NIST Technical Note 1960

Using Photoelectric Smoke Detection to Warn of Pre-Ignition Conditions of Unattended Cooking Fires

Erik L. Johnsson
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National Institute of Standards and Technology
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May 2017

U.S. Department of Commerce
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National Institute of Standards and Technology
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ABSTRACT

A series of 21 experiments was conducted to examine the potential to use kitchen-installed photoelectric smoke detection devices to warn of approaching ignition of food during unattended cooking. An electric range, range hood, and cabinets were installed in a mock-up kitchen. Research smoke meters and standard off-the-shelf photoelectric smoke detectors were installed above the food, on the ceiling, and on the upper wall. In addition to smoke meter and smoke detector outputs, pan and food temperatures along with digital videos of the experiments were recorded. Cooking oils and bacon were heated to ignition in frying pans on the range top. The standard-threshold smoke alarms activated minutes before ignition. Typically, smoke production reached alarm levels at least 2 min before ignition. Frying hamburger tests were also conducted to compare smoke levels from attended, but smoky, cooking to the unattended cooking smoke levels. Analysis indicates that there is an extensive time window of elevated smoke obscuration during the unattended cooking above smoky attended cooking and prior to ignition sufficient to allow warning that would either alert the cook to return and de-energize the range or to interface with an automatic de-energizing device connected to the range.

KEYWORDS

kitchen fires; smoke detectors; photoelectric detectors; unattended cooking; cooking fires; range fires; smoke alarms; pre-ignition warning

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1. INTRODUCTION

1.1 Motivation

In the United States from 2009 to 2013, cooking caused 45 % of home structure fires, 17 % of the associated deaths, 42 % of the injuries, and 16 % of the property damage [1]. Ranges and cooktops were involved in a majority of each of these losses and account for over 300 deaths and 4000 injuries per year. About half of cooking fires result from the equipment being unattended. Unattended cooking fires remain a leading cause of fire incidents, injuries, property loss, and deaths despite the fact that efforts to research the issue and develop technology to impact the problem have been ongoing for over 20 years. As one of the leading causes of residential fires, unattended cooking fires remain a high priority fire problem requiring solution.

1.2 Background

The National Institute of Standards and Technology (NIST), the Consumer Product Safety Commission (CPSC), Underwriters Laboratories (UL), the National Fire Protection Association's (NFPA) Fire Protection Research Foundation (FPRF), and contractors to these organizations have researched engineering solutions to unattended cooking fires for over 20 years [2-10]. Due to nuisance alarms, smoke alarms have not typically been deployed in kitchens and are not listed for such use. In the past, AHAM (the Association of Home Appliance Manufacturers) had identified potential issues concerning implementation of safety controls on kitchen ranges including added cost, liability, lack of workable detection devices, nuisance activation, and the potential negative effects on cooking quality and customer satisfaction. It was important that reliable safety technology could be implemented at reasonable costs for both the manufacturers and appliance users.

Through membership in Vision 20/20 and the NFPA's FPRF Cooking Safety Steering Committee, AHAM has contributed to discussions and helped steer the efforts to answer lingering questions about implementing safety devices. AHAM provided valuable comments to research recently performed by Dinaburg and Gottuk at Jensen Hughes and sponsored by the FPRF and NIST which was tasked with developing a test standard for cooking pre-ignition detection devices [11]. The successful test standard research at Jensen Hughes focused on sensing thermal conditions to prevent ignition, and while smoke near the range was measured, the experiments were performed under a hood and not in a room that would allow typical smoke accumulation. In 2015, AHAM, in cooperation with Underwriters Laboratories (UL), proposed a modification to the 16th edition of UL 858 standard Cooking Oil Ignition Test for electric ranges [12] which will be effective on April 4, 2019. The revised standard takes into account and tests any built-in device designed to prevent ignition of food on the range. Most devices designed for this purpose are thermal and expected to warn of approaching ignition temperatures.

From the beginning, the focus has been range-centric; i.e., the solution needed to be connected to the range to interrupt the heating process during unattended cooking to prevent ignition [7, 8, 9]. This modified UL standard is geared toward manufacturers building this capability into their ranges. However, NIST's recommendation in 1996 was to explore smoke as the most reliable

and early warning of approaching ignition [3]. Detection and alarming of smoke levels would necessarily need to be external from the range, probably on the ceiling, and would need to interface with a range to shut it down in the event of approaching ignition. This type of independent device that might be added on rather than included in the range itself is not accounted for in the Standard.

1.3 Approach

Since the initial study performed by NIST for CPSC, the focus has been on range-connected temperature sensors. Other solutions were worth exploring since acceptance of such sensors still seemed a long way off. In the concluding suggestions of that 1996 study [3], NIST said, "Increasing the sophistication and/or decreasing the sensitivity of standard smoke detectors may allow their use in the kitchen for detection of pre-ignition conditions". It was also noted at the time that the smoke produced during unattended cooking processes reached undesirable levels preceding ignition which would allow smoke to be used as an indicator of approaching ignition with margin to limit false alarms. In view of advances in smoke alarm technology and to explore more options for cooking fire prevention, NIST revisited the potential for using smoke to enable warning of approaching ignition.

Similar results to the earlier NIST effort were expected, but needed to be reproduced with a current range and a focus on smoke as the main potential solution. To be effective, a time window needed to be found between normal cooking smoke levels and approaching-ignition smoke levels generated by unattended cooking. A smoke level threshold could then be set which allowed for sufficient time for the homeowner to hear an alarm and respond or initiate automatic range shutdown prior to ignition.

1.4 Objectives

The project objectives were:

- To experimentally determine the levels of smoke produced and corresponding times before ignition of cooking fires that existing smoke detection technologies can utilize to alert of impending ignition during unattended cooking.
- To provide to the fire safety industry the smoke sensitivities and operating parameters for kitchen-deployable unattended cooking alarms that interrupt power to appliances and/or alert consumers and allow their intervention to prevent ignition of unattended cooking fires.

2. EXPERIMENTAL DESCRIPTION

Experiments were designed to explore the smoke produced by unattended cooking of various foods. The foods and pan sizes and materials were selected based partly on the experiments performed by Dinaburg and Gottuk [11] and the results generated by particular combinations. Conducting the experiments in a kitchen-like room with a range hood distinguishes NIST's effort from that performed at Jensen Hughes. The goal of the experiments was to generate data that could be analyzed to establish the relationship between smoke and time before ignition for fire prevention. Relatively smoky normal cooking was also needed to determine if it could be differentiated from the unattended cooking smoke levels. Smoky normal cooking provides the highest acceptable smoke levels and the basis for setting new thresholds for pre-ignition smoke levels.

2.1 Laboratory facility

The experiments were conducted at NIST in the fire detection laboratory. The lab is split into two sections, consisting of a control room and a test room. The test room is isolated from the control room and is held at negative pressure. The test room is 3.0 m wide x 2.45 m tall x 3.2 m deep. A pictorial layout of the kitchen setup in the NIST Fire Detection Lab is shown in Figure 1. The air supply and exhaust are located above a dropdown ceiling. In the back of the room, a 9.1 m wide and 2.0 m tall opening with a 0.44 m soffit allows the smoke to be exhausted out of the test area and thought the exhaust duct. A mockup of kitchen cabinets was built using cement board with a built-in range and a range hood. The range hood was vented into the test room exhaust. A door at the front of the room was closed during experiments. A top down view of the kitchen can be seen in Figure 2.

2.2 Cooking equipment and energy input

A residential electric (coil burner) range was purchased and installed. Mock up cabinets and a range hood were installed as well. The electric range used to conduct the experiments was a General Electric 5.3 cu. ft. model with four open-coil burners (Model # JB250DF1WW). The stove had two large burners, two small burners and an oven with self-cleaning capability. The large burner, small burner and the oven were 1.95 kW, 1.1 kW and 2.4 kW, respectively. Since the circuit providing current to the range was only 220 V, the rated burner power outputs were not realized, and actual power output of the large burner was about 2 % to 4 % less than 1.95 kW. An Extech Instruments power meter with an LCD display visible to one of the video cameras was used to monitor the heat output in kilowatts during the experiments. Additionally, a current meter was used to continuously monitor the current using the data acquisition system.

The range hood was a NuTone 30 in convertible (model # ACS30WW). It was connected to a duct so the effluent would flow above the false ceiling and then out the room exhaust hood. The front discharge vent was taped closed so the smoke would not reenter the main laboratory space.

The hood, when used, was always operated on its maximum flow setting of 104 L/s (220 ft^3/min).

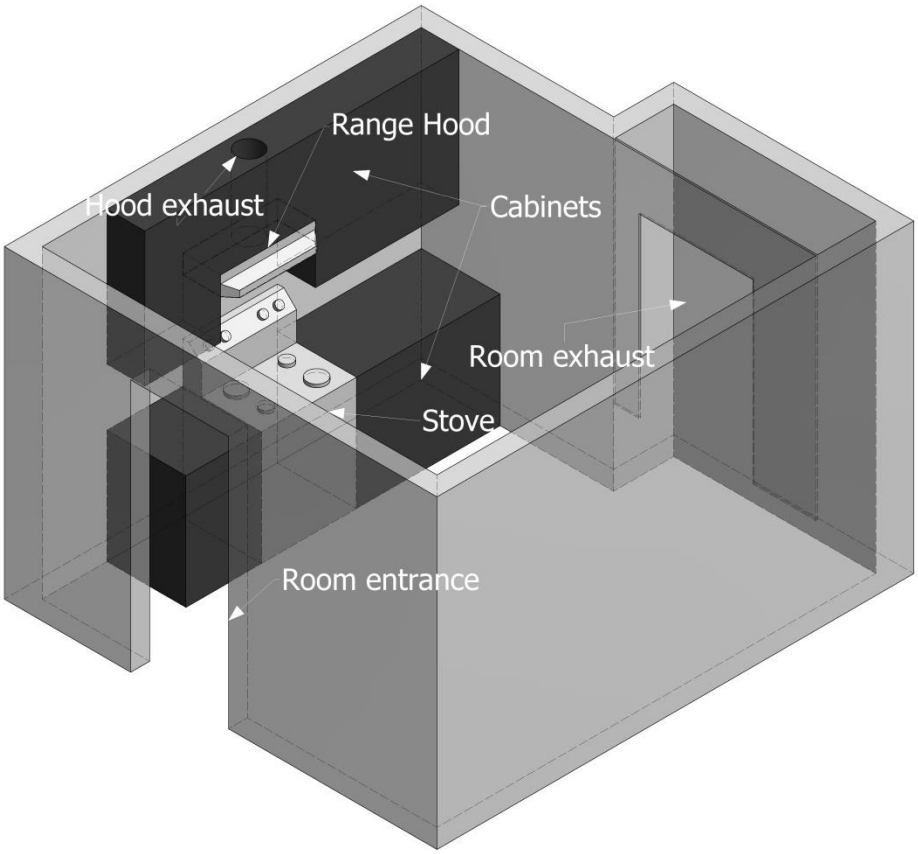

Figure 1 Kitchen setup at NIST fire detection lab.

The Jensen Hughes report determined that the pans that led to fastest ignition were low-end stainless steel pans [11]. NIST purchased the exact same pans in order to produce similar results. The pans used were 25 cm (10 in) diameter stainless steel covered sauté pans manufactured by Tramontina.

2.3 Measurement layout

The basic experimental set-up consisted of power, smoke, and temperature measurement devices. Power and current used by the stove were measured. Smoke was measured above the range, on the ceiling, and on one wall with laser-based smoke meters and photoelectric smoke detectors. One incandescent-light beam based smoke meter was located on the ceiling, and one ionization smoke detector was located on the wall. Temperatures were measured at the pan and also at each smoke measurement device location. Two high definition video cameras and a digital still camera were used. The following sections detail each of these measurements.

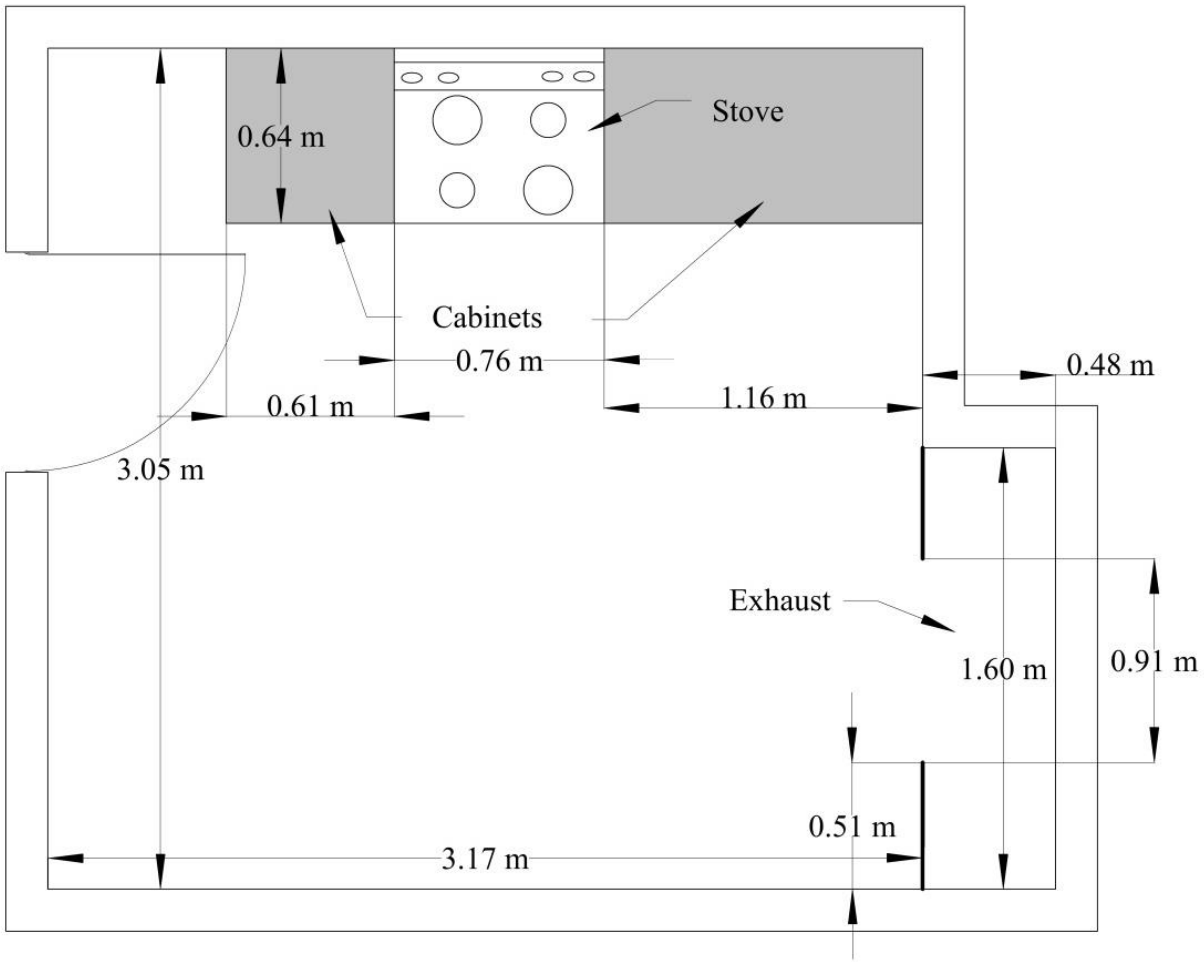

Figure 2 Kitchen layout at the NIST fire detection lab.

