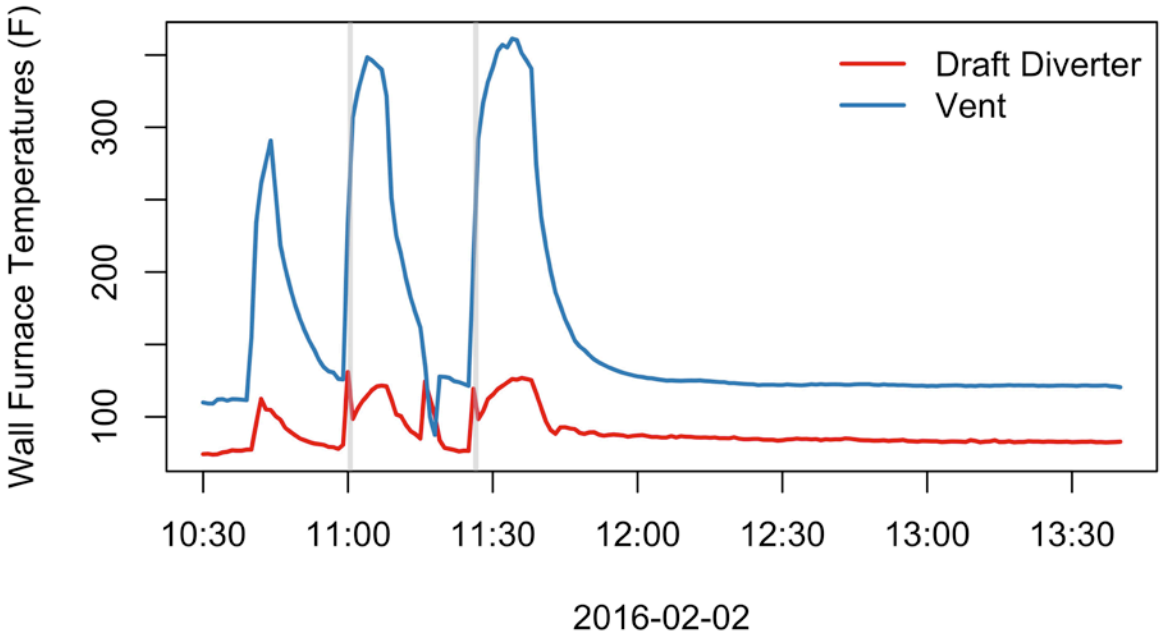

Figure 13 Example of apparent disagreement between furnace temperature sensor data and spillage indicated by AEA during diagnostic testing in Apt A_9_1.

The third burner cycle was identified by AEA as 'barely spilling' or 'minor spillage' until the divot in the peak around 350°F.

2.6.4.2.2 Training of Classification Models on Sensor Diagnostic Testing Data

With the diagnostic period test data manually labeled as described in Section 2.6.4.2.1, we then trained several classification algorithms on the spillage index using AEA test period data from all ten available apartments. Models assessed included logistic regression, linear discriminant analysis (LDA) and k-nearest neighbor (KNN) algorithms. All models used four features—vent and draft diverter temperatures, as well as differenced versions of both temperature series. The logistic regression model and linear discriminant analysis approaches create linear decision boundaries for classification, and the k-nearest neighbor algorithm is entirely non-parametric and non-linear. The structure of the data suggested that a linear decision boundary would perform better.

All data from the AEA diagnostic testing periods was split into training and test sets. For each test set, 75% of the data points were assigned randomly to the training set and the remaining 25% were used to assess model prediction performance on the occupied sensor data. Unlike the two other models, KNN is affected strongly by different scales in the data, because it uses absolute distance calculated between a given point and its set of neighbors to determine classification. For the k-nearest neighbors model, the training and test data were scaled and centered using the *scale()* function in R, which centers each data stream with mean zero and standard deviation of one.

Table 4 Characteristics of the training and test data sets used to train classification models.

Data Set	***Spillage***		
	Yes (minutes)	***No (minutes)***	***Fraction Yes***
Training Data	55	1769	0.03015
Test Data	20	588	0.03289

All models were trained and tuned using the Caret package in R (Kuhn, 2016). Only data from the training set was passed into the Caret package for model building. All models used 10-fold cross validation, repeated ten times randomly to estimate the model accuracy and to tune parameters in the case of the k-nearest neighbor algorithm (tuning length of 20 was used). Model tuning by cross-validation automatically chose the 'best' number of nearest neighbors—in this case five. The trained and tuned models were then applied to the holdout test data set to assess anticipated prediction accuracy on the sensor data from occupied periods. All classes were assigned based on a threshold probability of >50%.

The accuracy values of the three models assessed are summarized in Table 5 for training and test sets, along with the true negative (TrueNeg), false negative (FalseNeg), true positive (TruePos) and false positive (FalsePos) counts. Our overall goal was to limit the number of FalsePos values (i.e., inaccurately predicting spillage), even if select TruePos values were missed (e.g., one minute at start of a burner cycle is incorrectly classified as not spilling). *Overall Accuracy* is the fraction of correctly classified instances (i.e., (TruePos+TrueNeg) / (TrueNeg + FalsePos + FalseNeg + TruePos)). *Spillage Accuracy* is the fraction of all spillage minutes correctly classified (i.e., TruePos / (TruePos + FalseNeg)). *Not Spillage Accuracy* is the fraction of not spilling minutes correct classified (TrueNeg / (TrueNeg + FalsePos)). Not surprisingly, *Not Spillage Accuracies* are very high, because with 1,769 non-spillage minutes out of a data set of length 1,824, a model could just predict 'not spilling' for all data points and still achieve 97% accuracy (1769 / (1769+55)). From these results, we see that the accuracies are quite similar for all models, though the logistic regression model had the highest *spillage accuracy* in the holdout 'test' data set.

Table 5 Results of three classification models trained and tested on AEA diagnostic test period data.

Model	*Data*	*True Neg*	*False Pos*	*False Neg*	*True Pos*	*Overall Accuracy (%)*	*Spillage Accuracy (%)*	*NotSpillage Accuracy (%)*
Logistic Regression	Training	1763	6	20	35	98.6	63.6	99.7
	Test	585	3	6	14	98.5	70.0	99.5
Linear Discriminant Analysis	Training	1761	8	19	36	98.4	65.4	99.6
	Test	587	1	7	13	98.7	65.0	99.8
K-Nearest Neighbors	Training	1766	3	12	43	98.7	78.2	99.8
	Test	588	0	7	13	98.8	65.0	100.0

Note: It is crucial to recall that these models were trained on data that were hand labeled by the LBNL research team based on their visual assessment of the wall furnace temperature data taken during diagnostic testing. Field notes from AEA corroborated these. There were some disagreements between field reports by AEA staff and the trends observed in the sensor data, as were highlighted at length in Section 2.6.4.2.1. As such, we consider there to be no perfect ground truth for the occurrence spillage in this data set. To the extent that partial spillage occurred, our 'unambiguous spillage' estimates likely fail to capture these occurrences.

2.6.4.2.3 Application of Trained Models to Sensor Data During Occupancy

The 'best' model would be chosen based on its performance on the sensor data from the occupied period of the study, though 'performance' could only be assessed visually through inspection of data plots. We applied these same models to the data sets from each apartment unit. While the logistic regression model predicted a total of 36 minutes of spillage across all monitored minutes in all 16 apartments, the LDA and KNN models predicted 150 and 471 minutes, respectively. With no ground-truth to stand on, and with similar accuracy values from the model learning phases, we turned to visual review. Visual review clearly demonstrated that the KNN model vastly over-predicted the amount of spillage occurring. LDA and logistic regression performed more similarly, but ultimately visual review led us to choose logistic regression as the model that most consistently predicted unambiguous spillage. By any of these methods, the predicted spillage was only a very small fraction of the total monitored minutes, which exceeded 400,000. All unambiguous spillage results reported in subsequent sections are based on the logistic regression model.

2.6.4.3 Identification of Furnace Downdrafting

Downdrafting is distinguished from spillage, because it occurs whenever air flows down the vent pipe. This is not necessarily associated with appliance burner operation. It could be caused by weather effects or operation of exhaust devices in the apartment. In Figure 14, we provide an example from Apartment B_15_1 of the wall furnace temperature plots, where vent temperature (lower plot) clearly shows periods of sudden temperature depression characteristic of downdrafting. These periods are characterized by negative dips that drop the vent temperature down to around the outside ambient (roughly 50 or 60°F).

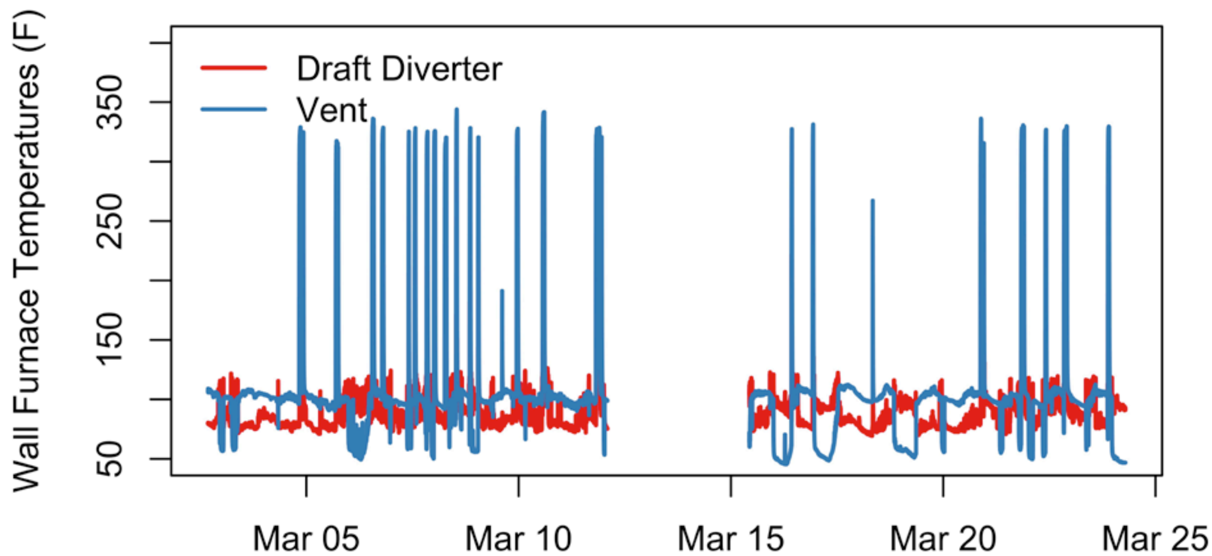

Figure 14 Wall furnace temperature measurements displaying downdrafting in Apt B_15_1. Downdraft periods are characterized by the vent temperature (blue) dropping suddenly to around outdoor ambient temperature (e.g., 50-70°F).

Our overall approach to identifying these periods was to calculate a 12-hour (720-minute) running average of the vent temperature along with a 12-hour running standard deviation (SD), and we would classify minutes as downdrafting where the vent temperature was more than three running SD below the running mean. Wall furnace temperature data are affected by burner events, downdrafting, variability in outside temperature, and variability in inside temperatures. So some data cleaning was required prior to calculating the moving average/SD. First, we removed either hot vent temperatures (>120°F) or cold vent temperatures (<90°F). This effectively removed burner events and downdrafting periods themselves from our running average/SD calculations. Otherwise during long periods of sustained downdrafting, the running average value would become the temperature under downdraft conditions, and this approach would no longer work. We then created a downdrafting index that classified a minute as downdrafting when the vent temperature was three running SD below the running mean. Several example downdrafting events are pictured in Figure 15 and Figure 16.

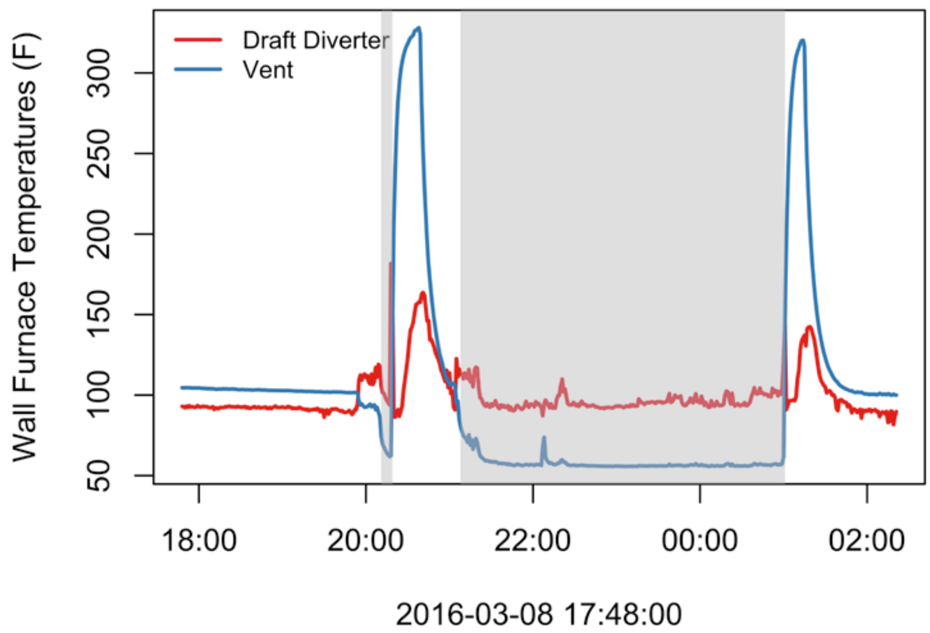

Figure 15 Example of a downdrafting events identified in Apt B_15_1.

One sustained 4-hour downdraft is pictured in the center. Note how an additional downdrafting event occurred prior to the first furnace burner cycle at 20:00, and the beginning of this event was missed, but then it was identified as the vent temperature dropped a second time.

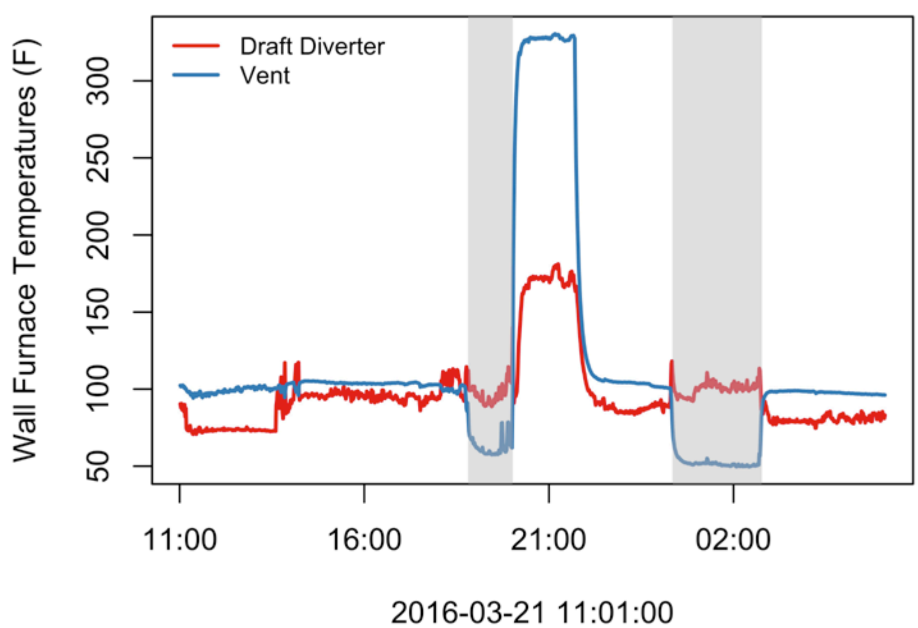

Figure 16 Example of downdrafting events identified in Apt B_15_1.

The first downdraft event occurred prior to the furnace firing, but it did not stop upward draft from being established.

As was common in this work, the only way of assessing our results was through a careful visual review of plotted data. The approach described above accurately classified most periods identified as downdrafting by visual review. During visual review, we noted some instances where a long, extended downdrafting event was broken up into two or more smaller events, due to an intermediate minute that rose above the 3 SD threshold. As a result, estimates of the duration of downdrafting events may be negatively skewed.

Some interesting patterns were noted in the data during our visual review. We observed some periods of unusual vent and draft diverter temperatures that were usually coincident with exhaust fan operation. Examples are provided in Figure 17, Figure 18, and Figure 19. In the first example (Figure 17), both the vent and draft diverter temperatures increased during bathroom exhaust fan operation (highlighted in grey) and the draft diverter temperature started to fluctuate. We hypothesize that the temperatures increased because of reduced dilution airflow through the draft diverter caused by depressurization from the bath fan operating. The reduced outflow of air through the draft diverter and temperature fluctuations suggest an increased risk of spilling combustion products from the standing pilot burner (which is the cause of the elevated vent temperature). The next example, provided in Figure 18, shows a comparison of the effect occurring with a low airflow bathroom exhaust (~30 cfm) and a higher airflow kitchen exhaust fan (~80-100 cfm). Bathroom fan operation caused the vent temperature to increase with no clear change in draft diverter temperature. When the kitchen exhaust fan operated, both temperatures increased and the draft diverter temperature had large fluctuations. In the final example, in Figure 19, vent temperature jumped rapidly by almost 10°F, but only midway through the bath fan cycle. A window being closed could explain the delay in this example.

