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Development of a Residential Smart Range Hood

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Development of a Residential Smart Range Hood

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Not all of the laboratory and/or field sites used for this work are certified rating test facilities. Some of the conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

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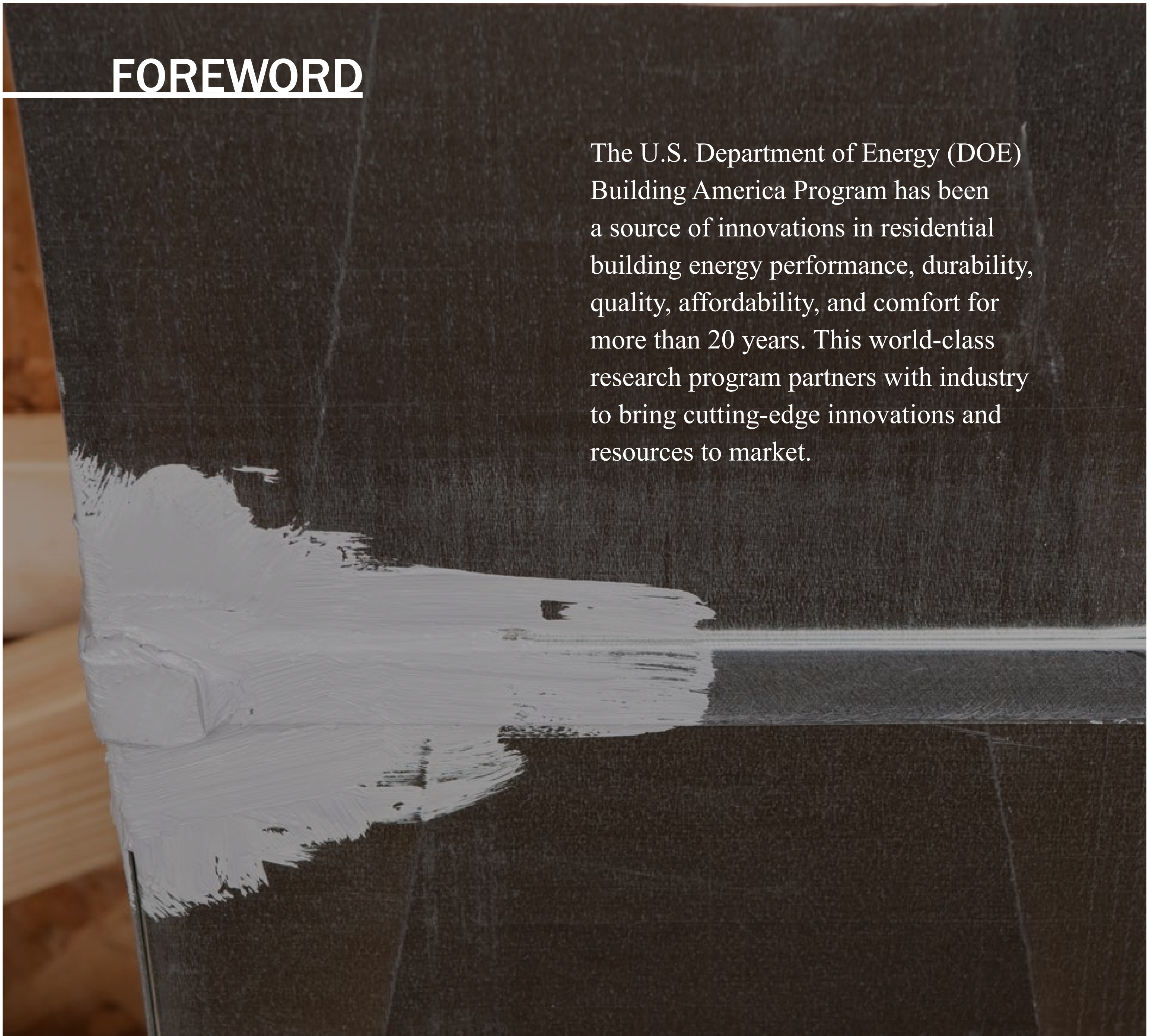

FOREWORD

The U.S. Department of Energy (DOE) Building America Program has been a source of innovations in residential building energy performance, durability, quality, affordability, and comfort for more than 20 years. This world-class research program partners with industry to bring cutting-edge innovations and resources to market.

In cooperation with the Building America Program, the Newport Partners team is one of many Building America teams working to drive innovations that address the challenges identified in the program's Research-to-Market Plan.

This report, "Development of a Residential Smart Range Hood," explores the development of a smart range hood designed to eradicate detrimental pollutants in the home, dramatically improve residential indoor air quality, significantly extend lives, and save billions of dollars in health-related costs annually.

As the technical monitor of the Building America research, the National Renewable Energy Laboratory encourages feedback and dialogue on the research findings in this report as well as others. Send any comments and questions to building.america@ee.doe.gov.

ACKNOWLEDGMENTS

The work presented in this report was funded by DOE's Office of Energy Efficiency and Renewable Energy Building Technologies Office. The research was conducted by Newport Partners.

The authors are grateful to the project partners and participants, without whom this project would not have been possible. Thanks to the Broan-NuTone and Venmar teams for their ingenuity and pursuit of excellence in developing a great product; Lawrence Berkeley National Laboratory for their contributions to the research plan, laboratory testing, and generous sharing of equipment; and the kind homeowners who volunteered to test the smart range hood in their homes.

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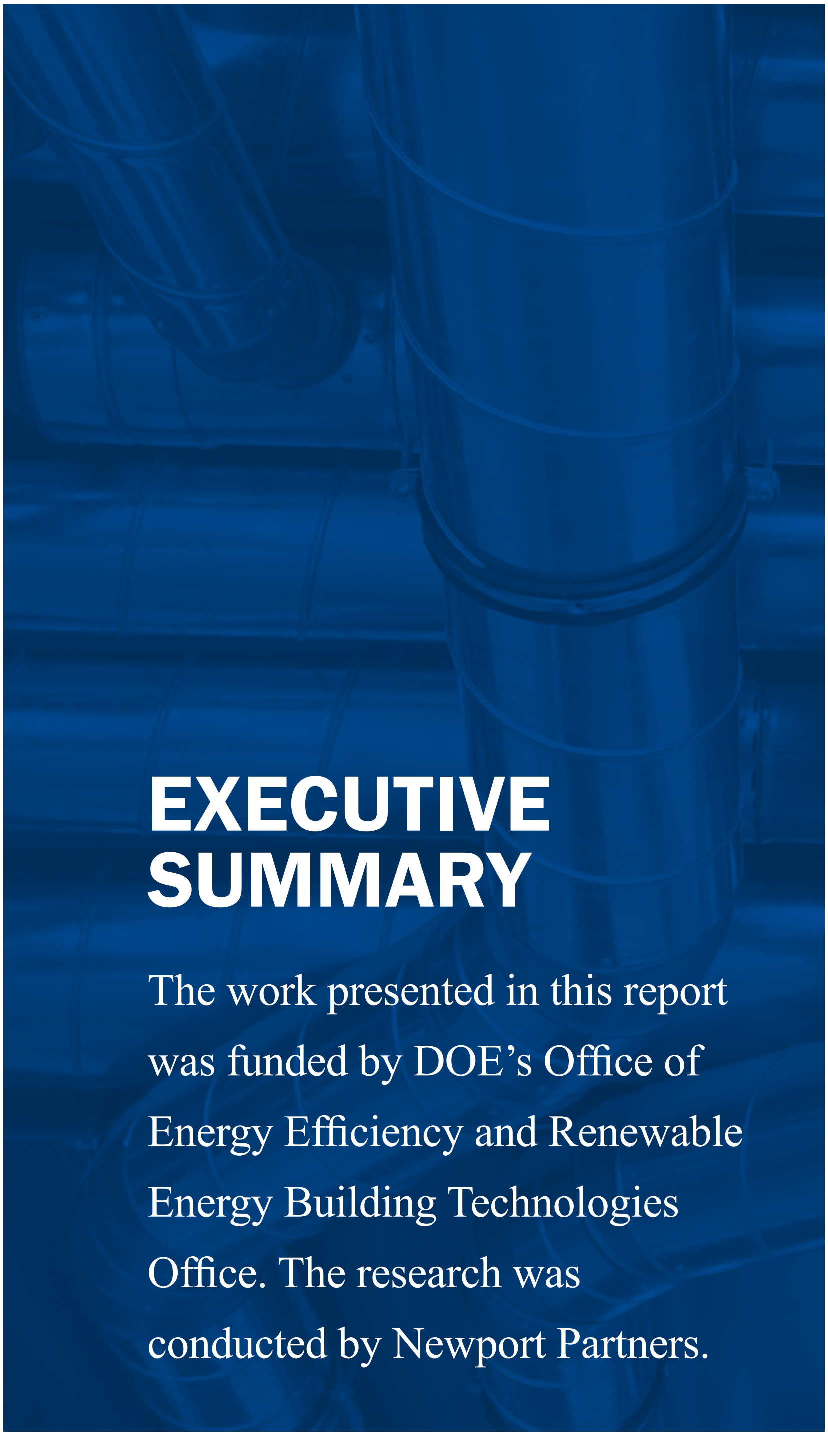
LIST OF ACRONYMS

ACH50	air changes per hour at 50 Pascals (a building envelope leakage metric)
ASHRAE 62.2	consensus standard for ventilation and acceptable indoor air quality in residential buildings from ASHRAE
ASTM	American Society for Testing and Materials
Btuh	British thermal units per hour
CO	carbon monoxide
CO_2	carbon dioxide
CFM	cubic feet per minute
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EUI	energy use intensity
fan efficacy	fan volumetric flow rate divided by the power required to deliver the flow
FRM	federal reference method
HVAC	heating, ventilating, and air conditioning
HVI	Home Ventilating Institute
IAQ	indoor air quality
ICC	International Code Council
LBNL	Lawrence Berkeley National Laboratory
MCF	one thousand cubic feet
MERV	minimum efficiency reporting value (a metric for air filter effectiveness)
NO_2	nitrogen dioxide
NO_X	oxides of nitrogen
PM_1	particulate matter with a diameter of less than 1 μm
$PM_{2.5}$	particulate matter with a diameter of less than 2.5 μm
PM_{10}	particulate matter with a diameter of less than 10 μm
PN	particle number
POC	proof of concept
PPB	parts per billion
RESNET	Residential Energy Services Network
sone	a unit of loudness equal to a pure 1,000 Hertz per second tone at 40 decibels above the listener's threshold of hearing
SRH	smart range hood
TVOC	total volatile organic compounds
μg	microgram
μm	micrometer



EXECUTIVE SUMMARY

The work presented in this report was funded by DOE's Office of Energy Efficiency and Renewable Energy Building Technologies Office. The research was conducted by Newport Partners.

"Whole-house" ventilation and source capture of indoor pollutants are critical components of healthy, tight, and energy-efficient homes. Research has identified kitchens as the primary location where the most harmful pollutants are generated in the home, "generating $PM_{2.5}$ at concentrations four times greater than major haze events in Beijing"[1] (Smith 2013) and increasing "ultrafine particle concentrations in the kitchen by up to a factor of 550" (Zhang 2010; also see Logue et al. 2012 and Wallace et al. 2004). Studies have shown that residential kitchen range hoods are seldom used and can be ineffective when operated (Stratton and Singer 2014). Homeowner reasons for not operating kitchen range hoods include their belief that the equipment is "not needed," "too noisy," or that they simply "don't think about it" (Mullen et al. 2013). In other words, range hoods can fall woefully short of being operated as needed to address the greatest indoor air quality (IAQ) health risks in a home. In keeping with the U.S. Department of Energy's (DOE's) *Building America Research-to-Market Plan* (U.S. DOE 2015) and its IAQ roadmap, this project's objective was to develop a smart range hood (SRH) that would be responsive to key pollutants, consumer friendly, quiet, effective, and efficient. Targeted performance metrics were established in the categories of rated noise, range hood capture efficiency, fan efficacy, and ability to sense and respond to pollutants.

The project team consisted of Newport Partners (Newport), a buildings-industry consulting company, and Broan-NuTone (Broan), the largest U.S. manufacturer of range hoods. Development of the SRH began with a literature search to identify the most appropriate cooking pollutants

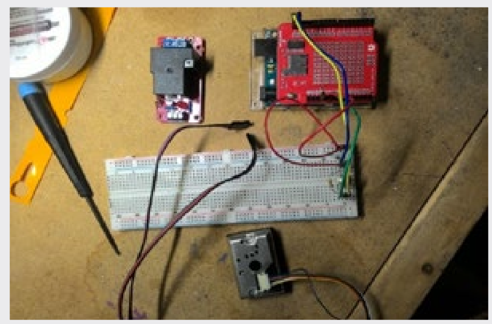
[1] $PM_{2.5}$ stands for fine particulate matter (with a diameter of less than 2.5 μm).

to sense and use as control inputs as well as evaluations of low-cost sensor performance. The initial suite of sensors selected to control the SRH were dry-bulb temperature, infrared temperature, humidity, and $PM_{2.5}$. A logic model was drafted and then coded into a basic Arduino controller framework that allowed for rapid prototyping with off-the-shelf components, resulting in a proof of concept (POC) range hood. Testing in a domestic kitchen ensued, identifying good responsiveness to pollutant events and also challenges with the user experience, primarily due to rapid and frequent speed cycling. To address this issue, the POC's control algorithm was modified using techniques such as engaging the range hood only when a cooking event was detected at the cooktop, multistep verification of cooking events, signal smoothing, and establishing minimum cycle times.

Newport's POC was then transferred to Broan to develop into a more refined first-generation SRH prototype. Newport and Broan collaborated to improve the control module, environmental sensor package, and control logic, which were then integrated with one of Broan's production model hoods that met the project's goals of industry-leading performance offered at a midmarket price point. Extensive testing in Broan's laboratory followed, simulating variable cooking environments with respect to cooking fuel, hood installation height, cooking styles, fan speeds, and burner location. Design of the SRH was iterated to optimize detection and response to cooking events, minimize response time, avoid false positives, demonstrate repeatable performance, maximize sensor longevity, and improve user perceptions regarding acceptability of run times (neither too short nor too long).

Laboratory testing confirmed that the SRH exceeded targeted performance in terms of range hood capture efficiency (greater than 90% with two front burners operating), noise performance (less than 1 sone at an airflow no less than 150 cubic feet per minute [cfm]), and fan efficacy (exceeding 1.5 times the ENERGY STAR® minimum). SRH responsiveness and the ability to control pollutants were evaluated through additional laboratory testing at

Lawrence Berkeley National Laboratory (LBNL), where scripted, replicate cooking events were performed with the SRH in "auto" mode and in off mode. The percent reduction in time-integrated pollutant concentrations achieved by the SRH in auto mode as compared to off mode ranged from 64% to 74% for nitrogen dioxide (NO_2), 80% to 94% for particle number, and 87% to 94% for particle mass. During laboratory testing, the SRH responded to cooktop burners within 30 seconds of starting. As expected of all wall-mounted hoods, performance of the SRH was notably better when capturing pollutants from back burners than pollutants from front burners.



Field testing was conducted in three homes with the objectives of: (1) gauging the ability of the SRH to reduce air pollutant concentrations under normal operating conditions, (2) assessing the responsiveness and frequency of SRH operation compared to homeowners' normal, elective operation of the homeowners' existing range hood, and (3) gaining insight on homeowners' perceptions of SRH performance. Homes were instrumented with indoor and outdoor air pollutant sensors and run-time sensors for cooking and ventilating equipment. Participants completed cooking logs that were thorough and highly useful in verifying observations from the data acquisition system. The duration of the field study was four weeks for each home, split into two weeks to monitor use of the homeowner's behaviors with the existing range hood and IAQ, followed by two weeks to monitor the same parameters with the SRH installed to operate in auto mode. Key performance findings from the field study include:

- The median ratio of range hood run time to burner run time during cooktop events was 2.3 under the operation of the SRH and zero under the elective operation of the existing hood, meaning that the SRH operated more frequently than the existing range hood and ran for about twice as long as the typical cooktop cooking event to continue to exhaust cooking pollutants that escaped into the kitchen.

- The SRH detected and responded to 94% of cooktop events across two homes (data from a third home were not available due to failure of an anemometer within the data acquisition system used to monitor range hood operation).

- SRH response time to cooktop events was less than one minute, on average.

- The median difference observed between the NO_2 peak associated with a cooktop event and the background NO_2 in the kitchen preceding cooktop events was reduced by 40% by the SRH (46 events) versus by the existing hood (57 events).

- The frequency of extreme NO_2 events was reduced under SRH operation, with zero SRH cooktop events exceeding a 100 ppb increase from the background NO_2 concentration, and five cooktop events with the existing range hood exceeding a 100 ppb increase from the background NO_2 concentration.

- The effect of the SRH on full-period time-integrated concentrations of NO_2 and $PM_{2.5}$ as well as time-resolved $PM_{2.5}$ could not be determined because of real-world variability in occupant behavior. For example, indoor pollution events that were not associated with cooking contributed significantly to $PM_{2.5}$ concentrations and were not equally distributed across the existing range hood period and SRH period.

Exit interviews with the participants provided useful, qualitative feedback on homeowner perceptions of SRH performance. Homeowners from two of the three test homes gave high ratings to the SRH and noted that they would likely purchase the SRH, depending on the cost premium. The third homeowner, whose existing hood had better performance specifications than the other two sites, was more critical of the SRH performance, noting that SRH benefits were marginalized by acceptable performance of their existing model, their frequency of manual use of their existing model, and the sound of the SRH cycling.

Benefits noted by the homeowners included the convenience factor of auto on/off operation, low noise (especially on the low-speed setting), the lighting quality, and its ability to remove odors from the home quickly. Two homeowners reported an improvement in IAQ as a result of the SRH operation, while the third (who was observed manually operating their existing range hood frequently prior to the installation of the SRH) could not determine any difference.

Opportunities for improvement noted by the homeowners were primarily related to noise and included minimizing SRH speed cycling during cooking events and eliminating a clicking noise that was associated with cycling between speeds. Recommendations also included instituting a more gradual ramp-up or ramp-down in speed. One homeowner commented, “The lowest setting was pleasant. I would prefer it to run for 10 minutes at low speed over 2 minutes at the highest volume.” Another suggested having various settings, such as a “quiet” mode so that others in the home would not be disturbed by cooking events that occur early in the morning or late at night. Such a mode would avoid automatically operating the high-speed setting, and perhaps the medium-speed setting. Homeowners requested expansion of the smart functionality to include an app providing information to the homeowner regarding what pollutants were being sensed and how the hood operated to address them. Each of these improvements could be incorporated in future generations of the SRH.

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1 Introduction

The negative health effects of cooking pollutants—including fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and others—are well established by a significant body of research (see Section 1.4). Although kitchen exhaust systems are effective at mitigating indoor cooking pollutants, research suggests that range hoods and other kitchen exhaust systems are generally unused or under-used. Unless activated by the occupants, kitchen exhaust systems cannot remove pollutants from the indoor environment. Rather than relying on occupant activation, smart controls could be integrated with the range hood to respond to the presence of pollutants and exhaust them. The noise produced by range hoods as well as a general lack of awareness about the risks of indoor air quality (IAQ) problems created by cooking are anticipated barriers to occupant acceptance of such an automated system. Even when used, the effectiveness of range hoods at capturing and removing pollutants can vary widely based on range hood geometry and flow rate.

Conversely, range hoods could be over-operated, resulting in excess ventilation, and requiring additional space heating/cooling energy. This happens when a range hood is turned on while cooking, but left on long after cooking pollutants are exhausted. Ideally, a range hood would be used only when cooking pollutants are present, thereby co-optimizing energy savings and IAQ objectives.

Developments in, and codification of, building practices that conserve energy and improve occupant comfort have resulted in tighter building envelopes and increased awareness of the importance of effective mechanical ventilation and pollutant source control to provide acceptable IAQ. Air pollutants produced in cooking events can be a critical source of acute and chronic pollutant exposure for occupants. This is especially true if the range hood (or other kitchen exhaust system) is not adequately operated. Effective and efficient kitchen exhaust systems are needed to support energy-efficient building practices while maintaining acceptable IAQ.

1.1 Scope and Objectives

The objective of this project was to develop, test, and demonstrate a smart range hood (SRH) that is affordable, responsive to key pollutants, consumer friendly, quiet, and efficient at capturing pollutants. The expected outcome is a paradigm shift of range hood functionality and perception as a primary instrument of health and IAQ in high-efficiency homes. The SRH was developed to achieve industry-leading performance in the categories of automatic responsiveness to cooking events, energy efficiency, rated noise, and rated capture efficiency. In addition, the SRH was intended to be consumer friendly in terms of affordability, maintenance, marketability, and environmental quality (especially in terms of perceptions related to noise, duration of operation, and cycling between speeds). The SRH should innovatively exceed state-of-the-art kitchen exhaust performance, while satisfying minimum requirements for local exhaust in the consensus standard, ASHRAE 62.2-2019 ("Ventilation and Acceptable Indoor Air Quality in Residential Buildings").

To be effective, the SRH would need to be equipped with a reliable sensor array and control logic to sense and respond to cooking events. To gain widespread adoption, the system would also need to operate effectively with limited noise—a major obstacle to range hood occupant use. Targeted performance metrics are shown in Figure 1.

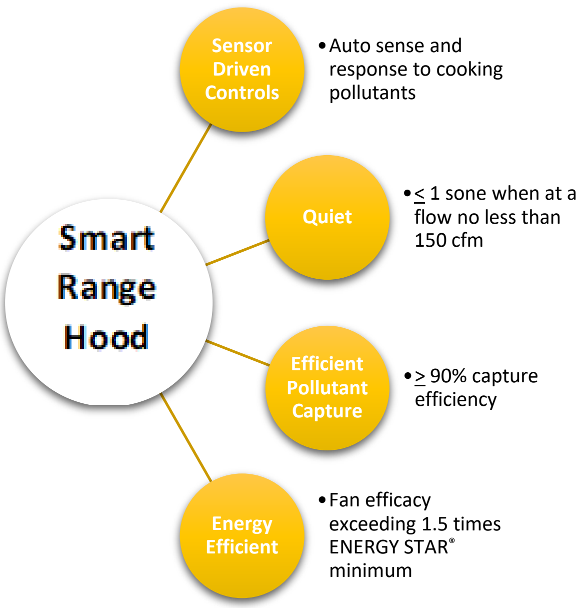

Figure 1. SRH design objectives

The SRH was developed in partnership with Broan, the nation's leading supplier of domestic range hoods. Prototype units were developed with sensors and controls responding to the presence of a variety of cooking-related indoor air pollutants. Although the exact mix of sensors is proprietary, a variety of pollutant sensors and control systems were tested during development. The project team conducted lab testing to confirm performance targets and then conducted field demonstrations to verify performance and collect consumer impressions on the prototype (see Figure 2).