2.4 Smoke alarms

A single combination ionization/carbon monoxide and three photoelectric/carbon monoxide spot detectors were installed around the room. The alarms were wired to a 3 Amp GW Instek DC power supply (Model #GPR6030 D). Every detector was connected to its own serial port. The output from the detectors corresponded to the value of the level of smoke and carbon monoxide at each location. The locations of the smoke detectors can be seen in Figure 3 (top view), Figure 4 (side view), and Figure 5 (front view).

2.5 Smoke meters

The smoke obscuration was monitored in several areas in the test room. Two laser smoke meters were placed on the ceiling and a third one was placed on top of the cabinet mockups. A single incandescent-light smoke meter was installed on the ceiling next to one of the laser meters. Figure 3 shows the top down view of the test room with the locations of the smoke alarms and the laser and light meters. The side view of the smoke and light meters can be seen in Figure 4. The range stove and the cabinet mockups can be seen in Figure 5. The laser smoke meter used a 635 nm wavelength laser source, and the light smoke meter used an incandescent light bulb. The

light meter used a biconvex lens to collimate the light that passed through the test section. The path length for both detectors was 1 m. An additional biconvex lens was used to focus the light onto a silicon detector for both meters. The laser smoke meters tend to drift when they are turned on, and had to be left on for several hours in order to stabilize. A more detailed explanation of how the laser and light meters work can be found in Putorti [13]. The expanded uncertainty (coverage factor of 2) in the laser extinction measurement generated by the meter design used was estimated to be ±10 % [14].

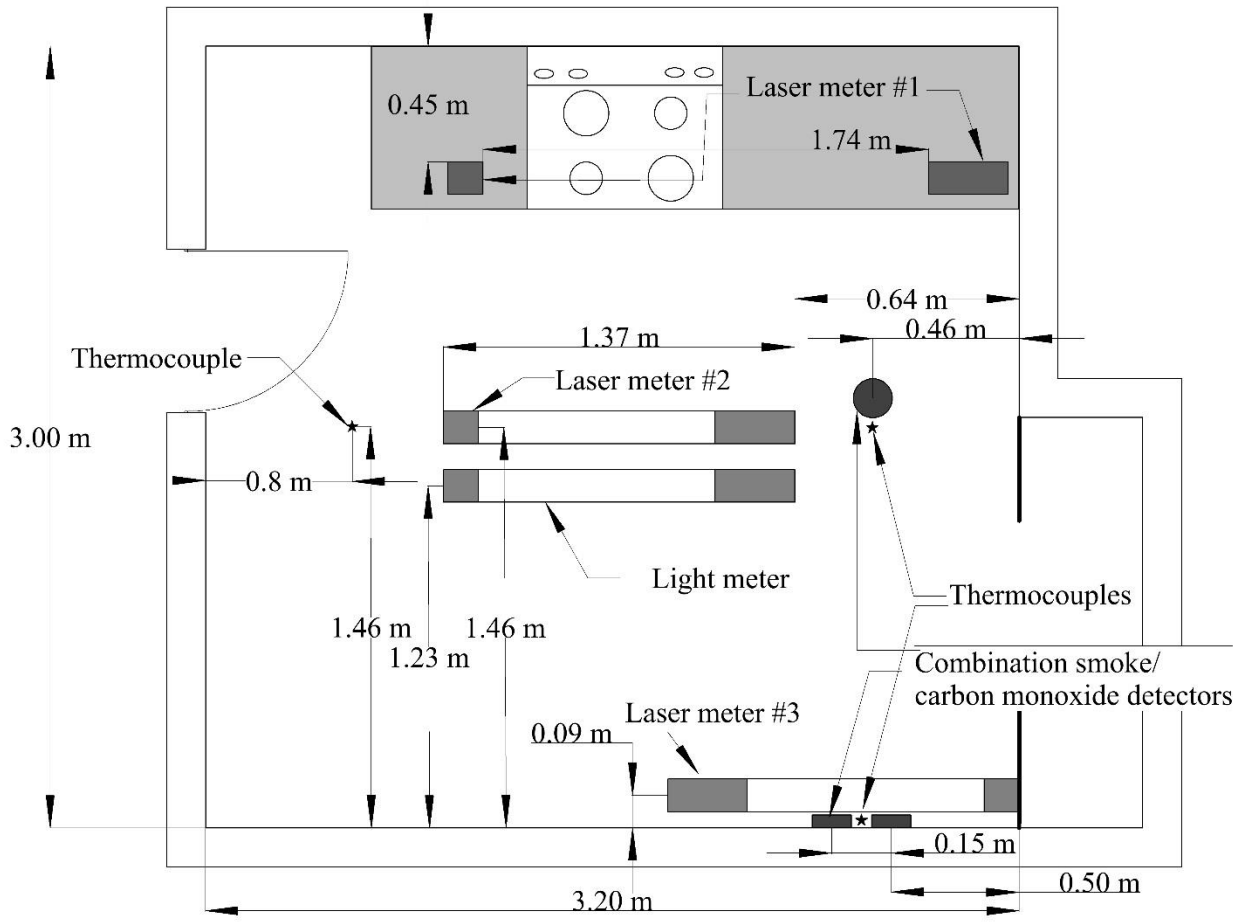

Figure 3 Top view of the instrument layout in the test room.

2.6 Temperatures

Pan and food temperatures were measured with K-type thermocouples with expanded uncertainties (coverage factor of 2) of less than ± 2 °C. The pan temperature thermocouple was initially (Tests 1 to 4) a bead-type welded to the inside bottom of the pan, but when the weld failed after use and cleaning, the method was changed (Tests 5 to 21) to insertion of the tip of a sheathed thermocouple (Omega TJ36-CAIN-032U-12) into a small hole drilled into the inside bottom of the pan. The food temperature was measured with a sheathed thermocouple (Omega KMQIN-020U-18) that was bent so the tip was located approximately 6 mm (0.25 in) from the pan bottom. The Jensen Hughes report [11] demonstrated that the oil temperatures do not vary

significantly relative to the location of the thermocouple across the pan or at different depths within the oil. The food and pan thermocouples were placed approximately 1/3 of the diameter of the pan from the pan center.

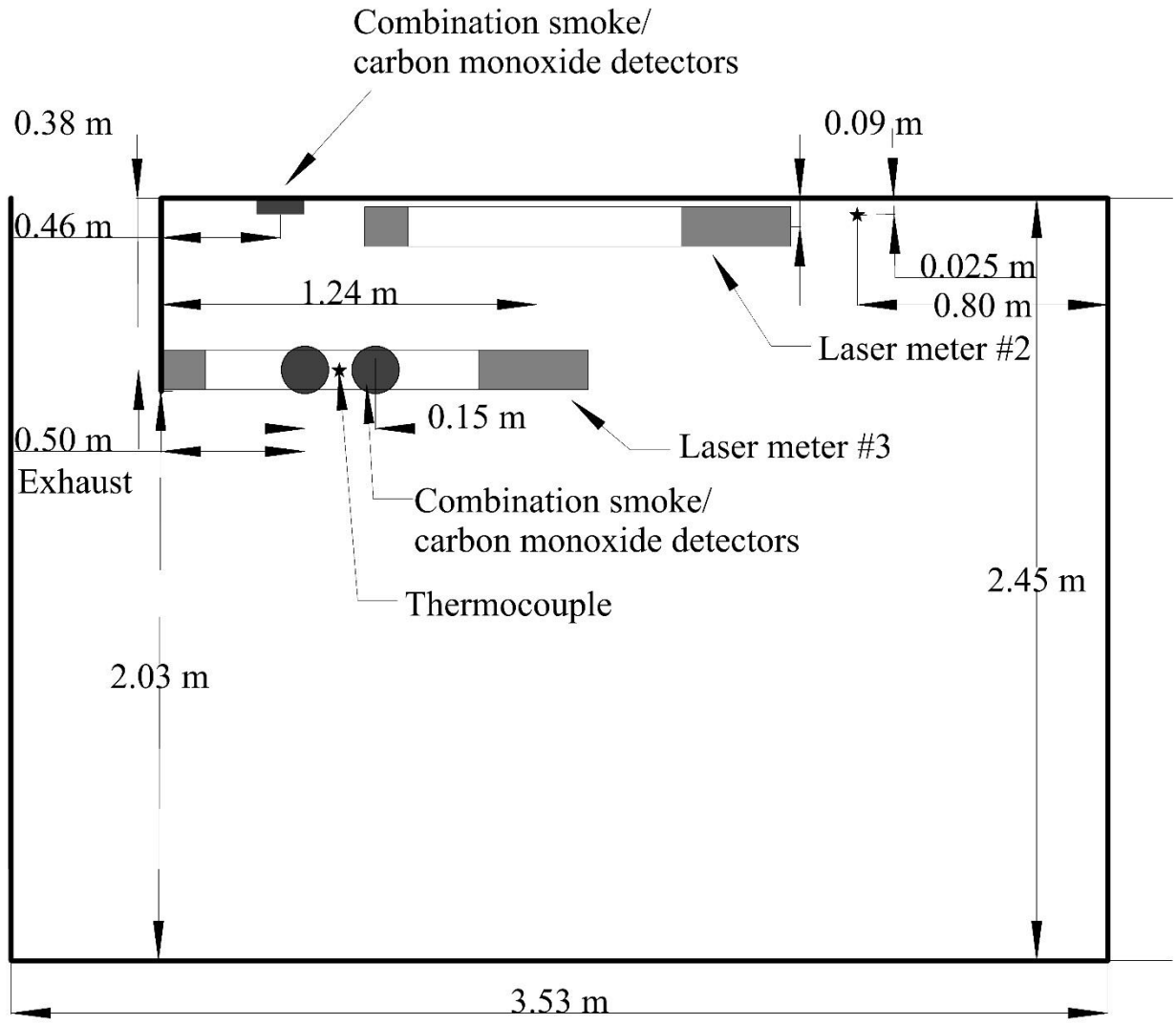

Figure 4 Side view of the instrument layout in the test room.

A series of K-type thermocouples were used to monitor temperatures around the room. A high accuracy 24 gauge wire (Omega HH-K-24-SLE) was used for the thermocouples. Each thermocouple had their ends welded together to form a 1 mm diameter bead. Uncertainties (expanded with coverage factor of 2) for these measurements were estimated at ± 1 °C. Thermocouples were placed 2.5 cm below the ceiling between each pair of combination ionization/carbon monoxide and photoelectric/carbon monoxide spot detectors.

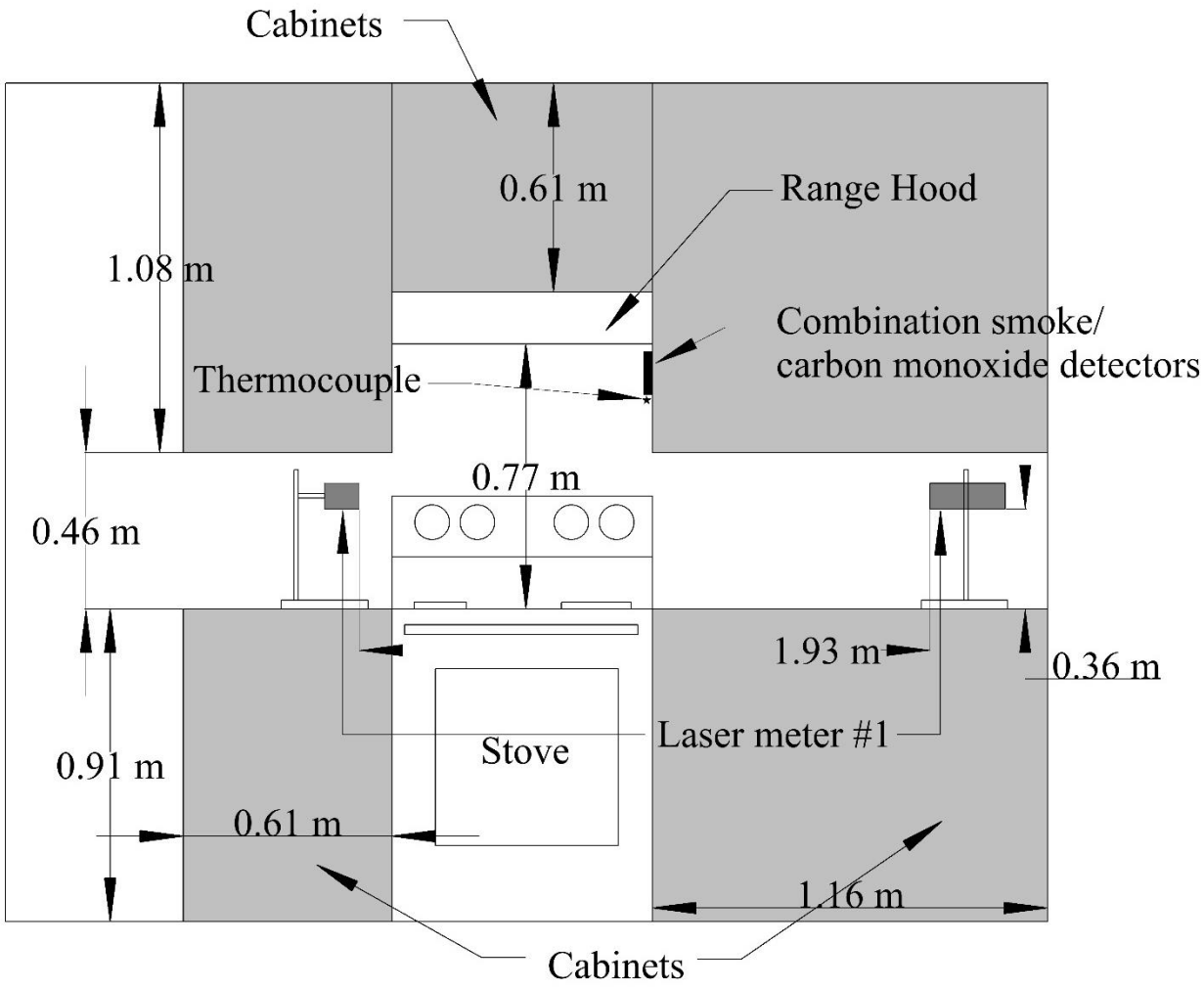

Figure 5 Front view of the kitchen mockup, and instrument locations near the range stove.

