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Development of Standardized Cooking Fires for Evaluation of Prevention Technologies: Data Analysis

Joshua B. Dinaburg
Daniel T. Gottuk
In collaboration with the Fire Protection Research Foundation

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National Institute of Standards and Technology
Gaithersburg, MD 20899-6880

By
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U.S. Department of Commerce
Penny Pritzker, Secretary

National Institute of Standards and Technology
Willie May, Under Secretary of Commerce for Standards and Technology and Director

Development of Standardized Cooking Fires for Evaluation of Prevention Technologies: Data Analysis

Final Report

Prepared by:

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FOREWORD

Beginning in 2010, the Foundation began a program to review the potential effectiveness of various technologies potentially capable of preventing cooking range top fires. A workshop conducted as part of that project considered the emergence of commercial products on the market and identified the need to develop standardized tests and criteria to evaluate the performance and effectiveness of such devices. This report summarizes and analyzes the results of two live fire test series conducted to form the basis for such a test protocol.

The Research Foundation expresses gratitude to the report author Joshua B. Dinaburg and Dr. Daniel T. Gottuk, who is with Hughes Associates, Inc. located in 3610 Commerce Dr., Suite 817, Balitmore, MD 21227 The Research Foundation appreciates the guidance provided by the Project Technical Panelists and all others that contributed to this research effort. In particular the Foundation thanks the National Institute of Standards and Technology for the award of funding for the project.

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

The content, opinions and conclusions contained in this report are solely those of the authors.

About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

NFPA is a worldwide leader in fire, electrical, building, and life safety. The mission of the international nonprofit organization founded in 1896 is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating consensus codes and standards, research, training, and education. NFPA develops more than 300 codes and standards to minimize the possibility and effects of fire and other hazards. All NFPA codes and standards can be viewed at no cost at www.nfpa.org/freeaccess.

Keywords: kitchen and cooking equipment, food and cooking materials, ranges, research report

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EXECUTIVE SUMMARY

Cooking range top fires account for over 91,000 home fires each year, causing over 300 and 3,700 annual deaths and injuries, respectively, based on data from 2006–2010 [1]. In addition, many cooking fire incident and injuries go unreported to fire departments and are not included within the data. Technologies potentially capable of preventing these fires have been considered and reviewed for the past 30 years. Beginning in 2010, Hughes started working with the Fire Protection Research Foundation (FPRF) to review the potential effectiveness of various technological options [2]. A workshop conducted as part of that project considered the emergence of commercial products on the market and identified the need to develop standardized tests and criteria to evaluate the performance and effectiveness of such devices. This report has summarized and analyzed the results of two live fire test series conducted to form the basis for such a test protocol.

The tests conducted were intended to: 1) develop the basic protocols for conducting standardized tests; 2) develop performance criteria for conduct of valid tests; and, 3) develop performance criteria for assessing fire protection performance of prevention technologies. The scope of this work was limited to assessing only fire preventing technologies, not those that would contain or alert after ignition.

Fire tests were conducted to assess the pre-ignition conditions for cooking oils in pans on electric surface cooktops of ranges. The pan temperatures, oil temperatures, effluent temperatures, and gas concentrations were measured continuously from the start of heating until ignition. Tests evaluated the impacts of oil types, oil brands, oil age and usage, oil depth, pan materials, pan sizes and thicknesses, range power, and range type (glass ceramic radiant element and coil element). It was intended to identify the test conditions that would present the greatest potential challenges to prevention devices and select them for inclusion in the recommended standard testing.

It was found that the type/age/use of oil only had a strong influence on the production of smoke, and not on the temperature of ignition. The percent free fatty acid (% FFA) of the oils tested were measured and correlated with the smoke and ignition temperatures. The % FFA varied for oils of different types (low for canola, vegetable, peanut oils, high for pork lard). The % FFA was also increased by artificially aging oils by sustaining them at high temperatures or using oils by repeatedly cooking food in them. Oils with increased % FFA produced smoke at lower temperatures, but ignited at approximately the same temperatures. Oils that produced smoke at lower temperatures were considered less challenging to detect before ignition. Fresh canola oil (lowest % FFA) was selected for continued testing and is recommended for a test standard. The brand of oil used (tested commercial grade and multiple consumer brands) did not affect the ignition properties, and no specific brand need be specified for testing.

Numerous criteria were used to identify “challenging” scenarios. Some examples include: 1) the total heating time to reach ignition; 2) the window of time available between a fixed pan temperature threshold (e.g. 300 °C) and ignition, 3) the window of time available between a measured smoke obscuration (e.g. 1.6 %/ft) and ignition; 4) the temperature of the pan at ignition; and, 5) the temperature of the oil at ignition. In general, the total heating time and available fixed pan temperature/smoke obscuration windows scaled proportionally, and were decreased by increasing the element power, decreasing the oil depth/volume, reducing the pan mass/specific heat capacity, and increasing the pan/element contact area. Conversely, the measured pan and oil temperatures at ignition were reduced inversely with the length of the test, presenting potential challenges for tests taking long periods to reach ignition.

The criteria used to identify challenging tests were directly related to the total heating time required to reach ignition. It is recommended that both fast and slow tests be conducted to challenge all potential detection technologies. The fastest tests ignited in less than 7 minutes of heating. The slowest tests required as much as 1 hour of heating before ignition occurred (if at all). Several combinations of test

variables were capable of producing heating times in these ranges by varying the range power, oil depth, etc. If a prevention device requires the use of a specific test variable (e.g. pan type, range type, etc.), it should be possible to produce a fast or slow test including this condition. The specific conditions producing fast/slow ignitions need not be specified or limited for standardized testing. The slowest tests were much more variable, with ignition times ranging from 20 minutes to over 1 hour for the same test conditions. A second set of “slow” tests (15-20 minute heating times) were also included in the recommendations to potentially provide a slow test but with more consistent results.

In order to demonstrate that a proposed test setup will meet the fast or slow test criteria, a heating test must be conducted without the prevention device activated or present. For safety reasons, the demonstration tests need not be conducted up to ignition. It has been proposed that the tests be run until an oil temperature of 350 °C (662 °F) has been reached and then the heating source turned off. Acceptable boundaries for allowable pan and oil temperatures and smoke obscuration have been developed from the test data for fast, slow, and the slowest test cases.

Pan and oil temperatures were measured in multiple locations in the tests conducted. Data showed that pan and oil temperatures measured at the center of the pan and at half of the initial oil depth above the pan surface provide a good representation of the spatial average. The oil temperature did not vary by more than 1–2 °C (3–4 °F) as a function of depth, and placement of the oil temperature measurement at the half oil depth (±1/16 inch) should be adequate for standardized testing.

The smoke obscuration need only be measured and demonstrated within the test bounds if the prevention device to be tested uses smoke as an activation criteria. The current test design measured the smoke in a 4 ft x 4 ft hood over the range. Evaluation of real smoke measuring devices would require a more realistic kitchen type installation to provide the proper smoke concentrations for activation. Development of a smoke test room has not been evaluated as part of this effort and will require subsequent analysis.

Performance criteria has been developed to evaluate the performance of prevention devices based on proposed limits to the measured oil temperature in the pan. For the tests utilizing the final recommended instrumentation, ignitions did not occur until the oil temperatures reached 374–406 °C (705–763 °F) and pan temperatures reached 385–432 °C (725–810 °F). Based on the available test data a threshold in the range of 300 to 350 °C (572 to 662 °F) should be sufficient for prevention of ignition. If a more conservative threshold is desired, such as 250 °C (482 °F) oil temperature, the minimum time to ignition increases to 130 seconds and the resulting pan surface temperatures decrease to 263–312 °C (505–594 °F). An oil temperature threshold of 300 °C is currently used by the Japanese Industrial Standard (JIS) 2103 and 2093 [6,7].

Some cooking methods may require the temperature of foods to reach as high as 260 °C (500 °F) [9]. Inclusion of a minimum oil temperature prevents devices from severely limiting the ability to cook. It is also suggested to include a maximum allowable deviation in heating rate. Tests conducted without the device operating (demonstration of acceptable fast/slow test) must heat the pan and oil within specified bounds. The inclusion of the device should not reduce the heating rate by more than a defined threshold, for example, 10% of the average temperature increase per minute.

The recommendations for the performance criteria would include a device that can: 1) operate after the desired minimum oil temperature is reached; 2) operate before the maximum oil temperature is reached; and, 3) does not drastically reduce the heating rate measured without the device present, it should be considered acceptable. These three criteria would be required for achieving a passing test result.

1. BACKGROUND

Cooking-equipment related fires are a leading cause of U.S. fire loss. The National Fire Protection Association (NFPA) reports that in 2006–2010, there were 157,300 annual average reported home cooking related fires per year (42% of all reported home fires), with associated annual losses of 380 civilian deaths (15% of home fire deaths), 4,920 civilian injuries (38% of home fire injuries), and $794 million in direct property damage (11% of home fire damages). Fires involving range tops accounted for 58% of these cooking equipment fire incidents and 87% and 76% of the deaths and injuries, respectively [1].

Beginning in the mid-1980s, the National Institute of Standards and Technology (NIST), Consumer Product Safety Commission (CPSC), and the home appliance industry undertook a comprehensive review of strategies to mitigate death, injury and property loss from cooking fires. All approaches were engineering strategies defined by a condition to be detected (e.g., overheat of pan or food in pan, absence of person actively engaged in cooking process, early-stage fire on stovetop) and an action to be taken (e.g., shut off cooking heat, sound alarm, suppress fire). As part of this study, a comprehensive review of existing technologies was done [2].

In February of 2010, a Vision 20/20 workshop on this topic was convened in Washington DC. Participants recommended that a study be undertaken to identify the barriers to the utilization of these technologies and to develop an action plan towards improving cooking fire safety.

In 2010, Hughes Associates, Inc. conducted a study for the Fire Protection Research Foundation (FPRF) supported by NIST to develop this action plan [2]. The study focused particularly on prevention technologies suitable for use on or with home electric and gas cooktops. and consisted of a literature and technology review; the development of an enhanced technology evaluation methodology based on an in-depth review of cooking fire statistics; and the evaluation of currently available technologies using this methodology. The project culminated with a one day workshop of 35 leaders from the kitchen appliance, fire service, and user communities who met to review the above findings and identify gaps in information. The highest priority action item identified at that workshop toward implementation of commercially available cooking fire mitigation technologies was:

> “Develop standard fire scenarios and create test methods and performance criteria which can feed into standards development”

Toward this end, NIST funded a project through the FPRF conducted by Hughes, consisting of two series of tests evaluating various cooking fire scenarios (referred to in this report as Phase 1 and Phase 2). The first phase evaluated the ignition characteristics for a range of cooking scenarios, including oils types, simulated oil aging, heating power, and pan size and thicknesses on electric coil elements. The second phase built on the initial tests to establish repeatability and to evaluate the impacts of used oils, various pan materials, oil depths, and glass ceramic radiant element cooktops on ignition characteristics. This report includes an evaluation of test data from both phases to quantify the impacts of the test variables, identify scenarios challenging to potential detection equipment, and recommendations for a standardized test. The standardized test includes procedures, criteria for conduct of valid tests, and criteria for evaluation of prevention devices.

2. OBJECTIVE

The primary objectives of the project were to:

1. Develop the basis for standardized tests for evaluation of range top cooking fire prevention technologies.
2. Develop performance criteria for conducting valid tests.

3. Develop performance criteria for assessing the fire protection performance of prevention technologies tested to the standard.

3. SCOPE

This project was limited to developing tests for evaluation of automatic fire prevention technologies for use on cooking range tops. Devices utilizing suppression, notification, user intervention, flame containment, etc. were not considered in the test development.

Tests evaluated a range of potential ignition scenarios, with different types of ranges, pans, and oils. It is the intent to use this test data to select standardized scenarios based on repeatability, ignition properties, and applicability to prevention technologies.

Although smoke obscuration was measured during this series of tests, the apparatus used does not represent a realistic kitchen environment. The smoke levels measured provide comparative information identifying when smoke is produced, the temperatures of the pan and oil at the time smoke is produced, and the relative amount of smoke produced for each tested scenario. Smoke was collected in a small hood enclosure resulting in much higher concentrations than expected for real cooking environments. Although the fire sources and procedures are appropriate, the hood enclosure would not be appropriate for evaluating the operation of a smoke operated control device for preventing range fires.

4. APPROACH

Full-scale testing was conducted using commercially available cooktops and cookware. Testing included the heating of various animal fats and plant derived oils to the point of flaming ignition. The term oil generally refers to any viscous liquid that is immiscible with water. In this report, the term oil is used to refer to any fat derived from a plant or animal that is used in cooking. This includes fats that are generally solid at room temperatures, including pork lard or beef shortening. Testing included both pure oils with no solid food use and oils that have been used for actual cooking of food. The oils were characterized by testing the free fatty acid (FFA) content. This oil property has been previously identified to correlate to the temperature of smoke production and ignition [3].

The temperatures of the pans, oils, and air, as well as the smoke and gas emissions were measured during heating to the point of ignition. This data was used to identify the conditions leading up to ignitions that may present challenges for initiation of automatic prevention devices. The most challenging scenarios are the leading candidates for use in standardized evaluation testing. The conditions leading up to ignition were also used to identify performance criteria for evaluating devices subjected to the proposed standardized testing.

The impact of several factors on ignition conditions were assessed during testing. Variables included:

1. Cooktop power and coil design
2. Electric coil and glass ceramic radiant element range elements
3. Pan sizes and thicknesses
4. Pan materials
5. Pan flatness
6. Cooking oil type
7. Cooking oil age/usage
8. Oil depth

5. TEST DESCRIPTION

5.1. Test Apparatus

A cooking fire test apparatus was constructed in the Hughes laboratory in Baltimore, MD. The apparatus consisted of an electric cooking range with cooktop placed beneath an enclosed collection hood. Pans were instrumented to measure temperature of the pan and the oil. The smoke and gases emitted by the heated oils were collected and measured inside the hood above the range.

5.1.1. Collection Hood

Testing was conducted with a range placed beneath a 4 ft x 4 ft x 1 ft (1.2 x 1.2 x 0.3 m) deep sheet metal collection hood. The hood was centered above the tested pan and located 3 ft (0.9 m) above the surface of the range. The collection hood did not have any duct work or mechanical means for removing the products of combustion. By eliminating a forced air flow duct connected to the hood, the fire effluent measurements are not dependent on the flow rate through the duct; hence, this should lead to a higher degree of reproducibility from test to test and lab to lab.

The collection hood setup is shown in Figure 1. The heated pan effluent collected in the hood, creating a smoke layer that descended lower in the hood over time. When the layer descended below the 1 ft (0.3 m) depth of the hood, it spilled directly in to an open, ventilated space to remove the products of combustion from the test area. In Phase 1 testing, the open space was a 16 ft x 16 ft x 12 ft (4.9 x 4.9 x 3.7 m) high room with a 1 x 1 ft (0.3 x 0.3 m) exhaust opening drawing approximately 600 ft^3/min (17 m^3/min) of air. In Phase 2 testing, the apparatus was placed beneath a 10 ft x 10 ft (3.0 x 3.0 m) exhaust hood continuously drawing approximately 7000 ft^3/min (198 m^3/min). In both test conditions, the effluent from the pan was observed to rise naturally into the collection hood until it spilled over. Neither condition produced a cross-flow that pushed effluent away from the hood, and the conditions were deemed approximately equivalent. The effects of the local airflow conditions are compared in detail in Section 6.1.3.

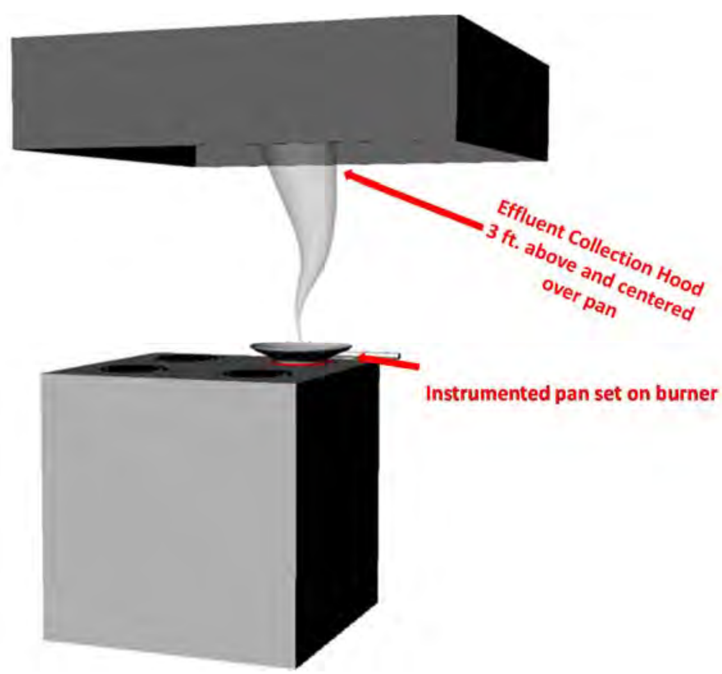


Figure 1 – Collection hood and range setup

5.1.2. Instrumentation

Continuous temperature and voltage measurements were recorded during testing by a National Instruments cDAQ-9174 compact data acquisition chassis. Temperatures were measured using a cDAQ-9214 thermocouple module and voltages were measured using a cDAQ-9205 ±10 V voltage module. Data was recorded by a Labview program at a rate of 1 Hz (Phase 1) or 2 Hz (Phase 2) during fire tests.

5.1.2.1. Cooktop Power

The cooktop power was measured by continuous current measurement during fire testing. The voltage supplied to the cooktop under test was measured prior to testing using an Omega multi-meter. The current was measured continuously by an Eaton EACP1420120SP AC current sensor. The voltage and current were multiplied to determine the wattage draw of the element during testing.

5.1.2.2. Pan Temperature

Pan temperatures were measured continuously during fire tests using 24 gauge fiberglass sheathed type K special limit of error (±1.1°C or 0.4%, whichever is greater) thermocouples welded to the top surface of the pan. Beads were welded at the ends of the wires by a TIGTECH 116SRL thermocouple welder with argon purge. The beads were then attached to the pan surface using a DCC Corporation HotSpot TC Welder.

Three thermocouples were placed in each pan at the center and along an axis with the handle, located 1 in. (2.5 cm) from the outside of the pan base. The pan thermocouple locations are shown in Figure 2.

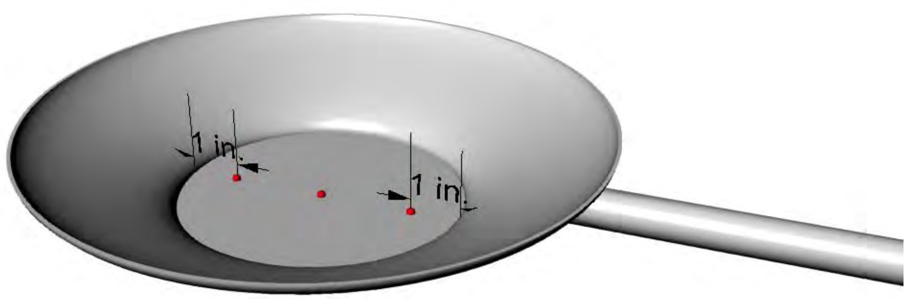
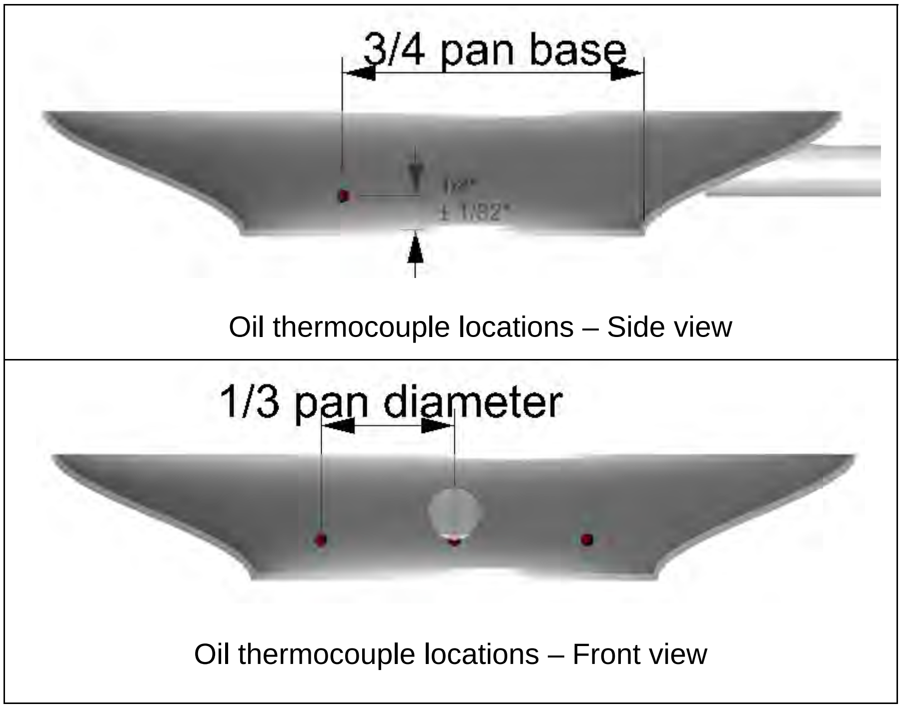


Figure 2 – Pan thermocouple measurement locations

5.1.2.3. Oil Temperature

Oil temperatures were measured continuously using type K thermocouples with welded beads. During Phase 1 testing, beads were welded at the ends of 24 gauge fiberglass sheathed wires special limit of error (±1.1°C or 0.4%, whichever is greater) using a TIGTECH 116SRL thermocouple welder with argon purge. The exposed beads were approximately 0.8 in. (2 mm) in size and inserted into the oil. During Phase 2 testing, the oil temperatures were measured using Inconel sheathed, 0.020 in. (0.5 mm) grounded thermocouples (Omega KMQIN-020G-18, ±2.2°C or 0.75%, whichever is greater). These thermocouples were smaller in size and easier to place at the desired oil depths. The response time of the smaller, yet shielded thermocouples was found to be shorter. The thermocouples were simultaneously plunged into a cup of hot water (~50°C), and the Inconel sheathed thermocouples reached steady state temperatures approximately 2 seconds faster than the 24 gauge welded beads. In addition, the Inconel was much easier to clean between fire tests, improving the efficiency of the test procedures.

The oil temperature measurement locations are shown in Figure 3. Nine thermocouples were placed in each pan at three locations each at three depths. The oil temperatures were measured along an axis perpendicular to the pan handle located ¾ of the pan base from the handle. The temperature was measured along the center line of the pan and 1/3 of the pan diameter to either side of the center axis. At each location, the oil temperature was measured at half the depth of the oil. For tests with a ¼ in. (6.3 mm) oil depth, the thermocouples were placed at a depth of 1/8 in. (3.2 mm). Additional measurements were made at each location 1/32 in. (0.8 mm) above and below half the oil depth (3/32 and 5/32 in. (2.4 mm and 4.0 mm)). For tests with a ½ in. (12.7 mm) oil depth, the TCs were placed at depths of ¼ in. (6.3 mm) ± 1/8 in. (3.2 mm). The additional vertical measurements were conducted to assess the sensitivity of the measured oil temperature to the thermocouple depth in order to properly specify a standard test setup.



Oil thermocouple locations – Side view

Oil thermocouple locations – Front view

Figure 3 – Oil temperature measurement locations for ¼ in. (6.3 mm) oil depths

The oil thermocouple beads were held in place by clamping the wires between two aluminum bars resting on angled feet inside the pan. The two clamping bars were cut to a length 2 in. (5.1 cm) shorter than the pan diameter. The feet consisted of two pieces of ¼ in. (6.4 mm) thick aluminum angle cut to ¼ in. (6.4 mm) widths. The two clamping bars were then screwed to the feet such that the bottom of the bars sat ¼ in. in. (6.4 mm) above the base of the feet. This provided a fill line to ensure ¼ in. (6.4 mm) of oil had been used in each test and kept the thermal mass of the bars outside of the tested oil. The thermocouple wires were run between the two bars and the screws were tightened to keep the beads in place. The TC depths were measured prior to each test by sliding a small steel bar with a thickness at the desired depth beneath the TC and adjusting until the TC just contacted the bar. Photographs of a pan with the aluminum mounting bars and the pan thermocouples, including a close up view of the mounting bar are shown in Figure 4 for Phase 1 (24 gauge exposed beads) and Figure 5 (Inconel sheathed).

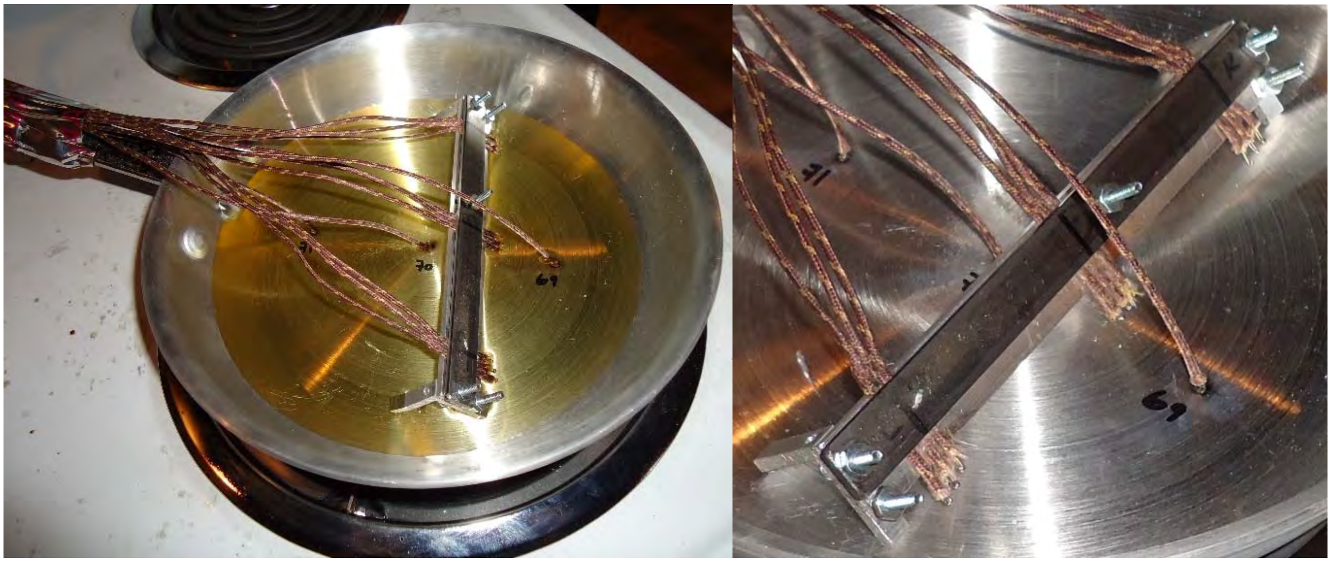


Figure 4 – Thermocouple measurements and mounting bar in test pan (Phase 1)

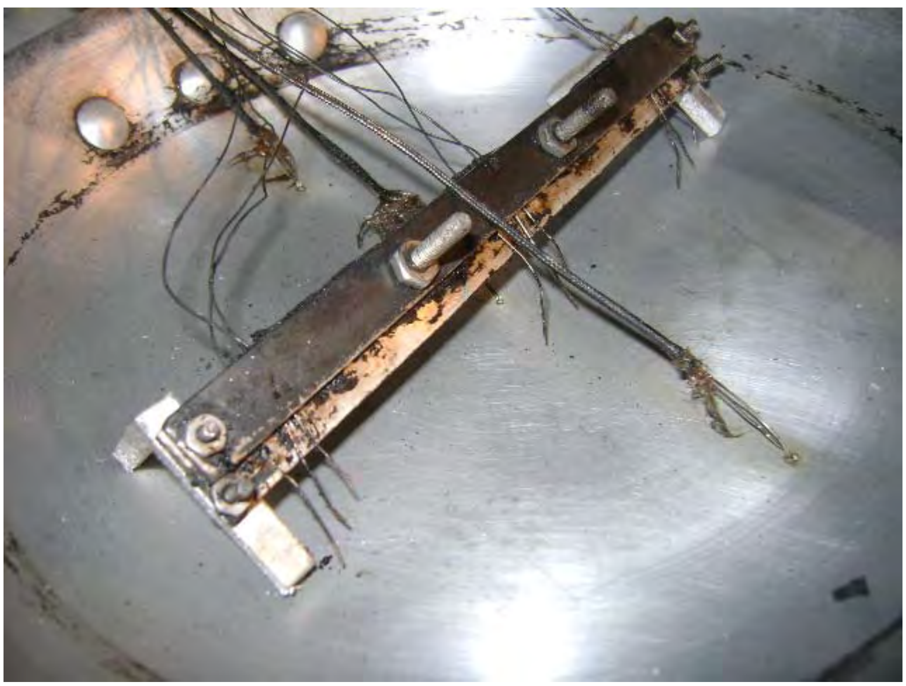


Figure 5 – Thermocouple measurements and mounting bar in test pan (Phase 2)

5.1.2.4. Effluent Temperature

The gas temperature in the hood was measured using 24 gauge fiberglass sheathed type K thermocouples with welded beads. Beads were welded at the ends of the wires by a TIGTECH 116SRL thermocouple welder with argon purge.

Thermocouples were uniformly spaced in the collection hood 2 in. (5.1 cm) below the top of the hood. The thermocouples were each located in the center of a quadrant of the hood, located 12 in. (30 cm) from the walls and 24 in. (61 cm) from the adjacent thermocouples. The effluent thermocouple locations are shown with the smoke and gas concentration measurements in the hood diagram in Figure 6.

5.1.2.5. Smoke Concentration

Smoke concentrations were measured in the collection hood through laser light extinction measurements. Two ThorLabs CPS186, 670 nm, 4.5 mW lasers were mounted to the outside of the collection hood pointing down parallel axes 3 in. (7.6 cm) below the top of the hood and 12 in. (30 cm) from either side. The laser beam paths and installation locations are shown in Figure 5. The lasers were powered by an EPSCO Model D-612T Filtered DC Power Supply at a constant 5 V. The laser intensity was measured on the opposite side of the collection hood by PDA36A amplified SI photodiode detectors with variable gain and sensitivity to 350-1100 nm light. The smoke concentration over the 4 ft (1.2 m) path lengths were recorded as both optical density and obscuration per foot by comparing the intensity of laser light on the photodiodes prior to and during fire testing.

The operation of the laser obscuration meters were verified using ThorLabs NG11 Schott Glass neutral density filters. The filters were placed in the beam path and the resulting obscurations and optical densities were calculated and confirmed. The lasers were verified using filters with optical densities at 670 nm of 0.112, 0.298, 0.374, 0.945, 1.838, and 2.732.

5.1.2.6. Gas Concentrations

Gas concentrations, including oxygen (O_2), carbon dioxide (CO_2), and carbon monoxide (CO), were measured in the collection hood. Gas samples were drawn and mixed from four locations in the hood, at the center of each quadrant and a distance of 1 in. (2.5 cm) below the top of the hood as shown in Figure 6. The gas samples were analyzed for concentration by a Horiba VA-3000 paramagnetic oxygen analyzer (reporting accuracy of 0.01% O_2, repeatability of 0.125% O_2), a Horiba VIA-510 infrared carbon dioxide analyzer (reporting accuracy of 0.001% CO_2, repeatability of 0.025 %CO_2), and a Rosemount Analytical Model 880A infrared carbon monoxide analyzer (reporting accuracy of 1 ppm CO, repeatability of 10 ppm CO). Analyzers were zeroed and spanned to full ranges daily prior to testing. Transport time delays were measured until 90% of known concentrations were reported using calibration gases introduced at the sampling ports. Transport times (t_{90}) between 45 and 60 seconds were measured when the setup was located in the enclosed room (Phase 1) and approximately 30 seconds when beneath the exhaust hood (Phase 2). These delay times were accounted for in the presented test data.

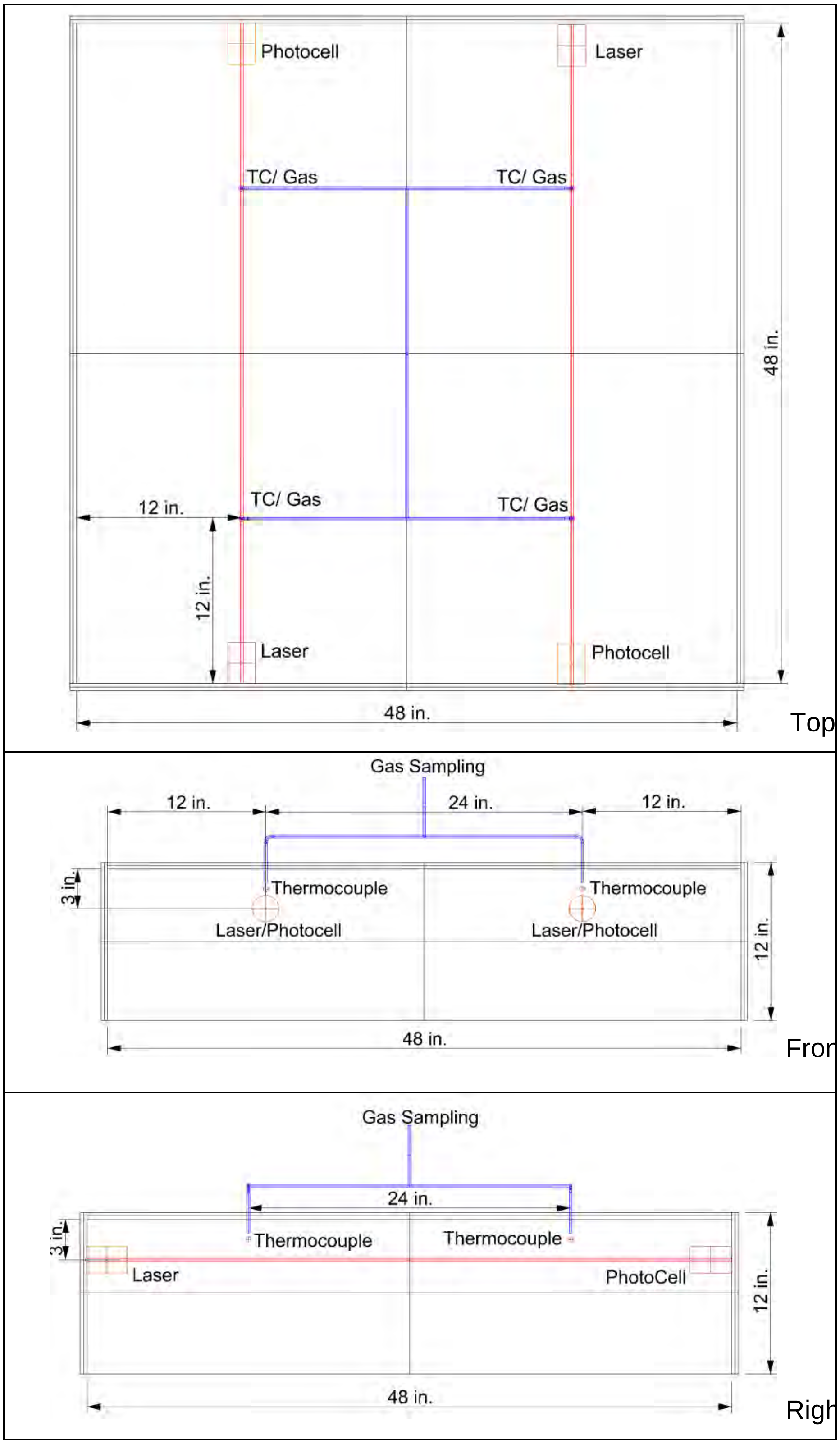


Figure 6 – Temperature, smoke, and gas measurements in the collection hood

5.2. Variables Evaluated

5.2.1. Ranges and Cooktops

Test fires were initiated using open coil electric and glass ceramic radiant range heating elements. A GE JBP23DRWW and a Frigidaire FFEF3011 LW were selected as the open coil electric ranges for testing due to differences in heat output and element coil surface area/shape. A GE JBS60DFWW glass ceramic range was selected based on input from the steering team and due to the 3000 W power boil element. Tests were conducted on the 8 in. (20 cm), 2600 W, 6 turn coil and the 6 in. (15 cm), 1500 W, 4 turn coil on the GE range. Tests were also conducted on the 8 in. (20 cm), 2100 W, 4 turn coil on the Frigidaire range. Tests were conducted with the element power turned on to the highest setting, except for several tests conducted on the 8 in. (20 cm) GE coil element where the power was matched to the 2100 W of the Frigidaire coil element for direct comparison of the element shape. The ranges and elements tested are shown in Figure 7.

Figure 7 – Range tops and elements used during testing

All three ranges required 240 VAC power. Power was provided by a Staco 5021CT-2S variable control AC transformer with 480 V input set and verified daily to provide 240 V ±1 V to the ranges tested. The voltage was measured prior to the start of each test day using a handheld voltmeter. The current drawn by the ranges was measured continuously during testing to determine the power output of the elements. When the power level on a element was reduced from maximum, the power was observed to cycle on and off, and the numeric power setting was related to the duration of on-cycles. The power was reduced on the GE coil element range by matching the element on cycling time to the desired power ratio, in this case 2100 W/2600 W. Therefore, the element power cycled on 81% of the time during the reduced power testing.

Even at the highest power setting, the glass ceramic range was observed to cycle power after the glass temperatures reached elevated levels. This power cycling was measured and recorded, and while ignition times were potentially delayed, ignitions were still observed to occur for these cooktops.

5.2.2. Cooking Utensils

Cookware used during testing included solid aluminum fry pans of varying thicknesses (5–10 gauge) and diameters (7–14 in. (18-36 cm)). According to the Cookware Manufactures Association (CMA), aluminum pans represent the majority (approximately 70%) of consumer products, and the selection of a single pan material allowed for evaluation of other variables that may impact ignition. For consistency and reproducibility, the evaluated pans were solid aluminum only and did not contain any non-stick coating and were not anodized. Additional tests were conducted using a Tramontina Everyday Stainless Steel sauté pan, an All-Clad 4110 Tri-Ply bonded stainless steel pan, and a Lodge LCS3 cast iron Chef's skillet. Due to the variability and uncertainty of construction of stainless steel pans, the two steel pans selected were chosen to represent a range of low-end (Tramontina ~$20) and high-end (All-Clad ~$120) pans. A summary of the pans tested is shown in Table 1. No pan gauge thicknesses were provided with the stainless steel or cast iron pan, and the reported thicknesses have been measured. Exemplar photographs of 8 gauge, 10 in. (25 cm) diameter pan, the two stainless steel pans, and the cast iron pan are shown in Figure 8.

Table 1 – Frying pans tested

Pan ID	Material	Manufacturer	Brand	Model	Gauge	Thickness (in.)	Diameter (in.)	Diameter (cm)	Mass (g)	Mass (lb)
AL-BH-8-5	Aluminum	Browne-Halco	Thermalloy	14808	5	0.1819 (4.6 mm)	8	20	811	1.8
AL-BH-10-5				14810			10	25	1130	2.5
AL-BH-8-8				13808	8	0.1285 (3.3 mm)	8	20	622	1.4
AL-BH-10-8				13810			10	25	936	2.1
AL-BH-14-8				13814			14	36	1717	3.8
AL-V-7-8	Aluminum	Vollrath	Wear-Ever	67907	8	0.1285 (3.3 mm)	7	18	454	1.0
AL-V-10-8			Arkadia	7010			10	25	817	1.8
AL-V-14-8				7014			14	36	1808	4.0
AL-V-8-10			Wear-Ever	4008	10	0.1019 (2.6 mm)	8	20	566	1.2
AL-V-10-10				4010	10		10	25	964	2.1
SS-T-10	Stainless Steel	Tramontina	Everyday	NA	NA	0.135 (3.4 mm)	10	25	694	1.5
SS-AC-10		All-Clad	Tri-Ply	4110	NA	0.19 (4.8 mm)	10	25	977	2.2
CI-L-10	Cast Iron	Lodge	NA	LCS3	NA	0.21 (5.3 mm)	10	25	1970	4.3

NA – Not available from product literature at time of purchase

Aluminum pans

Tramontina Stainless Steel All-Clad Stainless Steel

Lodge Cast Iron

Figure 8 – Exemplar frying pans used during testing

Cookware was only reused after a fire test if all solid material could be removed by cleaning and the flatness of the bottom of the pan remained within 0.006 times the pan diameter. This was considered the minimum amount of deviation in flatness that may impact test results. This level of flatness was selected in accordance with the flatness specifications included in UL 1026 41.2.9.1 [4]. The flatness was measured by placing a flat steel bar across the bottom of the pan and measuring the separation between the pan bottom and bar in three locations along two orthogonal axes. Measurements were made at the center and radial distances of 2 in. (5.1 cm). If the difference between any two of the six measurements exceeded 0.006 times the pan diameter, the pan was considered unacceptable. No pan was observed to exceed this allowance after repeated fire testing.

Additional testing was conducted to evaluate the ability to warp a pan using thermal cycling. A dry 10 gauge, 8 in. (20 cm) diameter pan was heated (with no contents) on the 8 in. (20 cm) GE electric coil element until the pan temperature measured approximately 750°F–840°F (400°C–450°C). All power was then cutoff to the element and duration and magnitude of any potential temperature overshoots were measured. When the temperature began to decrease it was dunked into a large water tank to initiate rapid cooling. This process was repeated through 30 heating and cooling cycles. The use of cookware with non-flat bottoms may impact the performance of a fire prevention device intended to make a contact temperature measurement with the bottom of the pan. In addition, these tests also quantified the degree of temperature overshoots that may occur after turning off the element.

5.2.3. Cooking Oils

Tests were conducted using both pure cooking oils without solid food products and oils previously used to cook foods. The intent of the overall project was to develop consistent standardized tests, and the use of solid food would likely increase the variability and uncertainty in the test results. If, however, the use of oil with food was found to increase the challenge for fire prevention, this type of source would require inclusion in the test standard. Various formulations of cooking oils were used including both plant and animal fats. Commercial brand oils purchased from industrial suppliers were tested and compared to consumer brand (off the shelf) oils. Evaluated oils were selected from the most common cooking applications and included:

- Soybean (vegetable) oil
- Corn oil
- Canola oil
- Peanut oil
- Beef shortening
- Pork lard

The beef shortening and pork lard were solid fats at room temperatures. In order to pour the oils to a consistent depth for testing, these oils were preheated in a separate pot to a temperature of 35°C (95°F) and melted. The liquids were then poured to a test depth of ¼ in. (6.4 mm) and testing conducted without allowing the liquid to re-solidify.

Consumer brand oils tested included Wesson, Crisco, Great Value, and a generic brand soybean (vegetable) and canola oils, and Morrell Snow Cap Pork Lard. All oils subjected to fire tests were analyzed for the FFA content by an external testing laboratory. This component of cooking oil has been reported to be inversely correlated with the auto-ignition temperature and smoke point [3]. It was recommended by the American Oil Chemists' Society (AOCS) to use FFA to characterize the various oil types tested.

In order to evaluate the potential impacts of used oil on ignition parameters, the commercial oils tested were artificially "aged" by maintaining a pot of oil at 204°C (400°F) for a total of 8 continuous hours in Phase 1 testing. Fire tests and FFA analyses were conducted on the aged oils to determine the potential impacts on ignition conditions. In addition to the artificially aged oils, a sample of used soybean (vegetable) oil was obtained from a fast food restaurant. The oil was used throughout lunchtime to cook french fries and chicken nuggets and was included to represent a scenario for heavily used oils.

In Phase 2 testing, samples of vegetable oil and pork lard were subjected to repeated cooking cycles to simulate home usage. One gallon (3.78 L) of each oil was placed into a large cookpot on a ceramic heating plate. The oil temperatures were raised to 204°C (400°F) and food was added to the pots. The food consisted of 3 lb (1.36 kg) of chicken thighs rolled in white flour, eggs, and seasoned bread crumbs. The addition of the cool chicken lowered the oil temperature to approximately 165°C (330°F) and the chicken was cooked for 20 minutes and removed. After cooking, the oil was allowed to cool naturally in the cookpot and then all solid material was removed using a fine kitchen strainer (Mainstays American Housewares 8” Food Strainer). After returning to room temperature, the process was repeated (typically a day or two later) until the oil was deemed unusable due to odor or color. This was found to occur after 10 cooking cycles with the pork lard and 12 cooking cycles with the vegetable oil. The color of oils between every two cooking cycles is shown in Figure 9.

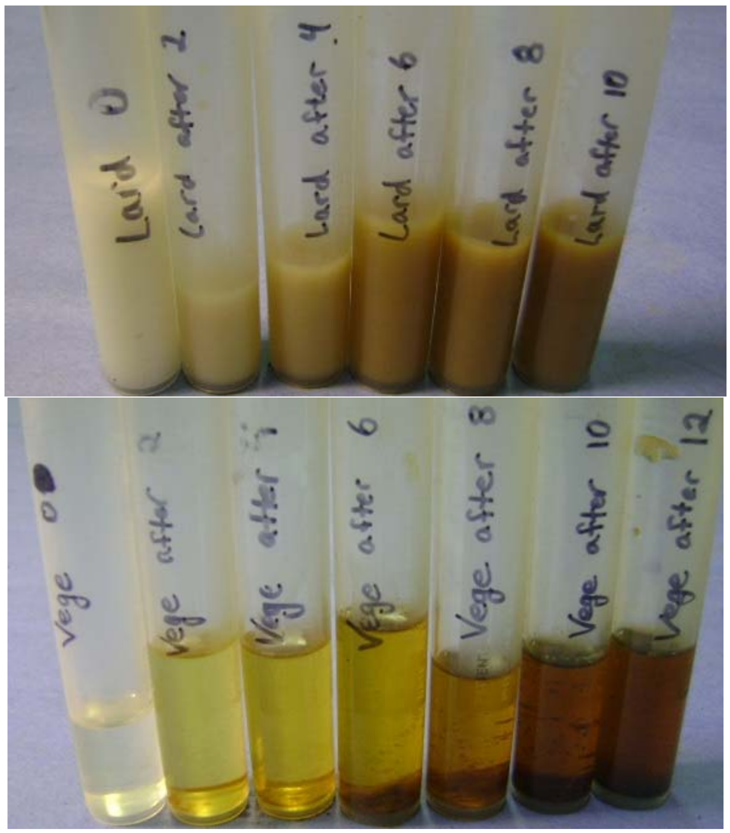


Figure 9 – Appearance of oils used for frying chicken, pork lard (top) and vegetable oil (bottom)

These tests were included due to concerns that residential cooking performed with used oils may present an increased hazard of ignition compared to cooking with fresh oil. This would present an additional challenge for a prevention device and was therefore considered for development of a standardized test.

Fire tests were conducted by pouring ¼ in. (6.4 mm) of oil into each pan evaluated. This depth of oil was used to minimize test time and was found to produce consistent ignition in all tests while providing sufficient depth to allow for insertion of temperature probes into the oil without contacting the surface of the pan. Additional tests were conducted during Phase 2 to evaluate the impact of ½ in (12.7 mm) oil depths.

5.3. Test Summary

A summary of all tests conducted in both Phase 1 and Phase 2 of the analysis is shown in Table 2. All Phase 2 tests were conducted in triplicate, and are organized according to the scenarios tested.

Table 2 – Summary of tests conducted

PHASE 1 TESTS							
		Oil				Range	
Test ID	Pan ID	Type	Brand	Condition	Depth (in)	Type	Power (W)
P1-1	AL-BH-8-8	Soybean	Commercial	Fresh	0.25	GE Coil	2600
P1-2	AL-BH-8-8	Corn	Commercial	Fresh	0.25	Coil	2600
P1-3	AL-BH-8-8	Corn	Commercial	Fresh	0.25	Coil	2600
P1-4	AL-BH-8-8	Corn	Commercial	Fresh	0.25	Coil	2600
P1-5	AL-BH-8-8	Canola	Commercial	Fresh	0.25	GE Coil	2600
P1-6	AL-BH-8-8	Canola	Commercial	Fresh	0.25	GE Coil	2600
P1-7	AL-BH-8-8	Peanut	Commercial	Fresh	0.25	GE Coil	2600
P1-8	AL-BH-8-8	Beef Shortening	Commercial	Fresh	0.25	GE Coil	2600
P1-9	AL-BH-8-8	Pork Lard	Commercial	Fresh	0.25	GE Coil	2600
P1-10	AL-BH-8-8	Soybean	Crisco	Fresh	0.25	GE Coil	2600
P1-11	AL-BH-8-8	Canola	Crisco	Fresh	0.25	GE Coil	2600
P1-12	AL-BH-8-8	Soybean	Wesson	Fresh	0.25	GE Coil	2600
P1-13	AL-BH-8-8	Canola	Wesson	Fresh	0.25	GE Coil	2600
P1-14	AL-BH-8-8	Soybean	Commercial	Aged	0.25	GE Coil	2600
P1-15	AL-BH-8-8	Corn	Commercial	Aged	0.25	GE Coil	2600
P1-16	AL-BH-8-8	Canola	Commercial	Aged	0.25	GE Coil	2600
P1-17	AL-BH-8-8	Peanut	Commercial	Aged	0.25	GE Coil	2600
P1-18	AL-BH-8-8	Lard	Commercial	Aged	0.25	GE Coil	2600
P1-19	AL-BH-8-8	Soybean	Commercial	Used[a]	0.25	GE Coil	2600
P1-20	AL-BH-8-8	Soybean	Commercial	Fresh	0.25	Frigidaire Coil	2100
P1-21	AL-BH-8-8	Canola	Commercial	Fresh	0.25	Frigidaire Coil	2100
P1-22	AL-BH-8-8	Soybean	Commercial	Fresh	0.25	GE Coil	2100[b]
P1-23	AL-BH-8-8	Canola	Commercial	Fresh	0.25	GE Coil	2100[b]
P1-24	AL-BH-8-8	Canola	Commercial	Fresh	0.25	GE Coil	1500[c]
P1-25	AL-V-7-8	Canola	Commercial	Fresh	0.25	GE Coil	2600
P1-26	AL-V-7-8	Soybean	Commercial	Fresh	0.25	GE Coil	2600
P1-27	AL-V-14-8	Canola	Commercial	Fresh	0.25	GE Coil	2600
P1-28	AL-V-14-8	Soybean	Commercial	Fresh	0.25	GE Coil	2600
P1-29	AL-BH-8-5	Corn	Commercial	Fresh	0.25	GE Coil	2600
P1-30	AL-BH-8-5	Lard	Commercial	Fresh	0.25	GE Coil	2600
P1-31	AL-V-8-10	Corn	Commercial	Fresh	0.25	GE Coil	2600
P1-32	AL-V-8-10	Lard	Commercial	Fresh	0.25	GE Coil	2600

PHASE 2 TESTS								
			Oil				Range	
Scenario	Test ID	Pan ID (Table 1)	Type	Brand	Condition	Depth (in)	Type	Power (W)
1	P2-1	AL-V-10-8	Soybean	Great Value	Fresh	0.25	GE Coil	2600
	P2-2	AL-V-10-8	Soybean	Great Value	Fresh	0.25	GE Coil	2600
	P2-3	AL-V-10-8	Soybean	Great Value	Fresh	0.25	GE Coil	2600
2	P2-4	AL-V-10-8	Canola	Great Value	Fresh	0.25	GE Coil	2600
	P2-5	AL-V-10-8	Canola	Great Value	Fresh	0.25	GE Coil	2600
	P2-6	AL-V-10-8	Canola	Great Value	Fresh	0.25	GE Coil	2600
3	P2-4a	AL-BH-10-8	Canola	Great Value	Fresh	0.25	GE Coil	2600
	P2-5a	AL-BH-10-8	Canola	Crisco	Fresh	0.25	GE Coil	2600
	P2-6a	AL-BH-10-8	Canola	Generic	Fresh	0.25	GE Coil	2600
4	P2-7	AL-BH-10-8	Lard	Morrell	Fresh	0.25	GE Coil	2600
	P2-8	AL-BH-10-8	Lard	Morrell	Fresh	0.25	GE Coil	2600
	P2-9	AL-BH-10-8	Lard	Morrell	Fresh	0.25	GE Coil	2600
5	P2-10	AL-V-10-8	Soybean	Great Value	Used	0.25	GE Coil	2600
	P2-11	AL-V-10-8	Soybean	Great Value	Used	0.25	GE Coil	2600
	P2-12	AL-V-10-8	Soybean	Great Value	Used	0.25	GE Coil	2600
6	P2-13	AL-BH-10-8	Lard	Morrell	Used	0.25	GE Coil	2600
	P2-14	AL-BH-10-8	Lard	Morrell	Used	0.25	GE Coil	2600
	P2-15	AL-BH-10-8	Lard	Morrell	Used	0.25	GE Coil	2600
7	P2-16	SS-T-10	Canola	Great Value	Fresh	0.25	GE Coil	2600
	P2-17	SS-T-10	Canola	Wesson	Fresh	0.25	GE Coil	2600
	P2-18	SS-T-10	Canola	Crisco	Fresh	0.25	GE Coil	2600
8	P2-19	SS-AC-10	Canola	Great Value	Fresh	0.25	GE Coil	2600
	P2-20	SS-AC-10	Canola	Wesson	Fresh	0.25	GE Coil	2600
	P2-21	SS-AC-10	Canola	Crisco	Fresh	0.25	GE Coil	2600
9	P2-22	CI-L-10	Canola	Wesson	Fresh	0.25	GE Coil	2600
	P2-23	CI-L-10	Canola	Crisco	Fresh	0.25	GE Coil	2600
	P2-24	CI-L-10	Canola	Great Value	Fresh	0.25	GE Coil	2600
10	P2-25	AL-V-10-8	Canola	Great Value	Fresh	0.25	Glass Ceramic	3000

	P2-26	AL-V-10-8	Canola	Wesson	Fresh	0.25	Glass Ceramic	3000
	P2-27	AL-V-10-8	Canola	Crisco	Fresh	0.25	Glass Ceramic	3000
	P2-25a[d]	AL-V-10-8	Canola	Great Value	Fresh	0.25	Glass Ceramic	3000
11	P2-28	SS-AC-10	Canola	Great Value	Fresh	0.25	Glass Ceramic	3000
	P2-29	SS-AC-10	Canola	Generic	Fresh	0.25	Glass Ceramic	3000
	P2-30	SS-AC-10	Canola	Crisco	Fresh	0.25	Glass Ceramic	3000
12	P2-31	CI-L-10	Canola	Great Value	Fresh	0.25	Glass Ceramic	3000
	P2-32	CI-L-10	Canola	Generic	Fresh	0.25	Glass Ceramic	3000
	P2-33	CI-L-10	Canola	Crisco	Fresh	0.25	Glass Ceramic	3000
13	P2-37	AL-V-10-8	Canola	Crisco	Fresh	0.50	GE Coil	2600
	P2-38	AL-V-10-8	Canola	Great Value	Fresh	0.50	GE Coil	2600
	P2-39	AL-V-10-8	Canola	Wesson	Fresh	0.50	GE Coil	2600
14	P2-40	SS-T-10	Canola	Great Value	Fresh	0.50	GE Coil	2600
	P2-41	SS-T-10	Canola	Wesson	Fresh	0.50	GE Coil	2600
	P2-42	SS-T-10	Canola	Wesson	Fresh	0.50	GE Coil	2600
15	P2-34	AL-BH-10-5	Canola	Great Value	Fresh	0.25	GE Coil	2600
	P2-35	AL-BH-10-5	Canola	Wesson	Fresh	0.25	GE Coil	2600
	P2-36	AL-BH-10-5	Canola	Generic	Fresh	0.25	GE Coil	2600
16	P2-43	AL-BH-14-8	Canola	Great Value	Fresh	0.25	GE Coil	2600
	P2-44	AL-BH-14-8	Canola	Wesson	Fresh	0.25	GE Coil	2600
	P2-45[e]	AL-BH-14-8	Canola	Wesson	Fresh	0.25	GE Coil	2600

a – Used oil obtained from fast food restaurant deep fryer
b – 2100 W obtained by lowering level to 8.75 power setting on 2600 W range
c – 1500 W obtained from small element on GE coil range
d – Repeat test conducted with brand new pan to verify results of test P2-25
e – Ignition did not occur after 1 hour of heating, stopped test

5.4. Measures of Performance

Data taken during testing provided transient growth profiles for temperature, smoke, and gas concentrations during heating and up to the point of flaming ignition. In addition to the temporal variations, spatial variations in temperature were measured on the pan surface, in the cooking oil, and in the effluent. Smoke concentrations were measured at two symmetric locations within the collection hood. This data has been processed and condensed to provide several measures of performance for each test conducted. These measures are intended to provide representative values for comparison of various test scenarios and to identify variability among repeat test scenarios.