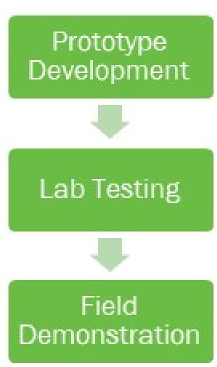

Figure 2. SRH research and development sequence

1.2 Research Questions

This project is intended to answer several research questions, which are listed here according to project phases:

1. **Overall Project**: Can a prototype SRH be developed that responds to the indoor air pollutants generated by cooking events? Can it deliver high-capture efficiency at low sound levels, and terminate operation when recently emitted cooking pollutants are removed?

2. **Development Phase**: Can a prototype SRH be developed that responds to cooking pollutants using IAQ sensors and controls?

3. **Lab Test Phase:**

   - Can the prototype SRH effectively remove pollutants generated by cooking?
   - Can the prototype SRH operate at a noise level < 1 sone at a flow no less than 150 cfm?
   - Can the prototype SRH provide a capture efficiency > 90%?

4. **Field Demonstration Phase:**

   - Can the prototype SRH effectively operate during cooking events?
   - What are occupant perceptions of the operation and effectiveness of the prototype SRH?

1.3 Background

The concept of the SRH is far beyond the current state of the industry for kitchen ventilation. In addition to issues already discussed, including noisy range hoods that are not activated by occupants and poor or unknown capture efficiency, the model codes and most state codes still do not even require range hoods to be ducted to the outdoors. The minimum requirements for kitchen ventilation in most jurisdictions still allow recirculating range hoods.

Above-code programs, such as ENERGY STAR® Homes and DOE Zero Energy Ready Home, do require a kitchen exhaust system ducted to the outdoors and a minimum airflow rate for kitchen ventilation (continuous or intermittent), but these systems are typically controlled with a simple on/off switch.

Integrating IAQ sensors and control logic, in addition to verifying industry-leading noise and capture efficiency performance, represents a major step forward for range hood technology. Integration and verification have the potential to increase ventilation efficiency while reducing kitchen pollutant exposures by 80% to 90%, assuming that the SRH transitions occupants from near-zero operation of their range hood to automatic operation with industry-leading capture efficiency.

1.4 Literature Review

A significant established body of research identifies cooking as a major source of indoor air pollutants—several of which can lead to long-term and acute health effects. An exhaustive literature review of this topic is beyond the scope of this report; however, this section highlights several studies that exemplify the knowledge surrounding the effects of cooking pollutants.

Many studies have examined and identified significant concentrations of indoor air pollutants commonly produced by residential cooking events. Examples of this research include work done by the California Air Resources Board in 2001, which characterized particulate matter, polycyclic aromatic hydrocarbons, NO_2, CO, and aldehyde exposures that result from both electric and gas cooking (Fortmann 2001); Zhang et al. (2010), examining ultrafine particles, $PM_{2.5}$, and black carbon exposures as a result of cooking; Dennekamp et al. (2001) reporting on ultrafine particles and oxides of nitrogen (NO_x) generated by gas and electric cooking; Singer et al. (2010) investigating indoor air pollution resulting from operation of gas appliances in residential applications; and Logue et al. (2014) simulating exposures resulting from operation of gas cooking burners.

Studies have also established significant negative health impacts of many cooking-generated pollutants. Examples include an EPA study on the health effects of NO and NO_2 (U.S. EPA 2016); as well as a 2012 study estimating the health impacts of indoor air pollutants such as $PM_{2.5}$, NO_2, CO, and others (Logue et al. 2012).

Domestic kitchen exhaust systems reduce the health impacts of cooking pollutants by exhausting a portion of them to the outdoors, thus limiting occupant exposure. Sun et al. (2018) reported reductions in exposure to ultrafine particles of 85% by using a higher flow rate on the range hood during cooking events. The ability of kitchen range hoods to reduce occupant exposure to pollutants is highly dependent on their effectiveness at capturing pollutants when operated (Lunden et al. 2014) as well as their frequency of operation. A Lawrence Berkeley National Laboratory (LBNL) study and accompanying survey of IAQ and exhaust fan use in 323 California homes revealed that most occupants with a functional kitchen exhaust hood reported using the hood “rarely or never” (Mullen et al. 2013). Mullen found that only 30% of occupants with a functional kitchen exhaust hood used the hood more than half of the time when cooking, while 52% of occupants with a functional kitchen exhaust hood used the hood “rarely or never.”

The existing research points to three primary conclusions, which are highly relevant to SRHs:

1. Cooking is a major source of indoor air pollutants in homes.
2. Indoor air pollutants generated by cooking can have significant negative health effects on occupants.

3. Kitchen exhaust systems are not used regularly, and when they are used, their performance varies widely.

In addition to identifying thematic conclusions with respect to the SRH, the literature review was used to inform the selection of sensors used in the development of the SRH.

2 Developing the Smart Range Hood

The development of the SRH was accomplished in cooperation between Newport and Broan in two phases: proof of concept (POC) and prototyping. Newport led the first phase, including researching, identifying, and sourcing sensors; incorporating sensors into a control; drafting and revising a control logic scheme and program; interfacing the control and sensor module with an existing Broan hood; and testing the POC in a domestic cooking environment. Broan's engineering team then used the POC as a springboard to develop several SRH prototypes, which were ultimately tested and demonstrated in laboratory and field applications. At the time of writing, Broan is pursuing patents for the SRH, so details in this section are limited in the interest of protecting intellectual property during the patent process.

2.1 Proof of Concept Development

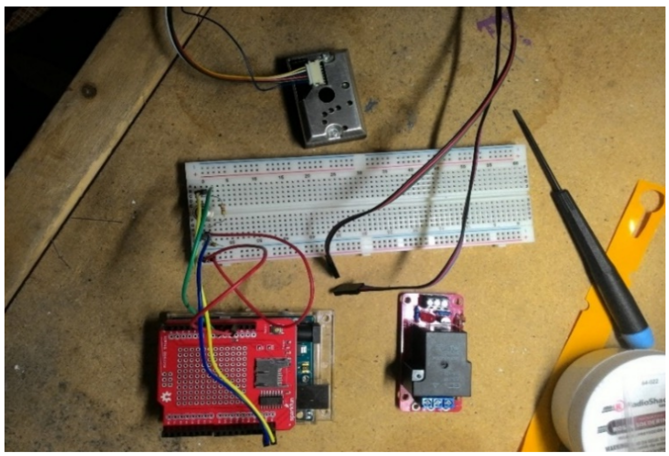

Figure 3. POC components

Figure 4. POC integrated with range hood

The POC was composed of an Arduino (a programmable microcontroller), multiple relays, and a sensor module. Selection of the initial sensor package was accomplished with consideration given to cost, accuracy, and ability to detect cooking-generated pollutants. A literature review, summarized and distilled within Appendix A, was used to identify targeted cooking pollutants, typical concentrations, and recommended thresholds. This information was used to guide the selection and specification of low-cost IAQ and environmental sensors for the SRH control. The initial POC was outfitted with sensors to measure dry-bulb temperature, humidity, infrared temperature, and $PM_{2.5}$. This combination met the criteria of being low cost, having potential for high accuracy, and having the ability to act as a surrogate/proxy for responding to other pollutants that are more difficult to sense accurately and at low cost. Data from cooking events recorded in literature suggest that controlling for $PM_{2.5}$ (augmented with temperature sensing and response) could also effectively address other pollutants of concern; see Figure 5, reproduced from Fortmann (2001) for an example.

Because low-cost $PM_{2.5}$ sensors are reported to have high correlation to reference sensors but limited accuracy (Wang et al. 2015), the logic model for the POC was configured to respond to changes in $PM_{2.5}$ concentration instead of $PM_{2.5}$ thresholds. The logic model was converted into a control algorithm program that was then uploaded into the Arduino. The initial version of the POC was configured to operate a kitchen exhaust system with two speeds. A subsequent version was incorporated with a three-speed range hood provided by Broan.

To test the ability of the POC to respond to cooking events, it was subjected to dozens of cooking scenarios in a domestic kitchen. These tests showed that the POC could quickly respond to cooking events, but the tests also revealed multiple deficiencies, including over-responsiveness (rapid cycling) and excessive cycle length. An immediate response to measured pollutant concentrations resulted in erratic operation of the range hood, and could lead to homeowner confusion and consternation. To improve the user experience, multiple methods were explored to moderate the POC response, including engaging the range hood only when a cooking event was detected at the cooktop, signal-smoothing, multistep verification of cooking events, and establishing minimum cycle times. After these and other improvements were made, the POC was then presented to Broan's engineers for review.

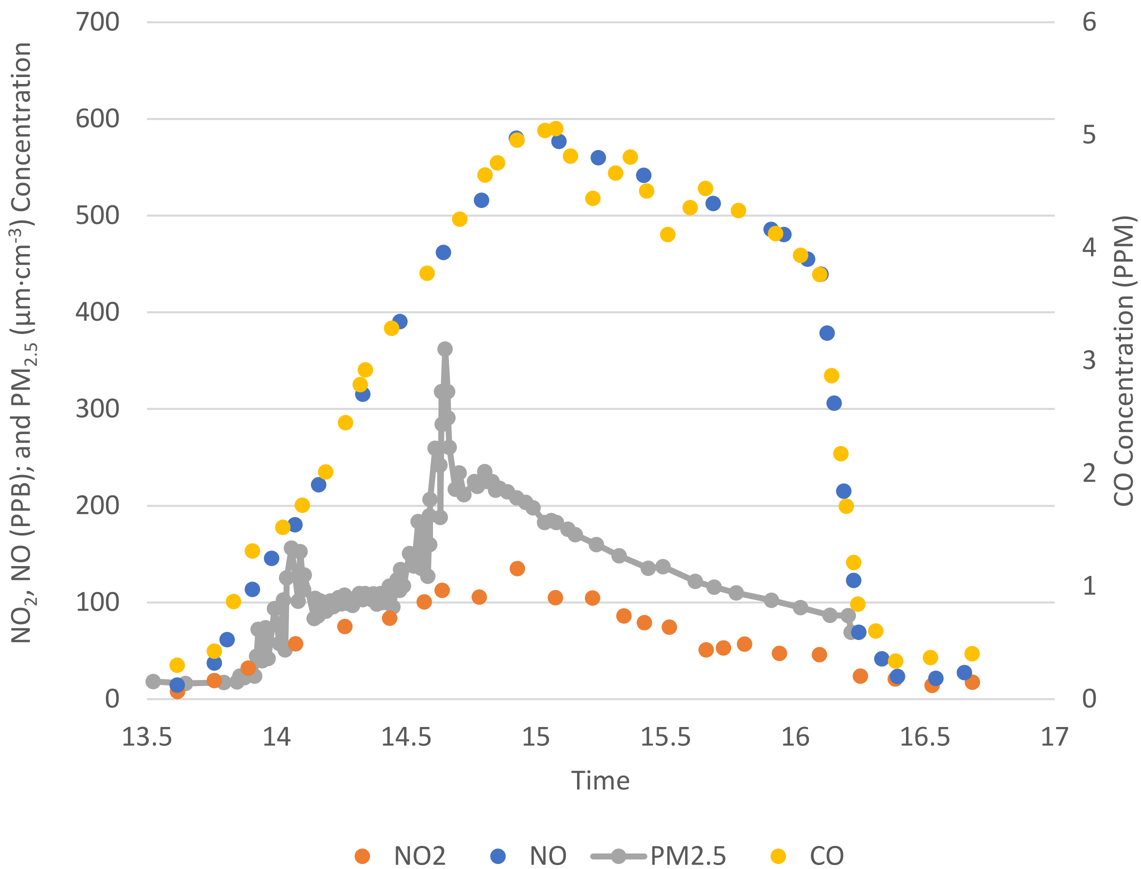

Figure 5. Pollutant concentrations during cooking event. This chart, reproduced from Fortmann (2001), shows similar pollution profiles, suggesting that controlling for one pollutant may offer the benefit of simultaneously addressing others.

2.2 Prototype Development

After receiving the POC and a demonstration of its functionality, Broan assigned a team of engineers to transition the POC into a first-generation SRH prototype. Revisions and improvements were made to the control module, environmental sensor package, and control logic. The control/sensor module was integrated with an under-cabinet range hood model with performance specifications that tracked closely with SRH performance targets. Several generations of the prototype were developed and tested in Broan's laboratory under simulated cooking environments with variations in cooking scenarios, cooking fuel (electric and gas), hood height (low versus high), cooking type (boiling water versus panfrying meat), fan speed (off and speeds 1, 2, and 3), and burner location (front and rear, left and right). Optimization was performed based on considerations for the following criteria: sensor ability to detect events from all burners, sensor location, sensor event detection response time, magnitude of sensor response to an event, repeatability and reliability of sensor responses given different scenarios, climatological stability, acceptability of run times (neither too short nor too long), and sensor longevity.

Additional laboratory testing, both in-house and third-party, was conducted to assess range hood capture efficiency, sound, flow rate, fan efficacy, and sensor response and longevity when exposed to heavy grease in cooking events. Once Broan's in-house laboratory testing was completed, Broan conducted a first round of informal domestic field testing with staff volunteers. As the SRH was readied for third-party laboratory testing with LBNL to verify its response to kitchen pollutants, Broan filed provisional patents for the SRH.

3 Lab Testing

Lab testing was conducted to verify performance of the SRH prototype. The objectives of the lab testing focused on verification that the SRH responded appropriately to pollutant levels during cooking events, as well as evaluating the hood's capture efficiency and sound levels using industry protocols. Specific research objectives include:

- Verification that the range hood responded properly to cooking pollutant signals—ramping up when targeted pollutants reached the specified concentration and ramping down once the pollutants were reduced.
- Determination of SRH capture efficiency for typical cooking events using the American Society for Testing and Materials (ASTM) draft capture efficiency standard methodology. The goal was to achieve a capture efficiency that met or exceeded 90%.
- Determination of the sound level of the SRH based on the Home Ventilating Institute (HVI) Publication 915. The goal was to achieve a sound rating of less than 1 sone at no less than 150 cfm fan operation.

3.1 Smart Range Hood Responsiveness and Impact on Pollutant Concentrations

In cooperation with Newport and Broan, LBNL conducted lab testing to compare air pollutant concentrations measured in a simulated kitchen test room with the SRH in off mode and the SRH in auto mode. The testing protocol, data analysis, and results presented in this section are drawn from an internal technical report prepared by Brett Singer, William Delp, and Ari Harding of LBNL in May 2019.

In the lab testing, three carefully designed cooking events were prepared three times with the SRH in auto mode, and three times without any range hood use. The condition of no range hood operation was selected as the reference for comparison based on surveys of homeowners that show that range hoods are infrequently operated during cooking events (Mullen et al. 2013). Two additional experiments were conducted to assess the benefit of the SRH when cooking on back versus front burners, using the breakfast meal protocol (see Section 3.2.3). Another pair of experiments was conducted to explore whether the SRH would detect and operate when cooking with an induction burner. These experiments involved sequential cooking with the same breakfast meal and the same pans, while using an induction hot plate for cooking instead of the gas burner.

During each of these cooking events, an array of sensors collected data on SRH operations relative to the cooking events, along with IAQ conditions within the lab-based kitchen. The data were then evaluated to assess the SRH's responsiveness to cooking event signals and the impact of its operation on indoor air pollutants as compared to the scenario of no range hood operation.

3.2 Testing Methods and Experimental Setup

3.2.1 Smart Range Hood

The SRH features a proprietary sensor array and sensor-driven control unit installed into a commercially available, under-cabinet range hood—the Broan Glacier series.[1] The Glacier range hood has certified airflows of 150 cfm at "working speed" and 390 cfm at "high speed" (corresponding to the lowest and highest of three available fan speed settings) when configured with 7-inch round vertical ducting and operated under the conditions set forth in HVI Publication 916 ("Airflow Test Procedure"). The SRH has a toggle switch to enable operation in manual or auto modes. Manual mode operation allows for selection of off, low, medium, and high speeds. When set to operate in auto mode, the unit is designed to collect 5 minutes of baseline sensor readings before initiating automatic operation. After the 5-minute warm-up, the SRH continuously assesses pollutant levels and stovetop operation through sensor array measurements, automatically turning on when a cooktop event is detected, increasing or decreasing speed settings as necessary to control pollutant concentrations, and turning off once the control algorithm identifies that the cooking event is complete and pollutant concentrations are mitigated.

3.2.2 Experimental Room

The lab testing of the SRH was conducted inside cell 3A of the FLEXLAB2 facility at LBNL in a room configured to represent a kitchen area. The floor area of the entire cell is 6.10 m wide by 9.36 m long. This space was carefully configured to represent a typical cooking area in a house, and included mixing of air within the space and supply of filtered, outdoor air. Outdoor air was supplied and indoor air exhausted at a baseline rate of 95 cfm during SRH auto mode and off mode. This flow rate was selected using professional judgment to approximate the air exchange rate and mixing benefits that could be expected for an open-concept kitchen in a typical new home provided with whole-house mechanical ventilation. During the SRH test, the outdoor airflow rate was automatically adjusted to provide sufficient airflow to maintain a roughly neutral pressure between the test chamber and outdoors (+/- 2 Pa) at each operating speed. The space also included a typical four-burner gas range; representations of counters and cabinets around the range (which influence airflow); and other features to replicate a residential cooking environment. The SRH was ducted to the outdoors through smooth, nominal 7-inch diameter ducting installed to the top exhaust outlet on the hood. Full details on the experiment room configuration are in Appendix B. A picture of the lab testing setup is shown in Figure 6.

[1] For more information, see: www.broan.com/Range-Hoods/Under-Cabinet/Glacier-BCDJ1-Series/BCDJ130SS.

Figure 6. Simulated residential kitchen area in experiment room. The main analytical instrumentation is shown on the left side of the picture.

3.2.3 Cooking Procedures

Detailed protocols were developed for three typical meals often cooked in U.S. homes. These protocols allowed for repeatable cooking events to occur under different range hood operation scenarios. The three "standardized" meals were:

- The **breakfast meal**, which included stovetop preparation of frozen hash browns, packaged bacon, and eggs in a quantity suitable for a relatively large breakfast for two people. Iterations of the cooking procedure involved both parallel and sequential cooking operations. Steps included:
    - Fry 2 partially precooked, frozen hash browns (64 g each) in small stainless steel skillet with 1 Tbs canola oil over medium heat; cook for 9 min.
    - Fry 4 strips (162–178 g) of apple-cured bacon in a large stainless skillet over medium heat; cook for 12 min.
    - Fry 2 eggs in a medium nonstick pan with 1 Tbs butter over medium heat; cook for 4 min.
- A **pasta meal**, which involved preparation of meat sauce and pasta using packaged ground beef and a jar of marinara sauce. The pasta meal also included frying freshly cut onions. The meal quantity was suitable for three to four adults. Multiple cooking

operations for this meal were done in parallel, such as cooking pasta sauce (28.5 minutes total) while bringing water to a boil and then cooking pasta. Steps included:

  - Cook pasta in 5L stainless steel pot: add 4L water and 2 tsp salt and bring to boil on high heat (16 min); add 454 g bowtie pasta, adjust to medium heat and cook for 13 min.
  - Prepare meat sauce in stainless steel sauté pan: fry 100 g diced onion in 2 Tbs olive oil over medium heat for 6 min; add 454 g of 85/15 ground beef and cook over medium heat for 8 min; add marinara sauce from jar containing 737 g and cook over medium-low heat for 11 min.
  - After draining excess water from pasta in colander (over larger pot, which is subsequently covered), mix pasta and meat sauce in 5L pot.

- A **mandarin orange chicken meal**, which involved oven heating precooked chicken cubes that were mixed with a prepared sauce (cubes and sauce sold in a frozen package as “mandarin orange chicken”). Steps were sequential and included:
  - Preheat oven to 400ºF for 10 min.
  - Heat 454 g of precooked chicken chunks in oven, on foil sheet, for 19 minutes.
  - After removing from oven, add chicken to 5L pot and mix with 170 g sauce provided as part of packaged meal.

Each meal was prepared at least three times using only the front burners or the oven with the SRH set to auto mode, and three times with the SRH set to off. The breakfast was prepared two additional times using the back burners, as a secondary evaluation.

Details on the preparation of each meal are provided in Appendix C.

3.3 Range Hood Airflow and Pollutant Measurements

Measurements were made to quantify airflow through the range hood. This flow was measured as a static value using a duct blaster test setup as the measurement device. Additionally, the following air quality measurements were made within the lab testing room and in the range hood exhaust duct using the sensors shown in Table 1. Table 1 does not include measurements made by the SRH sensor array, which is proprietary.

Table 1. Laboratory Air Quality Measurements and Devices

Parameter (units)	Location(s)	Measurement Device	Description
Temperature and humidity in SRH exhaust	Duct connecting range hood to outside	Onset HOBO U23-002	Weatherproof T/RH data logger with external probe
CO_2 (ppm) in SRH exhaust	Duct connecting range hood to outside	PP Systems EGM4	Infrared measurement of CO_2 concentration
Particle number concentration (#·cm^{-3}) in room	Center of room	Grimm Mini-WRAS, Model 1.371	Size resolved and total number concentration of particles using electrical mobility for particles with diameters 10–200 nm and laser-based optical counter for 0.2–35 µm diameter particles
$PM_{2.5}$ mass concentration (µg·m^{-3}) in room	Center of room	Grimm Mini-WRAS, Model 1.371	Estimate provided by Grimm 1.371 from size-resolved particle measurements
$PM_{2.5}$ mass concentration (µg·m^{-3}) in room	Center of room	MetOne BT-645 with sharp-cut $PM_{2.5}$ cyclone	Forward light scattering nephelometer that estimates mass based on calibration to 0.6 µm polystyrene latex spheres
NO_X, NO, NO_2 (ppb) in room	Center of room	TSI-API Model 200E	Chemiluminescence analyzer with catalytic reduction of NO_2 to NO. Direct measures of NO_X, NO; NO_2 by difference. Calibrated on-site.
CO_2 (ppm) in room	Center of room	Awair v2	Sensor data not provided on website. Auto baseline correction to 400 ppm based on prior 14 days of data.
Vertical mixing based on estimated $PM_{2.5}$ (µg·m^{-3})	Heights of 43, 133, 232 cm in center of room	Purple Air PA-I-Indoor	Plantower sensor measures laser light scattering to count particles in 6 bins from 0.3 to 10 µm; estimates PM_1, $PM_{2.5}$ and PM_{10} (µg·m^{-3}).
Horizontal mixing based on estimated $PM_{2.5}$ (µg·m^{-3})	3 locations in room at heights of 90–139 cm	Kaiterra Laser Egg 2	Plantower sensor measures laser light scattering to count particles in 6 bins from 0.3 to 10 µm; estimates PM_1, $PM_{2.5}$ and PM_{10} (µg·m^{-3}).

3.4 Data Analysis and Results

3.4.1 Smart Range Hood Airflow

The airflows measured at each speed setting with the SRH installed in the experimental room are provided in Table 2. As expected, the airflows recorded within an installed condition are lower than rated flows, but still comparable.