2.7 Data acquisition

Voltage and thermocouple data were collected using National Instruments NI-9205 and NI-9213 data acquisition boards, respectively, sampling at 75 samples per second per channel. The program saved the average of those points once per second to the output file.

The smoke detectors output signals through serial communication cables running to a National Instruments NI USB-232/4 data acquisition board. The data acquisition program checked each detector every 10 ms and saved the values. The program outputted the values to a text file once per second. If the value was not updated within 1 s interval, the value from previous iteration was used.

2.8 Digital photography and video

To track the heating time and time for ignition of the foodstuff, a DC-Digital timer was placed in view of the video cameras. The timer was started simultaneously with the burner. The two

video cameras were Sony model HDR CX-350. The first camera focused on the range top while the second camera recorded a wider view of the top of the range, cabinets, and corner of the ceiling. The digital still camera used was Sony model SLT-A58.

2.9 Food used for testing

In the Jensen Hughes study [11] conducted for the NFPA FRPF, canola oil was found to produce smoke at the highest temperatures (275 °C to 280 °C) and reach ignition at the same or faster times and similar temperatures to other oils. Peanut oil was also found to have similar ignition behavior. These two oils were chosen for the NIST study because they presented a challenge to the use of photoelectric smoke detection technology with late, high-temperature smoke production and similar or slightly earlier ignition times as other oils. The amount of oil chosen was 300 mL ± 3 mL which matched that used by Dinaburg and Gottuk for their Phase 2 study [11]. This amount of oil created a 6.4 mm (¼ in) depth in the pan.

Bacon was selected as a meat for unattended cooking because it tends to produce smoke and ignite relatively early compared to cooking oils. The cooking of bacon also went through an attended process (initial few minutes of heating) before continued heating would be considered unattended. Bacon often caused unwanted nuisance smoke alarm activation in rooms adjoining kitchens even during an attended cooking process. The bacon was kept frozen but thawed before testing. The amount of bacon used was 224 g ± 2 g. Figure 6 shows a photograph of bacon arranged in the pan prior to heating during Test 4.

Figure 6 A photograph of bacon arranged in the pan at the beginning of Test 4.

Frying hamburgers was selected as a surrogate for food undergoing attended cooking because, even while attended, it often produces smoke that can activate smoke alarms in adjacent rooms. The hamburger patties were frozen and not thawed before cooking. Each hamburger patty

weighed 112 g ± 1 g prior to cooking. Sets of two and three hamburgers were also tested in case they produced more smoke than a single hamburger.

2.10 Experimental plan

Table 1 is the test matrix for the experimental series. The table lists the number of the experiments, type of food, and status of the range hood. Unattended cooking experiments were conducted first, followed by the attended cooking experiments. Cases were repeated to allow statistical analysis.

Table 1 Test Matrix. Experimental conditions are listed for each experiment.

Unattended Cooking			Attended Cooking		
Test No.	**Food**	**Range Hood**	**Test No.**	**Food**	**Range Hood**
1	Canola Oil	Off	16	1 Hamburger	Off
2	Canola Oil	Off	17	2 Hamburgers	Off
3	Peanut Oil	Off	18	2 Hamburgers	Off
4	Bacon	Off	19	3 Hamburgers	Off
5	Canola Oil	On	20	1 Hamburger	Off
6	Peanut Oil	On	21	1 Hamburger	Off
7	Canola Oil	On			
8	Peanut Oil	On			
9	Peanut Oil	Off			
10	Peanut Oil	On			
11	Peanut Oil	Off			
12	Canola Oil	Off			
13	Canola Oil	On			
14	Bacon	Off			
15	Bacon	Off			

2.11 Experimental procedures

The detailed experimental procedures are included in Appendix A. Key steps were to initialize the smoke detectors, start data acquisition to record background voltages, start the video cameras, and start the clock timer at the same time as the range burner was energized at the highest setting. Upon ignition of the food, the range was de-energized using the circuit breaker outside of the lab. As can be seen from the fire shown in Figure 7 (ignited peanut oil), extinguishment was needed quickly after ignition to prevent damage to the range hood and smoke detector. Extinguishment was accomplished by pouring a cup of baking into the pan of burning food. This was done remotely through a hole in the laboratory wall with a rod supported by a ring stand. A mass of 500 g of baking soda were used for each ignition. Upon extinguishment, the room hood flow was increased from a low to high level to vent smoke.

Hamburgers were cooked to represent normal attended, but sometimes smoky, cooking, and the procedure for cooking one hamburger was taken from the method used by Cleary [14] for

nuisance smoke detector alarms. The procedure was as follows: set the burner on high for 3 min, change the setting to medium for 3 min, flip the hamburger and maintain on medium for 3 min 30 s before turning off the burner. For the first experiment with two hamburgers, the procedure for a single hamburger was repeated, but the combination of heat and timing was not sufficient to cook the two hamburgers to well-done and did not produce much smoke. For the second experiment with two hamburgers, the first stage of high heat was 3 min 45 s, the second stage of medium heat was also 3 min 45 s, and the burner was maintained on medium heat for 4 min 15 s after flipping the hamburgers. The procedure for cooking three hamburgers used 4 min on high, 4 min on medium, and 5 min on medium after flipping. Figure 8 shows two hamburgers in the pan at the beginning of Test 18. Figure 9 shows the same two hamburgers after completion of the experiment.

Figure 7 Ignited peanut oil during Test 10 before extinguishment.

Figure 8 A photograph of two hamburgers prior to being heated during Test 18.

Figure 9 A photograph of two hamburgers after heating during Test 18.

3. RESULTS AND DISCUSSION

3.1 Time to ignition comparisons

Figure 10 shows pan temperatures plotted versus heating time for the canola oil experiments. Time measurements for this study have an expanded uncertainty (coverage factor of 2) of about ± 1 s. Ignition occurred in the range of 589 s to 646 s after heating began. The pan temperatures at ignition ranged from 415 °C to 430 °C. Figure 11 shows a similar plot for the temperature of the canola oil itself. The canola oil ignition temperatures ranged from 384 °C to 395 °C.

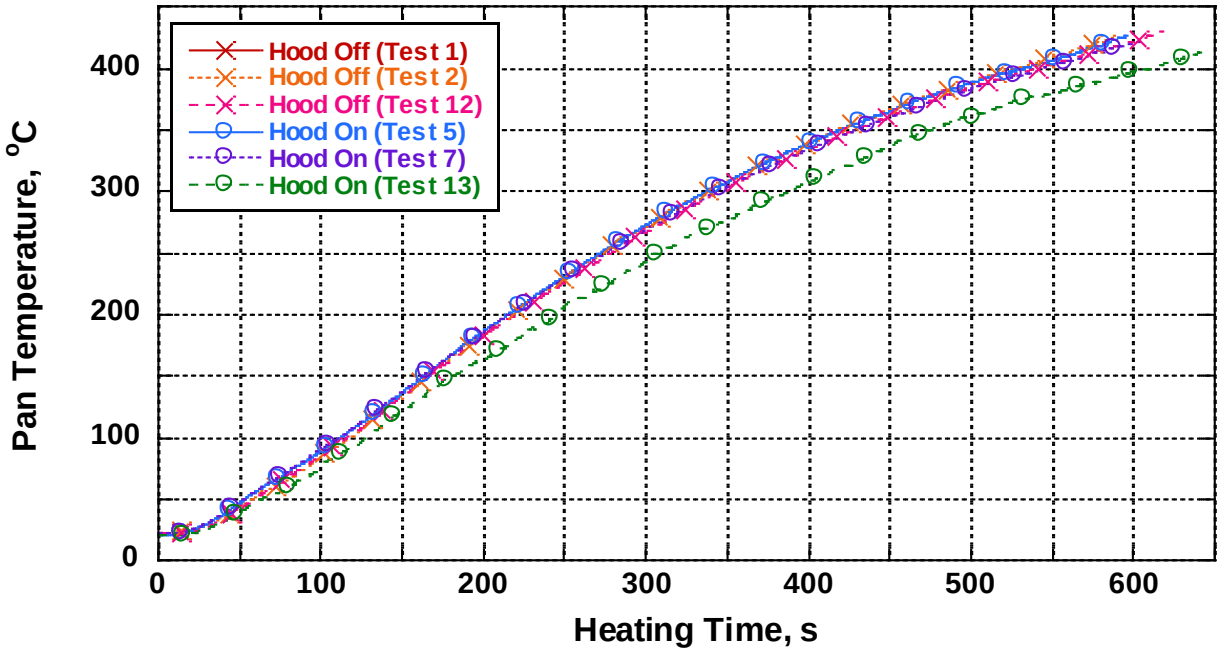

Figure 10 Pan Temperatures versus heating time for canola oil tests.

Figure 12 shows pan temperatures plotted versus heating time for the peanut oil experiments. Ignition occurred in the range of 514 s to 667 s after heating began. The pan temperatures at ignition ranged from 388 °C to 436 °C. Figure 13 shows a similar plot for the temperature of the peanut oil itself. The peanut oil ignition temperatures ranged from 349 °C to 398 °C.

Figure 14 shows pan temperatures plotted versus heating time for the bacon experiments. Ignition occurred in the range of 634 s to 667 s after heating began. The pan temperatures at ignition ranged from 374 °C to 436 °C. Figure 15 shows a similar plot for the temperature of the bacon itself. The bacon ignition temperatures ranged from 370 °C to 414 °C. The temperature curves for the bacon experiments are qualitatively different than those for cooking oils in that there is a steady period related to the heating and vaporization of water. Also, the thermocouple used to measure the bacon temperature was not always in the same extent of contact with the bacon or grease since the bacon moved and changed shape during the heating process. This may explain the qualitatively different temperature evolutions shown for the three experiments.

For both oils and the bacon, the temperature of the foodstuff lagged the temperature of the pan with a typical difference of 25 °C to 50 °C after the first 2 min of heating. The ignition times, ignition temperatures, and differences between pan and food temperature are comparable to those found in the Jensen Hughes study [11]. The status of the range hood being on or off did not have a consistent nor measurable effect on ignition times or temperatures.

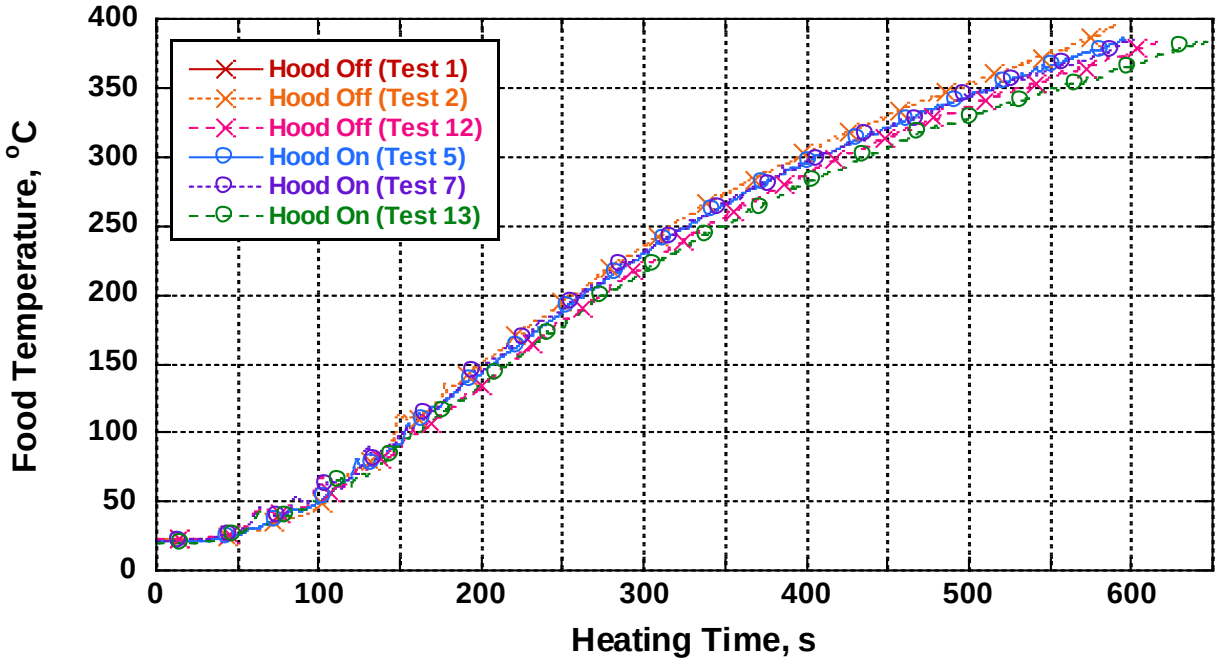

Figure 11 Food temperatures versus heating time for canola oil tests.

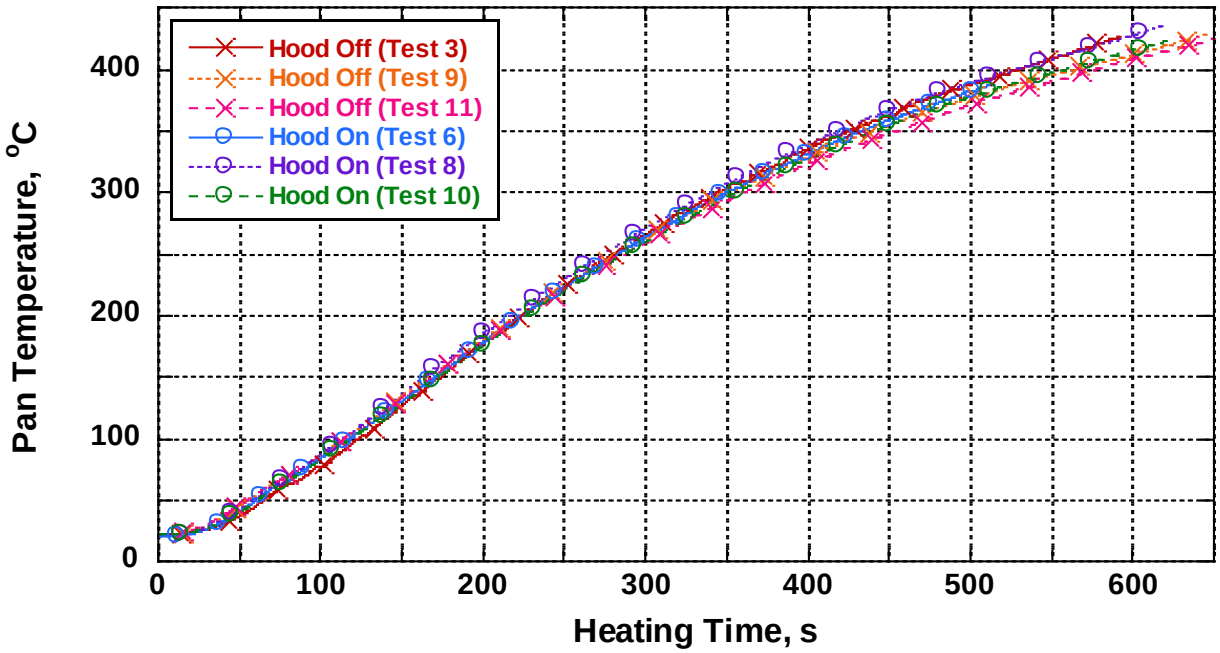

Figure 12 Pan temperatures versus heating time for peanut oil tests.

