Development of a Detection Algorithm for Kitchen Cooktop Ignition Prevention

Amy Mensch
National Institute of
Standards & Technology
100 Bureau Dr., MS-8664
Gaithersburg, MD 20899
301-975-6714
amy.mensch@nist.gov

Anthony Hamins
National Institute of
Standards & Technology
100 Bureau Dr., MS-8664
Gaithersburg, MD 20899
301-975-6598
anthony.hamins@nist.gov

Kathryn Markell
National Institute of
Standards & Technology
100 Bureau Dr., MS-8664
Gaithersburg, MD 20899

Background and Objectives

According to a recent NFPA report, 47 % of reported home fires involve cooking equipment, with cooktops accounting for 87 % of cooking-fire deaths and 80 % of the civilian injuries [1]. Electric-coil stovetops manufactured after June 2018 in the U.S. must pass the UL 858 [2] “abnormal cooking test.” The test prescribes a maximum dry-pan temperature or an ignition-prevention performance test using 50 g of canola oil with the coil element on its highest power setting. This standard does not apply to older cooktops or other types of cooktops, such as gas ranges. Therefore, a set of experiments was designed to investigate the feasibility of a robust and reliable, external, pre-ignition detection system that could be used to retrofit existing cooktops. The goal of such a system would be to prevent fires from unattended cooking, while ignoring normal cooking activities and nuisance sources. The proposed system could be located within the kitchen exhaust duct or on the ceiling in the kitchen. It could also be integrated into existing household systems via the “internet of things.”

There have been many studies investigating the performance advantages of multiple sensors over a single sensor for detection of generalized fire conditions and nuisance-alarm resistance. Gottuk et al. [3] compared the effectiveness of various multi-criteria fire-detection algorithms, using signals from carbon monoxide (CO) sensors and smoke detectors to reduce false fire alarms and to increase detection sensitivity. A cutoff value for the product of the signals from an ionization smoke detector and a CO sensor was reported to show improved effectiveness over typical smoke detectors.

In another study, Cestari et al. [4] included a thermocouple and ionization, photoelectric and CO detectors to 1) develop advanced fire detection algorithms that reduced nuisance sensitivity and 2) detect fires at least as fast as conventional ionization and photoelectric detectors. Eight parameters were identified from the four sensors by considering the magnitude and rate of rise of the output from each sensor. Algorithms developed from these parameters showed that the best fire sensitivity and nuisance immunity was observed for the algorithms based on: temperature rise and CO; CO and ionization detector; and temperature rise, CO and ionization detector. Another series of studies developed and tested a prototype four-sensor (ionization, photoelectric, CO and carbon dioxide (CO_2)) package for early warning seaboard applications [5]. Although these studies did not focus solely on cooktop fires, typical cooktop nuisance sources were considered, including steam as well as cooking aerosols (e.g., the effluent from hot cooking oil and bacon).

A small number of previous studies focused on cooktop fire sources and considered multi-detector sensing of pre-ignition signatures in a kitchen environment. Johnsson [6] conducted a series of experiments investigating the feasibility of distinguishing between normal cooking activities and preignition conditions using a variety of sensors in a mock kitchen with a closed door. Sensors were placed above the cooktop and on the compartment ceiling. Signals from alcohol, CO, and hydrocarbon sensors showed potential to predict ignition while discriminating from normal cooking. Nearly all the experiments were conducted with the range hood off and the effects of room configuration and transport likely played a significant role in the interpretation of results. More recently, Johnsson and Zarzecki [7] conducted experiments which suggested that modified photoelectric smoke detectors could be used to warn of pre-ignition conditions while not impacting normal cooking scenarios.

Jain et al. [8] conducted cooking-oil autoignition experiments, considering the effectiveness of various inexpensive sensors to detect pre-ignition conditions, and reported that the rate-of-change of the moving average of CO concentration was a robust indicator of impending ignition. The study, however, did not consider normal cooking or common nuisance sources. The objective of our study was to determine which sensors/sensor combinations showed potential for use as input to a detection algorithm for cooktop ignition prevention. The initial set of experiments were focused on sensor response and were designed to limit transport considerations.