Table 2. Airflow Measurements of the SRH as Installed in the FLEXLAB Experimental Room

Hood Setting	Airflow (cfm)
Off	–
Low	139
Medium	230
High	351

3.4.2 Air Quality Measurements

Time-resolved concentrations of several of the measured air pollutants were analyzed to assess the SRH's performance as compared to cooking events that occurred with no range hood operation. These analyses were conducted to provide informative but not definitive results in characterizing the impact of the SRH. Note that this analysis did not include the subtraction of pollutants coming into the chamber with outdoor air, which was expected to have a relatively low influence, especially because the outdoor air was filtered (MERV 8 followed by MERV 13) prior to introduction. Data from the horizontal and vertical mixing sensor arrays indicated good mixing throughout the chamber.

Figure 7 overlays the time-based series of NO_x, particle number (PN), and $PM_{2.5}$ measured with the SRH off and the SRH in auto mode during the breakfast cooking event. In the off mode, NO_x concentration profiles were very similar in two experiments, with the third experiment differing; cooking of the hash browns and bacon occurred sequentially in the "off-sequential" response and occurred simultaneously in the "off" response shown in Figure 7. In auto mode, NO_x concentration profiles also tracked closely, with room air pollutant concentrations much lower than in off mode; both "auto" responses shown in Figure 7 resulted from sequential cooking of hash browns and bacon.

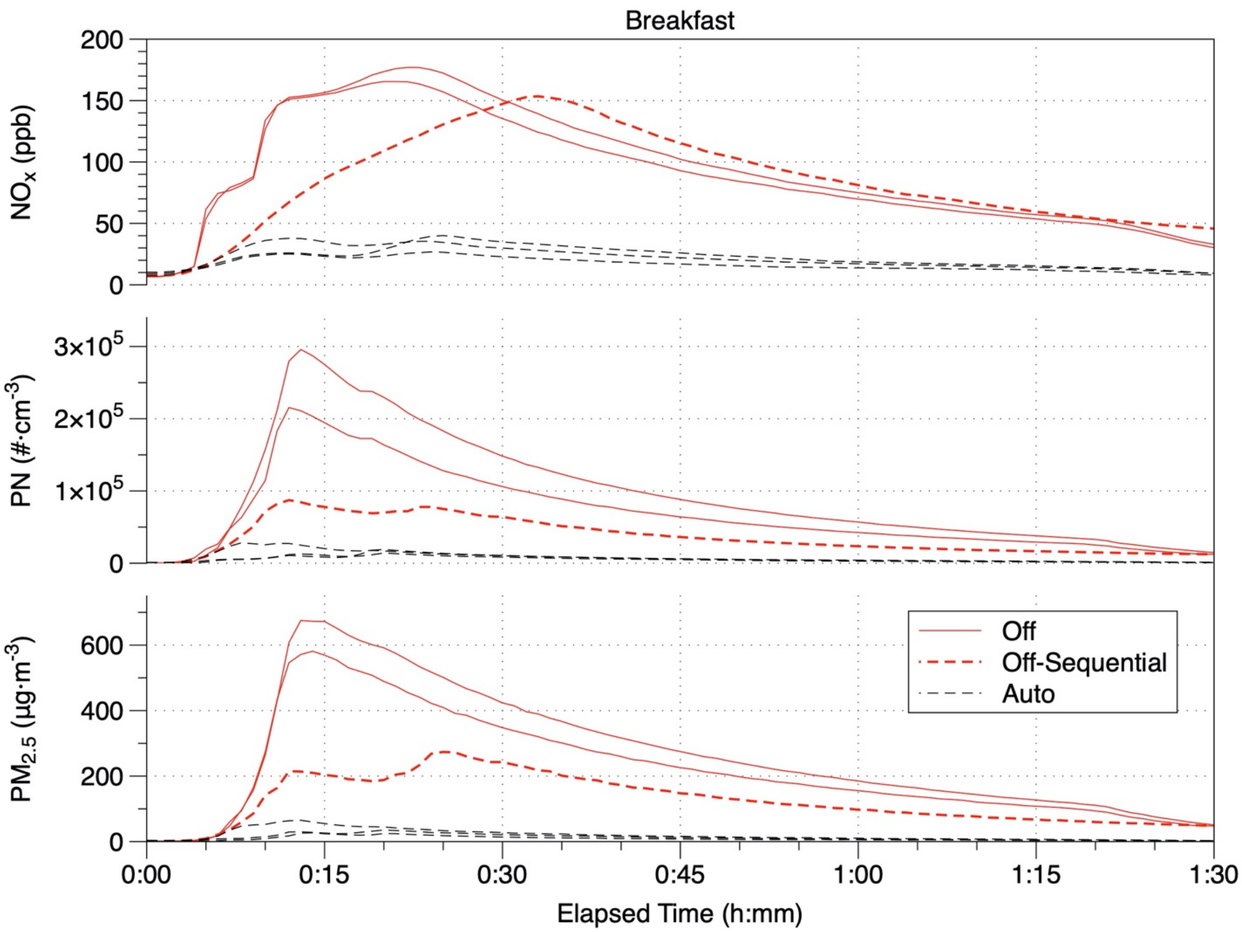

Figure 7. Room air pollutant concentrations during breakfast cooking using front burners of a gas cooktop, with (auto) and without (off) the SRH enabled

Prior research by LNBL has shown that wall-mounted range hoods have higher capture efficiency when cooking occurs on the back burners as opposed to front burners (Delp and Singer 2012). This is a function of geometry and physics and is not an issue that was expected to be resolved by the SRH, which has a similar geometry to traditional range hoods. Figure 8 presents additional data from the two experiments in which the breakfast meal was cooked on the back burners. As expected, room air pollutant concentrations were substantially lower than when cooking occurred on the front burners; nonetheless, they were low in both cases. These tests, combined with the activation time in Figure 12, provide assurance that the SRH is able to quickly respond to cooking events on back burners as well as front burners while significantly reducing time-integrated pollutant concentrations and peak pollutant concentrations versus off mode. SRH auto mode was enabled for both experiments shown in Figure 8.

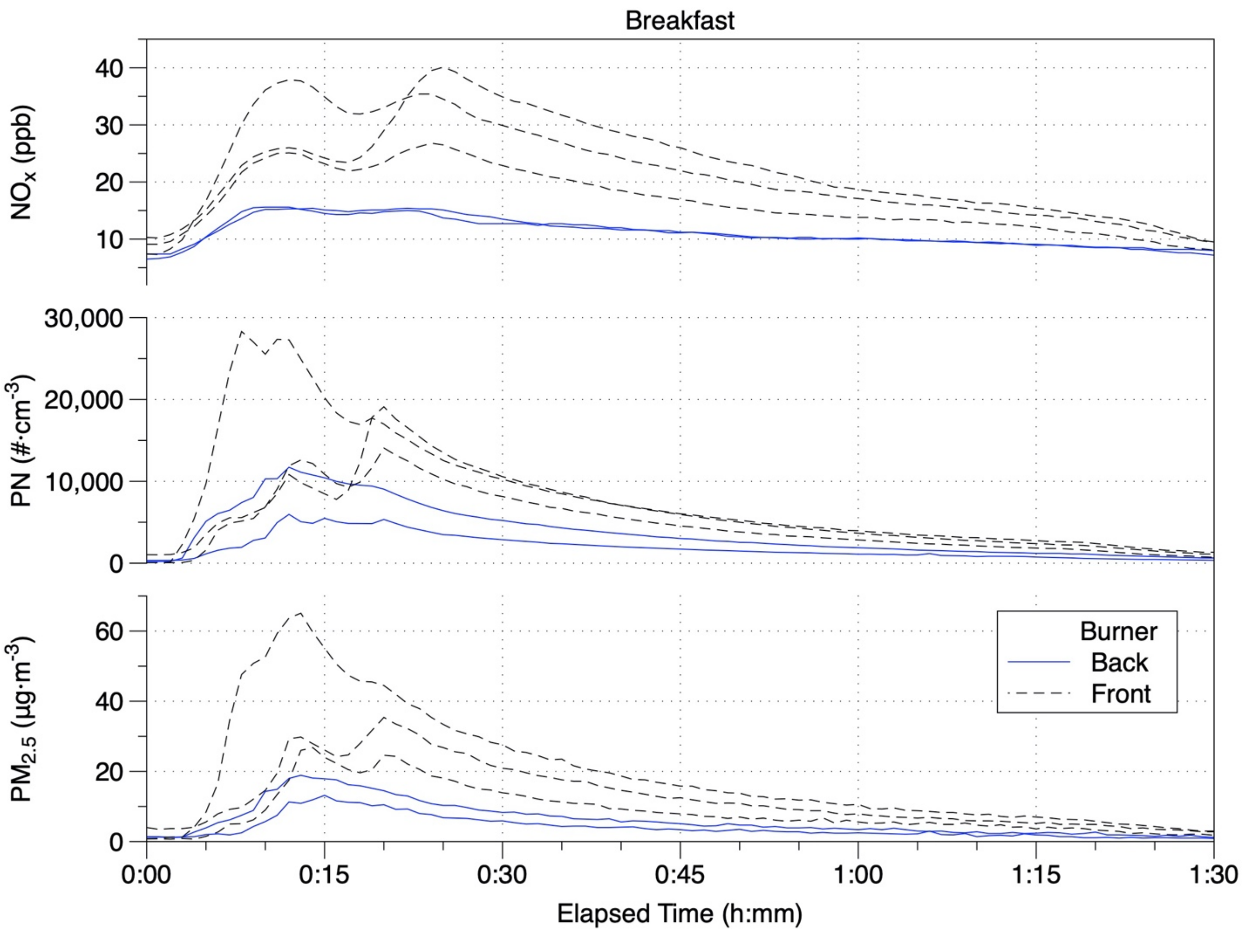

Figure 8. Room air pollutant concentrations during breakfast cooking using front burners and back burners of a gas cooktop. The SRH was in auto mode in both cases. The scale of the Y-axis has been changed from that shown in the prior figure.

Next, the time series data for the pasta meal cooking event (which used both front burners) is shown in Figure 9 for three meals with the SRH in auto mode and three meals with the SRH turned off. As the dashed lines in the graph illustrate, room air concentrations of NO_x, $PM_{2.5}$, and particle number were all significantly reduced with the SRH in auto mode. Like the breakfast meal shown in Figure 7, there was some variability in the replicate tests in the particle number and $PM_{2.5}$ concentrations.

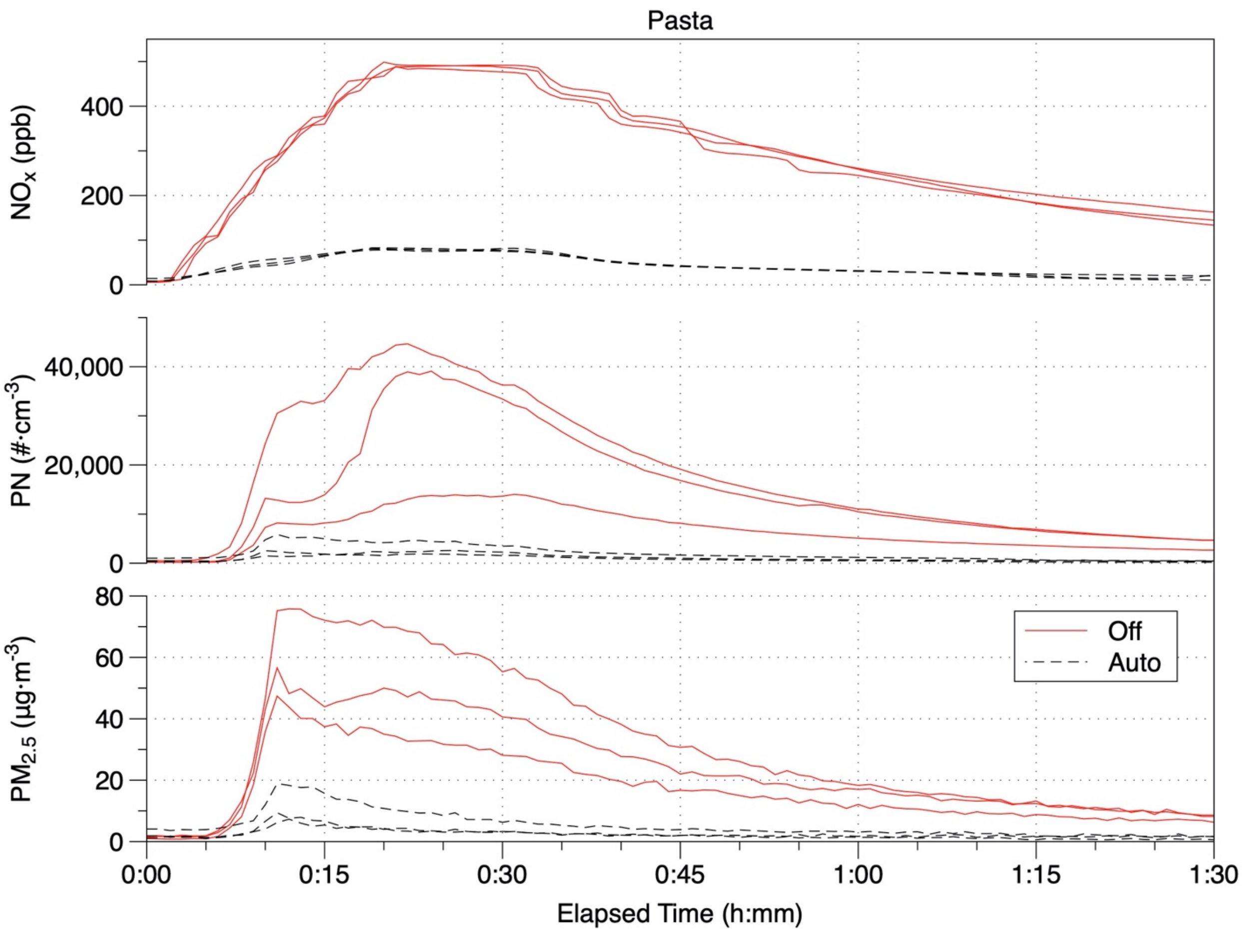

Figure 9. Room air pollutant concentrations resulting from cooking of pasta with meat sauce, with (auto) and without (off) the SRH enabled

The third meal cooking protocol, oven baking of the orange chicken meal, is illustrated in Figure 10. As with the breakfast and pasta meals, operation of the SRH in auto mode resulted in much lower measured levels of air pollutants.

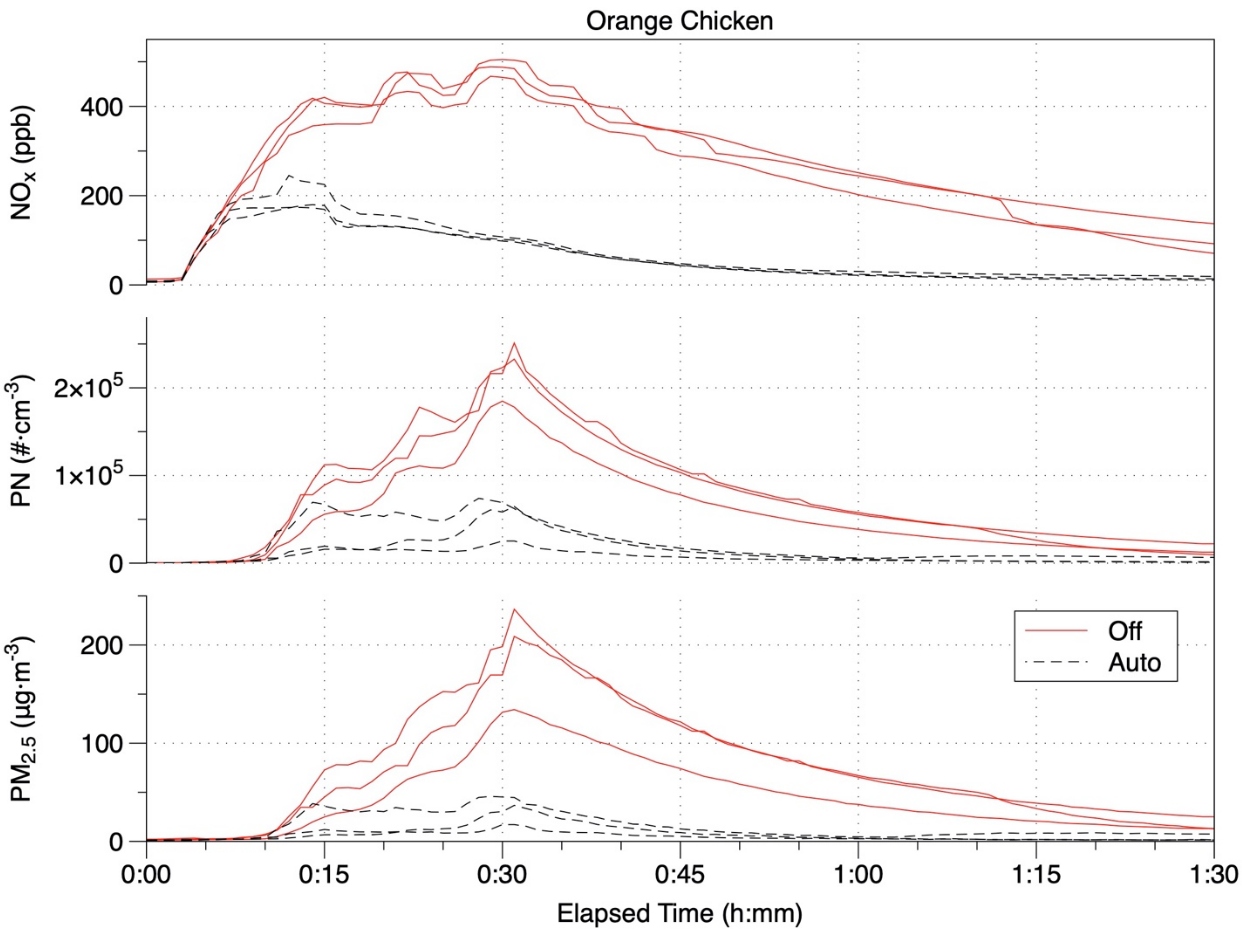

Figure 10. Room air pollutant concentrations resulting from cooking of orange chicken in a gas-fired oven, with (auto) and without (off) the SRH enabled

A final set of cooking tests evaluated whether the SRH would detect an event and operate when cooking with an induction burner. Figure 11 illustrates the pollutant levels during sequential cooking of the same hash browns and bacon in the same pans used in the breakfast meal, but with the pans heated by an induction hot plate placed on the cooktop surface. The induction hot plate was used to simulate an induction range. The results indicate that the SRH responded to cooking on the induction burner and significantly reduced particle concentrations. There were no NO_x emissions in tests using the induction burner.

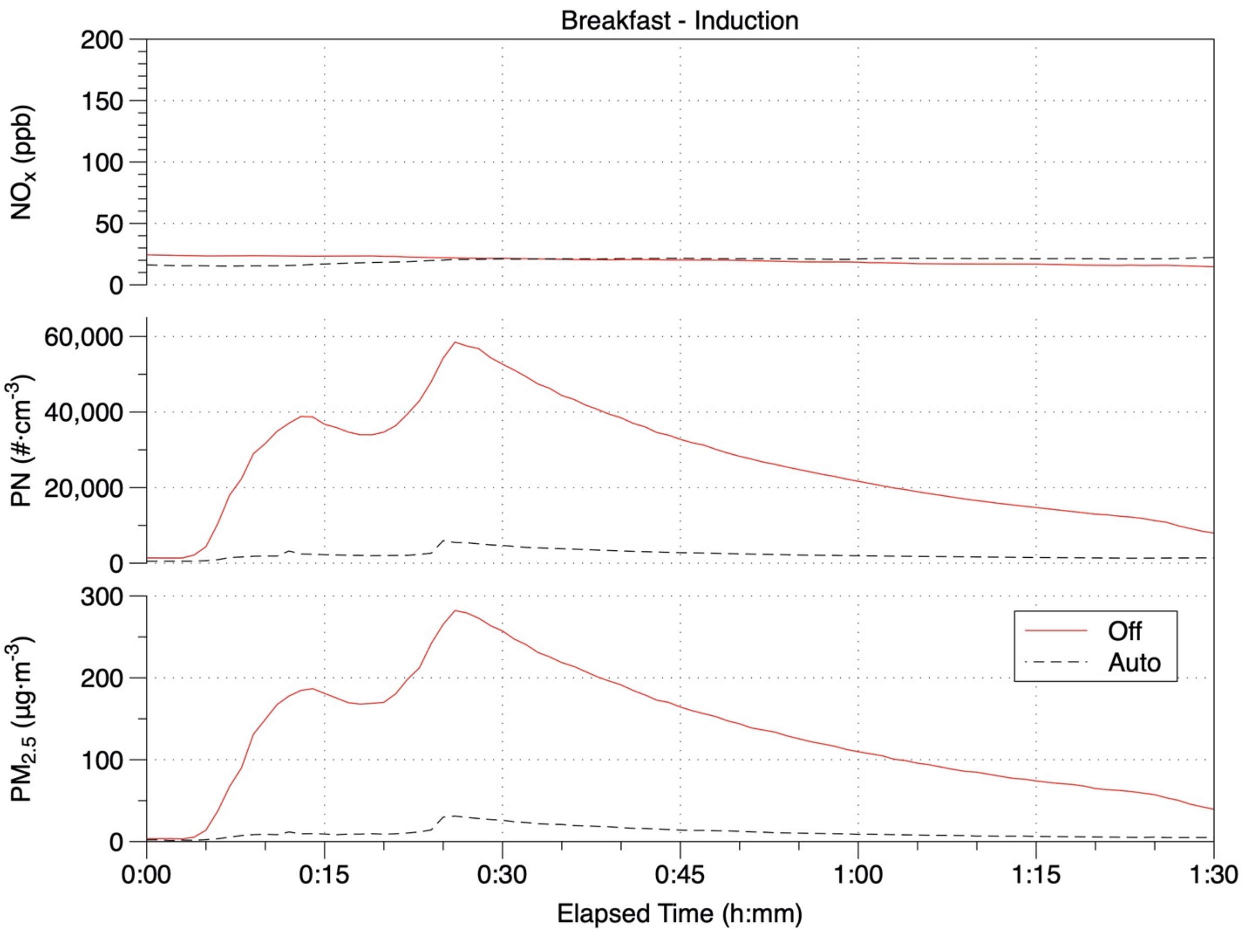

Figure 11. Room air pollutant concentrations resulting from cooking of a modified breakfast meal with sequential cooking of hash browns and bacon on an induction burner. The SRH is in auto mode or off.

3.4.3 Smart Range Hood Responsiveness

Figure 12 shows the responsiveness of the SRH to activate, measured by the time from the initial firing of the range or oven, for each of the three meals. The breakfast meal triggered SRH operation in approximately 30 seconds or less in all configurations (front burner, back burner, induction cooking). Preparation of all three pasta meals triggered the SRH operation in less than one minute (and less than 30 seconds for one of the pasta meals). Because the SRH was not designed to respond directly to oven cooking, there was a much longer delay for the three experiments with oven cooking of the orange chicken meal. However, in each test the SRH initiated before the oven had reached the desired operating temperatures and before the oven door was opened.