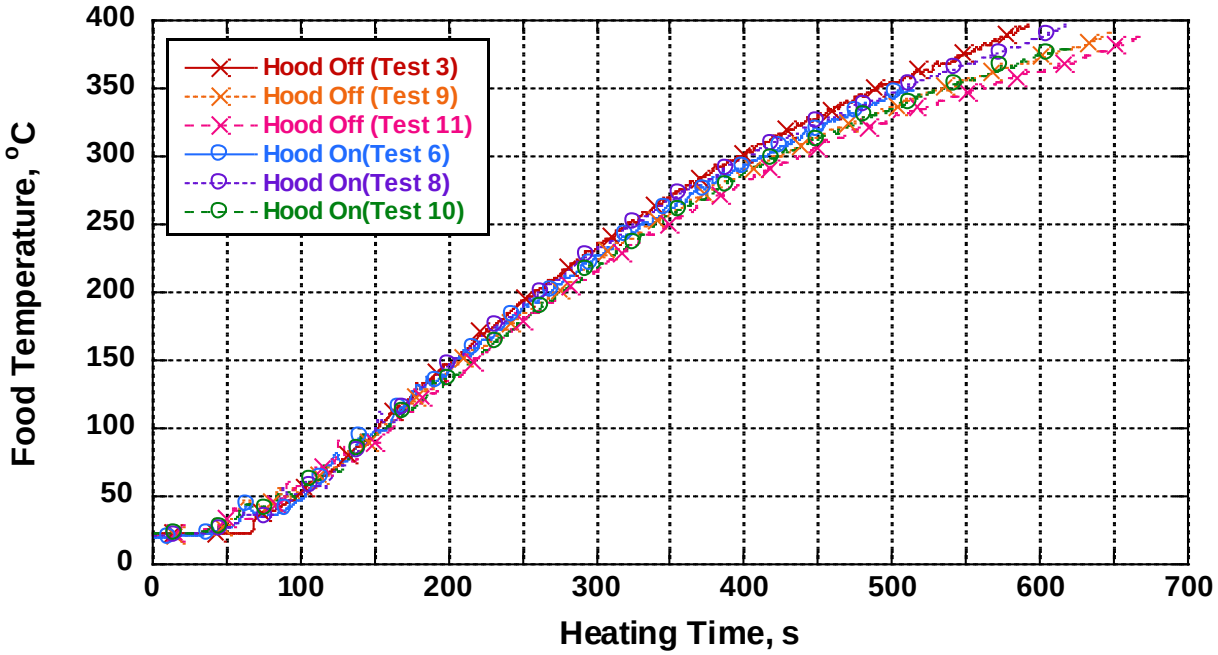

Figure 13 Food temperatures versus heating time for peanut oil tests.

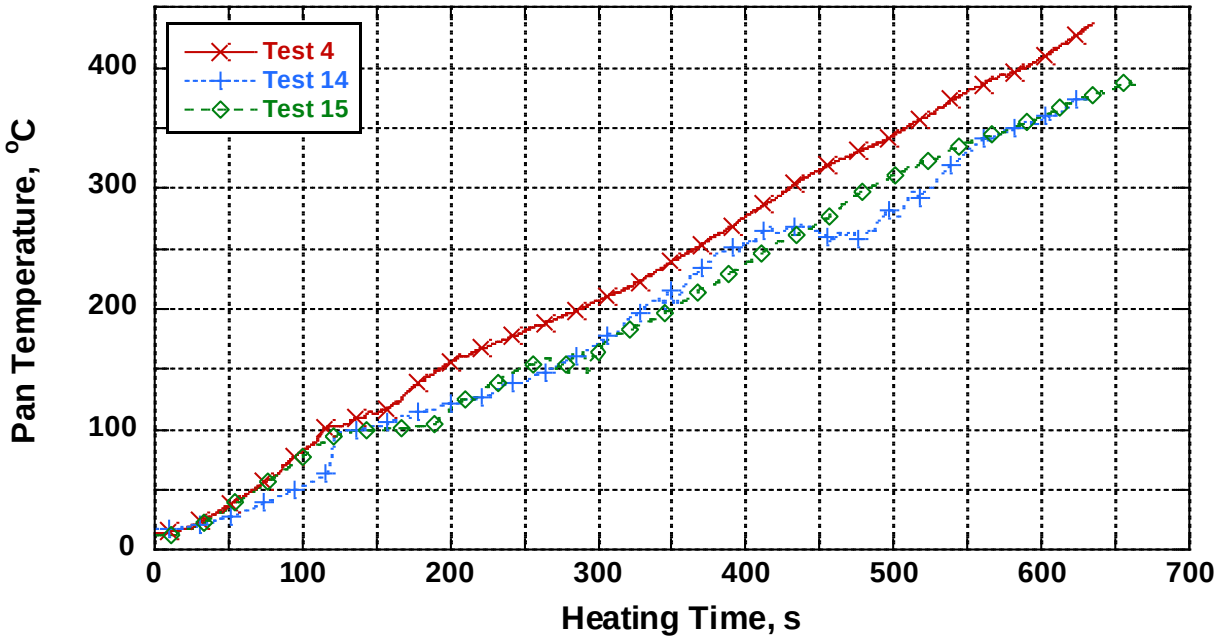

Figure 14 Pan temperatures versus heating time for bacon tests.

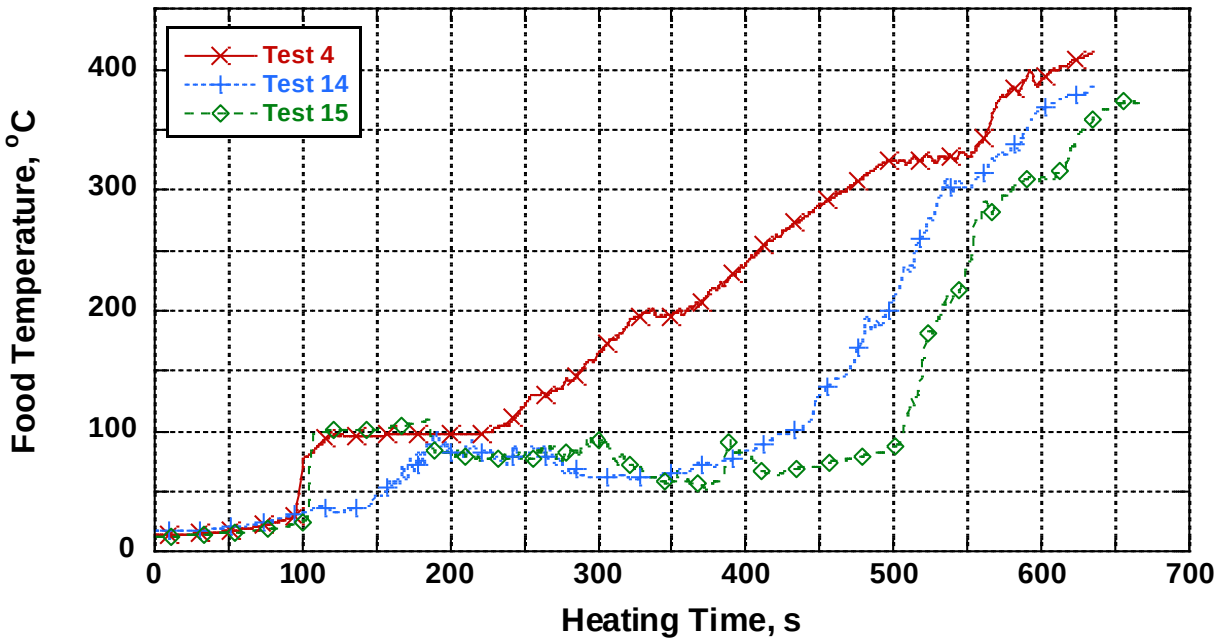

Figure 15 Food temperatures versus heating time for bacon tests.

Table 2 lists the results for time and food temperature at ignition for all of the experiments. Figure 16 is a plot of the food temperatures and duration of heating time at ignition for all of the experiments. Solid symbols represent the data for experiments with the range hood off. Symbols with the same color and shape are for experiments using the same foodstuff. There is no clear pattern of difference in ignition time or temperature related to the hood status. The plot does show similarly wide ranges of time and temperature for all of the foods tested. Peanut oil generally (but not always) had higher ignition temperatures than canola oil. This is consistent with what was found in the Jensen Hughes study [11].

Table 2 List of ignition times and food temperatures for various food types and hood conditions

Food	Hood	Time to Ignition (min:s/s)	Food Temp. at Ignition (°C)	Food	Hood	Time to Ignition (min:s/s)	Food Temp. at Ignition (°C)
Canola Oil	Off	9:17/557	297.3	Peanut Oil	Off	11:07/667	389.5
Canola Oil	Off	9:49/589	395.3	Peanut Oil	On	10:32/632	349.3
Canola Oil	Off	10:18/618	386.9	Peanut Oil	On	10:20/620	398.0
Canola Oil	On	9:56/596	385.4	Peanut Oil	On	10:32/632	380.9
Canola Oil	On	10:03/603	384.4	Bacon	Off	10:34/634	414.1
Canola Oil	On	10:46/646	384.3	Bacon	Off	10:34/634	385.9
Peanut Oil	Off	9:52/592	397.7	Bacon	Off	11:07/667	370.4
Peanut Oil	Off	10:49/649	391.5				

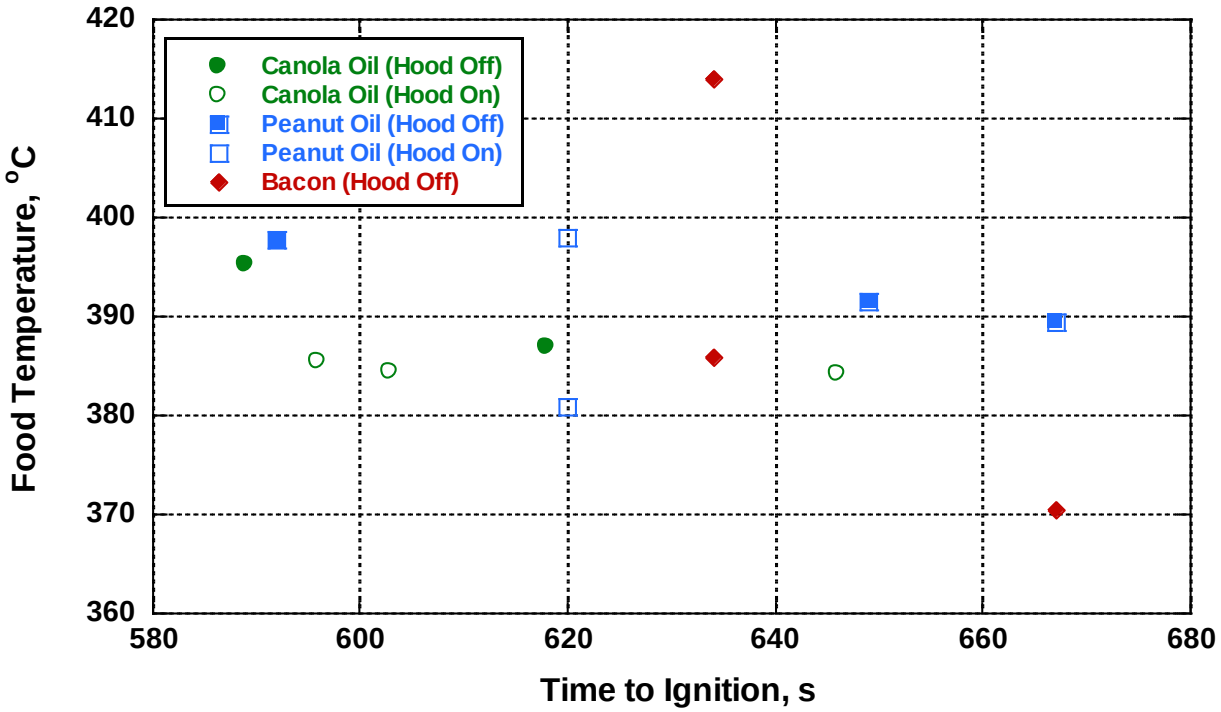

Figure 16 Food temperature versus ignition time for all experiments

3.2 Smoke meter responses

Obscuration expressed as %/ft is used as it is the industry standard measurement unit [15] and allows differentiation of high obscuration levels. Equation 1 used for obscuration is below:

Equation 1

$$\text{obscuration (\%/ft)} = (1-(I/Io)^{1/Lf}) \times 100$$

where Lf is the path length in feet

Table 3 below presents the conversion of English units to SI units for select obscuration values for an example system using simple intensities.

Table 3 Obscuration equivalences between English and SI units

Initial Intensity, Io	Intensity, I	Path Length, Lf (ft)	Path Length, Lf (m)	Obscuration, obs (%/ft)	Obscuration, obs (%/m)
10	9	3.28	1	3.2	10
10	8	3.28	1	6.6	20
10	6	3.28	1	14.4	40
10	4	3.28	1	24.4	60
10	2	3.28	1	38.8	80
10	1	3.28	1	50.4	90
10	0.5	3.28	1	59.9	95
10	0.1	3.28	1	75.4	99

Figure 17 is a plot of the laser light obscuration of the smoke meter located above the range burner versus time for all of the canola oil experiments. It is not known why the results for tests 1 and 2 reached higher obscuration levels earlier than the other tests. Those tests also reached ignition earlier and had qualitatively similar shapes as the other tests except for being compressed in time by 30 s to 80 s or 5 % to 13 %. The difference does not appear to be related to the hood status since test 12's obscuration curve (with the hood off) was nearly identical to those with the hood on.

Figure 18 is similar to the previous plot except it is for the peanut oil experiments. The obscuration curves are closer to each other with less variation for peanut oil compared to canola oil. Figure 19 is the corresponding plot for the bacon experiments. Tests 4 and 15 showed similar behavior to each other while Test 14 produced higher obscuration levels, sometimes as much as three times higher, earlier in the experiment.