5.4.1. Free Fatty Acid (FFA) Content

For each test conducted, the oil used was subjected to a FFA evaluation. The FFA has been reported to correlate to the auto-ignition temperature and smoke point. In addition to the presentation of the fire test data, the measured FFA content of the tested oils are reported.

5.4.2. Total Heating Time to Ignition

The time to ignition is the total amount of time from powering the element until flaming ignition occurred. Flaming ignition times were recorded through visual observation. This measure of performance provides an indication of how much thermal energy was required to initiate a flaming fire for the pan/element/oil tested.

5.4.3. Pan Temperature Thresholds

In order to assess the potential challenge an ignition test poses to a pan temperature measuring device, the time windows between fixed pan temperature thresholds and ignition have been compared. For a sensor designed to activate at a fixed temperature threshold, the amount of time available to respond prior to ignition is of key significance. When the average pan temperature reached 300°C (572°F), the remaining time to ignition and the average oil temperature has been determined and reported for each test scenario. In addition, the average pan and oil temperatures have been calculated at ignition for all spatial locations and ±3 seconds before and after ignition was observed.

For each test, several other metrics have been calculated at the time the center pan temperatures reached pan temperatures of 250, 300, 350, and 375°C (482, 572, 662, 707°F). Depending on the operation of a prevention device, these metrics may indicate the potential for challenges to detection. In addition, they provide distinct measures for comparison of variable test scenarios. Other metrics calculated at the fixed pan temperature thresholds include:

1. The slope of the line between the pan temperature threshold and the pan temperature at ignition (°C/min),

2. The slope of the line between the oil temperature at the time the pan threshold was reached and the oil temperature at ignition (°C/min),

3. The difference between the oil temperature and the fixed pan temperature at the time the threshold is reached (°C),

4. The integrated area beneath the smoke obscuration curve up to the time the pan reaches the pan temperature thresholds (%/m - min).

The pan temperature metrics calculated are explained graphically in Figure 10 for a pan threshold of 375°C (707°F). Comparable values have been calculated for the other pan temperature thresholds.

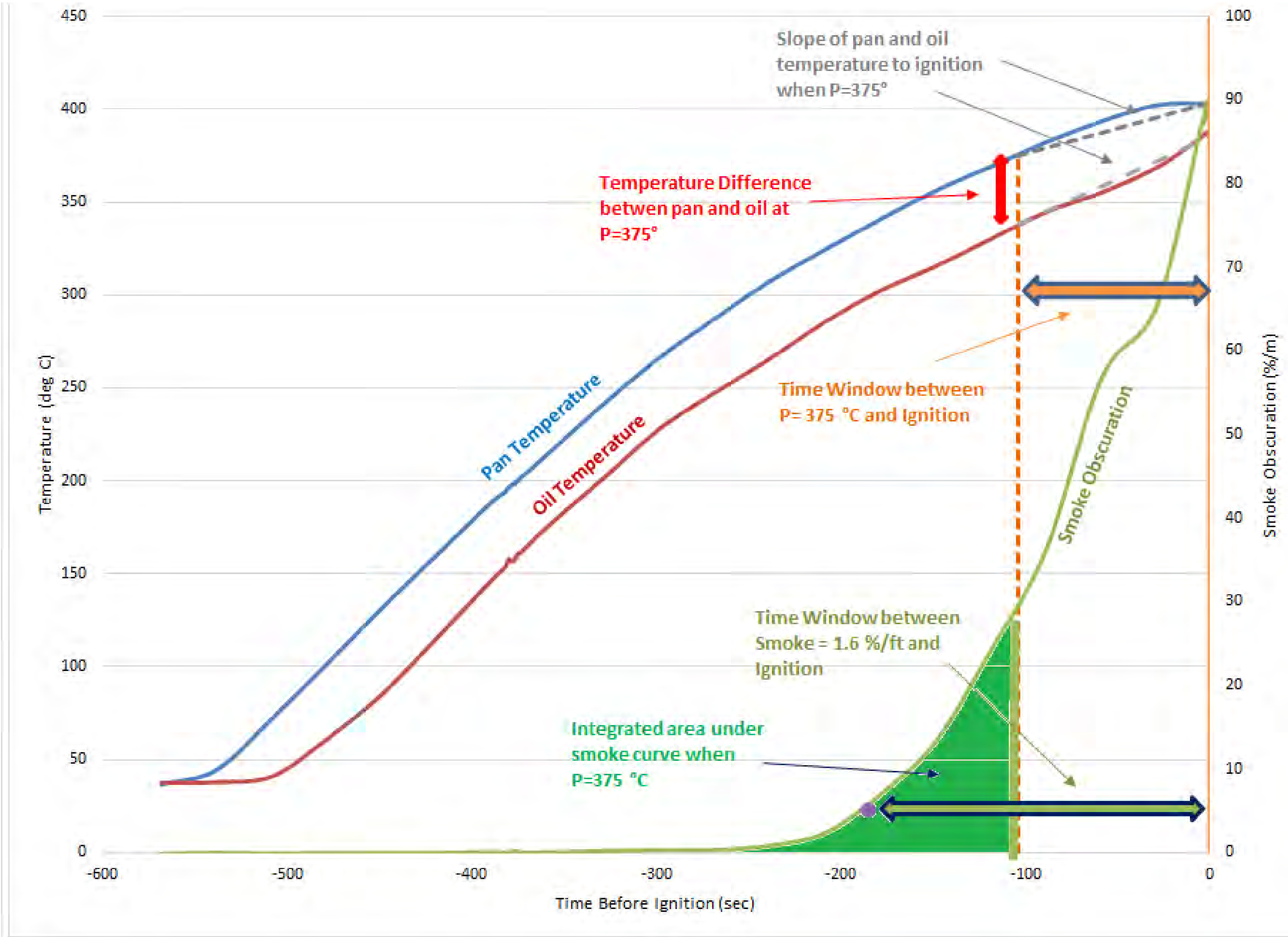


Figure 10 – Graphical representation of metrics calculated at pan temperature thresholds

5.4.4. Smoke Measurement

This measure of performance indicates the additional heating time between a low level smoke measurement in the hood and ignition. Visual observations of smoke production were found to be extremely variable, and it was determined through observation of data that smoke measurements exceeded the noise and continued to rise until ignition when an average obscuration of 1.6 %/ft (5 %/m) was measured between both lasers. When this condition had been met, the total remaining time until ignition has been reported.

This time represents a quantitative evaluation of the time window until ignition after a relatively low level of smoke is produced. The metric removes the subjectivity and uncertainty that occurs from evaluating first smoke (i.e., related to smoke point) based on a visual assessment of smoke noticeable to an observer. In addition to the remaining time, the average pan and oil temperatures at the time of this smoke measurement are reported. The averaged values reported include all spatial locations as well as data 3 seconds prior to and 3 seconds after each noted time.

During nearly all tests conducted, the measured smoke obscuration in the collection hood saturated the capabilities of the laser measurement system. For this reason, the integral of the smoke obscuration curve when fixed pan temperature thresholds have been reached have been calculated.

5.4.5. Gas Measurements

Gas measurements in the collection hood, including the O_2, CO, and CO_2, produced little to no responses prior to ignition for the tests conducted. Detection devices utilizing these parameters would likely provide no response prior to ignition. No additional gas concentration metrics have been considered for this analysis.

5.4.6. Correlation

The measure of correlation between the tested variables and the performance metrics have been calculated using the Pearson's correlation coefficient, r_{xy}. The correlation coefficient is calculated between two data sets by taking the means of the variable and data, and summing products of the differences between the data and the mean. This calculation is shown in Equation 1.

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad \textbf{Eq. (1)}$$

The Pearson's correlation provides an estimate of the relationship between the tested variable, x_i, and the resulting measurement, y_i. The value of r_{xy} can range from -1 to 1, with values indicative of the relationships shown in Figure 11. These ranges are only relative and interpretative, and do not reflect defined rules for the Pearson's correlation.

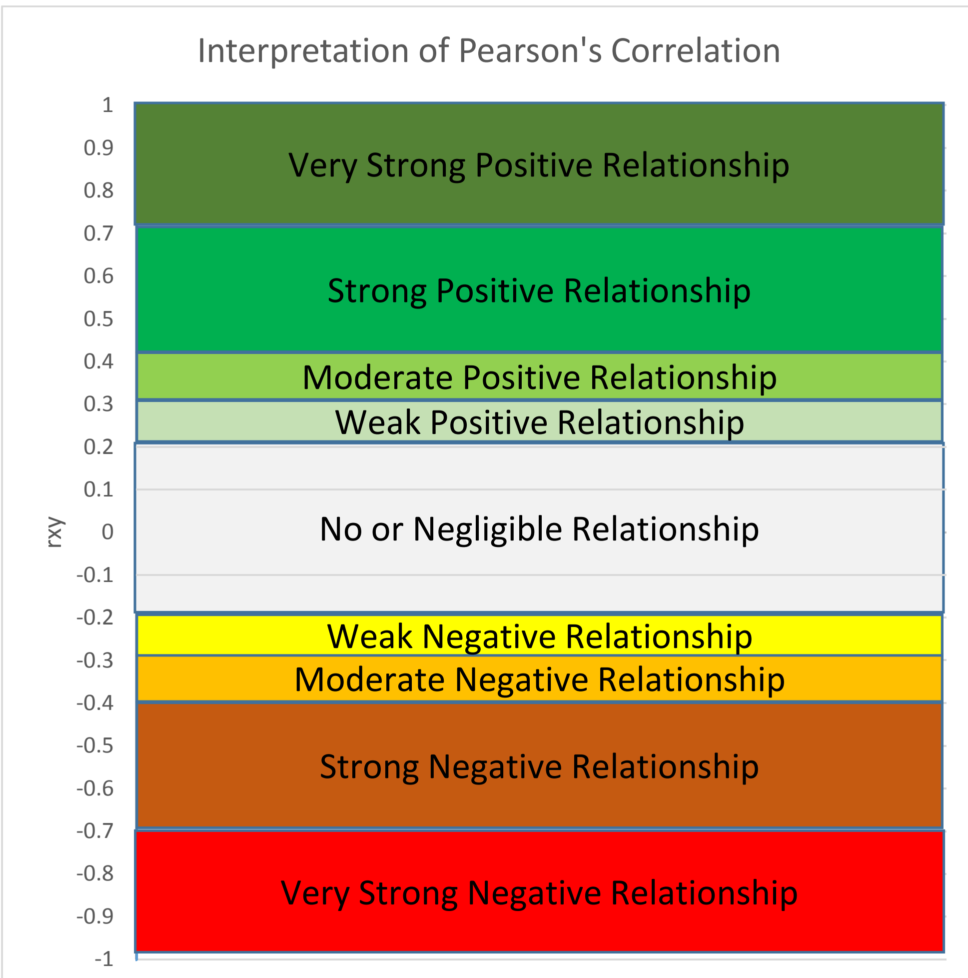


Figure 11 – Interpretation of Pearson's Correlation calculated for test data and variables

In addition to the correlation coefficient, the slope of the response curve is also calculated to provide an estimate of the magnitude of the influence of the variable. A correlation of 1.00 is less meaningful when the temperature change is only 1 degree in magnitude.

The correlation between test variables and test measurements has been calculated to identify potential relationships. Evaluated variables include:

- The FFA of the tested oil (%);
- The power input of the element to the pan (W);
- The total mass of the test pan (g);
- The estimated specific heat capacity of the pan;
  - Aluminum = 0.91 J/g-°C
  - Stainless Steel = 0.51 J/g-°C
  - Cast Iron = 0.46 J/g-°C
- The estimated thermal conductivity of the pan (W/m - °C);
  - Aluminum = 215 W/m - °C
  - Stainless Steel = 54 W/m - °C
  - Cast Iron = 80 W/m - °C
- The minimum possible heating time to ignition (sec);
  - Calculated as a combination of pan, oil and element variables as shown in Eq. (2)

$$t_{min} = \frac{M_{pan}c_{pan}T_{pan,ign}+\rho_{oil}V_{oil}c_{oil}T_{oil,ign}}{\dot{Q}_{element}} \quad \textbf{Eq. (2)}$$

  - Where:
    - M_{pan} = Pan mass
    - c_{pan} = specific heat capacity of the pan
    - $T_{pan,ign}$ = the pan temperature at ignition
    - p_{oil} = density of the oil (~0.85 g/cm^3)
    - V_{oil} = volume of oil, *coil* = specific heat capacity of oil (1.91 J/g-K)
    - $T_{oil,ign,}$ = the temperature of the oil at ignition
    - $Q_{element}$ = the thermal output of the element
- The radius of curvature of the pan base;
- The angle of tilt of the pan settled on the element surface; and,
- The diameter of the pan base on the element (cm).

The relationship between these variables and test measurements have been calculated. The test measurements evaluated for correlation include the performance metrics discussed in the preceding sections.

5.4.7. Instrumentation Comparison

The instrumentation used was also compared to determine the best potential configuration for use in standardized testing. For each test, the average pan temperatures were calculated from the 3 spatial locations. The difference between each location and the average pan temperature was then calculated and averaged across the duration of the test.

The average oil temperatures were calculated from the 9 spatial locations. The oil temperatures were measured in three spatial locations, each at three depths. The difference between the three temperatures measured at the half-depth of the oil and the average were calculated and averaged across the duration of the test. The difference between the three temperatures taken slightly above the half-depth and the average oil temperature was also calculated and averaged. This was also repeated for the three temperatures taken slightly below the half oil depth.

Differences between the average result and the two smoke lasers and the four effluent temperature measurements were also compared for each test conducted. This data provided a measure of uniformity of smoke and heat in the collection hood. The full set of instrumentation comparisons calculated for each test includes:

- The average difference between the pan temperatures by location (°C)
- The average difference between the oil temperatures by location (°C)
- The average difference between the oil temperatures by depth (°C)
- The average difference between the effluent temperatures by location (°C)
- The average difference between the smoke obscuration by location (%/m)

The comparisons of instrumentation were used for identification of the locations providing measurements closest to the average values. This will allow for inclusion of the minimum amount of total instrumentation in a test standard while still providing sufficient data for evaluation.

6. TEST DATA

6.1. Phase 1 and Phase 2 Test Conditions

There are three key differences between the Phase 1 and the Phase 2 test series. First, the large, exposed bead thermocouples used in the Phase 1 testing were replaced with smaller, Inconel sheathed thermocouples in Phase 2. These thermocouples had a faster response time, were easier to place at accurate depths, and were easier to clean between tests. Second, at the advice of the range industry, the base pan size was increased from 8 in. (20 cm) to 10 in (25 cm). This change increased the amount of oil needed to achieve a ¼ in. (6.4 mm) oil depth from 13.4 in.^{3} (220 mL) to 18.3 in.^{3} (300 mL). The 10 in. (25 cm) size pan was considered more appropriate for use on the large cooktop element. Third, the test apparatus was moved from an enclosed room to an operating exhaust hood. The test data have been compared to determine the impacts from these changes to the test conditions. Detailed analysis of these observations are provided in the following sections.

The primary observations include:

1. Oil temperatures measured from the start to ignition in Phase 1 were lower than those measured in Phase 2 by 18°C (32°F) on average. This effect is likely due to the greater thermal lag of the Phase 1 thermocouples. The difference between the oil temperatures measured in Phase 1 and Phase 2 tests was greatest when the oil temperatures were changing most rapidly and less difference was observed for slower heating rates.
2. Larger pans and greater oil volumes used for baseline testing in Phase 2 generally resulted in longer total heating times to reach ignition when all other variables remained the same (aluminum pans, 2600 W element).
3. Local airflow conditions does not appear to have affected the test measurements in any significant way. The ventilation hood removed the spillover but did not prevent effluent from rising naturally and collecting into the measurement hood.

The differences in measured oil temperatures (Phase 1 v. Phase 2) affected the usage of the data in the analysis. The difference in measured temperatures is considered systematic, and the Phase 1 data was still applicable to identify how a change in pan size or oil type affected the measurements. Data from both Phase 1 and Phase 2 oil TCs were used to establish the effect of variables and identify trends. Because the magnitude of the measured temperatures was different, however, the Phase 1 oil temperature data was excluded from any analysis conducted to establish the maximum allowable oil temperatures for a potential standard test.

6.1.1. Oil Temperature Measurement

The oil temperatures measured during the Phase 1 tests were \an average of 54°C (97°F) lower than the pan temperatures when measured from the start of heating until ignition occurred. The oil temperatures measured during the Phase 2 tests were an average of 36°C (65°F) lower than the pan temperatures. In general, the pan temperatures measured during both Phases were comparable, and so the Phase 1 tests measured an average oil temperature approximately 18°C (32°F) lower than in Phase 2 tests from the start of heating until ignition. For the same measured pan temperature, the measured oil temperature was lower in Phase 1 than Phase 2.

The difference between the oil temperatures measured in the Phase 1 and Phase 2 tests was the greatest when the temperatures were increasing most rapidly. The difference can therefore be attributed to the increased thermal inertia of the Phase 1 thermocouples. When considering only the last 60 seconds of each test, when the temperatures were observed to change less rapidly, the Phase 1 tests report an average pan/oil temperature difference of 35°C (63°F) and 20°C (36°F) for the Phase 2 tests.

A number of test variables were changed across the scope of the Phase 1 and Phase 2 tests including pan sizes, range types and power, pan materials, and oil types. These variables may also impact the measured pan and oil temperatures. When comparing only the most similar test conditions between the phases, the difference in measured oil temperatures remained consistent with the overall average values reported above. Figure 12 shows a comparison of Phase 1 and Phase 2 tests conducted with Crisco brand canola oil on the 2600 W electric coil element with 8 gauge aluminum pans (Tests P1-11 and P2-5a).

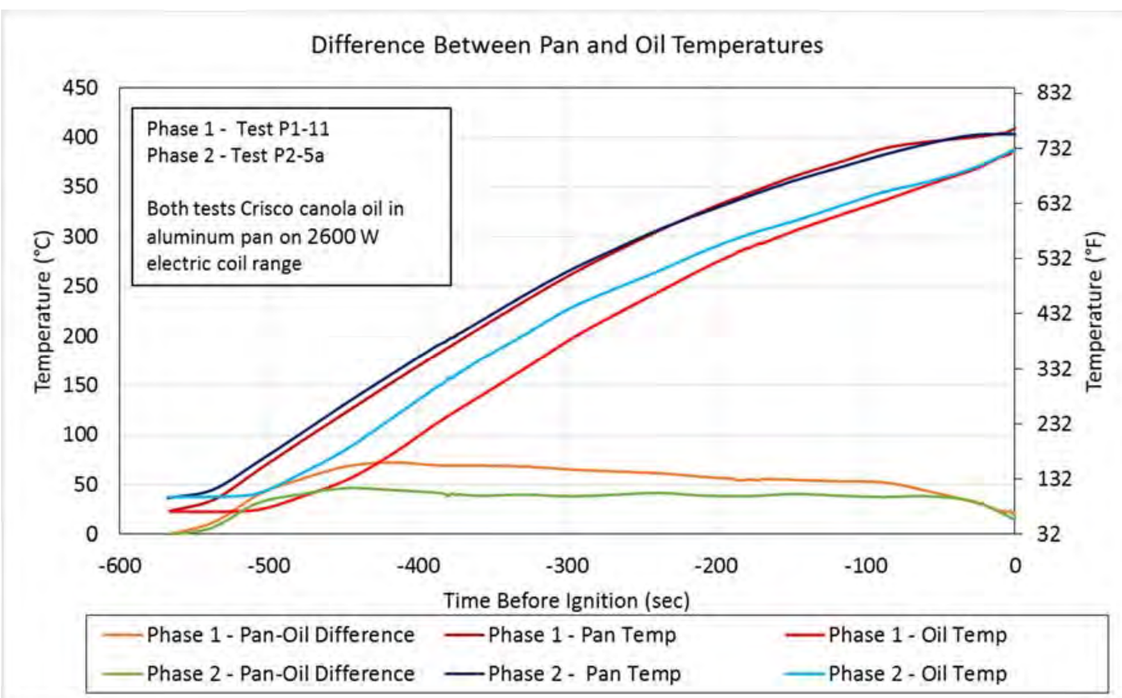


Figure 12 – Comparison of pan and oil temperature measurements in Phase 1 and Phase 2 tests

The only differences between the tests were the size of the pan (8 in. (20 cm) for Phase 1, 10 in. (25 cm) for Phase 2) and the volume of oil heated (same depth). It can be seen that the pan temperatures measured in the two tests are much closer than the oil temperatures. The difference between the pan and oil temperatures measured in test P1-11 were found to be 47°C (85°F) averaged over the entire test and 25°C (45°F) during the final 60 seconds before ignition. The average difference between the pan and oil temperatures measured in test P2-5a was 33°C (59°F) during the entire test and 20°C (36°F) during the final 60 seconds before ignition. These values are in line with the average across all tests in Phase 1 and Phase 2 discussed above.

The temperatures of the oil measured at the time of ignition between Phase 1 and Phase 2 tests are closer than the test average, differing by an average of 15°C (27°F). The slope of the temperature change was generally lowest at the point of ignition, and the slope was inversely proportional to the total heating time. Therefore, for tests reaching the ignition point rapidly, the oil temperatures measured during Phase 1 tests will be lower than for Phase 2 testing. The differences between the Phase 1 and Phase 2 oil temperatures at ignition were reduced for tests requiring longer heating times to reach ignition. The oil temperature measurements obtained during Phase 2 are considered more accurate. Where data is used for comparison of test scenarios and selection of potential tests, the Phase 2 oil data has been given precedence.

The data analysis was conducted in several discrete portions. When considering the impact of variables on the ignition times, temperatures, or smoke production, both the Phase 1 and Phase 2 data were included in the analysis. Although the oil temperatures measured in each Phase differ, the general trends resulting from changing test variables remain valid. The Phase 1 and Phase 2 data have been presented and considered for each variable discussed in this report. In Sections 7, 8, and 9, however, the magnitude of the oil temperatures is of key significance for determining the global trends, comparing the instrument locations, and recommending thresholds for a standardized test. Only the Phase 2 data was considered for these analyses.

6.1.2. Pan Size

At the recommendation of appliance industry representatives on the project technical panel, the baseline pan size was increased from 8 in. (20 cm) in Phase 1 to 10 in. (25 cm) in Phase 2. It was suggested that this was a more realistic application for the large range element. Increasing the pan size required an increase in the oil volume required to maintain a ¼ in. (6.4 mm) initial oil depth. In general, increasing the pan size and oil volume resulted in longer total heating times to reach ignition.

Direct comparisons were made between tests conducted in Phase 1 with fresh oils in 8 in. (20 cm), 8 gauge aluminum pans on the 2600 W electric coil (Tests P1-1 through P1-13) and the tests conducted in Phase 2 with fresh oils in 10 in. (25 cm), 8 gauge aluminum pans on the 2600 W electric coil (Tests P2-1 through P2-9). The average total heating time to reach ignition increased from 526 seconds in Phase 1 to 651 seconds in Phase 2. An increase in oil volume of 36% (220 mL to 300 mL) and an increase in pan diameter of 25% resulted in an average increase in ignition time of 23%.

6.1.3. Local Airflow Conditions

Phase 1 tests were conducted with the apparatus in an enclosed room with no airflow. The effluent from the pan rose naturally from buoyancy into the collection hood. The spillover was allowed to collect in a large room with a small operating exhaust duct in one corner of the ceiling. Phase 2 tests were conducted with the apparatus placed beneath an operating exhaust hood. When effluent spilled from the collection hood, it was immediately removed by the larger hood exhaust. This reduced the total turnaround time between tests conducted.

No horizontal air flows were observed across the range top, and the effluent rose vertically from buoyancy and collected in the hood. The operating exhaust hood was not found to visually impact the rising effluent. Measurements of the smoke obscuration in the hood confirm that comparable amounts of smoke were collected between similar test conditions.

6.2. Free Fatty Acid Content

All evaluated oils were tested for the FFA content. Details of the oils are discussed in Section 5.2.3. Several of the oil samples from Phase 1 tests were subjected to sustained heating in an attempt to simulate use and artificially increase the FFA through “aging.” One other sample of oil was obtained after lunch time from the deep fryer of a fast food restaurant. The vegetable oil and pork lard used in Phase 2 were subjected to repeated chicken frying to produce “used” oil. The various oils subjected to fire testing and the measured FFA of each are shown in Table 3.

Table 3 – Free fatty acid content of tested oils

PHASE 1 TESTING		
Oil Type	**New Oil FFA (%)**	**Artificially Aged 8 hour FFA (%)**
Soybean Oil (Commercial)	0.044	0.14
Wesson Vegetable Oil (Soybean)	0.024	
Crisco Vegetable Oil	0.023	
Used Fast Food Vegetable Oil (Soybean)		4.4[a]
Canola Oil (Commercial)	0.021	0.12
Wesson Canola Oil	0.023	
Crisco Canola Oil	0.020	
Corn Oil (Commercial)	0.064	0.16
Peanut Oil (Commercial)	0.021	0.035
Beef Shortening (Commercial)	0.023	0.07
Pork Lard (Commercial)	0.21	0.26
PHASE 2 TESTING		
Oil Type	**New Oil FFA (%)**	**Used Oil (fry chicken) FFA (%)**
Great Value Vegetable Oil	0.035	0.56
Morrell Pork Lard	0.23	0.56
Great Value Canola Oil	0.02	
Crisco Canola Oil	0.02	
Wesson Canola Oil	0.023	
Generic Brand Canola Oil	0.035	
a – Oil used in deep fryer not artificially aged 8 hours		

The simulated aging process of Phase 1 was observed to increase the FFA of the oils for all tested cases. The minimum resulting increase was observed for peanut oil, with an increase of 0.014% FFA, and the maximum increase in FFA was observed for both the soybean and corn oils, increasing by 0.096% FFA. However, the increase in the FFA due to sustained heating was less than observed for the oil used in a fast-food restaurant deep fryer for cooking, which reported 4.4% FFA, an increase over the commercial soybean oil of two orders of magnitude. Although no sample of the fresh fast food oil was obtained or tested, it was known that the oil was soybean oil. Based on other experiments comparing brands, it is expected to be comparable to both the commercial and consumer soybean oils tested, which did not show much difference based on source as discussed in section 6.5.

Oil usage through chicken frying conducted in Phase 2 increased the oil % FFA from 0.035 for the vegetable oil to 0.56% FFA and from 0.23 to 0.56% FFA for the pork lard. These values are significantly lower than the 4.4% FFA measured for the fast food oil obtained in Phase 1, possibly because of the straining of solid particulate or the consistent recipe and procedures used. These oils were used for real cooking of fatty meats with breading and were used to the point most people would likely dispose of them. They are representative of re-used oils in real kitchens.

Each of the oils were subjected to a baseline test, which included the use of an 8 gauge aluminum pan placed on the 2600 W, 8 in. (20 cm) element of the GE range on its highest setting. All tests used ¼ in. (6.4 mm) oil depth. Phase 1 tests used an 8 in. (20 cm) pan and Phase 2 tests used a 10 in. (25 cm) pan. The pan and oil temperatures when measureable smoke was observed and at ignition for these tests are shown in Figure 9 as a function of the FFA. The previously reported impact of FFA on heated oil smoke production and ignition are also shown in Figure 13 [3]. The reported data was obtained for observations of smoke and ignition of a droplet of oil placed onto a fixed temperature hotplate. The temperatures obtained for new test data are for the bulk oil temperatures when the smoke meters measured 1.6%/ft (5%/m) smoke obscuration or when the oil ignited, and are greater than the measured droplet temperatures from the previous data.

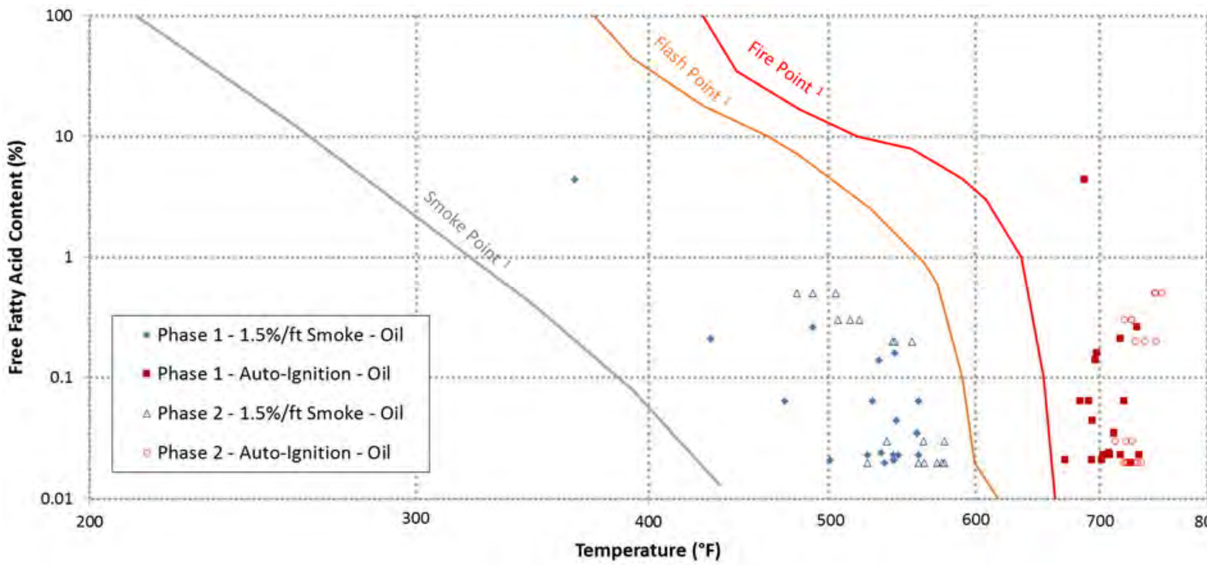


Figure 13 – Average oil temperatures at smoke measurement and ignition as a function of the % FFA content of the tested oil (lines are from Ref 3)

Although there is a significant amount of variability in the data, two distinct trends can be observed. The temperature of the oil when smoke is measured in the collection hood decreases with increasing % FFA. Although the magnitude of the temperatures are higher, the general trend of the smoke temperatures follows the trend of the reference data for smoke point.

The second trend is the temperature of the oil at ignition is relatively unaffected by the % FFA for the oils evaluated. The solid red point well above the rest of the data was obtained from the deep fryer oil test, with a % FFA of 4.4. The ignition temperature remained within the bounds of the fresh and aged oil tests conducted. In phase 2 testing, the % FFA increased as oil was used, and the average ignition temperatures increased as well, rather than decrease as predicted by the reference data. While the ignition temperatures may drop off drastically at much higher % FFA, it appears that for used cooking oils, even those used repeatedly, the % FFA does not increase enough to significantly impact the ignition temperatures.

6.3. Oil Type

Fire tests were conducted on numerous types of oils. Phase 1 tests were conducted using commercial grade oils, including soybean (vegetable), corn, canola, peanut, beef shortening, and pork lard. These commercial grade oils were obtained from an industrial supplier. In addition, Wesson and Crisco consumer brand soybean (vegetable) and canola oils were tested. Phase 2 tests were conducted using consumer brand soybean (vegetable) and canola oils, and pork lard. Detailed analysis comparing oil types is provided in the following section. The primary observations from comparisons of the oil data include:

- Oils with higher % FFA generally had
    - Longer heating times to reach ignition
    - Longer time windows between a fixed pan temperature measurement and ignition
    - Longer time windows between smoke production and ignition
    - Lower temperatures at the production of smoke
    - Unaffected temperatures at ignition
- Based on these results, canola oil was selected for continued testing due to:
    - Fastest heating to ignition
    - Shortest time window for both pan temperature and smoke activation devices

All Phase 1 oil evaluation tests were conducted on the 8 in. (20 cm) element of the 2600 W GE range, in an 8 in. (20 cm) diameter, 8 gauge aluminum frying pan. A total of 13.4 in.^{3} (220 mL) of oil was used for each test, resulting in an initial oil depth of ¼ in. (6.4 mm). All Phase 2 oil evaluation tests were conducted on the 8 in. (20 cm) element of the 2600 W GE range, in a 10 in. (25 cm) diameter, 8 gauge aluminum frying pan. A total of 18.3 in.^{3} (300 mL) of oil was used for each test, resulting in an initial oil depth of ¼ in. (6.4 mm). The tests included in the oil type analysis are listed in Table 4.

Table 4 – Tests included in oil type analysis

	Identifier	Oil Type	Test ID
Phase 1	Canola	Crisco Canola	P1-11
		Wesson Canola	P1-13
		Commercial Canola	P1-5
		Commercial Canola	P1-6
	Peanut	Commercial Peanut Oil	P1-7
	Shortening	Commercial Beef Shortening	P1-8
	Soybean (Vegetable)	Crisco Vegetable Oil	P1-10
		Wesson Vegetable Oil	P1-12
		Commercial Soybean oil	P1-1
	Corn	Commercial Corn Oil	P1-2
		Commercial Corn Oil	P1-3
		Commercial Corn Oil	P1-4
	Pork Lard	Commercial Pork Lard	P1-9
Phase 2	Canola	Great Value Canola Oil	P2-4
		Great Value Canola Oil	P2-5
		Great Value Canola Oil	P2-6
		Great Value Canola Oil	P2-4a
		Crisco Canola Oil	P2-5a
		Generic Brand Canola Oil	P2-6a
	Soybean (Vegetable)	Great Value Vegetable Oil	P2-1
		Great Value Vegetable Oil	P2-2
		Great Value Vegetable Oil	P2-3
	Pork Lard	Morrell Pork Lard	P2-7
		Morrell Pork Lard	P2-8
		Morrell Pork Lard	P2-9

6.3.1. Available Response Times

A key metric for comparison of the tests is the total amount of time required to reach ignition. The total heating times required to reach ignition are shown in Figure 14, with the oils approximately ordered from lowest to highest percent FFA. The blue bars show the full range of heating times from all included tests. The red line reports the mean time among each test type, with the dashed red lines showing ±1 standard deviation from this mean. The green line and shaded region and orange line and shaded region show the mean ±1 standard deviation for the Phase 1 and Phase 2 tests, respectively.

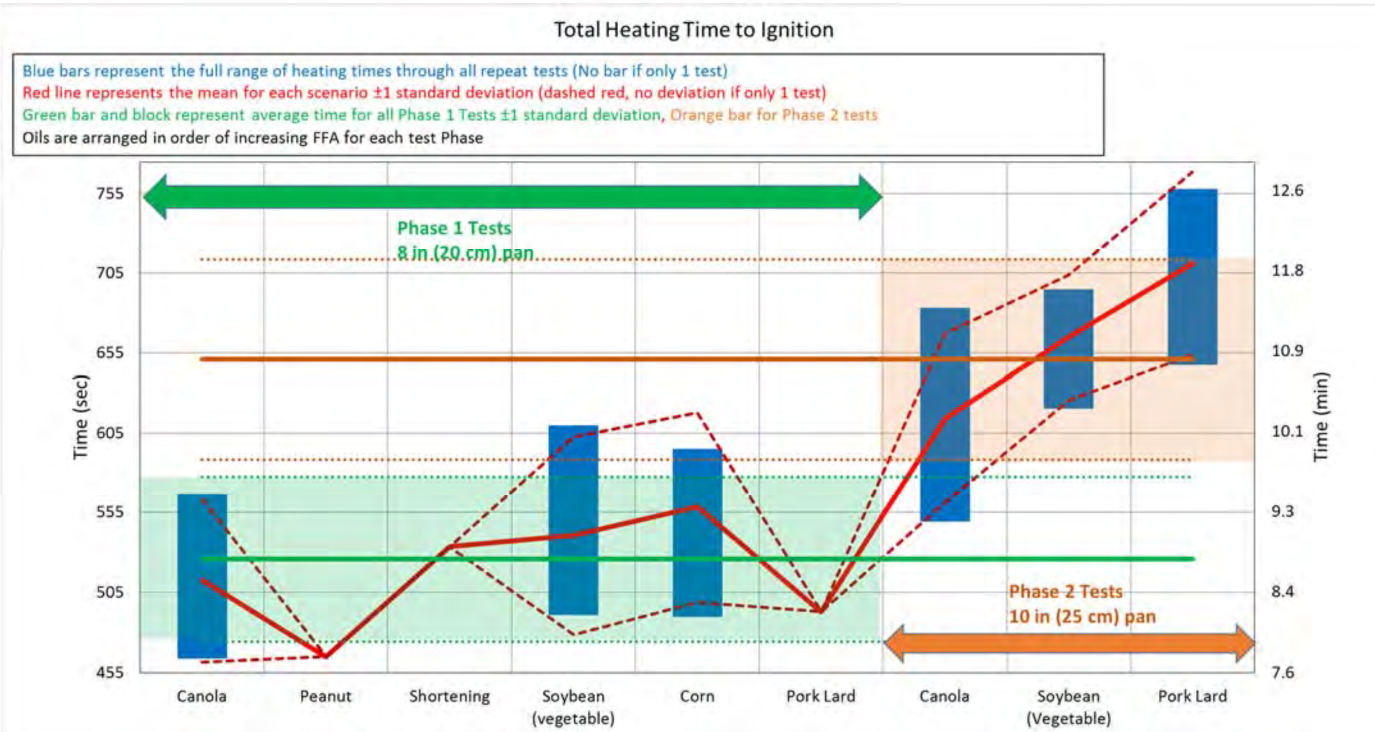


Figure 14 – Heating times until ignition for various oil types (Phase 2 times for larger pan with more oil volume than Phase 1)

The average heating time to ignition was increased from 526 seconds for the 8 in (20 cm) pans used in Phase 1 to 651 seconds for the 10 in (25 cm) pans with 300 mL of oil used in Phase 2. Heating times falling outside of a standard deviation from the averages of all tests in a test phase include one fast canola oil and a peanut oil test in Phase 1, one fast canola oil test in Phase 2, one slow corn and soybean oil test in Phase 1, and two slow pork lard tests in Phase 2.

The oil % FFA were correlated to the average total heating times for each of the test scenarios shown in Table 4. For test scenarios using several brands of oils with different % FFA (i.e., canola oils in Phase 2), an average % FFA was used for calculation. The calculation of these metrics is shown in Figure 15. However, a strong positive correlation was not measured for the Phase 1 tests. Rather, a weak negative correlation of -0.20 was calculated. This value was mostly caused by the high FFA of the pork and the fast heating time to ignition observed for the single test conducted. When the pork lard is removed from consideration, a correlation between FFA and total heating time to ignition of 0.67 is calculated for the Phase 1 data with a slope of 1307 sec per % FFA.

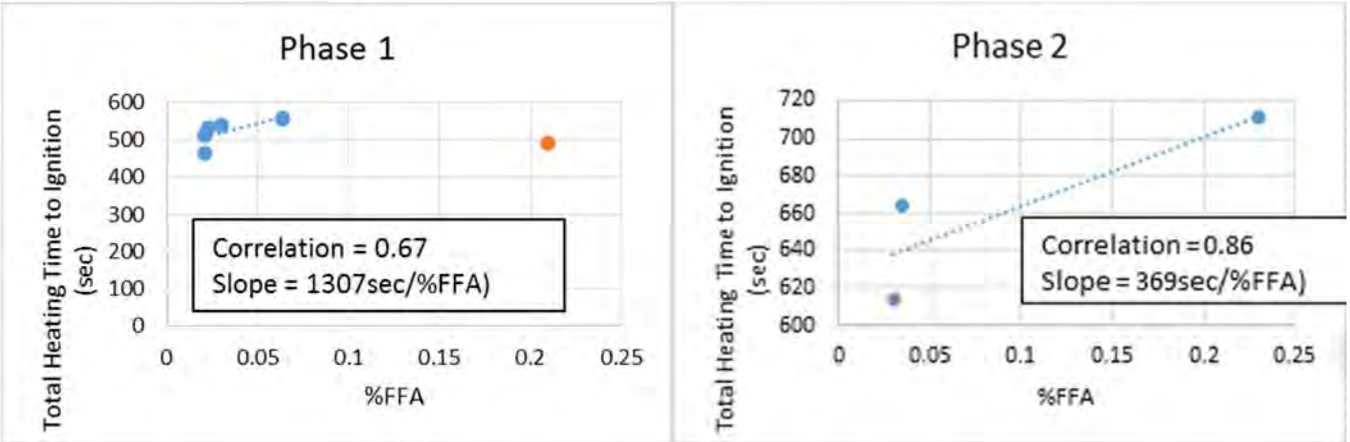


Figure 15 – Calculated correlations and slopes for heating time to ignition and % FFA

The potential challenge for a detection device measuring pan temperatures is related to the amount of time available between a specific pan temperature and ignition. For this analysis, an arbitrary fixed pan temperature of 300°C (572°F) has been chosen for evaluation. Other values in the range of 250–375°C (482–707°F) could also have been chosen, and the respective time windows would vary accordingly. The time windows between an average pan temperature of 300°C (572°F) and ignition for the Phase 1 and Phase 2 oil type tests are shown in Figure 16.

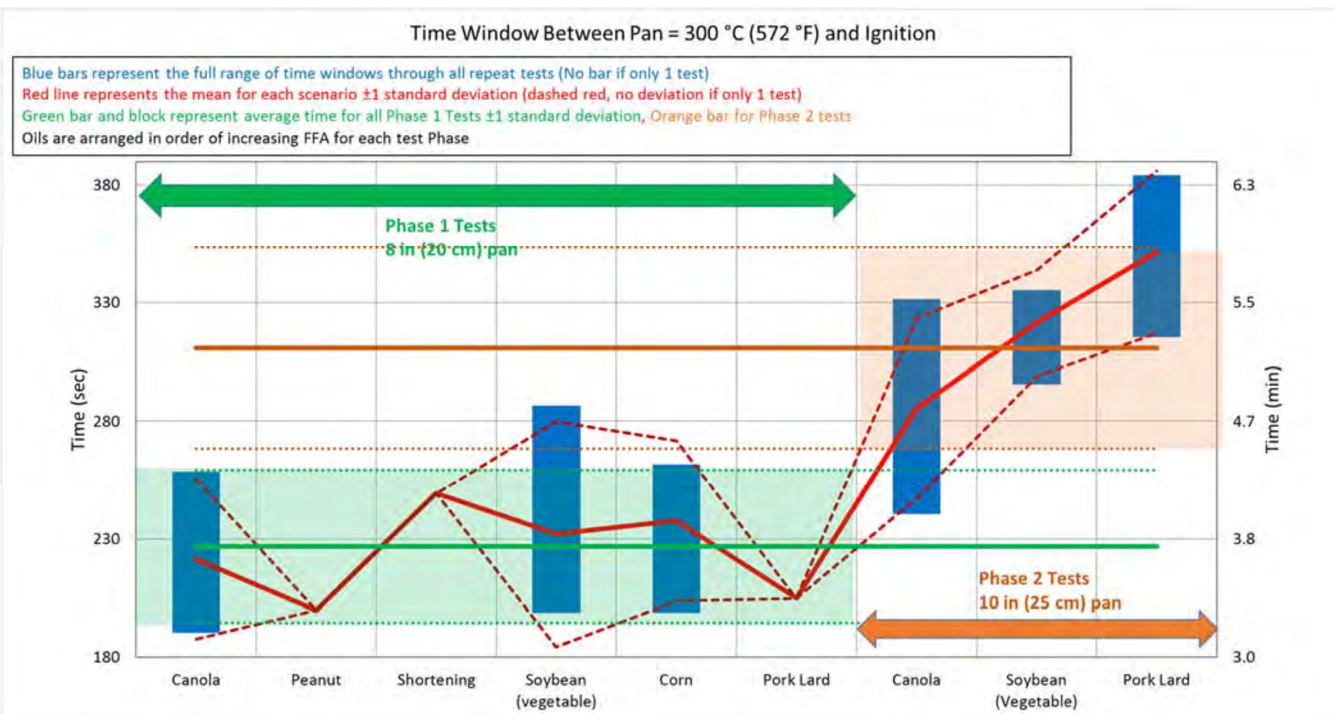


Figure 16 – Time window between pan temperature = 300°C (572°F) and ignition for various oil types

The potential time window for pan temperature activation devices scales nearly proportionally to the total heating times. Average time windows for 300°C (572°C) pan activation of 227 seconds and 311 seconds were measured for Phase 1 and Phase 2 tests, respectively. The correlations between the pan temperature windows and ignition times were 0.88 (0.50 sec window per sec heating time) and 0.99 (0.68 sec window per sec heating time) for the Phase 1 and Phase 2 tests, respectively. The tests with the shortest time windows for both tests series included the use of canola oil, which also had the lowest measured % FFA.

The potential challenge for a detection device measuring smoke is directly related to the amount of time between the initial production of smoke and ignition. For this analysis, the time of smoke production was defined as the time an average smoke obscuration of 1.6%/ft (5%/m) was measured by the lasers. The time window between this smoke measurement and ignition are shown for the various oil types in Figure 17.

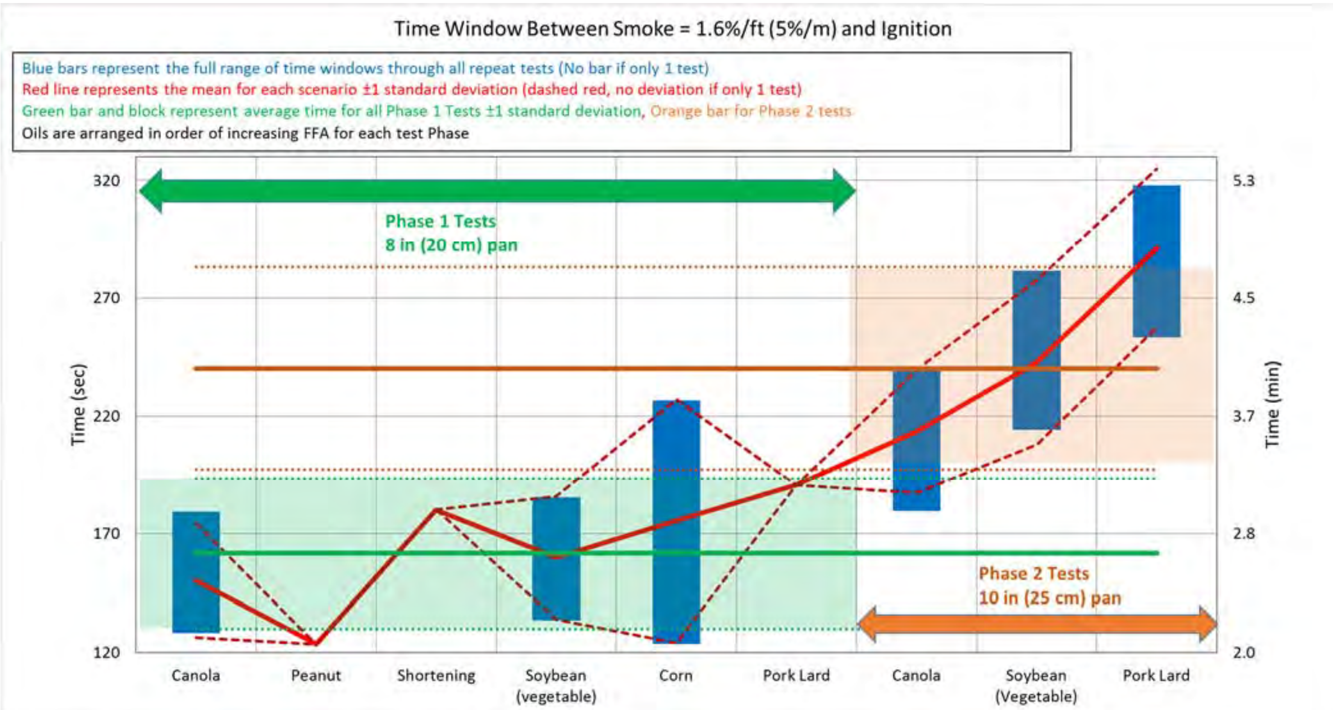


Figure 17 – Time window between smoke obscuration = 1.6%/ft (5%/m) and ignition for various oil types

The potential time window for smoke activation devices scales nearly proportionally to the total heating times and pan temperature windows. Average time windows for low smoke measurement of 162 seconds and 240 seconds were measured for Phase 1 and Phase 2 tests, respectively. This is approximately 1 minute shorter than the available time window for 300°C (572°F) pan temperature activation. It should also be considered that the smoke concentrations measured for this test apparatus are higher than those expected in larger kitchens, especially those with operating exhaust hoods. The available time window was observed to increase with increasing % FFA, with correlation factors of 0.63 (slope = 205 sec per % FFA) and 0.93 (slope = 322 sec per % FFA) for Phase 1 and Phase 2, respectively. These calculations are shown in Figure 18.

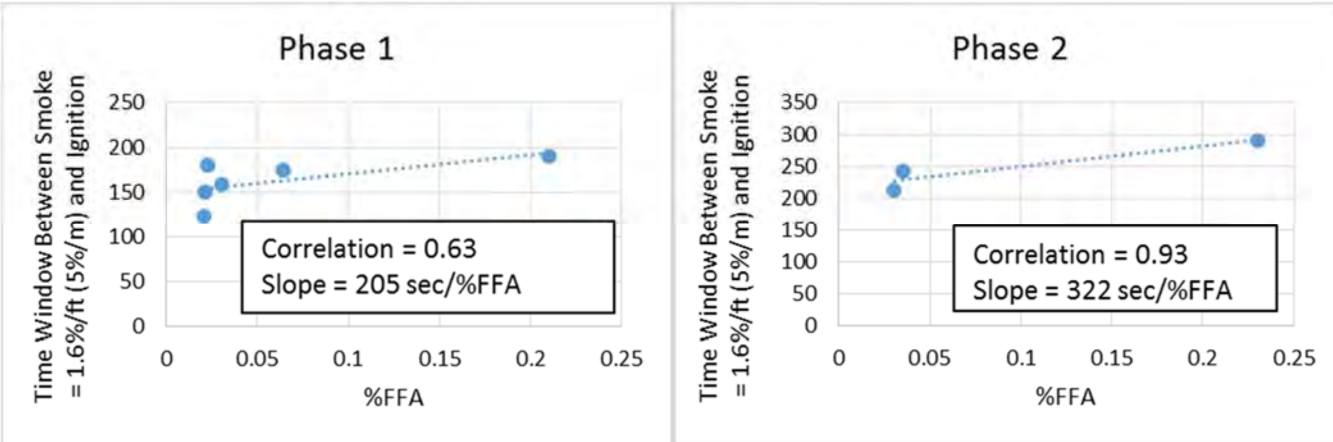


Figure 18 – Calculated correlations and slopes for time window between smoke and ignition and % FFA

6.3.2. Temporal Heating Curves

Temporal plots of the average pan and oil temperatures, and average smoke obscuration for all oils tested (Table 3) are shown in Figure 19. The tests have all been aligned by the time of ignition (T = 0). The solid lines show the average among the Phase 1 and Phase 2 tests included in the analysis, and the dashed lines show the maximum and minimum values measured at the given time before ignition occurred.