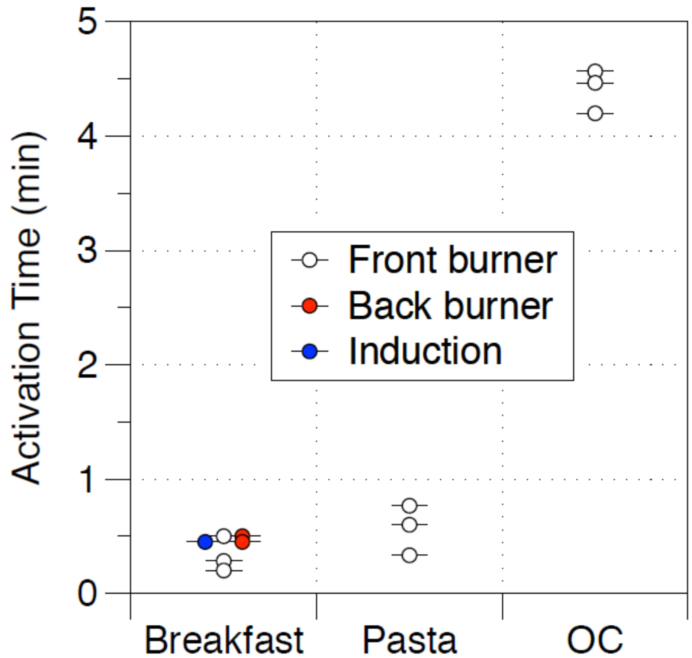

Figure 12. Activation time for the SRH during the breakfast, pasta, and orange chicken meals ("OC" = orange chicken)

Additional test data illustrating the SRH's responsiveness are shown in Figure 13. The graph shows time series data for a day of testing during which three meals were prepared, two with the SRH in auto mode ("on" in the graph) and one with the SRH off. The color-coded areas under the curve show the SRH fan speeds at different points during the "on" cooking events. For example, during the breakfast meal preparation, the SRH fan cycles on quickly (within 30 seconds based on the chart above) and cycles from low to medium to high speed, before cycling back to low shortly before the end of the meal preparation when the burner was turned off. It should also be noted that the test protocol included a purging of the testing space with the SRH in high speed following the completion of a test. For example, this occurs around 12:50 after the completion of a pasta meal test with the SRH off.

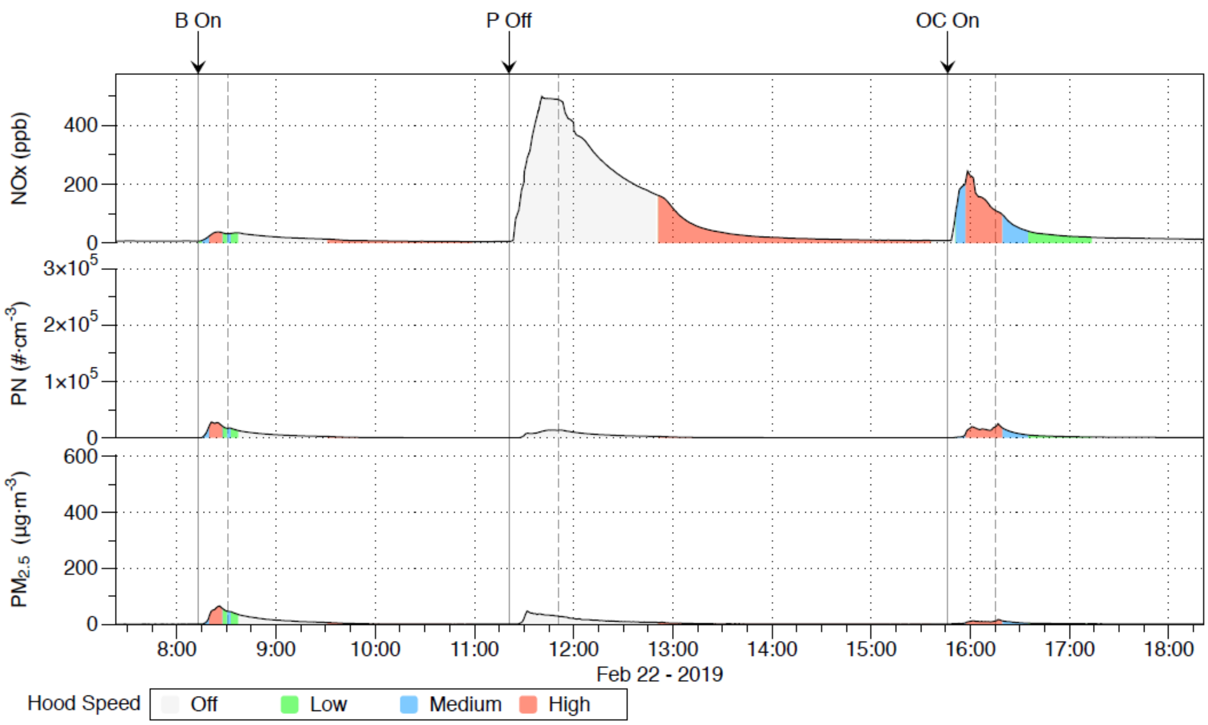

Figure 13. Air pollutant time series data. B = Breakfast; P = Pasta; OC = Orange Chicken. "On" indicates SRH in auto mode, while "Off" indicates no range hood operation.

3.5 Discussion of Responsiveness and Air Quality Results

Operation of the SRH in auto mode resulted in much lower air pollutant concentrations for NO_x, $PM_{2.5}$, and particle number compared to the same three cooking events conducted without range hood operation. The reduction in time-integrated concentrations ranged from 64% to 94%, depending on the event and pollutant (see Table 3). Within Table 3, results for NO_2, a constituent of NO_x, are reported separately because this pollutant is a respiratory irritant that is specifically addressed by the U.S. EPA's National Ambient Air Quality Standards. The lab testing results indicate good responsiveness of the SRH in relation to the start of a cooking event. The response of the SRH to the cooktop burner events was roughly 30 seconds or less. For oven events, response time was slower, on the order of 4 to 5 minutes. However, in each oven test the SRH initiated before the oven had reached the desired operating temperatures and when the food was added to the oven.

The lab testing explored SRH versus no range hood operation and showed promising results. These findings have the potential to translate reasonably well to real-world scenarios in which residents rarely use their range hood.

Table 3. Percent Reduction in Time-Integrated Laboratory Air Pollutant Concentration Resulting from SRH in Auto Mode as Compared to No Range Hood Operation

Concentrations were integrated over a period of 90 minutes following the peak concentration. Background concentrations were subtracted to normalize results.

Percent Reduction in Time-Integrated Pollutant Concentration				
Replicate Meal	**PN (# · cm^{-3})**	**$PM_{2.5}$ (µg · m^{-3})**	**NO_2 (ppb)**	**NO_x (ppb)**
Breakfast	91%	94%	71%	86%
Orange Chicken	80%	87%	64%	77%
Pasta	94%	94%	74%	89%

3.6 Capture Efficiency and Sound Testing

The effectiveness of a range hood at removing pollutants is a function of the pollutant profile of the cooking event, the flow rate and geometry of the hood, and installation characteristics. Occupant willingness to use a range hood has been linked to its loudness when operating, with quieter operation being more desirable. The design team achieved their goals of demonstrating excellent performance with respect to both pollutant capture efficiency (greater than or equal to 90%) and noise (less than one sone at a speed setting producing a flow greater than or equal to 150 cfm).

3.6.1 Capture Efficiency Test

ASTM E3087-18, Standard Test Method for Measuring Capture Efficiency of Domestic Range Hoods, was published in 2018 to provide a quantitative method for assessing a wall-mounted domestic range hood's ability to capture air pollutants generated during typical cooking events. The metric produced by the standard is range hood capture efficiency, calculated as the percentage of a tracer gas released near two front cooktop burners that is exhausted by the test hood during steady-state operation of the burners. The test method is a laboratory procedure that is meant to simulate operation of two front cooktop burners in a typical residential kitchen configuration. Because the capture efficiency test for the SRH was performed prior to ASTM E3087's publication, a draft version of the standard was used. Revisions from the draft version that were incorporated in the publication version included reducing the surface temperature of the pans and also modifying the tracer gas diffuser; these changes were made to improve safety and repeatability. Otherwise, test conditions were very similar. The variations between the draft and final versions of the standard were not expected to have a sizeable effect on the capture efficiency reported. Although tests were conducted on the base model of the SRH without integrated sensors and controls, the base model and SRH model are expected to have the same capture efficiency based on virtually identical geometry and flow rates.

Laboratory testing performed to the draft version of ASTM E3087-18 resulted in a capture efficiency of 57% at 150 cfm, 90% at 250 cfm, and 98% at 400 cfm (nominal flow rates), with the SRH installed between two side cabinets in accordance with the requirements of the draft standard and manufacturer instructions. Any speed setting that achieves a flow rate exceeding

250 cfm is therefore expected to exceed the laboratory capture efficiency goal of greater than or equal to 90%. Figure 14 shows the testing results.

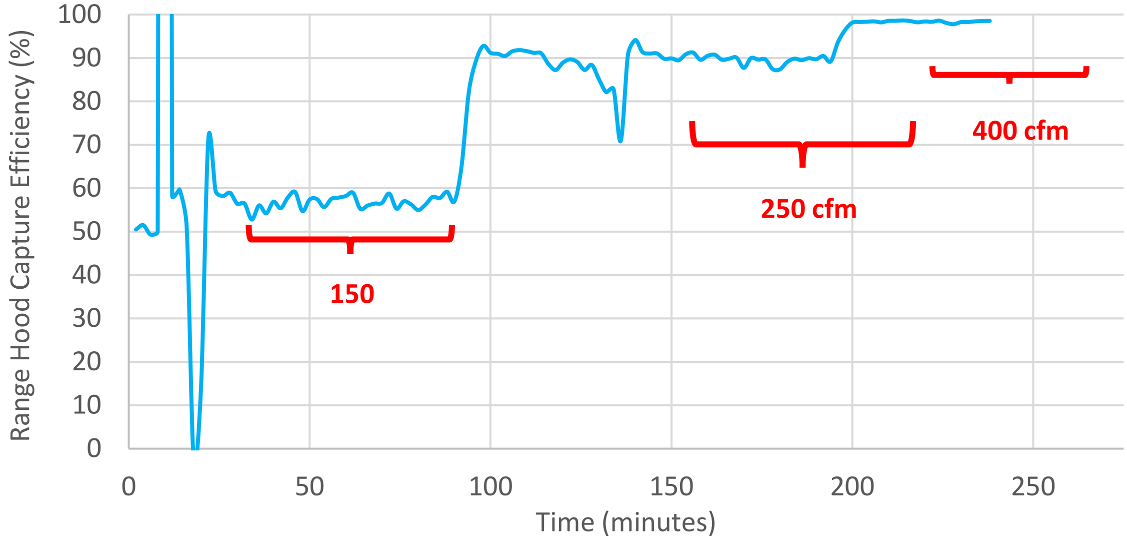

Figure 14. SRH capture efficiency testing data showing 57%, 90%, and 98% capture efficiency at flow rates of 150, 250, and 400 cfm, respectively

3.6.2 Sound Testing

ASHRAE 62.2 ("Ventilation and Acceptable Indoor Air Quality in Residential Buildings"), references HVI Publication 915 ("Procedure for Loudness Rating of Residential Fan Products"), for determining the loudness of range hoods. Publication 915 is a procedure based on three ANSI standards (S3.4, 300, and S12.51) that uses a six-microphone array in a reverberant laboratory chamber to report sound levels in terms of sones, which is a linear sound metric that is more intuitive for consumers than decibels, a logarithmic metric.

SRH sound testing was conducted by Texas A&M's REEL laboratory in compliance with HVI Publication 915, and the results are listed in the HVI product directory. On low speed, the SRH achieved a rating of 0.3–0.6 sones across various duct configurations associated with an airflow rate of 150–160 cfm, improving upon the project goal of achieving less than one sone at a flow no less than 150 cfm. This achievement represents class-leading sound performance, as only 3% of range hood sone listings in the HVI directory had a sone rating of less than one at a flow rate no less than 150 cfm as of January 2020. On high speed, the SRH had a sone rating of 5–6 sones, which is slightly quieter than the average sound level for HVI certified ratings of hoods operating between 380 and 400 cfm as of January 2020.

3.6.3 Fan Efficacy Testing

Fan efficacy is calculated as the airflow rate exhausted by the blower motor divided by the associated power consumption. SRH airflow rate and power testing were conducted by Texas A&M's REEL laboratory in compliance with HVI Publication 916 ("Airflow Test Procedure"), which is based on ANSI/AMCA 210-ANSI/ASHRAE 51 ("Laboratory Methods for Testing Fans for Aerodynamic Performance Rating”). Results were listed in the HVI directory, showing a fan efficacy at working speed (corresponding to a flow rate of 150–160 cfm) of 4.5–4.7 cfm/watt, which varied based on exhaust duct configuration. These values exceeded the target of 1.5 times the ENERGY STAR minimum of 2.8 cfm/watt.

4 Field Tests

After completing the lab testing, the next phase of the study involved conducting field tests with the SRH prototypes in occupied homes. In total, the research team conducted three separate field tests, two in Maryland and one in New York. Each field test included two weeks using the homeowners' existing range hood exhaust system, during which time the residents were encouraged to cook and operate their range hood as they normally would. Immediately following was another two-week monitoring period with the SRH installed in place of their existing range hood unit. Again, participants were encouraged to continue with their normal cooking behavior. In this case, however, range hood operation was automatic.

The field study was conducted with the following questions in mind:

1. Can the operation of an SRH substantially reduce air pollutant concentrations in homes with frequent cooktop operation, compared to the reference case of occupants electively and manually operating their existing kitchen exhaust system "as needed" or "rarely/never"?
2. What are the homeowner perceptions of the operation and effectiveness of the SRH?

4.1 Test Method

4.1.1 Recruitment

To ensure a successful field study, it was critical to recruit a group of participants that met specific criteria to allow for useful results. Recruitment of participants and field testing was conducted in accordance with a plan conforming with DOE's Human Subjects Review protocol to safeguard participants' privacy and health and was approved by the Central Department of Energy's Institutional Review Board. Conducting field evaluations of technologies in existing homes is challenging because of the large variation in how homes are constructed and designed, as well as the existing systems and technologies. Additionally, IAQ—specifically as related to kitchen ventilation—is a relatively new concern that may not have been considered when the house was built, and can vary significantly based on resident behavior.

Figure 15. Postcard

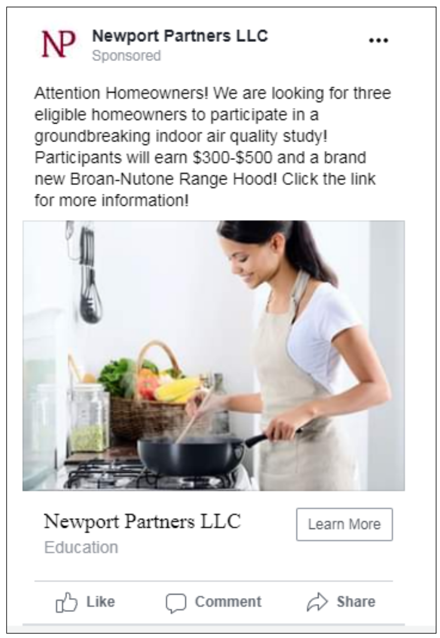

Figure 16. Social media ad

In order to make the study cost-effective, Newport targeted homes within close proximity to their company offices in Schenectady, New York; Davidsonville, Maryland; and Loveland, Colorado. Newport developed several outreach methods to gather a large pool of potential recruits, with the expectation that many would not be eligible based on the screening criteria. These outreach methods included:

- Informational postcards mailed to new homes within driving distance of the Newport offices (Figure 15)
- Email flyers

- Social media advertisements (Figure 16) targeting homeowners within a 50-mile radius of the Newport offices
- Project and contact information on the Newport company website.

Newport developed a project website; all outreach materials directed the recipients to this site, which contained further information about the study and linked to the online screening survey to determine eligibility. The online screening survey was followed by phone interviews and site visits to ensure that the participating homes and participants would be suitable for the field study.

4.1.2 Screening Criteria

To develop the online screening survey, Newport first developed screening criteria and identified certain responses that would disqualify a candidate. Survey respondents who met the minimum qualifications from the online screening survey were then contacted by phone to discuss more details about the study, answer additional questions to determine eligibility, and verify some of the responses from the online screening survey. The screening criteria included:

Home Characteristics

- Occupants own the home
- Occupants carry homeowners' insurance
- Home type is a single-family detached, duplex, or townhome
- Home is within driving distance to one of Newport's three geographical office locations
- Home size is 1,000 to 4,000 ft^2.

Occupant Behavior

- Cooktop is used at least four times per week, with preference given to daily usage
- Occupants confirm that they will be okay with keeping their windows shut during the test period and relying on mechanical ventilation whenever they need to exhaust stale air or provide fresh air
- Occupants report that there is no smoking inside the home
- Occupants agree to not operate a whole-house or "attic" fan during the test period
- Occupants agree to not operate air cleaners or leave the central fan in "on" mode during the test period. Instead, they agree to rely on mechanical ventilation, if present, whenever they need to exhaust stale air or to provide fresh air.

Existing Range Hood/Ventilation Appliances

- Homes must already be equipped with a range hood or an over-the-range microwave that is vented to the exterior (or located on or near an exterior wall[2]), and is manually controlled. There are no additional requirements for the existence or operation of other mechanical ventilation systems.
- Occupants report that they use their range hood or over-the-range microwave "as needed" or "rarely/never," and that they cook frequently.
- Existing range hood ducts must be ≥ 3.25" x 10" rectangular duct or ≥ 6" diameter round duct.
- Ranges or cooktops are a nominal 30" in width.

4.1.3 Site Verification Visits

Once a targeted pool of eligible participants was developed, Newport conducted site visits to verify criteria from the prior screening efforts. These were also an opportunity to record pretest-period measurements for air leakage and ventilation flow rates, and take inventory of the appliances and controls in the house relevant to the study. The pretest measurements and equipment inventory included:

- Verification that homes have a leakage rate of less than or equal to 7 ACH50 with an unguarded blower door test performed in accordance with RESNET/ICC 380, ASTM E779, or ASTM E1827.
- Taking photos and recording information on the types (model, make, and numbers where available) of heating and cooling appliances, ventilation systems, portable air cleaners, humidifiers, dehumidifiers, domestic water heaters, and cooking appliances. Recording and taking photos of any automated controls associated with these devices (e.g., occupancy, humidity-controlled, smart controls, minimum run time controls).
- Measurement of the airflow of exhaust systems in the kitchen, bathrooms, and laundry room and any whole-house mechanical ventilation systems in accordance with RESNET/ICC 380.
- Measurement of the ventilation flow rate of the existing range hood on each speed setting using a duct blaster configured as a flow hood, and mapped to a discrete anemometer reading. The discrete anemometer was left in place during the field study and used to map flow rates to those measured at the beginning of the study.

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[2] During the screening process it became evident that nearly all respondents did not have their existing range hoods vented to the outside. To expand the pool of potential participants, units that were located on or near an exterior wall were considered to be eligible, with the expectation that the existing fan would be re-ducted to the exterior.

- Recording and photographing the condition of the central air handler filter.

An example of the site verification checklist for each home is provided in Appendix D.

4.1.4 Participant Obligations

Participant obligations were presented to all eligible homeowners through online materials, phone calls, and in-person during the site verification visits. Newport representatives discussed all study requirements with each eligible homeowner, presented them with a consent form that outlined these requirements, and obtained a signed copy from each participant. The consent form provided permission to install monitoring equipment and the SRH during the test periods, outlined requirements/requests regarding occupant behavior during the test periods, and provided information on incentives homeowners would receive for their participation.

To evaluate the impact of the SRH during the field tests, and to accurately compare the results from the "existing period" (i.e., the first testing period with the homeowners' original/existing unit) to the SRH period (see Section 4.1.5 below), participants were asked to:

- Keep windows closed during the study, relying instead on central cooling and mechanical ventilation
- Not operate the central fan in "fan on" mode during the study, relying instead on mechanical ventilation to facilitate air changes
- Not operate discrete indoor air cleaners during the study, relying instead on mechanical ventilation, if present (does not include HVAC filters)
- Not operate the whole-house fan (if present) during the study; relying instead on air conditioning
- Leave the SRH to operate in auto mode
- Complete a cooking log (example shown in Figure 17) for each indoor cooking event, including cooking type, location of burners used, times at which the cooking event started and ended, and perception of the auto-operation of the SRH
- Cook the same meals during the existing period and the SRH period. Homeowners were financially incentivized to comply with this request. The rationale behind this incentive was that by recording indoor air pollutant concentrations during replicates of the same meal, it would be easier to isolate the effect of range hood operation on indoor air pollutant concentrations.

4.1.5 Test Configuration

Each home in the study was monitored for a two-week "as is" case test period using the existing home equipment (as mentioned above, referred to as the "existing period"). This was followed by an equivalent two-week test period with the SRH installed (the "SRH period"). For both test periods, sensors were installed to monitor IAQ, as well as temperature and run time for various cooking appliances and ventilation systems. Monitoring parameters are outlined in more detail in the next section. Locations of monitoring equipment within the homes varied due to differences in layout, appliances, and ventilation systems.

Two of the homes, "MD1" and "MD2," were located in Maryland. One home, "NY1," was located in New York. To remove cooking pollutants from the test homes, it was necessary to duct the SRH to the exterior. To provide better comparison across test periods, the test plan called for existing range hoods to also be ducted to the exterior. For homes in which the existing range hood was not vented to the outside (MD1 and MD2), Newport arranged for a licensed contractor to install a duct connecting the existing range hood to the exterior. The duct was sized to also accommodate the SRH to ensure that the duct was installed per manufacturers' specifications for both test periods.

At the start of both test periods, sensors were installed and launched to monitor various parameters. Homeowners were present during the installation of the sensors to make them aware of their location. At the conclusion of the existing period, Newport revisited the site to download the sensor data and relaunch the sensors for the SRH period. Newport had a licensed electrician remove the existing range hood and replace it with the SRH.

Two different base models were used for the SRH field testing to accommodate both under-cabinet and wall-mounted installations in the test homes. The under-cabinet model was the Glacier series, which was originally selected and modified for this project and was used in MD1 and MD2. The wall-mounted model selected was Broan's EW54, which did not meet the noise or fan efficacy targets for the project, but was selected for its ability to provide somewhat comparable performance to the Glacier and to be rapidly configured to accommodate SRH auto functionality.

At the conclusion of the SRH period, Newport again visited the site to download sensor data, remove all sensors and monitoring equipment, remove the SRH, and reinstall the homeowners' existing range hood, or a new one provided by Broan as an incentive for participating in the study. Homeowners completed an exit interview and received a cash incentive for their participation.