Experimental Apparatus and Procedures

In this study, ignition and normal cooking tests were conducted in a mock-up kitchen. Cooking oils were heated in a pan on an electric-coil stovetop with the highest power setting until ignition occurred. These tests used round, cast iron, aluminum, multi-layered, and stainless-steel pans with diameters of either 20 cm (8 in) or 25 cm (10 in). In most tests, the pans were placed in the rear locations on the cooktop, with the small burner used for the 20 cm pan and the large burner used for the 25 cm pan. On the highest setting, the stove power was about 1.1 kW on the small burner and 1.8 kW on the large burner.

Soybean, canola, olive, sunflower, and corn oils were tested, since these are commonly used cooking oils in the U.S [9]. Butter was also heated to ignition in one test. Normal cooking or nuisance sources included boiling water (steam), cooking hamburgers (80 % lean), and cooking seasoned salmon with butter. For the salmon cooking, the butter was heated on high for 3 min, the salmon was added and heated on high for 4 min, and the salmon was flipped and cooked on high for 4 min. Following that procedure, unattended cooking was simulated by continuing to cook the salmon at the high-power setting. In one case, the salmon eventually ignited. The cooking procedure for the hamburgers was the same as in Ref. [10]. Two hamburgers were also cooked in the oven on the broil setting according to the UL 217 Cooking Nuisance Smoke Test procedure [11]. A list of the experimental conditions is presented in Table 1.

Approximately 20 different sensor responses were selected for testing, including types that were based on various operating mechanisms, including electrochemical, catalytic, MOS-type, light scattering, and ionization. Sensors were selected to measure CO_2, CO, hydrocarbons, alcohols, H_2, natural gas, volatile organic compounds (VOCs), smoke, air quality, and aerosols/dust. Temperature and humidity were also measured. The dust sensor was modified twice to extend its range of sensitivity, and the dust-sensor iteration (1, 2 or 3) is listed in Table 1. The sensors were positioned approximately 3 m downstream of the exhaust duct inlet, which was located about 0.8 m above the cooktop. Data were acquired at ¼ Hz. The exhaust fan was set to high flow (about 3.4 m/s) in the duct. Part way into testing, aluminum foil was added to partially enclose the area from the cooktop up to the exhaust hood on the left and right sides. The partial enclosure ensured that most of the plume of hot aerosols and gases flowed into the hood and past the sensors stationed in the duct. In this way, it was possible to eliminate transport effects from consideration in interpretation of the experimental results after the aluminum foil was added, for experiments 8 – 15 and 18 – 33.