The total heating time and available activation windows are clearly shorter for the Phase 1 Tests using an 8 in. (20 cm) pan compared to the Phase 2 tests using a 10 in. (25 cm) pan. The smoke obscuration begins increasing rapidly after the pan and oils reach approximate temperatures of 340°C (644°F) and 280°C (536°F), respectively. Although the Phase 2 tests take longer to reach ignition, the pan and smoke temperatures generally converge at the ignition time with the faster Phase 1 tests. The oil temperature measurements, however, remain higher as a result of the more responsive thermocouples.

A number of metrics have been calculated to compare the temporal response curves of the various oil types. These metrics include the slopes of the temperature and obscuration curves to ignition at various fixed points, the difference between the pan and oil temperatures at the time of ignition, and the total integrated area under the smoke obscuration curve at ignition. These values are shown in Table 5.

In general, the greater the slope, the greater the challenge the fire source presents to a mitigation device since a greater slope indicates a more rapid change from normal to hazardous conditions. For the difference between pan and oil temperatures, the smaller the difference, the greater the challenge to a fire prevention device that is monitoring pan temperature. A smaller difference would result in higher oil temperatures for the same pan temperature measurement, therefore increasing the likelihood of ignition. For smoke detection devices, the lower the integrated value, the greater the challenge the fire source presents to a system that is monitoring smoke as a criteria for control. The cases presenting the greatest challenges to prevention devices are highlighted for each criteria and test phase.

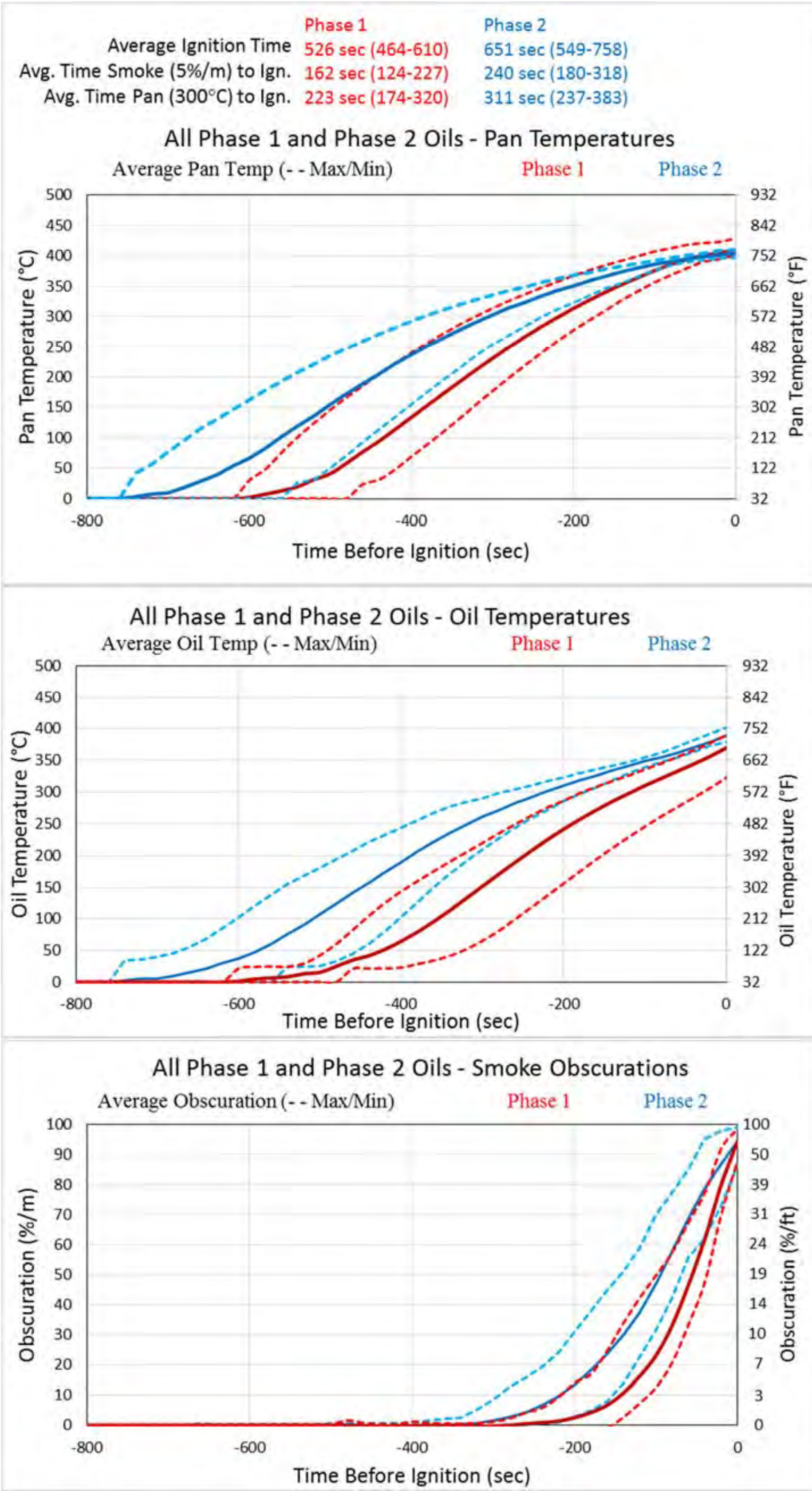


Figure 19 – Pan and oil temperatures and smoke obscuration curves for oil types tests (Table 3) aligned by ignition time

Table 5 – Calculated pan and oil temperature slopes and obscuration slope and integrated areas

		Average pan temp slope between fixed pan temperatures and ignition (°C/min)				Average oil temp slope between fixed pan temperatures and ignition (°C/min)				Difference between pan and oil temperature at fixed pan temps (°C)					Integral of smoke obscuration up to fixed pan temperatures (%/m – min)				
	Oil	250 °C (482 °F)	300 °C (572 °F)	350 °C (662 °F)	375 °C (707 °F)	250 °C (482 °F)	300 °C (572 °F)	350 °C (662 °F)	375 °C (707 °F)	250 °C (482 °F)	300 °C (572 °F)	350 °C (662 °F)	375 °C (707 °F)	IGN	250 °C (482 °F)	300 °C (572 °F)	350 °C (662 °F)	375 °C (707 °F)	IGN
P1	Canola	35	31	25	20	42	38	33	31	63	58	51	50	32	0	0	6	22	106
	Peanut	40	35	29	24	51	47	45	42	132	125	120	113	87	-8	-10	-8	2	84
	Shortening	33	29	24	21	41	36	30	29	80	72	60	60	38	1	1	6	12	120
	Soybean	33	29	24	20	37	34	32	29	65	65	63	60	41	0	1	5	13	103
	Corn	33	30	24	21	39	36	34	31	65	66	63	57	40	-2	-2	10	35	132
	Pork Lard	38	34	28	23	44	40	40	40	51	45	50	50	25	0	3	12	26	111
P2	Canola	26	22	17	14	29	26	24	24	33	31	35	35	14	0	0	7	30	153
	Soybean	23	20	15	12	26	24	20	19	43	45	41	41	21	0	0	6	26	170
	Pork Lard	21	18	14	12	25	23	22	21	40	42	41	38	12	0	0	12	49	236

6.3.3. Smoke Production and Ignition Temperatures

In addition to the total heating times and potential activation windows, the pan and oil temperatures measured at the time smoke is produced and at ignition provide a more direct comparison of the properties of the oil types. These metrics are not as affected by test variables such as the total oil volume or pan size. The average pan temperatures at the time of low smoke measurements are shown in Figure 20. The blue bars show the full range of all pan temperatures measured from each of three locations ±3 seconds from the measurement of 1.6%/ft (5%/m) smoke. The red line reports the mean time among each test type, with the dashed red lines showing ±1 standard deviation from this mean. The green line and shaded region and orange line and shaded region show the mean ±1 standard deviation for all the Phase 1 and Phase 2 tests, respectively.

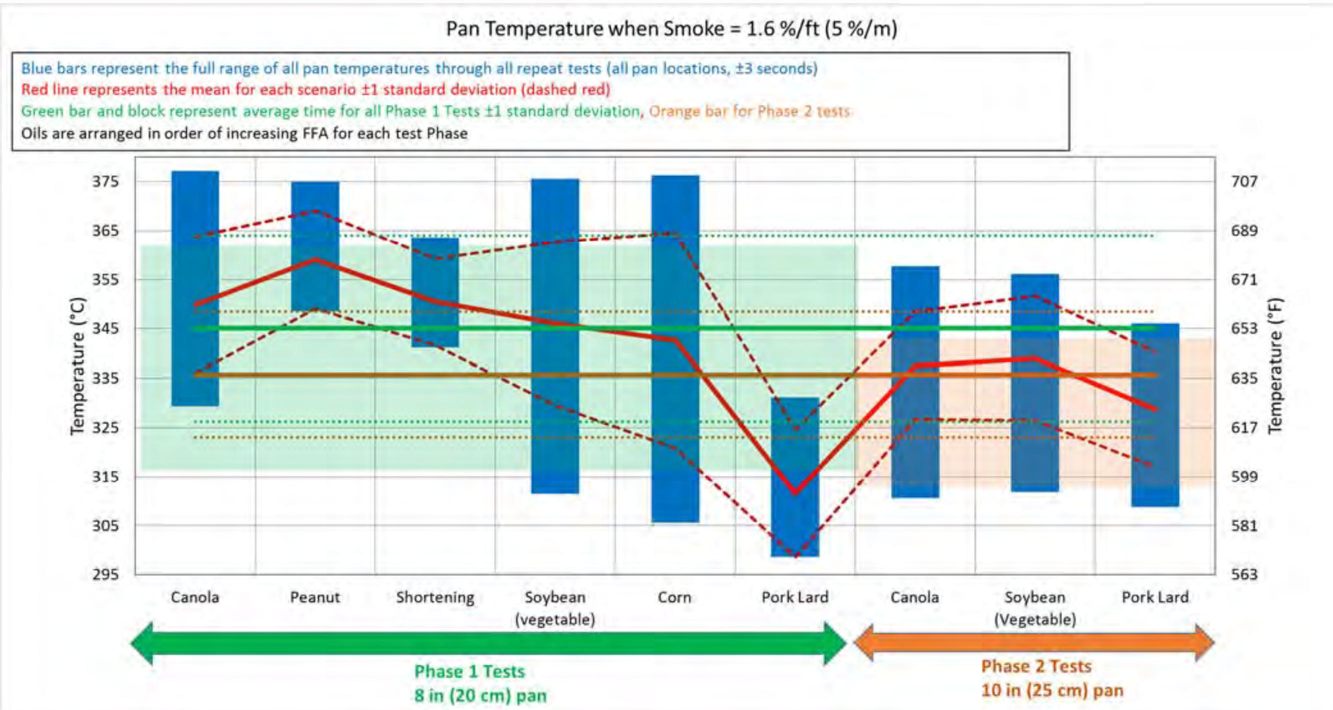


Figure 20 – Average pan temperature at 1.6%/ft (5%/m) smoke measurement for various oils

Average pan temperatures at average smoke obscuration of 1.6%/ft (5%/m) ranged from 312°C (594°F) for the Phase 1 pork lard to 359°C (678°F) for the Phase 1 peanut oil. The average pan temperatures measured when moderate smoke production begins decreased with an increase in % FFA. Correlation coefficients between pan temperatures at smoke and % FFA of -0.97 and -0.99 were calculated for the Phase 1 and Phase 2 tests, respectively. Although distributed evenly in the Figure, the pork lard has a % FFA an order of magnitude higher than the other oils, and the reduction in pan temperature at smoke production is apparent. Oils with low % FFA, such as canola oil, produce smoke at higher temperatures, and therefore likely present a greater challenge for ignition prevention devices measuring smoke. If potential nuisance alarms are a consideration, however, oils with higher % FFA, such as pork lard provide the greatest potential challenge. The correlations and slopes of the pan temperatures at smoke and % FFA for Phase 1 and Phase 2 tests are shown in Figure 21.

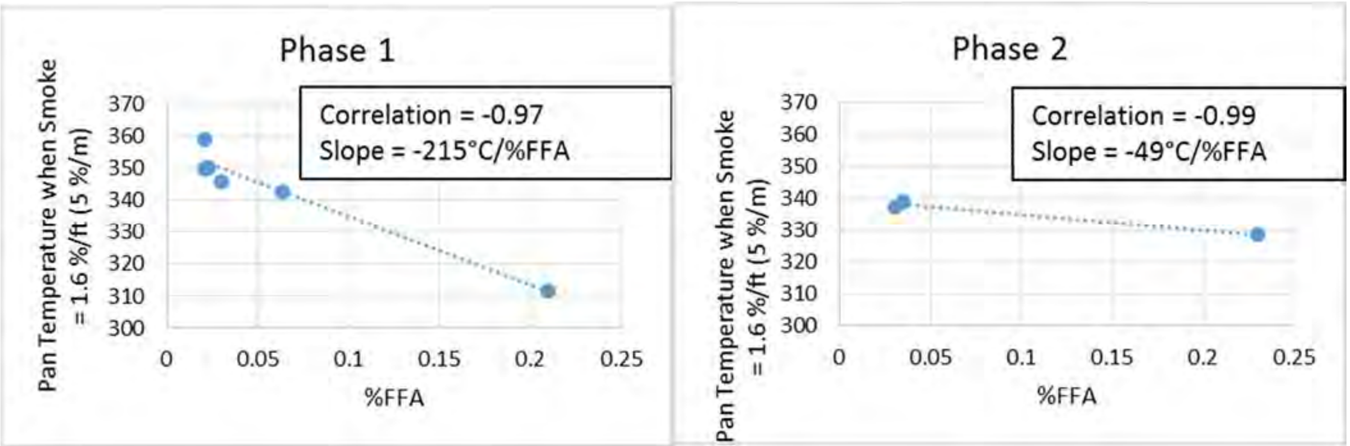


Figure 21 – Calculated correlations and slopes for pan temperatures at 1.6%/ft (5 %/m) smoke measurement and % FFA

The oil temperatures measured at the time of 1.6%/ft (5 %/m) smoke measurement are shown in Figure 22. The blue bars show the full range of all oil temperatures measured from each of nine locations ±3 seconds from the measurement of smoke. The red line reports the mean time among each test type, with the dashed red lines showing ±1 standard deviation from this mean. The green line and shaded region and orange line and shaded region show the mean ±1 standard deviation for the Phase 1 and Phase 2 tests, respectively.

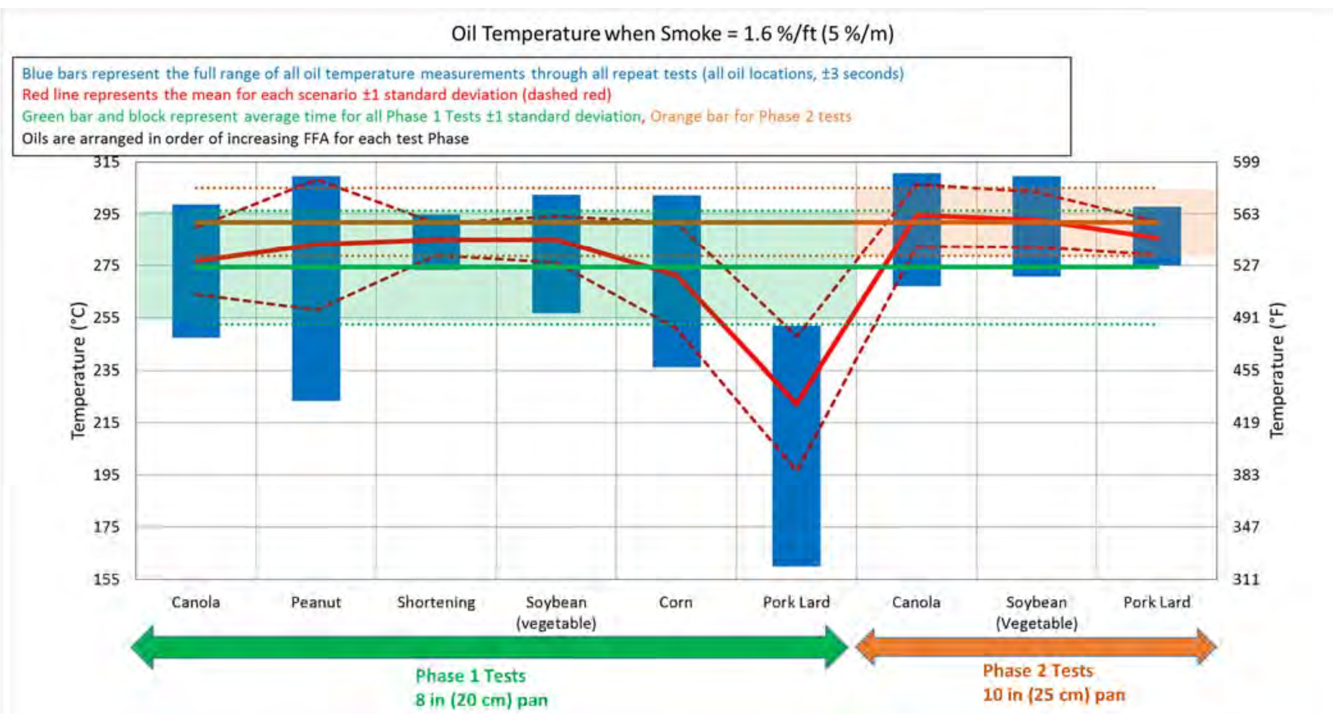


Figure 22 – Average oil temperature at 1.6%/ft (5%/m) smoke measurement for various oils

Average oil temperatures at smoke production ranged from 222°C (432°F) for the Phase 1 pork lard to 294°C (561°F) for the Phase 2 canola oils. It should be noted that the oil temperature measurements made in Phase 1 were less responsive and generally lower than those made for Phase 2 (see Section 6.1.1), and this can be seen in the data above. The oil temperatures when moderate smoke production begins show an extremely strong negative correlation to the % FFA of the oil. Correlation coefficients of -0.99 and -0.99 were calculated for the Phase 1 and Phase 2 tests, respectively. The calculation of the correlation coefficients are shown in Figure 23.

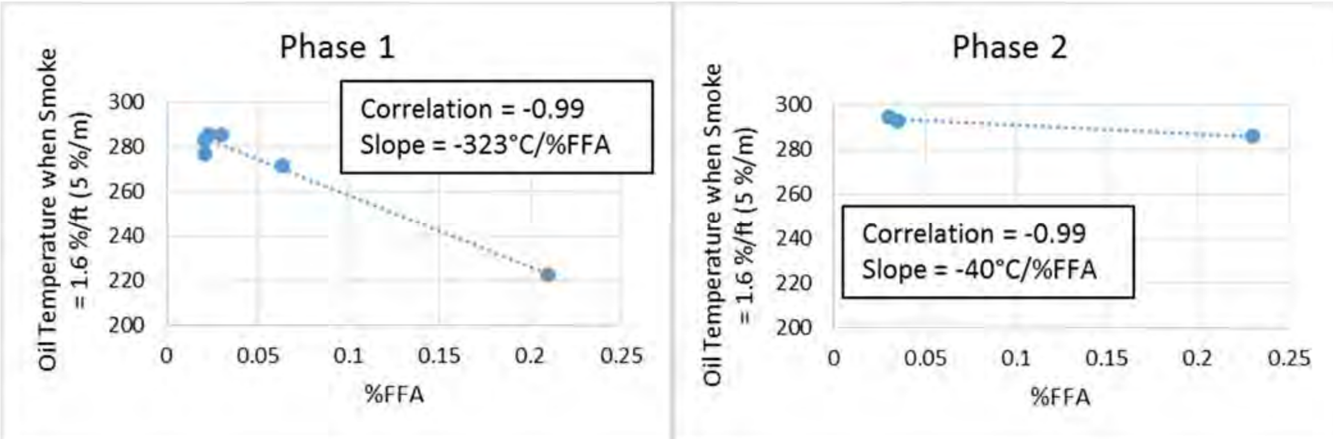


Figure 23 – Calculated correlations and slopes for oil temperatures at smoke measurement and % FFA

Scenarios with the lowest pan and oil temperatures at ignition present the greatest challenge for fire prevention systems. The pan and oil temperatures measured at ignition are shown in Figures 24 and 25, respectively.

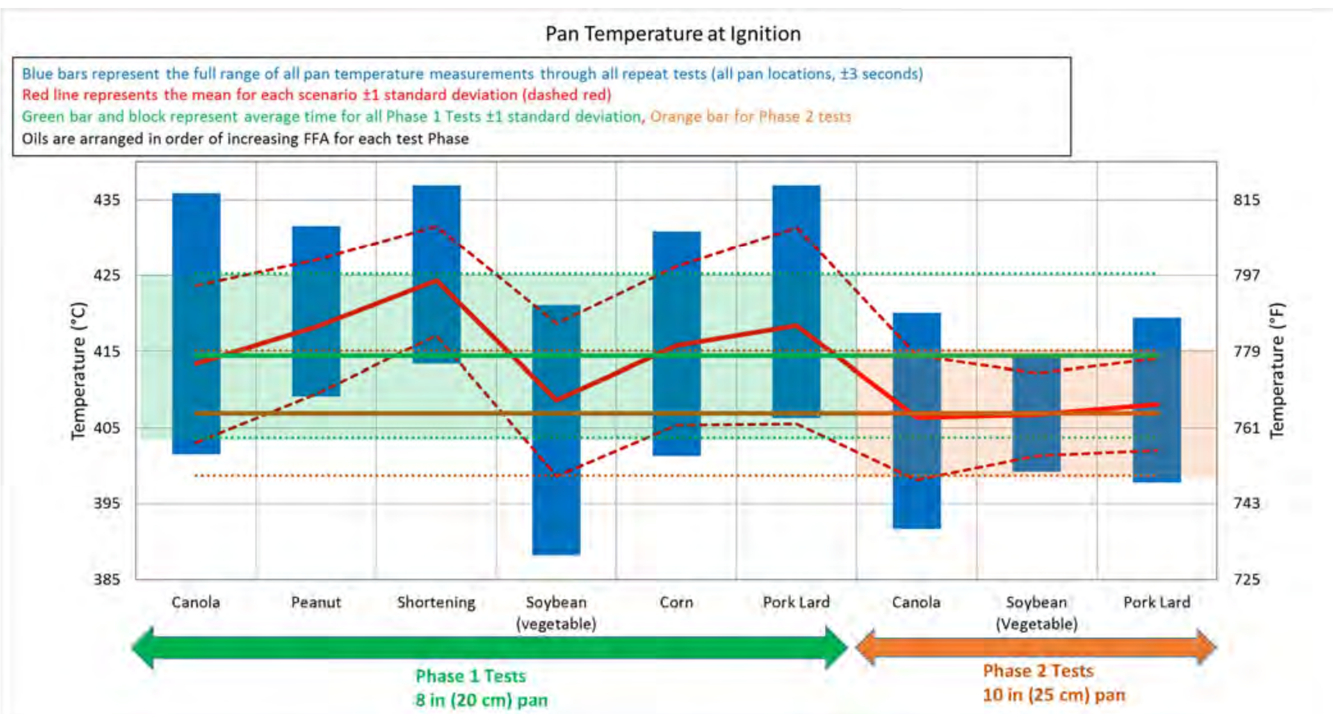


Figure 24 – Average pan temperatures at ignition for various oils

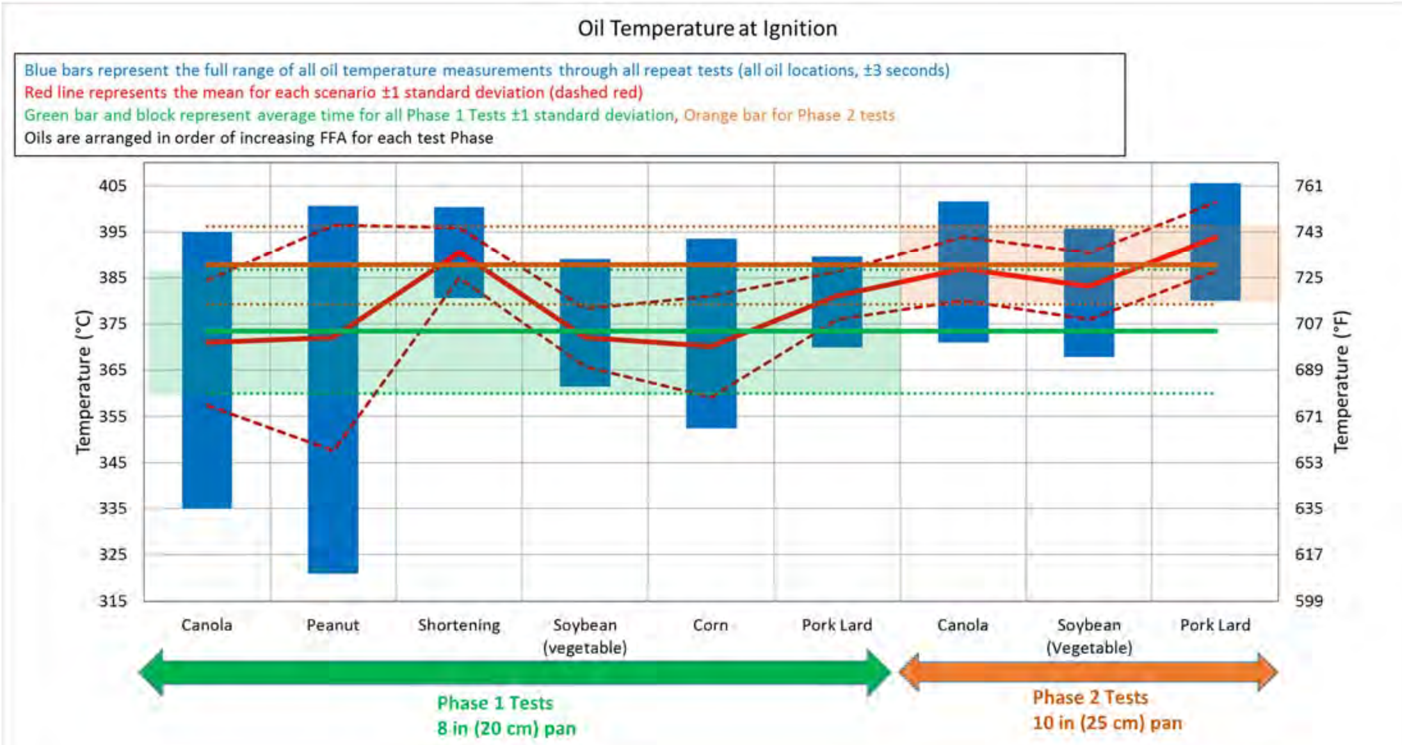


Figure 25 – Average oil temperatures at ignition for various oils

Average pan temperatures measured at ignition were 414°C (777°F) and 407°C (765°F) for Phase 1 and Phase 2, respectively. There were a few low temperature outliers in the Phase 1 data as shown by the blue bar, representing all measured values. Comparing the average and standard deviations shown by the red bars the two Phases are much closer in total variability. The reduced average pan temperature at ignition was often observed for tests with longer total heating times, as for the Phase 2 tests compared to Phase 1. This observation is discussed in greater detail in sections 6.6, 6.7, and 7.0. Average oil temperatures at ignition of 373°C (703°F) and 388°C (730°F) were measured for the Phase 1 and Phase 2 tests, respectively. It should be noted, however, that the thermocouples used in Phase 1 were less responsive (see discussion in Section 6.1.1) and found to measure lower temperatures in general than the Phase 2 test instruments.

The impact of the oil type (and % FFA) is much less pronounced for the pan and oil temperatures at ignition compared to the other evaluated test metrics. The pan and oil temperature correlations and calculated slopes as a function of % FFA are shown in Figure 26. The correlations between the pan and oil temperatures at ignition and % FFA for the Phase 1 tests were found to be 0.14 and 0.23, respectively. The correlations between the pan and oil temperatures and % FFA for the Phase 2 tests were much stronger, with values of 0.97 and 0.93, respectively. Although these show an extremely strong correlation, when put in context with the magnitude of temperature change, the effects are much less notable. The total change in average pan temperature from the canola to the pork lard was 2°C (4°F). The total change in average oil temperature from the soybean oil to the pork lard was 11°C (20°F). Regardless of the importance of the magnitude, a negative correlation between temperature at ignition and % FFA for fresh oils was not observed for these tests, as was predicted by previous oil test data [3].

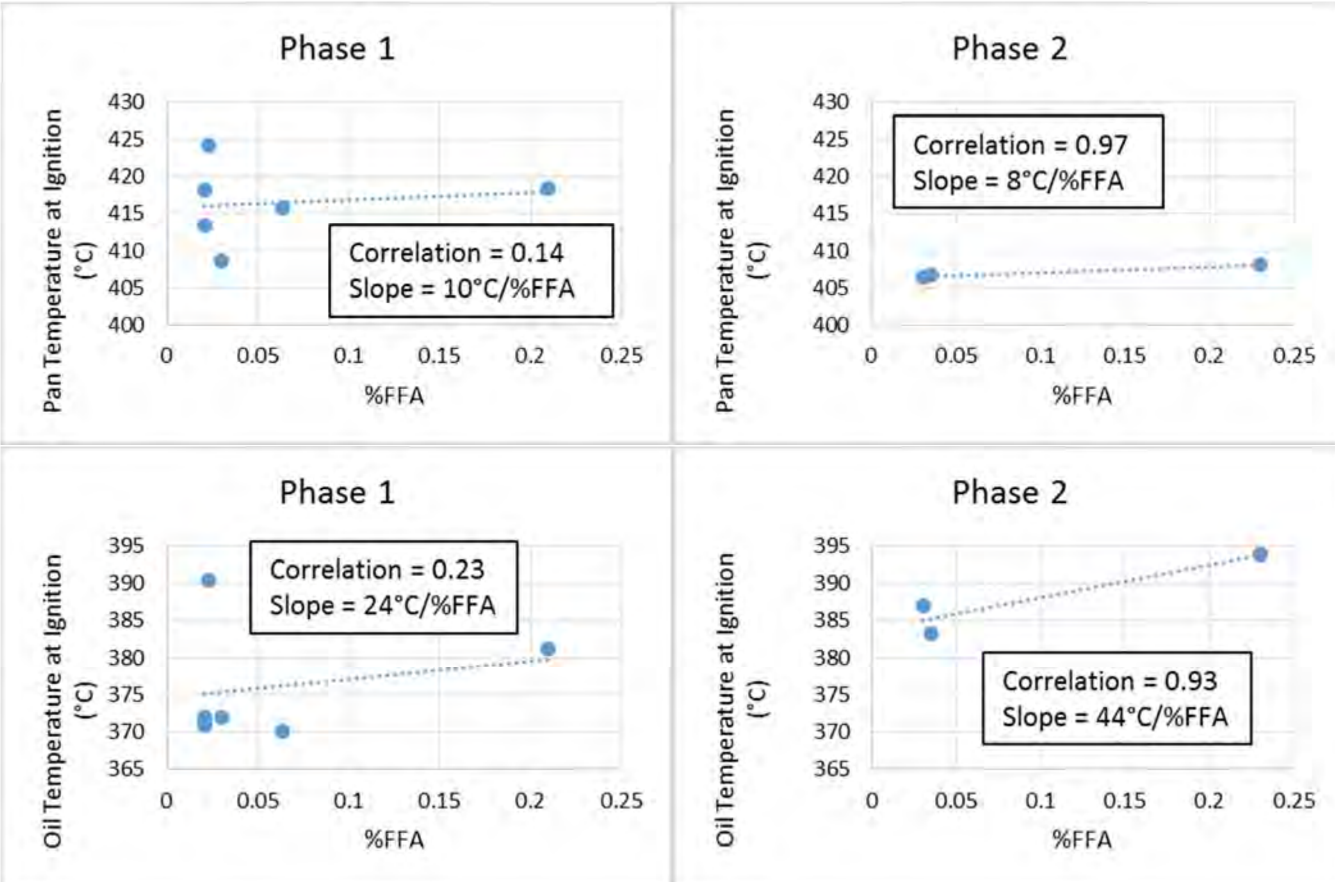


Figure 26 – Calculated correlations and slopes for pan and oil temperatures at ignition and % FFA

6.4. Aged/Used Oil

Commercial oil samples used in Phase 1 testing were artificially "aged" by continuous heating at 204°C (400°F) for 8 hours. In addition, a sample of used soybean (vegetable) oil was obtained from a fast food restaurant deep fryer in order to evaluate a used oil. Consumer oil samples used in Phase 2 testing were "used" by repeatedly cooking breaded chicken thighs until the oil was deemed unusable. The primary observations from these tests include:

- Aged oils had:
    - Higher % FFA
    - Little change in total heating time to ignition or the available time between pan temperature or smoke production thresholds, with slight reductions from fresh to aged oil within the fresh oil test standard deviation
    - Little to no change in the pan and oil temperatures at the production of smoke or at ignition, with variations within test standard deviations
- Used oils had:
    - Higher % FFA
    - Increased total heating time to ignition and available time between pan temperature and smoke production thresholds
    - Little to no change in the pan and oil temperatures measured at ignition
    - Reduced pan and oil temperatures at the time smoke production began

- Based on the results of these tests, the use of fresh canola oil is recommended to provide the greatest overall challenge for fire prevention systems based on pan temperature or smoke detection devices. Fresh canola oil had the:
  - Shortest heating time to ignition, and shortest time window for pan/smoke activation
  - Highest temperatures at smoke production
  - Same approximate ignition temperatures as other oils tested

All aged/used oil evaluation tests were conducted on the 8 in. (20 cm) coil element of the 2600 W GE range, in an 8 gauge aluminum frying pan. A total of 13.4 in.^{3} (220 mL) of oil was used in 8 in. (20 cm) pans for the Phase 1 tests, and 18.3 in.^{3} (300 mL) in 10 in (25 cm) pans for each Phase 2 test. Both phases evaluated an initial oil depth of ¼ in. (6.4 mm). The tests included in the aged/used oil analysis are listed in Table 6.

Table 6 – Tests included in aged/used oil analysis

	Identifier	Oil Type	Test ID
Phase 1	Canola	Crisco Canola Oil	P1-11
		Wesson Canola Oil	P1-13
		Commercial Canola Oil	P1-5
		Commercial Canola Oil	P1-6
	Aged Canola	“Aged” Commercial Canola Oil	P1-16
	Peanut	Commercial Peanut Oil	P1-7
	Aged Peanut	“Aged” Commercial Peanut Oil	P1-17
	Soybean (Vegetable)	Crisco Vegetable Oil	P1-10
		Wesson Vegetable Oil	P1-12
		Commercial Soybean oil	P1-1
	Aged Soybean	“Aged” Commercial Soybean Oil	P1-14
	Used Soybean	Vegetable oil removed from fast food deep fryer	P1-19
	Corn	Commercial Corn Oil	P1-2
		Commercial Corn Oil	P1-3
		Commercial Corn Oil	P1-4
	Aged Corn	“Aged” Commercial Corn Oil	P1-15
	Pork Lard	Commercial Pork Lard	P1-9
	Aged Lard	“Aged” Commercial Pork Lard	P1-18
Phase 2	Soybean (Vegetable)	Great Value Vegetable Oil	P2-1
		Great Value Vegetable Oil	P2-2
		Great Value Vegetable Oil	P2-3
	Used Soybean	“Used” Great Value Vegetable Oil	P2-10
		“Used” Great Value Vegetable Oil	P2-11
		“Used” Great Value Vegetable Oil	P2-12
	Pork Lard	Morrell Pork Lard	P2-7
		Morrell Pork Lard	P2-8
		Morrell Pork Lard	P2-9
	Used Lard	“Used” Morrell Pork Lard	P2-13
		“Used” Morrell Pork Lard	P2-14
		“Used” Morrell Pork Lard	P2-15

6.4.1. Available Response Times

The total heating times required to reach ignition are shown in Figure 27, with the oils approximately ordered from lowest to highest percent FFA for the fresh oils. The blue bars show the full range of heating times from all included tests. The red line reports the mean time among each test type, with the dashed red lines showing ±1 standard deviation from this mean. The green line and shaded region and orange line and shaded region show the mean ±1 standard deviation for the fresh oil and the aged/used oil tests, respectively.

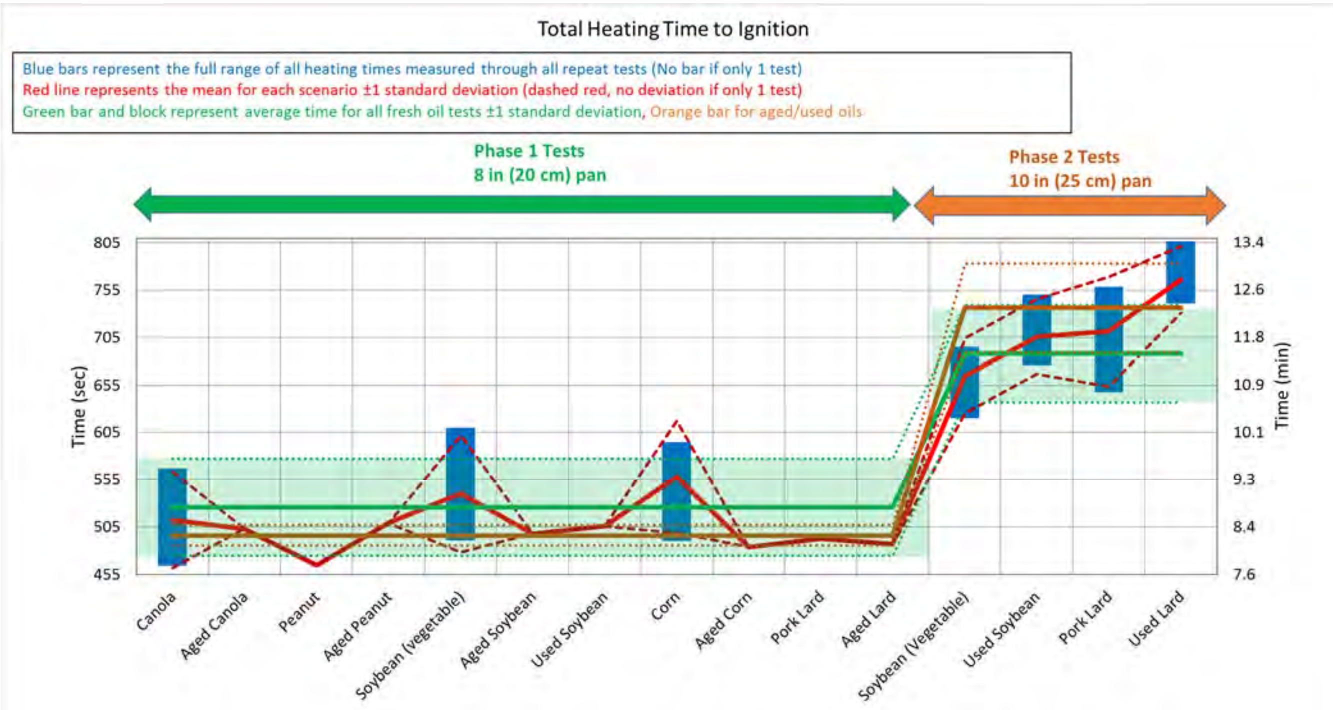


Figure 27 – Heating times until ignition for aged/used oils

The total heating time to ignition remained relatively unchanged for the aged oils tested in Phase 1, with the average time reduced from 526 to 498 seconds. The total heating time was increased for the used oils tested in Phase 2 from 688 to 736 seconds, an increase of approximately one standard deviation compared to the fresh oils. The correlation and slope of the heating time to ignition and % FFA are shown in Figure 28. The longer heating times required for Phase 2 are a result of the larger pans and oil volumes compared to Phase 1, and not due to the conditioning of the oils.

The potential time windows for activation of pan temperature and smoke detection devices have also been considered. The average, standard deviation, and full range of time for pan and smoke activation are shown in Figures 29 and 30, respectively.

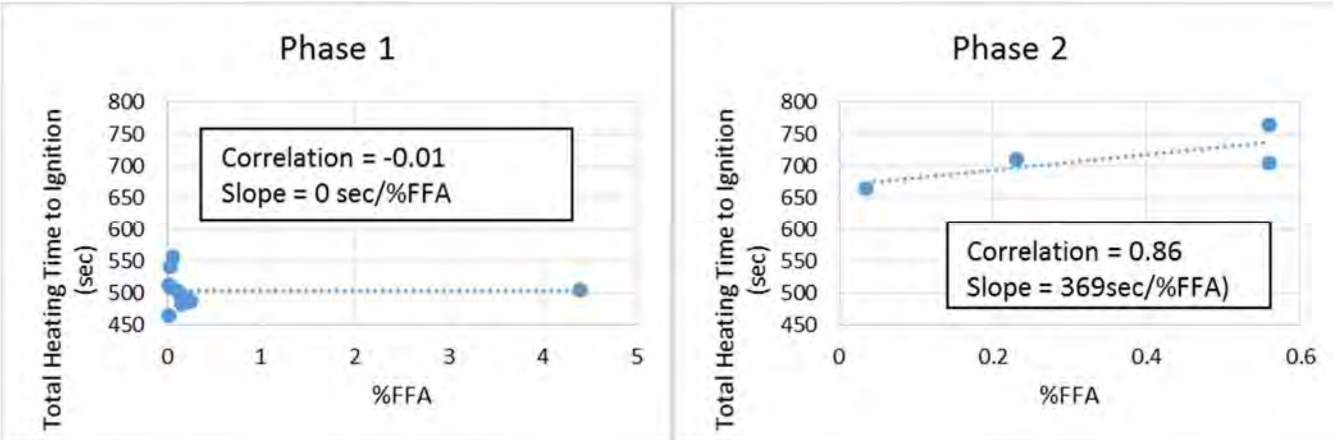


Figure 28 – Calculated correlations and slopes for total heating times to ignition and % FFA for used/aged oils

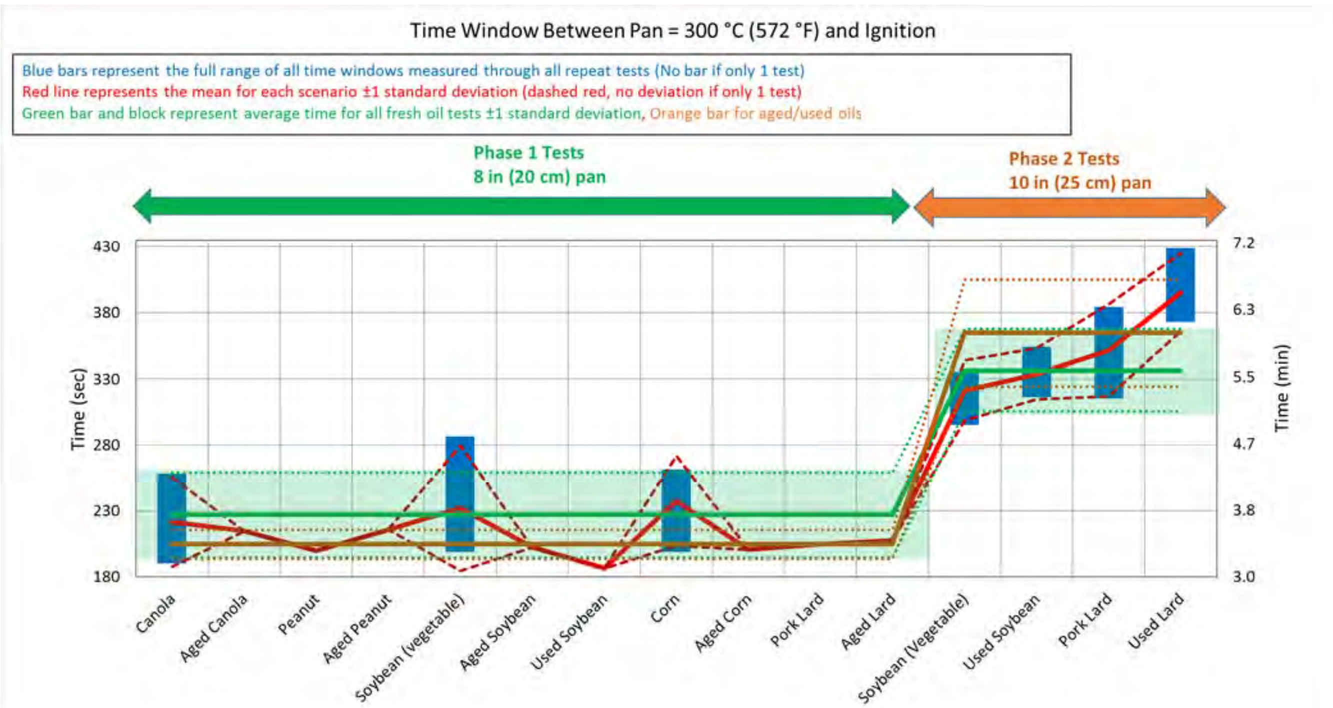


Figure 29 – Time window between pan temperature = 300°C (572°F) and ignition for aged/used oils

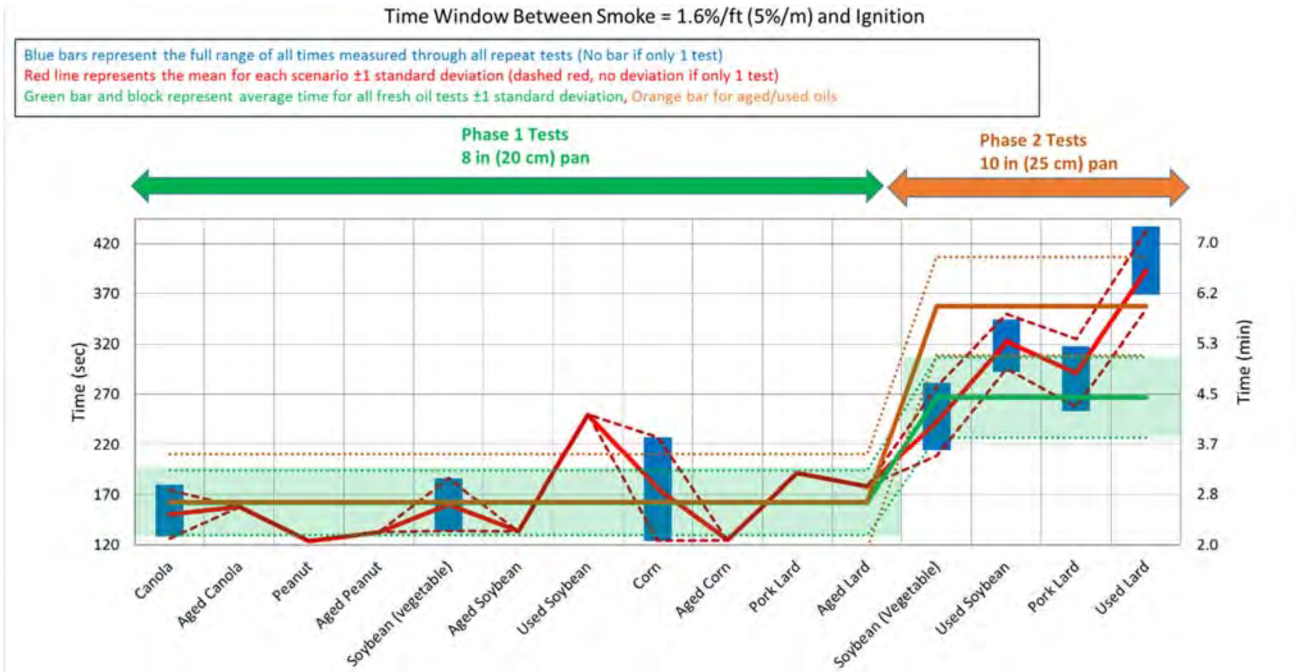


Figure 30 – Time window between smoke obscuration = 1.6%/ft (5%/m) and ignition for various oil types

The available time windows for pan temperature activation were relatively unaffected by the aging process used in Phase 1 testing. The average time window for pan temperature activation was reduced from 227 to 205 seconds for fresh and used oils, respectively, as shown by the brown and green lines in Figure 29. No clear trend in time reduction was observed when comparing each fresh oil to its aged counterpart for the Phase 1 tests. Both pan and smoke time windows were increased for the used oils tested in Phase 2, however.

The available time windows for smoke were increased more than the windows for pan temperature activation. This would result in less challenging detection/prevention scenarios for aged/used oils. The correlations and slopes for the smoke time and % FFA are shown in Figure 31. Correlation coefficients between the smoke windows and the % FFA were 0.81 and 0.89 for the Phase 1 and Phase 2 test, respectively. The increase in the duration of the smoke window was much greater for the Phase 2 tests, with an average increase in available time of 216 seconds per % FFA compared to 23 for Phase 1.

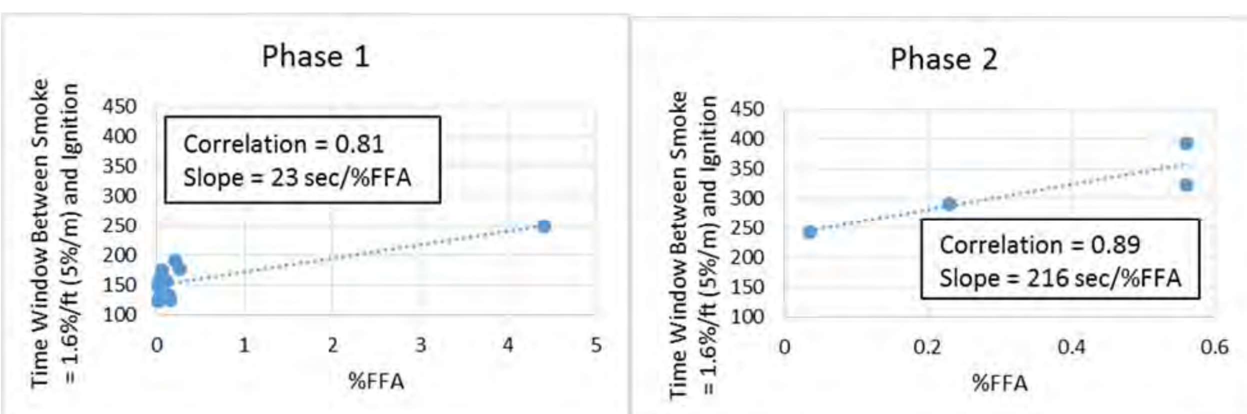


Figure 31 – Calculated correlations and slopes for smoke activation window and % FFA for used/aged oils

6.4.2. Temporal Heating Curves

Temporal plots of the average pan and oil temperatures, and average smoke obscuration for the aged/used oil tests are shown in Figure 32. The tests have all been aligned at the time of ignition (T = 0). The solid lines show the average among the Phase 1 and Phase 2 tests, and the dashed lines show the maximum and minimum values measured at the given time before ignition occurred.