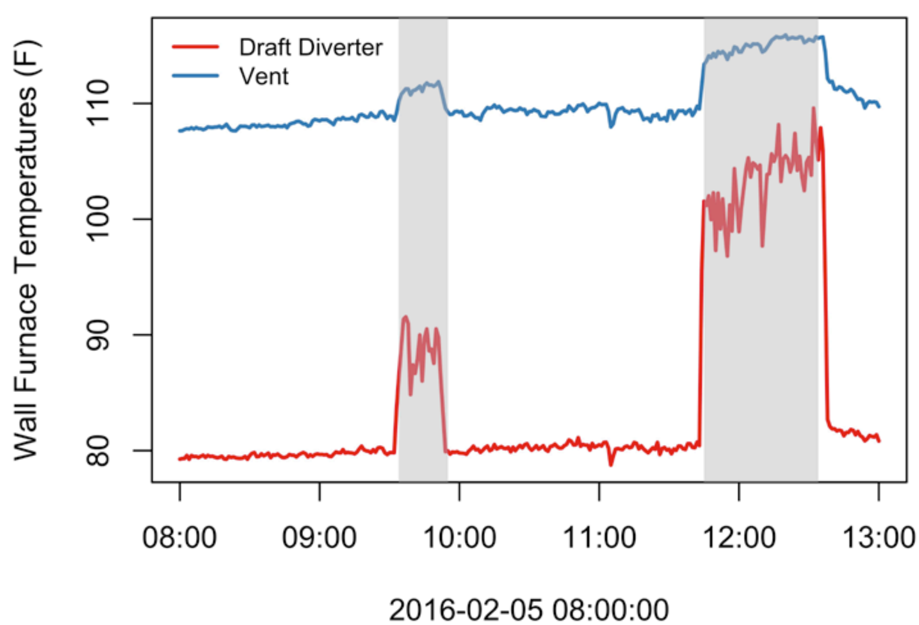

Figure 17 An example of bathroom operation (gray bands) impacting draft diverter and vent temperatures in Apt A_11_1, with possible implications for spillage of pilot exhaust gases.

Refer to discussion in text.

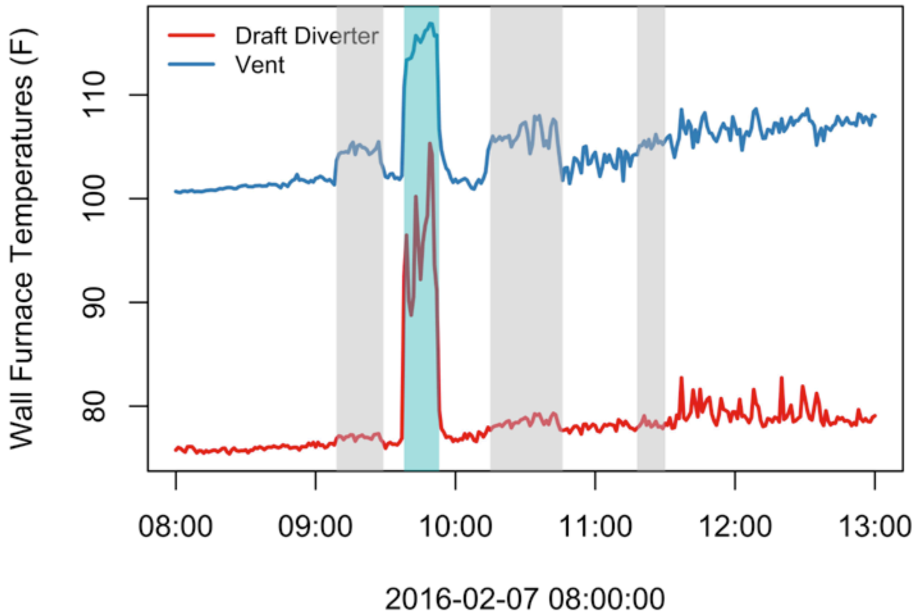

Figure 18 An example of kitchen (turquoise shading) and bathroom (grey shading) exhaust fan operation impacting vent and draft diverter temperatures in Apt A_7_2.

The higher airflow of the kitchen exhaust fan (roughly 80 vs. 28 cfm) produces greater depressurization which could reduce the flow of dilution air through the draft diverter, leading to higher temperatures and potentially increasing the chance of partial spillage of pilot burner pollutants.

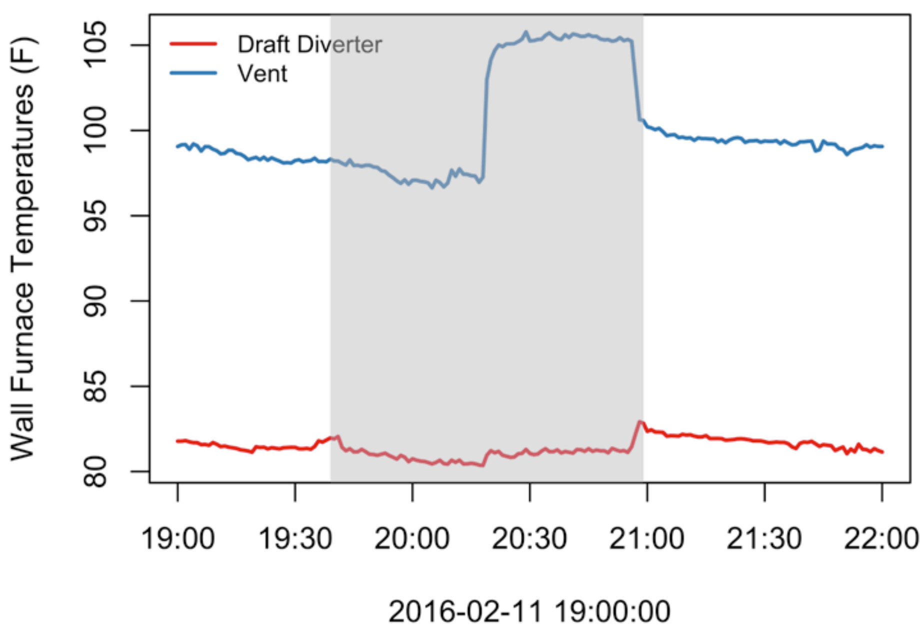

Figure 19 Example of increasing vent temperature during bath fan operation in Apt A_12_1.

The increase in hypothesized to correspond to a window being closed with consequent depressurization causing a reduction in flow through the draft diverter.

3 Results

3.1 Description of Apartment Units

Summary descriptions of all apartments included in the study are provided in Table 6.

Apartment units at Building A were mostly identical studio apartments with left and right hand orientations. There were two 1-bedroom units that had more square footage and an additional interior doorway creating more conditioned floor area. Many were interior units with only two exterior facing walls. Two participating units were located on the second floor of a two-story building. In addition to the roof adding more exterior surface area, this characteristic has an effect on drafting ability and is therefore noted above. Orientation information was not recorded for any of the units. Stovetops at Building A were electric. Apartments A_1_2 and A_10_1 used medical oxygen tanks. Apartment A_1_2 had an inoperable range hood through the midpoint data collection visit for that unit.

Apartments in Building B were all identical studio units. They had continuously exhausting bathroom fans that ramp up to a higher CFM when an occupant is detected in the space. There were also passive, tenant-adjustable passive air vents near the rear sliding glass doors. Three of the four participating units were located on the second floor of two story buildings. All stovetops at Building B were natural gas powered.

Table 6 Characteristics of tested apartment units.

Apt ID[1]	*Floor area (ft^2)*	*Description*
A_1_2	470	1st floor, Studio
A_2_2	560	3 exterior walls, 1st floor, 1 bedroom unit
A_3_2	470	2.5 exterior walls, 1st floor, Studio
A_5_1	470	2.5 exterior walls, 1st floor, Studio
A_6_1	470	1st floor, Studio
A_7_2	470	1st floor, Studio
A_8_1	470	1st floor, Studio
A_9_1	470	3 exterior walls, 1st floor, Studio
A_10_1	560	3 exterior walls, 1st floor, 1 bedroom
A_11_1	470	2nd floor, 1st floor, Studio
A_12_1	470	3 exterior walls, 2nd floor, Studio
B_13_1	510	2nd floor, studio, Gas Range
B_14_2	510	1st floor, Studio, Gas Range
B_15_1	510	2nd floor, studio, Gas Range
B_16_1	510	2nd floor, studio, Gas Range

[1]ID includes building (A,B), apt code, and number of occupants.

3.2 Diagnostic Testing

3.2.1 Envelope Airtightness

The airtightness of each apartment unit was tested upon initial inspection. The airflows at 50 Pascals of depressurization are reported in Table 7. These "CFM_{50}" values varied from roughly 400 to 700. These values represent total apartment leakage, which includes leakage areas between the unit tested and all adjacent parts of the building. These leakage areas are relevant for depressurization-induced spillage assessments, but are not relevant for energy calculations or outdoor air exchange.

Table 7 Airtightness test results in each apartment unit.

AptID	***CFM_{50}***
A_1_2	514
A_2_2	514
A_3_2	514
A_4_1	516
A_5_1	624
A_6_1	582
A_7_2	543
A_8_1	571
A_9_1	514
A_10_1	563
A_11_1	416
A_12_1	614
B_13_1	686
B_14_2	554
B_15_1	645
B_16_1	555
Median	*554*
Mean	*558*

3.2.2 Exhaust Device Airflow Testing

Calibrated fan flow meters were used to measure the airflow of exhaust devices in each apartment unit. The individual and maximum total airflows are reported in Table 8. Kitchen fans all had two settings. While the higher flow setting is used in worst-case depressurization testing, it is worth noting that the higher speed added only 21 CFM of exhaust flow on average and the highest increment was 47 CFM.

In Building B, bathroom fans[6] constantly operated on low speed and had motion sensors to ramp up airflow from low to high when the room was occupied. In the first unit tested (B_14_2) we were unable to detect any sign of the fan transitioning between low and high settings. The transition was noticeable in other units, but "low" flow rates could not be tested since any movement to measure the flow rate caused the fan speed to increase, and there was no way to permanently set the fans to the low speed. In addition, the HOBO motor loggers used to assess bathroom fan operation were unable to pick up the bathroom

[6] Panasonic Whispergreen

fans, likely due to the DC motors. Bathroom fan airflows were much higher in Building B than in Building A (98 vs. 49 CFM on average).

Table 8 Summary of exhaust fan airflow measurements and maximum installed exhaust capacity in each apartment.

AptID	*Kitchen Fan*		*Bathroom Fan (CFM)*	*Maximum Exhaust Capacity (CFM)*
	Low (CFM)	*High (CFM)*		
A_1_2	73	88	42	130
A_2_2	126	154	32	186
A_3_2	105	120	55	175
A_4_1	62	77	54	131
A_5_1	106	120	57	177
A_6_1	79	92	NA	92
A_7_2	80	98	28	126
A_8_1	68	115	56	171
A_9_1	87	108	49	157
A_10_1	118	140	81	221
A_11_1	107	131	37	168
A_12_1	107	131	38	169
B_13_1	28	48	97	145
B_14_2	40	62	39	101
B_15_1	31	63	100	163
B_16_1	33	49	98	147
Median	*80*	*103*	*54*	*160*

3.2.3 Step-Wise Depressurization and Spillage Testing

Combustion spillage diagnostics were performed for the wall furnace in each apartment and results are presented in Table 9. The testing included a step-wise assessment of draft/spillage at conditions varying from natural to worst-case depressurization. Table 9 reports the maximum combustion appliance zone depressurization with the installed exhaust fans. In some cases, this was not sufficient to cause spillage, so we introduced additional exhaust airflow was introduced using the blower door fan. Table 9 reports the exhaust fan and door configuration and lowest depressurization that caused spillage.

The ability of the installed exhaust fan capacity to depressurize the combustion appliance zone in each apartment was highly variable, from roughly -2 to -15 Pascal. In five apartments, the installed exhaust devices did not cause spillage of the wall furnaces even when operated under worst-case conditions. In these cases, a blower door fan was used to induce spillage with 150 cfm of exhaust airflow (labeled as 'Induced 150CFM'). The lowest level of depressurization leading to spillage in any apartment (via installed capacity or blower door) was -5 Pa. In some units, furnaces did not spill until depressurization reached 11 Pa. In the ten apartments with enough installed exhaust capacity to cause spillage, three could be spilled with only a single exhaust device operating. Furnaces in units A_2_2 and A_11_1 spilled with only the kitchen fan on low speed (at 126 and 107 CFM, respectively). The furnace in B_16_1 spilled with only the bathroom fan operating (at 98 CFM). All other apartments required coincident operation of two exhaust fans for the furnace to spill.

In general, the impact of opening or closing the bathroom door was small on CAZ depressurization, with median absolute change in CAS depressurization of 0.2 Pa for matched fan conditions. The maximum change in any case was 1 Pa (kitchen fan high, bath fan on in A_5_1); yet the same apartment at another fan combination condition (kitchen fan low, bath fan on) showed no change in depressurization with bathroom door position. These results suggest that most changes resulting from the bathroom door position are within the noise of the instrument and may not be worth test effort.

Notably, all apartments in Building B had passive ventilation air openings that could be set to high (mostly open) or low (mostly closed) settings. Tenants were encouraged to keep these in the high setting. At unit B_16_1 the tenant had previously blocked the vent opening by stuffing a T-shirt into the entrance and covering it with duct tape. This was done to impede the entry of cigarette smoke from downstairs neighbors. More recently, new rules have been enacted disallowing cigarette smoking in that area, so the tenant agreed to have the passive vent opened and operating as intended. It should also be noted that, as described in Methods Section 2.4, the wall furnaces in Building B had spill switches that were repeatedly tripped during this spillage testing.

Table 9 Summary of wall furnace spillage testing in each apartment unit.

AptID	CAZ pressure referenced to outside (Pa)		Least challenging condition that produced spillage			
	Maximum depressurization with installed fans	*Minimum depressurization to induce spillage*	*Kitchen fan*	*Bath fan*	*Bath door*	*Vents*
A_1_2	-2.9	-8	Induced 150 cfm	NA	NA	NA
A_2_2	-11.7	-7.2	Low	Off	Open	NA
A_3_2	-9.9	No Fail	No Fail	No Fail	No Fail	No Fail
A_4_1	-8.5	-9.6	Induced 150 cfm	NA	NA	NA
A_5_1	-12	-10	Low	On	Closed	NA
A_6_1	-8.2	-8.1	Induced 150 cfm	NA	NA	NA
A_7_2	-9.5	-8.4	Low	On	Closed	NA
A_8_1	-11	-11	High	On	Open	NA
A_9_1	-11	-10.5	High	On	Closed	NA
A_10_1	-8.6	-7	Low	On	Closed	NA
A_11_1	-14.9	-8.5	Low	Off	Open	NA
A_12_1	-6.9	-5.3	Low	On	Closed	NA
B_13_1	-4.2	-8.9	Induced 150 cfm	NA	NA	NA
B_14_2	-2.3	(Result not recorded)	Induced 150 cfm	NA	NA	NA
B_15_1	-7.5	-5	Low	On	Closed	Open
B_16_1	-4.1	None	Off	On	Open	Closed

3.2.4 Combustion Appliance Flue Carbon Monoxide Levels

Flue gases from each apartment's wall furnace were measured for air-free carbon monoxide concentrations in the flue during spillage testing. The CO values are reported for each unit in Table 10. Only one apartment had problematic CO during inspection, apartment A_2_2 initially tested flue CO above 1,000 ppm, but with repairs this was reduced to 0 ppm. Low appliance CO reduces some of the risks associated with combustion appliance spillage, but other pollutants are still of concern (e.g., NO_x, particles, water vapor).

Table 10 Wall furnace carbon monoxide measurements for each apartment unit.

AptID	*Wall Furnace CO (ppm)*	*Notes*
A_1_2	15	Kitchen range broken for majority of study
A_2_2	0	First visit was over 1000 ppm, repaired
A_3_2	5	
A_4_1	15	
A_5_1	0	
A_6_1	0	
A_7_2	6	
A_8_1	2	
A_9_1	2	
A_10_1	0	
A_11_1	7	
A_12_1	0	
B_13_1	0	
B_14_2	0	
B_15_1	6	
B_16_1	0	

3.3 Field Monitoring

3.3.1 Outside Conditions

The monitoring in the apartment units took place over the course of roughly two months—February and March of 2016—and outside weather varied during these periods. Daily average outside temperatures were retrieved from the Weather Underground website for the two building locations, using the Hayward Airport (KHWD) for Building A and the Moffett Federal Air Field (KNUQ) for Building B. The start and end of the monitoring periods for each apartment unit are listed in Table 11, along with the calculated base 65°F heating degree days per day during that time period. The coldest monitoring period (A_5_1) was 30% colder than the mildest period (A_2_2). This variability is expected to have a modest impact on heating system run times.

Table 11 Monitoring start and end dates (Year-Month-Day) for each apartment unit, along with mean heating degree-days per day for the period using a 65°F base temperature.