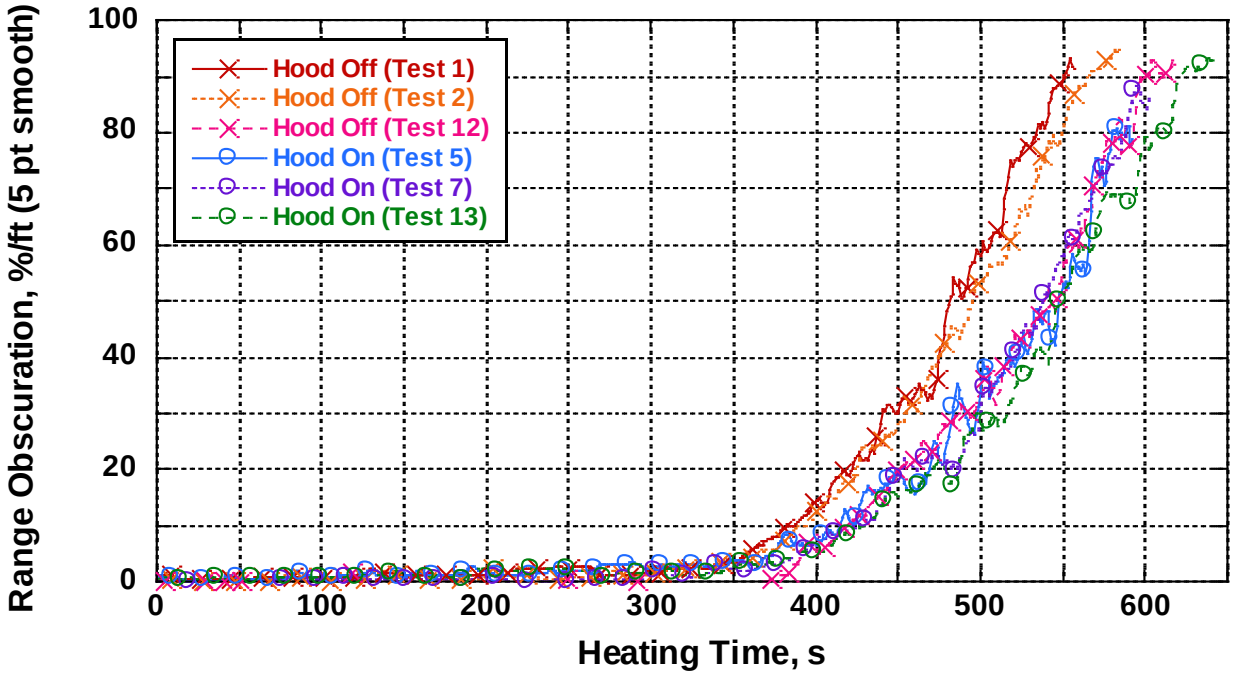

Figure 17 Obscuration versus heating time for canola oil for the smoke meter above the range.

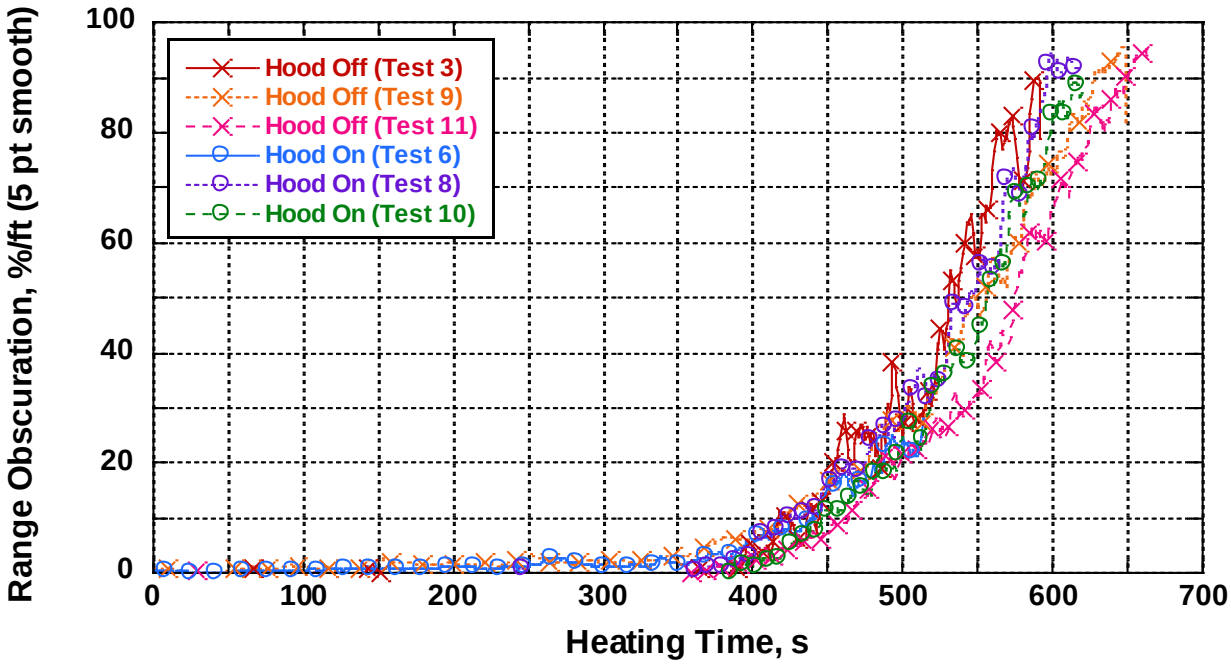

Figure 18 Obscuration versus heating time for peanut oil for the smoke meter above the range.

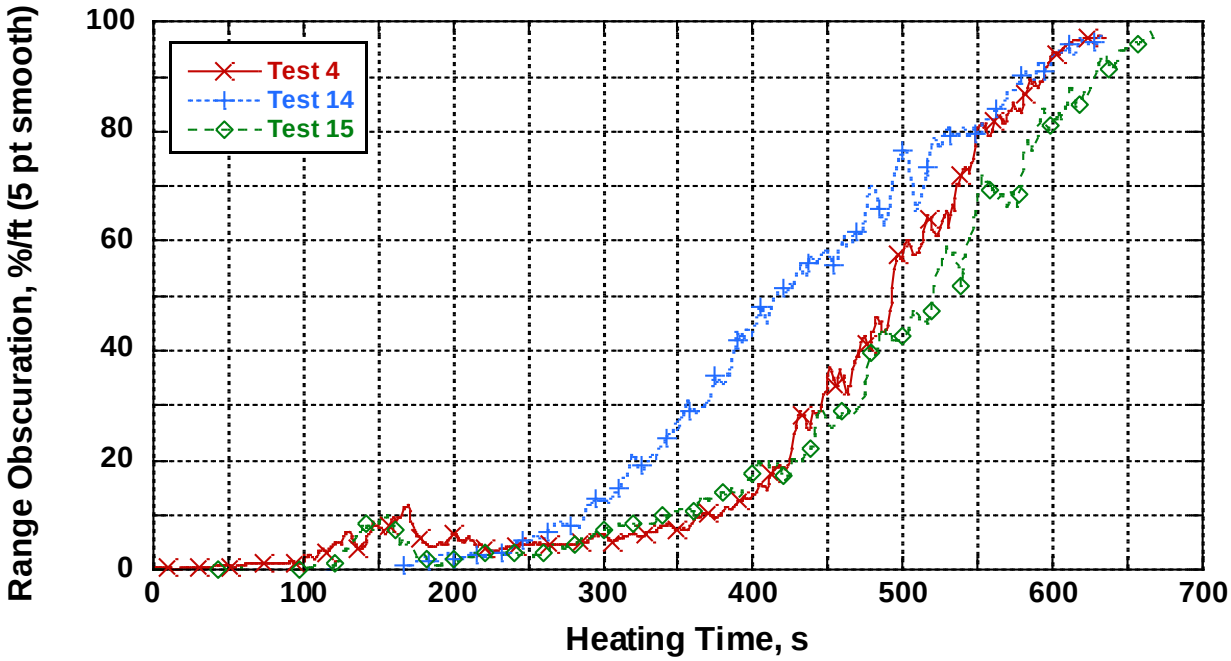

Figure 19 Obscuration versus heating time for bacon for the smoke meter above the range.

Figure 20 is a plot of the laser light obscuration of the smoke meter located on the ceiling versus time for all of the canola oil experiments. At the ceiling measurement position, the experiments with the hood off clearly produced more smoke than those with the hood on. This result was intuitively expected due to the removal of some of the cooking plume smoke via the range hood when it was on. Figure 21 is similar to the previous plot except it is for the peanut oil

experiments. Similar to the range-located smoke meter results, the ceiling obscuration curves are closer to each other with less variation for peanut oil compared to canola oil. There is no distinct difference between experiments with different range hood statuses. Figure 22 is the corresponding plot for the bacon experiments. At the ceiling location, the similarity between Tests 4 and 15 seen for the range location is less pronounced and the higher obscuration levels produced at the range early during Test 14 are still apparent, but only up to about two times as high as the levels for the other experiments.

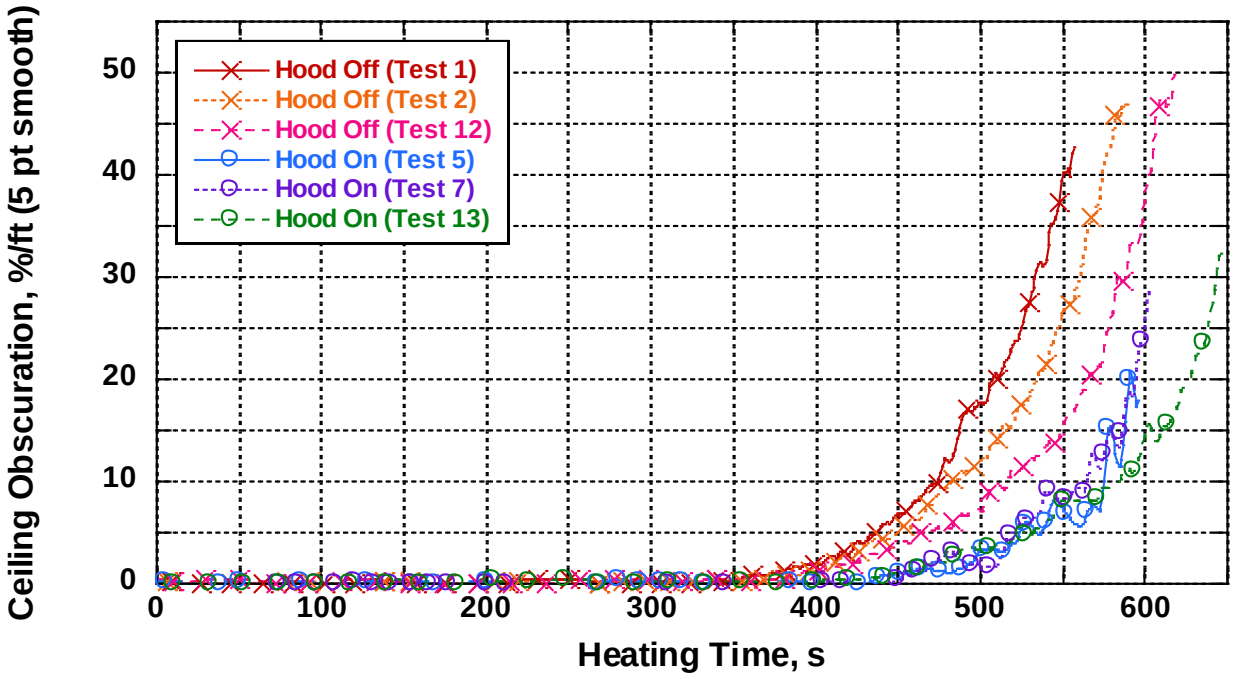

Figure 20 Obscuration versus heating time for canola oil for the smoke meter on the ceiling.

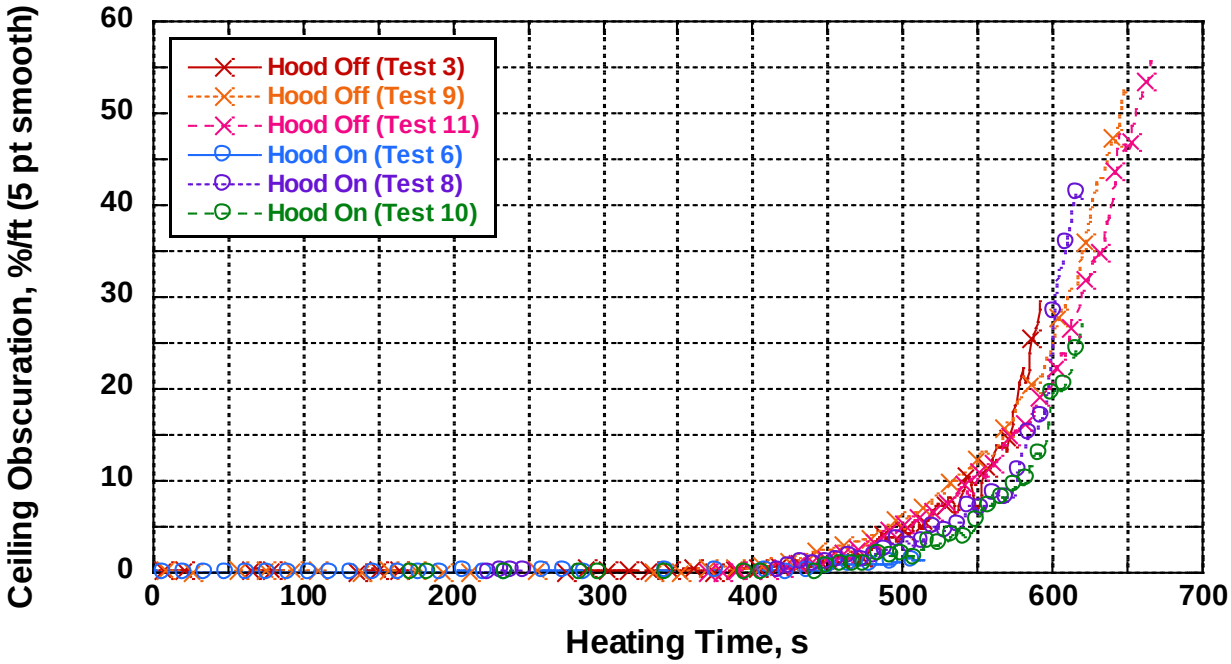

Figure 21 Obscuration versus heating time for peanut oil for the smoke meter on the ceiling.