Table 1. List of Experimental Conditions

Experiment	Pan Type	Pan Diameter	Food and Amount	Burner Location	Burner Size	Foil	Dust Sensor
1, ignition	cast iron	20 cm	50 mL canola oil	rear	small	no	1
2, ignition	cast iron	20 cm	50 mL canola oil	rear	small	no	1
3, ignition	cast iron	20 cm	50 mL canola oil	rear	small	no	2
4, ignition	cast iron	20 cm	50 mL canola oil	rear	small	no	2
5, ignition	cast iron	20 cm	50 mL canola oil	rear	small	no	2
6, ignition	cast iron	20 cm	50 mL canola oil	rear	small	no	2
7, ignition	cast iron	20 cm	50 mL canola oil	rear	small	one side	2
8, ignition	cast iron	20 cm	50 mL canola oil	rear	small	yes	3
9, ignition	cast iron	20 cm	100 mL canola oil	rear	small	yes	3
10, ignition	aluminum	20 cm	50 mL canola oil	rear	small	yes	3
11, ignition	multi-layered	20 cm	50 mL canola oil	rear	small	yes	3
12, ignition	stainless steel	20 cm	50 mL canola oil	rear	small	Yes	3
13, ignition	cast iron	20 cm	200 mL canola oil	rear	small	yes	3
14, ignition	cast iron	20 cm	50 mL canola oil	rear	small	yes	3
15, ignition	cast iron	25 cm	100 mL canola oil	rear	large	yes	3
16, ignition	aluminum	20 cm	50 mL corn oil	rear	small	no	1
17, ignition	cast iron	20 cm	50 mL corn oil	front	small	no	2
18, ignition	cast iron	25 cm	100 mL corn oil	rear	large	yes	3
19, ignition	cast iron	20 cm	50 mL corn oil	rear	small	yes	3
20, ignition	cast iron	20 cm	50 mL soybean oil	rear	small	yes	3
21, ignition	cast iron	25 cm	100 mL soybean oil	rear	large	yes	3
22, ignition	cast iron	20 cm	50 mL olive oil	rear	Small	yes	3
23, ignition	cast iron	25 cm	100 mL olive oil	rear	large	yes	3
24, ignition	cast iron	25 cm	100 mL sunflower oil	rear	large	yes	3
25, ignition	cast iron	20 cm	50 mL sunflower oil	rear	small	yes	3
26, ignition	cast iron	20 cm	50 mL butter	rear	small	yes	3
27, normal cooking	broiler pan	N/A	2 x 230 g (0.5 lb) hamburgers	oven	N/A	yes	3
28, normal cooking	cast iron	20 cm	230 g (0.5 lb) hamburger	rear	small	yes	3
29, normal cooking	cast iron	25 cm	2 x 230 g (0.5 lb) hamburgers	rear	large	yes	3
30, normal cooking	cast iron	20 cm	227 g (8 oz) salmon, 47 mL butter	rear	small	yes	3
31, ignition	cast iron	20 cm	227 g (8 oz) salmon, 47 mL butter	rear	small	yes	3
32, normal cooking	cast iron	25 cm	454 g (16 oz) salmon, 93 mL butter	rear	large	yes	3
33, normal cooking	cast iron	20 cm	50 mL water	rear	small	yes	3

Results and Discussion

Figure 1 shows the transient pan temperatures during a typical experiment with oil ignition. For the oils, ignition occurred between 630 s and 880 s after the cooktop was powered, when the pan temperature was between 410 °C and 470 °C, consistent with previous studies [12]. As expected, the transient CO_2 signal was fairly flat until ignition, when it sharply increased as seen in Figure 2. Figure 3 shows many of the rest of the sensor signals during experiment 8, with each signal normalized by its own peak, which occurred near the time of ignition. Each sensor signal was characterized by a unique profile with its absolute value and slope varying in time. Several of the sensors appeared to provide signals that may be useful for providing early detection of impending ignition, including the sensors sensitive to dust, CO, and VOCs.

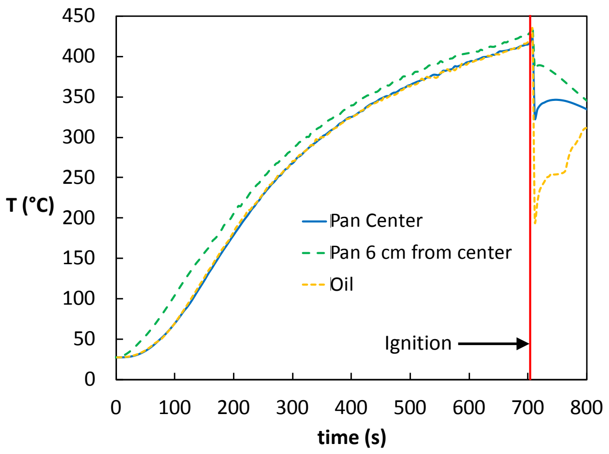

Figure 1. Pan temperatures for exp. 8.

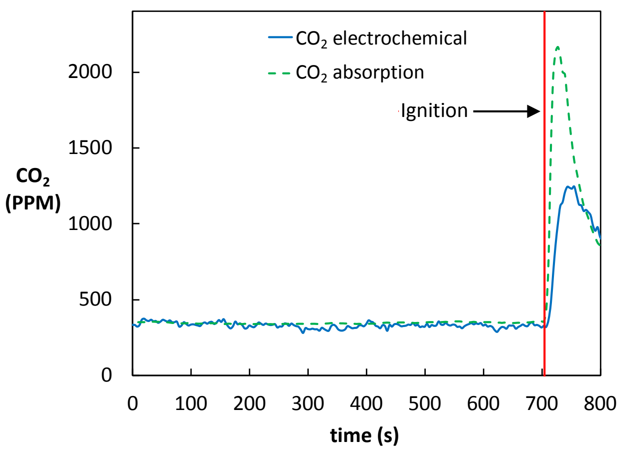

Figure 2. CO_2 measurements for exp. 8.