AptID	*Start*	*End*	*HDD_{65} per day*
A_1_2	2016-02-05	2016-02-26	6.7
A_2_2	2016-02-05	2016-03-07	6.3
A_3_2	2016-03-08	2016-03-25	7.4
A_4_1	2016-03-07	2016-03-25	7.7
A_5_1	2016-02-01	2016-02-25	8.1
A_6_1	2016-02-04	2016-02-26	7.0
A_7_2	2016-02-02	2016-02-25	7.8
A_8_1	2016-02-01	2016-02-25	8.1
A_9_1	2016-02-02	2016-02-25	7.8
A_10_1	2016-02-04	2016-02-29	6.6
A_11_1	2016-02-03	2016-02-26	7.4
A_12_1	2016-02-03	2016-02-26	7.4
B_13_1	2016-03-03	2016-03-24	7.2
B_14_2	2016-02-29	2016-03-25	6.7
B_15_1	2016-03-02	2016-03-30	7.3
B_16_1	2016-03-03	2016-03-25	7.2

3.3.2 Living Space Conditions

Measurements of temperature, relative humidity, carbon monoxide and carbon dioxide were made in the main living space of each apartment. Below are basic statistical summaries for these parameters across the participating apartment units.

3.3.2.1 Temperature

Indoor temperatures were measured in the central living space of each apartment unit at five-minute intervals during the study period. Average daily temperature profiles are pictured in Figure 20, and summary statistics for indoor temperatures are provided in Table 12. Indoor temperatures are in the expected range for occupied residences, with some staying stable throughout the day and others varying substantially over the course of the day. None of the apartments experienced any period below 60°F. Some over-heating occurred, with some units reaching maximum temperatures in the upper 80s and lower 90s. Some of the high indoor temperatures may have been by preference (as Building A occupants were all seniors) and some may have been over-heating caused by mismanaged thermostats.

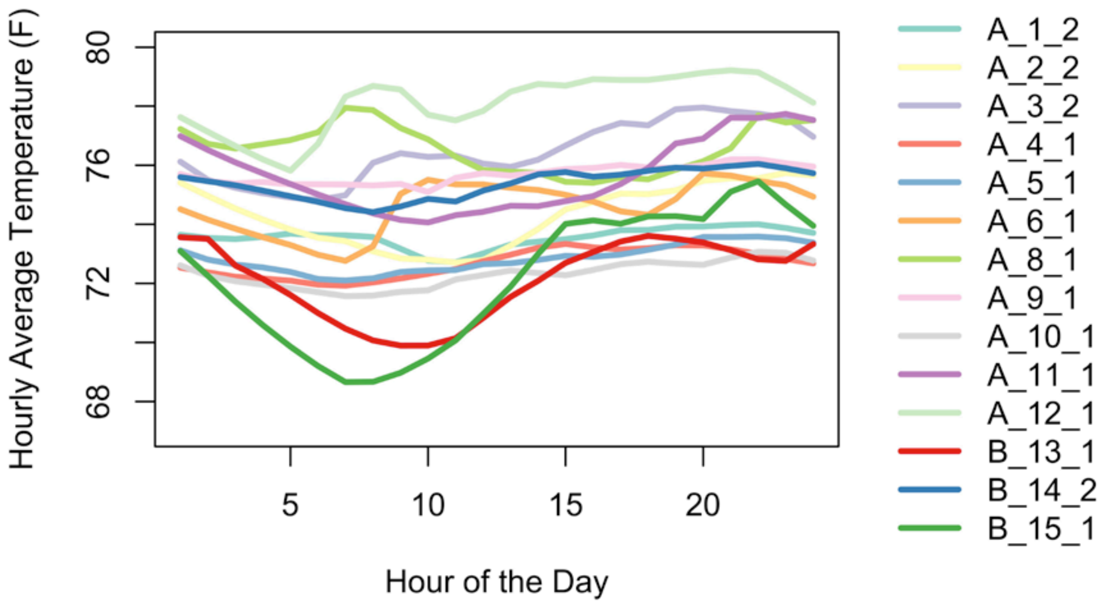

Figure 20 Average indoor temperatures for each hour of the day.

Table 12 Summary statistics of measured indoor temperatures.

AptID	*Indoor Temperature (°F)*					
	Min	*25th*	*Median*	*Mean*	*75th*	*Max*
A_1_2	70.0	72.7	73.4	73.6	74.3	80.0
A_2_2	62.8	73.1	74.5	74.3	75.5	79.5
A_3_2	66.9	75.3	76.4	76.4	77.8	82.2
A_4_1	67.2	72.0	72.6	72.7	73.2	81.1
A_5_1	69.1	72.2	73.1	72.9	73.6	77.4
A_6_1	71.0	73.6	74.8	74.6	75.5	83.9
A_7_2	NA	NA	NA	NA	NA	NA
A_8_1	72.4	75.4	76.7	76.6	77.6	84.1
A_9_1	68.4	75.8	76.3	75.7	76.7	78.8
A_10_1	65.2	71.5	72.3	72.3	72.9	86.3
A_11_1	71.2	74.1	75.7	75.7	77.1	83.9
A_12_1	72.2	76.5	78.3	78.2	80.2	82.5
B_13_1	66.0	70.0	71.9	72.1	74.3	84.1
B_14_2	65.9	74.5	75.3	75.4	76.4	90.3
B_15_1	65.2	69.8	71.7	72.1	74.1	90.5
B_16_1	NA	NA	NA	NA	NA	NA

3.3.2.2 Relative Humidity

Indoor relative humidity was measured at five-minute intervals in the same location as indoor temperature in each apartment unit. Summary statistics for measured indoor humidity are reported in Table 13. Indoor relative humidity was in the expected range for occupied dwellings, with study period minima of 30-40% and maxima of 50-70% RH. The 30-60% RH range is considered optimal for human health and comfort (Baughman & Arens, 1996).

Table 13 Summary statistics of measured indoor relative humidity.

	Indoor Relative Humidity (%)					
AptID	***Min***	***25th***	***Median***	***Mean***	***75th***	***Max***
A_1_2	30.7	48.0	51.1	51.5	55.0	68.1
A_2_2	36.2	55.8	59.0	58.3	61.7	76.4
A_3_2	37.0	45.8	49.6	49.5	53.5	68.3
A_4_1	42.5	49.4	51.6	51.4	53.9	59.6
A_5_1	37.7	46.3	49.5	49.3	52.5	59.7
A_6_1	36.8	47.7	49.7	49.7	51.4	70.7
A_7_2	NA	NA	NA	NA	NA	NA
A_8_1	34.0	42.8	45.2	45.6	48.5	60.4
A_9_1	33.1	43.8	46.3	46.5	49.4	67.9
A_10_1	34.4	44.9	47.9	47.4	49.7	58.1
A_11_1	36.8	45.3	46.7	46.3	47.6	51.5
A_12_1	26.4	36.4	39.5	38.8	41.8	51.8
B_13_1	34.4	44.3	46.7	46.3	48.5	56.8
B_14_2	29.9	42.2	44.3	44.6	46.9	58.6
B_15_1	32.9	42.6	45.4	45.9	48.4	71.2
B_16_1	NA	NA	NA	NA	NA	NA

3.3.2.3 Carbon Dioxide

CO_2 concentrations were measured on a five-minute time-step in the main living room of each apartment unit. The distribution of living room CO_2 is presented in Table 14 for each apartment. Measured levels were in-line with the expected range in occupied residences. Maxima were in the 1,500 to 2,000 ppm range, and median concentrations were just below 800 ppm.

Table 14 Summary statistics of measured 5-minute CO_2 concentrations in the main living room of each apartment.

AptID	*Room CO_2 (ppm)*					
	Min	***25th***	***Median***	***Mean***	***75th***	***Max***
A_1_2	518	619	759	772	866	1423
A_2_2	313[1]	903	1337	1317	1861	1892
A_3_2	405	655	805	793	947	1240
A_4_1	435	603	649	638	684	900
A_5_1	396	797	911	885	1010	1314
A_6_1	494	894	996	965	1065	1280
A_7_2	455	956	1100	1089	1242	1783
A_8_1	424	571	627	626	677	1076
A_9_1	424	557	618	625	685	1003
A_10_1	536	821	898	896	963	1318
A_11_1	411	725	957	897	1081	1318
A_12_1	410	518	797	793	1036	1481
B_13_1	410	488	569	578	655	974
B_14_2	400	610	704	709	786	1917
B_15_1	402	490	612	675	822	1941
B_16_1	NA	NA	NA	NA	NA	NA

[1] This value is sufficiently below the outdoor background that it is clearly erroneous. The cause of the error was not determined.

3.3.2.4 Carbon Monoxide

Carbon monoxide is the most commonly cited pollutant of concern that CAS testing is meant to address in residences. Accordingly, CO levels were measured on a one-minute time step in the main living area of each apartment unit throughout the study. Summary statistics for measured CO are provided in Table 15, along with maximum concentrations for one-minute, one-hour and eight-hour periods. For reference, the U.S. EPA's outdoor ambient air quality standards limit CO to 9 ppm averaged over an 8h period and 9 ppm averaged over 1h (U.S. EPA, 2012). These values are to be exceeded no more than once per year. According to these standards, there was only one instance of a CO measurement of concern. The event, which occurred in Apartment A_1_2, comprised CO increasing from the low background to about 60 ppm over a two-hour period. The event is of uncertain cause since the study participant in this apartment did not complete daily log sheets. Two wall furnace cycles occurred in the hour prior to the beginning of the event, and some cooking activity occurred during the decay period. But the profile of burner use does not match the increase in CO. Also, very low CO (15 ppm air-free) was measured in the wall furnace flue during testing, and the cooktop burners were electric. It is also not plausible that the CO could have come from outdoors, as this would have been observed in other apartments.

Table 15 Summary statistics of 1-minute carbon monoxide measurements in the living space of each apartment, including one-hour and eight-hour maximums.

	Indoor Carbon Monoxide (ppm)							
AptID	***Min***	***25th***	***Median***	***Mean***	***75th***	***Max***	***Max 1hr***	***Max 8hr***
A_1_2	0	0	0	1	0	59[1]	57[1]	34[1]
A_2_2	0	0	0	0	0	9	1	0
A_3_2	0	1	1	1	1	6	3	2
A_4_1	0	0	0	0	0	1	0	0
A_5_1	0	0	0	0	0	1	0	0
A_6_1	0	0	0	0	0	1	0	0
A_7_2	0	2	2	2	3	8	4	3
A_8_1	0	0	0	0	0	1	1	0
A_9_1	0	0	1	1	1	3	3	2
A_10_1	0	0	0	0	0	2	0	0
A_11_1	0	1	1	1	1	3	2	2
A_12_1	0	0	0	0	0	1	0	0
B_13_1	0	0	0	0	0	1	0	0
B_14_2	0	0	0	0	0	8	5	1
B_15_1	0	0	0	0	0	6	4	1
B_16_1	NA	NA	NA	NA	NA	NA	NA	NA

[1] The study participant in this apartment did not submit daily log sheets. We thus have no information about potential causes for this apparently high CO event.

3.3.3 Household Activities

As discussed in Section 1 of this report, the determination and assessment of an appropriate reduced challenge condition requires that we have some knowledge of how apartments are operated over time. It is crucial to note when reading the following sections that participating households were asked to operate their homes in a way that may not represent their typical behavior patterns. If during AEA diagnostic testing, the apartment's wall furnace showed any signs of spillage under natural conditions, the participant was instructed to open their windows when operating their range hood and/or cooking. If the tested apartment was not spilling under natural conditions, the participant was instructed to operate their windows as they normally do. Participants were also instructed to use their kitchen exhaust fans and bathroom fans whenever cooking or bathing.

Below we summarize the measurement results for the wall furnaces (including burner time, downdrafting and spillage), as well as cooking and use of bathroom and kitchen exhaust fans. These are discussed individually and then in combination with the heating appliance operation summarized in Section 3.3.4. Overall summaries of these household activities are provided in Table 16. Detailed results are provided for each apartment, along with discussion and illustrative plots in the sections below.

Table 16 Overall summary statistics for activities recorded in the apartments.

	Fraction of Monitored Minutes		***Events***			
Metric	***Mean***	***Max***	***Total Count (#)***	***Average per Apartment (#)***	***Average Duration (Minutes)***	***Max Duration (Minutes)***
Bath Fan	3.88%	13.45%	839	76	17	540
Kitchen Fan	2.42%	10.19%	368	23	28	267
Cooking Burners	3.32%	11.35%	583	36	32	302
Cooking (Burners or Kitchen Fan)	4.63%	13.27%	657	41	34	324
Heating	*2.76%*	8.89%	743	*46*	*14*	*162*
Spillage	0.03%	0.07%	25	6.3	1.4	5
Downdrafting	*3.11%*	18.47%	307	*24*	*34*	*750*

3.3.3.1 Wall Furnace Operation

The operation of the wall furnace in each apartment was monitored using temperature probes at the draft diverter and inside the vent pipe. Using methods described in Section 2.6.4, we identified heating burner cycles, downdrafting and spillage events. Downdrafting results are presented before spillage results, because in this study, downdrafting was the necessary pre-condition to the occurrence of unambiguous spillage.

3.3.3.1.1 Burner Cycles

The heating cycles are summarized for each apartment unit in Table 17, and the length of all heating cycles across all apartment units is cumulatively plotted in Figure 21. The average heating system runtime was 2.76% of the monitoring period, and 743 discrete burner cycles were identified. Across apartments, the average number of heating burner cycles was 46 with an average length of 14 minutes. Cumulative heating system run time was highly variable between units, varying between four minutes and 2,126 minutes. Cycle lengths were also highly variable, even between units with similar amounts of total furnace operation. For example, B_15_1 and A_6_1 both had approximately 1,000 minutes of heating operation, but with 30 versus 120 heating cycles (average cycle lengths of 36 versus 8 minutes). The longest heating cycles were on the order of one to two hours.

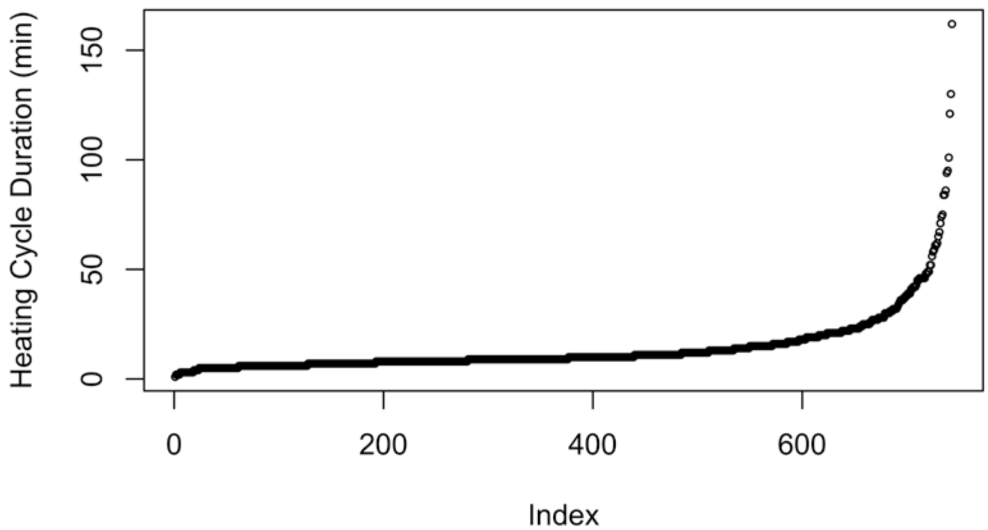

Figure 21 Cumulative distribution of all heating system cycles in all apartment units

Table 17 Summary statistics for all heating system cycles in all apartment units.

AptID	*Total runtime (min)*	*Runtime fraction (%)*	*Cycle count*	*Furnace Cycle Length (minutes)*					
				Min	*25th*	*Median*	*Mean*	*75th*	*Max*
A_1_2	26936	3.86%	75	5	8	10	14	14	74
A_2_2	13749	0.63%	8	2	7	13	11	14	19
A_3_2	13586	8.89%	81	3	8	13	15	20	59
A_4_1	23836	0.20%	7	5	7	7	7	7	7
A_5_1	27259	2.64%	64	5	10	11	11	11	27
A_6_1	27361	3.66%	118	2	6	6	8	8	58
A_7_2	26571	0.07%	2	6	8	9	9	11	12
A_8_1	27303	2.48%	45	2	8	16	15	21	35
A_9_1	26626	4.81%	149	1	8	9	9	9	25
A_10_1	27303	2.17%	10	5	37	41	59	82	162
A_11_1	27344	1.50%	10	31	36	39	41	47	52
A_12_1	26984	7.88%	115	3	9	11	18	19	95
B_13_1	25727	1.14%	26	3	5	11	11	16	28
B_14_2	27238	0.25%	5	10	10	10	11	11	14
B_15_1	26466	4.05%	28	5	17	29	38	47	130
B_16_1	27251	0.00%	0	NA	NA	NA	NA	NA	NA
Average		*2.76%*	*46*	*1*	*7*	*9*	*14*	*15*	*162*

3.3.3.1.2 Downdrafting

Downdrafting occurs when air flows down the vent pipe due to weather or exhaust fan effects, and is not limited to furnace operation. Summary statistics for downdrafting events occurring during the measurement periods are provided in Table 18, and a cumulative distribution of all downdraft events is provided in Figure 22. It is crucial to point out that these are simply events where flow is reversed in the vent pipe, NOT events where combustion pollutants spill into the living space. These downdrafting events likely occurred whenever exhaust fans were operated in the apartment and windows were closed. Variability in downdrafting was high, with some units experiencing no downdraft, and others downdrafting up to 14% of the monitoring period. A total of 307 downdraft events were identified across all apartments, with the average apartment having 24 downdraft events of 34 minutes each. The longest individual event lasted 750 minutes in Apt B_15_1 (roughly half of one day). The vast majority of downdraft events lasted less than 100 minutes. As discussed in Methods Section 2.6.4.3, these results only include full downdrafting conditions, and other reduced draft conditions are not included (e.g., when an exhaust fan causes a slowing of the exhaust vent gases or even partial spillage of pilot burner pollutants).