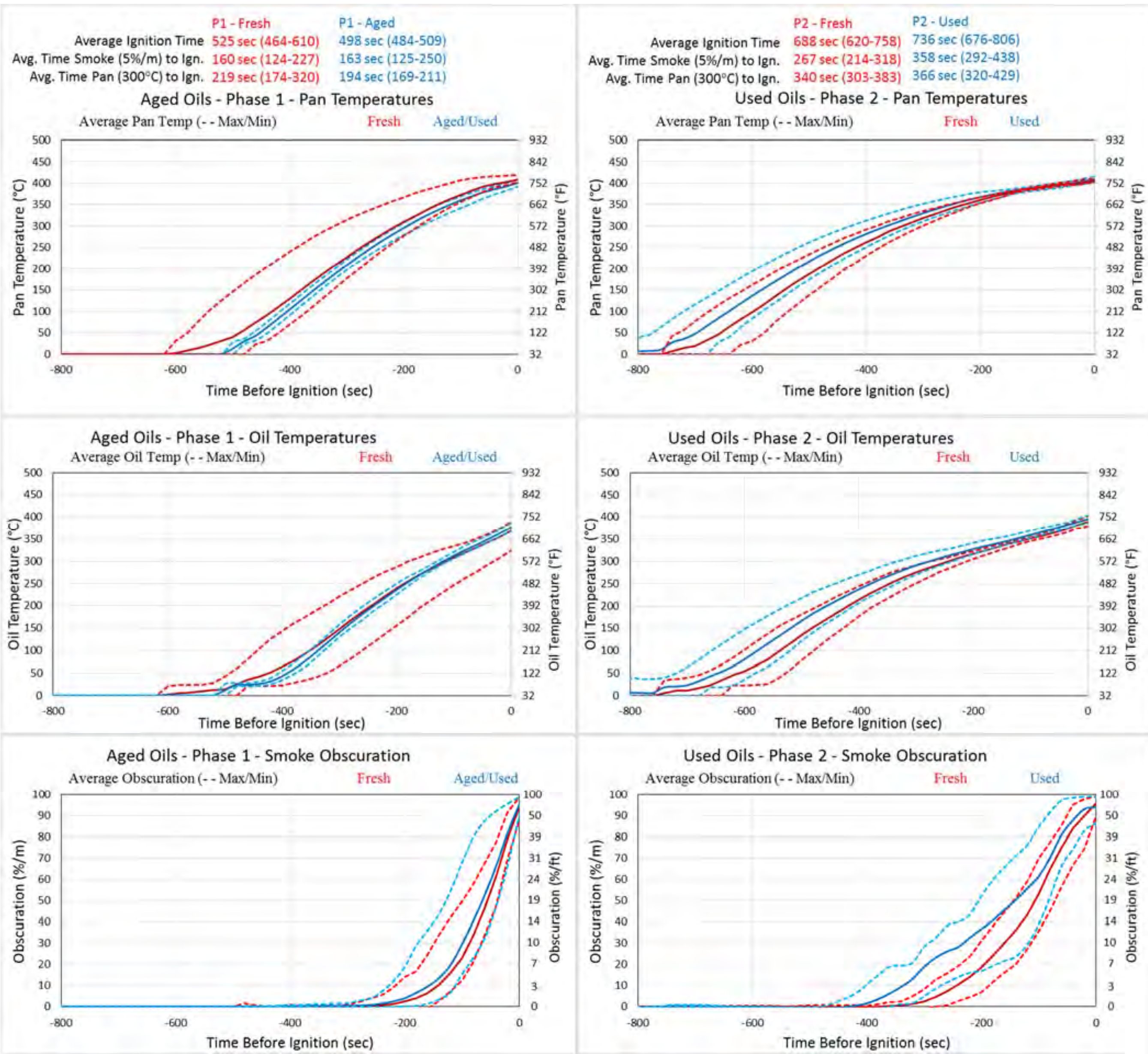


Figure 32– Pan and oil temperatures and smoke obscuration curves for aged/used oil tests aligned by ignition time

The average pan and oil temperature curves for the Phase 1 fresh and aged/used oils track nearly identically. There was greater variability in the Phase 1 fresh oil tests, and the aged/used oil pan and oil temperature bounds fit entirely within the range of fresh oil tests. A slightly greater amount of smoke was produced earlier in the aged/used oil tests of Phase 1, with greater variability than the fresh oils. With regard to temperature measurement, little to no difference would be seen between the fresh and aged/used oils tested. With regard to smoke measurement, the aged/used oils would be slightly easier to detect prior to ignition.

The used oils tested in Phase 2 heated more slowly than the fresh oils, with higher temperatures measured longer before ignition. In addition, more smoke was produced longer before ignition for the used oils. Using either pan or smoke detection devices, ignition prevention would likely be easier for the used oils tested.

A number of metrics have been calculated to compare the temporal response curves of the fresh and aged/used oils. These metrics include the slopes of the temperature and obscuration curves to ignition at various fixed points, the difference between the pan and oil temperatures at the time of ignition, and the total integrated area under the smoke obscuration curve at ignition. These values are shown in Table 7. The most challenging test conditions for each metric have been highlighted for each test phase.

6.4.3. Smoke Production and Ignition Temperatures

The pan and oil temperatures measured at the time smoke was produced and at ignition provide a direct comparison of the fresh and aged/used oils. These metrics reduce the importance of variables such as the total oil volume or pan size. The average pan temperatures at the time of low smoke measurements are shown in Figure 33. The blue bars show the full range of all pan temperatures measured from each of three locations ±3 seconds from the measurement of smoke. The red line reports the mean time among each test type, with the dashed red lines showing ±1 standard deviation from this mean. The green line and shaded region show the mean ±1 standard deviation for the fresh oil tests conducted in each Phase. The orange lines show the mean ±1 standard deviation for the aged/used oil tests conducted in each test phase.

The pan temperatures at smoke production were generally unaffected by the artificial aging process used for Phase 1 testing. The pan temperature at smoke production for the used oil removed from the fast food fryer was significantly reduced from the fresh oil average of 345°C (653°F) to 254°C (489°F). This indicates that the artificial aging process may not accurately replicate oil usage. However, the large difference may also be associated with commercial cooking use compared to home cooking use as seen with the Phase 2 used oils.

The pan temperatures at smoke production for the Phase 2 testing were noticeably reduced by the oil usage. The oils tested in this Phase were used to deep fry chicken, and the average pan temperature at smoke production was reduced by 30°C (54°F) for the soybean and pork lards tested. The effect was not as drastic as observed for the deep fryer oil tested in Phase 1, and this could be due to the fine mesh filter used to remove particulate for the Phase 2 oils. The % FFA for the used oils was increased to 0.56, and this was also an order of magnitude below the % FFA of 4.4 measured for the deep fryer oil in Phase 1. No filtration was used for the Phase 1 used oil test. A reduced pan temperature at the point of smoke production results in more measureable smoke longer before ignition, reducing the challenges to prevention devices. The use of fresh oil would be more challenging for smoke detection devices. Similar results were observed for the oil temperatures at the time of smoke production, as shown in Figure 34.

Table 7 – Calculated pan and oil temperature slopes and obscuration slope and integrated areas for aged/used oil tests

	Oil	Average pan temp slope between fixed pan temperatures and ignition (°C/min)				Average oil temp slope between fixed pan temperatures and ignition (°C/min)				Difference between pan and oil temperature at fixed pan temps (°C)					Integral of smoke obscuration up to fixed pan temperatures (%/m – min)				
		250 °C (482 °F)	300 °C (572 °F)	350 °C (662 °F)	375 °C (707 °F)	250 °C (482 °F)	300 °C (572 °F)	350 °C (662 °F)	375 °C (707 °F)	250 °C (482 °F)	300 °C (572 °F)	350 °C (662 °F)	375 °C (707 °F)	IGN	250 °C (482 °F)	300 °C (572 °F)	350 °C (662 °F)	375 °C (707 °F)	IGN
P1	Canola	35	31	25	20	42	38	33	31	63	58	51	50	32	0	0	6	22	106
P1	Aged Canola	36	31	25	26	44	40	39	37	62	57	58	40	24	1	1	6	28	123
P1	Peanut	40	35	29	24	51	47	45	42	132	125	120	113	87	0	0	0	2	84
P1	Aged Peanut	34	30	24	19	40	38	35	36	51	50	46	48	23	0	0	4	15	87
P1	Soybean	33	29	24	20	37	34	32	29	65	65	63	60	41	0	1	5	13	103
P1	Aged Soybean	35	31	26	25	43	39	36	28	62	54	43	28	26	1	2	11	40	87
P1	Used Soybean	36	33	29	26	38	36	32	16	34	36	30	19	26	9	33	108	197	230
P1	Corn	33	30	24	21	39	36	34	31	65	66	63	57	40	0	0	10	35	132
P1	Aged Corn	36	31	25	19	44	40	33	33	61	56	44	45	29	0	0	6	25	92
P1	Pork Lard	38	34	28	23	44	40	40	40	51	45	50	50	25	0	3	12	26	111
P1	Aged Lard	37	33	27	22	43	40	39	38	47	44	48	45	22	2	5	17	40	143
P2	Soybean	23	20	15	12	26	24	20	19	43	45	41	41	21	0	0	6	26	170
P2	Used Soybean	22	19	14	11	25	22	19	20	42	33	36	40	17	0	0	27	59	213
P2	Pork Lard	21	18	14	12	25	23	22	21	40	42	41	38	12	0	0	12	49	236
P2	Used Lard	20	17	14	12	24	22	19	19	39	42	38	35	12	0	1	38	96	342

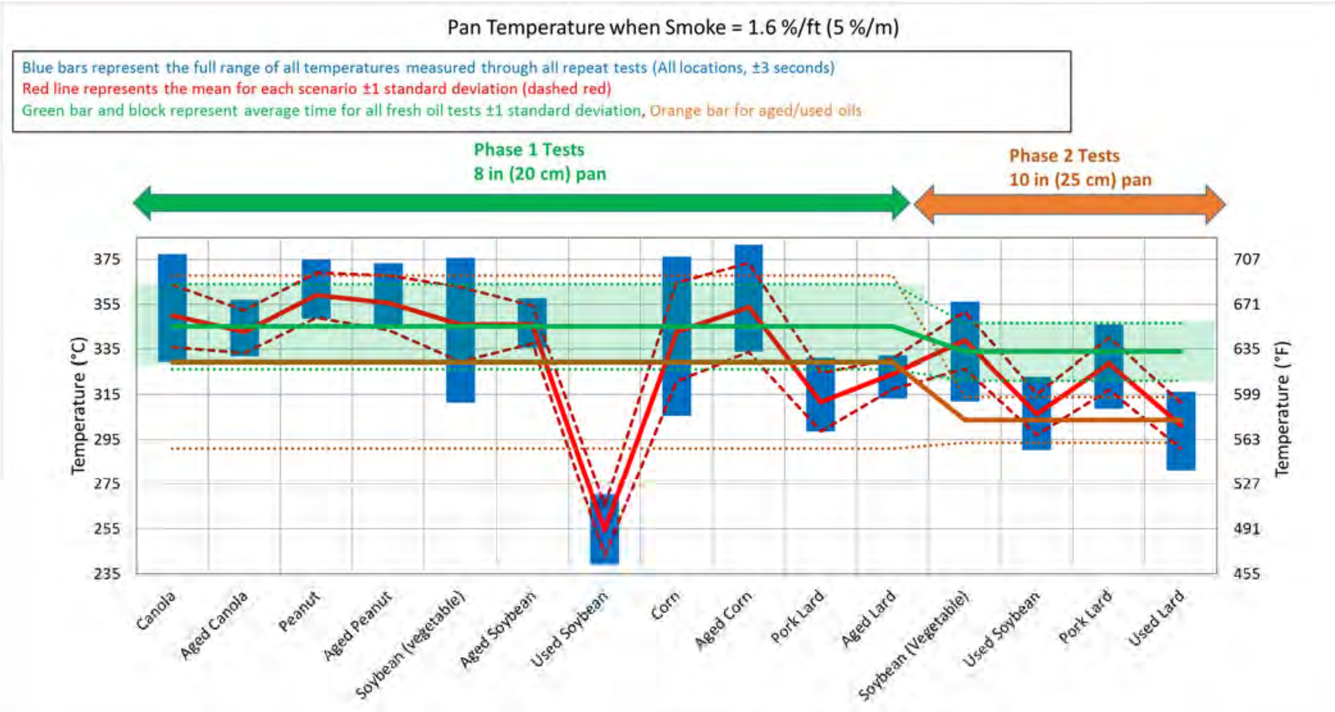


Figure 33 – Average pan temperature at 1.6 %/ft (5%/m) smoke measurement for aged/used oils

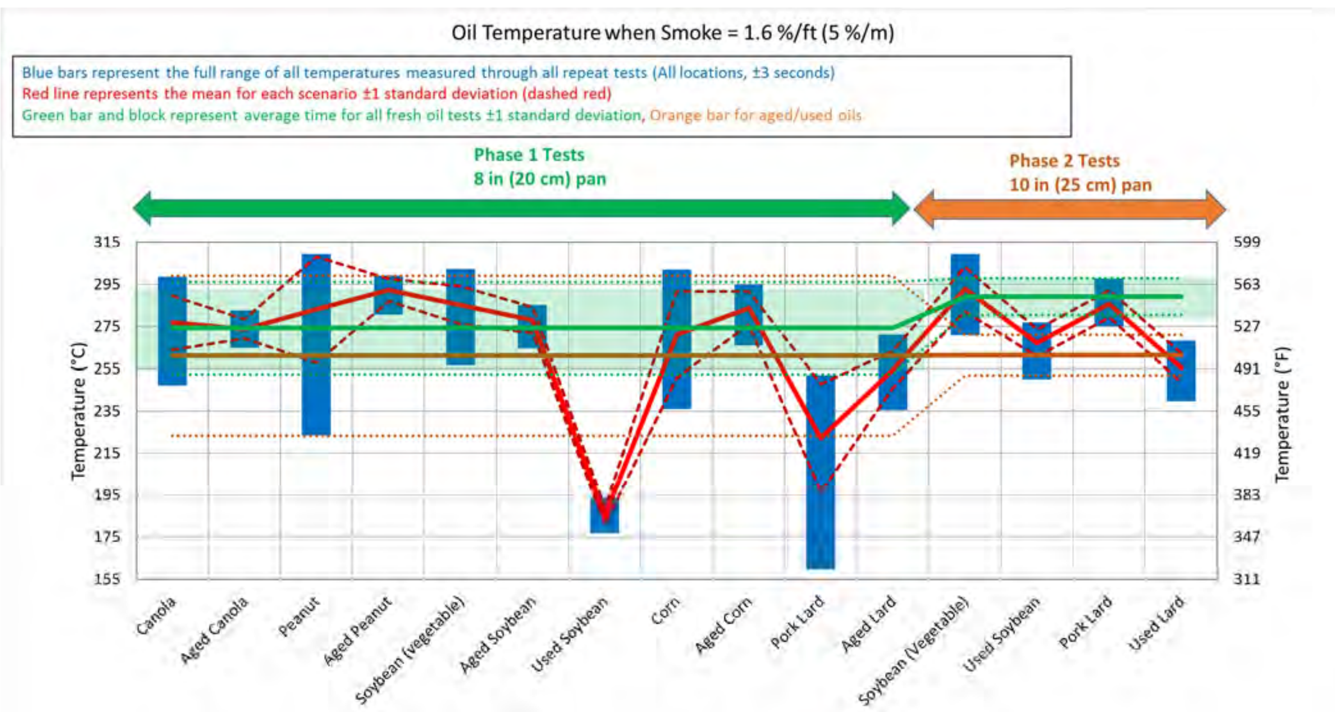


Figure 34 – Average oil temperature at 1.6 %/ft (5 %/m) smoke measurement for aged/used oils

The average oil temperature at smoke production was reduced from 274°C (525°F) for fresh oils to 185°C (365°F) for the used deep fryer oil in Phase 1. The average oil temperature was reduced from 289°C (552°F) for fresh oils to 261°C (502°F) for used oils in Phase 2. No such trend is observed for the artificially aged oils tested in Phase 1. The correlations and slopes of the pan and oil temperatures measured at smoke are shown in Figure 35.

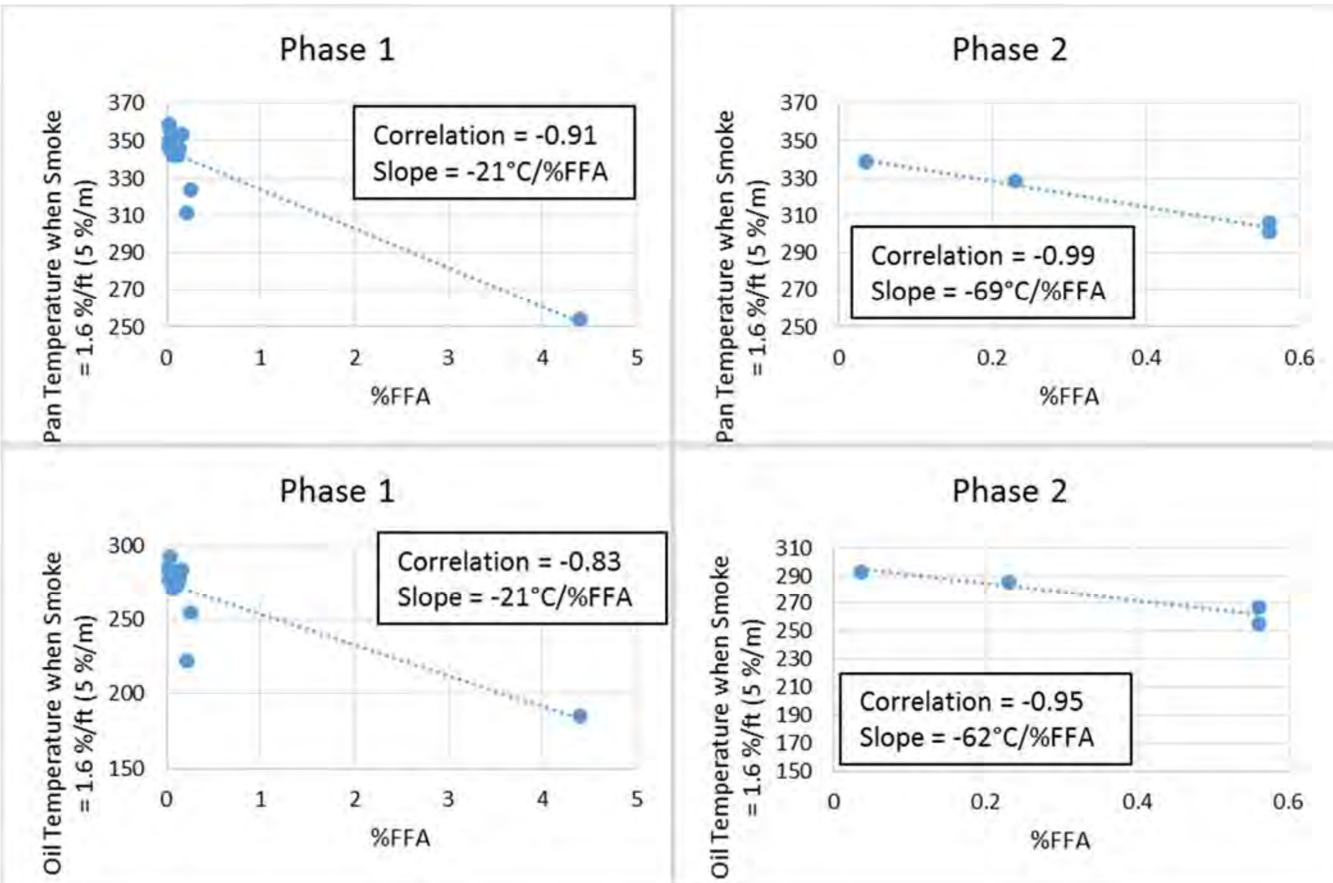


Figure 35 – Calculated correlations and slopes of pan and oil temperatures at smoke measurement and % FFA for used/aged oils

While the pan and oil temperatures at smoke production were reduced with increasing % FFA for the used oils tested, little to no effect was observed for the temperatures at ignition. No distinguishable trend was observed for % FFA and ignition temperature over the range of tests conducted. The pan and oil temperature ranges measured at ignition are shown in Figures 36 and 37, respectively.

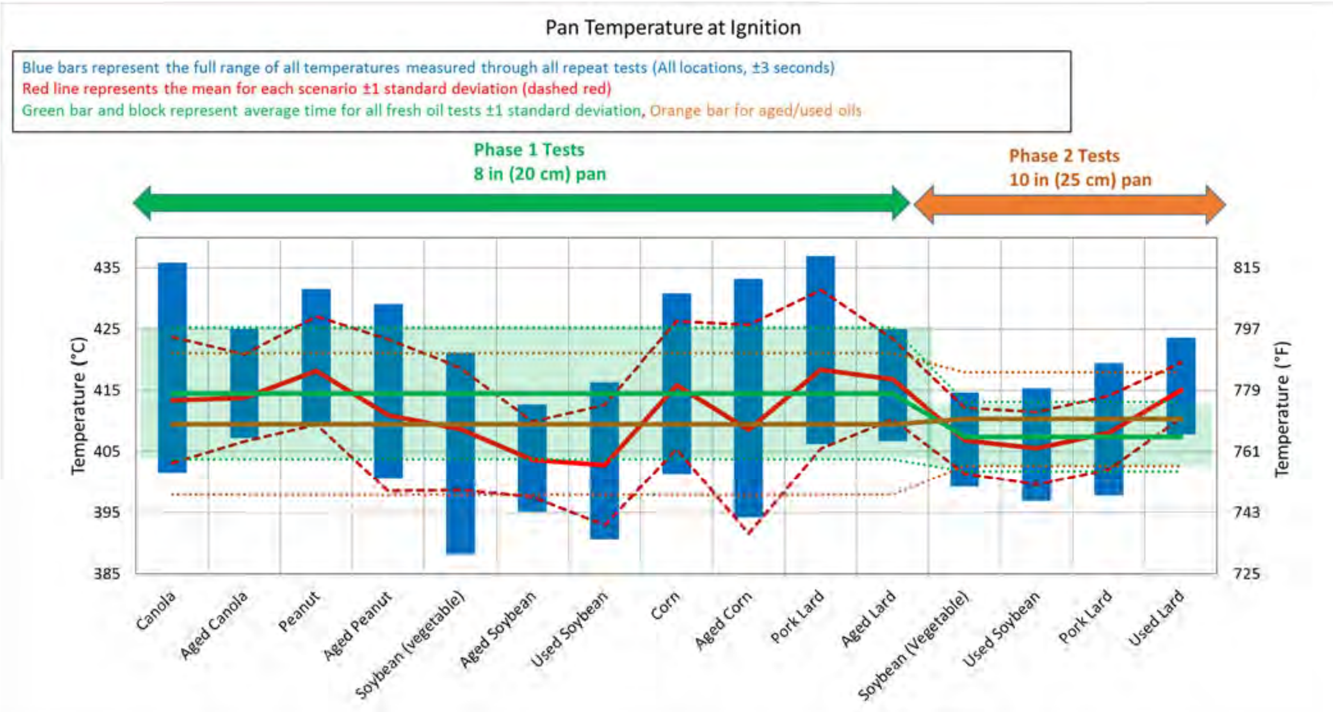


Figure 36 – Average pan temperatures at ignition for aged/used oils

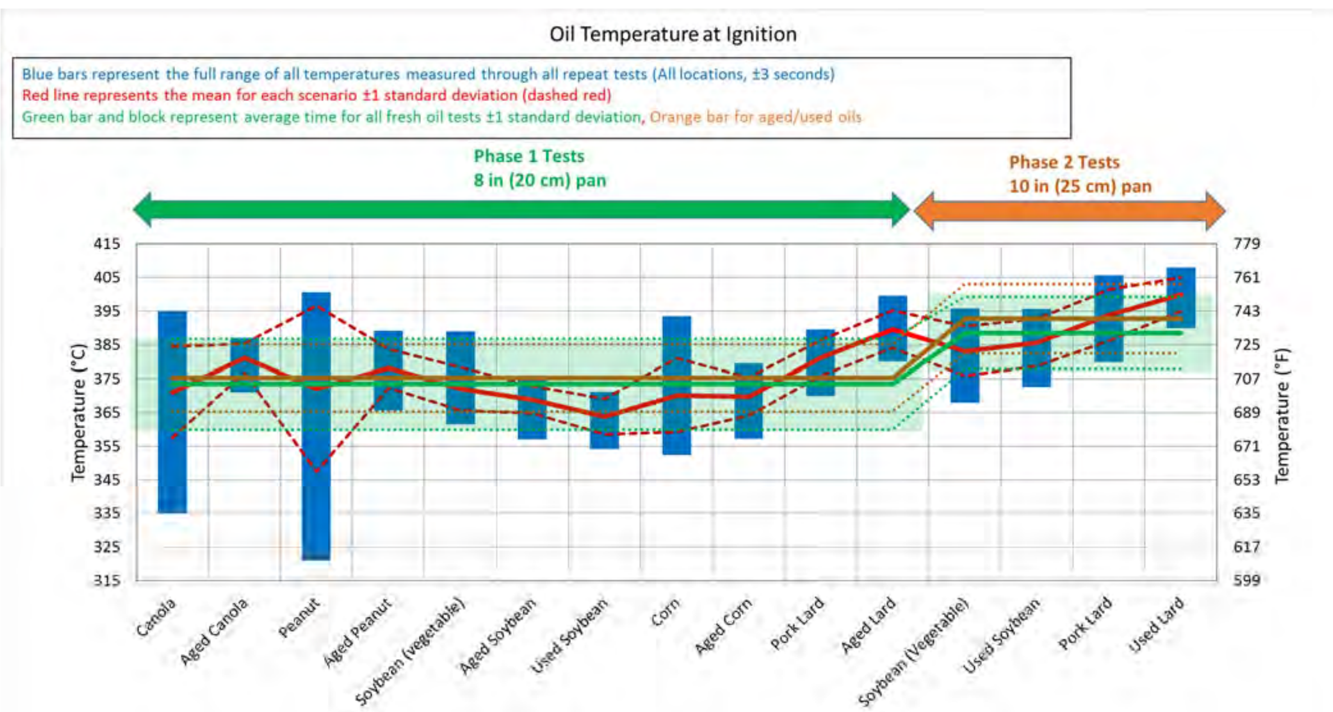


Figure 37 – Average oil temperatures at ignition for aged/used oils

No consistent reduction in the pan or oil temperatures measured at ignition was observed for the aged or used oils tested in either phase. There is some variation observed in the pan temperatures, but the variations were within statistical variability. The oil temperatures measured at ignition were higher for the tests conducted in Phase 2, but this is believed to be due to more responsive thermocouples rather than the properties of the oils. There was almost no difference observed in the oil ignition temperatures for fresh, aged, or used oil in either test phase. This is also evidenced by the weaker correlations and lower slopes calculated for the pan and oil temperatures at ignition and % FFA shown in Figure 38.

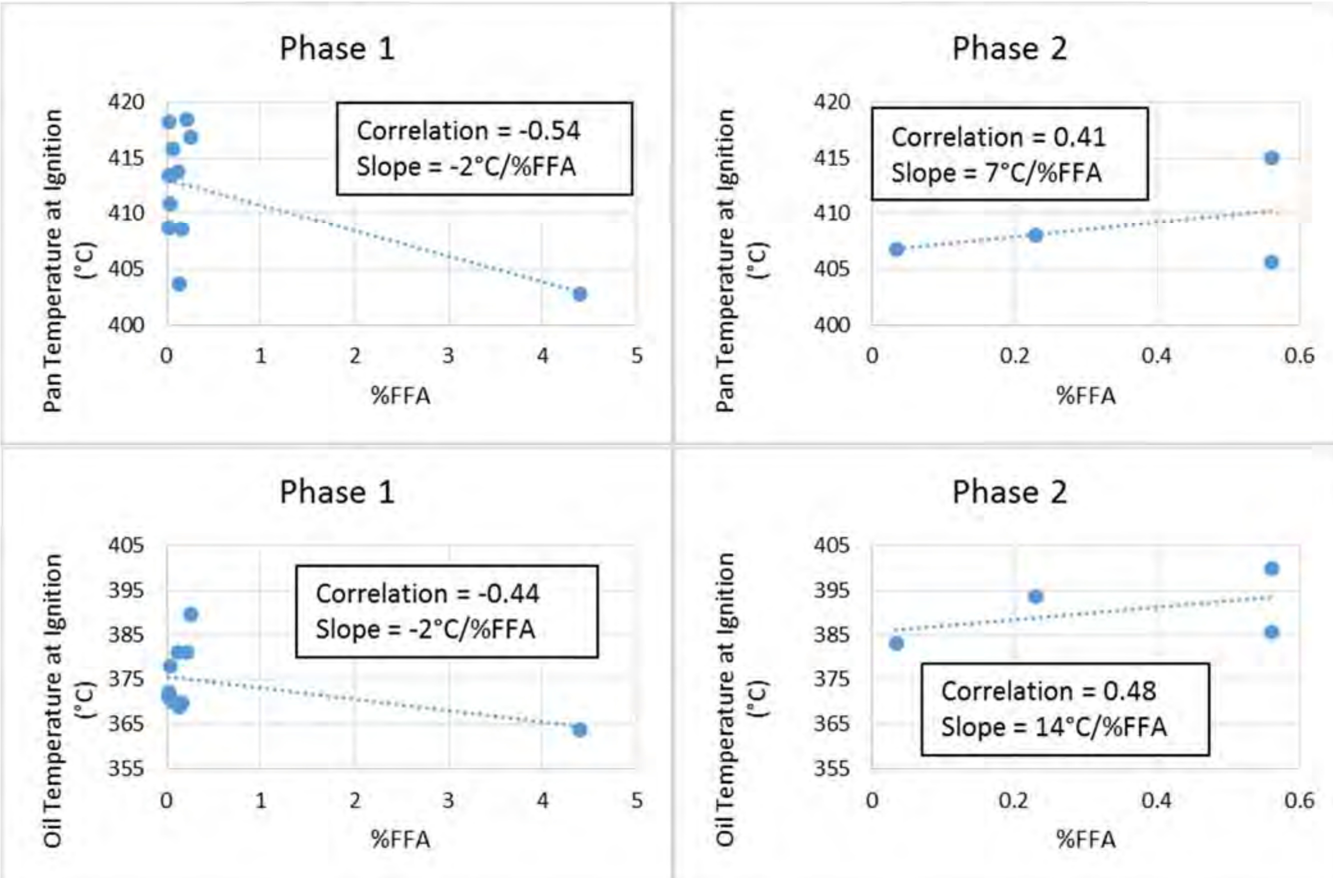


Figure 38 – Calculated correlations and slopes of pan and oil temperatures at ignition and % FFA for used/aged oils

6.5. Oil Brands

Several tests were conducted to evaluate the impacts of the oil brand on the smoke and ignition properties. For implementation of a standard test, it is important to know whether the brand can impact the test results. The primary metrics of concern for comparison of the oil brands are the measured oil temperatures at the time of smoke production and at ignition. Tests were conducted in Phase 2 using four different brands of canola oils, including Great Value, Crisco, Wesson, and a generic brand. They were tested in a wide array of scenarios, including various pan types, ranges, and oil depths. When comparing oils throughout these scenarios, it was determined that there was no discernible difference in the smoke and ignition properties of oil by brand.

The average oil temperatures measured when smoke levels of 1.6%/ft (5%/m) were measured in the hood are shown in Figure 39. The descriptions of each Scenario can be found in Table 2 in Section 5.3.

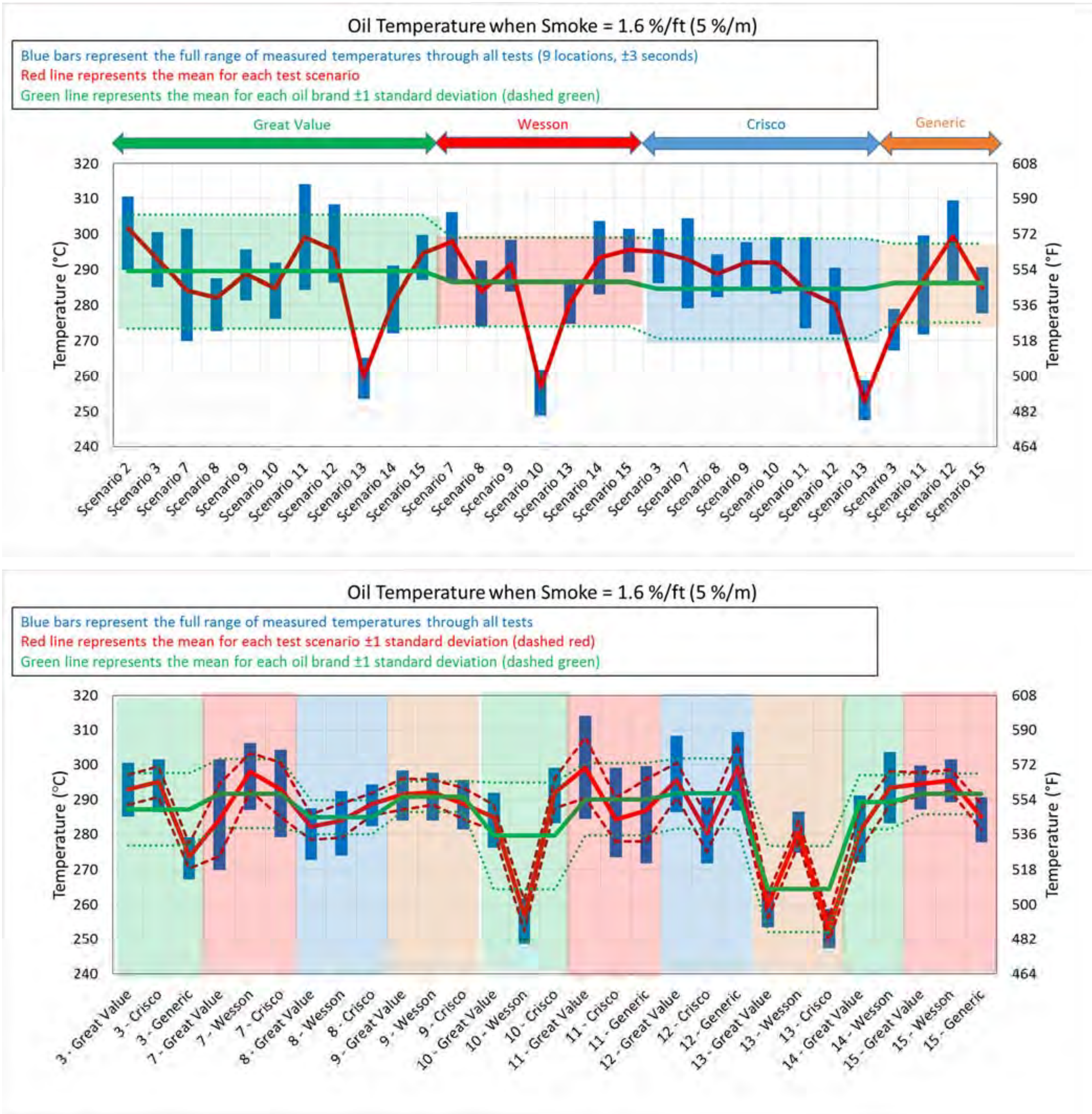
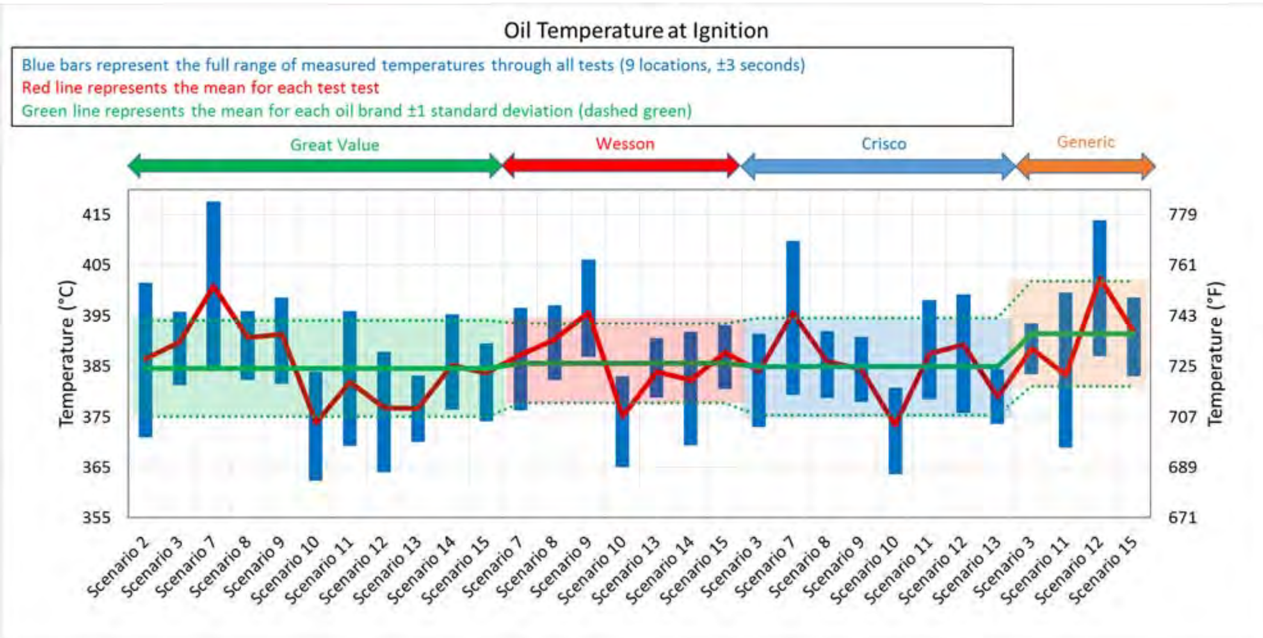


Figure 39 – Average oil temperature at 1.6%/ft (5%/m) smoke measurement for various brands of canola oils tested in Phase 2 for a range of cooking scenarios arranged by oil type (top) and test scenario (bottom)

Although there is some variation between test scenarios, the average temperature for each oil brand is nearly identical. The average oil temperature at smoke production varies from 285°C (545°F) for Crisco to 289°C (552°F) for Great Value. Some tests measured oil temperatures at smoke production higher or lower than the other oils tested for the same scenarios, (e.g., Wesson in Scenario 10 or 13), but the variation is not consistent for the oil brand. The Wesson canola oil measured both higher and lower temperatures than the other oils, depending on the scenario. This would indicate the differences are more the result of test variability, than an inherent property of the oil brand. The primary differences between the test scenarios were identified for tests with a very long total heating time to ignition.

Scenario 10 (aluminum pan on glass ceramic range) and Scenario 13 (1/2 in. (12.7 mm) depth oil) were among the longest tests conducted, and resulted in the low smoke temperatures shown above.

The average oil temperatures measured at ignition for the various canola oil brands are shown in Figure 40. The outliers observed for the smoke temperatures were not observed, and the average ignition temperatures range from 385°C (725°F) for Great Value and Crisco to 392°C (738°F) for the Generic brand. The increase in temperature in the generic oil is believed to result from a more limited test sample size, rather than any difference in the oil. Although some test to test variability was observed, no systematic differences were observed between the canola oil brands in smoke or ignition temperatures.



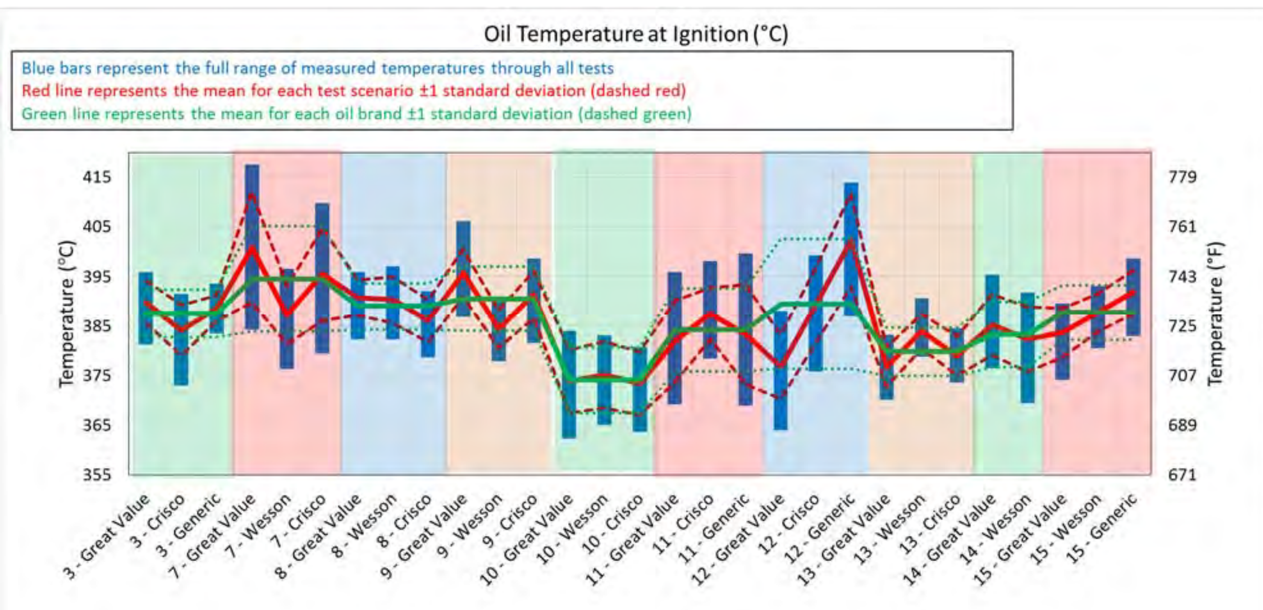


Figure 40 – Average oil temperatures at ignition for various canola oil brands for a range of cooking scenarios arranged by oil type (top) and test scenario (bottom)

Comparable results were observed for the Phase 1 tests conducted with commercial and consumer brand soybean and canola oils. The oil temperatures at smoke and ignition for Phase 1 tests are shown in Figures 41 and 42, respectively. The data shown represents only direct comparisons between oil types, with no other variables altered. Although the data samples were far more limited, the average pan and oil temperatures at smoke an ignition do not vary by more than a standard deviation for either oil type.

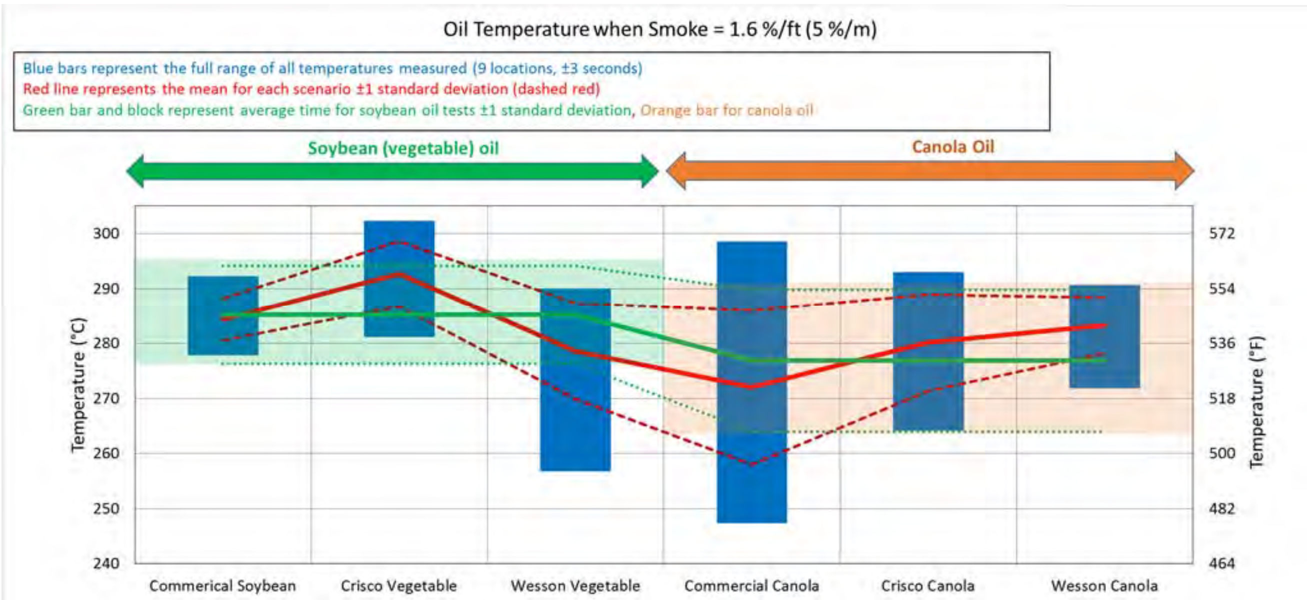


Figure 41 – Average oil temperature at 1.6%/ft (5%/m) smoke measurement for various brands of soybean and canola oils tested in Phase 1

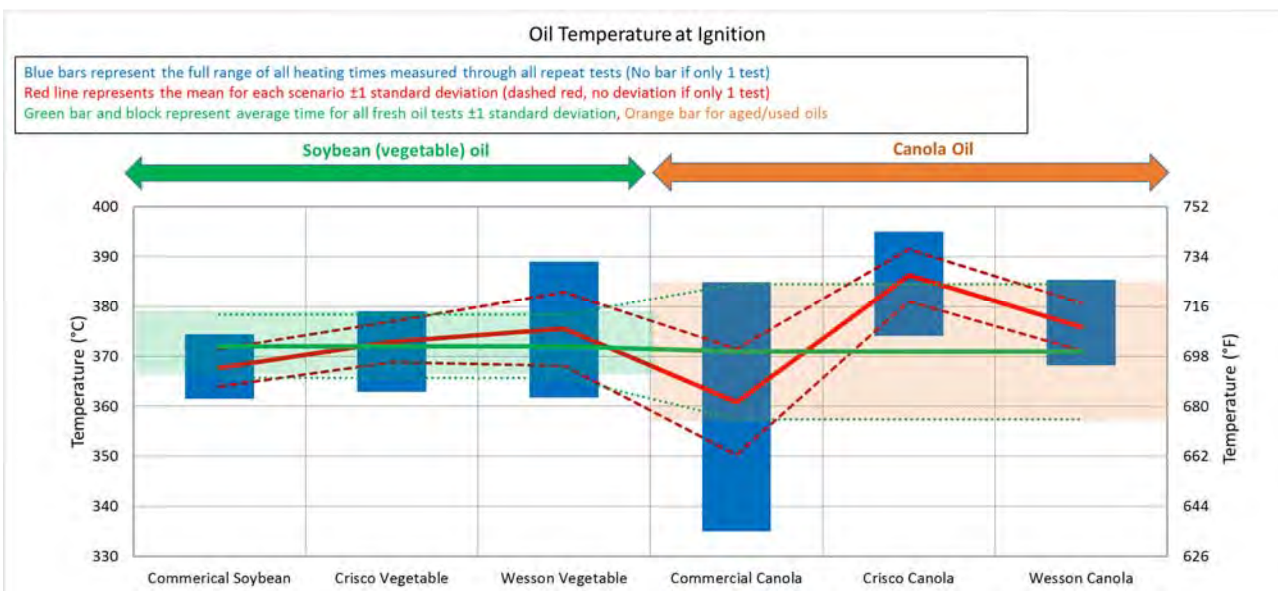


Figure 42 – Average oil temperature at ignition for various brands of soybean and canola oils tested in Phase 1

6.6. Pan Material

A series of tests were conducted in Phase 2 to evaluate the differences between aluminum, stainless steel, and cast iron pans. Five 10 in. (25 cm) pan types were tested with canola oil on the 2600 W electric coil element, including two brands of 8 gauge aluminum pans, two brands of stainless steel pans, and a cast iron pan. The primary observations from testing multiple pan materials include:

- The low end brand of stainless steel pan heated and reached ignition much faster than the other pans tested, likely due to:
  - Very thin metal, light weight pan
  - Wider pan base than other 10 in. (25 cm) pans (8.5 in. (22 cm) v. 7.5 in. (19 cm))
  - The time windows for operation of smoke or pan detection were proportional to the total heating time. The time windows could be reduced by reducing total heating time with:
    - Flatter pans
    - Wider pan base on element surface
    - More conductive pan metal
    - Lower specific heat capacity of pan
    - Less pan mass
- The differences between the average pan and oil temperatures were consistent for all pans
- The pan and oil temperatures at ignition were higher for tests reaching ignition faster
  - Highest for the low end stainless steel
  - Lowest for the aluminum pan

All pan material evaluation tests were conducted on the 8 in. (20 cm) element of the 2600 W GE range, with a 10 in. (25 cm) pan and canola oil at a depth of ¼ in. (6.4 mm). The tests included in the pan material analysis are listed in Table 8. Additional pan details are provided in Table 1 in Section 5.2.2.

Table 8 – Tests included in pan material analysis

Identifier	Pan Used	Test ID
Aluminum 1	Vollrath 8 gauge aluminum pan	P2-4
		P2-5
		P2-6
Aluminum 2	Browne-Halco 8 gauge aluminum pan	P2-4a
		P2-5a
		P2-6a
Low End SS	Tramontina stainless steel pan	P2-16
		P2-17
		P2-18
High End SS	All-Clad stainless steel pan	P2-19
		P2-20
		P2-21
Cast Iron	Lodge Cast Iron Pan	P2-22
		P2-23
		P2-24

6.6.1. Available Response Times

Changes to the pan materials or manufactures were found to have a greater effect on the heating time to ignition than the oil types/brands/ages previously tested. The total heating time to ignition for the five pan material/brand tests are shown in Figure 43. The blue bars show the full range of heating times for each pan tested, while the red lines shows the mean time ±1 standard deviation for each pan. The green line and shaded region represent the mean time for all pans ±1 standard deviation.

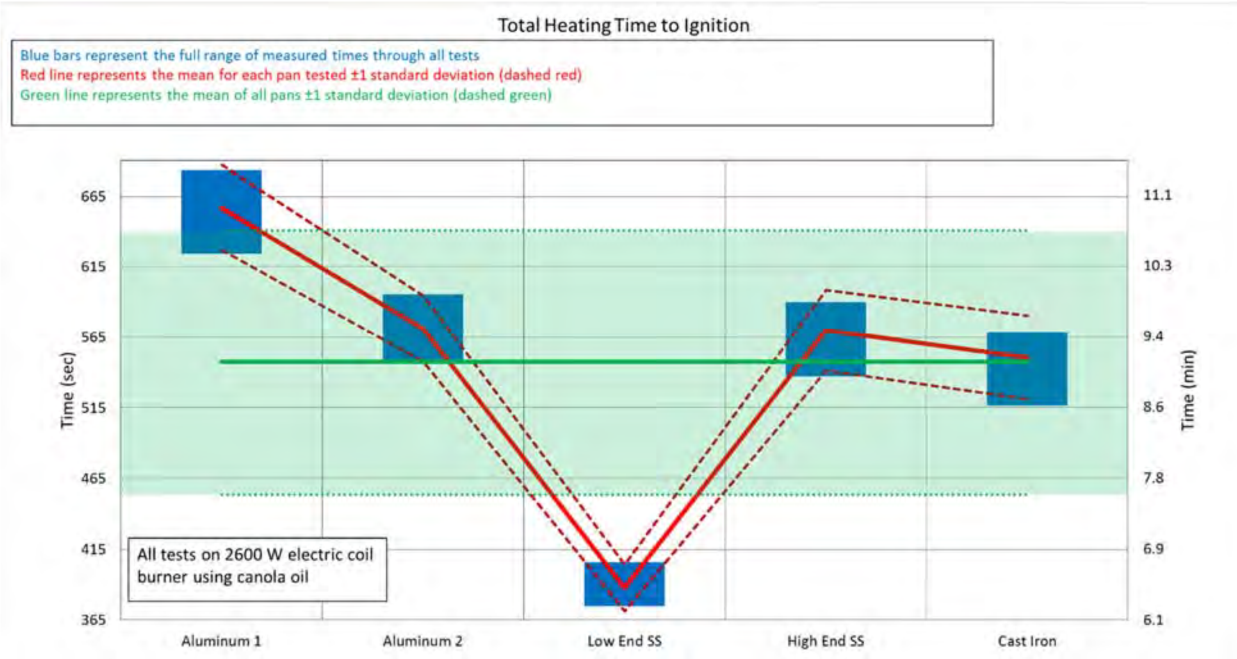


Figure 43 – Heating times until ignition for pan materials/brands

The low end stainless steel pan provided the fastest heating and ignition, igniting in an average of 388 seconds. This pan had the lowest mass of all the pans and an 8.5 in. (21.6 cm) flat base diameter. All other 10 in. (25 cm) pans tested had a 7.5 in. (19.0 cm) flat base diameter. This extra surface area contacting the element may have caused the increase in heating rate.

The two aluminum pans had the longest heating times to ignition, taking an average of 657 and 571 seconds, respectively. Despite the extra mass of the cast iron pan, more than double the aluminum or high end stainless, the cast iron pan heated comparably but slightly faster than the high end stainless steel pan and the aluminum 2 (Browne-Halco) pans. The estimated specific heat of the cast iron (0.46 J/g-K) was about half the aluminum (0.91 J/g-K) and slightly less than the stainless steel (0.51 J/g-K). This would imply that less energy is required on a mass basis to heat the pan, resulting in the reduced heating time for the cast iron pan.

Faster or slower heating times to ignition can be attributed to a few independent test variables. The pans can be described by the flat diameter of the base, the pan mass, the specific heat capacity and conductivity, and the overall flatness of the pan. Each of these variables can impact the heat transfer rate to the pan and to the oil in the pan, affecting the heating time to ignition.

The flatness of the pans have been measured using a flat bar and calipers along axes parallel and perpendicular to the handles. The deviation of the pan to the flat bar was measured along these axis at 1 in. (2.5 cm) increments. The flatness was then characterized using two metrics. First, the radius of curvature of the pan base was calculated between the center of the pan and the outside of element. A smaller number indicates a more curved pan base over the element. The second metric calculated is the angle of tilt toward the pan handle relative to the pan resting flat on the element surface. These metrics are shown in the flatness curves for aluminum pan 1 (shown in Figure 44).