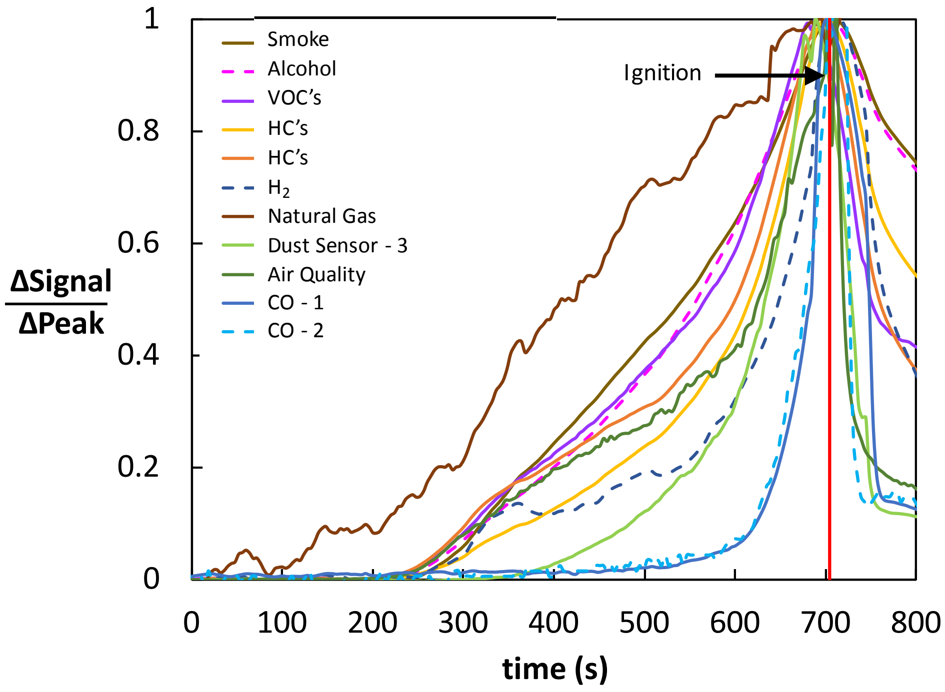

Figure 3. Normalized signals for exp. 8.

If a practical detection algorithm for cooktop ignition prevention is to be developed, detection must occur sufficiently before ignition to allow time to provide warning and/or direct action (e.g., cut the power), while also not impeding normal cooking activities. A time of 60 s before ignition is judged as a minimum time for a detection algorithm target, partly due to thermal inertia of the pan-cooktop system [6]. Many of the sensors, including the dust sensor and VOCs sensor, output a voltage reading, which has not been calibrated to concentration or other measurements at this point. If the value of one of these sensors is used in a proposed algorithm, these signals could be calibrated to be able to directly compare to other sensors.

Figure 4 compares the dust-sensor signal (minus the background signal), in volts, for all the experiments with a focus on two moments in time, namely 60 s before ignition and at the time of the peak signal. The results for the ignition of oils and butter are shown on the left portion of the graph. Normal cooking cases and unattended salmon ignition are on the right, with normal cooking results outlined by the box at the bottom right. A dust-sensor signal output of about 0.5 V seemed to distinguish the oil results from the normal cooking results except for one normal cooking experiment and one cooking-oil experiment (highlighted in the figure with unfilled squares).