Downdrafting was more common in Building B, likely because of the continuously operating bathroom exhaust fans. AEA was not able to measure the bath fan airflows on the continuous, low setting, but their airflows on high (activated by local sensor) were roughly 100 cfm. We expect that in these apartment units, the wall furnaces were likely under downdraft conditions whenever all of the windows were closed. In apartments where wall furnaces spilled residents were instructed to keep windows open during cooking. As a result, the data presented here may be underestimating downdrafting and spillage events that would occur under unguided circumstances (presumably with windows closed more often). The only exception may be Apt B_14_2 where no downdrafting was recorded. This apartment had much lower bathroom exhaust airflow (40 cfm at high, compared with 100 cfm in other building 2 apartments), and a low flow kitchen exhaust. As such, this apartment had the second lowest of all installed fan capacities (~100 cfm total). Downdrafting was also high in one Building A apartment (Apt A_8_1), which had by far the most bathroom and kitchen exhaust fan operation (13% and 10% of the monitoring period, respectively).

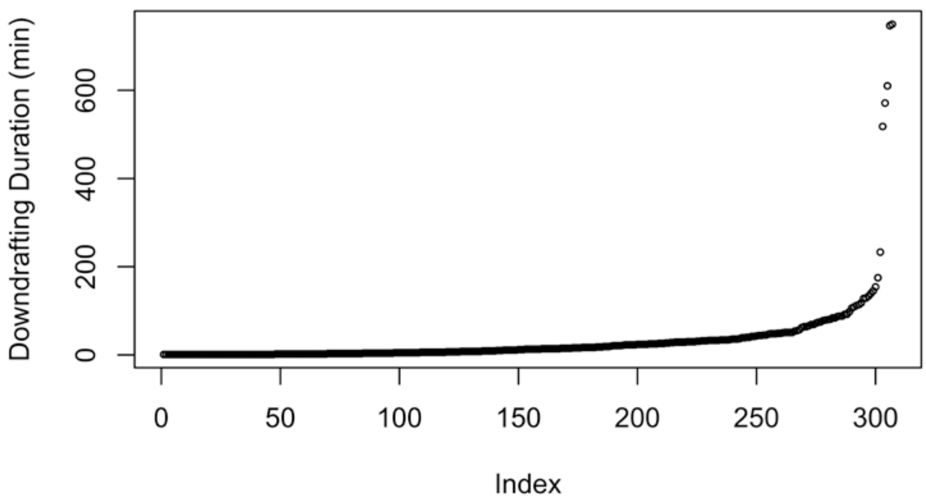

Figure 22 Cumulative distribution plot of all identified downdraft events.

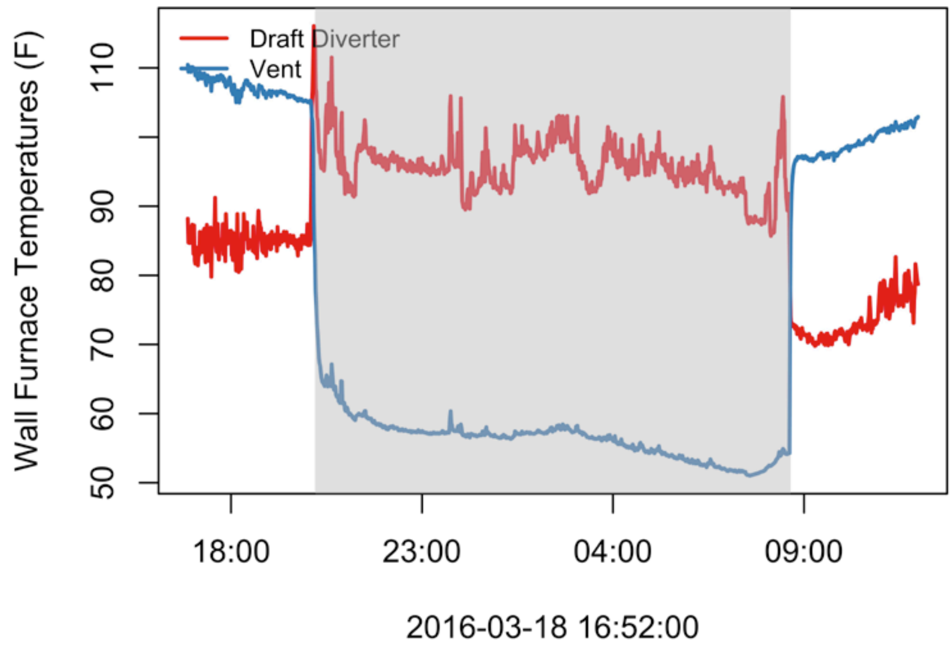

Figure 23 Longest downdraft event (highlighted grey) identified in any apartment unit, Apt B_15_1. This event lasted from approximately 10:00pm until 9:00am the following morning.

Table 18 Summary statistics for downdrafting cycles in all apartment units.

AptID	Total minutes operation	Total Downdraft Period (%)	Cycle count	Length of Downdraft Cycles (minutes)					
				Min	25th	Median	Mean	75th	Max
A_1_2	26936	0.11%	6	1	1	2	5	2	23
A_2_2	13749	0.56%	10	2	4	7	8	8	17
A_3_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_4_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_5_1	27259	1.21%	15	2	9	13	22	31	74
A_6_1	27361	0.09%	4	1	1	4	6	9	17
A_7_2	26571	0.68%	12	1	3	7	15	17	75
A_8_1	27303	6.58%	87	1	2	14	21	29	154
A_9_1	26626	0.27%	5	4	12	13	15	14	30
A_10_1	27303	0.93%	10	1	2	8	25	35	112
A_11_1	27344	0.59%	9	1	2	6	18	29	51
A_12_1	26984	0.16%	1	43	43	43	43	43	43
B_13_1	25727	8.73%	80	1	4	16	27	33	175
B_14_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_15_1	26466	18.47%	56	1	4	12	87	76	750
B_16_1	27251	2.04%	12	1	6	50	46	71	128
Average		*3.11%*	*24*	*1*	*3*	*13*	*34*	*33*	*750*

3.3.3.1.3 Spillage

Spillage occurs when some fraction of the combustion products produced by burner operation pass into the living space. Spillage can encompass a fraction of the burner combustion products or all of them. If the burner fires when the vent is in a downdraft condition, proper venting may still occur, as the buoyancy of the hot combustion gases may be sufficient to reverse flow. And even if the flow is not reversed immediately upon burner firing, the exhaust may over time warm the air above to create the intended updraft venting. Spillage events are of direct concern as they could present a health or material risk (depending on the contents of the combustion products emitted), whereas downdrafting is of secondary concern only, as it increases the likelihood of spillage. Many appliances may spill on start-up yet still establish good draft within a few minutes.

As noted in Section 2.3, in apartments where wall furnaces spilled under natural test conditions, occupants were instructed to open their windows during kitchen exhaust fan use. This may (or may not) have affected the frequency of measured unambiguous spillage. If anything, it is likely that our reports of spillage frequency and duration are biased low, relative to 'typical' operation, where the window may have remained closed during kitchen fan use.

Using the wall furnace temperature measurements, we identified spillage events using methods described in Section 2.6.4. As noted in the Methods section, here we only report results for unambiguous spillage events—those where spillage is strong and clear, with dramatic growth in the draft diverter temperature sensor while the vent temperature remains stagnant. This may dramatically under-predict partial or unclear spillage, which may or may not be hazardous.

Spillage statistics are reported for each apartment building in Table 19. Most apartments (12 of 16) had no unambiguous spillage occur outside of the AEA diagnostic test period, which was removed from these analyses. Four apartments—A_5_1, A_9_1, B_13_1 and B_15_1—experienced small amounts of unambiguous spillage during normal occupancy. At most, spillage occurred 0.07% of monitored minutes, and among apartments with any spillage, the average spillage period was 0.03% of monitored minutes. A total of 25 unambiguous spillage events were identified, with an average length of one-minute and maximum length of five-minutes. All of these unambiguous spillage events were shorter than the five-minute cold burner start-up period during which spillage is allowed by CAS test protocols.

It is interesting to note that these four apartments all required two fans to induce spillage during AEA diagnostic testing (see Table 9), and in the case of B_13_1, a duct blaster fan was required to induce spillage, because the installed fans were not able to do so. The installed fan exhaust airflows were above average, but not necessarily the highest of those measured. These apartments (with the exception of A_9_1) had high levels of downdrafting (see Table 18). Downdrafting was also high in A_8_1 and B_16_1, but they showed no unambiguous spillage.

Table 19 Summary statistics for wall furnace spillage cycles in each apartment unit.

AptID	*Total minutes of operation*	*Spillage Fraction (%)*	*Cycle count*	*Furnace spillage cycle duration (minutes)*					
				Min	*25th*	*Median*	*Mean*	*75th*	*Max*
A_1_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_2_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_3_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_4_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_5_1	27259	0.02%	1	5	5	5	5	5	5
A_6_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_7_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_8_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_9_1	26626	0.00%	1	1	1	1	1	1	1
A_10_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_11_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_12_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_13_1	25727	0.07%	14	1	1	1	1.4	2	2
B_14_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_15_1	26466	0.04%	9	1	1	1	1.2	1	2
B_16_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
Average		0.03%	6.3	1	1	1	1.4	2	5

In almost all identified cases of unambiguous spillage, the same pattern occurred. First, the wall furnace was in downdraft mode, then the burner turned on, the appliance spilled for one to five minutes, and then what appeared to be normal draft conditions were established. Examples of this are provided across several apartments in Figure 24, Figure 25, Figure 26 and Figure 27. These events clearly highlight the relationship between an appliance being in downdraft condition and then spilling upon burner start-up, and in the case of Apt B_13_1, tripping the spill switch. It is notable that in many cases, the downdrafting event is triggered only after several minutes of downdraft condition, which is the result of slower rates of change in the vent temperature (i.e., more like a decay downwards rather than a spike downwards). The exception is pictured in Figure 27, where the sharp decline in vent temperature is identified almost immediately.

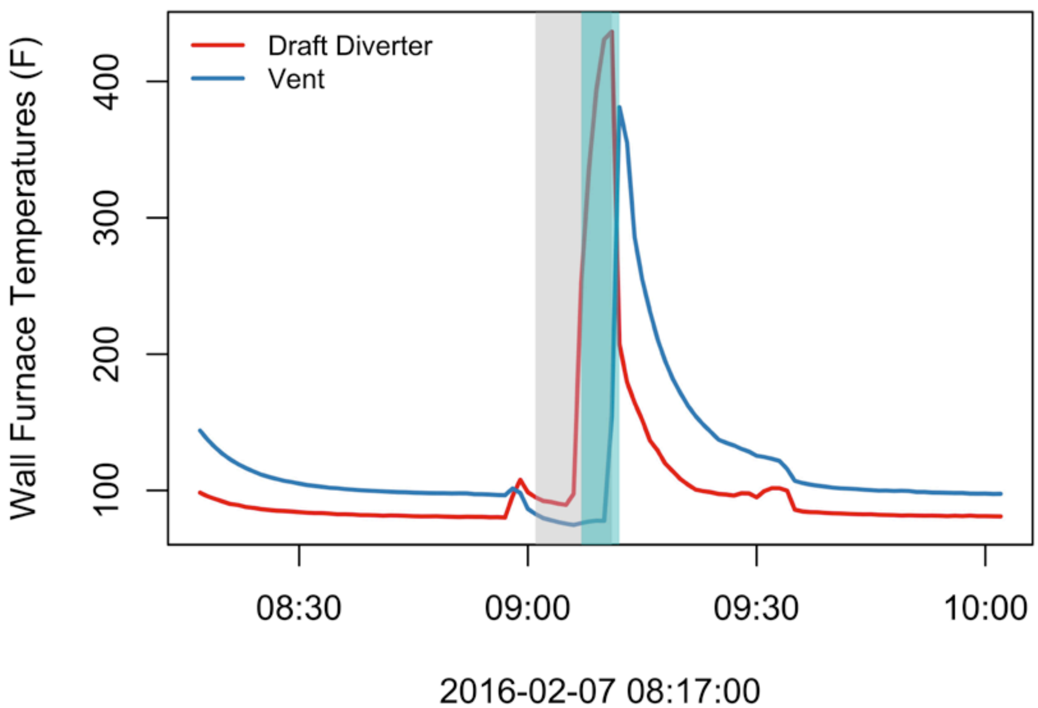

Figure 24 An example of an unambiguous spillage event occurring in Apt A_5_1. Note the downdraft period (highlighted grey) immediately preceding the five-minute spillage period (highlighted turquoise).

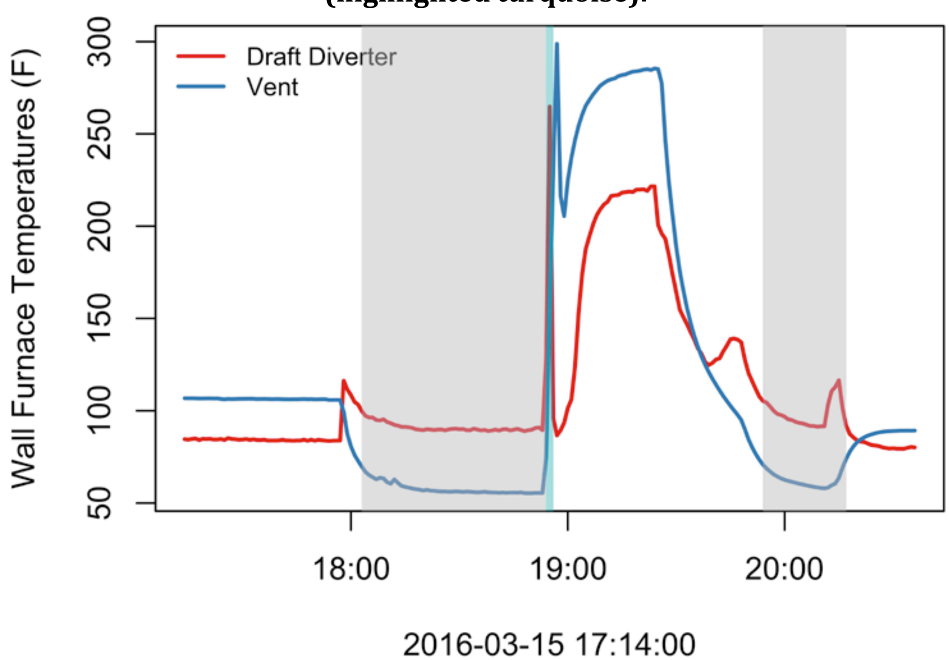

Figure 25 An example of an unambiguous spillage event occurring in Apt B_13_1.

Note the downdraft period (grey band) immediately preceding the spillage period (highlighted turquoise). Wall furnace possibly tripped its spill switch minutes after the burner turned on, and then the burner turned back on minutes later. Furnace was still in downdraft after the burner cycle ended (second grey period).