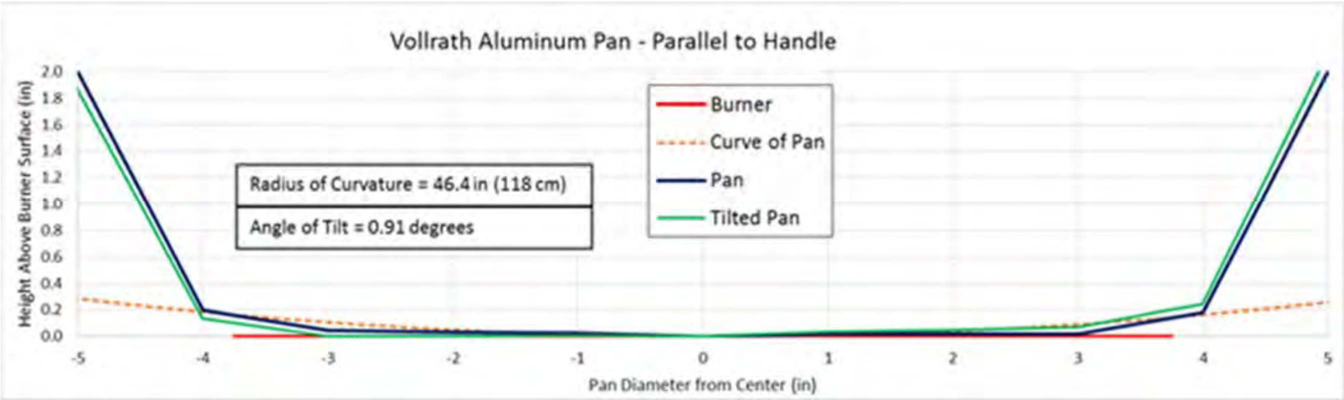


Figure 44 – Measured flatness of aluminum pan 1 (Vollrath Arkadia) measured parallel to the handle

This pan (Vorath Arkadia) was measured to have the smallest radius of curvature (46.4 in. (118 cm) and the largest angle of tilt (0.91°). It also produced the longest total heating times to ignition. The Browne-Halco Thermalloy aluminum pan was similar in shape but with a flattened curvature (187 in. (475 cm)) and reduced tilt angle (0.10°). The increased flatness and reduced tilt angle resulted in better contact with the element and a decrease of heating time to ignition. The base of this pan parallel to the handle is shown in Figure 45.

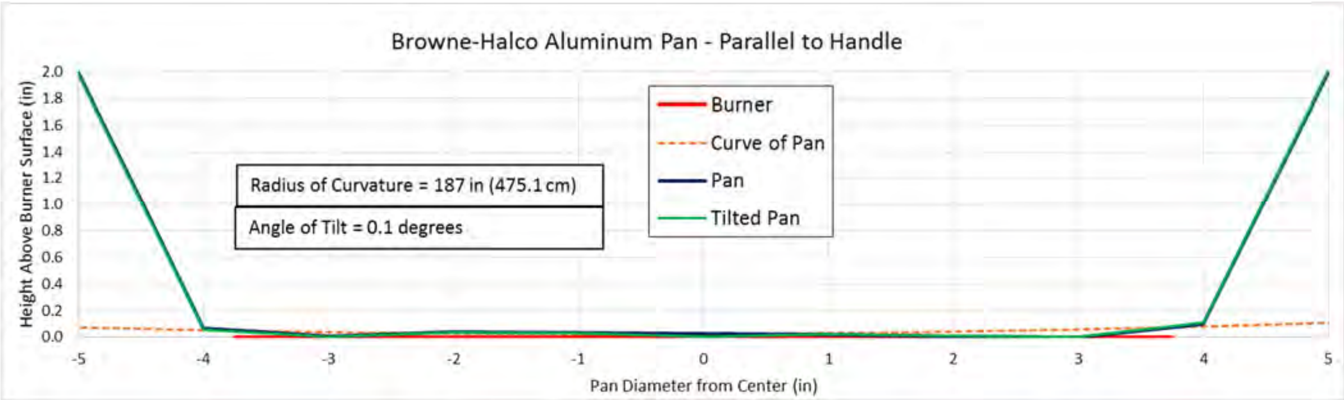


Figure 45 – Measured flatness of aluminum pan 2 (Browne-Halco Thermalloy) measured parallel to the handle

The low end stainless steel pan (Tramontina Everyday) with the shortest heating time to ignition had the largest flat base over the element, the greatest flatness over the element diameter (highest radius of curvature), and nearly no pan tilting to stabilize on the element (0.02°). The low end stainless pan base parallel to the handle is shown in Figure 46.

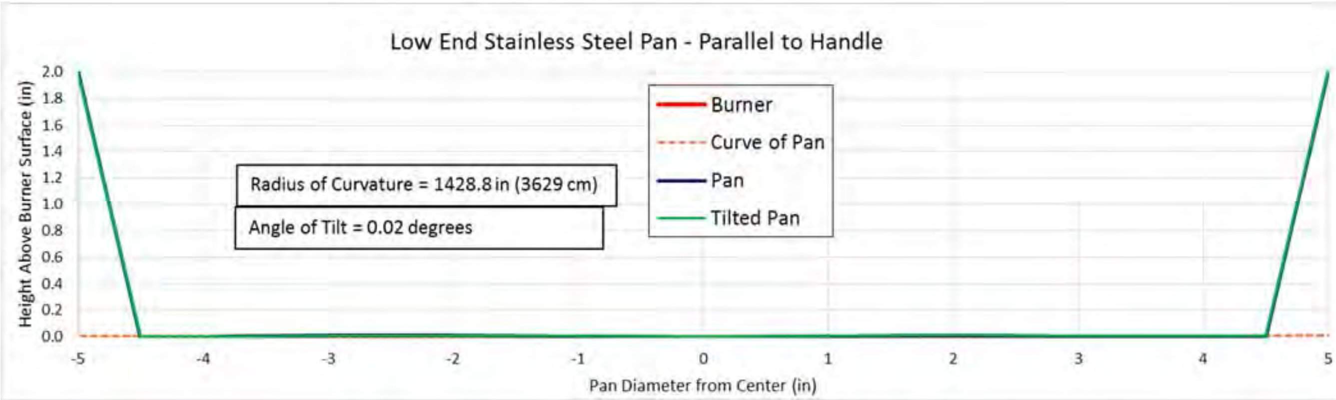


Figure 46 – Measured flatness of the low end stainless steel pan (Tramontina Everyday) measured parallel to the handle

The high end stainless steel pan (All-Clad Tri-Ply) had a slightly convex pan surface, making contact around the outer diameter and protruding slightly upward in the center. This stable outer ring resulted in a pan tilt angle of 0°. The base of the high end stainless steel pan is shown in Figure 47.

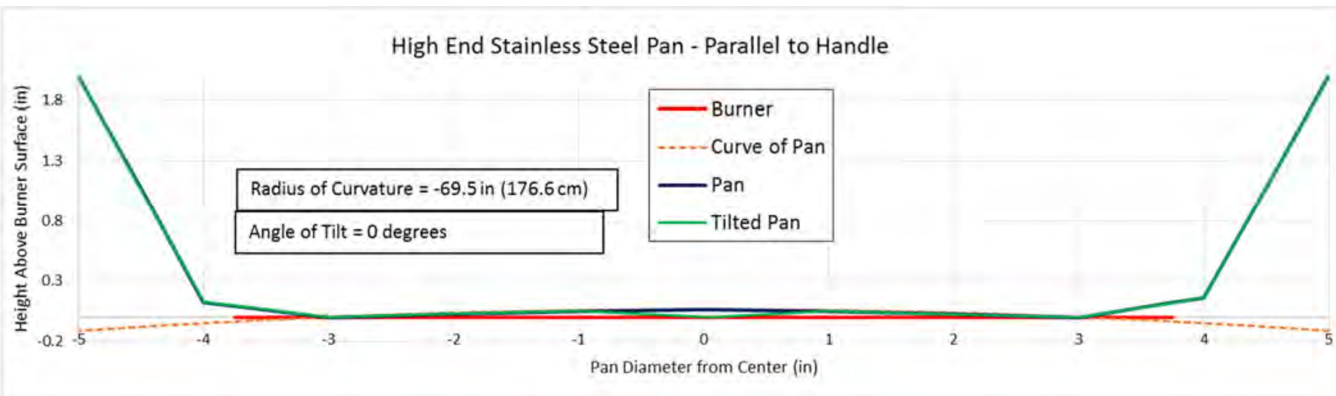


Figure 47 – Measured flatness of the high end stainless steel pan (All-Clad Tri-Ply) measured parallel to the handle

The cast iron pan (Lodge) also showed a slightly convex base, but with the protrusion pushing up between the center of the pan and the outer ring. This resulted in a small protruding torus ring around the pan. The flat outer ring preventing any tilting, and no angle was needed to stabilize the pan. The flatness of the cast iron pan is shown in Figure 48.

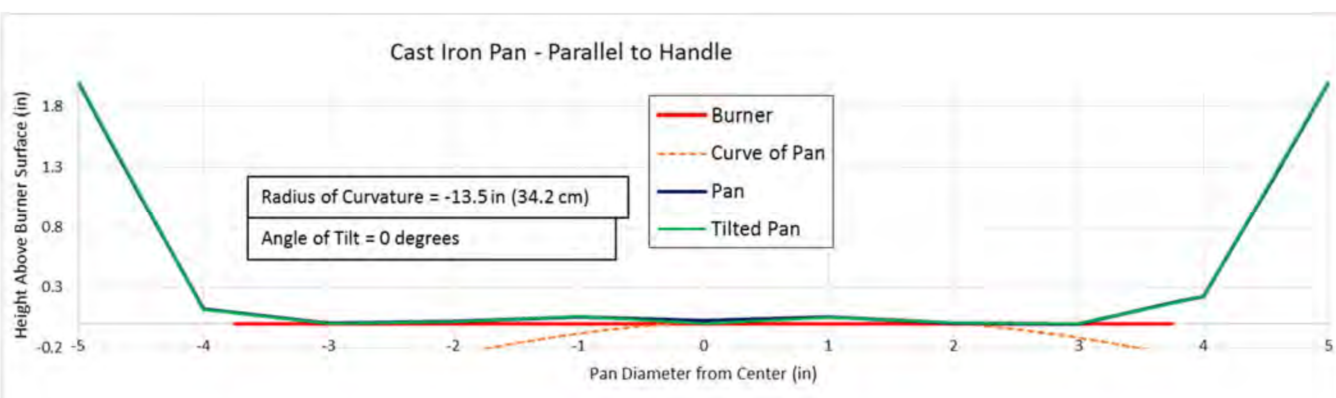


Figure 48 – Measured flatness of the cast iron pan (Lodge) measured parallel to the handle

The pan variables and a calculated correlation with the total heating time to ignition are shown in Table 9. The minimum possible heating time is calculated by combining the specific heat and mass of the pan, the specific heat, density, and volume of oil, and the output of the element as shown in Eq. (2) in Section 5.4.6. Scatter plots of the average heating time to ignition and several pan variables are shown in Figure 49.

Table 9 – Variable associated with pan materials and correlation to heating time to ignition

Pan	Pan Base Diameter (in (cm))	Pan Mass (g (lb))	Specific Heat Capacity (J/g-K)	Minimum Possible Heating Time (sec)	Conductivity (W/m-K)	Average Curvature (in (cm))	Pan Tilt (deg)
Alum 1	7.5 (19.0)	817 (1.8)	0.91	188	215	51 (129)	0.91
Alum 2	7.5 (19.0)	936 (2.1)	0.91	207	215	193 (489)	0.10
Low end SS	7.5 (19.0)	694 (1.5)	0.51	131	54	1286 (3266)	0.02
High end SS	7.5 (19.0)	977 (2.2)	0.51	152	54	-69 (-175)	0.00
Cast Iron	7.5 (19.0)	1970 (4.3)	0.46	215	80	-12 (-31)	0.00
Correlation to average heating time to ignition	-0.91	0.15	0.59	0.62	0.65	-0.89	0.64
Slope of average heating time to ignition	-199 (sec/in)	0.03 (sec/g)	253 (sec/(J/g-K))	1.69 (sec/sec)	0.76 (sec/(W/m-K))	-0.15 (sec/in)	158 sec/deg

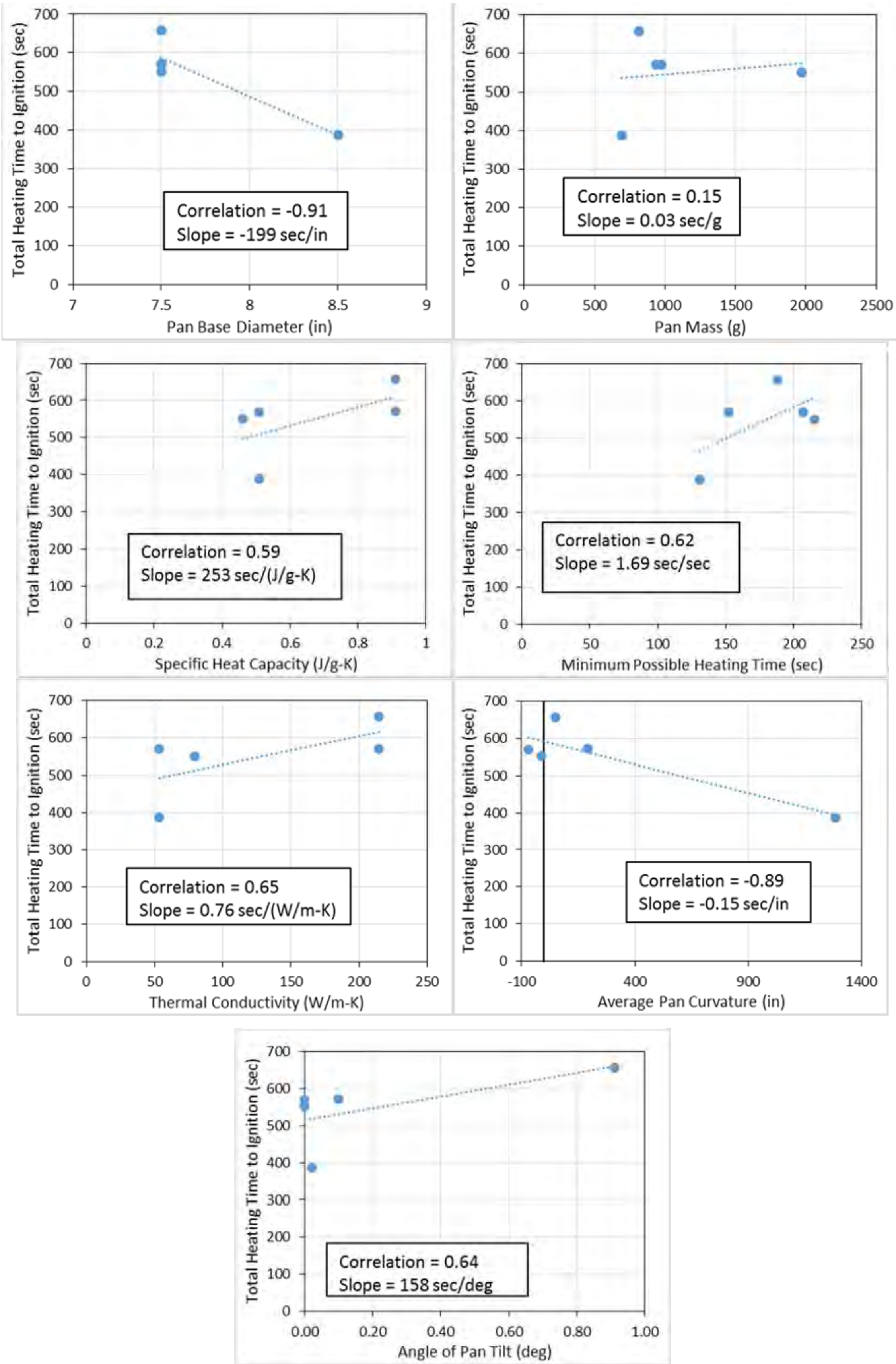


Figure 49 – Calculated correlations and slopes for heating time to ignition and pan variables

The total heating time can be reduced by increasing the heat transfer rate between the pan and the element. This can be accomplished by using flatter pans with a wider base on the element, and using more conductive pans with lower specific heat capacity and mass. Most other measured test parameters are proportional to the total heating time to ignition. The time windows between reaching an average pan temperature of 300°C (572°F) during the heating process and ignition and a smoke obscuration of 1.6%/ft (5%/m) and ignition are shown in Figures 50 and 51, respectively.

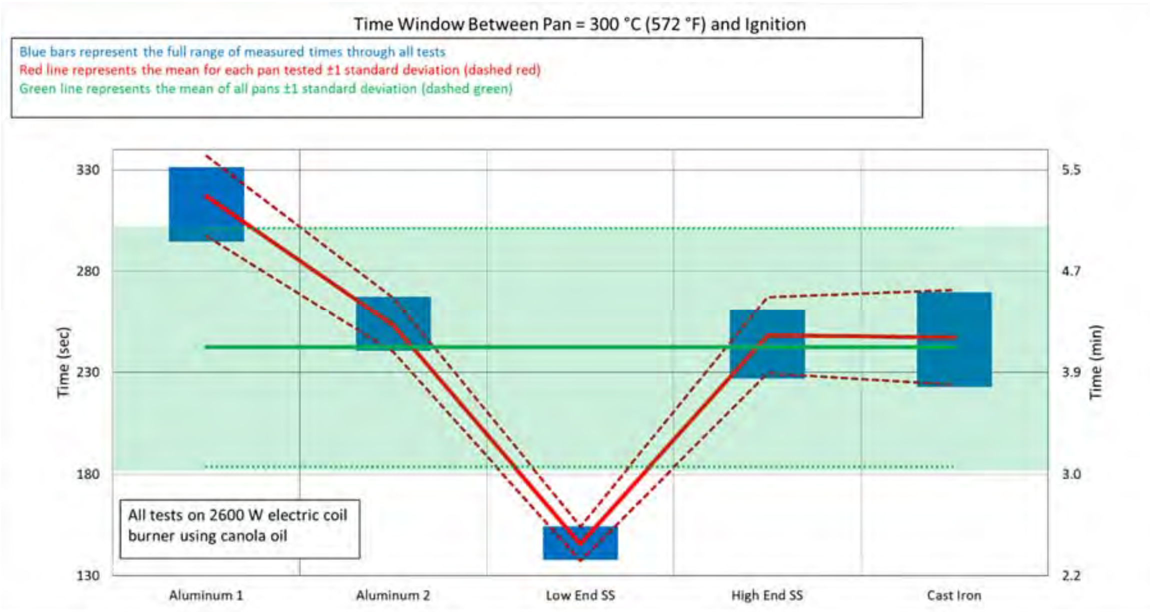


Figure 50 – Time window between pan temperature = 300°C (572°F) and ignition for various pan materials

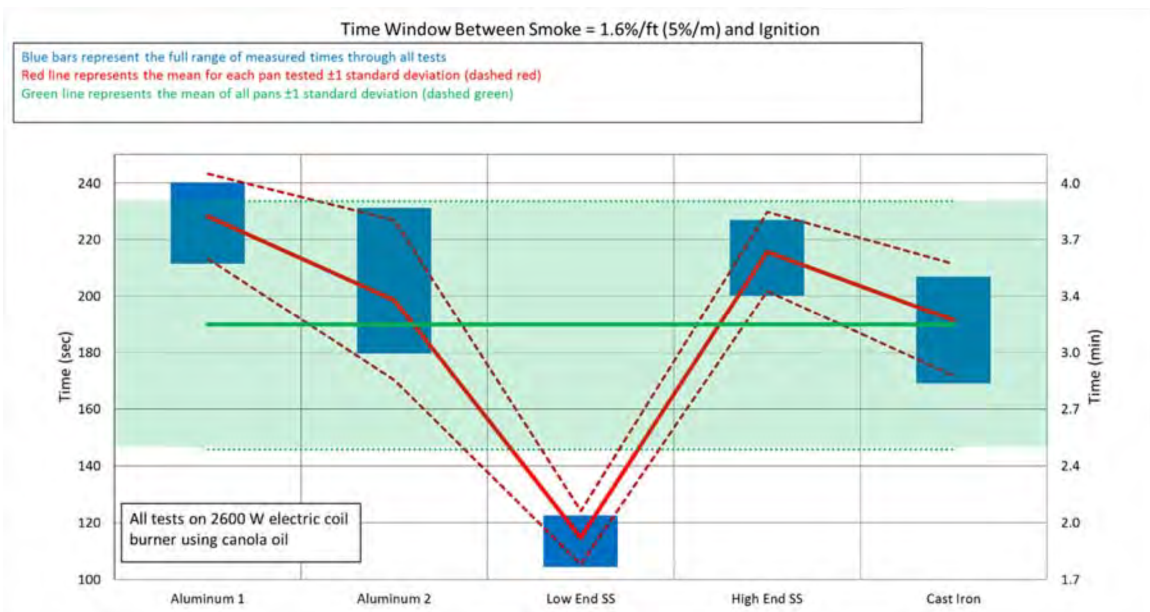


Figure 51 – Time window between smoke obscuration = 1.6%/ft (5%/m) and ignition for various pan materials

Both the pan temperature and smoke windows were nearly proportional to the total heating time to ignition (see Figure 52). The pan temperature window correlated to within 1.00, and the smoke window to 0.98. There was more time available for activation by pan temperature = 300°C (572°F) than for smoke = 1.6%/ft (5%/m), as the time window for pan activation was 0.62 times the total heating time and the smoke window was 0.44 times the total heating time.

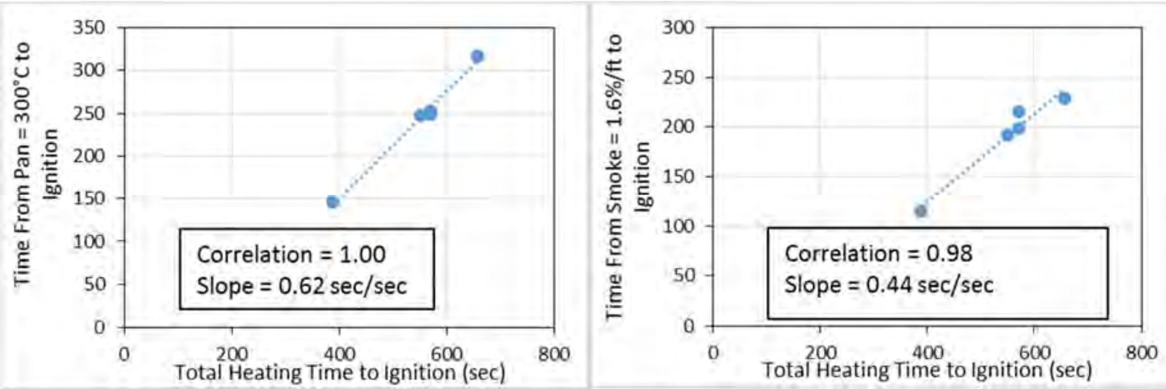


Figure 52 – Correlations and slopes between smoke and pan temperature activation windows

6.6.2. Temporal Heating Curves

Temporal plots of the average pan and oil temperatures, and average smoke obscuration for the fastest (Low end SS) and slowest (Alum 1) pan materials are shown in Figure 53 aligned at the time of ignition (T = 0). The solid lines show the average for each material, and the dashed lines show the maximum and minimum values measured at the given time before ignition occurred.

The measured pan and oil temperatures and smoke obscuration were higher longer before ignition for the slower aluminum pan test, increasing the available time windows for activation. It can be seen from the curves, however, that the pan and oil temperatures at the time of ignition were lower for the longer aluminum pan test than for the fast stainless steel tests. This is discussed in greater detail in Section 6.6.3.

The calculated slopes in the pan and oil temperature curves, differences between the pan (center of pan) and oil (center of oil) temperatures at ignition, and the integrated smoke obscuration at fixed pan temperatures are shown in Table 10. The most challenging scenarios for each metric are highlighted.

Several interesting effects can be seen from comparing the results of the data. The slope of the pan and oil temperature curves is much greater for the fast stainless steel test compared to the slow aluminum test. A difference of 30–40°C (54–72°F) per min was observed between the fastest and slowest tests.

The difference between the pan and oil temperatures is much lower for the high end stainless steel and cast iron pans compared to the aluminum and low end stainless steel. This is due to the curvature of the pans. The center pan thermocouples were used for this analysis only, and the high end stainless steel and cast iron pans were found to have convex surfaces, with the center protruding away from the element. In these tests, the center thermocouples measured the lowest of the three pan thermocouples, resulting in much closer measurements to the oil temperatures. The pan temperatures in the high end stainless steel pan and in the cast iron pan at ignition are shown in Figure 54.

The integral of the smoke obscuration is also nearly proportional to the total heating time to ignition. All pans were tested using fresh canola oil, and the smoke production rate was a function of the total test duration. The correlation and slope between the smoke integral and the total heating times are shown in Figure 55.

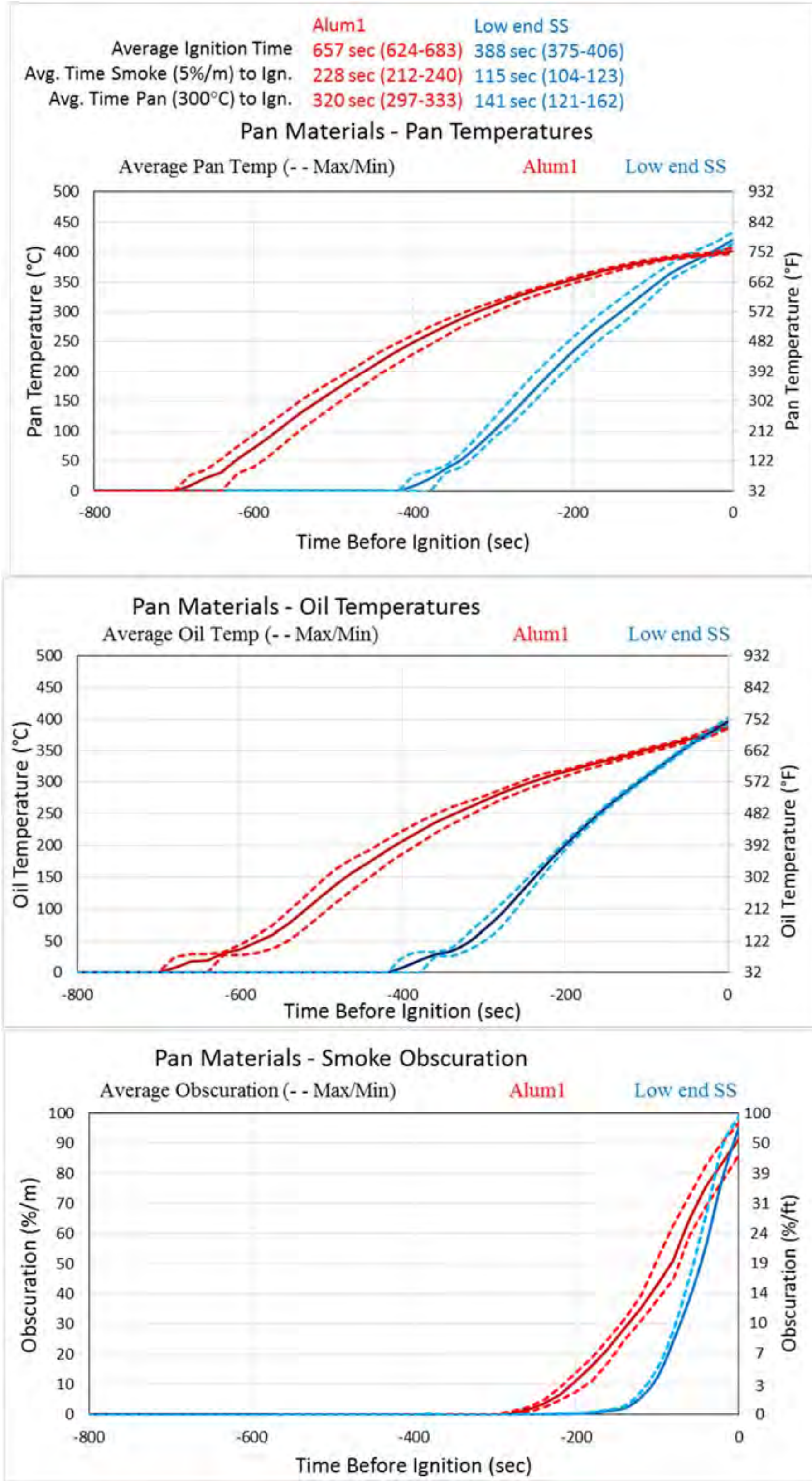
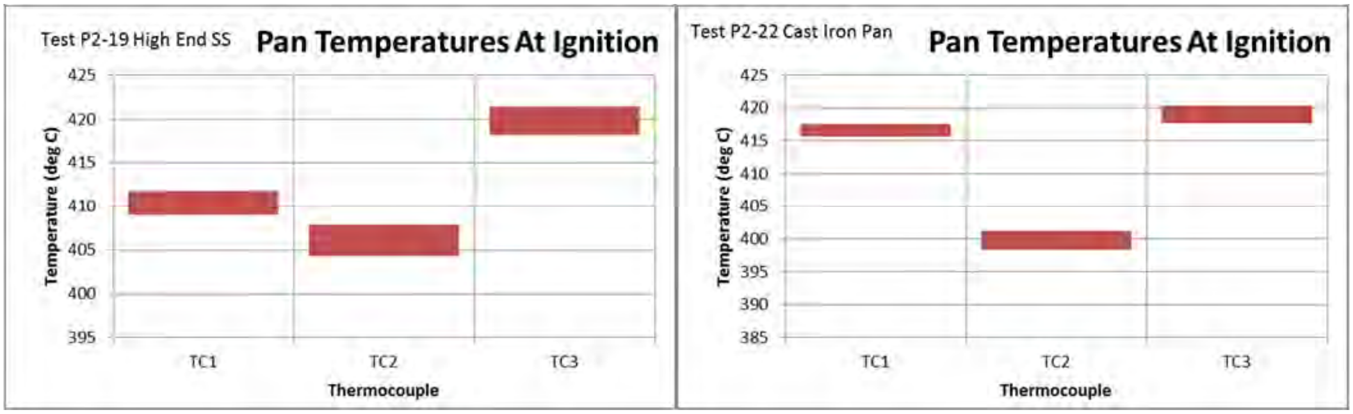


Figure 53 – Pan and oil temperatures and smoke obscuration curves for fastest (low end stainless steel – Tramontina Everyday) and slowest (Aluminum 1 – Vollrath Arkadia) pan materials aligned by ignition time

Table 10 – Calculated pan and oil temperature slopes and obscuration slope and integrated areas for various pan materials

Oil	Average pan temp slope between fixed pan temperatures and ignition (°C/min)				Average oil temp slope between fixed pan temperatures and ignition (°C/min)				Difference between pan and oil temperature at fixed pan temps (°C)					Integral of smoke obscuration up to fixed pan temperatures (%/m – min)				
	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	IGN	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	IGN
Aluminum 1	23	19	15	11	26	23	21	21	33	32	34	36	13	0	0	4	27	162
Aluminum 2	29	25	20	16	33	29	28	27	33	31	35	34	15	0	2	11	34	144
Low End SS	55	52	46	41	55	52	49	38	25	24	28	22	23	0	2	9	30	89
High End SS	31	28	24	23	31	28	25	23	12	16	17	15	15	2	5	25	69	165
Cast Iron	31	27	23	21	33	29	28	26	9	9	12	7	2	1	3	27	69	138



TC1 located closest to handle, TC 2 in center of pan, and TC3 away from handle (see Figure 2)

Figure 54 – Pan temperatures at ignition by location for the high end stainless steel and cast iron pans

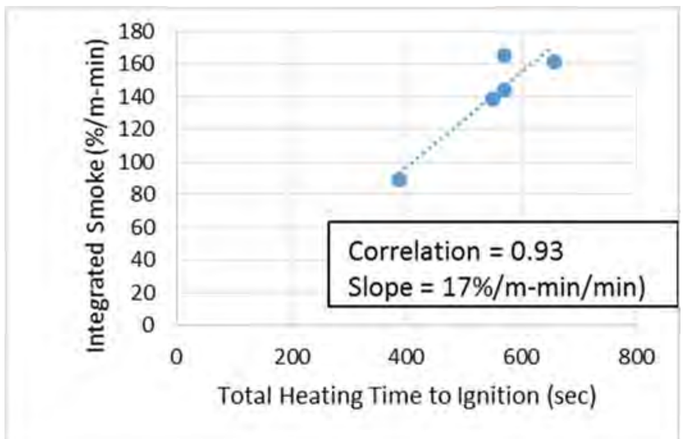


Figure 55 – Correlation and slope between the integrated smoke obscuration and total heating time to ignition

6.6.3. Smoke Production and Ignition Temperatures

The pan and oil temperatures measured at the time smoke was produced and at ignition provide a direct comparison of the impacts of the pans on the heating of oils. The average pan and oil temperatures at the time of low smoke measurements are shown in Figures 56 and 57, respectively.

The pan and oil temperatures measured when low levels of smoke was measured were not strongly affected by the type of pan used or the resulting heating rate. The measured pan and oil temperatures were very consistent, varying by as much as 21°C (38°F) and 17°C (31°F) for the pan and oil, respectively. The strongest correlation for the pan and oil temperatures at smoke was observed for the conductivity of the pan. The pan temperature correlated to 0.71 with a slope of 0.07°C (0.13°F) per W/m-K, and the oil temperature correlated to 0.47 with a slope of 0.04°C (0.07°F) per W/m-K.

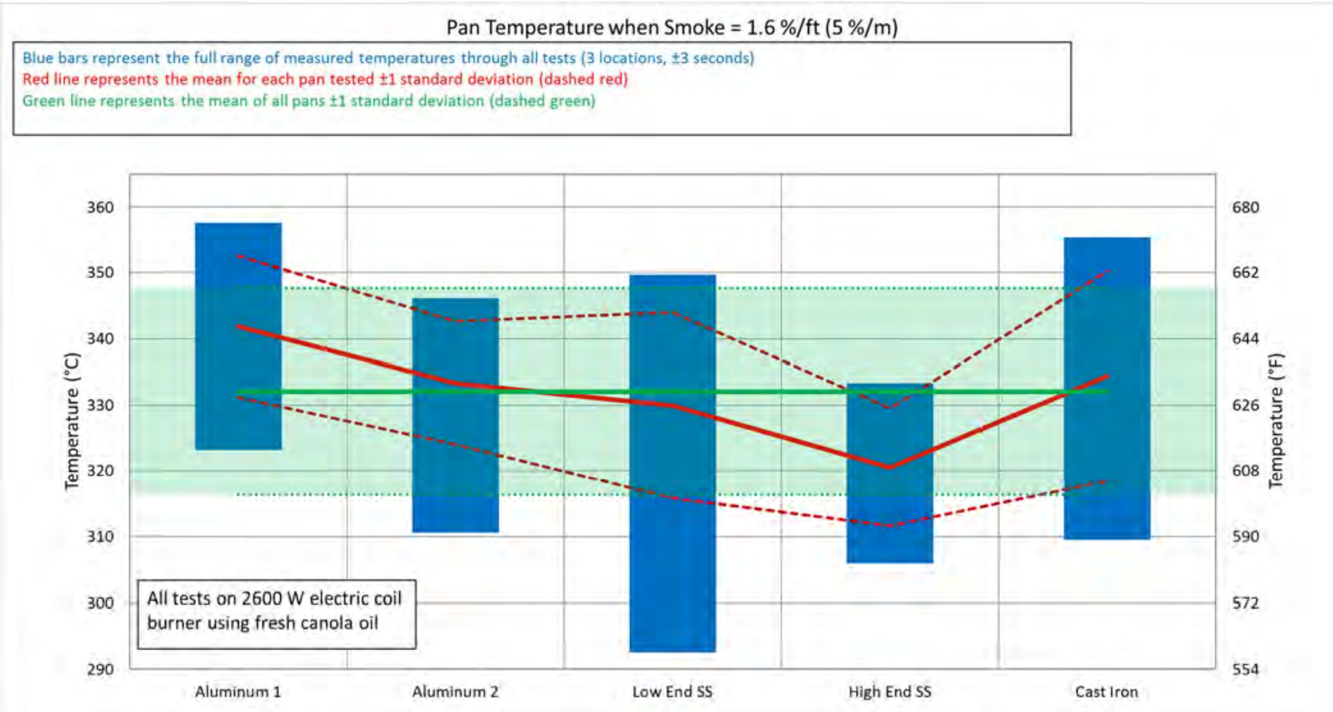


Figure 56 – Average pan temperature at 1.6%/ft (5%/m) smoke measurement for various pan materials

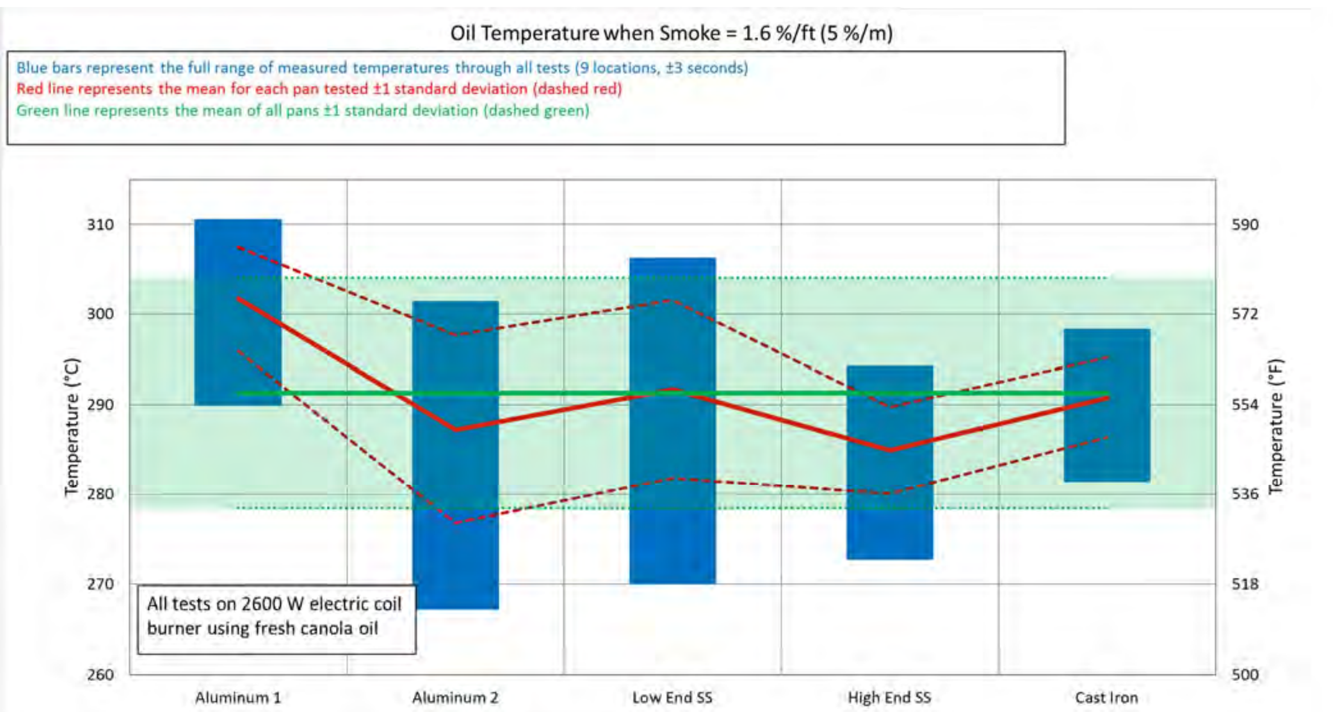


Figure 57 – Average oil temperature at 1.6%/ft (5%/m) smoke measurement for various pan materials

The average temperatures of the oil at the time the average pan temperature measured 300°C (572°F) are shown in Figure 58. Unlike the differences calculated and shown in Table 10, these values represent the bulk average oil temperature and the average of 3 pan temperature locations.

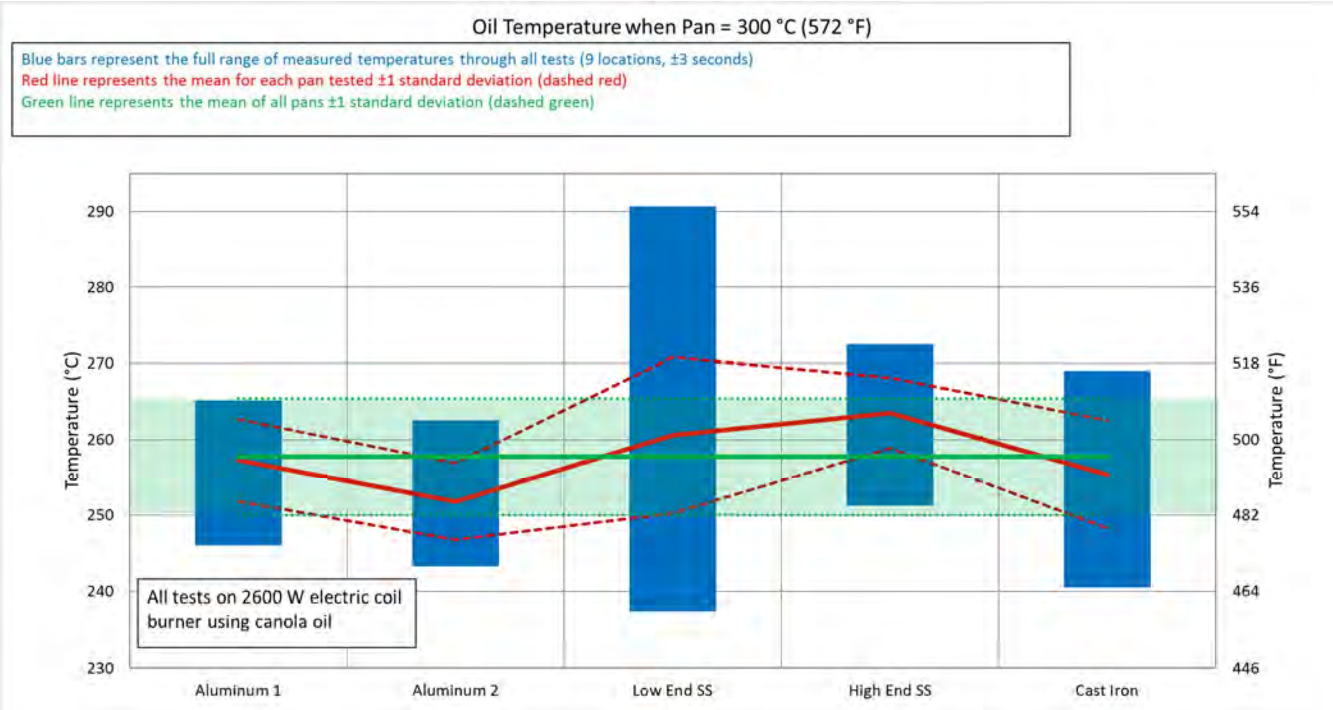


Figure 58 – Average oil temperatures when pan temperature = 300°C (572°F) for various pan materials

The average temperature of the oil measured when the pan reached a threshold of 300°C (572°F) was consistent for all pan materials, with all pans measuring an averaging temperature of 258°C (496°F) ± 6°C (11°F). There was a wide range of variability in the low end stainless steel pan (237–291°C (459–556°F)), but the average fell in line with the other pan materials. This indicates that the pan temperature can provide a good estimate of the oil temperature regardless of the properties of the pan being used for testing. As discussed in Section 6.6.2, the location of the pan temperature measurement can impact the difference between the pan and oil temperatures. If a measurement is made where the pan does not make good contact with the element, the pan temperature may be lower and could underestimate the temperature of the oil.

The average temperatures of the pan and oil at ignition do vary with the pan material. The impact appears to be linked to the total heating time to reach ignition. The pan and oil temperatures at ignition are shown in Figures 59 and 60, respectively. The blue bars represent every thermocouple in the pan plus minus 3 seconds from ignition in every test. There were spatial variations in the measured temperatures causing a wide range of values among all measurements. The center measurements were closest to the average measurements, but lower or higher temperatures were measured to the left or right of center as discussed in Section 8. The way the average temperature is affected by variables provides the best indication of the effect of the variable. The red bar shows the average, and the dashed red bars show the standard deviation from the average, a different interpretation with narrower bounds than the absolute maximum and minimum temperatures measured.

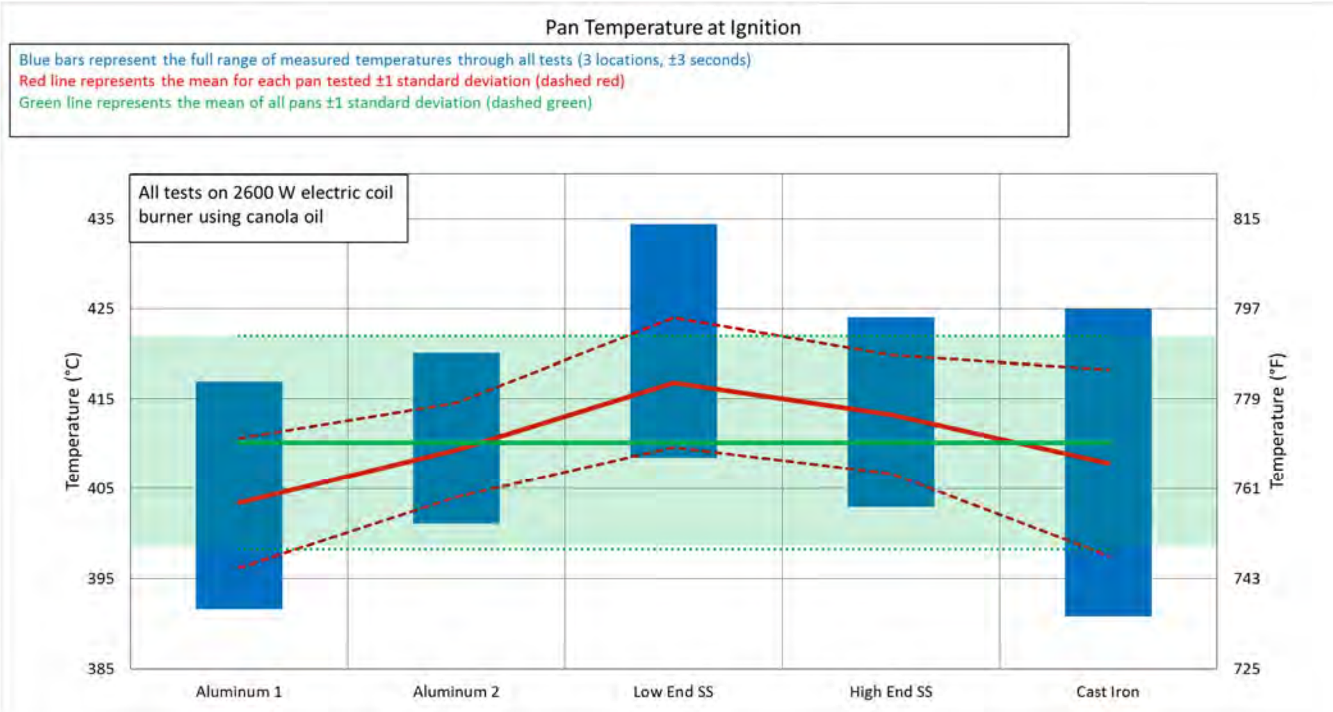


Figure 59 – Average pan temperatures at ignition for various pan materials

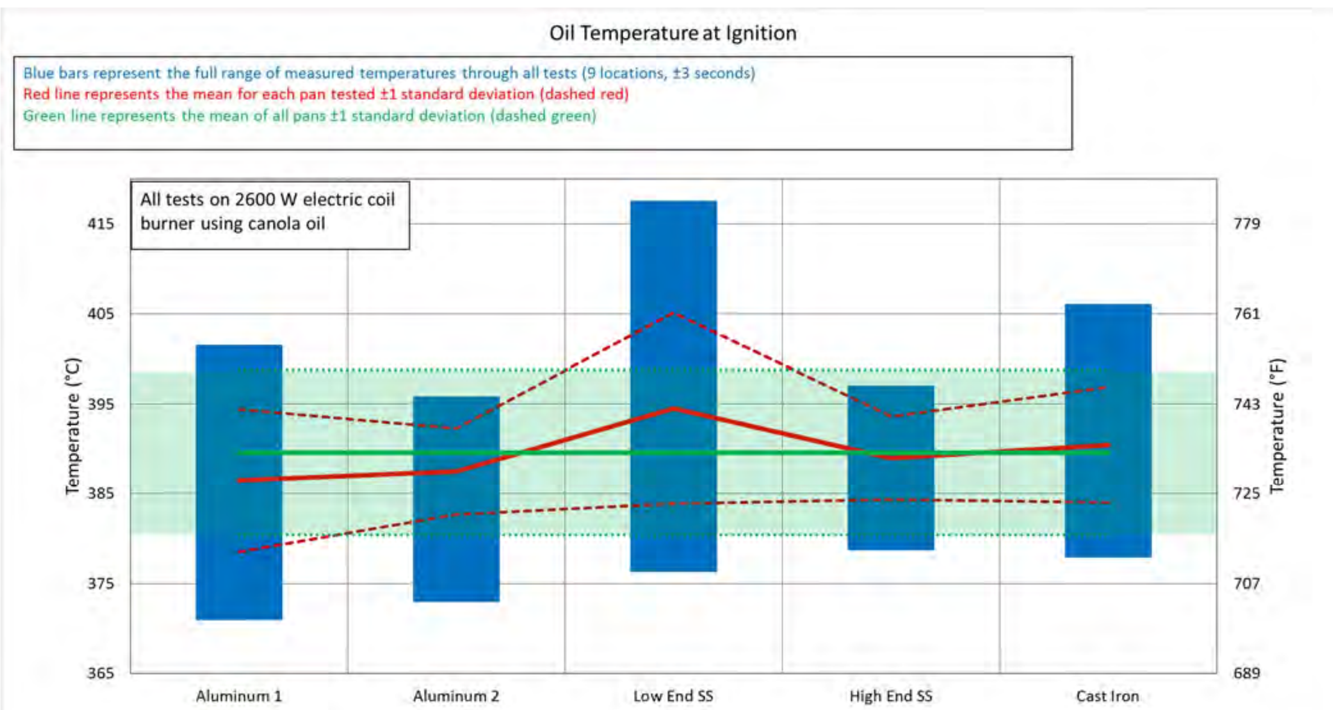


Figure 60 – Average oil temperatures at ignition for various pan materials

The pan and oil temperatures measured at ignition did vary for different pan materials, with the highest temperatures measured for the fastest tests (low end stainless steel) and the lowest temperatures measured for the slowest tests (aluminum 1). The pan and oil temperatures at ignition both correlated well with the total heating time to ignition, with correlation coefficients of -0.87 and -0.96 for the pan and oil temperatures, respectively. Although the changes were not drastic, -0.05°C per second for the pan temperatures and -0.03°C per second for the oil temperatures, the correlation was noticeable over the long differences in ignition times. These calculations are shown in Figure 61.

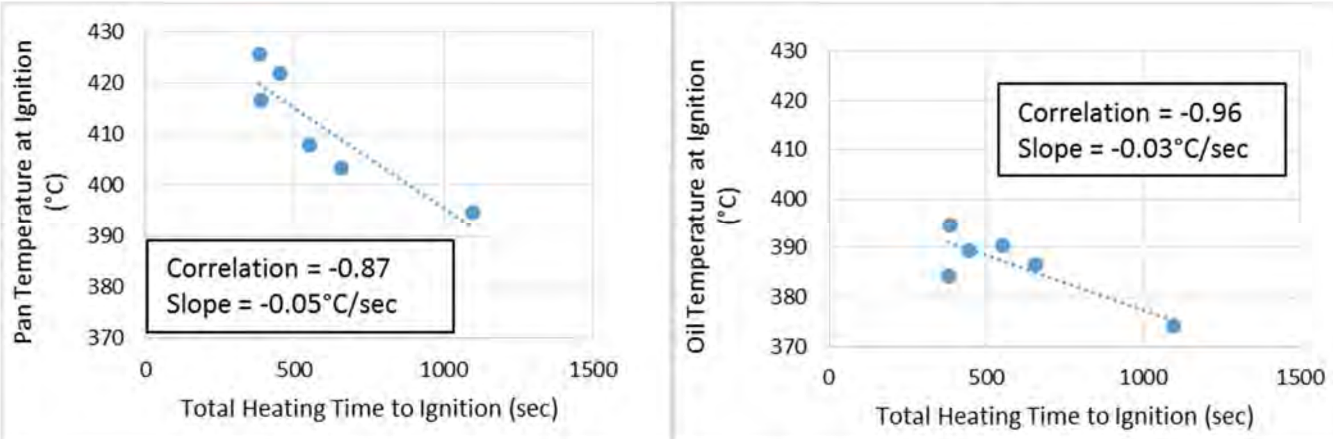


Figure 61 – Correlation and slope between pan and oil temperatures at ignition and total heating time

6.7. Ranges

Testing was conducted to quantify the impacts of the element power input (Phase 1) and the element type (Phase 2). The intent of these tests were to determine how much the element or power setting would impact the heating times and ignition temperatures. The primary observations include:

- Lower element power output increases total heating times and windows for activation
  - Heating times could not be replicated by reducing the power on an element to "match" the power of a lesser element
  - When element power cycles, the total heating time to ignition is greatly increased
    - Observed both for turning the power level down and for automatic glass break sensor control
- The pan dictates the impact of the glass ceramic radiant element vs. electric coil element
  - Aluminum pan much slower to ignition
  - Cast iron and stainless steel pans faster to ignition
  - May be due to flatness, radiative absorption, or other factors
- Test with slower heating rates have lower pan and oil temperatures at ignition

The tests included in the range analysis are summarized in Table 11. The Phase 1 tests included the use of two brands of electric coil range with different power outputs, one scenario with the high power range turned down to "match" the lower power range, and one test with a small element. The Phase 2 tests included aluminum, stainless steel, and cast iron pans on an electric coil range and on a higher power glass ceramic range element.