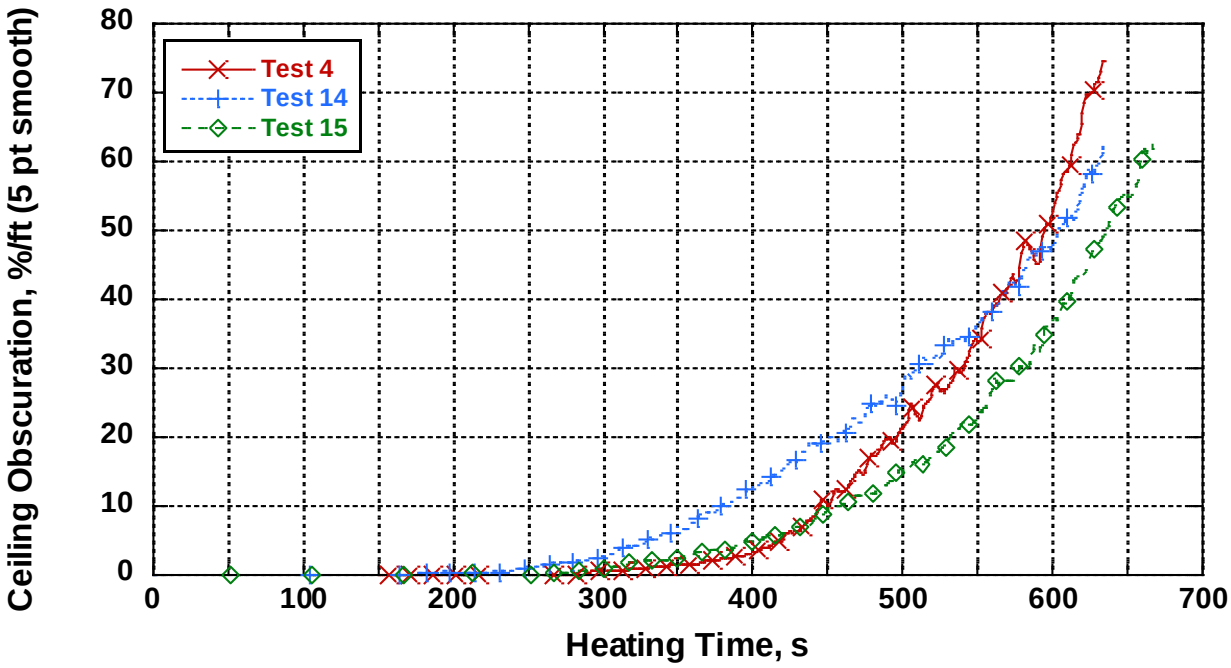

Figure 22 Obscuration versus heating time for bacon for the smoke meter on the ceiling.

Figure 23 is a plot of the laser light obscuration of the smoke meter located on the wall versus time for all of the canola oil experiments. At the wall measurement position, like the results for the ceiling position, the experiments with the hood off clearly produced more smoke than those with the hood on. Again, this was expected due to the removal of some of the cooking plume smoke by the active range hood. The experiments with the range hood off have a lot more

variation from test to test than those with the range hood on. This is even more pronounced at the wall location than it was at the ceiling. The obscuration-time curves with the hood on nearly lie on top of each other.

Figure 24 is similar to the previous plot except it is for the peanut oil experiments. Similar to the range- and ceiling-located smoke meter results, the wall obscuration curves are closer to each other with less variation for peanut oil compared to canola oil. However, for the wall location, there is a discernable difference between experiments with different range hood statuses. The experiments with the hood off do show slightly higher smoke levels than the experiments with the hood on. Figure 25 is the corresponding plot for the bacon experiments. At the wall location, the obscuration-time curves are very similar to those for the ceiling location.

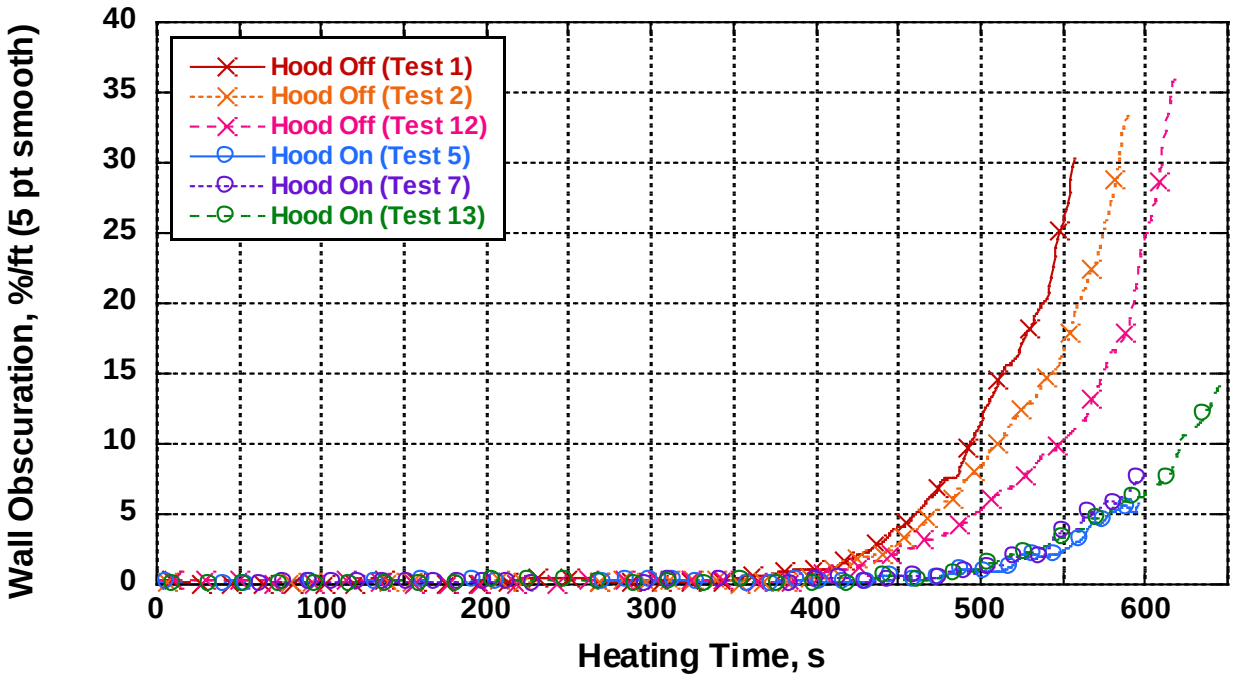

Figure 23 Obscuration versus heating time for canola oil for the smoke meter on the wall.

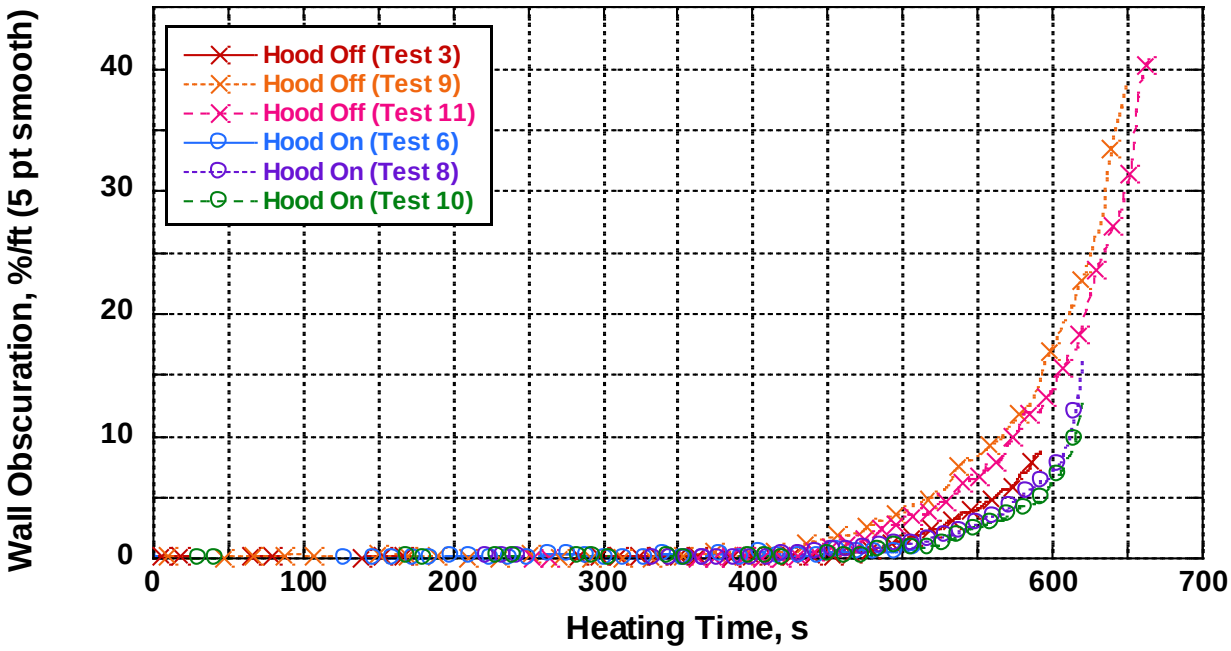

Figure 24 Obscuration versus heating time for peanut oil for the smoke meter on the wall.

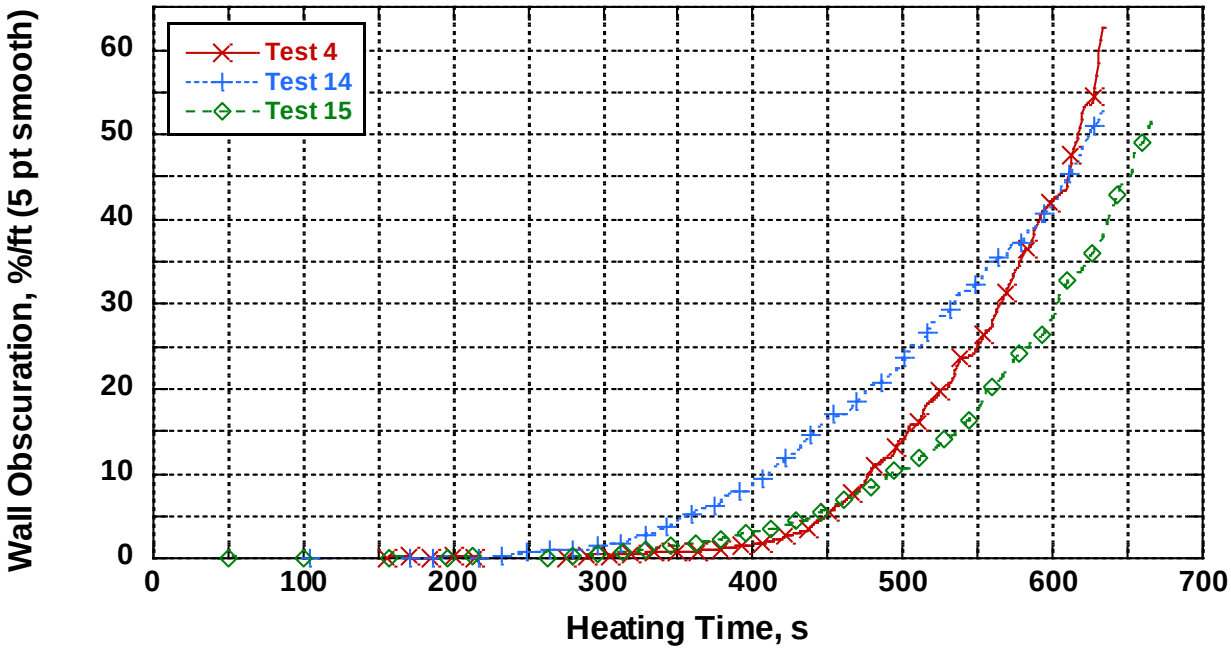

Figure 25 Obscuration versus heating time for bacon for the smoke meter on the wall.

3.3 Attended cooking smoke levels

Figure 26 is a plot of the laser light obscuration of the smoke meter located above the range versus time for all of the hamburger experiments. The single hamburger experiments show the most repeatability, but this is due to the variation in the cooking procedure for two and three hamburgers. The last experiment with two hamburgers (Test 18) did produce the same amount of smoke as the experiments with one. By the last 2 min of the experiment with three hamburgers (Test 19), similar obscuration levels were reached as those achieved with one hamburger. The highest smoke obscuration levels at the range for any of the hamburger experiments were about 6.8 %/m (11 %/ft).

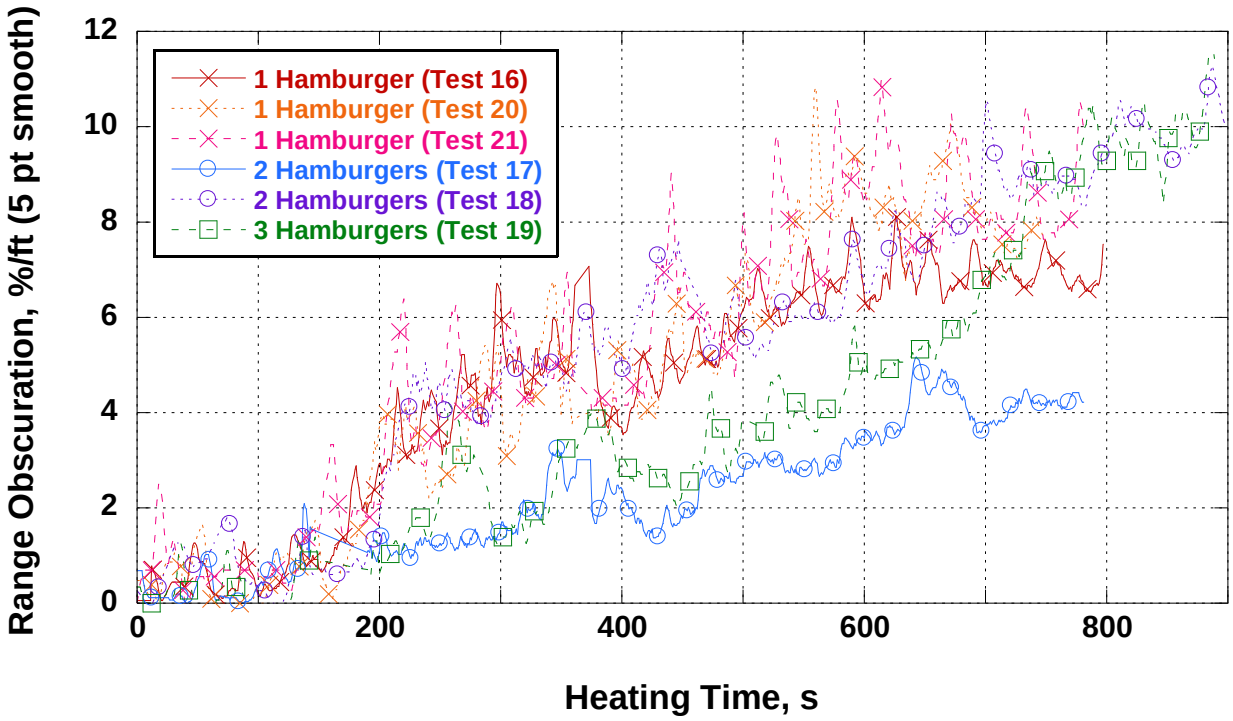

Figure 26 Obscuration versus heating time for hamburgers for the smoke meter above the range.