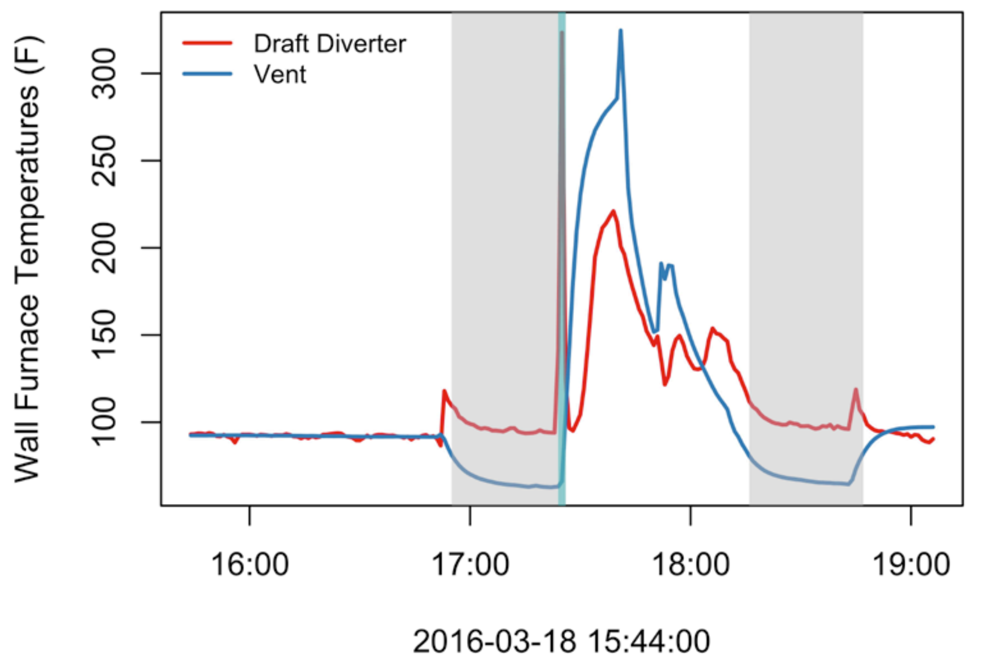

Figure 26 Another example of an unambiguous spillage event occurring in Apt B_13_1.

Note the downdraft period (grey band) immediately preceding the spillage period (highlighted turquoise). Wall furnace possibly tripped its spill switch minutes after the burner turned on, and then the burner turned back on minutes later. Furnace was still in downdraft after the burner cycle ended (second grey period).

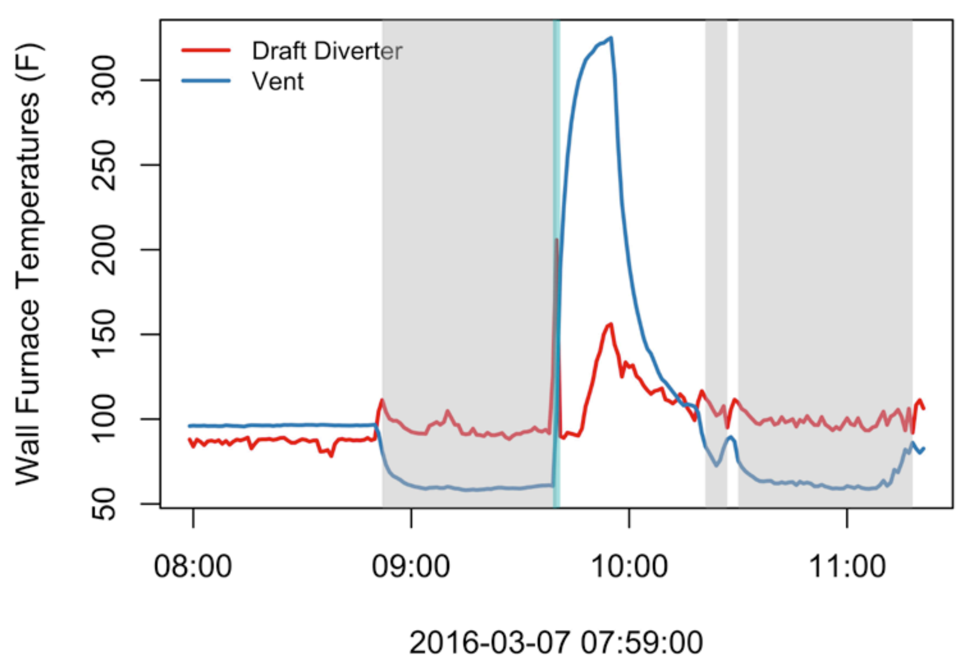

Figure 27 An example of an unambiguous spillage event occurring in Apt B_15_1.

Again, the furnace is in downdraft (grey band) before and after the burner cycle, and the appliance spills (turquoise) clearly for two-minutes at the start of the cycle.

It should be noted that all four apartments at Building B had adjustable passive vents located high on the rear wall near the sliding glass door. None of the interviewed participants were aware of the purpose of these vents. AEA staff explained that the vents were intended to provide a minimum level of outdoor air to protect indoor air quality, and how to operate them. Due to the tightness of units at Building B, AEA staff instructed the participants to have these vents open when cooking and operating the range hood. Most participants preferred to leave the vents open permanently for the duration of the study. Apartment B_16_1 had a large shirt and duct tape plugging the vent when AEA staff arrived for the first visit. This was due to complaints and concerns regarding a unit below that smoked regularly.

3.3.3.2 Bathroom Exhaust Usage

Bathroom exhaust fan usage was monitored in 11 of 16 apartment units using fan motor fraction sensors. Motor sensors did not work in five of the units, likely due to DC fan motors. Notably, these included the four Building B apartments, in which continuous bathroom fans were operated. 'NA' results for these apartments in Table 20 should not be construed to mean that bathroom fans did not operate, only that sensors failed to log operation. Total bathroom fan operation and summaries of events are reported in Table 20. Bath fan use varied substantially across units from 0.5 to 13.4% of the monitoring period, averaging 3.9% of monitored minutes. A total of 839 bath exhaust use events were identified, with an average number of 76 per apartment at 17 minutes in duration. The longest continuous bathroom exhaust use period was 540 minutes, likely the result of it being left in the on position.

Table 20 Summary of bathroom exhaust fan use in each apartment unit.

AptID	*Total (min)*	*Total Bath Fan Use (%)*	*Count of Bath Fan Events*	*Bath Fan Event Durations (min)*					
				Min	*25th*	*Median*	*Mean*	*75th*	*Max*
A_1_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_2_2	36013	0.54%	24	1	2	7	8	14	17
A_3_2	24289	1.02%	24	1	3	5	10	11	48
A_4_1	26000	0.85%	80	1	2	2	3	3	14
A_5_1	34558	1.22%	124	1	2	2	3	3	17
A_6_1	31647	1.35%	36	1	3	8	12	14	90
A_7_2	32940	2.62%	72	1	3	7	12	17	99
A_8_1	34414	13.45%	234	1	4	7	20	32	136
A_9_1	33119	5.17%	75	1	3	11	23	26	227
A_10_1	35674	0.83%	60	1	2	3	5	5	23
A_11_1	33099	6.26%	55	2	8	22	38	48	172
A_12_1	33333	9.34%	55	1	3	8	57	83	540
B_13_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_14_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_15_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_16_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
Average		3.88%	76	1	2	5	17	16	540

3.3.3.3 Cooking and Kitchen Exhaust Fan Usage

Cooking activities were assessed in each apartment unit using stovetop temperature measurements in all burner locations, as well as by monitoring of the operation of the kitchen exhaust fan (see Sections 2.6.1 and 2.6.2). Residents of each apartment unit agreed as part of their participation to operate the kitchen exhaust fan whenever they were cooking. So, we expect that kitchen exhaust fan usage was much higher than would typically occur in these apartments or in other residences.

Statistics for kitchen fan operation are presented in Table 21 and statistics for cooking burner use are presented in Table 22. Statistics for times that either activity occurred are presented in Table 23. The coincidence statistics for these two activities are presented in Table 24 and Figure 28.

Some kitchen exhaust fan use was logged in most apartment units, with usage periods varying between 0 and 10% of monitored minutes, averaging 2.4% of minutes (Table 21). A total of 368 kitchen exhaust use events were identified, with an average count of 23 per apartment and average duration of 28 minutes. The longest single kitchen fan use event lasted 267 minutes.

Table 21 Summary of kitchen exhaust fan use in each apartment unit.

AptID	*Total (min)*	*Total Kitchen Fan (%)*	*Count of Kitchen Fan Events*	*Kitchen Fan Event Durations (min)*					
				Min	*25th*	*Median*	*Mean*	*75th*	*Max*
A_1_2	30391	2.31%	14	3	22	43	50	63	132
A_2_2	14771	4.54%	39	2	6	10	17	18	200
A_3_2	24300	0.45%	11	1	4	10	10	14	32
A_4_1	26020	0.37%	17	1	3	5	6	9	12
A_5_1	30184	3.25%	29	5	17	21	34	36	144
A_6_1	30478	0.34%	10	1	5	9	10	17	22
A_7_2	28818	1.72%	22	2	7	15	23	27	84
A_8_1	30055	10.19%	83	3	18	33	37	47	154
A_9_1	28880	2.75%	53	1	5	10	15	18	66
A_10_1	31853	1.00%	8	6	11	42	40	55	89
A_11_1	30433	3.15%	21	4	17	29	46	63	207
A_12_1	15817	0	0	NA	NA	NA	NA	NA	NA
B_13_1	14419	0	0	NA	NA	NA	NA	NA	NA
B_14_2	30132	4.11%	38	1	10	13	33	42	267
B_15_1	15806	3.59%	15	1	13	29	38	46	127
B_16_1	31630	0.94%	8	1	19	48	37	52	60
Average		*2.42%*	*23*	*1*	*9*	*18*	*28*	*38*	*267*

Some cooking was logged in every apartment in this study, with use times varying between 0.7 and 11% of monitored minutes, averaging 3.3% of minutes (Table 22). A total of 583 cooking events were identified, with an average count of 36 events in each apartment, lasting an average of 32 minutes. The longest recorded cooking event was just over 300 minutes.

Table 22 Summary of all cooking burner activities in each apartment unit, where at least one cooking burner was being used.

AptID	*Total (min)*	*Total Cooking Burner (%)*	*Count of Cooking Burner Events*	*Cooking Burner Event Durations (min)*					
				Min	*25th*	*Median*	*Mean*	*75th*	*Max*
A_1_2	30372	4.89%	53	3	12	20	28	39	127
A_2_2	14741	2.38%	54	4	12	14	20	17	130
A_3_2	24360	1.95%	16	6	15	24	30	35	87
A_4_1	26078	0.31%	8	2	9	11	10	11	16
A_5_1	34558	1.58%	16	2	14	26	34	41	105
A_6_1	31662	0.93%	13	2	13	15	23	39	60
A_7_2	32940	1.74%	23	4	10	18	25	30	83
A_8_1	30432	6.06%	87	1	13	20	24	30	89
A_9_1	33123	9.42%	91	4	9	18	34	51	159
A_10_1	33541	0.89%	7	10	18	39	45	56	119
A_11_1	33144	3.23%	23	4	13	33	47	58	271
A_12_1	33329	1.67%	25	4	10	13	22	22	148
B_13_1	31319	0.66%	4	8	10	15	52	57	169
B_14_2	30527	3.25%	32	4	12	16	36	45	267
B_15_1	34693	11.35%	100	4	16	37	46	54	302
B_16_1	32069	2.84%	31	2	9	22	29	43	97
Average		3.32%	36	1	12	19	32	41	302

A cooking index that included either burner use or kitchen exhaust fan use was assessed, usage duration varied from 0.6 to 13% of the monitored period, averaging 4.6% of minutes (Table 23). A total of 657 such events were identified, with an average count of 41 events per apartment and duration of 34 minutes. The longest single event lasted 324 minutes. This combined index is only used to assess coincident operation with the bathroom exhaust fan and wall furnace. This provides an estimate of spillage or downdrafting that would occur if the kitchen fan were always used during cooking burner activity.

Table 23 Summary of all cooking activities in each apartment unit, as characterized by either cooking burner operation or kitchen fan operation.

AptID	*Total (min)*	*Total Cooking (%)*	*Count of Cooking Events*	*Cooking Event Durations (min)*					
				Min	*25th*	*Median*	*Mean*	*75th*	*Max*
A_1_2	30636	6.30%	58	3	12	21	33	41	142
A_2_2	14771	8.42%	53	2	12	16	23	21	209
A_3_2	24523	2.25%	24	1	7	17	23	32	87
A_4_1	26278	0.63%	22	1	3	7	8	11	26
A_5_1	34851	2.98%	31	2	17	23	33	40	144
A_6_1	31800	0.97%	15	1	9	15	21	30	60
A_7_2	33111	2.30%	29	2	9	18	26	31	96
A_8_1	30660	11.10%	88	1	20	35	39	49	155
A_9_1	33404	9.71%	95	2	10	18	34	50	159
A_10_1	33738	1.42%	9	6	24	47	53	71	119
A_11_1	33359	3.81%	24	4	17	35	53	62	287
A_12_1	33569	1.66%	25	4	10	13	22	22	148
B_13_1	31974	0.64%	4	8	10	15	52	57	169
B_14_2	30956	5.54%	49	4	10	14	35	41	324
B_15_1	34933	13.27%	100	4	16	38	46	55	302
B_16_1	32318	3.01%	31	2	9	22	31	46	97
Average		4.63%	41	1	12	21	34	44	324

Finally, the coincident use of the kitchen exhaust fan and cooking burner operation is summarized in Table 24 and compared in Figure 28. As expected, coincident operation was less than either kitchen exhaust fan or cooking use statistics, because sometimes cooking occurred with no exhaust use and the exhaust fan may have been left on after cooking finished or possibly used to remove other odors from the kitchen. Coincident use varied between 0 and 5.6% of monitored minutes, averaging 1.5% of minutes. 292 events were identified, with an average count of 18 per apartment at 22 minutes duration. The longest single coincident use event lasted 210 minutes.

Table 24 Summary of coincident cooking burner and kitchen fan operation.

AptID	*Total (min)*	*Total Cooking (%)*	*Count of Cooking Events*	*Cooking Event Durations (min)*					
				Min	*25th*	*Median*	*Mean*	*75th*	*Max*
A_1_2	30372	0.85%	9	9	17	25	29	35	59
A_2_2	14741	3.27%	40	2	5	8	12	12	121
A_3_2	24300	0.13%	3	4	9	13	10	14	14
A_4_1	26018	0.04%	3	2	3	3	3	4	5
A_5_1	30184	1.63%	14	5	18	27	35	38	105
A_6_1	30478	0.30%	8	4	6	10	11	16	21
A_7_2	28818	1.07%	16	2	9	14	19	20	71
A_8_1	30055	5.80%	82	3	11	17	21	27	80
A_9_1	28880	2.32%	49	1	4	9	14	17	57
A_10_1	31853	0.49%	6	6	8	24	26	43	49
A_11_1	30418	2.49%	20	4	10	21	38	59	191
A_12_1	15817	<0.005%	0	NA	NA	NA	NA	NA	NA
B_13_1	14419	<0.005%	0	NA	NA	NA	NA	NA	NA
B_14_2	30132	2.27%	19	1	12	19	36	46	210
B_15_1	15806	3.07%	15	1	13	25	32	40	127
B_16_1	31630	0.74%	8	1	19	26	29	44	60
Average		1.53%	18	1	8	14	22	27	210

Despite the commitment by participants to operate exhaust fan whenever cooking, the cooking and exhaust fan use figures diverge quite sharply in some cases; and in some cases where the values are roughly similar, only moderate fractions are coincident. In apartment B_15_1, which did the most cooking of any unit, the exhaust fan was only operated roughly one-third of the time that cooking was logged, and nearly all kitchen exhaust use was coincident with cooking. Apartments A_2_2, A_5_1, and A_8_1 had exhaust fan usages double or triple monitored cooking rates. Apartments A_7_2, A_10_1 and A_11_1 had similar cooking and exhaust fan usage fractions, but their coincident usage was somewhat lower.

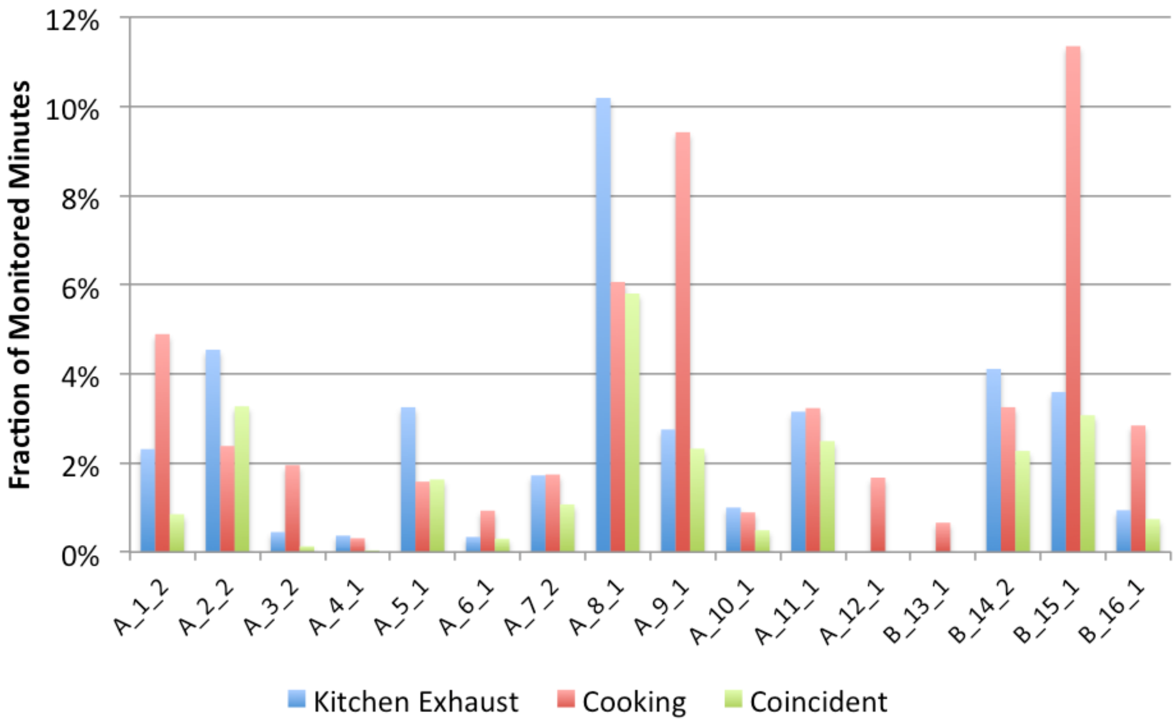

Figure 28 Comparison of kitchen exhaust fan, cooking and coincident use minutes for each apartment.