Table 11 – Tests included in range analysis

	Identifier	Oil Type	Description	Test ID
Phase 1	2600 W	Commercial Soybean Oil	Browne-Halco 8 in. aluminum pan on GE 2600 W electric coil element on highest setting	P1-1
		Commercial Canola Oil		P1-5
		Commercial Canola Oil		P1-6
		Crisco Vegetable Oil		P1-10
		Crisco Canola Oil		P1-11
		Wesson Vegetable Oil		P1-12
		Wesson Canola Oil		P1-13
	2100 W	Commercial Soybean Oil	Browne-Halco 8 in. aluminum pan on Frigidaire 2100 W coil element on highest setting	P1-20
		Commercial Canola Oil		P1-21
	2600 W set to 8.75	Commercial Soybean Oil	Browne-Halco 8 in. aluminum pan on GE 2600 W coil element with power lowered to 8.75 of 10, power cycle on/off with average power of 2100 W	P1-22
		Commercial Canola Oil		P1-23
	1500 W	Commercial Canola Oil	Browne-Halco 8 in. aluminum pan on GE 1500 W coil element on highest setting	P1-24
Phase 2	Alum - Coil	Great Value Canola Oil	Vollrath 10 in. aluminum pan on 2600 W electric coil element	P2-4
		Great Value Canola Oil		P2-5
		Great Value Canola Oil		P2-6
	Alum - Smooth	Great Value Canola Oil	Vollrath 10 in. aluminum pan on 3000 W glass ceramic element	P2-25
		Wesson Canola Oil		P2-26
		Crisco Canola Oil		P2-27
		Great Value Canola Oil	Brand new Vollrath 10 in. aluminum pan on 3000 W glass ceramic element	P2-25a
	SS - Coil	Great Value Canola Oil	Tramontina 10 in. stainless steel pan on 2600 W electric coil element	P2-16
		Wesson Canola Oil		P2-17
		Crisco Canola Oil		P2-18
	SS - Smooth	Great Value Canola Oil	Tramontina 10 in. stainless steel pan on 3000 W glass ceramic element	P2-28
		Generic Canola Oil		P2-29
		Crisco Canola Oil		P2-30
	CI - Coil	Wesson Canola Oil	Lodge 10 in. Cast Iron pan on 2600 W electric coil element	P2-22
		Crisco Canola Oil		P2-23
		Great Value Canola Oil		P2-24
	CI - Smooth	Great Value Canola Oil	Lodge 10 in. Cast iron pan on 3000 W glass ceramic element	P2-31
		Generic Canola Oil		P2-32
		Crisco Canola Oil		P2-33

6.7.1. Range Power Level (Phase 1)

Fire tests were conducted in Phase 1 for two ranges with different maximum power levels and element coil designs. Tests were conducted at the maximum power level of one range (2600 W), and at the maximum power level of the other range (2100 W) on both range types. The higher power range was set to a element power of 8.75 (out of 10) in order to match the total power output of the elements. The element power was matched by reducing the element cycling time by 19%, as measured by total current.

In addition, a test was run on the small 6 in. (15 cm) 1500 W element of the higher power range at its maximum power setting. All Phase 1 range/element evaluation tests were conducted with an 8 in. (20 cm) diameter, 8 gauge aluminum frying pan. A total of 13.4 in.^{3} (220 mL) of oil was used for each test, resulting in an initial oil depth of ¼ in. (6.4 mm).

6.7.1.1. Available Response Times

The total heating times required to reach ignition are shown in Figure 62. The time to ignition was observed to increase with decreasing range power, indicating a correlation of -0.57. The shortest time to ignition was observed for the GE range at its highest power setting for both canola and soybean oils. The 2100 W Frigidaire range produced ignition 62 and 95 seconds slower than the 2600 W GE for soybean and canola oil, respectively. When the power output of the GE range was reduced to 2100 W, however, the ignition times for the oils increased by 401 seconds and 317 seconds for soybean and canola oil, respectively. Despite matching the total power output between the two ranges, the ignition time was greater for the range with a coil operating with cyclic, rather than continuous heating. This effect may be due to the heat transfer rate of the element coil, but the GE range has more coils than the Frigidaire range and the ignition time for the 1500 W GE coil element with continuous heating was faster than the ignition time for the large element with cyclic heating.

Figure 62 – Heating times until ignition for various range power levels

The time windows between the pan temperature threshold and the smoke window scaled proportionally with the total heating times. The correlation of the total heating times to element heat output, and the pan and smoke time windows to total test time are shown in Figure 63. The pan temperature windows correlated to 1.00 with the total heating times, with a slope of 0.58 second window per second of total heating time. The smoke windows correlated to 0.99 with the heating time, with a slope of 0.44 second window per second of total heating time. The available window for the pan temperature threshold was consistently longer than for the smoke threshold.

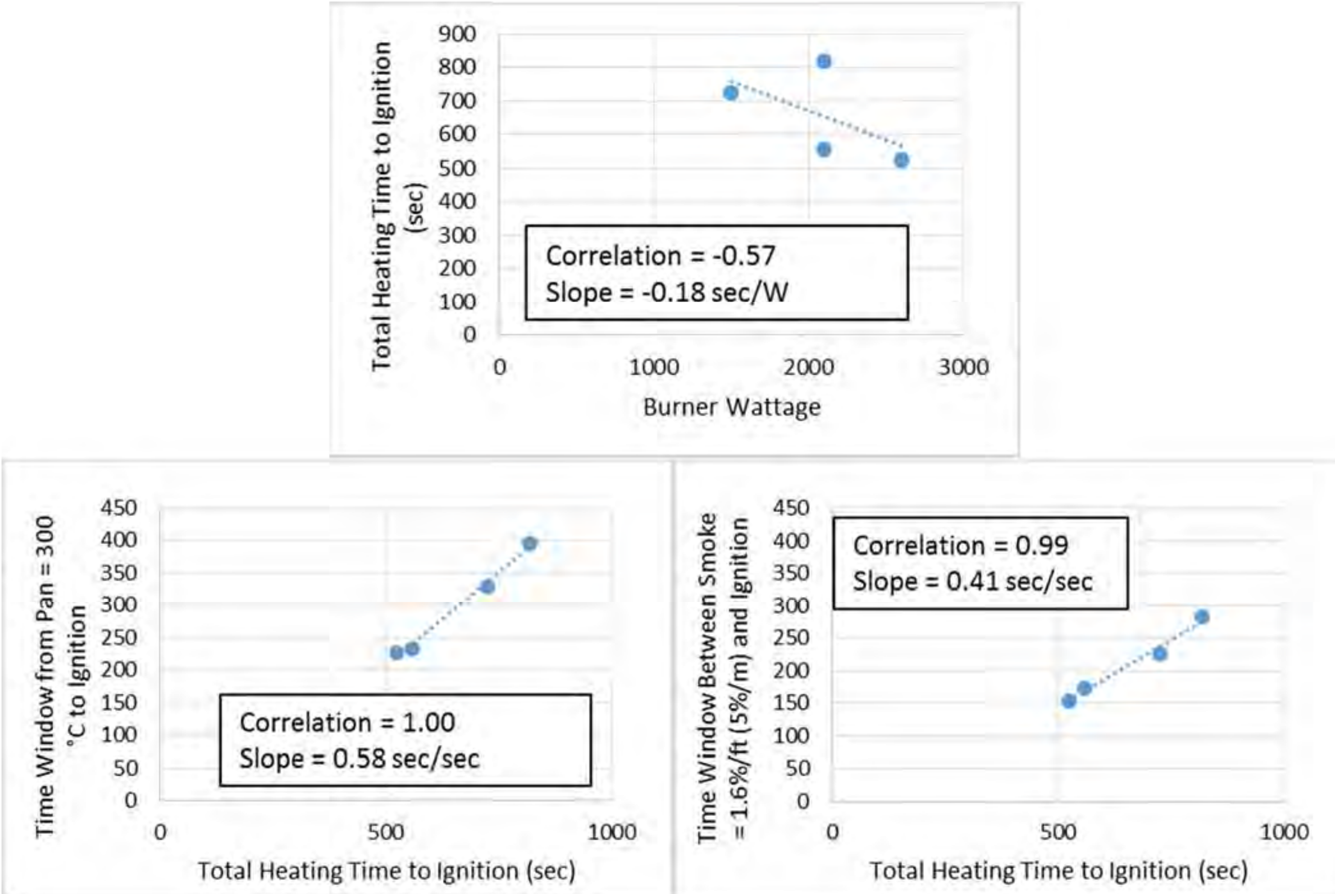


Figure 63 – Correlation between the total heating time and element input power and the smoke and pan temperature time windows

6.7.1.2. Temporal Heating Curves

Temporal plots of the average pan and oil temperatures, and average smoke obscuration for the fastest and slowest pan materials are shown in Figure 64 aligned at the time of ignition (T = 0). The solid lines show the average for each material, and the dashed lines show the maximum and minimum values measured at the given time before ignition occurred.

The curves shown represent the fastest (High Power (2600 W element)) and the slowest (Low Power (2600 W set to 8.75 power)) test conducted. There was greater variability observed for the high power tests, but this is due to the greater number of tests included. Slightly lower pan temperatures were measured at ignition for the low power tests. This is consistent with the results for slower tests observed in the analysis of other test variables.

The calculated slopes in the pan and oil temperature curves, differences between the pan (center of pan) and oil (center of oil) temperatures at ignition, and the integrated smoke obscuration at fixed pan temperatures are shown in Table 12.

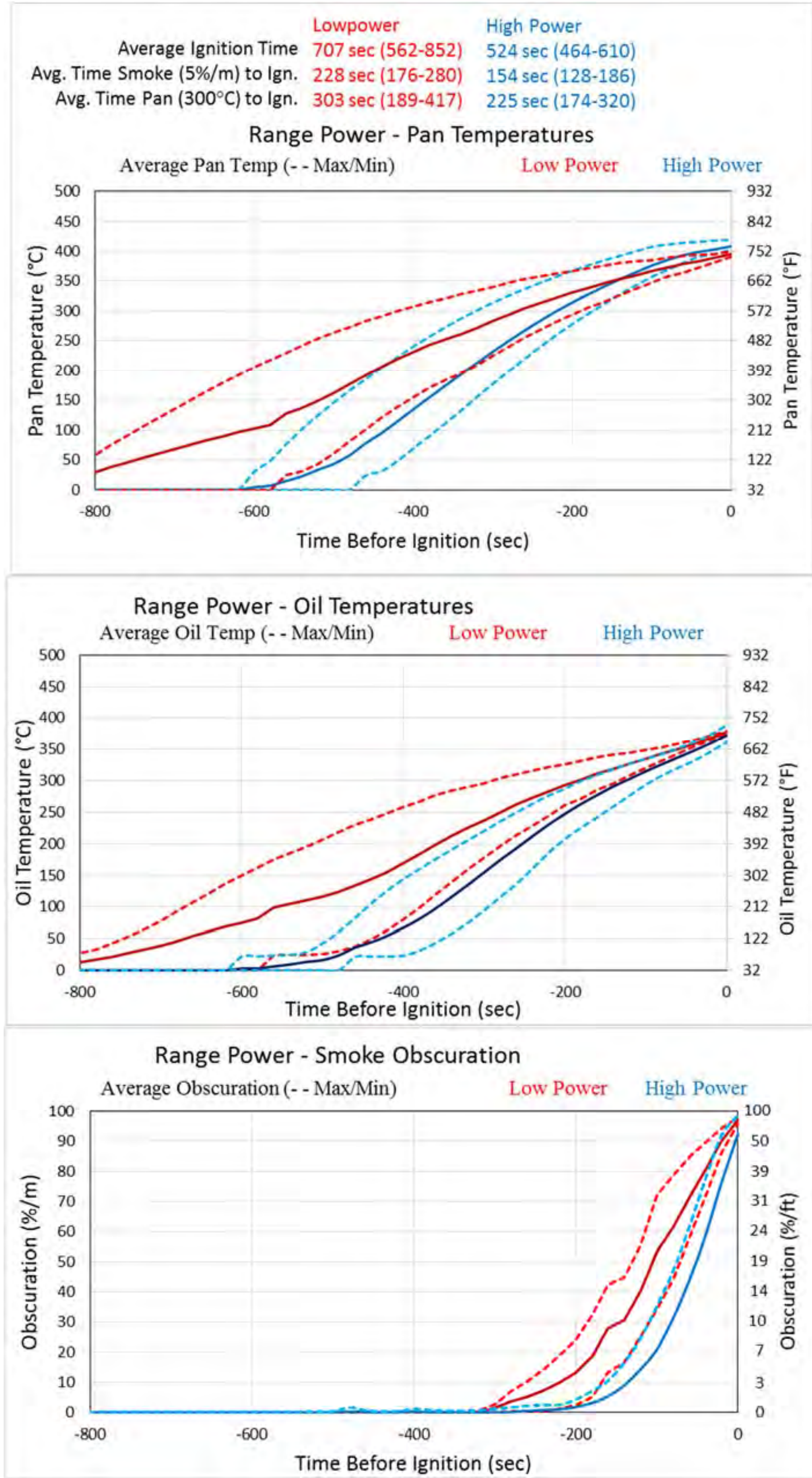


Figure 64 – Pan and oil temperatures and smoke obscuration curves for fastest and slowest element power outputs aligned by ignition time

Table 12 – Calculated pan and oil temperature slopes and obscuration slope and integrated areas for various element power inputs

Oil	Average pan temp slope between fixed pan temperatures and ignition (°C/min)				Average oil temp slope between fixed pan temperatures and ignition (°C/min)				Difference between pan and oil temperature at fixed pan temps (°C)					Integral of smoke obscuration up to fixed pan temperatures (%/m – min)				
	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	IGN	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	IGN
2600 W	34	30	24	20	40	36	32	30	64	61	56	54	36	0	1	6	19	104
2100 W	31	27	24	22	37	34	29	26	48	44	29	28	17	0	1	24	64	129
2600 W set 8.75 power	18	16	12	10	22	19	17	16	49	38	38	36	19	0	0	5	51	225
1500 W	11	9	6	4	13	11	8	8	46	46	41	40	22	0	0	29	119	433

Although the total heating time to ignition was shorter for the test with the 1500 W element than with the 2600 W element turned down, the slope of the pan and oil temperatures was actually lower. This test also had the greatest integrated smoke production. There was little to no trend observed for the differences between the pan and oil temperatures measured at fixed pan temperatures for the various element power outputs.

6.7.1.3. Smoke Production and Ignition Temperatures

The pan and oil temperatures at the time smoke obscuration measured 1.6%/ft (5%/m) are shown in Figures 65 and 66, respectively. The oil temperatures were observed to increase slightly with decreasing range power output, and therefore with increasing total time to ignition. No visible trend was observed for the pan temperatures, however.

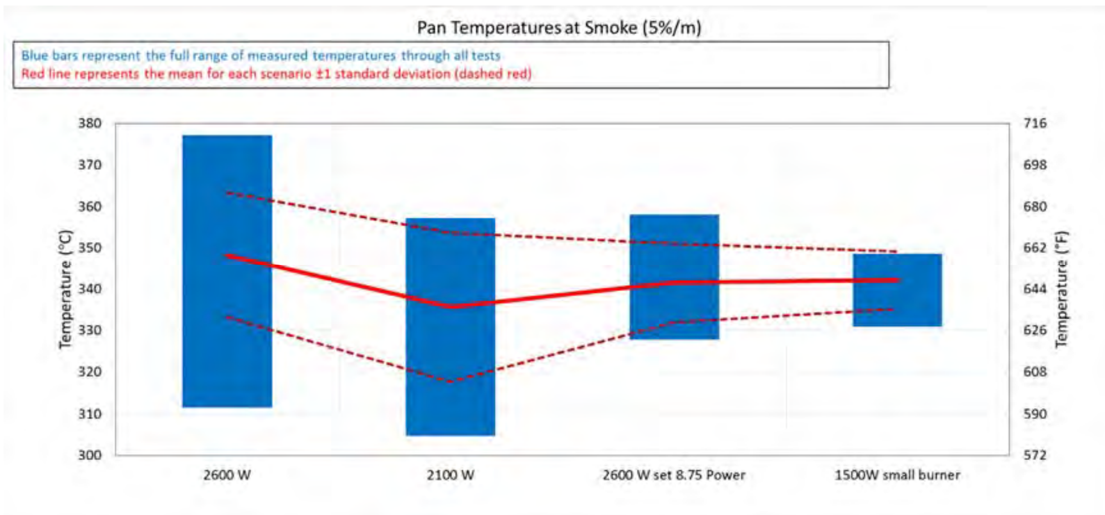


Figure 65 – Average pan temperature at 1.6%/ft (5%/m) smoke measurement for element power outputs

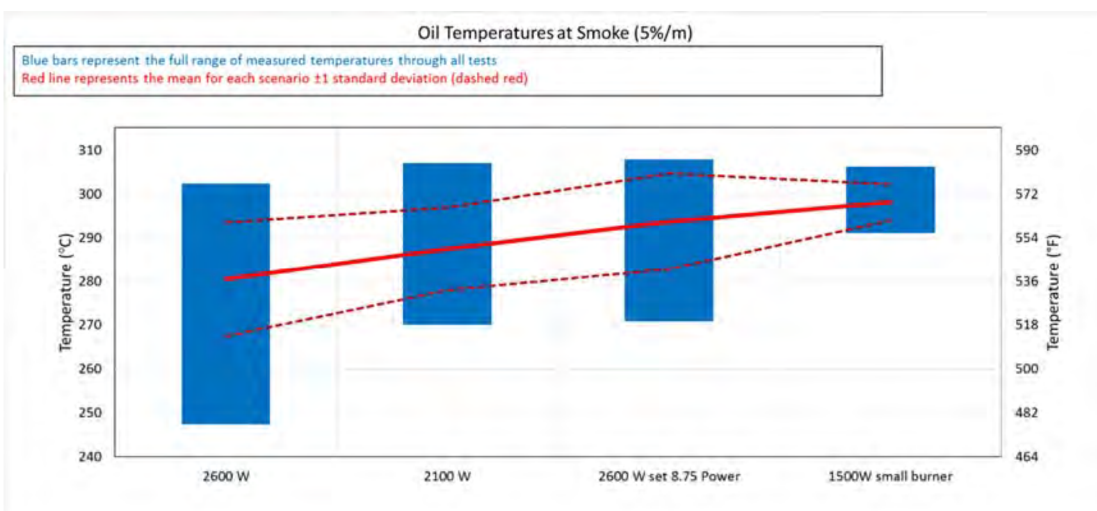


Figure 66 – Average oil temperature at 1.6%/ft (5%/m) smoke measurement for element power outputs

The increase in oil temperatures without a corresponding increase in the pan temperatures at smoke can also be observed when the pan temperature reached 300°C (572°F). The measured oil temperatures increased with longer tests/lower power given a fixed pan temperature measurement. The oil temperatures at this pan temperature are shown in Figure 67.

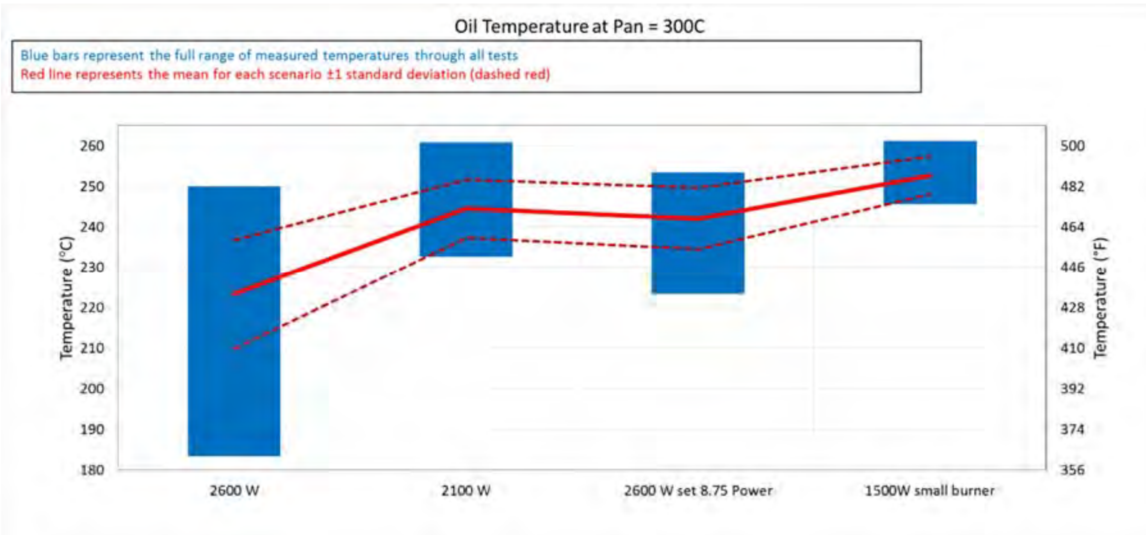


Figure 67 – Average oil temperature when pan = 300°C (572°F) for various element power outputs

The calculated correlations between the total heating time to ignition and the pan and oil temperatures at smoke measurement, and the oil temperatures at 300°C (572°F) pan measurement are shown in Figure 68. As shown, there is little to no correlation in the pan temperature at smoke, but the measured oil temperatures at the smoke and pan thresholds were observed to increase with the duration of the tests.

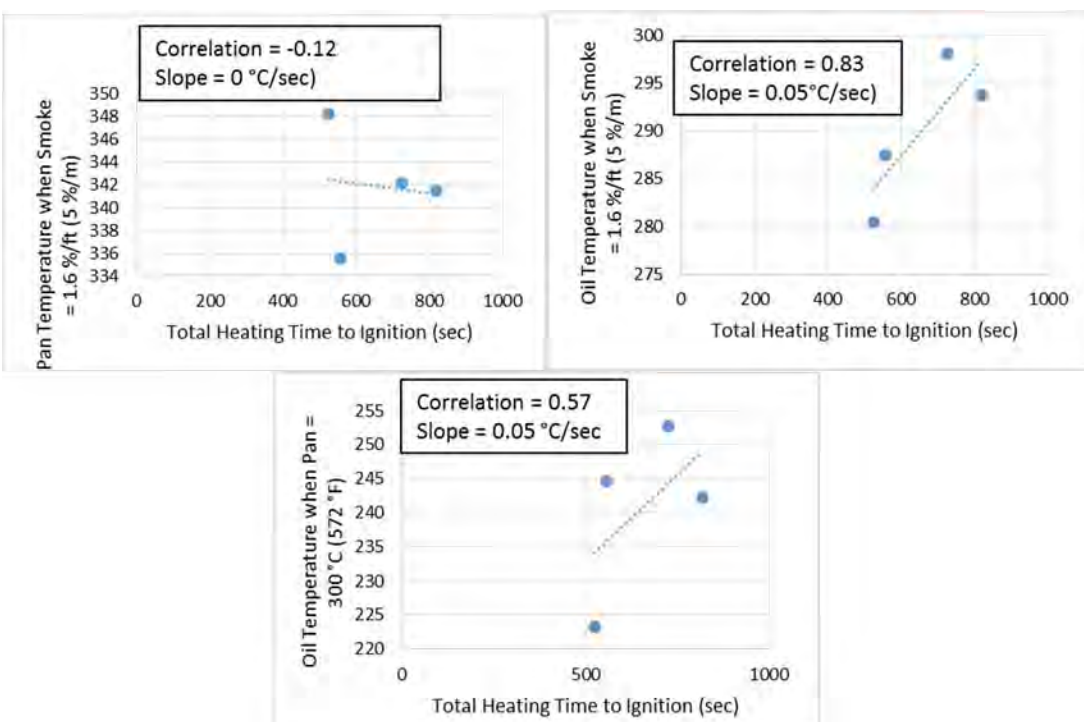


Figure 68 – Correlations and slopes for total heating time and pan and oil temperatures at smoke production and oil temperatures at fixed pan temperature

The pan and oil temperatures at the time of ignition are shown in Figures 69 and 70, respectively. The pan temperatures were observed to decrease slightly with decreasing range power output, and therefore with increasing total time to ignition. No visible trend was observed for the oil temperatures, however. This is the opposite effect observed for the pan and oil temperatures at the time of smoke production.

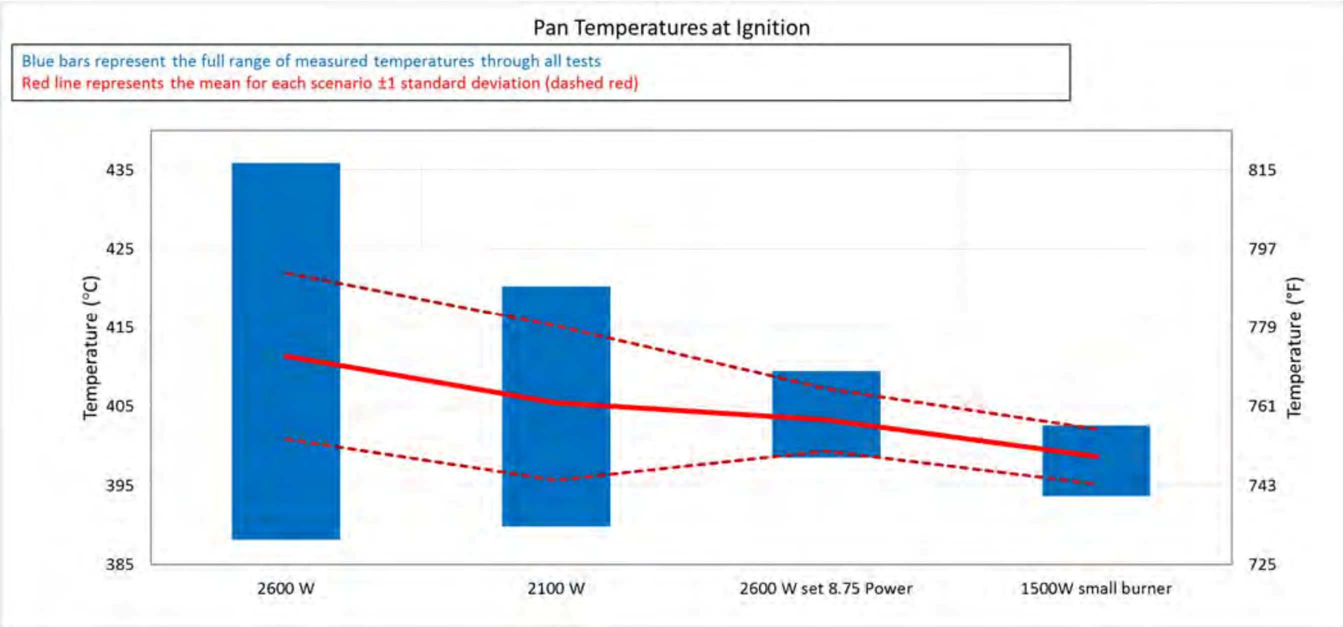


Figure 69 – Average pan temperature at ignition for various element power outputs

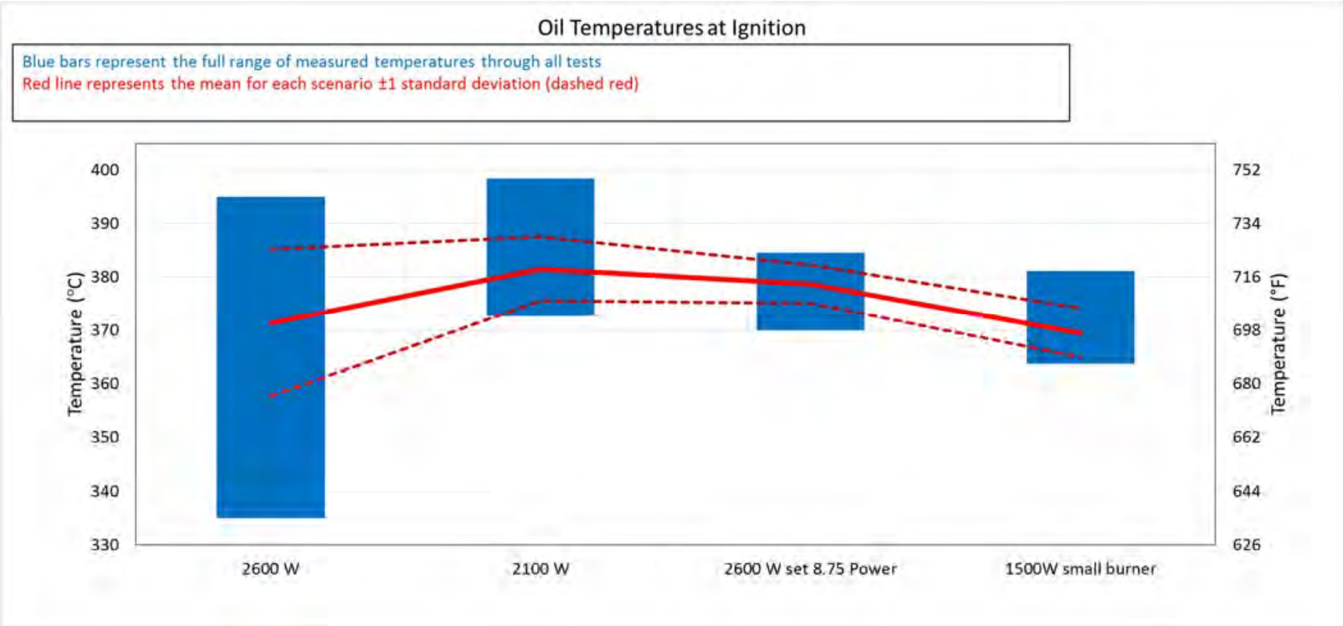


Figure 70 – Average oil temperature at ignition for various element power outputs

The calculated correlations between the pan and oil temperatures at ignition and the total heating time to ignition are shown in Figure 71. A strong negative correlation was observed in the pan temperature with a small slope of -0.03°C/sec, and almost no relationship was observed for the oil temperatures at ignition.

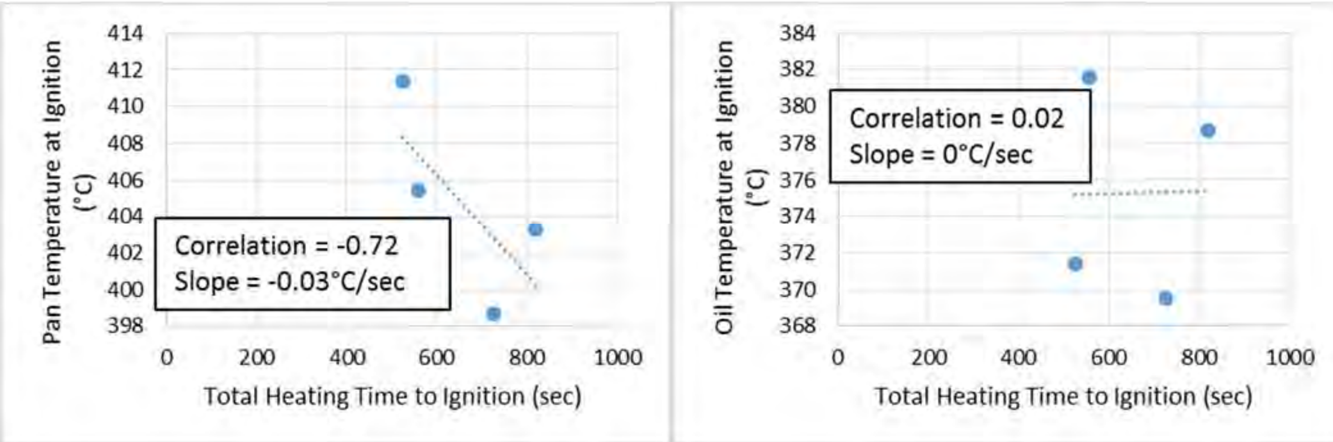


Figure 71 – Correlations and slopes for total heating time and pan and oil temperatures at ignition for various element powers

6.7.2. Range Type (Phase 2)

Fire tests were conducted in Phase 2 for an electric coil range with a 2600 W element and for a glass ceramic top range with 3000 W element. All Phase 2 range evaluation tests were conducted in a 10 in. (25 cm) diameter, aluminum, stainless steel, and cast iron frying pans. A total of 18.3 in.^{3} (300 mL) of oil was used for each test, resulting in an initial oil depth of ¼ in. (6.4 mm).

6.7.2.1. Available Response Times

The total heating time to ignition for each pan tested on the coil range and the glass ceramic range is shown in Figure 72. For the glass ceramic range, the aluminum pan had an increased total ignition time compared to the coil range, while the stainless steel and cast iron pans both heated faster on the glass ceramic range top.

Figure 72 – Heating times until ignition for coil and glass ceramic (smooth) top ranges

The aluminum pan heated much more slowly because the glass break sensor in the range began to cycle the power on and off, reducing the total power input. This effect is described in more detail in Section 6.7.2.2. With the power cycling on and off, the average power output during the aluminum pan tests on the glass ceramic top range dropped from 3000 W to approximately 2000 W. When making this adjustment for the range output, the total heating time to ignition and the range power correlate to -0.89 at a slope of -0.7 sec/W of power as shown in Figure 73.

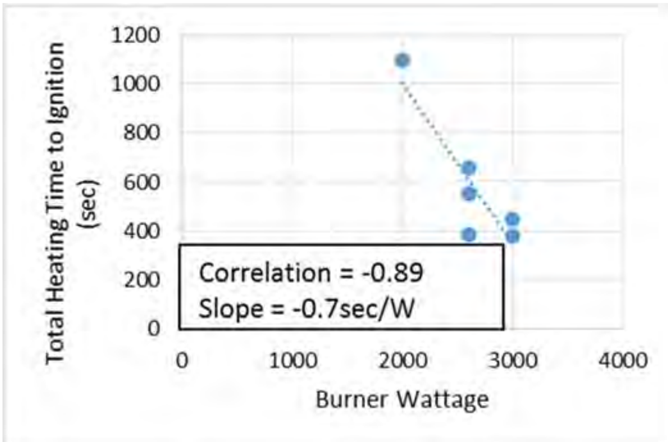


Figure 73 – Correlation and slope between range input power and total heating time to ignition for coil and glass ceramic (smooth) top tests

The time windows between the pan temperature and smoke thresholds and ignition scaled proportionally to the total heating times for each test (see Figure 74). Both correlate nearly exactly with the total heating time, with the pan temperature window slightly longer than the smoke window.

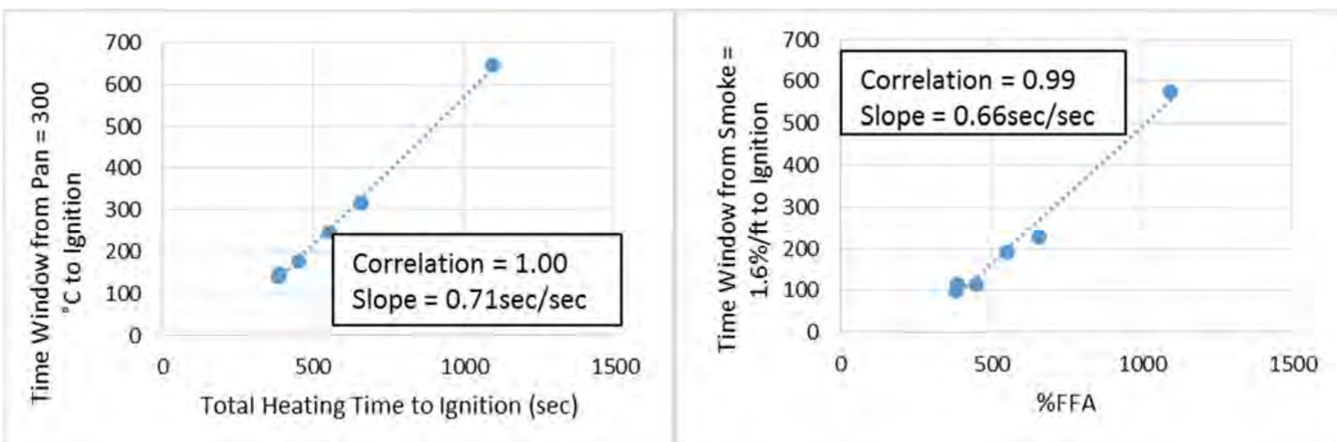


Figure 74 – Correlation and slope between total heating time to ignition and pan temperature and smoke windows to ignition for coil and glass ceramic top tests

6.7.2.2. Temporal Heating Curves

There was a wide range in total heating time to ignition for the coil and glass ceramic top tests. The pan and oil temperatures and smoke obscuration of the longest (aluminum on glass ceramic top) and shortest (stainless steel on glass ceramic top) tests are shown in Figure 75.

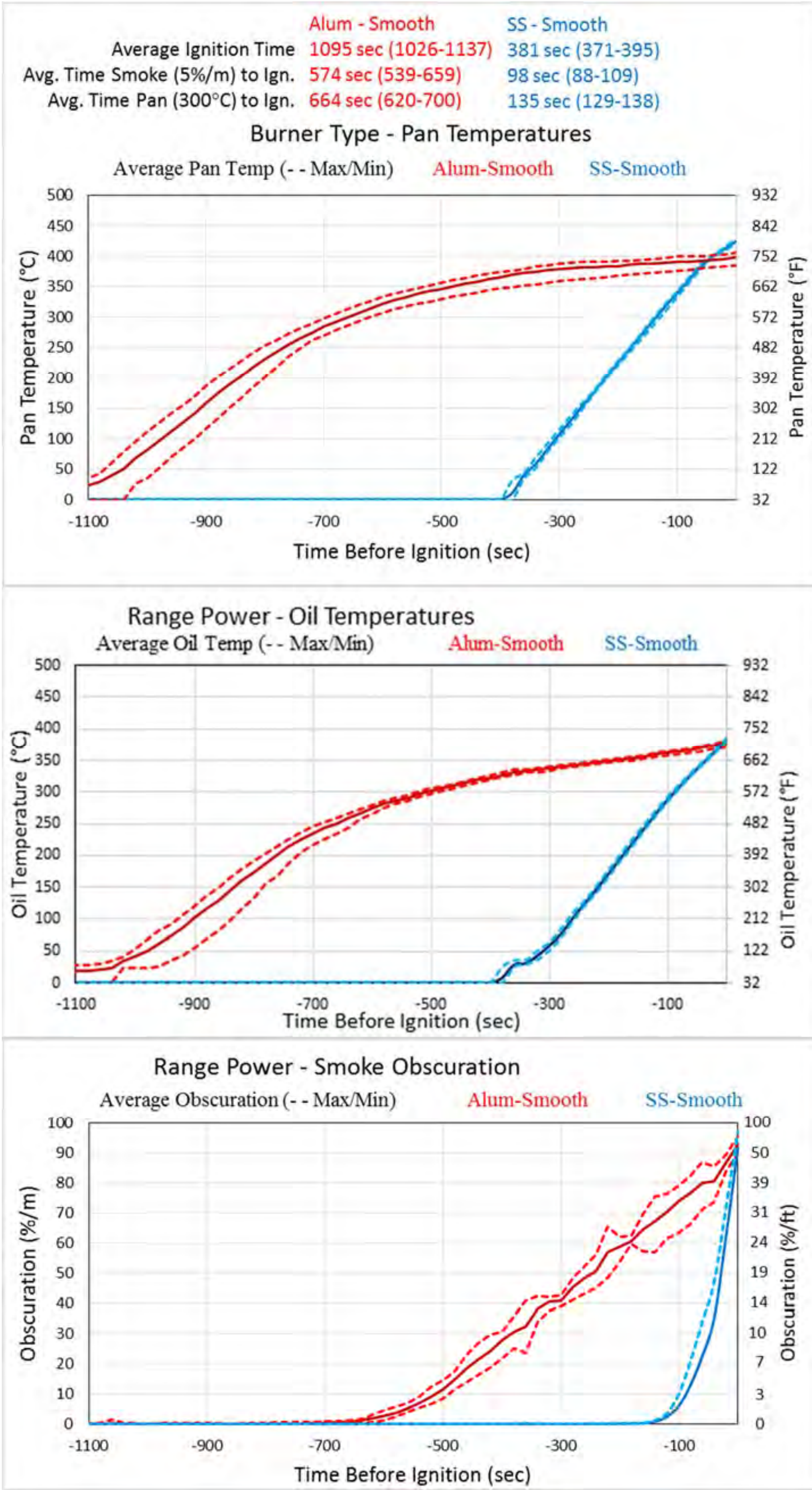


Figure 75– Pan and oil temperatures and smoke obscuration curves for fastest and slowest range types aligned by ignition time

A sensor in the glass ceramic top glass began to cycle the element power on and off during the aluminum pan tests. When the element power began cycling, the average power was reduced to 1750 W, resulting in a test average power of 2010 W. The stainless steel pan reached ignition after one to two power cycles, and the cast iron pan reached ignition before activation of the sensor. As a result, the times to ignition for the stainless and cast iron pans were reduced compared to the electric coil, while the time to ignition was greatly increased for the aluminum pan. The pan and oil temperatures from one of the aluminum pan on glass ceramic top range tests and the range power values are shown in Figure 76.

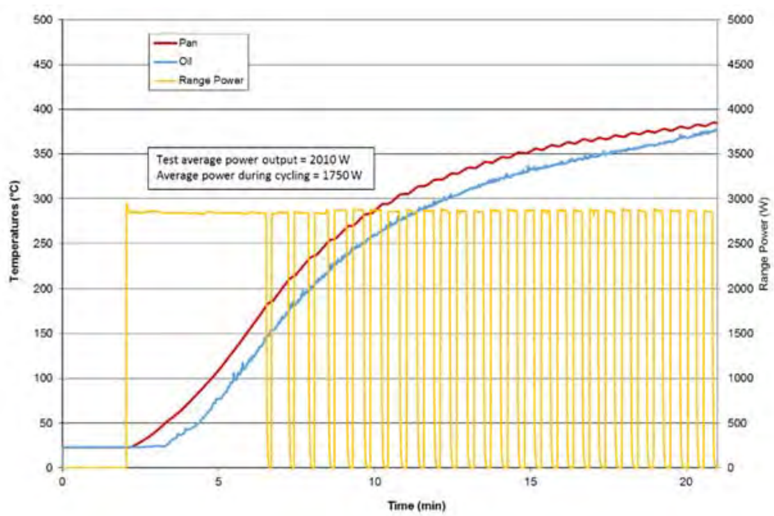


Figure 76 – Pan and oil temperatures and range power during an aluminum pan on glass ceramic range test

During testing, it was believed that the significant increase in aluminum heating time could have been a result of damage to the pan caused by repeated testing. A test on the glass ceramic top range was conducted using a brand new pan. This pan had slightly less curvature than the used pan (56.4 in. (143 cm) compared to 50.8 in. (129 cm) for the used pan) and slightly less tilt angle (0.36° v. 0.91° for the used pan). The heating time to reach ignition and the heating rates were nearly identical (1108 seconds for the new pan v. 1026,1137, and 1109 seconds for the three used pan tests), and this test is included in the temporal curves shown in Figure 75. The significant increase in heating time was not related to the aluminum pan flatness or tilt, and the new pan responded the same as a used pan.

The calculated slopes in the pan and oil temperature curves, differences between the pan (center of pan) and oil (center of oil) temperatures at ignition, and the integrated smoke obscuration at fixed pan temperatures are shown in Table 13. The metrics indicative of the greatest challenges for detection devices are highlighted. The slopes of the pan and oil temperatures are reduced for the longer tests, as evidenced by the glass ceramic top aluminum pan tests. These tests also had significantly more integrated smoke obscuration than the faster tests conducted.

A very small difference (2–12°C (4–22°F)) was measured between the pan and oil temperatures in the cast iron pan on the electric coil range. This difference is attributed to reduced pan temperatures measured in the center of the pan resulting from the convex shape of the pan as discussed in Section 6.6.2. This effect was not observed for the glass ceramic top range tests with the same pan, however. This may be a result of more even heating from radiant exposure than for conductive contact.

Table 13 – Calculated pan and oil temperature slopes and obscuration slope and integrated areas for various coil and glass ceramic element tests

Oil	Average pan temp slope between fixed pan temperatures and ignition (°C/min)				Average oil temp slope between fixed pan temperatures and ignition (°C/min)				Difference between pan and oil temperature at fixed pan temps (°C)					Integral of smoke obscuration up to fixed pan temperatures (%/m – min)				
	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	IGN	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	IGN
Alum - Coil	23	19	15	11	26	23	21	21	33	32	34	36	13	0	0	4	27	162
Alum - Smooth	11	9	6	4	13	11	8	8	46	46	41	40	22	0	0	29	119	433
SS - Coil	55	52	46	41	55	52	49	38	25	24	28	22	23	0	2	9	30	89
SS - Smooth	59	55	49	45	61	52	49	50	47	34	41	47	42	0	1	6	11	63
CI - Coil	31	27	23	21	33	29	28	26	9	9	12	7	2	1	3	27	69	138
CI - Smooth	47	43	37	33	49	48	47	43	39	46	51	45	31	0	0	0	8	73

6.7.2.3. Smoke Production and Ignition Temperatures

The pan and oil temperatures at the time smoke obscuration measured 1.6%/ft (5%/m) are shown in Figures 77 and 78 respectively. In addition to the full range, average, and standard deviation for each test scenario, the average and standard deviation among all electric coil tests and all glass ceramic tests are shown for relative comparison. The pan temperatures were observed to decrease with the increasing ignition time for the aluminum, stainless steel, and cast iron pans. The aluminum pans took longer to ignite on the glass ceramic top range (decreasing pan temperature) while the cast iron and stainless steel pans ignited faster (increasing pan temperatures).

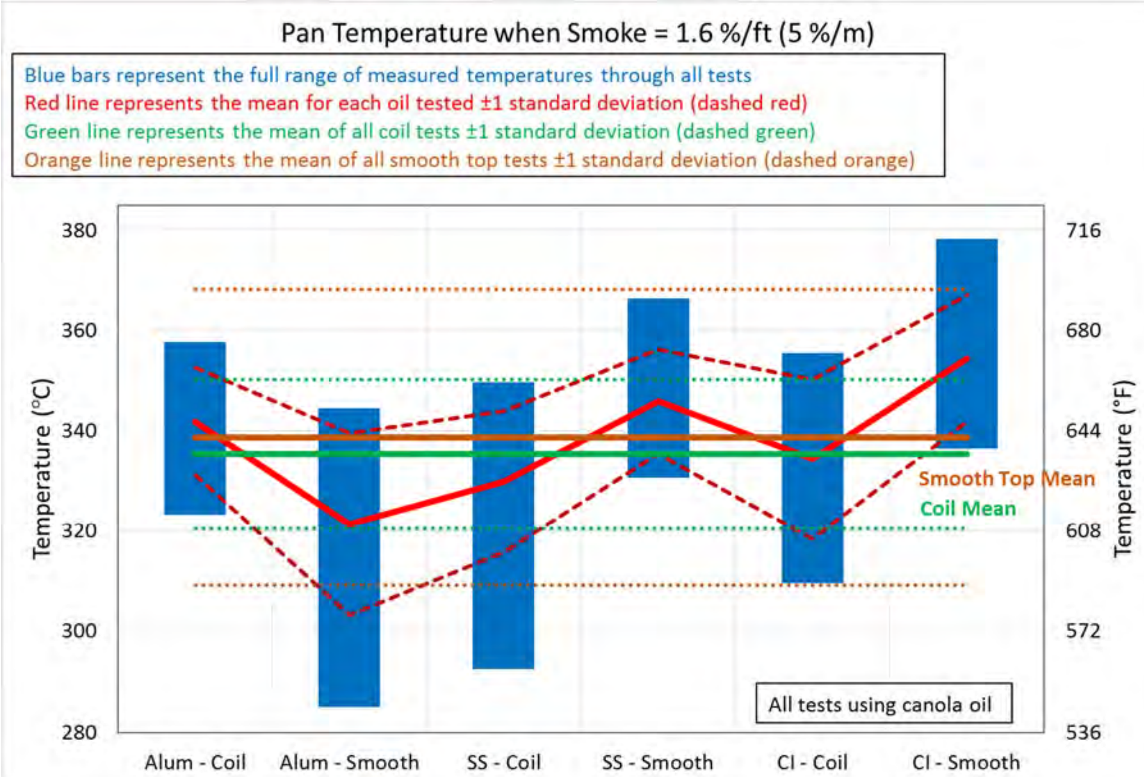


Figure 77 – Average pan temperature at 1.6%/ft (5%/m) smoke measurement for electric coil and glass ceramic (smooth) top ranges

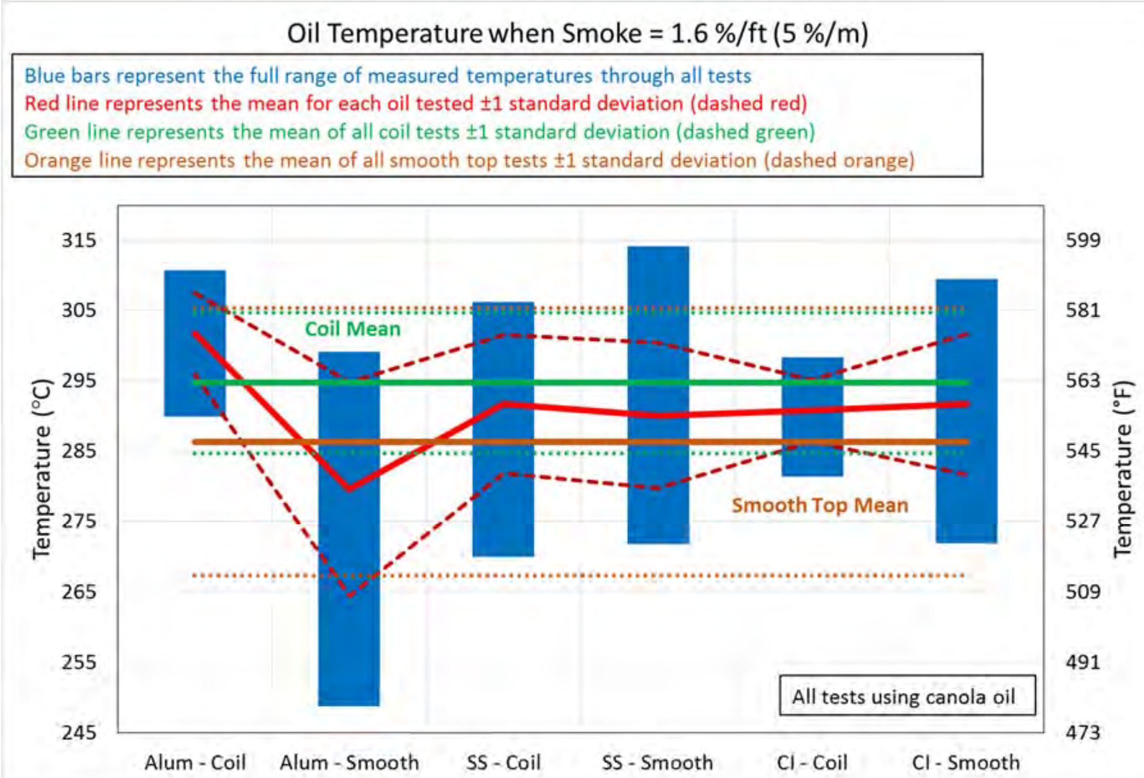


Figure 78 – Average oil temperature at 1.6%/ft (5%/m) smoke measurement for electric coil and glass ceramic (smooth) top ranges

The measured temperature of the oil at smoke production also decreased for the longer aluminum pan, glass ceramic top range tests. For the stainless steel and cast iron pans on glass ceramic top ranges, there was an increase in measured pan temperatures (for faster tests) without a corresponding increase in the oil temperatures at smoke production. This would imply that the increased element power causes more heat transfer from the pan to the oil, resulting in a greater temperature gradient. The physical properties of the oil are not changed, and so the production of smoke stills occurs at the same oil temperature. Conversely, the extremely slow heating rate of the aluminum pan on the glass ceramic top range may actually result in a breakdown of the oil, causing reduced oil smoke temperatures as was observed for aged and used oils analyzed in Section 6.4.

The increased temperature gradient at high heating rates can be observed from the reduced oil temperatures measured at a fixed pan temperature value of 300°C (572°F) (see Figure 79). The slower heating electric coil tests conducted with the stainless steel and cast iron pans resulted in increased measured oil temperatures with respect to fixed pan temperatures. A device measuring a fixed pan temperature would therefore allow higher oil temperatures to occur for reduced heating rates, which may be a more challenging condition for fire prevention.