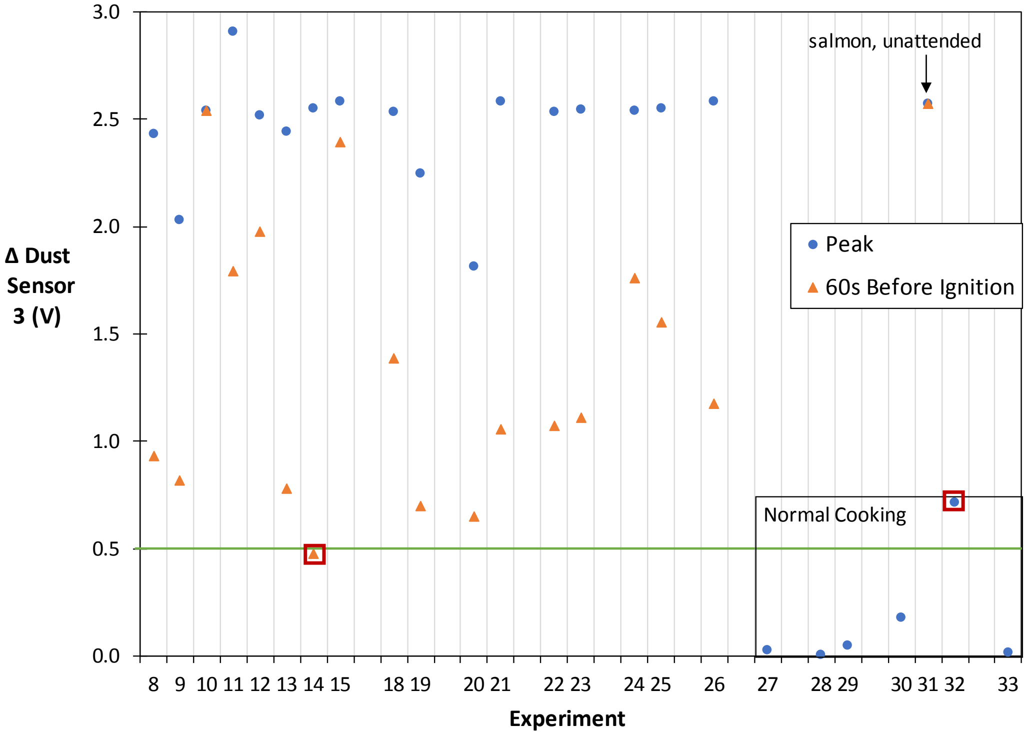

Figure 4. Change in dust sensor signal for experiments using configuration 3: peak and at 60 s before ignition.

Figure 5 shows analogous results for the time rate-of-change of CO. The figure compares the raw values of d(CO)/dt for all the experiments with a focus on 60 s before ignition and at the time of the peak signal. The results for the oils are shown on the left portion of the graph; normal cooking results are shown on the right. Since the CO signal tends to increase very rapidly close to ignition, the derivative values are plotted on a log axis. A derivative value on the order of d(CO)/dt = 0.6 generally seemed to distinguish the ignition results from the normal cooking results. This value would not prevent any of the normal cooking activities, but it would not catch two tests with oil ignition until < 60 s before ignition. For experiments 5 and 6, d(CO)/dt would reach 0.6 V 35 s before ignition and at ignition, respectively.