Many factors may be contributing to the apparent divergence between cooking and kitchen exhaust fan use. First it is important to note that the participants were asked to operate the exhaust fan whenever they cooked, but were not given specific instructions about when to start and stop the exhaust fan. Occupants may have sometimes failed to operate the exhaust fan while cooking, and at other times the exhaust fan may have been left on after cooking was completed. Algorithms for detecting cooking activity also may have missed some cooking events, particularly during oven usage. It is also possible that timestamps on the various sensors used were not in perfect alignment, such that coincident cooking and fan usage were artificially separated. Given this variability and the uncertainties, all assessments of 'cooking' coincident with heating system operation include both cooking and exhaust fan usage. The combined cooking index was not used to inspect wall furnace temperature data, which we would not expect to respond in any way to cooking burner operation with no kitchen exhaust fan operation.

3.3.4 Coincident Operation Assessments

Above we reported on heating system operation, cooking activity, and kitchen and bathroom exhaust fan use. Here we combine these data together in order to assess the frequency that each apartment unit was in a worst-case, Challenge or other depressurization condition. We assessed operation of the heating appliance coincident with cooking (combined cooking burner and kitchen exhaust fan index) and bathroom exhaust fan use, both individually and combined together. Finally, we assessed the coincident operation of the bathroom exhaust and cooking, irrespective of heating system operation. We refer to these as 'Heating+Cooking', 'Heating+BathFan', 'Heating+Cooking+BathFan' and 'Cooking+BathFan'. Summary coincidence results are plotted in Figure 29, and full results are presented in Table 26, Table 25, and Table 27. Given the questions about ambiguous vs. unambiguous spillage (see Section 2.6.4.2), as well as the question about window operation in response to AEA instructions, these coincident operation assessments give an additional estimate of spillage and downdrafting conditions. Spillage or downdrafting likely did not occur during all coincident exhaust fan usage, but these results should put an upper bound on the frequency of occurrence in these apartments.

We conservatively consider any combination that includes Cooking+BathFan as possibly being the worst-case depressurization condition, and describe them as such for the remainder of this report. This is a conservative or upper-bound estimate of worst case conditions because (a) the Cooking metric includes all the time that the kitchen exhaust fan was used and any other time the main cooking appliance was used (since it is best practice to operate the exhaust fan during all cooking); (b) we treat all kitchen exhaust fan use as being on the highest setting (i.e. the setting used for worst-case conditions), even though some use is undoubtedly on the lower speed, quieter setting; and (c) we don't exclude times when windows were open (which is appropriate since we advised some participants to open windows when using the kitchen exhaust fan, and would have in any case been impossible for us to analyze since we didn't monitor window opening).

These coincidence values are intended to represent an estimate of potential spillage that is independent of window operation, an issue that may affect the quantitative relevance of our spillage estimates in Table 19. Furthermore, our analysis only identified unambiguous spillage, which may mean that substantial partial spillage is occurring unidentified. To overcome these issues, we have highlighted the minimum number of fans required to produce spillage during diagnostic testing (see Table 9) in yellow, and we then highlight the relevant coincidence values in red. Rows with no highlighting required a duct blaster fan to induce spillage, so no challenge condition was determined. Based on this approach, the maximum spillage period in apartments with measured data is 0.075% of monitored minutes in Apt A_9_1. One spillage event was identified using wall furnace temperature data in this apartment. For those apartments where two fans were required to spill the wall furnace, a challenge condition that would lead to spillage is represented by the last column of coincident fan use, with a maximum period of 1.98% of monitored minutes. The apartments that spilled when only one fan operated included A_2_2, A_11_1 and B_16_1 (no fan data for the fan that caused spillage). For these two apartments in Building A with data, they spilled with the kitchen fan on low, so we take the challenge condition to be any 'cooking' activity (see Table 23), and these occurred for 8.4 and 3.8% of monitored minutes, respectively.

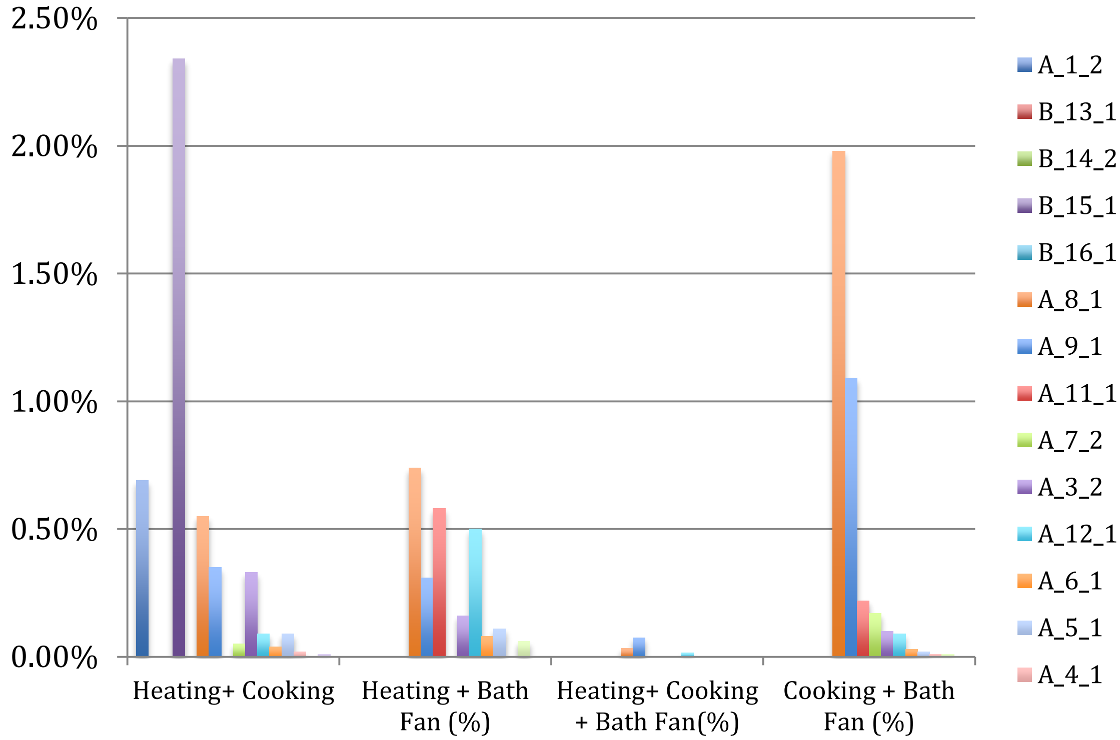

Figure 29 Plot of the coincident operation summaries for cooking, bathroom exhaust fan use, and heating system operation.

The results indicate correlations between activities in some apartments but not others. Activities are considered to be correlated if there is more frequent overlap than would be predicted as the simple product of the individual activity frequencies. We expected activities to be correlated, as cooking and bathing only occur during waking, occupied time periods, and heating hopefully occurs more frequently during occupied times. Yet, in many cases, the frequency of coincident operation is roughly the same as predicted by simply multiplying the use fractions for each element together, e.g. 1% bath fan use and 1% kitchen fan use would be coincident 0.01 x 0.01 = 0.0001 or 0.01% of the time if not correlated. There were exceptions, for example in Apt A_9_1, there was much more coincident heating, bath fan use and cooking than would be predicted if the activities were unrelated (actual coincidence was 0.075% of minutes versus 0.025% calculated as the product of the three independent frequencies). Similarly, in Apt A_7_2, there was more frequent Cooking + Bath Fan use than would have occurred if the two activities were uncorrelated (0.17% vs. 0.06% calculated from the product of Cooking and Bath Fan use. Setting aside these cases, when events were only very weakly associated, the coincident operation values were generally one or more orders of magnitude lower than the individual activities. Notably, the correlation between activities may be lower in continuously occupied low-income senior housing than in a home occupied by a family, where activities are more likely to be condensed into shorter periods before and after work.

Table 25 Summary of coincident operation of the heating system, cooking (either cooking burners or kitchen exhaust fan), and bathroom exhaust fan. The minimum fan operation conditions required for spillage during diagnostic testing (from **Table 9**) and the corresponding relevant coincidence values are highlighted in red, bold text.

AptID	*Heating (%)*	*Cooking (Burners or Kitchen Fan) (%)*	*Bath Fan (%)*	*Heating+ Cooking (%)*	*Heating + Bath Fan (%)*	*Heating+ Cooking + Bath Fan (%)*	*Cooking + Bath Fan (%)*
A_1_2	3.86%	6.30%	NA	0.69%	NA	NA	NA
A_2_2	0.63%	**8.42%**	0.54%	**0.01%**	<0.005%	**<0.0005%**	**<0.005%**
A_3_2	8.89%	2.25%	1.02%	0.33%	0.16%	<0.0005%	0.10%
A_4_1	0.20%	0.63%	0.85%	0.02%	<0.005%	<0.0005%	0.01%
A_5_1	2.64%	**2.98%**	**1.22%**	0.09%	0.11%	**<0.0005%**	**0.02%**
A_6_1	3.66%	0.97%	1.35%	0.04%	0.08%	<0.0005%	0.03%
A_7_2	0.07%	**2.30%**	**2.62%**	0.05%	<0.005%	**<0.0005%**	**0.17%**
A_8_1	2.48%	**11.10%**	**13.45%**	0.55%	0.74%	**0.033%**	**1.98%**
A_9_1	4.81%	**9.71%**	**5.17%**	0.35%	0.31%	**0.075%**	**1.09%**
A_10_1	2.17%	**1.42%**	**0.83%**	<0.005%	0.06%	**<0.0005%**	**0.01%**
A_11_1	1.50%	**3.81%**	6.26%	**<0.005%**	0.58%	**<0.0005%**	**0.22%**
A_12_1	7.88%	**1.66%**	**9.34%**	0.09%	0.50%	**0.015%**	**0.09%**
B_13_1	1.14%	0.64%	NA	<0.005%	NA	NA	NA
B_14_2	0.25%	5.54%	NA	<0.005%	NA	NA	NA
B_15_1	4.05%	**13.27%**	**NA**	2.34%	NA	**NA**	**NA**
B_16_1	0.00%	3.01%	**NA**	0.00%	**NA**	**NA**	**NA**
Average	2.76%	4.63%	3.88%	0.29%	0.23%	0.011%	0.34%

Coincident operation was generally very low, but not always. For example, in Apt B_15_1 2.3% of monitored minutes were spent with the heating system operating coincident with cooking. In this apartment, the minimum condition required for spillage during diagnostic testing was the kitchen fan on low and bathroom fan on high (i.e., not continuous low flow) (see Table 9). This was another example of correlated operation leading to higher than random coincidence. The coincidence of Heating+Cooking and Heating+BathFan occurred 0.29% and 0.23% on average, with maxima of 2.34% and 0.74% of monitored minutes across apartments. Heating+Cooking+BathFan was an order of magnitude lower (0.011% of minutes, maximum of 0.075%). Coincident Cooking+BathFan was similar to Heating+Cooking and Heating+BathFan, with an average of 0.34% of monitored minutes.

Complete statistics on coincident Cooking+BathFan events are reported in Table 26, representing the conservative estimate of worst-case depressurization frequency. A total of 93 such events were recorded, with average coincident operation of 0.34% of monitored minutes (maximum of 1.98%). An average of six events for each apartment unit were recorded, with an average duration of 13 minutes (maximum duration of 92 minutes). As noted above, these values do not include the apartments in Building B, where continuously low-speed bathroom fans operated and the sensors did not record fan data.

Table 26 Summary statistics for coincident Cooking+BathFan events in each apartment unit (i.e., worst-case depressurization conditions). This is representative of spillage risk independent of heating system operation.

AptID	Total (min)	Total Worst-Case (%)	Count of Worst-Case Events	Worst-Case Event Durations (min)					
				Min	25th	Median	Mean	75th	Max
A_1_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_2_2	36013	0.00%	0	0	0	0	0	0	0
A_3_2	24289	0.10%	2	10	11	12	12	13	14
A_4_1	26000	0.01%	1	2	2	2	2	2	2
A_5_1	34558	0.02%	3	2	2	2	2	2	2
A_6_1	31647	0.03%	2	5	5	6	6	6	6
A_7_2	32940	0.17%	7	1	3	5	8	12	21
A_8_1	34414	1.98%	47	1	3	8	14	23	61
A_9_1	33119	1.09%	23	1	3	9	16	17	92
A_10_1	35674	0.01%	1	2	2	2	2	2	2
A_11_1	33099	0.22%	4	6	7	8	19	19	53
A_12_1	33333	0.09%	3	4	8	12	10	13	13
B_13_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_14_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_15_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_16_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
Average		0.34%	6	1	3	7	13	17	92

The risk of spillage is greatest when the wall furnace burner operates during worst-case depressurization (Heating+Cooking+BathFan), so we summarize these events in Table 27. Most apartments experienced no minutes at this condition. In fact, this only occurred in three of the 11 apartments that had heating, cooking and bath fan data. A total of five such events were identified with an average length of seven minutes and maximum length of 12 minutes. Notably, if bath fan sensors had recorded data from the continuously operated two-speed fans in the apartments in Building B, we expect that more worst-case events would have been identified, almost certainly with longer durations. If, in fact, the bathroom exhaust operated continuously in Apt B_15_1, then 2.43% of monitored minutes would have been logged at Heating+Cooking+BathFan, though the bath fan airflow rate would have been at the 'low' rate (i.e., not the 'worst-case' condition).

Table 27 Summary statistics for coincident Heating+Cooking+Bath fan events in each apartment unit.

AptID	*Total (min)*	*Total Coincident Use (%)*	*Count of Coincident Events*	*Coincident Event Durations (min)*					
				Min	*25th*	*Median*	*Mean*	*75th*	*Max*
A_1_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
A_2_2	13748	0.000%	0	NA	NA	NA	NA	NA	NA
A_3_2	13586	0.000%	0	NA	NA	NA	NA	NA	NA
A_4_1	23836	0.000%	0	NA	NA	NA	NA	NA	NA
A_5_1	27259	0.000%	0	NA	NA	NA	NA	NA	NA
A_6_1	27361	0.000%	0	NA	NA	NA	NA	NA	NA
A_7_2	26571	0.000%	0	NA	NA	NA	NA	NA	NA
A_8_1	27303	0.033%	1	9	9	9	9	9	9
A_9_1	26626	0.075%	3	1	4	7	7	10	12
A_10_1	27303	0.000%	0	NA	NA	NA	NA	NA	NA
A_11_1	27344	0.000%	0	NA	NA	NA	NA	NA	NA
A_12_1	26983	0.015%	1	4	4	4	4	4	4
B_13_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_14_2	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_15_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
B_16_1	NA	NA	NA	NA	NA	NA	NA	NA	NA
Average		0.011%	0	1	4	7	7	9	12

All of these coincident events are dependent on the operation of the heating system, which can vary with some building features, namely the heating system output relative to the load it is serving. In general, heating system output capacities scale with heating demand, and we expect the system runtimes to be roughly independent of climate severity. This is because smaller systems are paired with lower loads, and larger systems are paired with larger loads, resulting in similar runtimes. But a system with excess heating output capacity might short-cycle (less runtime) or generally have very different operating times than a 'right-sized' or under-sized heating system (longer runtime). Thermostat set points and other occupancy patterns can also have substantial effects on system runtimes. These factors could substantially impact our assessments of coincident exhaust fan and heating system operation.

AEA staff noted that in Apts A_8_1 and A_9_1, the participants were very responsive to requests by AEA staff to use their range hood and bath fan when possible. It is possible that the magnitude of fan use and coincident operation in these units is partially due to the diligence of the participants in complying with AEA requests for the study. In addition, both participants in Apts A_8_1 and A_9_1 were concerned about gas leaks from their wall furnaces, which was an initial misunderstanding of the study's purpose. Due to these noted issues, it is possible that these participants ran their exhaust fans more than they would typically. In this context, it is worth noting that 70 of the 93 Cooking+BathFan events occurred in just these two apartments, and that four of five Heating+Cooking+BathFan events were in these two apartments. To the extent that occupant's can accurately report on their habits, this suggests that a good screening approach might simply be to ask occupant's how frequently they use exhaust devices in their residence.