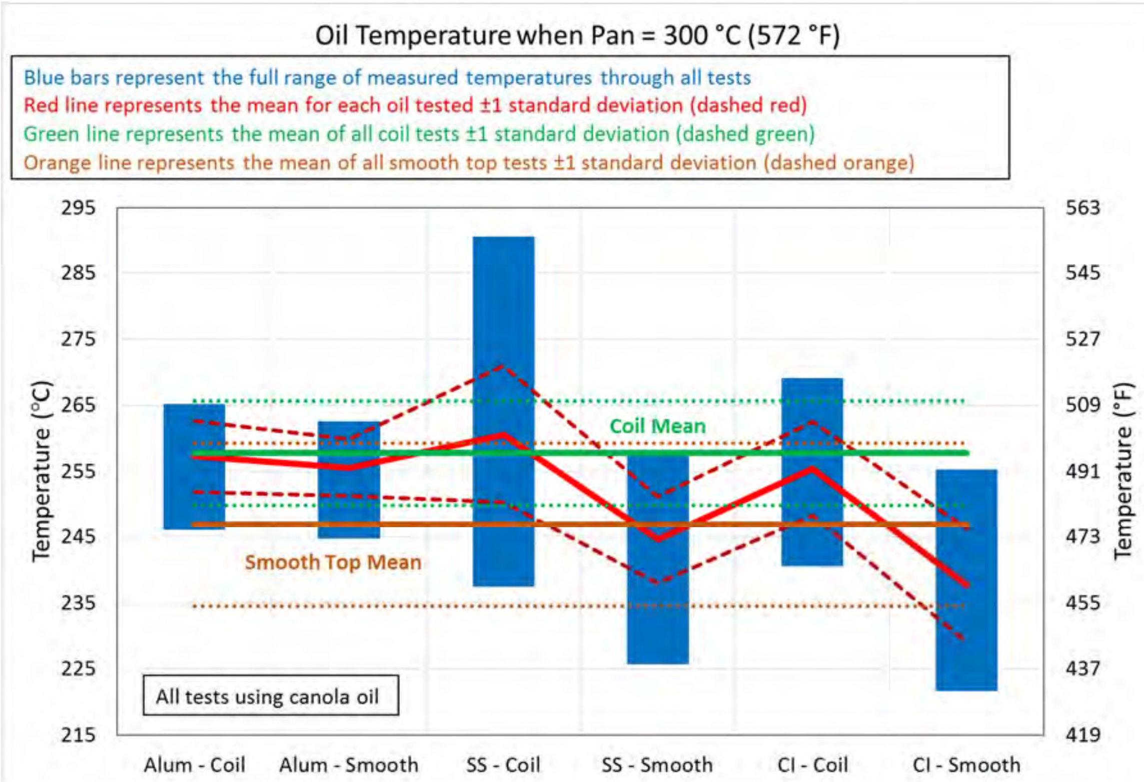


Figure 79 – Average oil temperature when pan = 300°C (572°F) for electric coil and glass ceramic (smooth) top ranges

The calculated correlations between the total heating time to ignition and the pan and oil temperatures at smoke measurement, and the oil temperatures at 300°C (572°F) pan measurement are shown in Figure 80. While the calculated correlations do show the relationships discussed above, the magnitude of the changing temperatures with respect to ignition time are extremely small (0.01 to 0.03°C change per second of heating time).

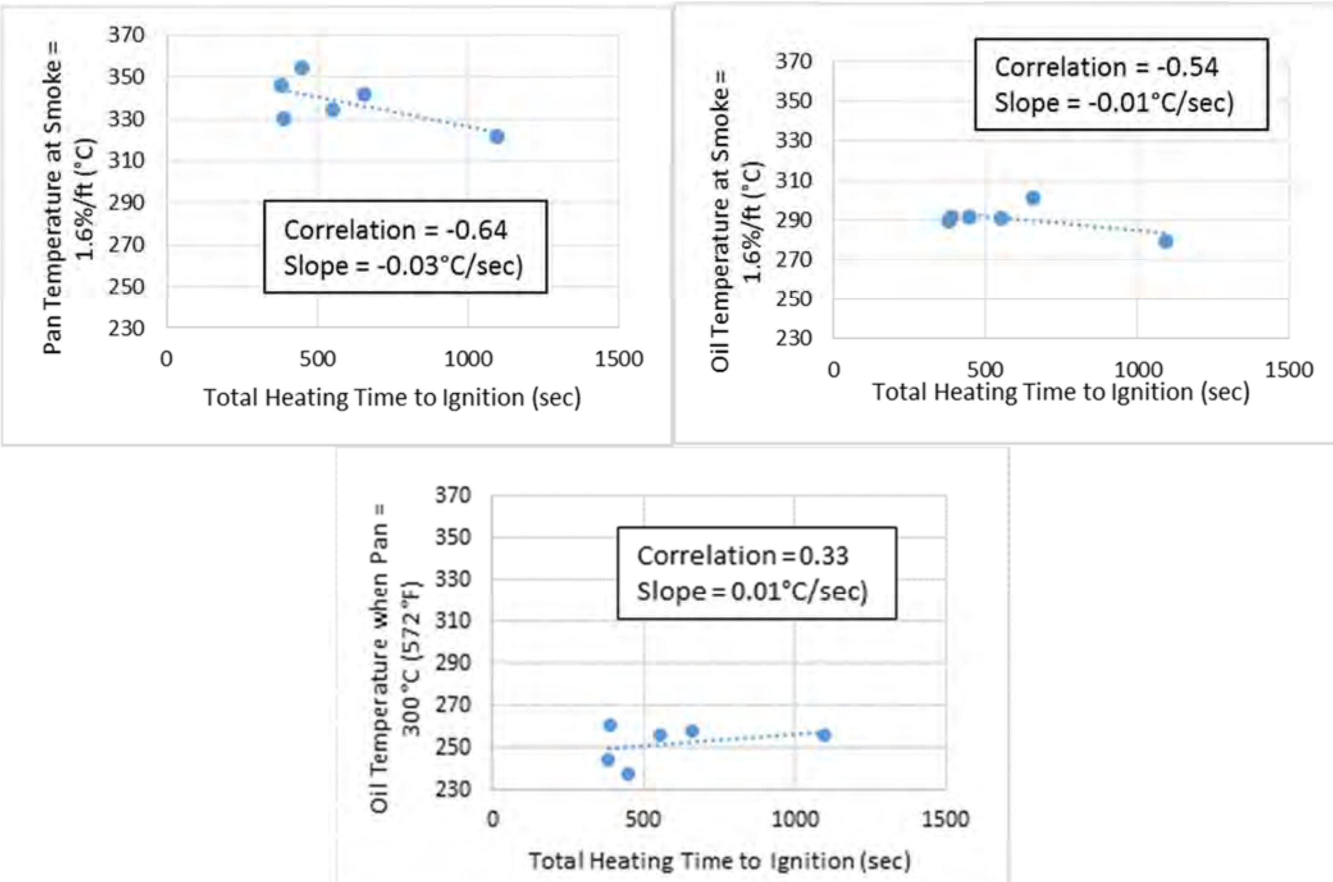


Figure 80 – Correlations and slopes for total heating time and pan and oil temperatures at smoke production and oil temperatures at fixed pan temperature

The pan and oil temperatures at the time of ignition are shown in Figures 81 and 82, respectively. The pan temperatures were observed to decrease slightly with increasing total time to ignition. This is demonstrated by the decrease in pan temperature for the aluminum pan from coil to glass ceramic top range (slower test), and the increase in pan temperature for the stainless steel and cast iron pans from coil to glass ceramic top range (faster tests).

The oil temperatures measured at ignition decreased for all three pan types on the glass ceramic top range compared to the coil. It is possible that the reduced overall pan temperatures at ignition for the slow aluminum pan on glass ceramic top also resulted in lower oil temperatures at ignition, while the increased heat transfer rates for the fast stainless steel and cast iron on glass ceramic top tests resulted in greater gradients and therefore reduced oil temperatures. The observed effects may also have been the result of random test variation, as the changes in average oil temperature were within one standard deviation for the stainless steel and cast iron pans. The change in the oil temperature for the aluminum pan is greater than one deviation in magnitude, and is likely related to the increased total heating time to reach ignition.

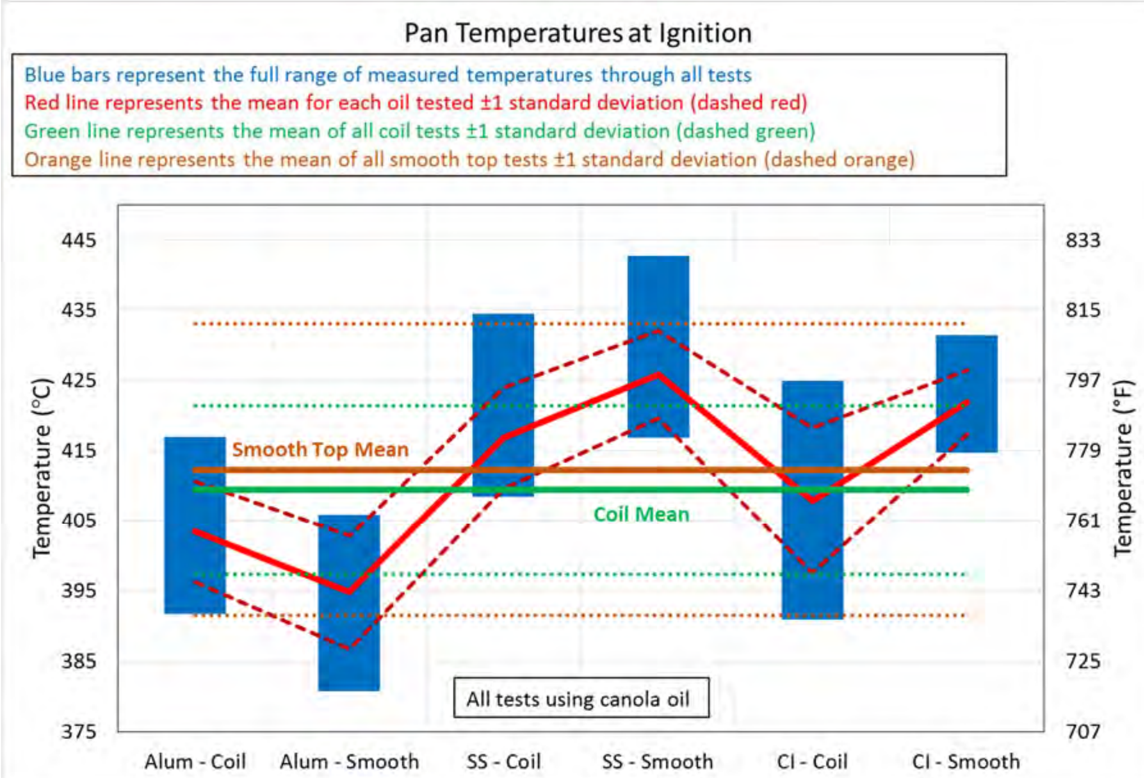


Figure 81 – Average pan temperature at ignition for various element power outputs

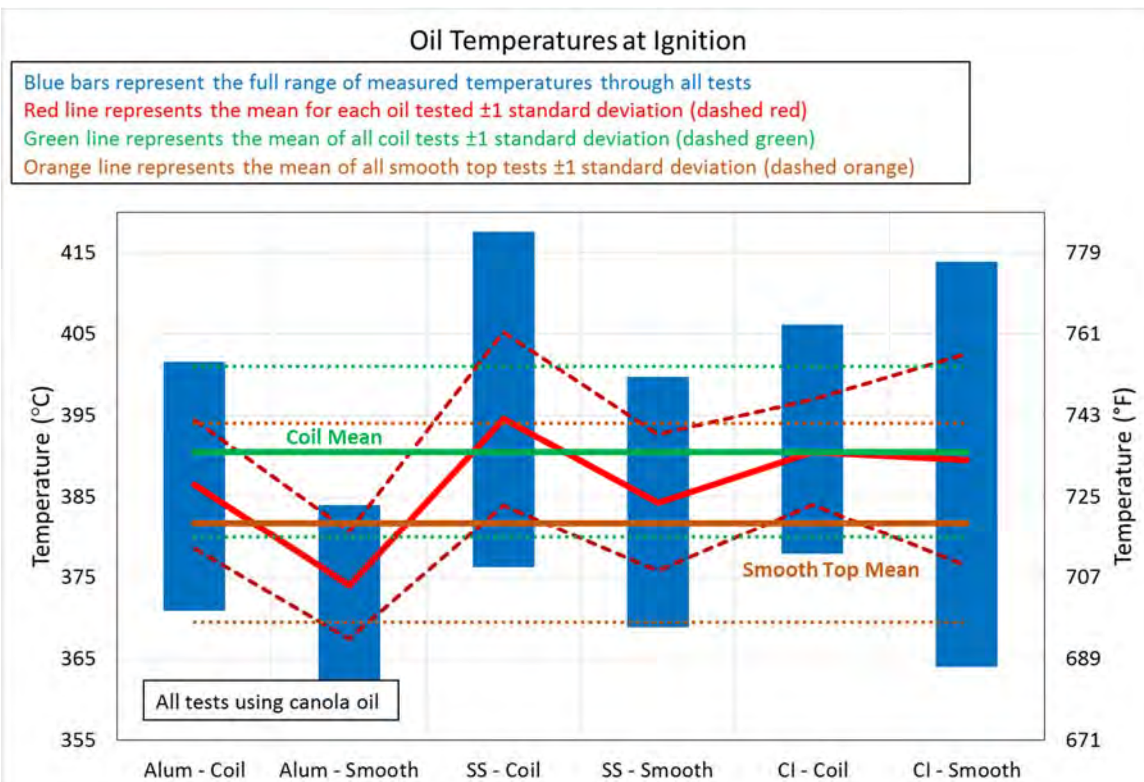


Figure 82 – Average oil temperature at ignition for various element power outputs

The calculated correlations between the pan and oil temperatures at ignition and the total heating time to ignition are shown in Figure 83. Strong negative correlations were observed in both the pan and oil temperatures at ignition relatively small slopes of -0.04°C/sec and 0.02°C/sec, respectively.

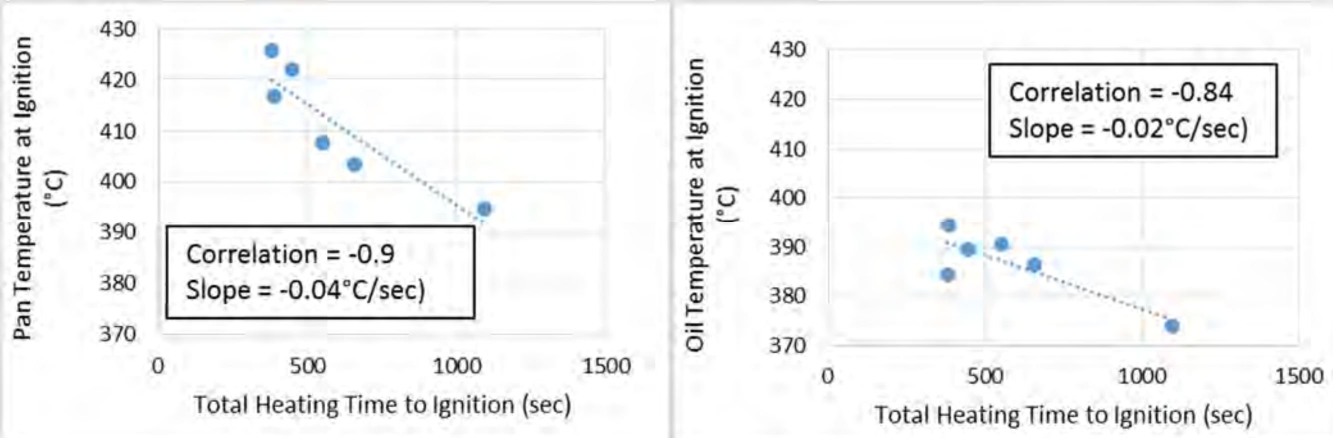


Figure 83 – Correlations and slopes for total heating time and pan and oil temperatures at ignition for various element powers

6.8. Oil Depth

A series of tests were conducted in Phase 2 to evaluate the impacts of increasing the depth of oil. Tests were conducted with ¼ in. (6.4 mm) and ½ in. (12.8 mm) depths of canola oil in 10 in. (25 cm) aluminum and stainless steel pans on the 2600 W electric coil element. The primary observations from testing deeper oils include:

- The additional mass of oil slows the heating process and the tests take longer to reach ignition
- Most metrics correlate well with the total heating time to ignition
    - Total heating time to ignition correlates well with the combined pan and oil heat capacities (minimum possible heating time, see Eq. (2) in Section 5.4.6)
    - Time window for smoke or pan temperature activation
    - Pan and oil temperatures at smoke production and ignition reduced with increased heating time
    - Difference between pan and oil temperature increased with longer heating times
- The temperature of the oil is nearly uniform as a function of oil depth

All oil depth tests included in this analysis use the 10 in. (25 cm) Vollrath aluminum pan or the Tramontina (low end) stainless steel pan. Tests were conducted at only two oil depths. The tests included in the oil depth analysis are listed in Table 14.

Table 14 – Tests included in oil depth analysis

Identifier	Oil Type	Description	Test ID
Alum – 1/4	Great Value Canola Oil	Vollrath aluminum pan with ¼ in (6.4 mm) canola oil on 2600 W coil	P2-4
	Great Value Canola Oil		P2-5
	Great Value Canola Oil		P2-6
SS – 1/4	Great Value Canola Oil	Tramontina stainless steel pan with ¼ in (6.4 mm) canola oil on 2600 W coil	P2-16
	Wesson Canola Oil		P2-17
	Crisco Canola Oil		P2-18
Alum – 1/2	Crisco Canola Oil	Vollrath aluminum pan with ½ in (12.8 mm) canola oil on 2600 W coil	P2-37
	Great Value Canola Oil		P2-38
	Wesson Canola Oil		P2-39
SS – 1/2	Great Value Canola Oil	Tramontina stainless steel pan with ½ in (12.8 mm) canola oil on 2600 W coil	P2-40
	Wesson Canola Oil		P2-41
	Wesson Canola Oil		P2-42

6.8.1. Available Response Times

The total heating time to reach ignition was increased by increasing the depth of oil tested. The average times to ignition for the four test scenarios are shown in Figure 84. The average time to ignition for the ¼ in. (6.4 mm) depth tests was 522, which increased to 776 seconds for the ½ in. (12.8 mm) oil depths.

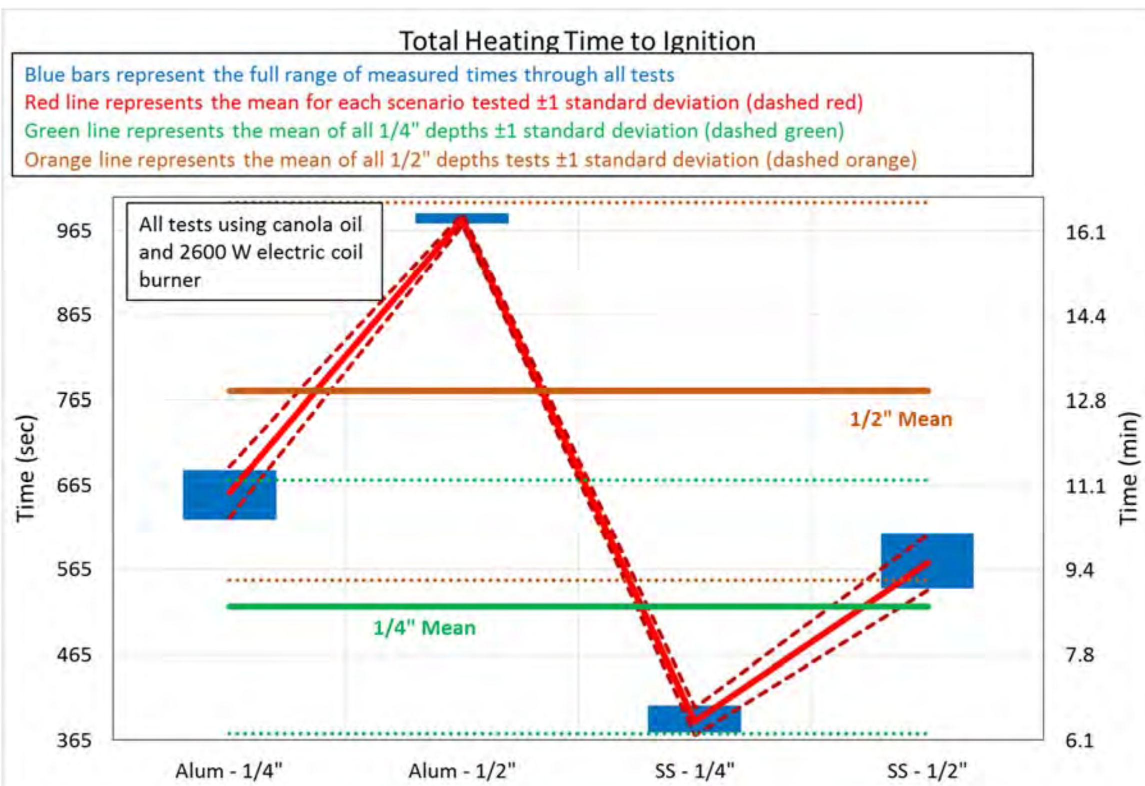


Figure 84 – Heating times until ignition for multiple oil depths

The heating time to ignition has been related to both the depth of the oil and the minimum possible heating time as shown in Figure 85. Increases in heating times were observed for increasing oil depth for the aluminum (1284 sec/in.) and the stainless steel (743 sec/in.). The minimum possible heating time is a calculated estimate of the ignition time based on pan and oil material properties and element power (see Eq. (2) in Section 5.4.6). This calculation accounts for the differences between the aluminum and stainless steel pans, allowing for calculation of a correlation to total heating time to ignition. Correcting for the pan material properties, the measured heating time correlates to 0.96 with the calculated minimum heating time, with a slope of 4.6 seconds of heating per calculated minimum second.

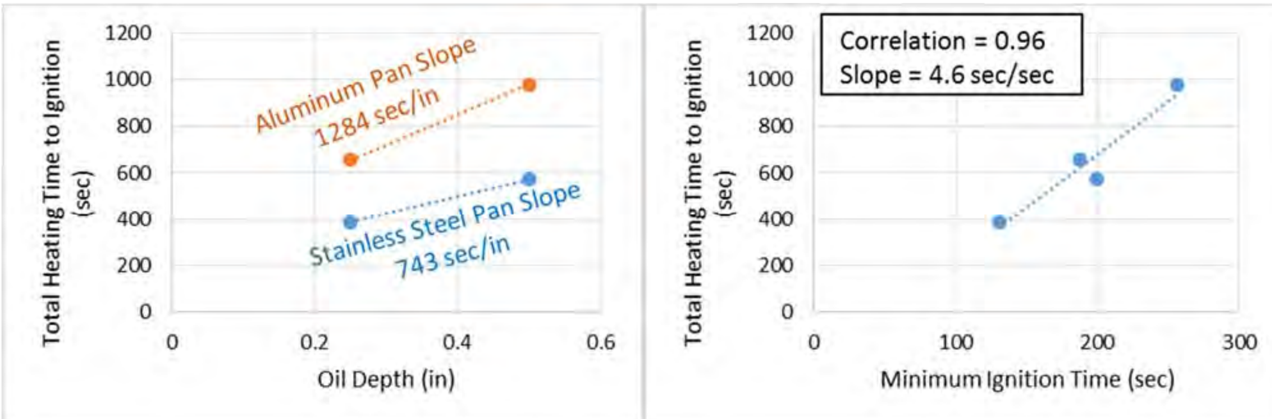


Figure 85 – Correlation between the total heating time to ignition and the oil depth (left plot) and calculated minimum heating time to ignition (right plot including both AL and SS pans)

The time windows available between a fixed pan temperature of 300°C (572°F) and ignition or smoke obscuration of 1.6%/ft (5%/m) and ignition scaled proportionally with the total time to ignition. The correlation and calculated slopes for these parameters are shown in Figure 86.

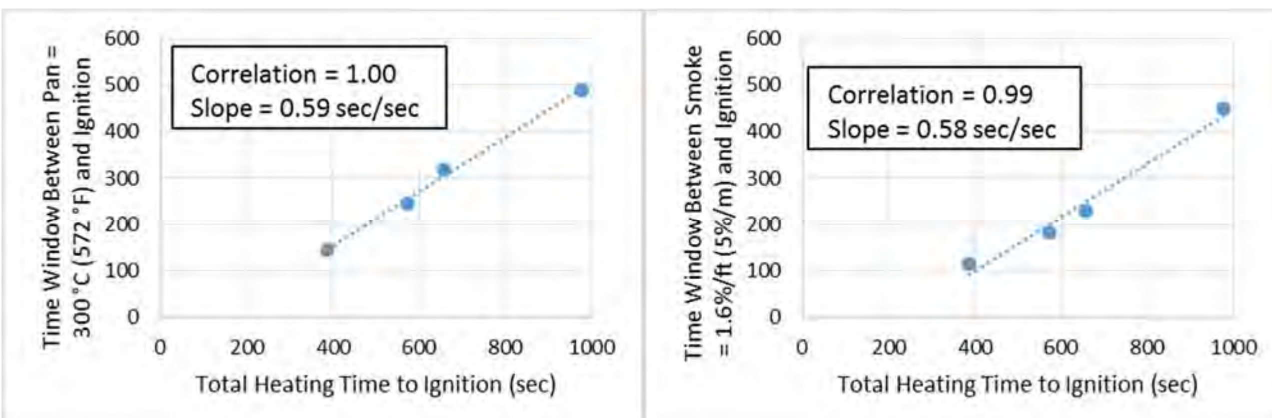


Figure 86 – Correlation between the total heating time to ignition and the pan and smoke time windows to ignition

Both time windows correlate nearly proportionally (0.99 and 1.00) and with comparable slopes of 0.59 and 0.58 seconds of window per second of total heating time. These available time windows are independent of the differences between the two pans tested.

6.8.2. Temporal Heating Curves

Temporal plots of the average pan and oil temperatures, and average smoke obscuration for the fastest (stainless steel with ¼ in. of oil) and slowest (aluminum with ½ in. of oil) of the oil depth tests are shown in Figure 87 aligned at the time of ignition (T = 0). The solid lines show the average for each material, and the dashed lines show the maximum and minimum values measured at the given time before ignition occurred.

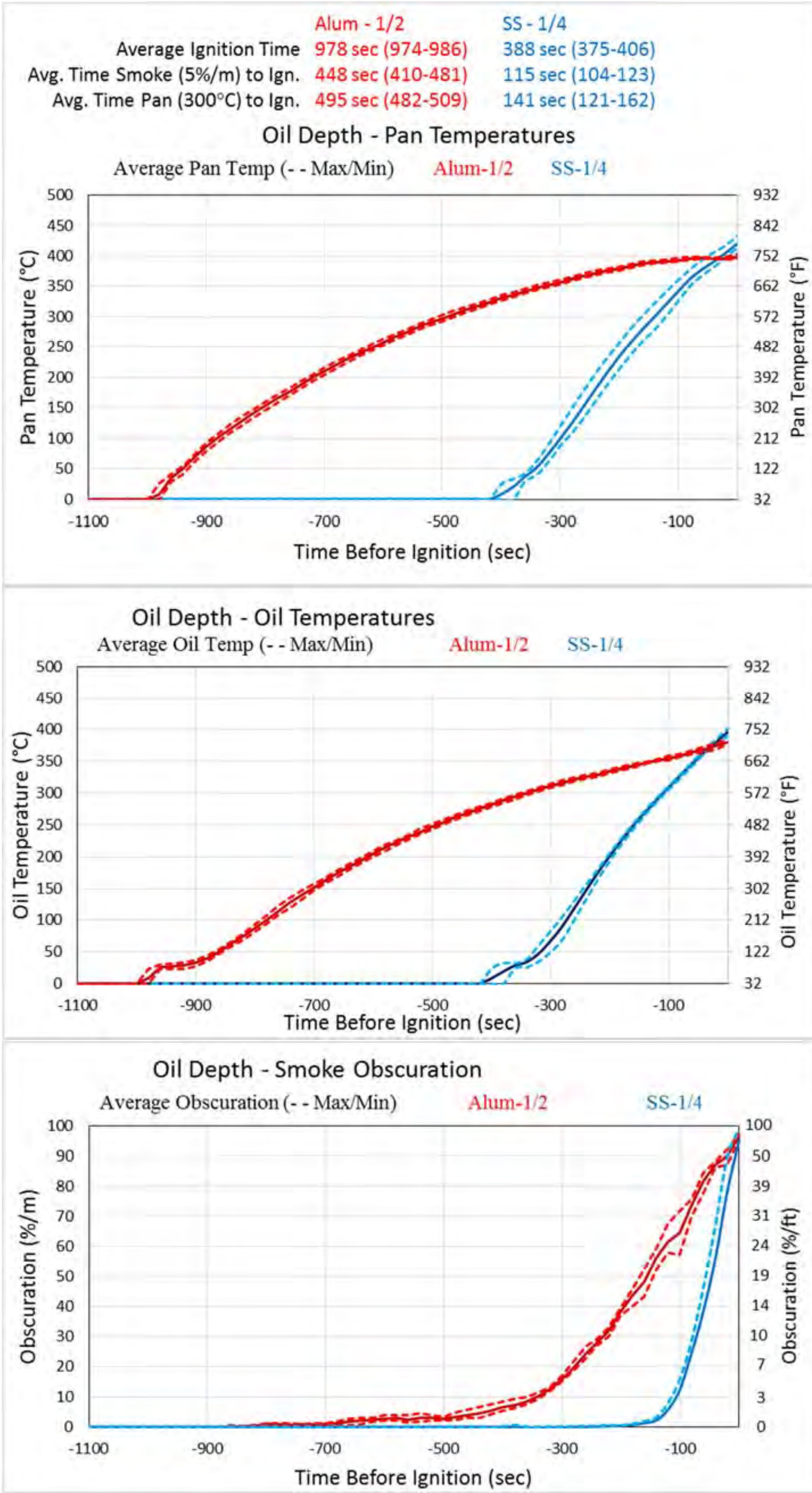


Figure 87 – Pan and oil temperatures and smoke obscuration curves for fastest and slowest oil depths aligned by ignition time

As shown in the temporal curves, there is a large disparity in ignition times between the aluminum pan with ½ in. (12.8 mm) of oil and the stainless steel pan with ¼ in. (6.4 mm) of oil. The longer test scenario has lower measured pan and oil temperatures at the time of ignition. This is a trend observed through several other evaluated variables, including pan materials and range power/type. In almost all cases tested, tests taking longer to reach ignition also measured lower temperatures at ignition.

The calculated slopes in the pan and oil temperature curves, differences between the pan (center of pan) and oil (center of oil) temperatures at ignition, and the integrated smoke obscuration at fixed pan temperatures are shown in Table 15. The most challenging test conditions are highlighted for each metric evaluated. The shallower oil provided greater challenges for the aluminum pan for all metrics considered. The shallower oil also provided greater challenges for the stainless steel pan for all metrics except the difference between the pan and oil temperatures, which were nearly the same for both oil depths, varying by less than 6°C.

Table 15 – Calculated pan and oil temperature slopes and obscuration slope and integrated areas for multiple pan depths

Oil	Average pan temp slope between fixed pan temperatures and ignition (°C/min)				Average oil temp slope between fixed pan temperatures and ignition (°C/min)				Difference between pan and oil temperature at fixed pan temps (°C)					Integral of smoke obscuration up to fixed pan temperatures (%/m – min)				
	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	IGN	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	IGN
Alum – 1/4	23	19	15	11	26	23	21	21	33	32	34	36	13	0	0	4	27	162
Alum – 1/2	14	12	9	6	17	15	14	13	50	46	44	44	18	3	9	28	69	241
SS – 1/4	55	52	46	41	55	52	49	38	25	24	28	22	23	0	2	9	30	89
SS – 1/2	31	28	26	23	33	30	28	27	28	25	22	22	17	1	3	23	58	133

6.8.3. Smoke Production and Ignition Temperatures

The pan and oil temperatures at the time smoke obscuration measured 1.6%/ft (5%/m) are shown in Figures 88 and 89, respectively. In addition to the full range, average, and standard deviation for each test scenario, the average and standard deviation among the ¼ in (6.4 mm) and ½ in (12.8 mm) depths for both pans are shown for relative comparison. The pan and oil temperatures were observed to decrease with an increase in oil depth for the aluminum pan (-29°C (52°F) pan, -38°C (68°F) oil). Comparable effects were not observed for the stainless steel pan, with the pan temperature increasing by 7°C (13°C) and the oil temperature decreasing by 3°C (5°F).

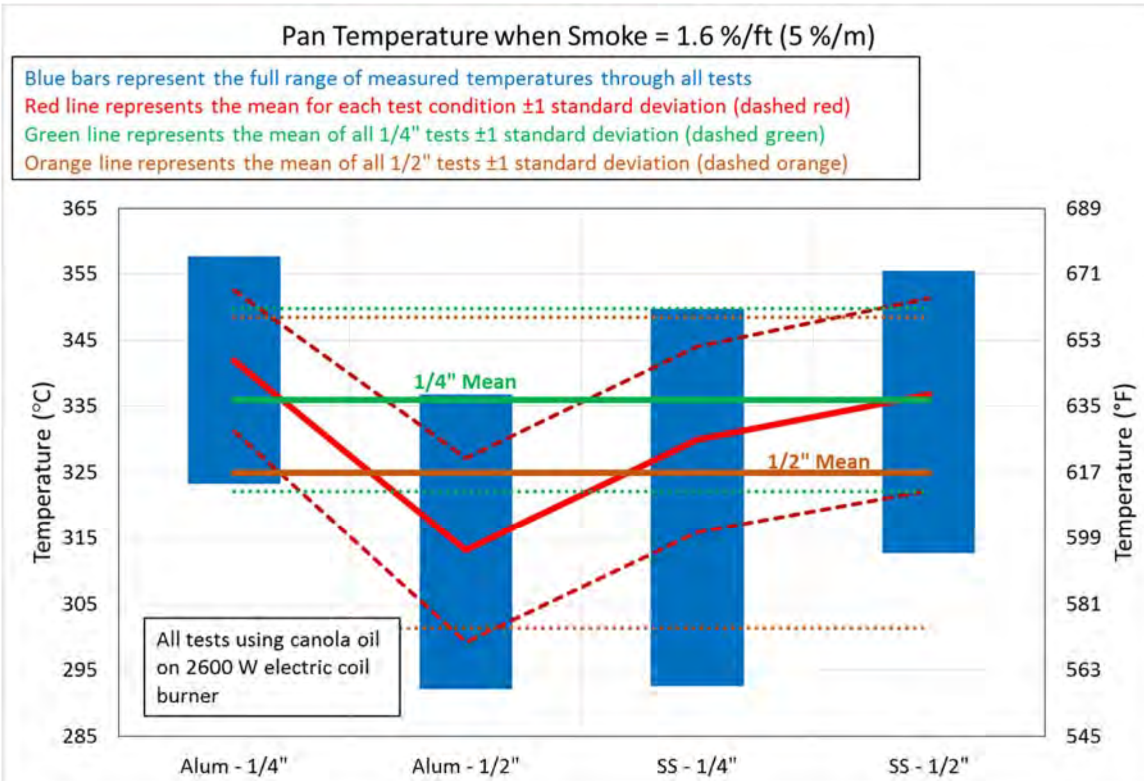


Figure 88 – Average pan temperature at 1.6%/ft (5%/m) smoke measurement for multiple oil depths

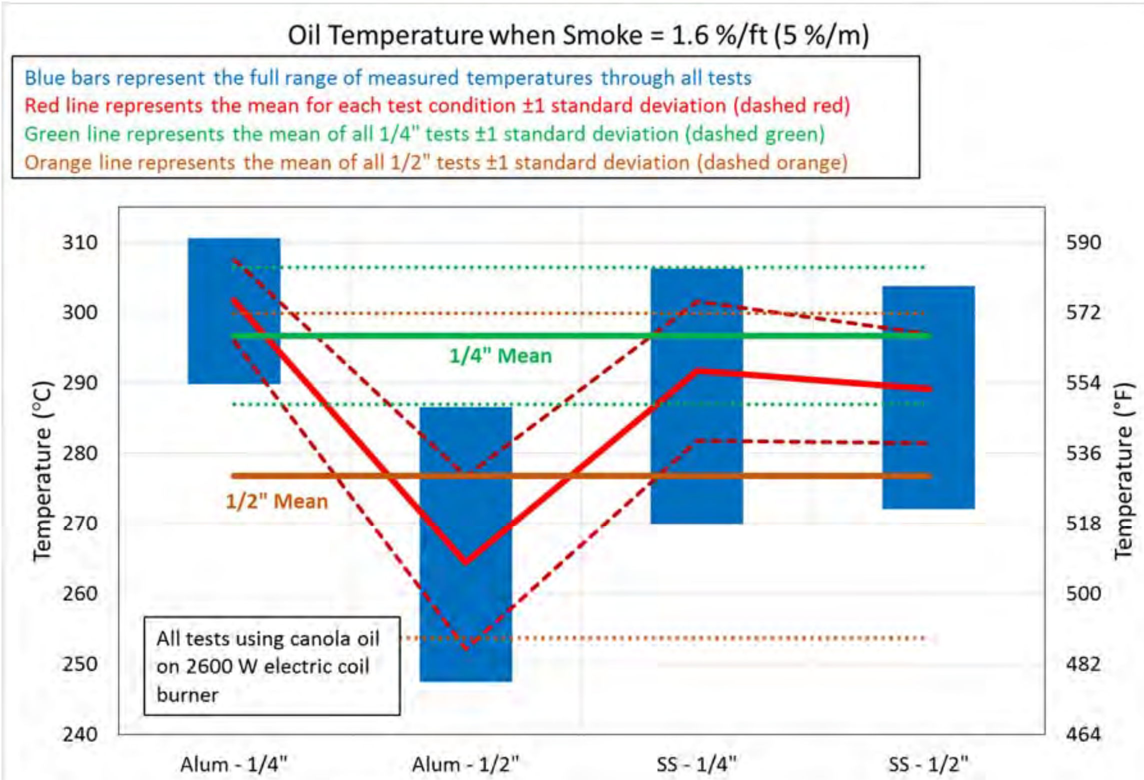


Figure 89 – Average oil temperature at 1.6 %/ft (5%/m) smoke measurement for multiple oil depths

The measured oil temperatures when the pan temperature reached 300°C (572°F) decreased for both pan types with an increase in the oil depth. The oil temperatures at this pan temperature are shown in Figure 90. The average oil temperature decreased for deeper oil by 7°C (13°F) and 11 °C (20°F) for the aluminum and stainless steel pans, respectively.

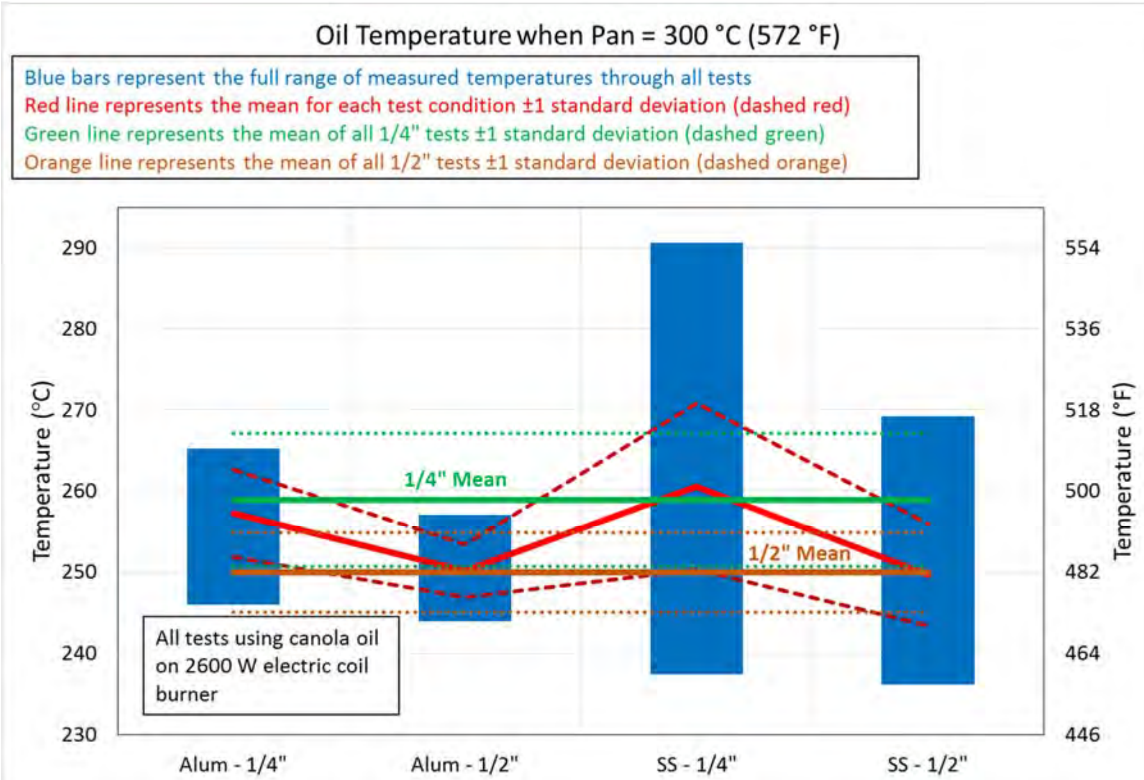


Figure 90 – Average oil temperature when pan = 300°C (572°F) for multiple oil depths

The calculated slope between the total heating time to ignition and the pan and oil temperatures at smoke measurement for each individual test, and the oil temperatures at 300°C (572°F) pan measurement are shown in Figure 91. The measured temperatures were all observed to decrease with increasing total time to ignition and oil depth except for the pan temperature at smoke for the stainless steel pans. The pan and oil temperatures at the time 1.6%/ft (5%/m) smoke was measured decreased in the aluminum pans by 5.4 and 6.9°C (9.7 and 12.4°F) per additional minute of heating time to ignition, respectively. The average oil temperature when the average pan temperature reached 300°C (572°F) also decreased with increasing total heating time to ignition. This effect was observed for both pan materials, with the average oil temperature decreasing by 1.3 and 3.5°C (2.3 and 6.3°F) per minute of heating time to ignition for the aluminum and stainless steel pans, respectively. This effect implies that the bulk oil temperature is greater at a given pan temperature threshold for tests conducted with less oil depth. A greater oil temperature at a fixed pan temperature would provide a greater challenge to devices using pan temperature sensing technologies.

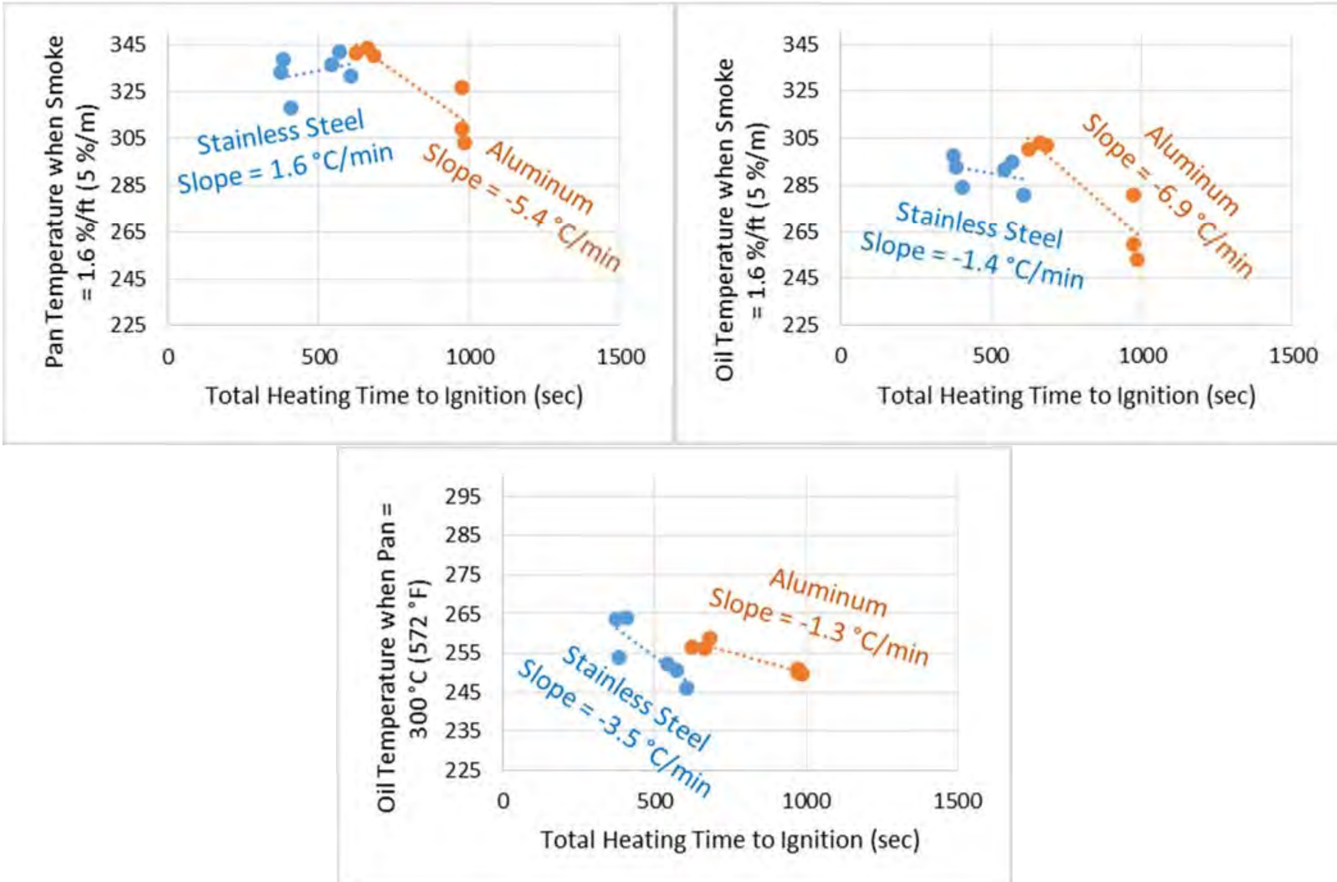


Figure 91 – Slopes for total heating time and pan and oil temperatures at smoke production and oil temperatures at fixed pan temperature for multiple oil depths

The pan and oil temperatures at the time of ignition are shown in Figures 92 and 93, respectively. The pan and oil temperatures were observed to decrease slightly (3°C (5°F) for pan, 6–12°C (11–22°F) for oil) for both aluminum and stainless steel pans with increased oil depth, and therefore with increasing total time to ignition.

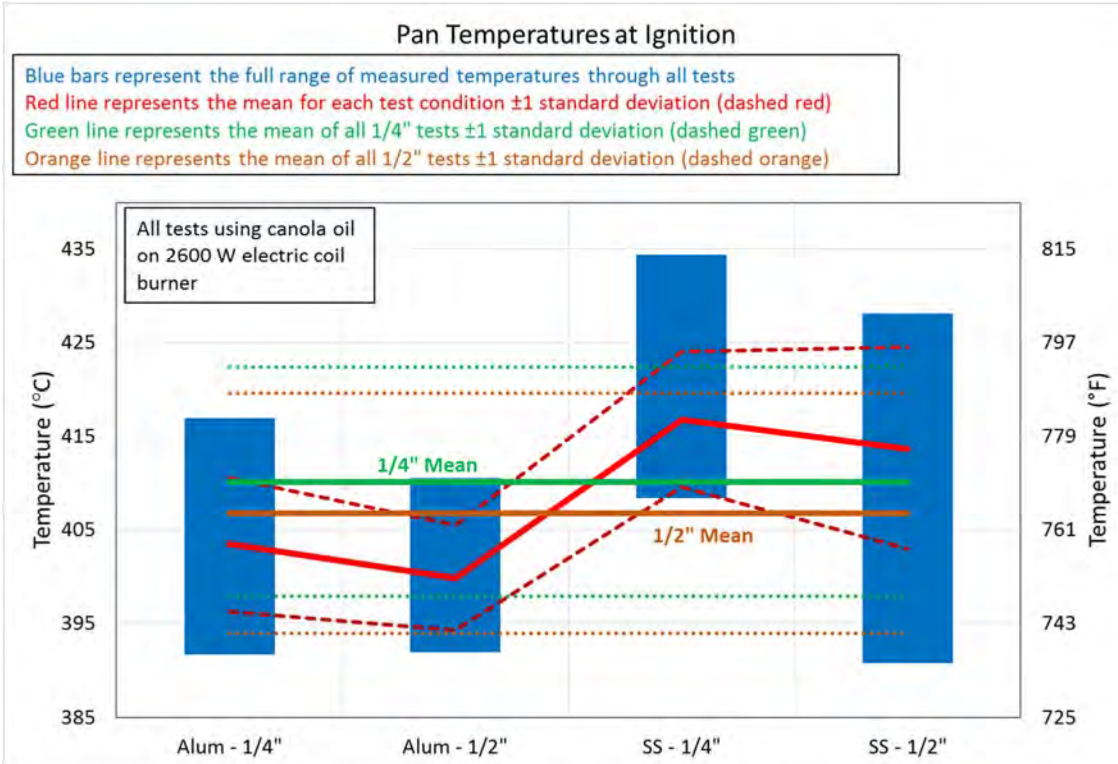


Figure 92 – Average pan temperature at ignition for multiple oil depths

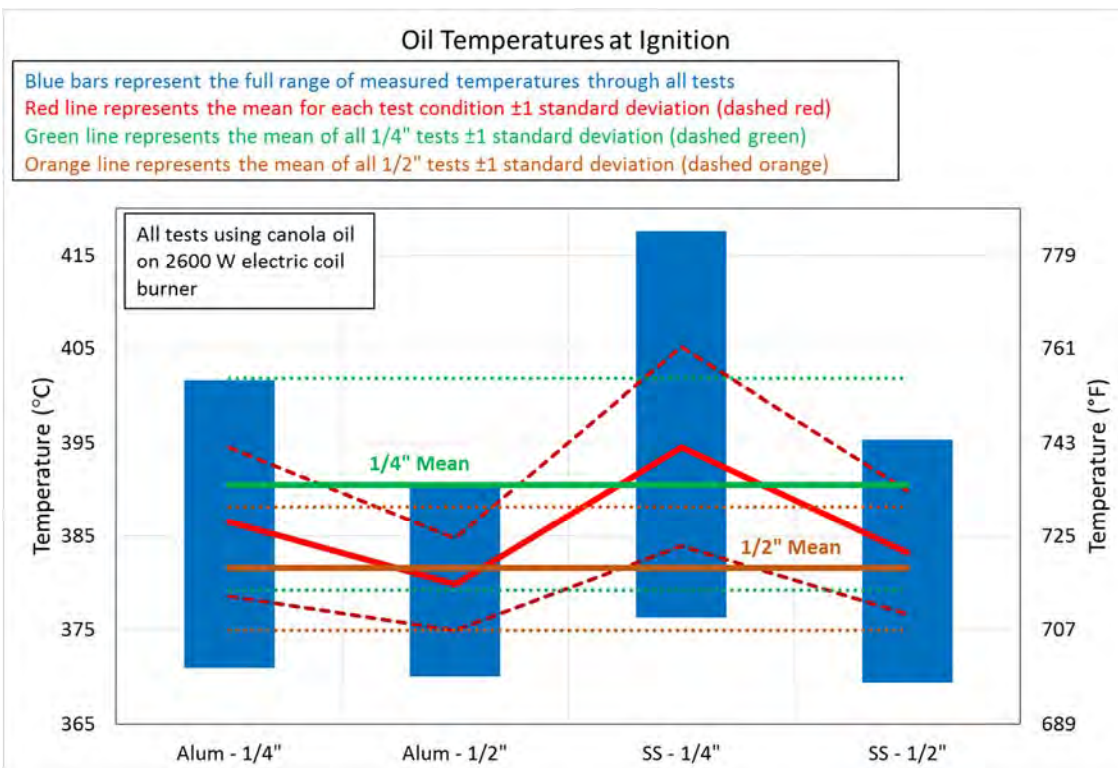


Figure 93 – Average oil temperature at ignition for multiple oil depths

The calculated slopes between the pan and oil temperatures at ignition and the total heating time to ignition for each test are shown in Figure 94. Both the pan and oil temperatures at ignition decreased with increased heating time, and therefore oil depth. This was observed for both aluminum and stainless steel pans. The average pan and oil temperatures at ignition in aluminum pans decreased by 0.6 and 1.2°C (1.1 and 2.2°F) per minute of heating time, respectively. The effect was slightly greater for the stainless steel pans, with the average pan and oil temperatures decreasing by 0.8 and 3.0°C (1.4 and 5.4°F) per minute of heating, respectively. Obviously this trend would not continue indefinitely and would asymptotically approach a minimum oil ignition temperature.