4.1.6 Monitoring Parameters

During the test periods, the homes were monitored for IAQ by recording time-resolved measurements of $PM_{2.5}$ and NO_2 using a Clarity Node in two indoor locations: the kitchen and a remote location on the level above the kitchen (either in an unoccupied bedroom or in an area such as a hallway). If located in an unoccupied bedroom, home occupants were asked to leave the bedroom door open. A Clarity Node was also installed at an on-site, outdoor location. Measurements of NO_2 were duplicated on a time-integrated basis at both indoor locations using

Ogawa samplers. Ogawa samplers were deployed for both the existing period and for the SRH period.

The combustion of natural gas by cooking appliances contributes directly to the concentration of indoor pollutants such as CO_2 and NO_2. As such, the natural gas consumption associated with cooking appliances was estimated by using a pulsing gas meter to record total gas consumption in the home and then adjusting the total gas consumption for the operation of other combustion appliances that happen to operate simultaneously. Operation of the central air conditioner, furnace, and the central air handling unit was monitored using motor on/off sensors and thermocouples, a device used to measure temperature. Gas water heater operation as well as cooking appliances (individual cooktop burners, oven, and toaster) were monitored using thermocouples.

All ventilation equipment in the home (bath and laundry room exhaust fans and the range hood) was monitored using anemometers, a device used to measure wind/fan speed. The range hood flow rate and operation were monitored with a data logging vane anemometer that was calibrated to match flows at each speed setting. See Appendix E for a list of monitored parameters and a description of the devices used for monitoring.

In addition to the data gleaned from monitoring equipment, homeowners were asked to keep a cooking log, shown in Figure 17. This prompted the homeowners to record food prepared on the cooktop or in the oven, and to include such details as start and end time of cooking event, the location of burners used, the type of cooking (baking, frying, etc.), and what food was prepared. The information collected through the cooking log was used to associate polluting events with certain types of cooking (e.g., frying, baking, broiling, boiling, etc.), corroborate cooking sensor data, record occupant satisfaction with SRH performance, and identify replicate cooking events. Cooktop burner location was recorded to help identify replicate cooking events and was not used to characterize the in-situ effectiveness of the hood under the operation of front versus back burners. Multiple studies have shown that range hoods are less effective in capturing pollutants that are generated by cooking on the front burners, and this research was not repeated here. During the SRH period, participants were also asked to give their perception of the auto-operation of the SRH (e.g., too long, too short, just about right).

Date	Time Start; Stop	Cooking Event Description	Comments on Operation of Smart Range Hood *(Circle Answers)*	Cooking Appliances Used	Cooktop Burners Used
3/21/2019	8:15 AM; 8:50 AM	Breakfast: pancakes, eggs, bacon. I forgot the bacon in the oven and burned it. Whoops! THIS ROW FOR EXAMPLE ONLY	**Time to start:** OK, too slow **Run time should be:** same, shorter, longer **Speed cycling:** OK, not acceptable **Loudness:** OK, too loud **Other:**	☒ Cooktop ☐ Oven ☒ Toaster ☐ Microwave ☐ Other:________	
			Time to start: OK, too slow **Run time should be:** same, shorter, longer **Speed cycling:** OK, not acceptable **Loudness:** OK, too loud **Other:**	☐ Cooktop ☐ Oven ☐ Toaster ☐ Microwave ☐ Other:________	
			Time to start: OK, too slow **Run time should be:** same, shorter, longer **Speed cycling:** OK, not acceptable **Loudness:** OK, too loud **Other:**	☐ Cooktop ☐ Oven ☐ Toaster ☐ Microwave ☐ Other:________	

Figure 17. Sample cooking log

4.2 Housing and Ventilation Characteristics

4.2.1 Selected Homes

As mentioned, Newport selected three homes for the study—two in Maryland and one in New York, each approximately 20 miles from Newport's offices. Several other homes that were visited also met the minimum requirements for the study, but these three homes were selected because they offered an accurate representation of the different home types, sizes, tightness (air leakage rate), and existing ventilation equipment that are commonly found in the existing housing stock. Additionally, these homeowners responded to various survey and phone interview questions with preferred answers related to occupant behavior. Preferred occupant behavior included:

- Homeowners who use their cooktops four or more times per week
- Homeowners who rarely/never use their current range hood
- Homeowners who rarely/never open their windows.

Upon finalizing the selection of homes, Newport obtained signed homeowner consent forms from all parties.

4.2.1.1 MD1

The first house in the study, MD1, was located in Anne Arundel County, Maryland. The home, an end-unit townhome, was just over 2,000 ft^2 with three floors, all above grade. The bottom floor, where the entrance of the home was located, included a half bathroom, clothes washer and dryer, and recreational area. The bottom floor also included an attached garage, which was not included in the overall square footage and volume when calculating the blower door test results. During the study, homeowners used the garage periodically to park a vehicle. No effort was made by the research team to determine the effect of the garage on indoor pollutant concentrations.

The second floor of the home was the main living floor, which included a family room, dining area, half bathroom, and kitchen. The home had a gas cooktop with oven underneath, and a wall-mount range hood installed above. Other cooking appliances included a toaster oven and microwave. The oven/range was located on the exterior wall and the range hood was vented directly to the outside. The third floor of the home included three bedrooms and two full bathrooms.

Table 4. MD1 Profile

Home Characteristics		
Home Type	Townhome (end unit)	
Home Size	2,057 ft^2	
Blower Door Test Results	6.9 ACH_{50}	
Range Hood	**Existing Range Hood**	**Smart Range Hood**
Make/Model	Ancona AN-1129X	Broan EW54
Type	Wall-mount	Wall-mount
Speed Settings	3 operational speeds	3 operational speeds
Tested Flow Rate (cfm)	Low: 182 Medium: 235 High: 267	Low: 163 Medium: 238 High: 298
Lighting	(2) 20W Halogen Lamps	(2) GU-10 Halogen Lamps
Noise Rating	Low: 6.3 Sones High: 14.2 Sones Ratings from manufacturer and not listed by HVI	Low: 1.3-1.5 Sones High: 10.5-12 Sones (expected to be lower in this application, because the high-speed setting was modified to provide a lower flow rate for the field test)
Other Existing Equipment		
Cooking Equipment	Range with cooktop (gas) and oven (gas), toaster oven (electric), microwave (electric), griddle (electric)	
Exhaust Fans	3 bathroom, 1 clothes dryer	
Water Heating	Gas-fired tank	
Space Heating	Gas-fired forced air furnace	
Air Conditioning	Central	
Occupant Behavior		
Occupants	2 adults, 1 child	
Window Operation	Rarely/never (agreed to keep closed during study)	
Smoking	None	
Range Hood Operation	Rarely/never (unless smoke is building up)	
Home Cooking	4–6 times per week	

4.2.1.2 MD2

The second home selected for the study, MD2, was also located in Anne Arundel County, Maryland. This home was a single-family detached home, and the largest home in the study at 3,300 ft^2. The home included three floors, two above grade and a basement. The top floor of the home had four bedrooms, one of them vacant and used as a spare room, and two full bathrooms. The basement of the home was finished and used primarily as a recreational area; it also included a home bar and a utility closet.

The middle floor served as the main living floor with kitchen, living room, dining room, office space, laundry room with washer and dryer, and half bathroom. The middle floor included an attached garage, which was not used to park any vehicles during the study. No effort was made by the research team to determine the effect of the garage on indoor pollutant concentrations. The home featured a gas range with an over-the-range microwave/hood unit above. Because the over-the-range unit was not on the exterior wall, it was vented to the outside through the cabinets. Other cooking appliances in the kitchen included an air fryer, toaster, and microwave.

Table 5. MD2 Profile

Home Characteristics		
Home Type	Single-family detached	
Home Size	3,300 ft^2	
Blower Door Test Results	5.0 ACH50	
Range Hood	**Existing Range Hood**	**Smart Range Hood**
Make/Model	Frigidaire FGMV174K	Broan Glacier Series: BCDJ130SS
Type	Over-the-range microwave with integral exhaust fan	Under-cabinet
Speed Settings	2 operational speeds	3 operational speeds
Tested Flow Rate (cfm)	Low: 114 High: 303	Low: 103 Medium: 183 High: 298
Lighting	(2) 20W incandescent lamps	(2) 3-level LED modules
Noise Rating	*Discontinued product. No sound rating available.*	Low: 0.3-0.6 Sones High: 5-6 Sones
Other Existing Equipment		
Cooking Equipment	Range with cooktop (gas) and oven (gas), toaster (electric), microwave (electric), air fryer/pressure cooker (electric)	
Exhaust Fans	3 bathroom, 1 clothes dryer	
Water Heating	Gas-fired tank	
Space Heating	Gas-fired forced air furnace	
Air Conditioning	Central	
Occupant Behavior		
Occupants	2 adults, 2 children	
Window Operation	Rarely/never (agreed to keep closed during study)	
Smoking	None	
Range Hood Operation	Rarely/never (unless smoke is building up)	
Home Cooking	4-6 times per week	

4.2.1.3 NY1

The third home in the study was located in Saratoga County, New York. This home was a single-family detached unit and the smallest home in the study at 1,940 ft^2. This two-story home was all above grade with the first floor serving as the main living floor and all bedrooms on the second floor. The second floor featured three bedrooms and two full bathrooms, and a small reading nook. The home had a detached garage.

The first floor served as the main living floor for the home and included the kitchen, dining area, recreational area, office space, a half bathroom, and a utility closet. In the kitchen was a gas range with a wall mounted range hood installed above. Because the cooktop and range hood were located on an exterior wall, the range hood was vented directly to the outside of the home. In addition to the cooktop and the range hood, the kitchen included a toaster and a microwave.

Table 6. NY1 Profile

Home Characteristics		
Home Type	Single-family detached	
Home Size	1,940 ft^2	
Blower Door Test Results	2.5 ACH50	
Range Hood	**Existing Range Hood**	**Smart Range Hood**
Make/Model	IKEA LUFTIG	Broan EW54
Type	Wall-mount	Wall-mount
Speed Settings	2 operational speeds	3 operational speeds
Tested Flow Rate (cfm)	Low: 169 High: 332	Low: 178 Medium: 269 High: 346
Lighting	(2) 2.5W LED Lamps	(2) GU-10 Halogen Lamps
Noise Rating	High: 7.3 Sones. Rating from manufacturer and not listed by HVI.	Low: 1.3-1.5 Sones High: 10.5-12 Sones (expected to be lower in this application, because the high-speed setting was modified to provide a lower flow rate for the field test)
Other Existing Equipment		
Cooking Equipment	Range with cooktop (gas) and oven (gas), toaster (electric), microwave (electric)	
Exhaust Fans	3 bathroom, 1 clothes dryer	
Water Heating	Gas-fired tankless	
Space Heating	Gas-fired hydronic radiant	
Air Conditioning	None	
Occupant Behavior		
Occupants	2 adults, 2 children	
Window Operation	Rarely/never (agreed to keep closed during study)	
Smoking	None	
Range Hood Operation	Rarely/never (unless smoke is building up)	
Home Cooking	4-6 times per week	

4.3 Test Results

The objective of the field evaluation was to measure the SRH effectiveness. Specifically:

1. Can the operation of the SRH substantially reduce air pollutant concentrations in homes with frequent cooktop operation, compared to the reference case of occupants electively and manually operating their existing kitchen exhaust system "as needed" or "rarely/never"?
2. What are the homeowner perceptions of the operation and effectiveness of the SRH?

4.3.1 Cooking Frequency and Type

Test sites were selected based on cooking frequency, with all participants confirming that they typically use their cooktop at least four times per week. The results confirmed this assertion, with participants averaging between 10 and 26 cooktop events per week; see Table 7. Cooktop-only events accounted for the majority in each case, and represented 66% of the total events observed across the three homes (103 of 156 events). Oven-only and oven-cooktop events also played significant roles, individually accounting for half of the remaining events (17% each). Average daily cooking statistics are provided in Table 8.

Although capable of responding to a wide array of air pollutants and polluting events, the SRH prototype was designed to respond specifically to cooktop events. This decision was made to prevent the SRH from activating in response to outside events, such as burnt toast, use of cleaning chemicals, over-microwaved popcorn, or operation of a vacuum cleaner; the objectives of limiting the SRH response were to improve user experience and reduce cycling triggered by events that could be unknown to the homeowner. However, based on the frequency of oven operation and the significance of associated increases in air pollutant concentrations, future versions of the SRH should be configured to respond directly to oven events in addition to cooktop events. Further discussion is included in Section 4.3.3.

Oven and cooktop cooking events were inferred using thermocouples with one-minute recording intervals. These thermocouples, which were external to the SRH and part of the study's data acquisition system, were placed in proximity to the cooktop burners (at the corners of the cooktop surface) and affixed with metallic tape to the oven air outlet. An algorithm was used to associate increases in temperature with burner or oven operation. Events were determined to end when thermocouples registered a sustained decrease in temperature.

Two types of logging thermocouples were deployed in the study to measure cooking temperatures: iButtons and Onset's UX-100-014M thermocouple with an external, type K thermocouple. Both are comparable in price. iButtons were initially chosen based on a much smaller form factor (less intrusive in field studies than other options), wireless functionality, and recommendations from fellow researchers. Unfortunately, two iButtons failed during the study—each was monitoring a heavily used front burner. Failure was likely caused by boiling-over or spillage of liquid on the devices. In both cases, the associated burner operation was estimated from observations of adjacent iButtons and through confirmation from the cooking logs. Although the Onset devices had a larger form factor than the iButtons, they were more reliable because they used external, wired thermocouples. During the field test, the Onset's thermocouple wires were affixed to the range using metallic tape, and loggers were tucked behind the cooktop to maintain a visually clean and functional installation.

Table 7. Cooktop and Oven Events in Field-Monitored Homes

	Cooktop Events			Combined Cooktop and Oven Events			Oven Events			Total Events	
Site	Existing	SRH	Total	Existing	SRH	Total	Existing	SRH	Total	Existing	SRH
MD1	12	8	20	3	6	9	1	8	9	16	22
MD2	19	11	30	4	3	7	8	3	11	31	17
NY1	26	27	53	6	5	11	4	2	6	36	34
Total	57	46	103	13	14	27	13	13	26	83	73

Table 8. Average Daily Cooking Statistics. Toasters were present but not monitored at MD2 or NY1.

Cooking Parameter	MD1		MD2		NY1	
	Existing	SRH	Existing	SRH	Existing	SRH
Average daily cooktop cooking time (minutes)	16	19	30	29	34	30
Average daily oven cooking time (minutes)	12	39	34	22	29	24
Average daily toaster oven cooking time (minutes)	18	9	--	--	--	--

4.3.2 Range Hood Operation

The SRH demonstrated rapid and consistent responsiveness to cooktop events, turning on within one minute or less of an event's beginning, as confirmed by thermocouple and anemometer readings (minimum data resolution was one minute). This finding aligns well with the lab testing results showing SRH response time of about 30 seconds for most cooktop events. Across two sites, NY1 and MD1, the SRH responded to 93% and 100% of all cooktop events. There were two missed events across approximately four weeks of operation. The two missed cooktop events, both occurring at NY1, were boiling water for coffee, which averaged 15 minutes in duration and resulted in a relatively minor increase in NO_2 and $PM_{2.5}$ concentrations in the kitchen.

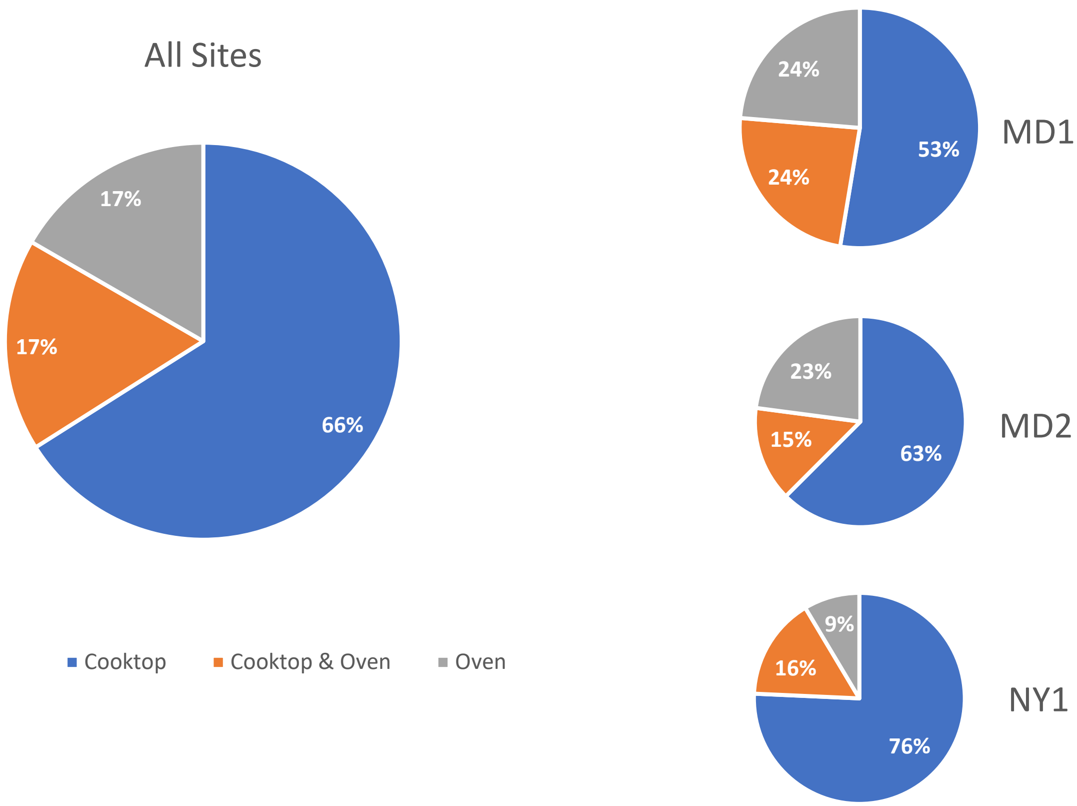

Figure 18. Cooktop and oven events as percent of total across SRH and existing periods

Operational data for the SRH at MD2 were not available due to anemometer sensor failure at that location. This could have been because of the challenging environmental conditions (e.g., high dry-bulb temperature and moisture content) experienced above the cooking surface, though such conditions were also present in MD1 and NY1, with no anemometer failure.

The responsiveness and frequency of operation for the SRH compared favorably to manual operation of the existing range hoods for MD1 and NY1. Elective use of the range hood in the existing period was limited and generally inconsistent. For example, the existing hood for MD1 was operated for 0% of cooktop events. For NY1, the existing hood was operated for 15% of cooktop events, and when operated, the average time to activate the range hood after the start of a cooking event was 8 minutes (with a range of less than one minute to 17 minutes). Delaying operation or not operating the existing hood led to higher pollutant concentrations than would otherwise be experienced under an auto response setting. Conversely, auto operation of the SRH resulted in more consistent range hood response and run times. Also, the SRH operated for longer durations than the existing hood when compared to cooktop burner operation.

Across the two homes reporting range hood run time, the median ratio of range hood run time to burner run time during cooktop events was 2.3 under the operation of the SRH (35 events) and zero under the elective operation of the existing hood (38 events). More than half of the run time events of the SRH associated with cooktop-only events had a hood-to-burner run time ratio of 2 or greater; in other words, the SRH started within the first minute of operation of the cooktop and ran for at least twice as long as the cooktop for more than half of the cooktop events. See Table 9 through Table 11 for detailed information. MD2 was excluded from the analysis of data reported in these three tables due to lack of available data resulting from anemometer failure.

Table 9. Ratio of Hood-to-Cooktop Burner Run Time at MD1 and NY1

Hood to Burner Run Time Ratio	Percent of Cooktop Events	
	Existing	SRH
0	89%	6%
0-1	0%	17%
1-2	0%	23%
2-3	0%	34%
3-4	3%	9%
4-5	3%	3%
5-6	3%	3%
6-7	0%	0%
7-8	0%	0%
8-9	0%	6%
9-10	3%	0%
Median	0.0	2.3
Total Events	38	35

Table 10. Range Hood Run Time as a Function of Cooktop Burner Run Time (MD1 and NY1)

Cooktop Burner Run Time (minutes)	Existing Hood		SRH	
	Events	Median Run Time (minutes)	Events	Median Run Time (minutes)
0-5	1	0	1	14
5-10	10	0	8	20
10-15	21	0	13	25
15-20	1	87	4	21
20-25	3	0	5	51
25-30	0	--	3	27
30-35	0	--	0	--
35-40	1	124	1	23
40-45	0	--	0	--
45-50	0	--	0	--
50-55	0	--	0	--
55-60	1	0	0	--
Cooktop Burner Operation: All Events	38	12	35	12
Hood Operation: All Events	4	0	33	25

Table 11. Range Hood Operational Statistics

Range Hood Operation Parameter	MD1		NY1	
	Existing	SRH	Existing	SRH
Percent of cooktop events where range hood was activated	0%	100%	15%	93%
Average delay in activation of range hood after start of cooktop event, when range hood was activated for an event (minutes)	--	< 1	8	< 1
Average daily range hood operation L=low, M= medium, H=high (minutes)	L: 0 M: 2 H: 1	L: 10 M: 14 H: 12	L: 7 M: N/A H: 87	L: 28 M: 63 H: 31
Average daily range hood air volume exhausted (MCF)	1	9	30	33

4.3.3 Air Pollutant Concentrations

4.3.3.1 Considerations for IAQ Sensor Utility

Indoor air pollutant concentration measurements were compiled using equipment providing time-integrated and time-resolved data. A Clarity Node was specified to provide indoor and outdoor time-resolved measurements of several pollutants, with the focus being on NO_2 and $PM_{2.5}$. The Node's manufacturer specifications report greater than 0.8 R^2 correlation to a $PM_{2.5}$ FRM instrument, and an accuracy of ± 10 µg/m3 for readings less than 100 µg/m3 and ± 10% for readings exceeding 100 µg/m3. The Node's NO_2 sensor is reported to have an R^2 correlation to an FRM instrument exceeding 0.7 with an accuracy of ± 30 ppb for readings less than 200 ppb, and ± 15% for readings exceeding 200 ppb.

The Node provides measurements at intervals of 2–3 minutes, so it was necessary to process the data to estimate readings at one-minute intervals. Data were postprocessed by a method discussed with Clarity's technical support team and LBNL. The process involved zeroing out the lowest 10% of the readings and then applying a multiplier to the remaining readings until the time-integrated value of the Clarity NO_2 data were equivalent to the time-integrated data of the Ogawa passive NO_2 samplers. No additional calibration was applied to the Clarity's $PM_{2.5}$ sensors. All things considered, the resolution and accuracy of the Clarity's NO_2 and $PM_{2.5}$ sensors as deployed in this study were sufficient to characterize air pollution events, especially in relative terms, but were not meant to provide definitive absolute values.