4 Discussion

This study sought to improve understanding of the risk of wall furnace exhaust spillage in apartments that failed the worst-case depressurization testing common in CAS protocols. Ten of the 16 apartments recruited to the study failed worst-case testing with installed exhaust fan capacities, and seven of these passed a one-fan challenge condition. The study initially sought to quantify the frequency of spillage when kitchen and bath exhaust fans are used as intended, i.e. whenever cooking or bathing occurs. However, since many of the apartments did not pass the reduced challenge test of kitchen on low and bath fan, and some did not even pass with just the kitchen fan on high speed, participants of most apartments were advised to open a window when using the exhaust fans. As a result of this, we were not able to assess the frequency of spillage and downdrafting under typical operating conditions. The study nevertheless produced valuable data to inform the frequency of coincident exhaust fan use and wall furnace operation when occupants have been directed to follow the best practice of using available venting whenever cooking or bathing. These coincidence data provide an estimate of potential downdrafting and spillage frequency that are independent from window operation.

Study results support the suggestion by (Rapp et al., 2015) and others that many combustion appliance hazards in residences can be identified by test procedures that focus on visual inspection methods and/or non-worst-case testing. In these apartments, the greatest hazards were: (1) high appliance CO (>1,000 ppm in Apt A_2_2), which was identified and corrected prior to monitoring, (2) appliances that were spilling and tripping spill switches under 'natural' test conditions (low-flow continuous bathroom exhaust, in this case), and (3) occupant efforts to defeat the engineered safety features included in their systems (in this case, the intentional blocking of combustion air vents using t-shirts and repeated manual resetting of spill switches). These hazards were identified by visual inspection, testing of appliances under natural conditions, and brief discussions with the occupant(s).

Results also support the idea that the worst-case test condition commonly used in CAS testing might be irrelevant to occupied residences even when exhaust fans are used as recommended (i.e. with all cooking and bathing) and certainly with how they are actually used in most residences. In the apartments measured in this study, it was quite rare for the both kitchen and bath fans to be operated together, at the worst-case depressurization condition used in CAS testing. Coincident usage averaging 0.34% of monitored minutes across apartments, and was 2% in the apartment with the highest coincident usage. The longest continuous period of coincident use of the bath fan with any Cooking (including both cooking burner activity and kitchen exhaust fan use) was 92 minutes and the average event duration was 13 minutes. In those two apartments (with sufficient data) where only one exhaust fan was required to spill the appliance during diagnostic testing, time spent at this 'Challenge' condition was greater. In these cases, the Challenge condition occurred for up to 8% of monitored minutes. A wall furnace was operated during the worst-case depressurization condition in only 3 of the 11 units with all the data needed to make this determination. At the very most, a unit spent 0.075% of monitored minutes at this condition, with the longest continuous event lasting 12 minutes. We were not able to differentiate low- vs. high-speed kitchen fan operation, so time spent at the worst-case condition (kitchen fan on high and bath fan on) may be even lower than reported here. Worst-case depressurization conditions in residences with a greater number of exhaust fans may be even more rare, as we expect coincident operation of all fans to be even lower than reported in this work. But in some of the units most prone to spillage (i.e., in Building B), bathroom fan data failed to log, and these units had continuous low-flow bathroom exhaust fans, which almost certainly increased time spent at or near worst-case or in a reduced challenge condition.

Assessments of unambiguous spillage and downdrafting frequencies are additional outcomes of this work. Downdrafting was quite common, whereas unambiguous spillage was extremely rare. The presence of continuous bathroom exhaust fans in the Building B apartments led to wall furnaces being in a downdraft condition for extended periods. The longest downdraft event was roughly 12-hours. Nearly all of the recorded spillage events occurred when the appliance was already in downdraft; however, draft was established relatively quickly in all cases. Also, due to low rates of CO production by the wall furnaces, we could not associate spillage with any substantial CO events in the living space. And even with higher CO generation rates, the exhaust fans that caused the downdrafting and spillage would have provided substantial dilution for any CO that was released.

Overall, the results of this study indicate that caution is warranted about the robustness of venting of natural draft wall furnaces in small residences with airtight shells. This finding derives from the observation of frequent downdrafting in such apartments, corresponding to the operation of either the kitchen or bathroom exhaust fan at highest settings. If a small residence with an airtight shell has continuous mechanical exhaust – as several apartments in this study had – then any operation of the kitchen exhaust fan will produce greater depressurization than it would otherwise and raise the risk of downdrafting and spillage.

The observed tendency of some apartments in this study to frequently reach a downdraft condition is particularly troubling, because engineered safety features (e.g., spill switches and CVA openings) were disabled in some apartments. Had the one apartment with an intentionally clogged combustion air inlet not been opened prior to monitoring, we hypothesize that we would have seen higher frequencies of downdrafting and spillage in that unit. Similarly, had occupants not been instructed to open windows during cooking, downdrafting and spillage likely would have increased (at least in apartments with spillage under 'natural' conditions).

It is difficult to draw firm conclusions about CAS test methods in the larger population of residences in California, due to the small number of residences assessed in this study. We believe that a larger sample set would be required to justify revisions to CAS test protocols.

Any future work should address, at least in part, the following additional limitations. First, these apartment units did not have vented clothes dryers, which can contribute to house depressurization and may have long runtimes in some cases. Second, this study also did not cover a range of heating system sizes and thermostat behaviors that might dramatically affect heating system runtimes. For example, apartment units with right-sized heating systems might have substantially more heating burner runtime, such that coincident operation of exhaust devices and heating burners could be substantially higher. Outdoor temperature conditions were especially mild during the this study, so heating runtimes may be underestimated relative to a typical heating season. That being said, maximum total operation of any exhaust device was generally in the 10-15% range (see Table 25), so we expect the theoretical maximum period spent at a Challenge condition to still be substantially below 10-15%. Third, this study did not assess residences containing multiple natural draft gas appliances (e.g., tank water heater and a wall furnace). While coincident operation of all appliances would go down, coincident operation of any single combustion appliance with exhaust fans would increase. This is due to the additional gas burner runtime on the second appliance. A caveat to this point is that the larger burner sizes in water heaters and especially central furnaces will produce more heat and stronger draft. Similarly, larger residences tend to have more leakage area, which lessens the depressurization effect of exhaust equipment. Finally, the demography of the study population undoubtedly influenced the results. Eleven of the sixteen apartments in the study had only one resident and the other five had only two residents. Homes with more residents are expected to have higher coincident fan usage rates, though not strictly proportional to the number of people. The fact that many of the apartments had only senior occupants may also have impacted activities such as cooking and bathroom exhaust fan use. Lastly, participants in this study likely used exhaust fans more frequently than is 'typical', because they were instructed to use them during all cooking and bathing (which we think is atypical). Occupants also likely opened windows during cooking more than typical, as these were specific instructions provided to some participants at the start of the study.

5 Recommendations

Based on the findings of this study we recommend the following:

- Additional research should be conducted to assess the suitability of the worst-case challenge conditions that are currently used in combustion appliance safety protocols, with the specific goal of identifying challenge conditions that occur for long enough to result in an air pollutant hazard should a spillage event occur.
- The research into a suitable challenge condition should be conducted in residences with higher than average occupancy and various combinations of exhaust fans in particular including residences with dryers, which were not present in the apartments in this study.
- Future research into coincident exhaust fan usage and potential impacts on venting should not ask residents to modify their normal window use. Advising residents to use kitchen exhaust ventilation when cooking is a reasonable condition because such use is generally recommended as a healthy homes measure.

- Research may also be warranted to assess the indoor air quality impacts of frequent downdrafting causing pilot burner pollutants to enter the living space of the home.
- Consideration should be given to modifying CAS protocols to use the alternative challenge condition that is more commonly encountered in normal use or when residents use kitchen and bath exhaust fans as recommended.
- Combustion safety testing should continue to emphasize carbon monoxide measurements in the flue or vent to identify improperly functioning burners, and careful visual inspection to identify hazards such as blocked combustion ventilation air openings, both of which were observed in this study.
- A potentially highly cost-effective approach to improving knowledge about combustion safety hazards would be to capture information already being collected during CAS tests by developing digital CAS data collection forms that can be readily uploaded to a statewide database of CAS test results.
- Special attention should be paid to the venting of natural draft wall when including envelope air sealing in energy efficiency retrofits of small homes.
- Residents should be educated about the importance of not blocking trickle vents and other combustion ventilation air openings, and inspections of CVA opening by building managers should be considered if they are deemed essential to safety.
- Though not included in this study, the suitability of technology options including furnaces that draw combustion air directly from outside and supply or balanced mechanical ventilation systems (in place of exhaust ventilation) can improve protections in residences that are found to have depressurization-induced combustion safety hazards.
- In light of the finding of frequent downdrafting, there should be an investigation of the impacts to occupant exposures to combustion pollutants from pilot burners and the potential benefits of replacing pilot burners with spark igniters.

6 Summary and Conclusions

Indoor environmental conditions, heating appliance operation, use of exhaust fans and cooking activity were monitored for approximately three-week periods in 16 affordable apartment units in Northern California. These units were also assessed for combustion appliance safety using standard CAS test methods and enhanced protocols. Occupants were surveyed at the outset of their participation, and they filled in daily activity logs about occupancy, window operation, cooking, etc.

Almost all of the studied apartments failed a key component of the Combustion Appliance Safety test procedure used for energy retrofits in California—their natural draft wall furnaces spilled combustion pollutants to varying degrees under "worst-case" depressurization conditions of all exhaust fans operating on their highest settings. Since the apartments had only two exhaust fans, the worst-case condition was the kitchen exhaust fan on high and bath fan operating at the single available speed (or the high speed in apartments that had a two-speed bath fan). In many of the apartments, the wall furnaces also spilled with the kitchen fan on low and bath fan on, and some with just the kitchen fan on high or low. The conditions assessed in this study correspond to recommended best practice but may not represent 'typical' behavior. Residents were asked to use exhaust fans whenever bathing or cooking, and in units that spilled under natural test conditions, they were instructed to open windows during kitchen fan use.

Outdoor weather conditions during the monitoring periods were relatively mild, such that furnace operation was limited and highly variable. Indoor environmental conditions were typical of occupied residences with temperatures in the range of 60 to 90°F (averaging 75°F), and RH in the range of 30-70%. CO_2 concentrations measured in the main living spaces were also typical, ranging from 400 to 2,000 ppm (averaging roughly 800 ppm).

On average, bathroom exhaust fans were operated 3.9% of monitored minutes (13.5% max), and cooking (burner or kitchen fan operation) occurred 4.6% of minutes (max 13.3%). Event lengths averaged 17 minutes (max 540) and 34 minutes (max 324), respectively. Their coincident operation averaged 0.34% of minutes (max 2.0%), with average event length of 13 minutes (max 92 minutes). This suggests that the operation of apartment units at or near the currently used worst-case challenge condition is quite rare. Wall furnace burners operated an average of 2.8% of minutes (max of 8.9%), with average burner cycle length of 14 minutes (max 162). Coincident bath fan use, cooking and wall furnace operation was very rare, occurring only a handful of times across all apartments. The highest rate was 0.075% of monitored minutes in one apartment, and the longest event length was 12 minutes. This represents an estimate of the frequency of the worst-case condition that is independent of window operation. In fact, coincident operation of any two appliances (heat+bath fan, bath+kitchen fan, etc.) was generally at least an order of magnitude less than the operation of either appliance individually.

Given the extremely low rates of wall furnace burner operation during worst-case conditions, it is not surprising that unambiguous spillage was identified in only four of sixteen apartments. The longest period of continuous spillage was only five minutes, and at most, an appliance spilled 0.07% of monitored minutes. On the other hand, wall furnace downdrafting was quite common, and in some cases it occurred for prolonged periods. Longer periods of downdrafting were observed in apartments with continuous bathroom exhaust fans. The frequency and long duration of downdrafting is notable since the wall furnace being in a downdraft condition immediately preceded each unambiguous spillage event. All burner cycles eventually established draft within the 1-5 minutes currently deemed acceptable by the gas industry (Rapp et al., 2015), but uncertainty remains about the possibility that draft may not always have been complete and robust.

Our findings suggest that visual inspection and combustion appliance tests under more realistic challenge conditions, and possibly even “natural” conditions at the time of the test, can identify truly hazardous installations.

Notably, this study included apartments with only one natural draft gas appliance (i.e., no water heater), without any vented clothes dryers, with low occupancy rates, senior-aged inhabitants and exclusively in a mild California climate; all factors that could reduce periods at or near the Challenge condition. More research is needed to assess different house types, appliance configurations, combustion appliance types, occupancy rates/types and climates.

7 References

Baughman, A., & Arens, E. A. (1996). Indoor Humidity and Human Health–Part I: Literature Review of Health Effects of Humidity-Influenced Indoor Pollutants. *ASHRAE Transactions*, *102*, 193.

Brand, L., Cautley, D., Bohac, D., Francisco, P., Shen, L., & Gloss, S. (2015). *Combustion Safety Simplified Test Protocol Field Study*. Washington, D.C.: U.S. DOE Building America. Retrieved from http://www.gastechnology.org/Solutions/Documents/BAPARR-Reports/Combustion-Safety-Simplified-Test-Protocol-Field-Study.pdf

Kuhn, M. (2016). Package “caret.” CRAN. Retrieved from https://cran.r-project.org/web/packages/caret/caret.pdf

Rapp, V. H., Less, B. D., Singer, B. C., Stratton, C. J., & Wray, C. P. (2015). *Assessment of Literature Related to Combustion Appliance Venting Systems* (No. LBNL-176805). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/node/51254

U.S. EPA. (2012). National Ambient Air Quality Standards. Retrieved March 22, 2013, from http://www.epa.gov/air/criteria.html

8 Appendix

8.1 Daily Log Sheet

The following table was provided to participants to record daily activities. Each page contained tables for two days.

Study of Natural Gas Appliance Venting in Apartments

Occupancy and Indoor Activities Data Log

Instructions: Please enter your best estimates for each day and time period. Do not list the names of any people. Please make sure all information in a table is for the same day.

Day____: Date ________________ Date completed __________________

	Midnight to 7am	7am to 11am	11am to 1pm	1pm to 5 pm	5pm to 9pm	9pm to Midnight
Number of people in home						
Number of times cooktop or oven used						
Number of times kitchen exhaust fan used						
Number of baths or showers						
Number of times bath exhaust fan used						
Number of windows open more than a few minutes						

Sign and print name of person filling in table above: ……………………………………………………

8.2 Occupant Survey

Study of Natural Gas Appliance Venting in Apartments
Participant Survey

Instructions: Please provide an answer for each question. If you are unsure, please provide your best guess. Do not list the names of any people.

Home ID: ____________________

A. Number of residents by age

1. Please indicate the number of people living in the apartment who are in the following age categories. If you prefer, you can just indicate the total number of people living in the apartment.

Under 5 years old ……………………
5 to 17 years old ……………………
18 years or older ……………………
Total number of people ……………………

B. Indoor and outdoor air quality

2. How satisfied or dissatisfied are you with the air quality **inside** in your home?

Very Dissatisfied — Neutral — Very Satisfied

☐	☐	☐	☐	☐	☐	☐	☐	☐

3. How satisfied or dissatisfied are you with the air quality **outside** your home?

Very Dissatisfied — Neutral — Very Satisfied

☐	☐	☐	☐	☐	☐	☐	☐	☐

C. Comfort

4. In **<u>fall and winter</u>**, how often do the following conditions affect the comfort of occupants in your home?

	Never	Few times a year	Few times in a month	Few times a week	Every day
Too hot in some room(s)	☐	☐	☐	☐	☐
Too cold in some room(s)	☐	☐	☐	☐	☐
Indoor air is too dry	☐	☐	☐	☐	☐
Indoor air is too humid	☐	☐	☐	☐	☐
Indoor air has musty odor	☐	☐	☐	☐	☐
Cold drafts	☐	☐	☐	☐	☐

5. How often do you use portable electric heaters during the winter?

	Never	Few times a year	Few times in a month	Few times a week	Every day
Use portable electric heater	☐	☐	☐	☐	☐

D. Window Opening

6. On average, how many hours per day are your **windows open** during each season?

	0 hours per day	1 to 2 hours per day	2 to 8 hours per day	8 to 16 hours per day	More than 16 hours per day
Summer	☐	☐	☐	☐	☐
Fall	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐
Spring	☐	☐	☐	☐	☐

7. On a typical **cool, fall day**, which rooms have windows open during each part of the day? Please check all boxes that apply.

	Overnight 10 pm to 6 am	Early morning 6 to 9 am	Late morning 9 am to noon	Afternoon 12 to 5 pm	Evening 5 to 10 pm
Master bedroom	☐	☐	☐	☐	☐
Other bedroom	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐
Living room	☐	☐	☐	☐	☐
Bathroom	☐	☐	☐	☐	☐
Other room	☐	☐	☐	☐	☐

8. On a typical **cold, winter day**, which rooms have windows open during each part of the day? Please check all boxes that apply.