Figure 27 is a plot of the laser light obscuration of the smoke meter located on the ceiling versus time for all of the hamburger experiments. The single hamburger experiments again showed the most repeatability, especially during the first 7 min. The obscuration for the second experiment with two hamburgers (Test 18) tracked the single-hamburger experiments' obscuration for the first 6 min before exhibiting slightly lower levels for the remaining time. The experiment with three hamburgers (Test 19) produced about one third of the smoke level produced by the single hamburger experiments. The highest sustained smoke obscuration levels at the ceiling for any of the hamburger experiments were about 6.4 %/m (2 %/ft), but there were excursions to about 15 %/m (5 %/ft) during the flipping operation. Figure 28 is the comparable plot for the smoke meter located on the wall. The wall obscuration levels are similar to those at the ceiling except the highest are truncated by about 20 %. This make sense due to the dilution of the smoke as it descends from the ceiling and forms a thicker layer. The peaks related to flipping were also broadened at the wall location.

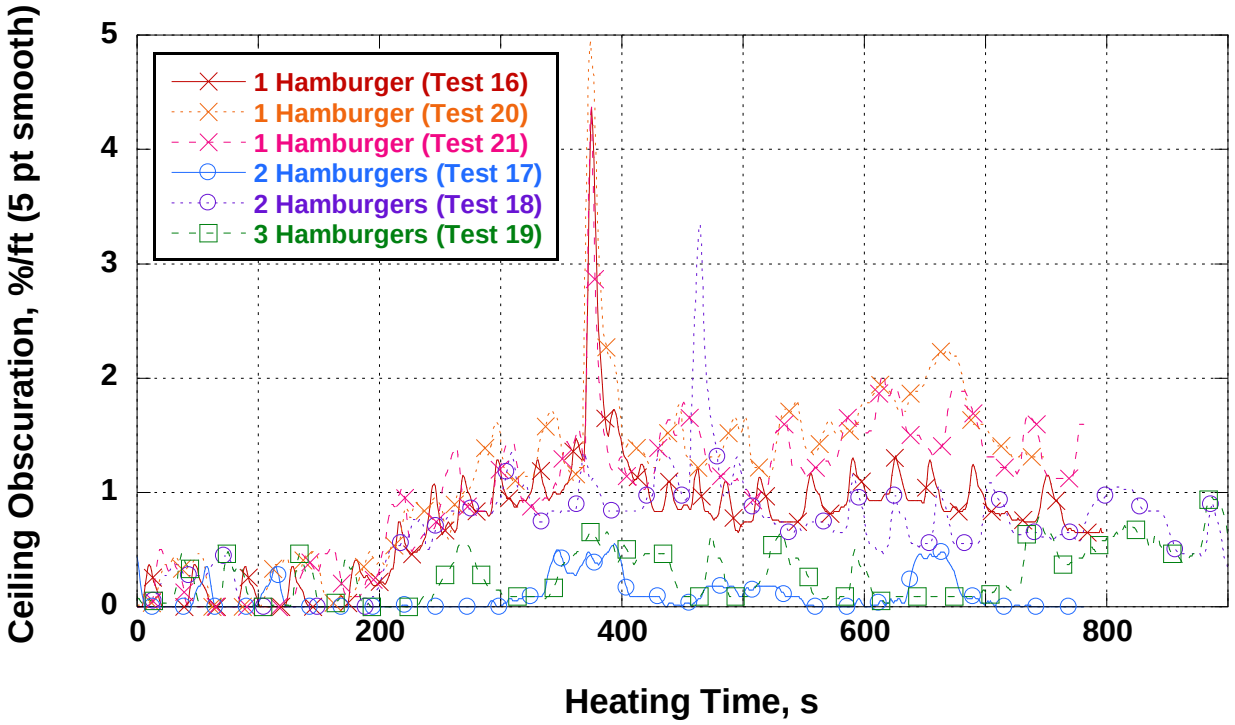

Figure 27 Obscuration versus heating time for hamburgers for the smoke meter on the ceiling.

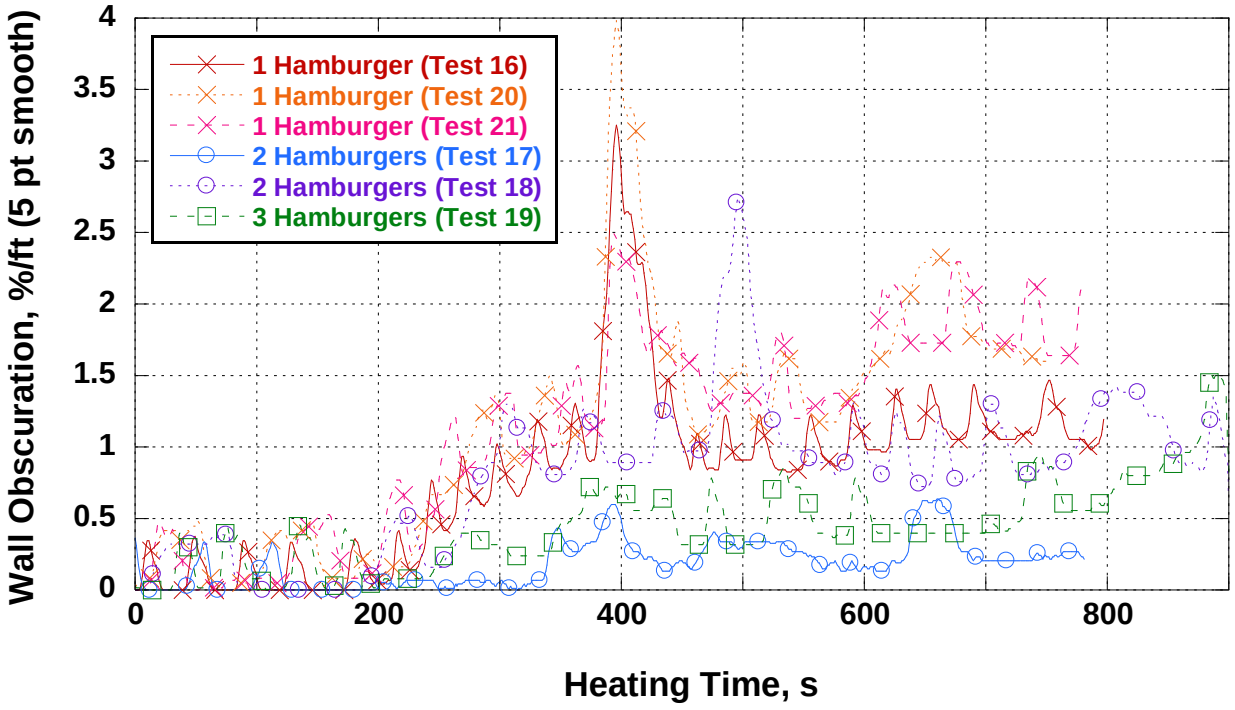

Figure 28 Obscuration versus heating time for hamburgers for the smoke meter on the wall.

3.4 Time window after attended cooking before ignition

The reason for conducting experiments that represent attended, yet smoky, cooking as well as those that represent unattended cooking and led to ignition is to determine if there is a sufficient difference between the smoke levels long enough before ignition to provide an alarm or warning threshold. It is important that the threshold is above maximum normal cooking obscuration levels so nuisance warnings are not experienced. The threshold should also be at minimum obscuration levels achieved during unattended cooking to allow the most time available for warning and manual shutdown or automated shutdown before ignition occurs.

Figure 29 is a plot of the minimum obscuration levels for the smoke meter located above the range for all of the experiments versus time before ignition. The time before ignition axis starts with 2 min before ignition on the left and ignition at 0 s on the right. The line drawn across the bottom of the plot is the maximum obscuration at the range at any time during any of the hamburger experiments. The plot shows that for the range smoke meter position that captures the obscuration due to the smoke plume, all of the minimum obscurations for the different foods even as long as 2 min before ignition are still higher than the maximum obscuration produced by any of the hamburger experiments. Figure 30 is a photograph just after ignition during a bacon experiment (Test 15), which shows how much smoke is visible near the range and provides a visual representation of the extremely high obscuration level.

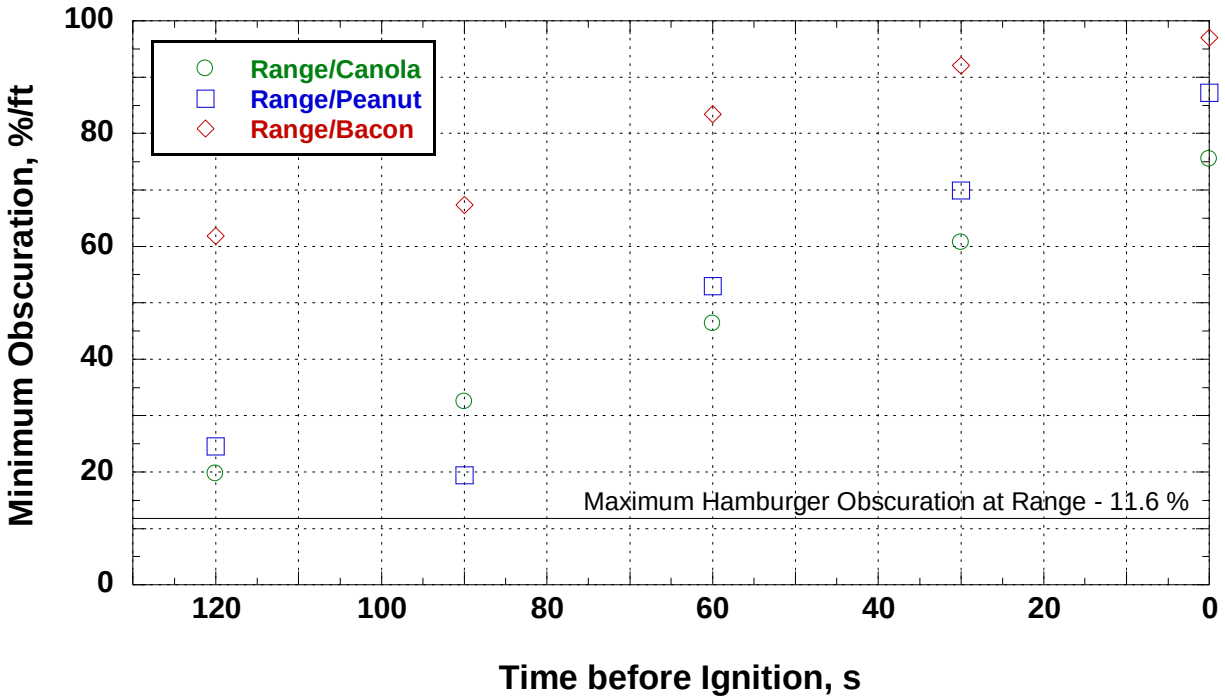

Figure 29 Minimum obscuration for the range smoke meter location plotted versus time before ignition. The maximum obscuration at the range location is shown for all of the hamburger experiments.

Figure 30 A photograph of ignited bacon during Test 15 showing the visual obscuration of the laboratory due to accumulated smoke.

Figure 31 is similar to the previous figure and is a plot of the minimum obscuration levels for the smoke meter located on the ceiling for all of the experiments versus time before ignition. This time, the line drawn across the bottom of the plot is the maximum obscuration at the ceiling at any time during any of the hamburger experiments. The plot shows that for the ceiling smoke meter position, which captures smoke as it starts to build a layer, all of the minimum obscurations for the different foods at 1 min before ignition and later are higher than the maximum obscuration produced by any of the hamburger experiments. This reveals that a time window on the order of 1 min is available at the ceiling location, during which a warning threshold could indicate approaching ignition without also being triggered by nuisance smoke levels.

Figure 32 is similar to the previous figure but is for the wall location. The line drawn across the bottom of the plot is the maximum obscuration at the wall location at any time during any of the hamburger experiments. The plot shows that for the wall smoke meter position, which sees smoke after it has been further diluted (compared to at the ceiling) and descended as a thickening smoke layer, the minimum obscurations for the different foods are only greater than the maximum hamburger obscurations about 30 s to 35 s before ignition. This shows that a time window only on the order of 30 s is available at the wall location when a warning threshold

could indicate approaching ignition without also being triggered by nuisance smoke levels. This is still sufficient time for a burner to be de-energized even accounting for the continued heating and increasing temperature (overshoot) of the pan and food after power is cut. This overshoot period was found to be about 5 s [11].

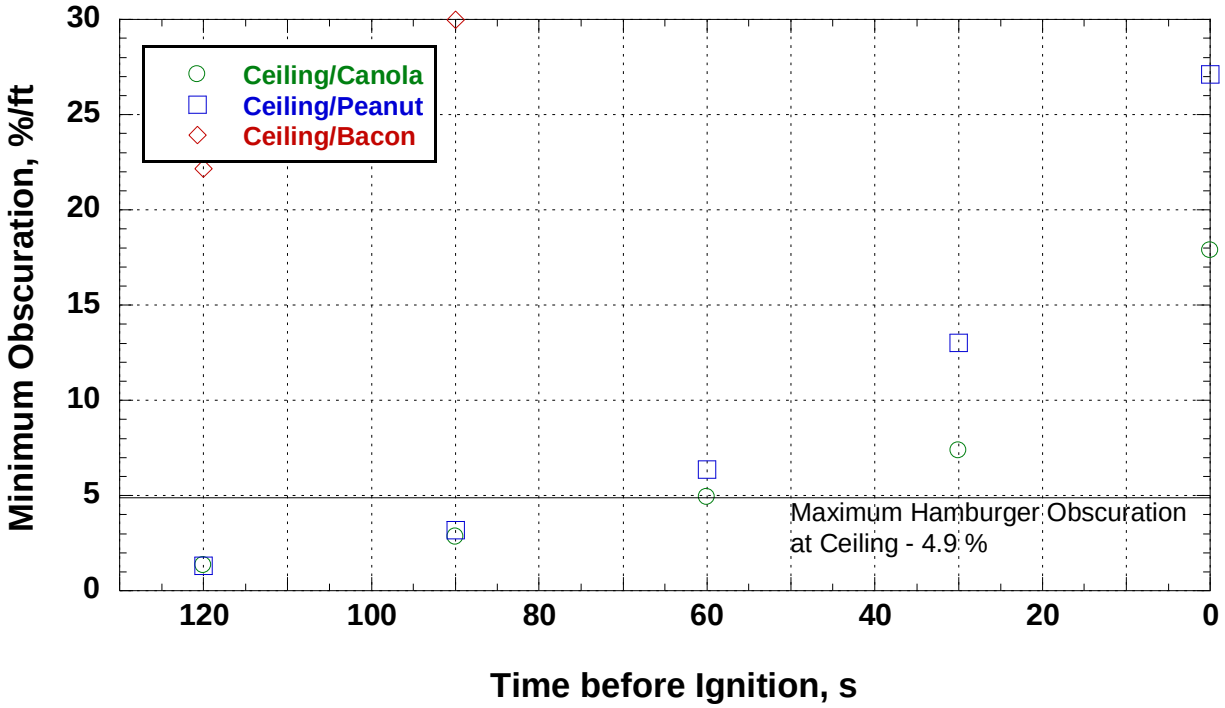

Figure 31 Minimum obscuration for the ceiling smoke meter location plotted versus time before ignition. The maximum obscuration at the ceiling location is shown for all of the hamburger experiments. Some bacon data points are higher than the range displayed.