4.3.3.2 $PM_{2.5}$ Concentration Profiles

$PM_{2.5}$ is widely viewed as a major cooking pollutant in terms of negative health impact. Data collected from the field study, however, showed that reduction in $PM_{2.5}$ concentration was not a reliable metric for comparing performance of the SRH versus the kitchen exhaust in the existing period. In general, $PM_{2.5}$ concentration resulting from cooking events depends upon the type of cooking; the temperature and duration of cooking; the cleanliness of the cooking burners, grates, and vessels; and so on. This finding is consistent with monitoring results for $PM_{2.5}$ in the lab testing, where even highly standardized replicate tests showed variability in concentration levels. Although the lab tests did show a clear benefit for the SRH in reducing $PM_{2.5}$ concentration, the time-integrated $PM_{2.5}$ mass concentration sometimes varied by a factor of up to 3 (see Figure 7). Additionally, sources of $PM_{2.5}$ are not confined to cooking, and some of the largest $PM_{2.5}$ events seen in the study's kitchens were not associated with cooking. Occupants kept a cooking log, but did not keep a log of other pollutant-generating events (such as burning candles or vacuuming), so the source of the noncooking $PM_{2.5}$ events is unknown.

Within this project's field study, measurements of kitchen $PM_{2.5}$ were taken on a counter several feet away from the cooktop/oven to provide a general kitchen reading after some amount of mixing. Each field study kitchen was well-coupled to adjacent spaces, with large openings facilitating pollutant distribution. Pollutant concentrations at the cooktop/oven are expected to be much higher than that reported several feet away. In fact, data from the Fortmann study (2001) show that a cook's exposure can be 4–5 times that experienced elsewhere in the kitchen. Of the three homes monitored in this study, the highest recorded kitchen $PM_{2.5}$ concentrations resulting from cooking occurred at MD1, where operation of an electric griddle resulted in $PM_{2.5}$ concentrations exceeding 600 µg·m-3. Operation of the toaster oven and preparation of burgers on the cooktop also registered high $PM_{2.5}$ concentrations in MD1 (250–300 µg·m-3). The monitored $PM_{2.5}$ concentration at NY1 was less severe, with only one event (burning rolls in the oven) exceeding 100 µg·m-3 Figure 19 through Figure 22 provide an overview of major cooking events, with meal descriptions as recorded in occupant cooking logs, and associated pollution concentrations during the SRH and existing periods at MD1 and NY1. For each of these figures, range hood operation is indicated by a value of 1 (on) or 0 (off).

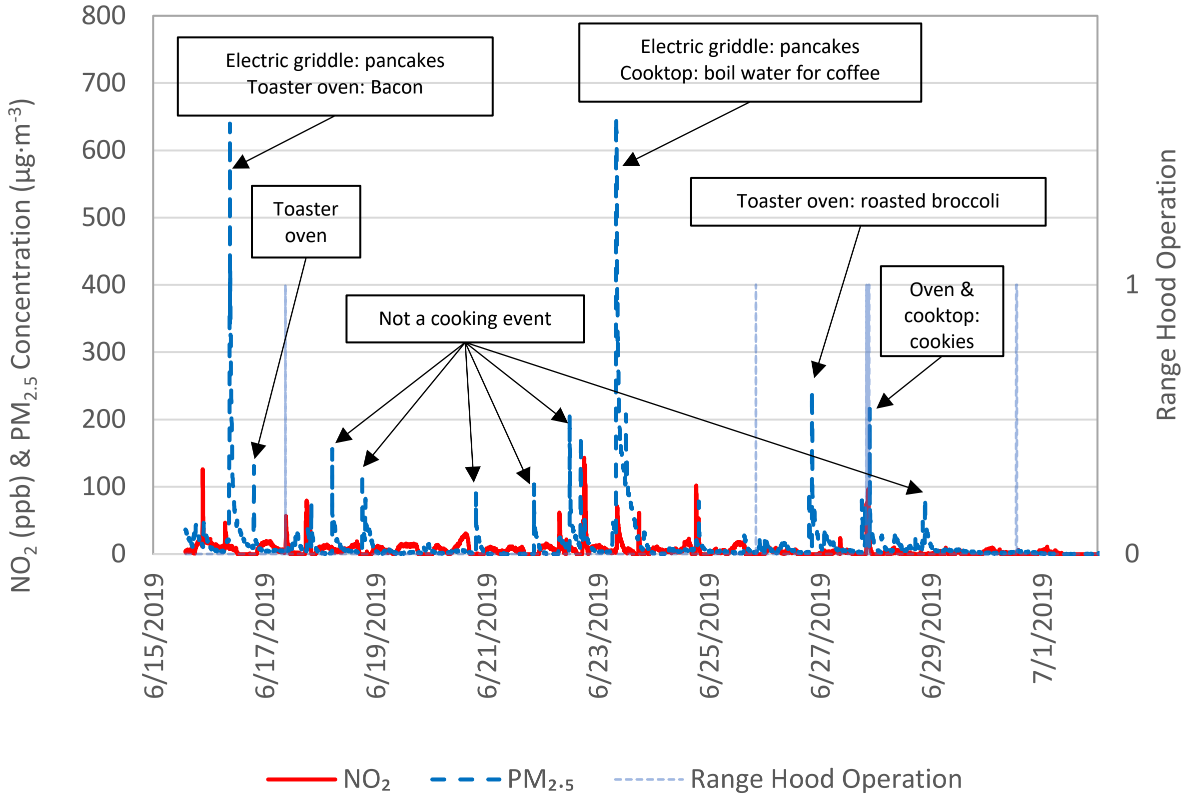

Figure 19. MD1 existing period: kitchen $PM_{2.5}$ and NO_2. Very little elective use of the range hood was observed, and its timing was rarely coordinated with high-polluting events. The largest polluting events occurred from the operation of the electric griddle and toaster oven, although causes other than cooking also contributed significantly to pollutant concentrations in the kitchen.

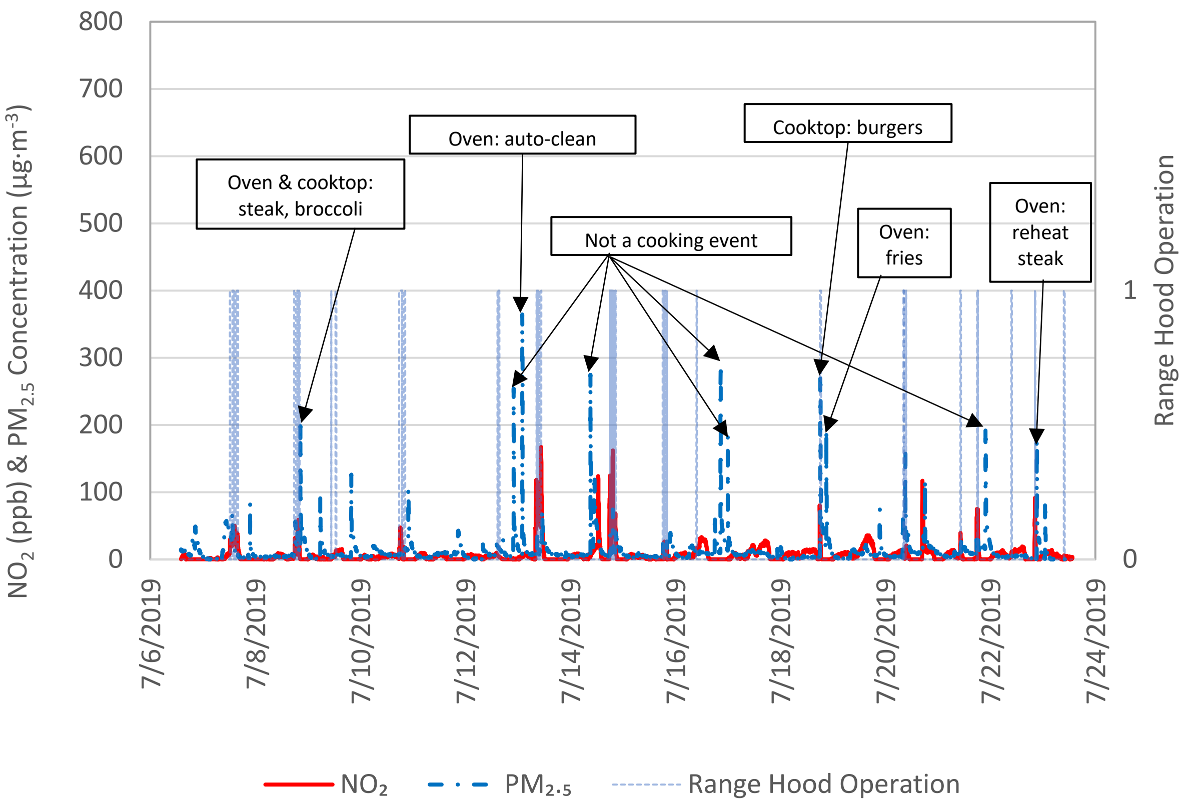

Figure 20. MD1 SRH: kitchen $PM_{2.5}$ and NO_2. Causes other than cooking (including oven auto-cleaning) accounted for most of the significant polluting events, though use of the cooktop (burgers) and oven (fries, steak, and broccoli) also were significant events. The pollutant contribution from cooktop-only events, which the SRH prototype was designed to directly address, was relatively minor.

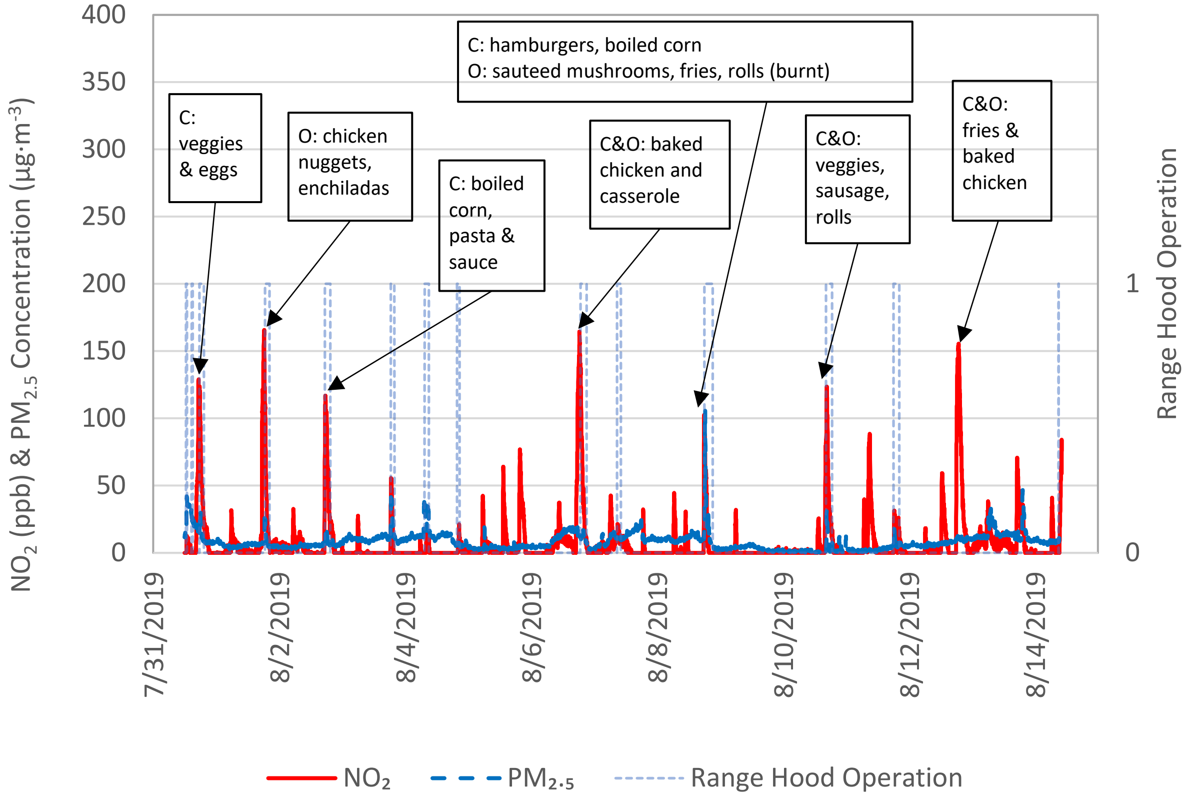

Figure 21. NY1 existing period: kitchen $PM_{2.5}$ and NO_2. "C" = cooktop. "O" = oven. In most cases, $PM_{2.5}$ concentration was not excessive. Five of the largest seven polluting events, each of which exceeded NO_2 concentrations of 100 ppb, were associated with oven operation.

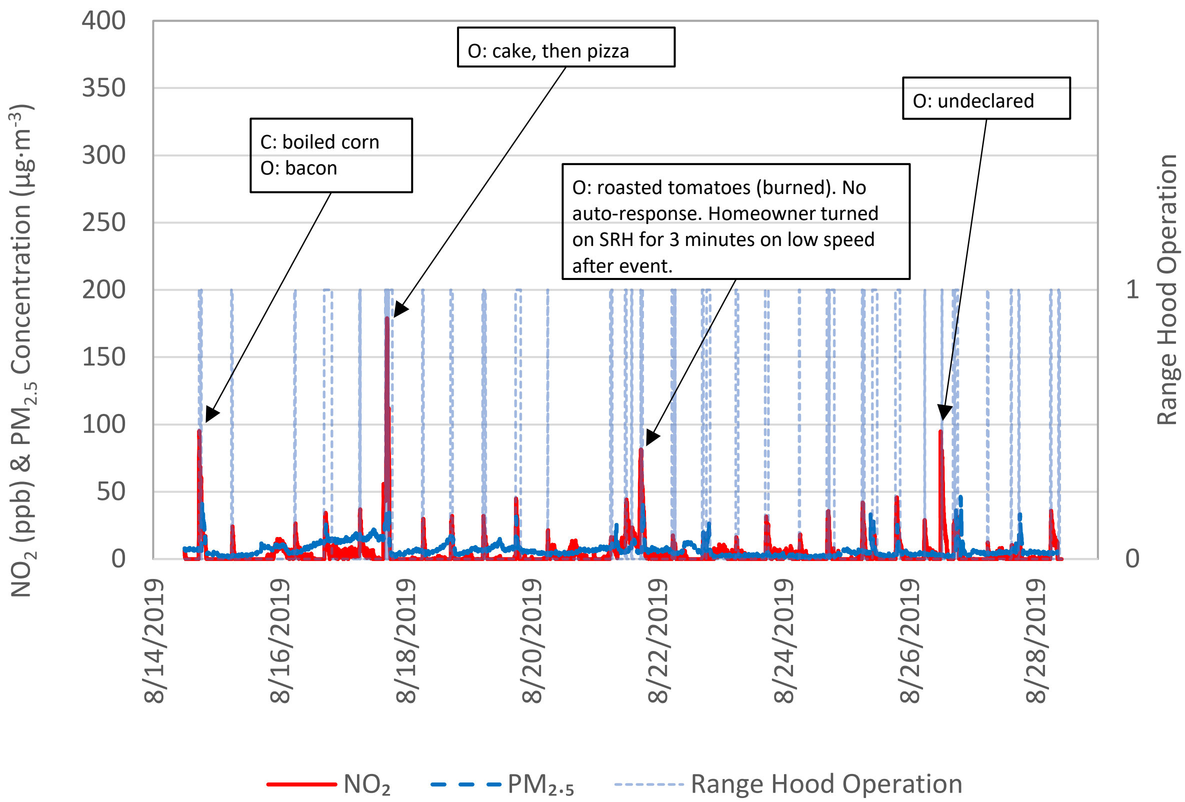

Figure 22. NY1 SRH: kitchen $PM_{2.5}$ and NO_2. "C" = cooktop. "O" = oven. In most cases, $PM_{2.5}$ concentration was not excessive. The largest NO_2 concentrations were associated with oven operation, for which the SRH prototype was not designed to respond. NO_2 exceeded 100 ppb in only one case, and that was during an oven-only event.

4.3.3.3 NO_2 Concentration Profiles

For experimental control and to assist in isolating the performance of the SRH from the existing hood, occupants were asked to replicate cooking events across both two-week periods. Participants were offered $20 for each replicated event (up to $200) in addition to the $300 given for participation in the study. Despite this incentive, replicate events were difficult to identify within the data set, and, when present, often had a large amount of variability in their results. For example, the NY1 homeowner recorded six water boiling events in the existing period and six water boiling events for the SRH period, each for making coffee at breakfast. The profile of the NO_2 concentrations during and after the cooking events were similar, with a rapid rise followed by a decay, but the NO_2 concentrations identified were very low (frequently less than the accuracy of the Clarity Node), and there was too much variability in the results to provide any meaningful conclusions with respect to the performance of the different hoods (see Figure 23).

Despite the aforementioned limitations with the sensors and the challenges associated with variability in occupant cooking behavior, improvement in kitchen air quality was observed under the operation of the SRH. For example, Figure 24 illustrates a replicate dinner event at NY1 involving both cooktop and oven use. This replicate event shows a time-integrated NO_2 concentration for the SRH case that is about a third of what was seen in the existing case. Both cases used the range hood, but the SRH began operating almost immediately, whereas the existing hood was not started by the homeowner until about 17 minutes after the start of the cooking event, which began at minute 10 in Figure 24. Besides the delay in operating time, some of the increase in NO_2 for the existing case could also be related to differences in capture efficiency resulting from two front burners being used for the existing case (versus one front and one back for the SRH) and higher average cooking temperatures during the existing case.

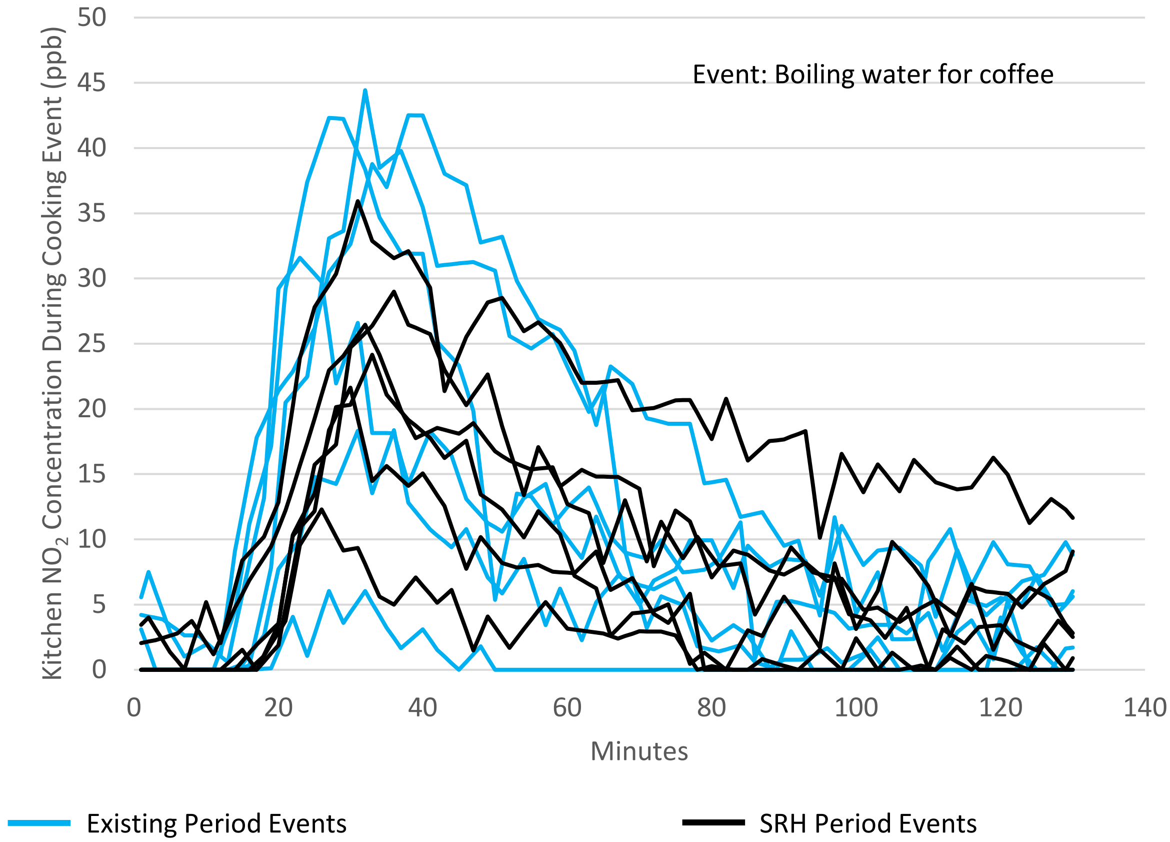

Figure 23. Kitchen NO_2 concentration during NY1 replicate event: boiling water for coffee. “Ex” = existing period event. “SRH” = SRH period event.

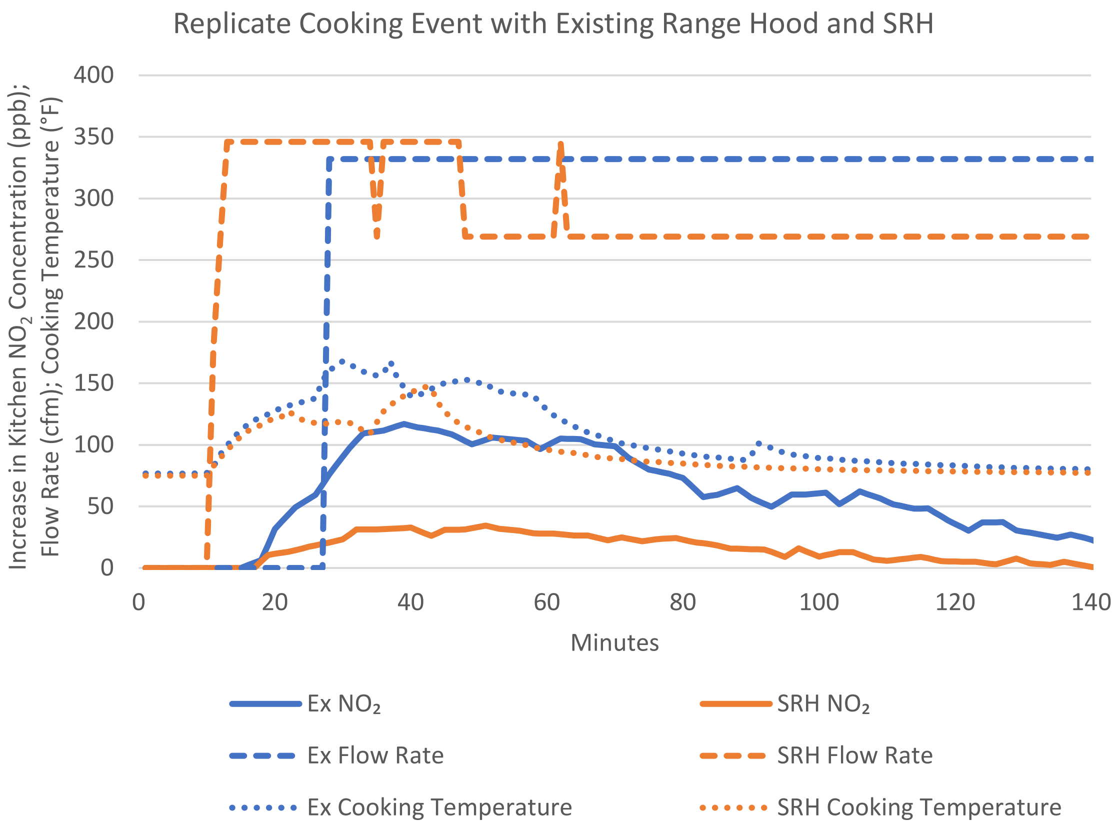

Figure 24. NY1 replicate cooking event: boiled pasta, sautéed pasta with tomato and olives, and boiled corn on the cob. Cooking temperatures are the average across cooktop and oven exhaust thermocouples.