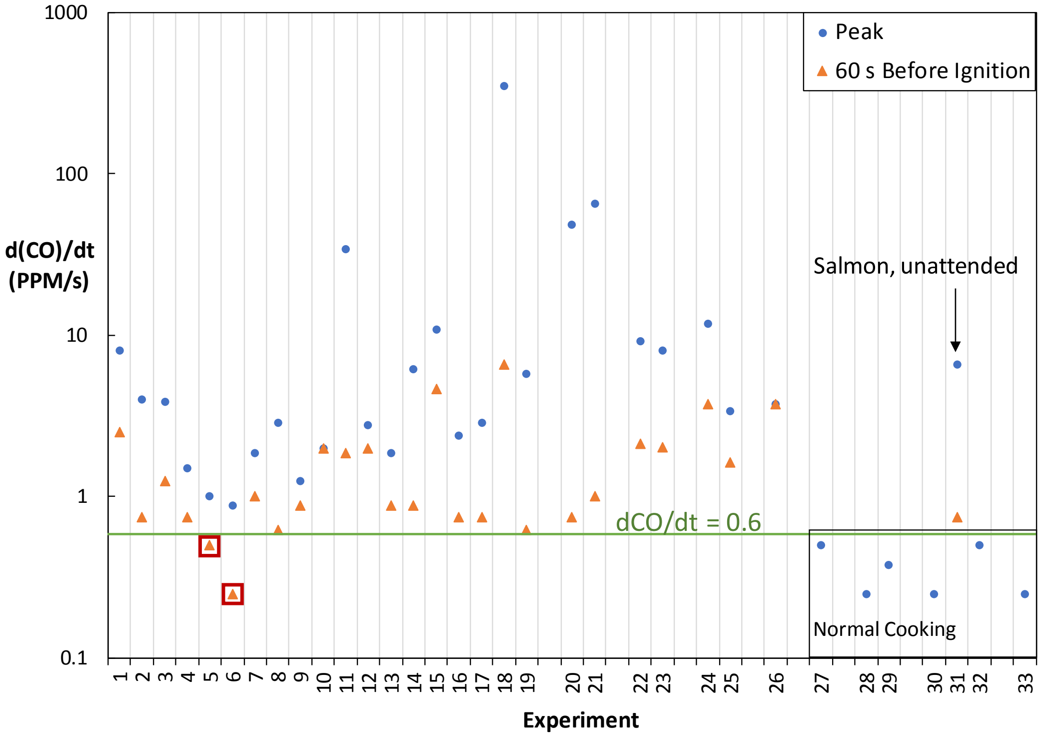

Figure 5. Rate of change of CO: peak and at 60 s before ignition.

Figure 6 shows analogous results for the change in the VOC signal from the background, in volts, comparing the peak signal and 60 s before ignition for all the experiments. A value on the order of 0.55 V appeared to differentiate the results for normal cooking from the cases with ignition. This criterion would have no false positives within 60 s of ignition and no false negatives with normal cooking for the experiments in this test series. However, there is not a large difference between the cutoff point and the highest signals from the normal cooking cases. Without additional repeat experiments of these cases and other similar experiments to determine the variability of these signals, we cannot be sure of the robustness of this algorithm to prevent all false alarms and ignitions.

Summary and Conclusions

A series of experiments was conducted to investigate the possibility of sufficiently early detection of imminent ignition during cooking. The results suggest that 1) a variety of sensors are sensitive to the plume of gases and aerosol associated with cooking. and 2) a number of algorithms show promise in distinguishing imminent (within 60 s) ignition from normal cooking activities, particularly with sensors that detect dust, CO and VOC’s. Further work is needed to determine the variability of the sensor signals under a broader set of realistic conditions that encompasses sensor location and hood fan flow. This would test the robustness of current algorithms, as well as other algorithms incorporating other signals or additional signals. It would be beneficial to consider algorithms that are transport independent. Possible transport independent algorithms could be the time rate-of-change of a sensor, a ratio of the signals from two different sensors, or the derivative of one sensor signal with respect to another sensor signal. Additionally, tests will need to be conducted to ensure that if the stove power is shut off when the condition(s) of a certain algorithm have been met, that ignition is prevented.