	Overnight 10 pm to 6 am	Early morning 6 to 9 am	Late morning 9 am to noon	Afternoon 12 to 5 pm	Evening 5 to 10 pm
Master bedroom	☐	☐	☐	☐	☐
Other bedroom	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐
Living room	☐	☐	☐	☐	☐
Bathroom	☐	☐	☐	☐	☐
Other room	☐	☐	☐	☐	☐

E. Cooking and Kitchen Range Hood or Exhaust Fan

9. On average, how many times per week is your **cooktop or oven** used for cooking, including boiling water?

	0 times per week	1 to 2 times per week	3 to 4 times per week	5 to 6 times per week	7 or more times per week
Breakfast	☐	☐	☐	☐	☐
Lunch	☐	☐	☐	☐	☐
Dinner	☐	☐	☐	☐	☐
Other cooking	☐	☐	☐	☐	☐

10. In a typical week, how many times is the oven or cooktop used for more than 30 minutes at a time? ………….

11. In a typical week, how many times is the oven or cooktop used for more than 60 minutes at a time? ………….

12. How often is the range hood or kitchen exhaust fan used when cooking with the cooktop or oven?
    ……. Always or almost always (More than 4 out of 5 times)
    ……. Usually (4 out of 5 times)
    ……. Sometimes (2 - 3 out of 5 times)
    ……. Occasionally (1 out of 5 times)
    ……. Rarely or never (Less than 1 out of 5 times)
    ……. Don't know

13. When the range hood or kitchen exhaust fan is used, on what speed it is used most frequently?
    ……. Only one speed available
    ……. Low
    ……. Medium
    ……. High
    ……. Varies; more frequently on low
    ……. Varies; more frequently on high
    ……. Varies with person using it

14. When the range hood or exhaust fan is not used, why is it <u>NOT</u> used? Select all that apply.
    ……. Forget to turn it on
    ……. Not needed for what is being cooked
    ……. Too noisy
    ……. Doesn't seem to remove cooking fumes or odors
    ……. Uses too much energy
    ……. We open a window instead
    ……. Other. Please describe: ……………..

F. Bathroom Ventilation

15. How often is the **bathroom exhaust fan** used for the following activities?

	Rarely or never (Less than 1 out of 5 times)	Infrequently (1 out of 5 times)	Sometimes (2 - 3 out of 5 times)	Usually (4 out of 5 times)	Always or almost always (More than 4 out of 5 times)
When showering or bathing	☐	☐	☐	☐	☐
When using toilet	☐	☐	☐	☐	☐
When using personal care products or cosmetics	☐	☐	☐	☐	☐
All other. Please describe below.	☐	☐	☐	☐	☐

Other reasons for using bath fan: ……………………………………………………………

……………………………………………………………

……………………………………………………………

16. When the bathroom exhaust fan is not used when **showering**, why is it <u>NOT</u> used? Select all that apply.

……. Forget to turn it on

……. Not needed

……. Too noisy

……. Doesn't work well

……. Open window instead

……. Uses too much energy

……. The extra moisture is helpful in winter

……. Other. Please describe: ……………..

G. Occupancy and Indoor Activities

17. On average, how many hours per day is your home occupied by at least one person, including day and night hours?

	Fewer than 8 hours per day	8 to 12 hours per day	12 to 16 hours per day	16 to 20 hours per day	More than 20 hours per day
Weekday	☐	☐	☐	☐	☐
Weekend	☐	☐	☐	☐	☐

18. During a typical week, how often do the following activities occur inside your home? Enter “<1” if the activity occurs occasionally but not every week.

Shower	……….. Times per week
Bath	……….. Times per week
Dishwasher	……….. Loads per week
Clothes washing	……….. Loads per week
Clothes dryer	……….. Loads per week
Hang clothes to dry indoors	……….. Loads per week
Use humidifier	……….. Hours per week

19. When you are at home and awake, are bedroom doors usually open or closed?

…….. Mostly Open …….. Mostly Closed …….. Varies

20. Overnight, are bedroom doors usually open or closed?

…….. Mostly Open …….. Mostly Closed …….. Varies

8.3 Results of Occupant Survey

Table 8.3.1: Indoor and Outdoor Air Quality

How satisfied or dissatisfied are you with the air quality inside & outside your home? Scale 1-9 (1 = very dissatisfied, 5 = neutral, 9= very satisfied)		
Home ID	**Inside Air Quality (IAQ)**	**Outside Air Quality (OAQ)**
A_1_2	7	5
A_2_2	9	9
A_3_2	9	5
A_4_1	9	9
A_5_1	7	7
A_6_1	5	5
A_7_2	8	5
A_8_1	1	1
A_9_1	5	5
A_10_1	8	5
A_11_1	9	5
A_12_1	5	5
B_13_1	4	7
B_14_2	7	5
B_15_1	7	7
B_16_1	3	5

Table 8.3.2: Comfort

In fall and winter, how often do the following conditions affect the comfort of occupants in your home?							
Home ID	**Too hot**	**Too cold**	**Too dry**	**Too humid**	**Musty odor**	**Cold drafts**	**Use of portable electric heaters**
A_1_2	Few Times a Month	Few Times a Year	Few Times a Month	Few Times a Year	Never	Never	Few Times a Week
A_2_2	Few Times a Week	Everyday	Few Times a Month	Few Times a Month	Few Times a Month	Few Times a Month	Everyday
A_3_2				Everyday	Everyday		Everyday
A_4_1	Never	Never	Never	Never	Never	Never	Never
A_5_1	Never	Few Times a Week	Never	Never	Never	Never	Never
A_6_1	Never	Never	Never	Never	Never	Never	Never
A_7_2	Never	Few Times a Year	Few Times a Month	Never	Few Times a Year	Few Times a Month	Few Times a Week
A_8_1	Never	Few Times a Week	Never	Few Times a Year	Never	Never	Never
A_9_1	Few Times a Month	Few Times a Month	Few Times a Month	Few Times a Month	Few Times a Month	Few Times a Month	Never
A_10_1	Never	Never	Never	Never	Never	Never	Never
A_11_1	Few Times a Month	Few Times a Year	Few Times a Month	Few Times a Year	Never	Few Times a Year	Never
A_12_1	Never	Never	Never	Never	Never	Never	Never
B_13_1	Few Times a Month	Few Times a Year	Few Times a Year	Never	Few Times a Year	Never	Few Times a Week
B_14_2							
B_15_1	Few Times a Year	Few Times a Month	Never	Never	Few Times a Year		Few Times a Year
B_16_1	Everyday	Everyday	Everyday	Few Times a Year	Never	Few Times a Week	Never

Table 8.3.3: Window Opening By Season

On average, how many hours per day are your windows open during each season?				
Home ID	**Summer**	**Fall**	**Winter**	**Spring**
A_1_2	2-8 hrs	1-2 hrs	1-2 hrs	1-2 hrs
A_2_2	16+ hrs	1-2 hrs	1-2 hrs	8-16 hrs
A_3_2	8-16 hrs	2-8 hrs	1-2 hrs	8-16 hrs
A_4_1	0 hrs	0 hrs	0 hrs	0 hrs
A_5_1	8-16 hrs	1-2 hrs	1-2 hrs	1-2 hrs
A_6_1	1-2 hrs	0 hrs	0 hrs	0 hrs
A_7_2	8-16 hrs	1-2 hrs	1-2 hrs	1-2 hrs
A_8_1	16+ hrs	2-8 hrs	1-2 hrs	2-8 hrs
A_9_1	2-8 hrs	1-2 hrs	1-2 hrs	1-2 hrs
A_10_1	2-8 hrs	1-2 hrs	1-2 hrs	1-2 hrs
A_11_1	2-8 hrs	1-2 hrs	1-2 hrs	2-8 hrs
A_12_1	8-16 hrs	1-2 hrs	0 hrs	2-8 hrs
B_13_1	2-8 hrs	1-2 hrs	1-2 hrs	8-16 hrs
B_14_2				
B_15_1	8-16 hrs	2-8 hrs	1-2 hrs	2-8 hrs
B_16_1	16+ hrs	16+ hrs	16+ hrs	16+ hrs

Table 8.3.4: Window Opening By Room – Fall

On a typical cool, fall day, which rooms have windows open during each part of the day?						
Home ID	**Master bedroom**	**Other bedroom**	**Kitchen**	**Living room**	**Bathroom**	**Other room**
A_1_2			10 pm - 6am			
A_2_2			12am - 5pm	12am - 5pm		
A_3_2			9 am - 12pm			
A_4_1						
A_5_1	9 am - 12pm		9 am - 12pm	9 am - 12pm		
A_6_1						
A_7_2	10 pm - 6am		10 pm - 6am			
A_8_1			12am - 5pm			
A_9_1			9 am - 12pm	9 am - 12pm		
A_10_1				12am - 5pm		
A_11_1						
A_12_1		6am-9am				
B_13_1			5pm - 10pm	5pm - 10pm		5pm - 10pm
B_14_2						
B_15_1			5pm - 10pm			
B_16_1	all day		all day	5pm - 10pm		

Table 8.3.5: Window Opening By Room – Winter

On a typical cold winter day, which rooms have windows open during each part of the day?						
Home ID	**Master bedroom**	**Other bedroom**	**Kitchen**	**Living room**	**Bathroom**	**Other room**
A_1_2			10 pm - 6 am			
A_2_2			12am - 5pm			
A_3_2		6 am - 9 am	6 am - 9 am		6 am - 9 am	
A_4_1						
A_5_1	9 am - 12pm		9 am - 12pm	9 am - 12pm		
A_6_1						
A_7_2	10 pm - 6 am		10 pm - 6 am			
A_8_1			12am - 5pm			
A_9_1			9 am - 12pm	9 am - 12pm		
A_10_1				12am - 5pm		
A_11_1						
A_12_1		6 am - 9 am				
B_13_1			5 pm – 10 pm	12am - 5pm		5 pm – 10 pm
B_14_2						
B_15_1			12am - 5pm			
B_16_1	5 pm – 10 pm		all day	5 pm – 10 pm		

Table 8.3.6: Cooking

On average, how many times per week is your cooktop or oven used for cooking, including boiling water?						
Home ID	**Breakfa st**	**Lunch**	**Dinner**	**Other cooking**	**Number of times used more than 30 min**	**Number of times used more than 60 min**
A_1_2	3 - 4	3 - 4	3 - 4	3 - 4	3	1
A_2_2	7+	7+	7+	7+	7	4
A_3_2	7+	7+	7+	5 - 6	5	6
A_4_1	7+	3 - 4	7+		17	0
A_5_1	5 - 6	3 - 4	5 - 6		4	4
A_6_1			7+		0	0
A_7_2	7+	1 - 2	7+	1 - 2	14	14
A_8_1	7+	7+			14	14
A_9_1				7+	14	14
A_10_1	3 - 4	3 - 4	1 - 2	0	2	2
A_11_1	7+	7+	7+	7+	7	4
A_12_1	3 - 4	5 - 6	7+	7+	3	6
B_13_1	5 - 6	1 - 2	3 - 4	1 - 2	3	1
B_14_2	7+	3 - 4	7+	3 - 4	4	0
B_15_1	7+	1 - 2	0	1 - 2	7	3
B_16_1	1 - 2	0	3 - 4		3	2

Table 8.3.7: Kitchen Range Hood or Exhaust Fan

Home ID	How often is the range hood or kitchen exhaust fan used when cooking with the cooktop or oven?	When used, on what speed it is used most frequently?	When not used, why is it NOT used?
A_1_2	Always or almost always (More than 4 out of 5 times)	High	Not needed for what is being cooked
A_2_2	Always or almost always (More than 4 out of 5 times)	Varies; more frequently on high	Forget to turn it on, Not needed for what is being cooked, We open a window instead
A_3_2	Always or almost always (More than 4 out of 5 times)	High	Too noisy, We open a window instead
A_4_1	Always or almost always (More than 4 out of 5 times)	High	
A_5_1	Usually (4 out of 5 times)	Medium	Not needed for what is being cooked, Too noisy
A_6_1	Occasionally (1 out of 5 times)	Varies; more frequently on low	Not needed for what is being cooked
A_7_2	Usually (4 out of 5 times)	Low	Uses too much energy
A_8_1	Always or almost always (More than 4 out of 5 times)	High	We open a window instead
A_9_1	Usually (4 out of 5 times)	Medium	Not needed for what is being cooked
A_10_1	Sometimes (2 - 3 out of 5 times)	High	Not needed for what is being cooked
A_11_1	Always or almost always (More than 4 out of 5 times)	Only one speed available	Not needed just to heat up food
A_12_1	Always or almost always (More than 4 out of 5 times)	Only one speed available	Not needed for what is being cooked, Too noisy
B_13_1	Sometimes (2 - 3 out of 5 times)	Low	Not needed for what is being cooked
B_14_2	Always or almost always (More than 4 out of 5 times)	High	Not needed for what is being cooked
B_15_1	Rarely or never (Less than 1 out of 5 times)	Medium	We open a window instead
B_16_1	Usually (4 out of 5 times)	High	Forget to turn it on

Table 8.3.8: Bathroom Ventilation

How often is the bathroom exhaust fan used for the following activities?						
Home ID	**Showering & Bathing**	**Using the toilet**	**Using personal care products/ cosmetics**	**Other**	**Other reasons for using bath fan**	**When not used, why is it not used?**
A_1_2	Less than 1 out of 5 times	More than 4 out of 5 times	Less than 1 out of 5 times	Less than 1 out of 5 times		Not needed
A_2_2	More than 4 out of 5 times	2 - 3 out of 5 times	2 - 3 out of 5 times			Not needed, too noisy, doesn't work well
A_3_2	More than 4 out of 5 times	More than 4 out of 5 times	Usually (4 out of 5 times)	More than 4 out of 5 times	smell and moisture	Too noisy
A_4_1	More than 4 out of 5 times	More than 4 out of 5 times	Less than 1 out of 5 times	Less than 1 out of 5 times		
A_5_1	Less than 1 out of 5 times	Less than 1 out of 5 times	Less than 1 out of 5 times			Too noisy
A_6_1	1 out of 5 times					Not needed
A_7_2						
A_8_1						
A_9_1	4 out of 5 times	More than 4 out of 5 times	4 out of 5 times		smell of using cleaning detergents	Forget to turn it on
A_10_1	1 out of 5 times	Less than 1 out of 5 times				Forget to turn it on
A_11_1	More than 4 out of 5 times	More than 4 out of 5 times	Less than 1 out of 5 times			
A_12_1	More than 4 out of 5 times	More than 4 out of 5 times			Bathroom has no windows	Other
B_13_1	More than 4 out of 5 times	More than 4 out of 5 times	More than 4 out of 5 times	More than 4 out of 5 times	fan turns on automatically by itself	
B_14_2	More than 4 out of 5 times	More than 4 out of 5 times	More than 4 out of 5 times	More than 4 out of 5 times		
B_15_1					"Panasonic motion sensor"	
B_16_1	More than 4 out of 5 times	More than 4 out of 5 times	More than 4 out of 5 times			

Table 8.3.9: Occupancy & Bedroom Doors

On average, how many hours per day is your home occupied by at least one person, including day and night hours?		
Home ID	**Weekday**	**Weekend**
A_1_2	16 -20 hrs	20+ hrs
A_2_2	20+ hrs	20+ hrs
A_3_2	8 - 12 hrs	12 - 16 hrs
A_4_1	8 - 12 hrs	
A_5_1	8 - 12 hrs	8 - 12 hrs
A_6_1	8 - 12 hrs	8 - 12 hrs
A_7_2		
A_8_1		
A_9_1	8 - 12 hrs	< 8 hrs
A_10_1	20+ hrs	20+ hrs
A_11_1	20+ hrs	20+ hrs
A_12_1	12 - 16 hrs	20+ hrs
B_13_1	8 - 12 hrs	8 - 12 hrs
B_14_2	20+ hrs	12 - 16 hrs
B_15_1	12 - 16 hrs	8 - 12 hrs
B_16_1	< 8 hrs	12 - 16 hrs

Table 8.3.10: Indoor Activities

During a typical week, how often do the following activities occur inside your home?							
Home ID	Shower (#/week)	Bath (#/week)	Dishwasher (loads/ week)	Clothes washing (loads/ week)	Clothes dryer (loads/ week)	Hang clothes to dry (loads/ week)	Use of humidifier (hrs/ week)
A_1_2							
A_2_2	4						
A_3_2	4	4		5	5		
A_4_1	2						
A_5_1	5	<1					
A_6_1	5						
A_7_2							
A_8_1							
A_9_1	4	4					
A_10_1	3						
A_11_1	2	2					
A_12_1	7			1	1		
B_13_1	6						
B_14_2	5					2	
B_15_1	2						
B_16_1	5	1					

Table 8.3.11: Bedroom Doors

Home ID	When you are at home and awake, are bedroom doors usually open or closed?	Overnight, are bedroom doors usually open or closed?
A_1_2	Varies	Mostly open
A_2_2	Mostly open	Mostly open
A_3_2	Varies	Varies
A_4_1	Mostly closed	Mostly closed
A_5_1	Mostly closed	Mostly closed
A_6_1	Varies	Mostly open
A_7_2		
A_8_1		
A_9_1	Mostly closed	Mostly closed
A_10_1	Mostly open	Mostly open
A_11_1	Varies	Mostly closed
A_12_1		
B_13_1	Mostly closed	Mostly closed
B_14_2		
B_15_1	Varies	Varies
B_16_1	Mostly open	Mostly open