Generally, across the three homes monitored, the kitchen NO_2 peak concentration was mitigated under the operation of the SRH during cooktop events. The median difference between the NO_2 peak associated with a cooktop event and the background NO_2 in the kitchen preceding the event was reduced by 40% under the SRH period (46 events) versus the existing period (57 events). Further, the frequency of extreme NO_2 events was also reduced under operation of the SRH across all three homes, with zero SRH cooktop events exceeding a 100 ppb increase from the background NO_2 concentration, and five cooktop events in the existing case exceeding a 100 ppb increase from the background NO_2 concentration.

Full-period NO_2 concentration data provided little clarity in terms of the ability of the SRH to reduce gaseous pollutant concentrations. This was influenced by multiple factors, including significant and sometimes disproportionate operation of the oven across the SRH and existing periods, to which the SRH prototype was not designed to respond. For example, at MD1, the time-integrated NO_2 concentration for the existing period was approximately 30% less than for the SRH period. However, a closer examination of the oven run time data show that the existing period average daily oven run time was less than a third of the daily oven run time during the SRH period. Additionally, MD1 was unoccupied for several days during the existing period while the homeowners were on vacation, reducing background NO_2 levels that would have otherwise been established through other cooking events. The test homes were in areas with relatively good outdoor air quality, with outdoor NO_2 concentration ranging from 1–4 ppb. By comparison, the annual outdoor NO_2 level in a U.S. urban setting can be more than three times the upper end of this range. A summary of time-integrated pollutant concentrations is provided in Table 12.

Table 12. Full-Period, Time-Integrated Pollutant Concentration Under Existing and SRH Periods for Each of Three Sites

Full-Period, Time-Integrated Pollutant Concentration	MD1		MD2		NY1	
	Existing	SRH	Existing	SRH	Existing	SRH
NO_2, kitchen (ppb)	5	7	8	3	8	5
NO_2, outdoors (ppb)	3	3	4	2	2	1
$PM_{2.5}$, kitchen (µg/m3)	11	11	9	7	8	7
$PM_{2.5}$, outdoors (µg/m3)	15	17	18	18	13	9

4.3.3.4 Indirect Response to Oven Events

The SRH prototype used in the field tests was designed to respond to cooktop events, with responses to oven events occurring only coincidentally or through misdiagnosis of an oven event (e.g., when the cooktop surface became hot enough from extended use to trigger the SRH algorithm to attribute sensed air pollutants to a cooktop event; see Figure 25). Oven events accounted for some of the largest NO_2 and $PM_{2.5}$ pollutant concentrations produced by cooking events seen across the sites (see Figure 19 through Figure 22).

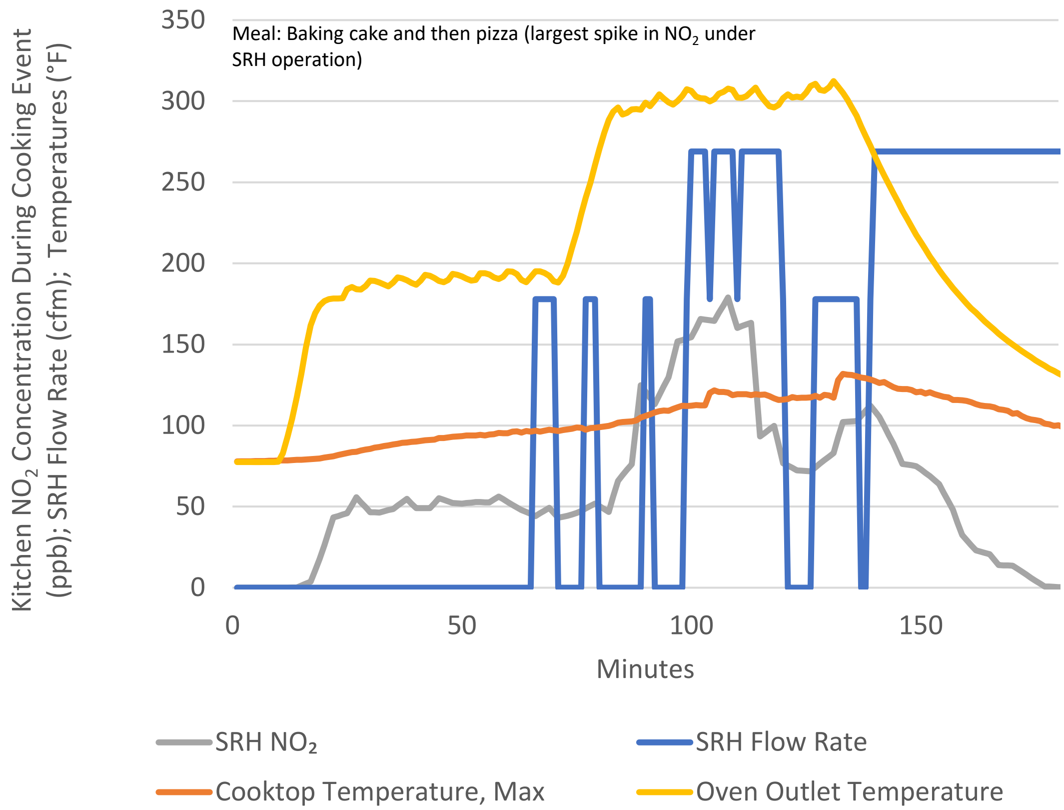

Figure 25. NY1 oven event: cake and pizza. This figure shows the response of the SRH to a sequential oven event (the SRH was not designed to respond to an oven event). It did activate after about one hour, showing some success in reducing NO_2 concentration, but the response was somewhat sporadic, as shown by the variability in cycling between speeds. To better control pollutant concentrations in the kitchen, future generations of the SRH should be designed to respond directly to oven events.

4.3.4 Homeowner Experience

At the conclusion of the SRH period, homeowners were given an exit interview to better understand their perceptions of and experiences with the SRH prototype. Participants were asked to compare the SRH to their existing units, identify what they liked and disliked about the prototype, and rate their experience and likeliness to purchase it.

4.3.4.1 SRH vs. Existing Range Hood

Homeowners were asked to compare the SRH to their existing unit relative to three key attributes: removal of smoke and odors, lighting, and quiet operation. Overall, homeowner perception along these three attributes was positive toward the SRH. When it came to removing smoke and odors and lighting, all homeowners indicated that the SRH performed better than their existing unit. Results varied with regard to noise. Table 13 summarizes the results from these comparison questions.

It is important to note that the perception of the SRH, specifically with regard to lighting and noise, largely depends on the specifications and use of the participant's existing range hood and the model used for the SRH replacement. As outlined previously, the three participating homes had a variety of existing range hoods installed. Also, two different base models were used for the SRH field testing to accommodate both under-cabinet and wall-mounted installations in the test homes. The under-cabinet SRH model was the model originally selected and modified for this project. The wall-mounted SRH model, the EW54, did not meet the noise or fan efficacy targets for the project, but was the closest fit available from Broan's product line that could be rapidly configured to accommodate SRH auto functionality. The loudness ratings of the EW54 were approximately two to three times that of the Glacier on high speed and low speed, respectively, but the low-speed sone rating was far lower than the 3 sone maximum permitted by ASHRAE 62.2 at 0.1 inches of water, meaning the EW54 was still considered a relatively quiet hood when operated on low speed. To reduce the loudness of the EW54's high speed for the field study, Broan's engineers reduced the high-speed flow rate by approximately 200 cfm. The unit was not laboratory tested for noise at this modified setting. Despite this effort, the loudness of the range hood was a complaint of one of the homeowners who participated in the study.

Table 13. Homeowner Perceptions of the SRH as Compared to Their Existing Kitchen Exhaust Unit

Site	Ability to Remove Smoke and Odors	Lighting	Noise
MD1	Significantly better	Significantly better	Significantly better
MD2	Significantly better	Better	The same
NY1	Better	Significantly better	Worse

Table 14. Comparison of Rated and Installed Performance of the Two SRHs Used in the Field Test (sone results are not available for the installed case because they are a laboratory metric)

Parameter	Glacier Series		EW54	
	Rated	Installed (MD2)	Rated	Installed (MD1 and NY1)
Sones at low speed	0.3–0.6	N/A	1.3–1.5	N/A
Low-speed flow (cfm)	150–160	103	180–200	163–178
Sones at high speed	5–6	N/A	10.5–12 (expected to be lower in this application, because the high-speed setting was modified to provide a lower flow rate for the field test)	N/A
High-speed flow (cfm)	348–400	298	484–550 (modified to provide a lower flow rate for the field test)	298–346

4.3.4.2 Homeowner Likes and Dislikes

Homeowners were also asked what they liked and disliked about their experience with the SRH. The convenience factor of not having to remember to turn it on and having it shut off automatically was mentioned by two of the participants as a positive feature. Other features that homeowners liked about the prototype was the noise level, the lighting quality, and its ability to remove odors from the home quickly. In two cases homeowners indicated they noticed a change in the air quality in their home as a result of the SRH operation, while the third could not determine whether the air quality had changed in their home.

One of the more significant issues participants had with the SRH was related to the cycling between fan speeds during cooking events. Although each noted that the fan would change speeds relative to the type of cooking, temperatures, and smoke/odors, they also each said that it happened too frequently. One homeowner noted, "A few times it cycled up and down (and beeped) 15+ times during cooking. It was too indecisive." Similarly, another homeowner noted, "It couldn't ever decide on a speed and would continuously adjust." The noise from the fan speed cycling, described as a "beep" or a "click," was annoying to the participants.

4.3.4.3 Range Hood Operation

Overall, the SRH was perceived by the homeowners to work as advertised. For more than 90% of cooking events that took place on the cooktop, the SRH turned on automatically, ran for a period of time, and shut off on its own once the cooking event had ended. In some instances, the SRH turned on for no apparent reason, or would not turn on—which generally was tied directly to cooking in the oven rather than on the cooktop. These were not common occurrences, but as one homeowner noted, "It seemed a bit random. It would always turn on when I boiled water for coffee, but cooking bacon in the oven didn't turn it on." Others noted similar experiences. The overall sense, though, was that the SRH worked as intended.

Given their two-week test period experience with the SRH, homeowners were asked to rate their experience on a scale of 1 to 10, based on the likelihood that they would buy one when/if they were available, and what cost premium would they be willing to pay for the new technology. Two of the homeowners (MD1 and MD2) had high ratings for the SRH from their experience, 10 and 8 respectively, and indicated they would likely purchase one as long as the cost premium was not too high. NY1 was a recently built custom home with a modern range hood. The SRH prototype benefits were marginalized by their existing model, frequency of manual use of their existing model, and the sound of the SRH cycling. As such, NY1 provided a rating of 5 for the SRH.

4.3.4.4 Homeowner Recommendations

Homeowners were asked to provide any recommendations on improving the prototype. The primary recommendation was directly related to the fan cycling issues described above. The "beeping" or "clicking" coupled with frequent cycling between speeds was the most significant concern for each of the homeowners. They suggested a preference for modes that slowly ramped speeds up or down rather than the clicking and sudden change. One said, "[It] reminded me of an old standard transmission."

Another suggestion was running the fan at low speeds for longer, rather than sudden bursts at high speeds. "The lowest setting was pleasant. I would prefer it to run for 10 minutes at low speed over 2 minutes at the highest volume."

Lastly, one homeowner suggested the addition of an "airplane" or "quiet" mode so that others in the house would not be disturbed, should cooking take place in the early morning or late at night. "When I would boil water at 5:30 a.m. with kids sleeping, it was sudden and loud; it actually woke people up."

Another suggestion, not related to the speed cycling issue, was to have the SRH connect to an app that would provide feedback to the homeowner. The app would let the homeowner know what the range hood is sensing and provide some insight as to why and for how long the hood operates. Introducing the homeowner to more information on the benefits related to IAQ would help them understand what cooking pollutants are present and being addressed by the operation of the SRH during various cooking events.

5 Summary and Conclusions

This project resulted in the successful development and demonstration of an SRH. Controlled lab testing demonstrated that the SRH achieved project goals with respect to rated performance (energy efficacy, capture efficiency, noise), indoor air pollutant mitigation, and responsiveness to cooktop events (ability to successfully identify events, minimization of delay until start). The field tests also demonstrated that the SRH could effectively operate during real and various cooking events in occupied homes.

Rated performance was achieved with a Broan production model hood with a midrange price point—showing that top-tier performance can be widely accessible. Further, as LBNL test data of the SRH demonstrated, a range hood combined with low-cost environmental sensors and an intelligent control is highly effective at reducing kitchen-generated pollutant concentrations (64% to 94% reduction across key pollutants).

Reduction of pollutant concentration was also observed in the field study, where the median difference between the NO_2 peak associated with a cooktop event and the background NO_2 in the kitchen was reduced by 40% under the SRH period versus the existing range hood period. Further, the frequency of extreme NO_2 events was reduced under operation of the SRH across all three homes, with zero cooktop events exceeding a 100 ppb increase from the background NO_2 concentration the SRH period and five cooktop events exceeding a 100 ppb increase from the background NO_2 concentration in the existing range hood period.

Within the field study, full-period, time-integrated indoor NO_2 concentration was sometimes lower under the operation of the existing hood than under the operation of the SRH. The reason for this is unknown but could be attributed to such factors as outdoor concentration, the presence of an attached garage in the case of MD1, backdrafting of natural draft appliances (unknown), and differences in total natural gas consumed for cooking under existing versus SRH periods. Reduction in $PM_{2.5}$ concentration was not a reliable metric for comparing performance of the SRH versus the kitchen exhaust in the existing period. $PM_{2.5}$ concentration is a factor of noncooking events, which produced some of the largest concentrations seen in the study, and cooking events where $PM_{2.5}$ concentration is affected by the type of cooking; the temperature and duration of cooking; the cleanliness of the cooking burners, grates, and vessels; and so on. There was not sufficient control in the field study to develop conclusions regarding the effectiveness of the SRH in mitigating $PM_{2.5}$.

Although homeowners participating in the field tests were generally pleased with the performance of the SRH, they did have a few suggestions to improve the SRH. Most suggestions were targeted at reducing the noise associated with the operation of the SRH. Two suggestions in this regard could be achieved relatively easily: eliminating a clicking noise heard while cycling between speeds and providing a “quiet mode” that would only use the lowest one or two speeds when engaged. Both of these suggestions could likely be achieved through modifications to the control hardware and control logic without triggering a need to modify the sensor array.

Another homeowner suggestion was further smoothing the SRH response to avoid frequent changes in speed. Smoothing the SRH response is expected to improve user acceptability, but it can also have the effect of reducing the responsiveness of the SRH to real-time variations in pollutant concentrations. This was a known issue during the development of the prototype, and much effort was dedicated to optimizing the response of the SRH prior to its deployment for the field study. The field study provided a wider spectrum of cooking scenarios than considered during the prototype design phase, especially scenarios involving oven use. The variation in scenarios presented a challenging environment to the SRH control and revealed that further revisions need to be made to the control algorithm to smooth the response while maintaining responsiveness and minimizing pollutant concentrations.

Though not suggested by the homeowners, modifying the SRH to respond more directly to oven events is an additional modification that has the potential to greatly decrease homeowner pollutant exposure, especially because many homeowners may not consider operating their range hood during oven events. Across the field study's small sample set, the oven was used in 34% of the total cooktop and oven events. Run time for oven events comprised 43%–67% of the total kitchen range (i.e., cooktop and oven) run time across each period of the field study. Pollutant concentrations associated with oven events were among the highest seen across the three sites.

A surprising finding from this study was that some of the largest $PM_{2.5}$ concentrations seen in kitchens were not related to the use of the cooktop or oven. Use of a remotely located toaster oven was observed to significantly increase $PM_{2.5}$ concentrations. At MD1, use of an electric griddle resulted in $PM_{2.5}$ concentrations exceeding that produced by running the gas oven on an auto-clean cycle. At MD1, events that could not be correlated to cooking were responsible for roughly half of the highest-registered concentrations of $PM_{2.5}$. If the homeowners had elected to operate their bathroom exhaust fans to provide the minimum dwelling unit ventilation required by ASHRAE 62.2, background concentrations of $PM_{2.5}$ and other pollutants would likely have been lower. Even so, these data suggest that there is merit to configuring the SRH to respond to remote cooking events and high polluting events that are experienced in the kitchen but not associated with cooking, a change that could be made by adjusting the SRH control algorithm at relatively small cost.

Future work in developing the next generation of the SRH should focus on incorporating these modifications and determining their effect on occupant acceptance and pollutant exposure. For example, participants noted that the high-speed setting of the SRH prototype (rated at 5–6 sones for the under-cabinet model) was often perceived as too loud. The low-speed setting of the SRH prototype (rated at 0.3–0.6 sones for the under-cabinet model and 1.3–1.5 sones for the wall-mounted model) received no complaints. Future work should explore the maximum rated sone level that is generally acceptable to occupants, especially when auto-responding. However, achieving lower sone levels might require lower fan speeds and/or lower airflow rates, which could result in lower capture efficiency and higher pollutant concentrations. Future field studies should increase the sample size, expand the study to include locations with poor outdoor air quality, and normalize the kitchen air pollution as a function of natural gas consumed for cooking. These measures would help to better isolate the effects of cooking on indoor air pollutants and of range hood operation on its ability to mitigate them. Although more laboratory and field work are needed to co-optimize the SRH design in terms of user acceptability and pollutant exposure, the first generation showed good promise for the technology. DOE's investment in this technology has validated the performance of a prototype SRH and helped to facilitate the delivery of this innovation, and its benefits to occupants, to the market. Within a few years it seems likely that U.S. consumers will have multiple options for smart range hoods that are a vast improvement over the status quo for domestic kitchen exhaust and that deliver significant IAQ benefits with improved range hood performance for occupants.

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Appendix A

Characteristic	NO_2	CO	$PM_{2.5}$	Ultrafines	VOCs
Description	Gaseous and toxic by-product of combustion	Gaseous and toxic by-product of combustion	Particles < 2.5 µm in diameter	Particles < 0.1 µm in diameter	Organic compounds that are easily volatized
Health Effects	Respiratory irritant and aggravant of respiratory diseases, including asthma. Can be a precursor to ozone and PM.	Chronic: linked with increase of heart disease (CDC 2018). Acute: dizziness, headache, vomiting, nausea, death (CDC 2018).	PM is "associated with respiratory problems, lung cancer and cardiopulmonary deaths" (Zhang 2010 citation of Boldo 2006 and Pope 2006).	PM is "associated with respiratory problems, lung cancer and cardiopulmonary deaths" (Zhang 2010 citation of Boldo 2006 and Pope 2006). Additionally, "UFPs have been shown to be more toxic than larger particles to laboratory animals and humans due to the smaller size and larger surface area of these particles" (Zhang 2010 citation of Oberdorster 1995, Brown 2001, Kuschner 1997, Nemmar 2001, Renwick 2004).	Aldehydes are potentially carcinogenic (Zhang 2010 citation of Yang 2000, Lin 2000, Fullana 2004, and Hung 2007); Polycyclic aromatic hydrocarbons are also potentially carcinogenic (Zhang 2010 citation of Yang 2000, Lin 2000, Fullana 2004, and Hung 2007).
Recommended Short-Term Thresholds	0.09 ppm = 170 µg/m^3 (1 h, Health Canada) 0.1 ppm = 190 µg/m^3 (1 h, NAAQS) 0.11 ppm = 210 µg/m^3 (1 h, WHO)	35 ppm (1 h, NAAQS) 25 ppm (1 h, Health Canada) 25 ppm (1 h, WHO) 50 ppm (30 min, WHO)	100 µg/m3 = 0.1 µg/cm^3 (1 h, Health Canada 1995)	Not established	Acrolein: 2.5 µg/m^3 (1 h, California EPA) Formaldehyde: 55 µg/m^3 (1 h, California EPA)

(cont.)

Common Background Levels Reported in Studies	4-10 µg/m3 (Health Canada)	Median value of 48-hour average CO concentration was 1.2 ppm in CA residences (Wilson 1993); outdoors was 0.8 ppm.	5 µg/m3 (Zhang 2010) < 15 ug/m3 (Health Canada)	Varies	Varies
Levels Seen During Cooking	25-125 ppb for typical gas range cooking; 400+ ppb for gas oven cleaning; 15-35 ppb for electric range cooking and oven cleaning (Fortmann 2001).	Up to 120 ppm (U.S. EPA 2000); ~1-4 ppm avg for gas stove (Fortmann 2001, Fig 4-26); ~0.5-3 ppm avg for electric stove (Fortmann 2001, Fig 4-27).	Up to 3-90x background concentration for $PM_{2.5}$ (Zhang 2010 citation of Wallace 2004 and He 2004, respectively); 10x-3,000x increase in PM1-2 for pan frying or stir frying, respectively (Lunden 2014); Up to 5-10x background concentration for PM < 1 um (Zhang 2010 citation He 2004 and Li 1993, respectively); Average mass concentration over cooking events: 10-239 µg/m3 (Zhang 2010); Max concentration reached up to 15 minutes after cooking event ended (Zhang 2010).	Up to 10x background concentration (Zhang 2010 citation of Wallace 2004); up to 550x background concentration (Zhang 2010); average UFP number concentration over cooking event: 1.34×10^4 to 6.04×10^5 particles/cm^3. Peak concentration observed after burners turned off.	Varies. Fortmann (2001) reports on several dozen VOCs.
Decay Rate	~1/hr (Yamanaka 1984)	Negligible (Hirschler 1990)	~0.3/hr (Olson 2006)	~1.3/hr (Wallace 2013)	Varies.

(cont.)