3.5 Smoke alarm responses

Three photoelectric smoke detectors (range, ceiling, and wall locations) and one ionization detector (wall location) were installed to see what their response was to initial and attended smoke levels as well as how they behaved when smoke levels far exceeded their alarm thresholds during unattended cooking. Access to the smoke detectors' raw signals was enabled by the manufacturer. Unfortunately, the signals were not consistently indicative of when the detectors reached their alarm states and also did not continue to output magnitudes that were proportional or relatable to the higher laser obscurations. This would be consistent with the detectors being tuned to use most of their dynamic sensing range below the alarm threshold which might limit the response to higher smoke concentrations.

The detectors were useful in showing their sensitivity early in the unattended cooking experiments and especially for the attended hamburger experiments. Table 4 lists all of the experiments grouped by food and hood status (red for off and green for on). Within each grouping, the experiments are ordered by increasing time to ignition. Alarm times for the photoelectric smoke detector at the range are listed. These alarms could be confirmed by the video recordings. Also listed are the alarm times for distant smoke detectors. These could not

be easily distinguished from each other and so are grouped together. The results show that the range-located detector consistently alarmed 2 min to 4 min before ignition. The distant detectors sometimes alarmed earlier, but typically alarmed within 2 min of the range detector alarm. Except for a couple of cases, the distant alarm times for experiments with the range hood on were delayed a minute or two compared to those with the hood off. For the range detector, the difference due to the hood status was less pronounced. These results indicate that although the smoke detectors used were not detuned with higher alarm thresholds to prevent false alarms, they performed well at providing sufficiently early warning of approaching ignition.

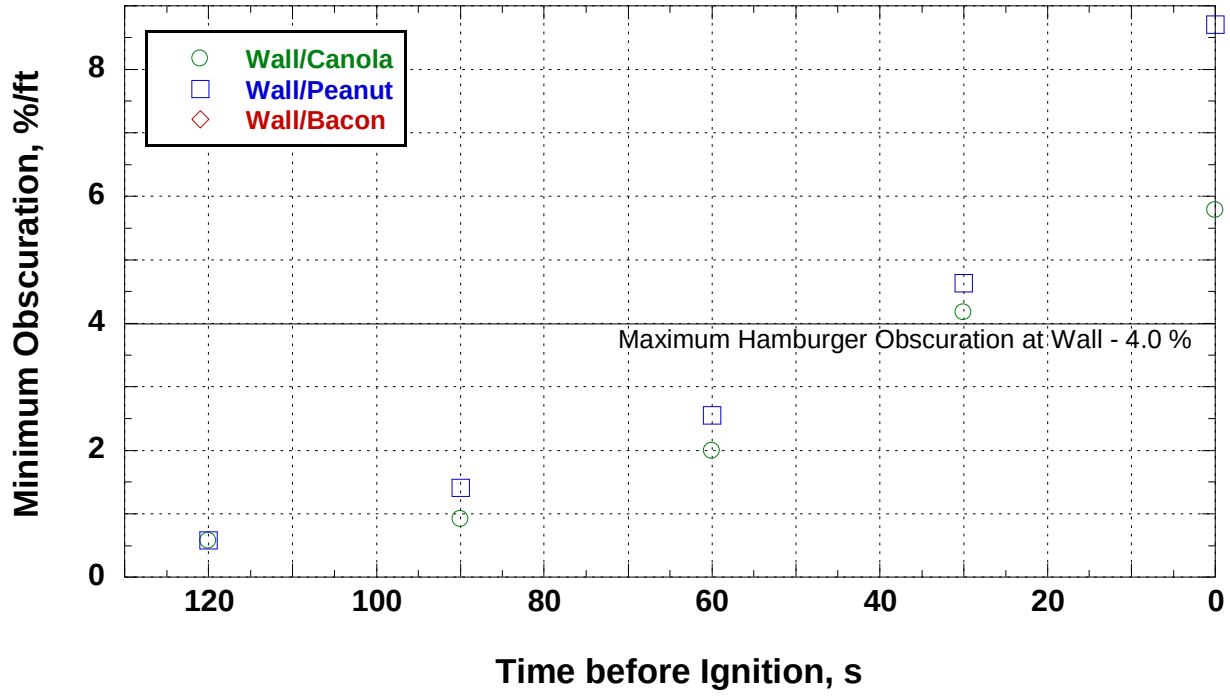

Figure 32 Minimum obscuration for the wall smoke meter location plotted versus time before ignition. The maximum obscuration at the wall location is shown for all of the hamburger experiments. Some bacon data points are higher than the range displayed.

Table 4 Smoke detector (SD) response times and ignition times for all foods and hood conditions.

Food [Test no.]	Hood	Time to Ignition (min:s)	Alarm Time for SD near stove (min:s)	Alarm Time for Distant SD (min:s)
Canola Oil [1]	Off	9:17	6:09	6:04
Canola Oil [2]	Off	9:49	6:09	7:02
Canola Oil [12]	Off	10:18	6:22	6:44
Canola Oil [5]	On	9:56	6:40	2:50
Canola Oil [7]	On	10:03	6:35	8:26
Canola Oil [13]	On	10:46	8:21	7:51
Peanut Oil [3]	Off	9:52	7:44	7:32
Peanut Oil [9]	Off	10:49	6:32	7:07
Peanut Oil [11]	Off	11:06	6:31	7:24
Peanut Oil [8]	On	10:20	6:35	8:17
Peanut Oil [10]	On	10:20	7:19	8:34
Peanut Oil [6]	On	10:32	6:29	8:39
Bacon [14]	Off	10:34	3:30	3:53
Bacon [4]	Off	10:34	5:47	6:55
Bacon [15]	Off	11:07	4:52	5:43
Hamburger (1) [16]	Off		4:38	4:26
Hamburger (1) [20]	Off		3:43	4:16
Hamburger (1) [21]	Off		no alarm	no alarm
Hamburgers (2) [17]	Off		no alarm	no alarm
Hamburgers (2) [18]	Off		4:27	4:59
Hamburgers (3) [19]	Off		no alarm	no alarm

4. SUMMARY AND CONCLUSIONS

4.1 Summary

Experiments were conducted to examine the potential to use photoelectric smoke measurement devices to warn of approaching ignition of food during unattended cooking. A mock-up kitchen was installed with an electric range, range hood, and cabinets. Research smoke meters utilizing laser attenuation were installed above the food, on the ceiling, and on the upper wall. Standard off-the-shelf photoelectric and ionization smoke detectors were also installed at the same locations to assess if their sensor outputs could track smoke levels beyond their alarm thresholds. Pan and food temperatures were recorded along with digital videos of the experiments. Cooking oils (canola and peanut) and bacon were heated to ignition. Standard hamburger experiments were also conducted to compare smoke levels from attended, but smoky, cooking to the unattended cooking smoke. The following findings were observed:

- Similar qualitative results were found to the earlier NIST effort [3].
- Ignition temperature results were comparable to Jensen Hughes' results [11].
- Smoke production above the range usually reached unacceptably high obscuration levels greater than 52 %/m (20 %/ft) at least 2 min before ignition.
- A 2 min window was found between normal cooking smoke levels (for hamburgers) and approaching-ignition smoke levels from unattended cooking for smoke measured above and near the range burner.
- A 1 min window was found between normal cooking smoke levels (for hamburgers) and approaching-ignition smoke levels from unattended cooking for smoke measured at the ceiling.
- A 30 s window was found between normal cooking smoke levels (for hamburgers) and approaching-ignition smoke levels from unattended cooking for smoke measured on the wall.
- Standard threshold smoke detectors not designed for kitchen use alarmed minutes before ignition.
- Standard smoke detectors used for this study do not have the dynamic range to provide smoke measurement data beyond their programmed alarm threshold.

4.2 Conclusions and Future Work

There are useful time windows (which vary by measurement location) for differentiation of smoke obscuration levels generated by normal and unattended cooking situations that could be utilized to either (1) alert an occupant to return and de-energize the range or (2) interface with an automatic de-energizing device connected to the range. This limited set of data was conducted in a single kitchen configuration. Results in kitchens of different dimensions than the configuration used in this test series could be impacted by the larger or smaller kitchen volumes. Larger kitchen volumes could decrease/delay the obscuration concentrations resulting in less time between alarm and ignition. In addition, a maximum line voltage would accelerate heating and shorten the time windows.

Follow-on work is needed by industry and organizations working on increasing cooking fire safety to establish standards for kitchen-deployed unattended cooking alarms that are not

necessarily built into a range. Photoelectric (or ionization) devices might need to be detuned to alarm or activate de-energizing devices at much higher smoke levels to allow the detectors to be positioned in areas of higher smoke concentrations. Additional more severe or smoky normal cooking activities (e.g., stir frying) would need to be performed to ensure that the higher alarm thresholds are sufficiently high to not cause nuisance alarms. It will be important to clearly differentiate unattended cooking alarm devices designed for kitchen use from standard smoke detectors. Confusion in use of the two types of devices and installation in inappropriate locations would cause higher levels of undetected fires or nuisance alarms. While range-centric devices are gradually being developed along with standards, using smoke detection technology could more quickly and easily bring about significant decreases in residential cooking fires and their associated deaths, injuries, and structural damage.

5. ACKNOWLEDGEMENTS

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- Tom Cleary for his consultations, smoke detector expertise and connections, and his lab space;
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- Larry Ratzlaff of Kidde Safety for facilitating communication with detectors;
- Bob Backstrom, Tom Fabian of UL for helpful consultations;

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7. APPENDICES

Appendix A. Kitchen Smoke Detector Feasibility and Nuisance Alarm Characterization Standard Safe Operating Procedures

General Test Procedure

Experiment Preparation

1. Turn on smoke meter detectors the day before testing and leave on.
2. Turn on smoke meter lasers at least 2 hours before testing.
3. Check whether batteries or detectors should be replaced and replace them.
4. Change date and test identification labels attached to the front of the range.
5. Make sure the video cameras are plugged in and ready.
6. Plug in and turn on power meter, current meter, data acquisition system.
7. Put the room exhaust hood flow on low. Verify operation.
8. Make sure range hood exhausts to space above drop ceiling.
9. If using range hood, make sure plugged in.
10. Make sure pan and food thermocouples are installed and ready.
11. Turn on the range hood to the proper setting if required for the particular experiment.
12. Measure out the volume or mass of food to be tested
13. Measure the masses of pan components and food separately and together and record.
14. Place the appropriate amount of the food to be cooked (well-thawed and/or stored at room temperature) in the pan.
15. Carefully center the pan on burner and position the bottom-measuring thermocouple.
16. Make sure the pan handle is secured using a clamp and weighted stand or similar.
17. Place food temperature measuring thermocouple at proper location.
18. Make sure lid can be used on pan without interference from thermocouple.
19. Check range-surface thermocouples.
20. Make sure lasers are on and focused on detectors.
21. Check smoke meters for drift.
22. Check operation of extinguishing agent device, then position and fill. Weigh the amount of agent being used.
23. Check ABC CO_2 fire extinguisher proximity to the inner lab room.
24. Check personal protective equipment (PPE) and safety equipment:
    Safety eyeglasses with side shields must be worn by all workers and visitors.
    Closed-toe shoes and long pants must be worn by anyone working on the experiment.
    Visitors/observers must wear closed-toe shoes.
    Half-face respirators should be ready for use.

Experiment

25. Turn off the range burner knob and re-energize the circuit breaker.
26. Conduct a safety briefing including duties of each participant. Post a “testing in progress” sign and “lasers in use” sign on the door.
27. Start LabView program.
28. Power and initialize the detectors

29. Begin experiment with a 5 s countdown and start two stopwatches and data acquisition system with the clock set to clock time.
30. Use a 5 s countdown to 1 min to start the video cameras. After a few seconds, put the clock into timer mode and reset to zero.
31. During the 2 minutes of background data, verify that signals are reasonable before continuing.
32. With a 5 s countdown to zero (at 2 min overall), turn the appropriate burner on and adjust the setting while also activating the timer. For normal cooking, follow instructions/recipe. For unattended cooking, use the highest burner setting.
33. Observe the behavior of the food, recording important observations and times on the log sheet.
34. If performing normal cooking, de-energize the burner and stop the process when the instructions are completed.
35. For unattended cooking, as smoke increases and ignition approaches, one person should be stationed at the door watching and prepared announce ignition and to empty the extinguishing agent into the pan while another is at the electrical panel prepared to switch off the breaker.

Post Ignition

36. Upon ignition, dump the extinguishing agent in the food and de-energize the range via the circuit breaker.
37. Increase the room exhaust to high.
38. Put on the respirator in case there is re-ignition.
39. Upon re-ignition, use the lid to cover the pan and snuff the fire and/or use a CO2 extinguisher if necessary (being careful not to blow the lid off of the pan). Exit the room immediately upon final extinguishment.
40. Continue the experiment at least 5 minutes after the fire is extinguished or the cooking procedure is completed for background data. Wait until smoke levels return to normal.
41. After extinguishment, wait sufficient time (>3 min) before removing lid to prevent re-ignition. Leather gloves must be worn when handling hot cooking utensils and when cleaning up hot material.
42. After the pan has cooled sufficiently for safe handling, weigh the pan, food, and lid together.
43. Clean pan(s) and test area. Prepare for another experiment.

<u>The following safety rules are used to prevent injury to test personnel:</u>

1. For unattended cooking experiments, no personnel are permitted in the laboratory enclosure after significant smoke begins to be produced and a layer of smoke begins to develop unless a respirator is utilized.
2. All personnel conducting or observing the experiment must wear appropriate safety equipment including closed-toe shoes and safety glasses or goggles.
3. Laser use signage will be posted.
4. Visitors must not enter the inner lab during a test.
5. At least one fire extinguisher is to be positioned near the inner lab doorway.
6. The fire extinguisher is checked for sufficient charge each day.
7. Ionization smoke detectors are installed at least 61 cm from potential flames.

8. Upon any fire or health related emergency call x2222 and move to safety while following emergency shutdown procedures if an experiment is in progress.

Data Acquisition and Smoke Detector Preparation Procedures

Program:
Enter filename and description
Press run button – program creates a file
To stop, press exit button in bottom right corner

Resetting Detectors:
Program has to be running
Turn on the power supply
Photoelectric – hold the button down on the detector until it starts beeping
Ionization – hold the button down until it chirps twice