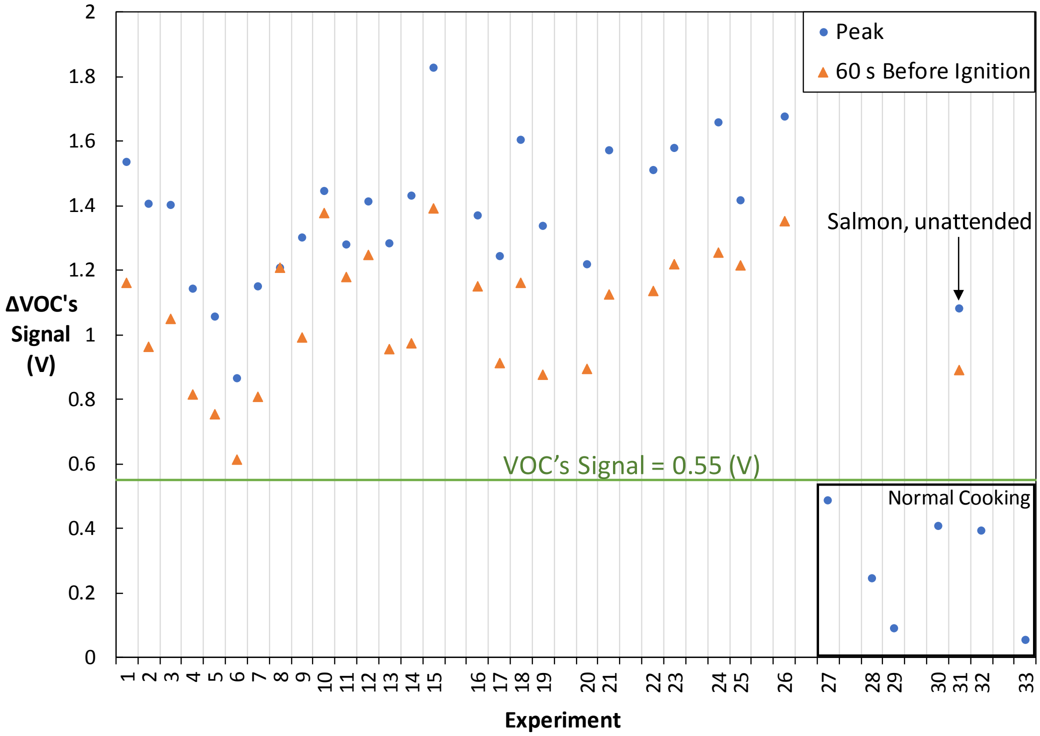

Figure 6. Change in VOC signal: peak and at 60 s before ignition.

References

[1] M. Ahrens, Home Fires Involving Cooking Equipment, National Fire Protection Association, Quincy, MA(2017).

[2] Underwriter's Laboratory, Northbrook, IL, Standard for Household Electric Ranges, Underwriter's Laboratory, Northbrook IL **UL 858** (2014).

[3] D.T. Gottuk, M.J. Peatross, R.J. Roby, and C.L. Beyler, Advanced fire detection using multi-signature alarm algorithms, Fire Safety Journal **37** (4), 381–394 (2002).

[4] L.A. Cestari, C. Worrell, and J.A. Milke, Advanced fire detection algorithms using data from the home smoke detector project, Fire Safety Journal **40** (1), 1–28 (2005).

[5] D.T. Gottuk, M.T. Wright, J.T. Wong, H.V. Pham, S.L. Rose-Pehrson, S. Hart, M. Hammond, F.W. Williams, P.A. Tatem, and T.T. Street, Prototype Early Warning Fire Detection System: Test Series 4 Results, (2002).

[6] E.L. Johnsson, Study of Technology for Detecting Pre-Ignition Conditions of Cooking-Related Fires Associated with Electric and Gas Ranges and Cooktops, Final Report, National Institute of Standards & Technology, Gaithersburg, MD(1998).

[7] E. Johnsson and M. Zarzecki, Using Smoke Obscuration to Warn of Pre-Ignition Conditions of Unattended Cooking Fires, *16th International Conference on Automatic Fire Detection (AUBE '17) & Suppression, Detection and Signaling Research and Applications Conference (SUPDET 2017)*, (2017).

[8] A. Jain, P. Nyati, N. Nuwal, A. Ansari, C. Ghoroi, and P. Ghandi, Pre-Detection of Kitchen Fires due to Auto-Ignition of Cooking Oil and LPG Leakage in Indian Kitchens, Fire Safety Science **11** 1285–1297 (2014).

[9] M. Ash, Edible fats and oils: U.S. Supply and disappearance, 2002/03-2015/16, Economic Research Service, United States Department of Agriculture, (2016).

[10] T.G. Cleary, A study on the performance of current smoke alarms to the new fire and nuisance tests prescribed in ANSI/UL 217-2015, National Institute of Standards and Technology, Gaithersburg, MD(2016).

[11] Underwriter's Laboratory, Northbrook, IL, Standard for Safety Smoke Alarms, **ANSI/UL 217** (2015).

[12] J.B. Dinaburg and D.T. Gottuk, Development of Standardized Cooking Fires for Evaluation of Prevention Technologies: Data Analysis, National Institute of Standards and Technology, (2015).