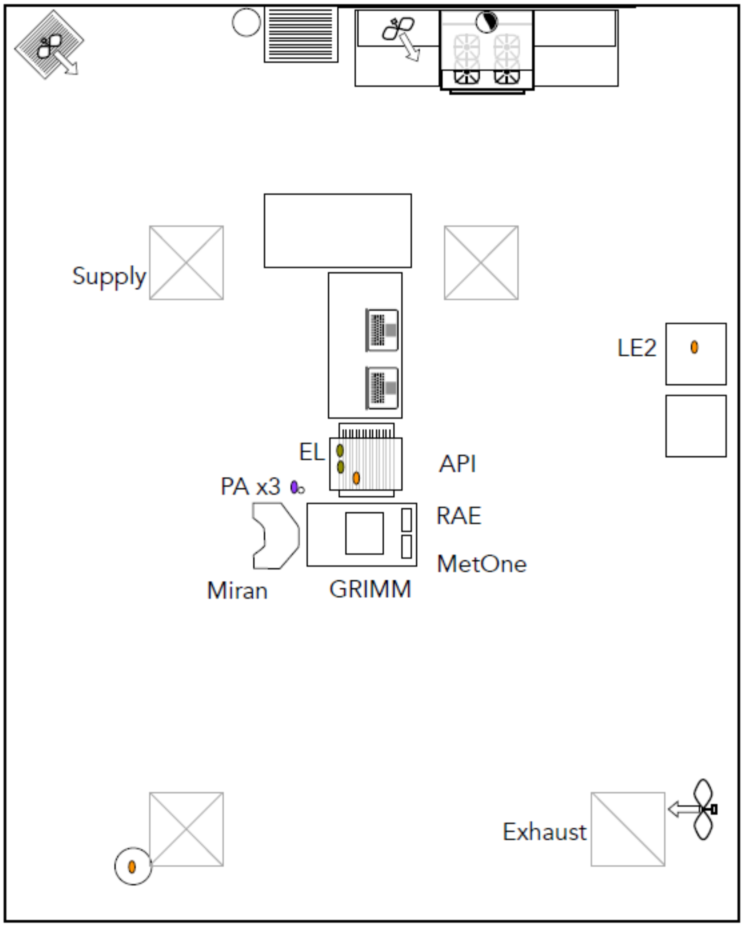
Synopsis	Significant for gas, less so for electric. Decay rate is faster than particulates. A sensor network responding to temperature and $PM_{2.5}$ should also address NO_2 emissions.	Typical concentrations reported do not exceed recommended thresholds. Sensors can be low cost and are ubiquitous, but we have not found much information on their accuracy. Also, CO alarms in compliance with UL 2034, are not supposed to trip when the CO concentration is less than 70 ppm, which is ~2x the recommended 1-hour threshold. So, low-cost CO sensors may be more appropriate for acute response versus control for chronic exposure.	Significant delta during cooking events, regularly exceeding one hour recommended exposure limit. Expected to have the most significant chronic health impacts. Low-cost sensors with good linearity. Could be coupled with temperature sensor to address this and other pollutants.	Large deviations. Significant health effects are expected, but there are no established thresholds. No low-cost sensors available. UFP concentration will be reduced by a $PM_{2.5}$ ventilation controller.	VOC detection is still a nascent field. Wide array of gases that are difficult to sense with accuracy, especially at low cost. Ventilation with $PM_{2.5}$ controller is expected to reduce exposure.

Appendix B

Laboratory evaluation was conducted inside cell 3A of the FLEXLAB2 facility at LBNL in a room configured to represent a kitchen area. The floor area of the entire cell is 20 ft (6.10 m) wide by 30.7 ft (9.36 m) long. An interior room was defined by a drop ceiling installed at 9 ft (274 cm) height with tiles taped to the supports to limit mixing to the space above and an interior wall installed 5.7 ft (174 cm) from the exterior door, creating a small antechamber and providing a room length of 30.7-5.7=25 ft (762 cm). A 2.4 ft (73 cm) wide by 6.8 ft (207 cm) high doorway between the experimental room and antechamber was covered with two overlapping sheets of a vinyl welder's curtain (Steiner #339 16 mil. thickness) to reduce air mixing between the room and antechamber. The calculated mixing volume of the room was 4499 ft^3 (127.4 m^3).

A cooking area designed to simulate the physical configuration of an under-cabinet range hood over a nominal 30 inch (75 cm) natural gas cooking range was constructed on the short wall of the room, opposite the opening to the antechamber and cell exit door. Figure 26 shows the layout of the room. The cooking area was installed on a temporary wall that was attached to the 3 ft (91 cm) high lower portion of the cell wall (beneath windows that extended across the width of the cell). The cell window frames were set back 0.3 ft (9 cm) from the wall and glazing was 0.5 ft (16 cm) from the interior edge of the wall. The SRH was installed such that its bottom edge was 2 ft (60 cm) above the tops of the cooktop grates. Floor cabinets and counters—which impact airflow around the range and range hood—were simulated by installing containers fabricated by placing gypsum wallboard over strut on both sides of the range and taping all edges with metal tape. These structures had dimensions of 3 ft (91 cm) height, 2.3 ft (69 cm) wide and 2.1 ft (64 cm) deep (from the wall). The roughly 2.5 ft (77 cm) distance between the faux side cabinets left a gap of roughly 1/4 in (7 mm) on each side of the 2.5 ft (75.5 cm) wide range. Faux cabinets (also constructed of gypsum wallboard on framing) with dimensions of 3.1 ft (93.5) cm high by 2.2 ft (68 cm) wide by 1 ft (31 cm) deep were hung on either side of the SRH.

The range hood was ducted to the outdoors through smooth, nominal 7-inch (17.8-cm) diameter ducting installed to the top exhaust opening. Starting from the SRH, there was a 2.7-foot (82-cm) straight section, a flexible 90º bend, and a 0.8-foot (24-cm) straight section connected to a Broan aluminum wall cap (Model 647) for 7-inch round duct. All joints were taped with metal tape.



Legend

API: TSI-API Model 200E NOX sensor

GRIMM: Grimm MiniWRAS1, Model 1.371 $PM_{2.5}$ and particle number sensor

EL: preproduction IAQ sensors from eLichens

Exhaust: Ancillary exhaust air location

LE2: Kaiterra Laser Egg 2 PM sensor

MetOne: MetOne BT645 with sharp-cut $PM_{2.5}$ cyclone $PM_{2.5}$ sensor

Miran: Miran SapphIRe portable infrared analyzer for analyzing tracer gas

PA x3: Three Purple Air PM sensors

RAE: PpbRAE3000 VOC instrument

Supply: Makeup air supply location

Figure 26. Schematic of experimental room showing kitchen area and placement of air quality measurement

The gas range (Kenmore Model 790.70502013) had a nominal 12,000 Btuh (3.52 kW) burner at the front right position, and the other three cooktop burners had nominal firing rates of 9,500 Btuh (2.78 kW). The oven burner had a nominal firing rate of 18,000 Btuh (5.28 kW). The range was operated with “CP” grade methane (purity 99.5%) provided from a compressed gas cylinder (Airgas) through a gas regulator set to provide gas to the range at a standard residential pressure of approximately 7 psi (48,263 Pa). The gas flow during cooking was modulated using the range controls and set to achieve specified gas flow rates verified with an inline mass flow meter (Alicat Model MLD-20SLPM-D/5M) that was visible from the front of the range. The flow meter was calibrated for methane and checked against a primary flow standard.

Ventilation to the chamber was provided as a single-pass system (no return air) that pulled in outdoor air through a MERV8 filter, conditioned the air, and supplied it to the chamber through a MERV13 filter. Air was injected into the chamber through three 1.6 ft (50 cm) square registers; two other supply registers were blocked with Duct Mask Premium Register Sealing Tape (The Energy Conservatory). The positions of the registers are shown in Figure 26. Air was exhausted from the experimental room continuously through a single 2 ft (60 cm) square grille that was open to the over-ceiling exhaust plenum. Additional airflow through the room was driven by intermittent operation of the SRH. The supply airflow was modulated using a variable frequency drive (VFD) that was set to provide approximately 95 cfm (0.045 m^3/s) continuously and to increase flow to balance the SRH, with the aim of maintaining a target positive pressure of approximately 2.9 x 10^{-4} psi (2 Pa) in the chamber. In actuality, during SRH operation, the chamber pressure varied and was centered around neutral pressure but extended to positive and negative pressures mostly within the range of -1 to +2 Pa. The VFD settings needed to balance each of the three fan speeds of the SRH were determined prior to the start of the experiments. The VFD flow was adjusted when airflow through the SRH changed (from manual or automatic operation), as indicated by the output of a differential pressure probe connected to the SRH ducting, approximately 1.8 ft (56 cm) above the hood.

Three fans set to fixed positions provided mixing in the experimental space. The fan in the corner was an AirKing (Intertek) Model 9146G, with blades extending to a 3.1 in (8 cm) radius. The fan placed above the faux side cabinet was a Holmes FAOH90, with 4 in (10 cm) radius blades. The box fan on the floor was an AirKing (Intertek) Model 9723F, with blades that extended to a 9.5 in (24 cm) radius. All fans were operated on their lowest speed settings throughout all experiments.

Appendix C

Researchers at LBNL developed detailed protocols to enable replication of typical cooking activities in U.S. homes. Specifically, LBNL developed protocols for three simple meals, one representing a typical U.S. breakfast and the other two representing lunch or dinner. The breakfast meal includes stovetop preparation of frozen hash browns, packaged bacon and eggs in a quantity suitable to a relatively large breakfast for two people. The second meal involved preparation of meat sauce and pasta using packaged ground beef and a jar or marinara sauce and incorporating frying of freshly cut onions; the quantity was suitable for three to four adults. The third meal involved oven heating precooked chicken cubes that were mixed with a prepared sauce (cubes and sauce sold in a frozen package as "mandarin orange chicken").

Each meal was prepared at least three times with the SRH set to auto mode and three times with SRH set to off, using only the front burners. Breakfast was prepared an additional two times using the back burners.

The process for each meal is described in the bullets below and in more detail in the tables that follow.

Breakfast

- Fry 2 partially precooked, frozen hash browns (64 g each) in small stainless steel skillet with 1 Tbs canola oil over medium heat; cook for 9 min.
- Fry 4 strips (162–178 g) of apple-cured bacon in a large stainless skillet over medium heat; cook for 12 min.
- Fry 2 eggs in a medium nonstick pan with 1 Tbs butter over medium heat; cook for 4 min.

Pasta with Meat Sauce

- Cook pasta in 5L stainless steel pot: add 4L water and 2 tsp salt to and bring to boil on high heat (16 min); add 454 g bowtie pasta, adjust to medium heat and cook for 13 min.
- Prepare meat sauce in stainless steel sauté pan: fry 100 g diced onion in 2 Tbs olive oil over medium heat for 6 min; add 454 g of 85/15 ground beef and cook over medium heat for 8 min; add marinara sauce from jar containing 737 g and cook over medium-low heat for 11 min.
- After draining excess water from pasta in colander (over larger pot, which is subsequently covered), mix pasta and meat sauce in 5L pot.

Mandarin Orange Chicken (frozen prepared food item)

- Preheat oven to 400ºF for 10 min.
- Heat 454 g of precooked chicken chunks in oven, on foil sheet, for 19 minutes.
- After removing from oven, add chicken to 5L pot and mix with 170 g sauce provided as part of packaged meal.

Hash Browns and Bacon on Induction Hot Plate

- Fry 2 partially precooked, frozen hash browns (64 g each) in small stainless steel skillet with 1 Tbs canola oil over medium heat; cook for 9 min.
- Fry 4 strips (162–171 g) of apple-cured bacon in a large stainless skillet over medium heat; cook for 12 min.

Cooking Equipment (all dimensions pertain to inside of cookware)

Table 15. Cooking Equipment Used in LBNL Laboratory Experiments

Pot or Pan	Base (cm)	Top (cm)	Height (cm)	Mass (g)
Large stainless skillet, used	22	28	5	1281
Small stainless skillet, used	14	20	4	669
Medium nonstick fry pan, used	18	25	4	667
Saute pan, stainless, Ikea Oumbarlig,	24	24	6.4	1114
5L stainless pot, Ikea, used	22.5	22.5	14.5	1697
Lid for 5L stainless steel pot	NA	NA	NA	291

Cooking Method Notes

Choreography of walking away and returning to cooktop: When working at stovetop, stand centered, in front of the burner being used. When cooking on 2 burners, stand at center of cooktop.

Walk away: step back, turn around, slowly walk at least 5 steps directly away from stove.

Return: approach stove slowly via straight path perpendicular to front of range.

Purchase and handling of food ingredients: Almost all ingredients were purchased from a chain grocery store within approximately a two-week period. The exceptions are the bottles of canola oil and olive oil, which were purchased months earlier.

Breakfast Cooking Procedures

Materials:

- Small stainless steel skillet (for hash browns)
- Large stainless steel skillet (for bacon)
- Nonstick lightweight pan (for eggs)
- Tongs for bacon
- Slotted metal spatula for hash browns and eggs.

Ingredients:

- 2 hash browns, frozen, approximately 128 g (Trader Joe's brand); pack of 10 is 638 g
- 4 strips of apple-cured bacon (Trader Joe's brand); select strips with approximate mass of 178 g
- 2 large AA eggs (Trader Joe's brand)
- 1 Tbs canola oil (Trader Joe's brand)
- 14 g (1 Tbs) salted butter (Trader Joe's brand).

Preparation:

- Weigh 4 bacon strips and set into large skillet
- Measure 1 Tbs of cold butter; place on left counter
- Set plate with paper towel on left counter (for hash browns)
- Set plate with paper towel on right counter (for bacon)
- Break 2 eggs into individual small bowls, set on counter
- Add 1 Tbs canola oil to small skillet; turn pan to spread oil; place skillet on front left burner
- Place large skillet with bacon on right counter cooktop.

Table 16. Breakfast Cooking Procedure: SEQUENTIAL Cooking of Hash Browns and Bacon

Minute	Activity
0	Start front left burner on medium (2 lpm) for hash browns; walk away
1.5	Return; add 2 hash browns to small skillet (cook 9 min); walk away
3.5	Return; press hash browns 5 seconds each; walk away
5.5	Return; flip hash browns; press 5 seconds each; walk away
8	Return; press hash browns 5 seconds each; walk away
10	Return; flip hash browns; press
10.5	Stop front left burner; remove hash browns to plate with paper towel; place skillet on back left burner. Place large skillet on front right burner.
11	Start front right burner on medium (2 lpm) for bacon (cook 12 min); walk away
13	Return; flip bacon and adjust in pan; remain at cooktop
15	Flip bacon and adjust in pan; remain
17	Flip bacon and adjust in pan; remain
18-23	Flip bacon once per minute or more as needed, remain
23	Stop front right burner; remove bacon to plate; move pan to rear burner; leave uncovered
23.5	Place nonstick pan with butter on front left burner, start and adjust to medium (2 lpm)
25	Add eggs to nonstick pan (cook 4 min); remain
28	Flip eggs
29	Stop front left burner; remove eggs to plate; place pan on front right burner
60	Remove skillets and fry pan from cooktop

Table 17. Breakfast Cooking Procedure: PARALLEL Cooking of Hash Browns and Bacon

Minute	Activity
0	Start front left burner on medium (2 lpm) for hash browns
0:15	Start front right burner on medium (+2 lpm; total 4 lpm); bacon already in pan (cook 12 min); remain to watch oil
1.5	Add 2 hash browns to small skillet (cook 9 min); remain at cooktop
2	Flip bacon and adjust in pan; remain
3.5	Press hash browns 5 seconds each; remain
4	Flip bacon and adjust in pan; remain
5.5	Flip hash browns; press 5 seconds each; remain
6	Flip bacon and adjust in pan; remain
7	Flip bacon and adjust in pan; remain
8	Press hash browns 5 seconds each; remain
8-12	Flip bacon every 30 seconds
10	Return; flip hash browns; press
10:30	Stop front left burner; remove hash browns to plate with paper towel; place skillet on back left burner
12	Stop front right burner; remove bacon to plate; move pan to rear burner; leave uncovered
12.5	Place nonstick pan with butter on front left burner, start and adjust to medium (2 lpm)
14	Add eggs to nonstick pan (cook 4 min); remain
17	Flip eggs
18	Stop front left burner; remove eggs to plate; place pan on front right burner
48	Remove skillets and fry pan from cooktop

Pasta with Meat Sauce Cooking Procedures

Ingredients

- 454 g package of farfalle (Trader Joe's brand)
- 454 g package of 85-15 ground beef (Trader Joe's brand)
- 737 g jar of marinara sauce (Tomato and Basil, Trader Joe's brand)
- 100 g fresh onion, diced to approximately 1 cm
- 15 mL (2 Tbs) olive oil
- 5 g (2 tsp) table salt.

Preparation

- Add 4 quarts water and 2 tsp salt to 5 L pot; cover pot and place pot on front right burner
- Add 2 Tbs olive oil to sauté pan, swirl pan to spread oil; place on front left burner
- Place lid to sauté pan on left counter
- Dice onion to 1 cm squares, weigh 100 g and place in small bowl on left counter
- Set up colander over large pot to drain pasta; place on table with lid adjacent
- Open package of ground beef and place on left counter
- Place wooden spoon for meat sauce on left counter
- Place open bag of pasta on right counter.

Table 18. Pasta and Meat Sauce Cooking Procedure

Minute	Activity
0	Start front right burner on high (6 lpm) for pasta; walk away
1.5	Return; start front left burner; adjust to medium (+2 lpm, 8 lpm total); remain
3	Spread oil with wood spoon; add onions (cook 6 min); stir 15 seconds; walk away
5	Return; stir onions 5s; walk away
6	Adjust flow of FRONT LEFT burner to 8 lpm total; stay as far as possible from range hood
7	Return; stir onions 5 seconds; remain
8	Stir onions 5 seconds; remain
9	Add beef (cook 8 min); stir and break chunks for 30 seconds
9.5	Walk away
11	Return; stir beef for 30 seconds
11.5	Walk away
14	Return; stir beef for 15 seconds; lift pot lid to check water, replace lid; remain
15	Stir beef 15 seconds; remain
16	Remove pot lid to confirm rolling boil; add pasta (cook 13 min); stir 5 seconds; remain
17	Add jar of sauce to sauté pan; stir 15 seconds; place lid on sauté; remain
18	Stir pasta 5 seconds; adjust front right burner to medium (+2.5 lpm, 4.5 lpm total); remain
18.5	Stir sauce 5 seconds; remain
19	Stir sauce; adjust front left burner to medium-low (3.5 lpm total); place lid on sauté
19.5	Walk away
21, 24	Return; stir pasta 5 seconds; stir sauce 5 seconds and replace lid; walk away
27	Return; remove one piece of pasta from pot, taste; remain
29	Turn off front right burner; drain pasta; put pasta back into pot and place on stove
30	Turn off front left burner (sauce); pour meat sauce into pasta pot or another bowl on cooktop; cover sauté pan; remove pasta and meat sauce; leave pots on back burners.
60	Remove pots from chamber

Mandarin with Orange Chicken Cooking Procedures

Ingredients

- 672 g package of Mandarin Orange Chicken (Trader Joe's Brand, Frozen).

Preparation

- Cover baking sheet with heavy-duty aluminum foil
- Place frozen chicken nuggets on foil on baking sheet.

Table 19. Mandarin Orange Chicken Cooking Procedure

Time (min)	Activity
0	Set oven to preheat at 400ºF for 10 minutes (start timer when gas valve opens)
10	Place chicken nuggets on cookie sheet and insert in oven
29	Turn oven off. Remove cookie sheet from oven, place cookie sheet on cooktop, transfer nuggets to a pot, cover, and move to separate table

Appendix D

Screening Visit Data Collection Form

Candidate house	

Confirm before visit

Year of home construction	
Total floor area (square feet)	
Type of home	

Confirm on-site

Cooking appliances

Type of primary cooking appliance	
Cooking fuel, cooktop	
Cooking fuel, oven	
Cooktop/range nominal width (in)	
Toaster	
Crockpot	
Other?	

Range hood

Type	
Mount	
Nominal width (in)	
Exhausts to exterior?	

Duct dimension(s) (in)	
Operational on each speed setting?	

General

Does the home smell like smoking occurs there?	
Number of indoor air cleaners identified?	
Is there sufficient space to install a natural gas submeter for the range? Recommended location?	

Diagnostic testing

Blower door result (cfm at 50 Pascals)	
Blower door result (ACH50)	
House depressurization with range hood operating on speed 1, Pascals	
House depressurization with range hood operating on speed 2, Pascals	
House depressurization with range hood operating on speed 3, Pascals	

Other appliances

Total number of ceiling exhaust fans (bathrooms, laundry, hall, etc.)	
Number of water heaters	
Water heater type	
Water heater fuel	
Space heater type	
Space heater fuel	

Air conditioning type	
Whole-house cooling fan present?	
Clothes dryer location?	

Appendix E

Parameter	Metric	Device	Description	Location(s)	Error Estimate
IAQ (CO_2, NO_2, $PM_{2.5}$, TVOC, T, RH)	Time resolved; varies	Clarity Node air quality monitoring station	Multi-pollutant concentration monitoring station	Indoors: kitchen, one bedroom on first floor or central area on second floor Outdoors: air quality station	$PM_{2.5}$: +/- 10 ug/m3 NO_2: +/-30ppb or +/-15% if > 200 ppb CO_2: +/-7%; TVOC: +/-14% T: +/- 0.2 °C; RH: +/- 2%
NO_2, NO_x	Time integrated; ppb	Ogawa passive air samplers	Passive air samplers with cartridges	Indoors: kitchen, same bedroom as Clarity Outdoors: air quality station	Unknown
Range hood flow rate, operational	cfm	Oakton WD-20250-22	Digi-Sense Data Logging Vane Anemometer	Range hood	Measure flow rate at each hood speed setting. Accuracy: +/- 3%
Range hood flow rate, one-time measurement	cfm	Duct Blaster or equivalent	Blower door & duct blaster w/DG-700 manometer.	N/A	+/- 3%
Time of use: cooking appliances	T	DS1922T 8K High Temp iButton; Hobo UX100-014M & Type K TC	Proximity T logger: iButton	Up to 6: oven, toaster, one for each cook top burner	iButton: +/- 0.5 °C UX100-014M: +/- 0.7 °C
Time of use and flow rate: bath/laundry exhaust fans	cfm	Oakton WD-20250-22	Digi-Sense Data Logging Vane Anemometer	Bath and laundry exhaust fans	Flow rates to be calibrated to each speed setting of exhaust fans using the TEC Exhaust Fan Flow Meter with an accuracy of +/- 10%

Time of use: central air handler unit	T, On/Off	Onset UX90-004; Onset UX100-003	Motor on/off logger: UX90-004; Ambient T/RH logger: UX100-003	Central AHU motor; supply register for T-logger	N/A; used for run time only
Time of use: clothes dryer	T	DS1922T 8K High Temp iButton	Proximity T logger: iButton	Dryer exhaust outlet surface	iButton: +/- 0.5 °C
Natural gas consumption, range/oven	ft^3	AM250 Pulsing Gas Meter	Pulsing gas meter with 1 ft^3 resolution. Combine with Onset 4-channel Pulse Data Logger, UX120-017M to read pulses	Main line. Installation of meter to isolate oven/ cooktop was not possible.	+/- 0.5%
Time of use: gas water heater	T, On/Off	Onset UX100-014M	Assess run time based on T reading at gas water heater flue. Remote T logger: UX100-014M	Gas water heater flue	UX100-014M: +/- 0.7 °C
Home leakage	cfm50	Blower door and duct blaster	Blower door and duct blaster with DG-700 manometer	N/A	+/- 3%

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