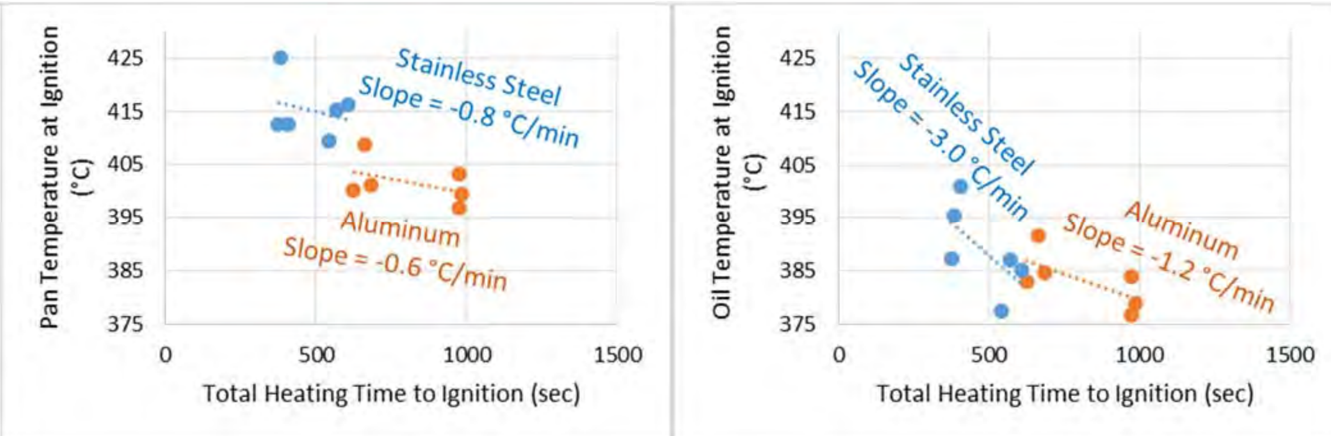


Figure 94 – Correlations and slopes for total heating time and pan and oil temperatures at ignition for multiple oil depths

For tests with a ½ in. (12.8 mm) depth of oil, the thermocouples were separated vertically by ⅛ in. (3.2 mm) for each oil temperature location. This was expanded from the 1/32 (0.8 mm) spacing evaluated for the ¼ in. (6.4 mm) oil depth tests. The intent of expanding this spacing was to determine the impact of insertion depth on the measured oil temperatures with a more proportional variation for the larger oil depth. The range of oil thermocouple temperatures measured at all locations for a ½ in. (12.8 mm) depth test (P2-37) are shown at the time the pan temperature reached 300°C (572°F), the time smoke obscuration of 1.6%/ft (5%/m) was measured, and at ignition in Figure 95.

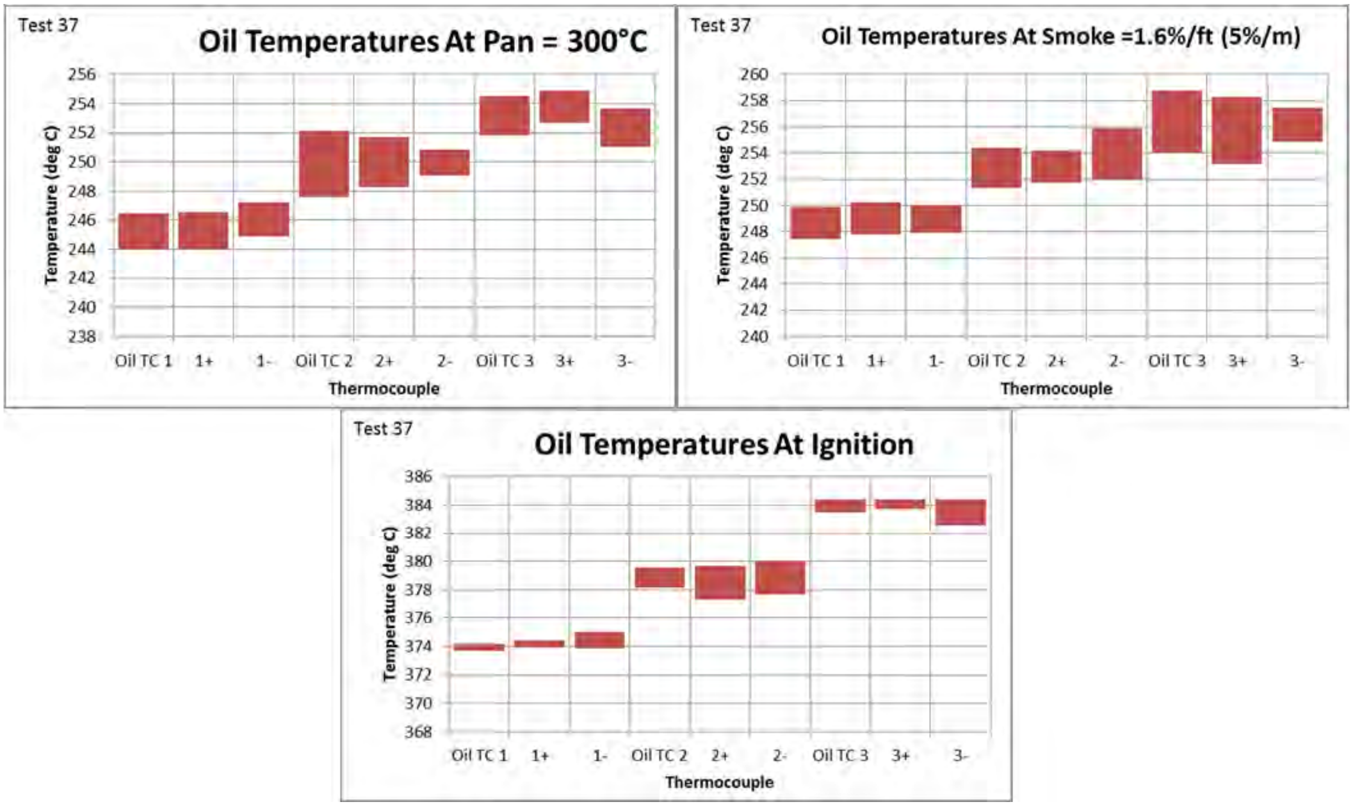


Figure 95 – Oil temperatures measured across all spatial locations for a test with ½ in. (12.8 mm) oil depth

The oil temperature designations in the figure describe locations one, two, and three, which are spread laterally across the pan. The designations + and – indicate that the thermocouple was located above or below the half depth of the oil, respectively. While there is some variation in the oil temperature measurements by lateral position (approximately 10°C (18°F), there is little variation among the thermocouples at different heights in the oil (approximately 1–2°C (1.8–3.6°F). The variability between the vertical oil temperature measurements is less at ignition compared to earlier in the test, indicating a more vertically uniform oil temperature. The uncertainty of the thermocouples in these temperature ranges is approximately 2.2°C (4.0°F), and the difference in vertical temperature is comparable to this value.

6.9. Pan Thickness and Diameter

A series of tests were conducted in both Phase 1 and Phase 2 to determine the impacts of pan diameter and thickness on the heating rates and measured pan and oil temperatures. The primary observations of the pan thickness and diameter tests show:

- The heating time to ignition increases for larger and thicker pans
  - Pans smaller than the element increase heating time compared to pans approximately the same size as element
  - Pans much larger than the element do not heat the pan surface evenly, measuring higher temperatures in the center
    - Ignition times can vary greatly for the largest pans
    - Ignition times ranged from 20 minutes to 1 hour, and one test did not ignite after 1 hour of heating

  - o The available time windows for operation of pan or smoke measuring devices are directly proportional to the total heating time to ignition
- The pan temperatures measured at ignition and at smoke production were reduced for tests with longer total heating times compared to shorter tests
  - o The oil temperatures were relatively unaffected by the length of the test
  - o Ignition at lower pan temperatures with the same oil temperature may increase challenge for detection

The tests included in the pan size evaluation are summarized in Table 16, include all tests conducted with 8 gauge aluminum pans on the 2600 W electric coil element using either soybean or canola oils. Pans sizes ranged from 7 in. (18 cm) to 14 inch (36 cm). The brand of the aluminum pans was found to have an impact on the total heating time for the same size and thickness (see Section 6.6), and multiple brands were tested in this analysis due to availability. The brand (either Vollrath (V), or Browne-Halco (BH)) have been noted in the test identifiers.

The tests included in the pan thickness evaluation are also summarized in Table 16. These tests include the Phase 2 tests conducted with the 10 inch Browne-Halco pans of 8 and 10 gauge, thicknesses. In addition, all Phase 1 tests conducted with 8 in. (20 cm) aluminum pans on the 2600 W electric coil range using either corn oil or pork lard are included. The tests included both Vollrath (10 gauge and 8 gauge) pans, and Browne-Halco (5 gauge) pans due to availability.

Table 16 – Tests included in pan size/thickness analysis

	Identifier	Oil Type	Description	Test ID
Pan Size Evaluation	7 inch (V)	Commercial Canola	180 mL of oil in 7 in., 8 gauge Vollrath aluminum pan	P1-25
		Commercial Soybean		P1-26
	8 inch (BH)	Commercial Soybean Oil	220 mL of oil in 8 in., 8 gauge Browne-Halco aluminum pan	P1-1
		Commercial Canola Oil		P1-5
		Commercial Canola Oil		P1-6
	10 inch (V)	Great Value Vegetable Oil	300 mL of oil in 10 in., 8 gauge Vollrath aluminum pan	P2-1
		Great Value Vegetable Oil		P2-2
		Great Value Vegetable Oil		P2-3
		Great Value Canola Oil		P2-4
		Great Value Canola Oil		P2-5
		Great Value Canola Oil		P2-6
	10 inch (BH)	Great Value Canola Oil	300 mL of oil in 10 in., 8 gauge Browne-Halco aluminum pan	P2-4a
		Crisco Canola Oil		P2-5a
		Generic Canola Oil		P2-6a
	14 inch (V)	Commercial Canola Oil	600 mL of oil in 14 in., 8 gauge Vollrath aluminum pan	P1-27
		Commercial Soybean Oil		P1-28
	14 inch (BH)	Great Value Canola Oil	600 mL of oil in 14 in., 8 gauge Browne-Halco aluminum pan	P2-43
		Wesson Canola Oil		P2-44
		Wesson Canola Oil		P2-45*
		*Test P2-45 did not ignition after 1 hour of heating and the test was stopped, the results are presented but not included in the average test results		
Pan Thickness Evaluation	10 inch diameter pans			
	10 gauge (10-V)	Great Value Canola Oil	300 mL of oil in 10 in., 10 gauge Vollrath aluminum pan	P2-34
		Wesson Canola Oil		P2-35
		Generic Canola Oil		P2-36
	8 gauge (10-BH)	Great Value Canola Oil	300 mL of oil in 10 in., 10 gauge Vollrath aluminum pan	P2-4
		Crisco Canola Oil		P2-5
		Generic Canola Oil		P2-6
	8 inch diameter pans			
	10 gauge (8-V)	Commercial Corn Oil	220 mL of oil in 8 in., 10 gauge Vollrath aluminum pan	P1-31
		Commercial Pork Lard		P1-32
	8 gauge (8-BH)	Commercial Corn Oil	220 mL of oil in 8 in., 8 gauge Browne-Halco aluminum pan	P1-2
		Commercial Corn Oil		P1-3
		Commercial Corn Oil		P1-4
		Commercial Pork Lard		P1-9
	5 gauge (8-BH)	Commercial Corn Oil	220 mL of oil in 8 in., 5 gauge Browne-Halco aluminum pan	P1-29
		Commercial Pork Lard		P1-30

6.9.1. Available Response Times

The average times to ignition for the pan size and thickness tests are shown in Figure 96. The ignition times for the 14 in. (36 cm) pan tests were highly variable and much longer than the other scenarios tested. The ignition times are also shown in Figure 97 with the time axis zoomed in to compare the shorter test scenarios.

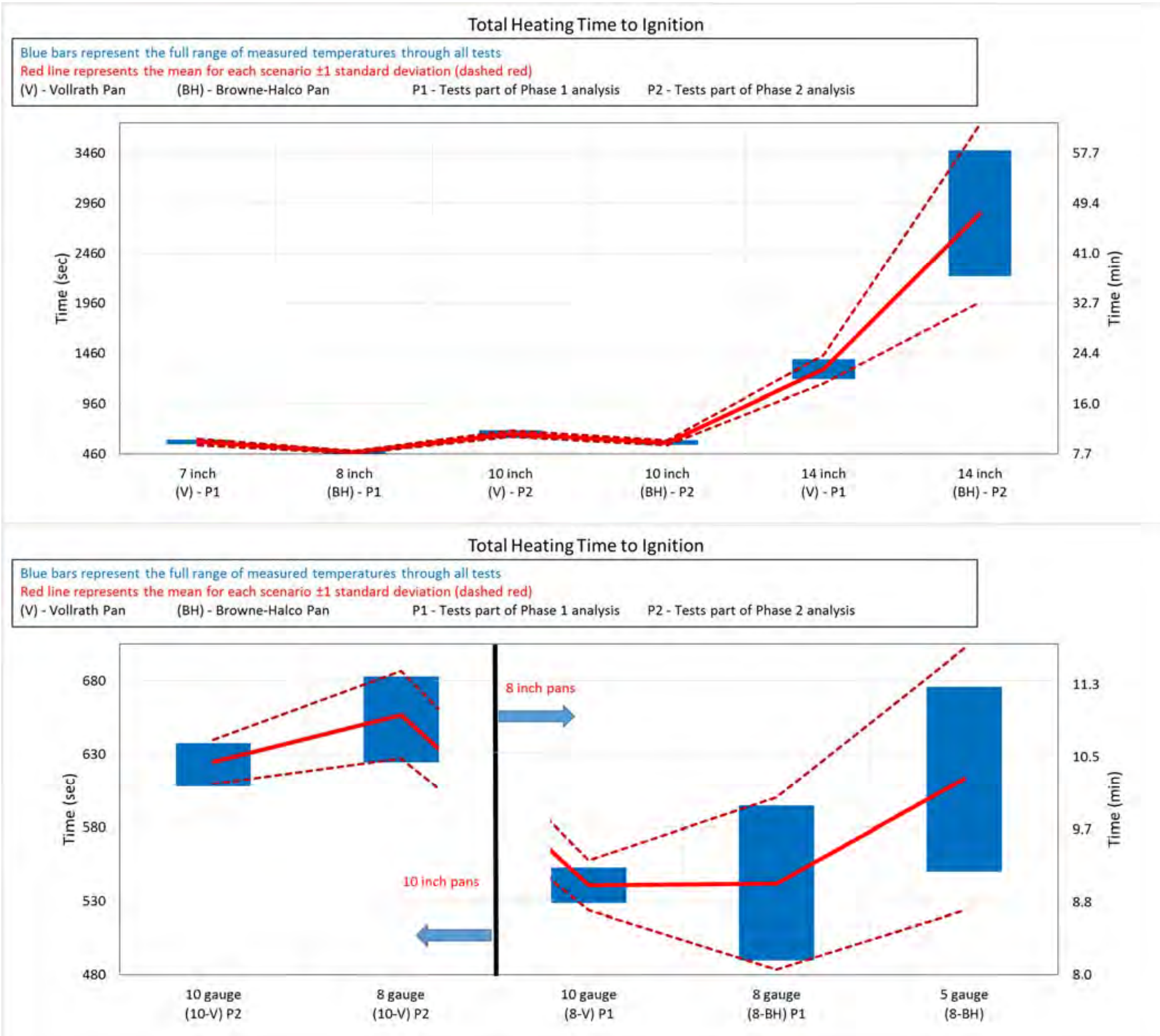


Figure 96 – Heating times until ignition for pan size (top) and thickness (bottom) tests

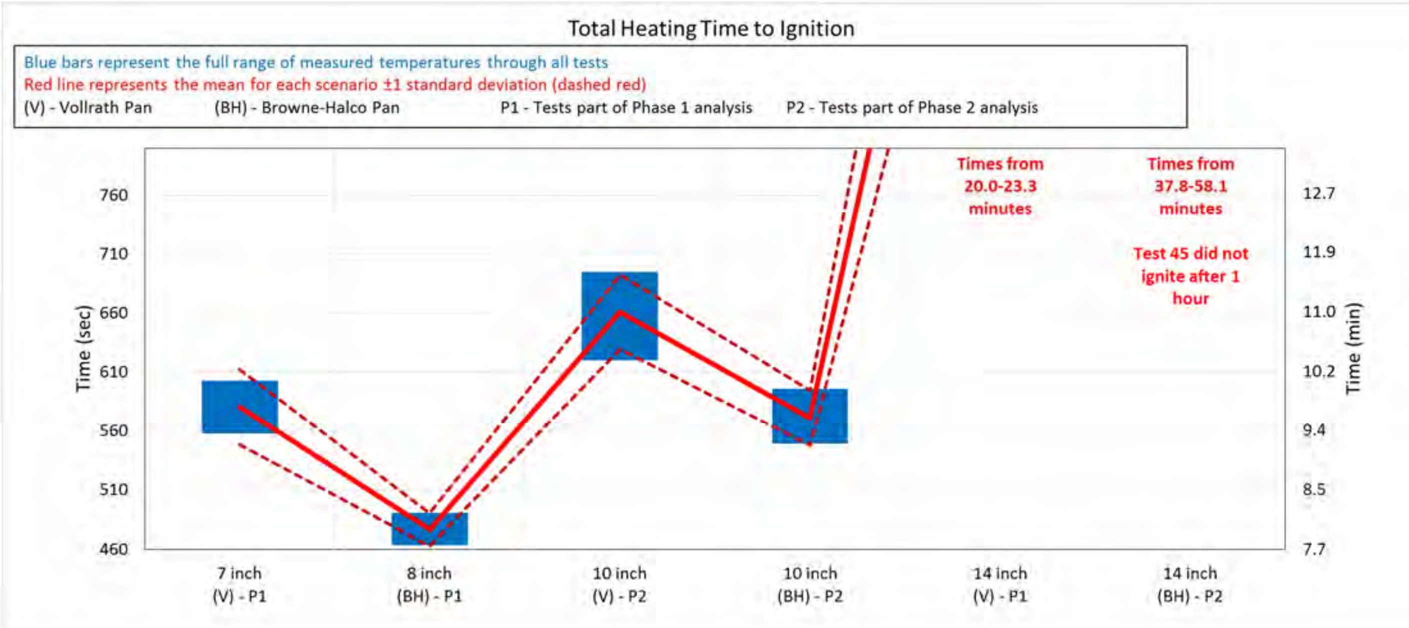


Figure 97 – Heating times until ignition for pan size/thickness tests with reduced time axis

The fastest heating times to ignition were achieved for the 8 in. (20 cm), 8 gauge Browne-Halco pan. Increasing the pan size (and total oil volume) increased the ignition time from this value. Conversely, decreasing the pan size and oil volume also increased the total ignition time. This is likely due to reduced element coverage and loss of input power, although may also have been the result of changing the brand of the pan. The large 14 in. (36 cm) pans extended well beyond the element surface, making ignition timing highly variable. The temperature increases were very slow at the end of these tests, and slight variations in ignition temperature could increase the length of a test by many minutes. One 14 in. (36 cm) test conducted did not reach ignition (P2-45) after an hour of heating.

The heating time to ignition has been correlated to the diameter of the pan and the thickness of the pan for the separate tests considered. In addition, all tests have been correlated to the minimum possible heating time as shown in Figure 98. The minimum possible heating time is a combination of the pan and oil mass and element heat output (see Eq. 2 in Section 5.4.6). The heating time to ignition increases with both pan diameter (approximately 246 sec per inch diameter) and pan thickness (900–1200 sec per inch thickness). When the pan thickness and diameters are combined in the minimum possible heating time, a correlation to total heating time of 0.80 with a slope of 6.3 seconds heating time per minimum second is calculated as shown.

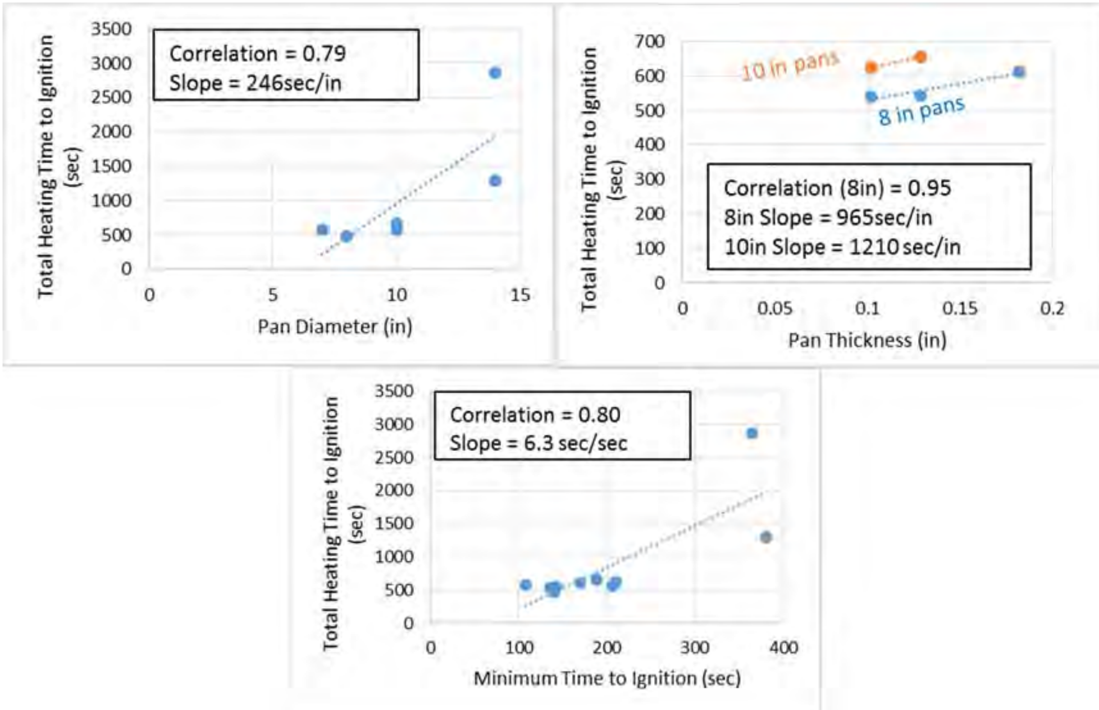


Figure 98 – Correlation between the total heating time to ignition and pan size/thickness and calculated minimum heating time to ignition

The time windows available between a fixed pan temperature of 300°C (572°F) and ignition or smoke obscuration of 1.6%/ft (5%/m) and ignition scaled proportionally with the total time to ignition. The correlation and calculated slopes for these parameters are shown in Figure 99, both correlating to 1.00 with average slopes of 0.80 and 0.78 sec window per second heating time for smoke and pan temperature, respectively. These available time windows are independent of the differences between the pan sizes or thicknesses.

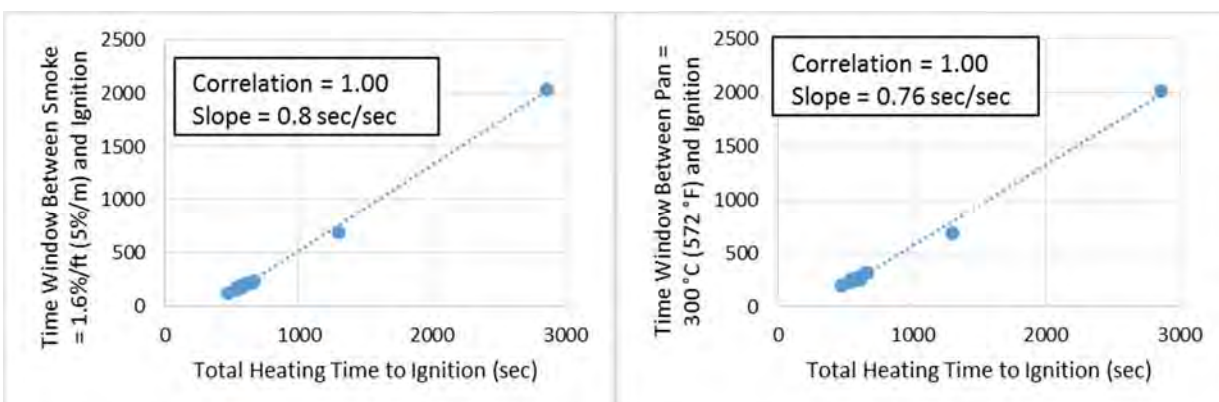


Figure 99 – Correlation between the total heating time to ignition and the pan and smoke time windows to ignition for pan size/thickness tests

6.9.2. Temporal Heating Curves

Temporal plots of the average pan and oil temperatures, and average smoke obscuration for the fastest and slowest of the oil depth tests are shown in Figure 100 aligned at the time of ignition (T = 0). The solid lines show the average for each material, and the dashed lines show the maximum and minimum values measured at the given time before ignition occurred. Due to the high level of variability, the average curve for the 14 in (36 cm) pan tests is not shown, only the maximum and minimum curves.

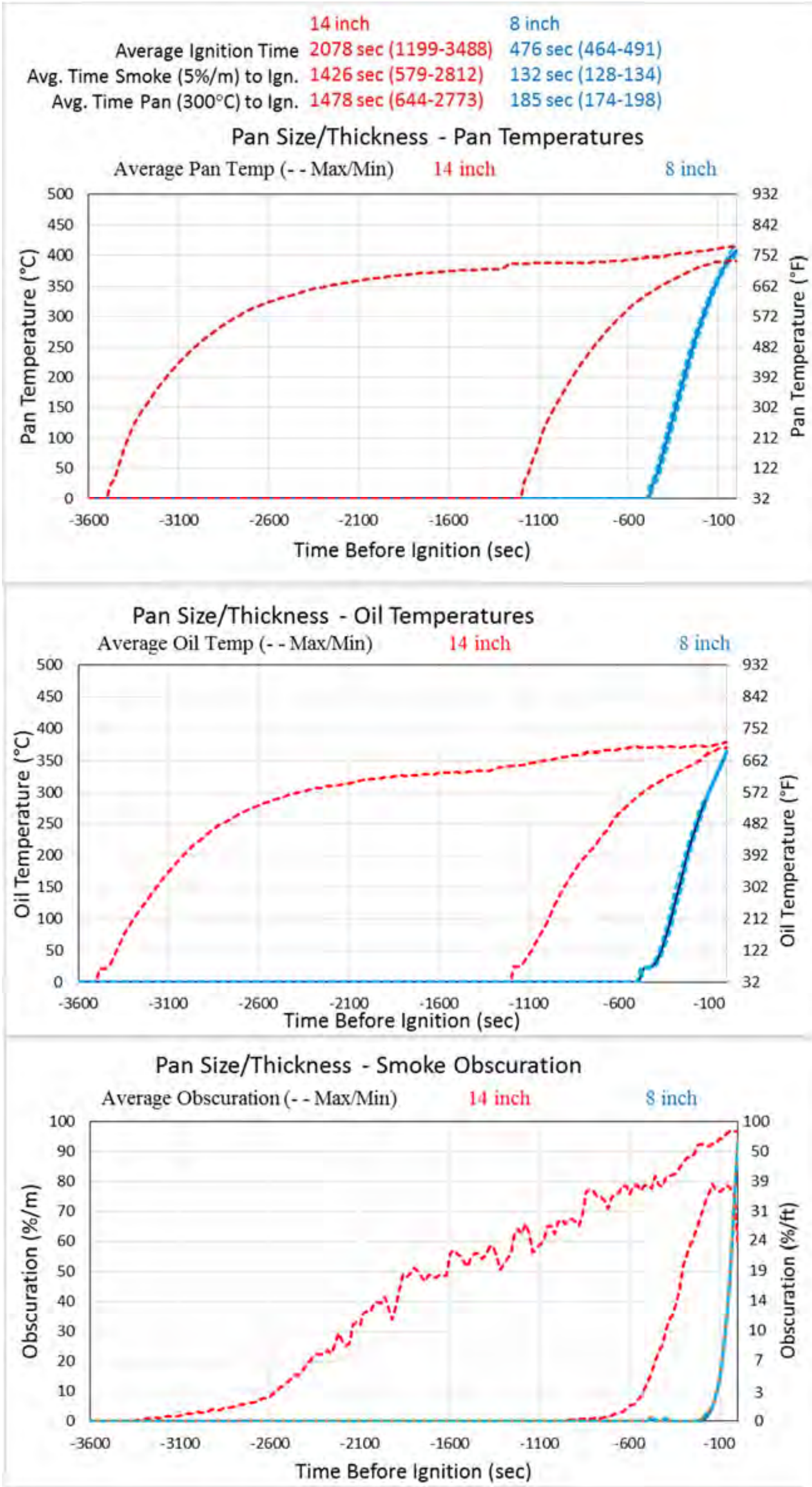


Figure 100 – Pan and oil temperatures and smoke obscuration curves for fastest and slowest pan size/thickness tests aligned by ignition time

As shown in the temporal curves, there is a variability in the 14 in. (36 cm) pan curves, with ignition times ranging from 20 minutes to nearly an hour. This is also much longer than the tests conducted in the 8 in. (20 cm) pans, which had ignition times of approximately 7.5 minutes. Much higher levels of smoke and temperatures were measured long before ignition occurred for the larger pan tests. This also resulted in much lower slopes, with the pan and oil temperatures nearly reaching steady state before ignition occurred. The difference between the 7, 8, and 10 inch (18, 20, 25 cm) pans was less pronounced than for the 14 in. (36 cm) pans. In general, it appeared as though the 8 in. (20 cm) pan provided the fastest heating to ignition and shortest activation windows, likely due to the reduction in oil volume and pan mass compared to the 10 in. (25 cm) pan, and the increase in pan/element contact area compared to the smaller 7 in. (18 cm) pan.

The calculated slopes in the pan and oil temperature curves, differences between the pan (center of pan) and oil (center of oil) temperatures at ignition, and the integrated smoke obscuration at fixed pan temperatures are shown in Table 17. The tests utilizing different brands of the same size and gauge pans have been combined in the table (e.g., the 10 inch pans referenced for pan size tests include both the Vollrath and Browne-Halco pans tested). The 14 in. (36 cm) pan tests have much lower pan and oil temperature slopes approaching ignition than the shorter tests conducted. The total integrated smoke concentration is also nearly 5 times that for other tests conducted. The difference between the pan and oil temperatures was the lowest for the 10 inch pan tests conducted, but that is mostly attributed to the use of more responsive thermocouples for oil measurement in Phase 2.

Table 17 – Calculated pan and oil temperature slopes and obscuration slope and integrated areas for pan size/thickness tests

Pan	Average pan temp slope between fixed pan temperatures and ignition (°C/min)				Average oil temp slope between fixed pan temperatures and ignition (°C/min)				Difference between pan and oil temperature at fixed pan temps (°C)					Integral of smoke obscuration up to fixed pan temperatures (%/m – min)				
	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	IGN	250°C (482°F)	300°C (572°F)	350°C (662°F)	375°C (707°F)	IGN
8 Gauge Aluminum Pans – Pan Diameter																		
7 inch	30	27	23	20	35	33	31	28	71	67	67	58	44	3	6	13	26	111
8 inch	39	35	29	25	44	39	35	33	64	57	55	54	44	0	0	5	19	84
10 inch	25	21	17	13	28	25	23	23	36	36	37	37	16	0	0	7	29	159
14 inch	7	5	3	2	8	7	5	5	50	47	44	43	24	5	13	75	306	1225
10 inch pans – Pan Thickness																		
10 gauge	26	23	18	15	31	28	25	24	42	40	37	37	17	0	2	12	35	161
8 gauge	25	21	17	13	28	25	23	23	36	36	37	37	16	0	0	7	29	159
8 inch pans – Pan Thickness																		
10 gauge	32	29	23	20	40	35	31	29	98	87	83	82	57	4	6	5	9	134
8 gauge	34	31	25	22	40	37	35	34	62	61	59	55	37	0	0	11	33	126
5 gauge	31	28	24	21	33	28	28	24	52	41	47	42	38	0	2	16	45	138

6.9.3. Smoke Production and Ignition Temperatures

The pan and oil temperatures at the time smoke obscuration measured 1.6%/ft (5%/m) are shown in Figures 101 and 102, respectively. The pan temperatures were observed to decrease with an increase in pan size and with an increase in pan thickness. The oil temperatures were less affected, with the exception of low oil temperature measurements in the pork lard test included in the 8 gauge, 8 in. (20 cm) pan thickness analysis.

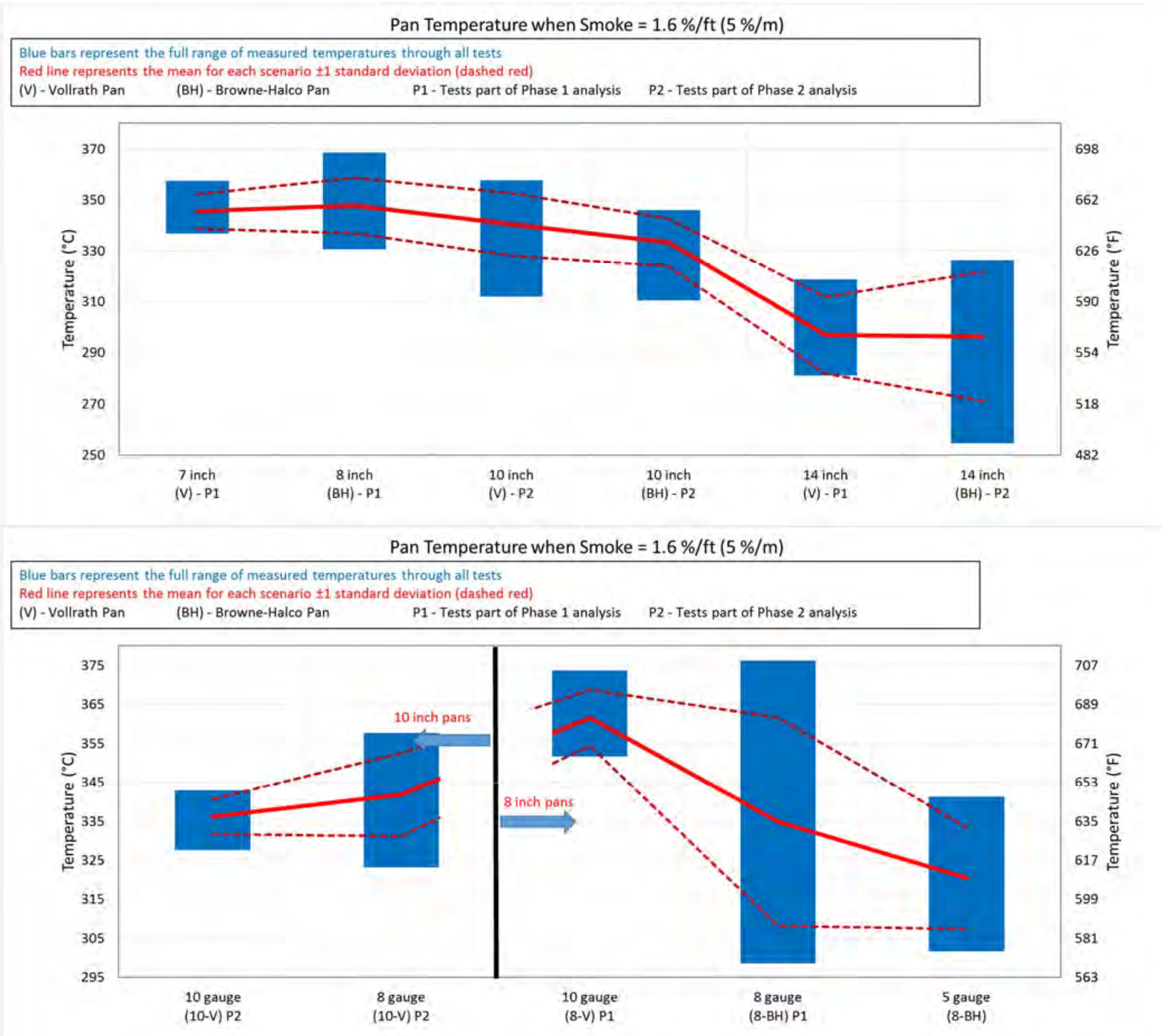


Figure 101 – Average pan temperature at 1.6%/ft (5%/m) smoke measurement for various pan sizes (top) and thicknesses (bottom)

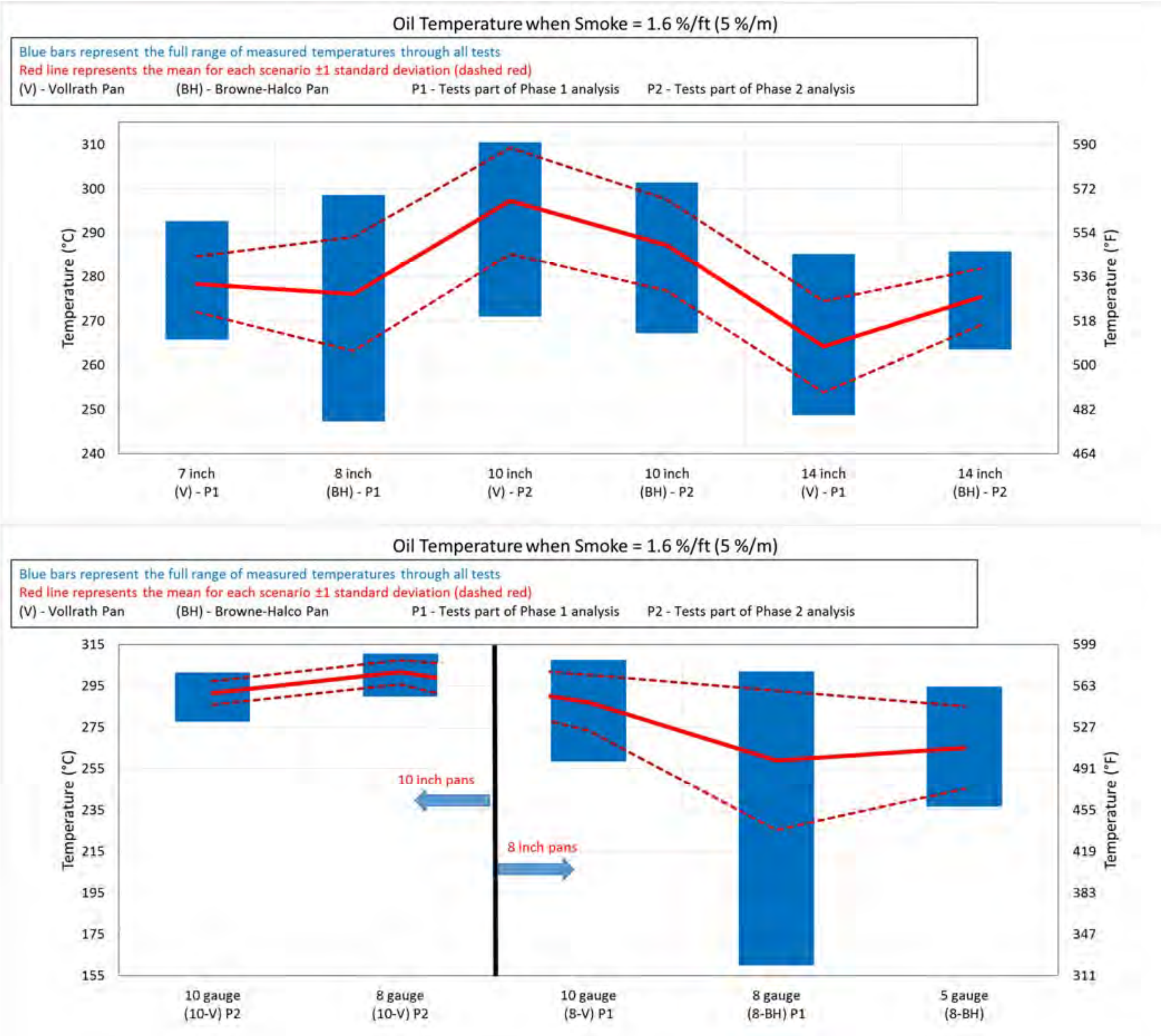


Figure 102 – Average oil temperature at 1.6%/ft (5%/m) smoke measurement for various pan sizes (top) and thicknesses (bottom)

The oil temperatures when the average pan temperature reached 300°C (572°F) are shown in Figure 103. The average pan temperatures measured for the 14 in. (36 cm) pan were reduced due to the pan thermocouples location outside the diameter of the element. Pan TC2 is located in the center of the element and pan, but pan TC1 and TC3 were located at the outer edges of the pan, outside the diameter of the element. These thermocouples, especially TC1, measured reduced temperatures (by as much as 70°C (126°F), as shown in Figure 104. This chart shows the temperatures measured at each pan location when the average of the three locations was 300°C (572°F). The center pan temperature was consistently higher than the outer measurements. The reduced outer pan temperatures result in reduced average pan temperatures. This causes an increase in the average oil temperature when fixed pan temperature threshold of 300°C (572°F) is reached, as shown in Figure 103. No similar relationship was observed relating to pan thickness.

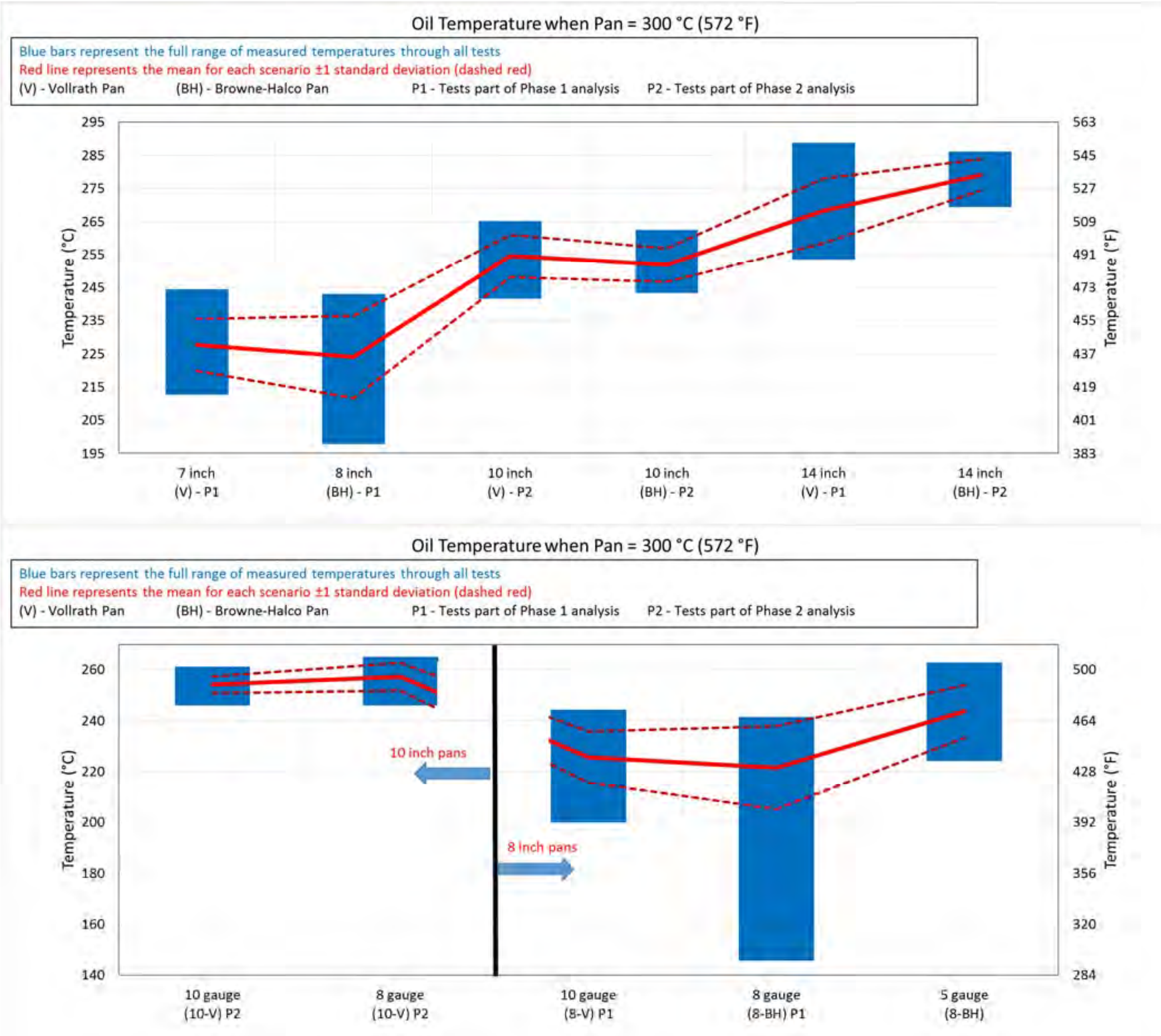


Figure 103 – Average oil temperature when pan = 300°C (572°F) for multiple oil depths

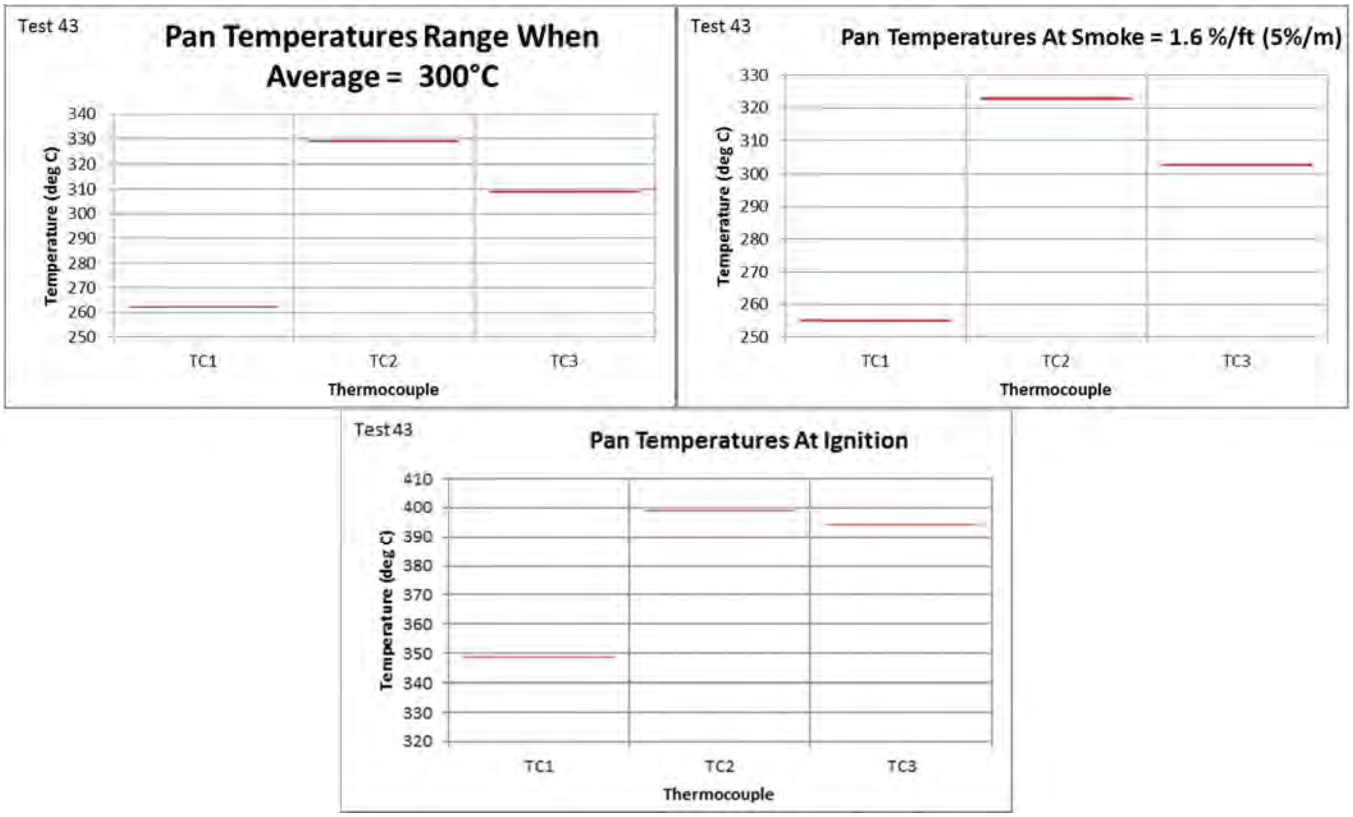


Figure 104 – Pan temperatures measured across all spatial locations for a test with 14 in. (36 cm) pan

The calculated correlations between the total heating time to ignition and the pan and oil temperatures at smoke measurement, and the oil temperatures at 300°C (572°F) pan measurement are shown in Figure 105. The correlations are strongly influences by the outlying points for the 14 in. (36 cm) pan, and much less discernable trends are observed when this point is neglected from the analysis. The pan temperature at smoke production and the oil temperature at the fixed pan temperature appear to be more asymptotic than linear. With longer and longer tests, the pan temperature at smoke will not get lower than approximately 290°C (554°F) and the oil temperature when the pan temperature reaches 300°C (572°F) will not increase above 280°C (536°F). Both of these results would make physical sense, as the length of test cannot indefinitely continue to reduce/increase measured temperatures at fixed points. The oil temperature at smoke production varies by over 40°C (72°F) with almost no discernable relationship with the total heating time to ignition. No clear correlation can be drawn.

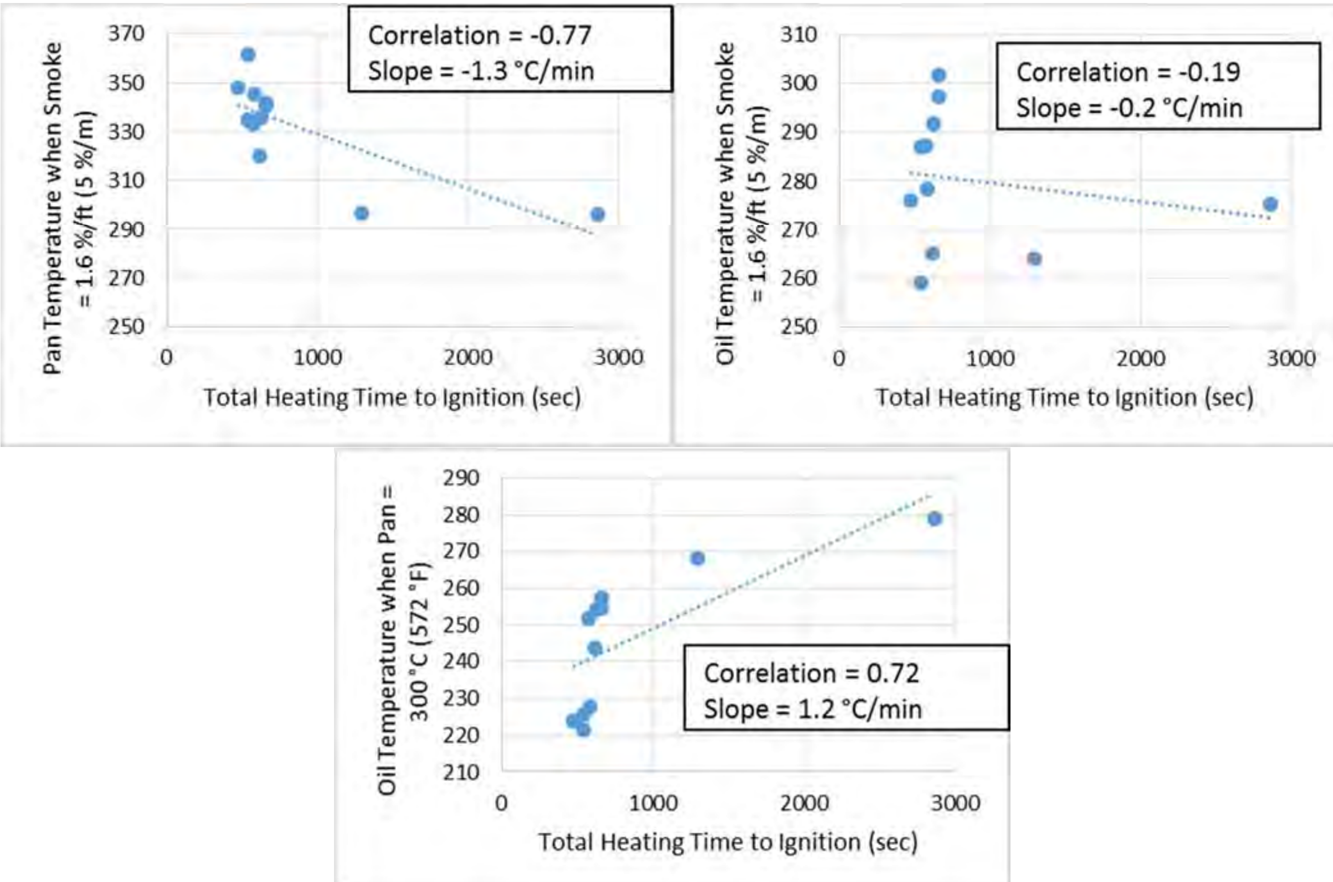


Figure 105 – Correlations and slopes for total heating time and pan and oil temperatures at smoke production and oil temperatures at fixed pan temperature

The pan and oil temperatures at the time of ignition are shown in Figures 106 and 107, respectively. The pan temperatures at ignition were observed to decrease slightly both with increasing pan size and with increasing pan thickness. The effect is most pronounced for the change from 10 in. (25 cm) to 14 in. (36 cm) pans, with the pan temperature at ignition decreasing by approximately 20°C (36°F). This is to be expected, as the larger pan extends farther off the element, reducing the overall average pan temperature. A similar but less dramatic effect can be observed for the thicker pans, with average temperatures at ignition decreasing by approximately 5°C (9°F) for increasing pan gauges.

Oil temperatures did not trend with pan size or thickness as did the pan temperatures. No consistent trend was observed for the oil temperature at ignition due to either pan size or thickness. The average temperatures did vary by as much as 20°C (36°F), but the effect did not appear systematically related to the pan characteristics, but rather test variability.

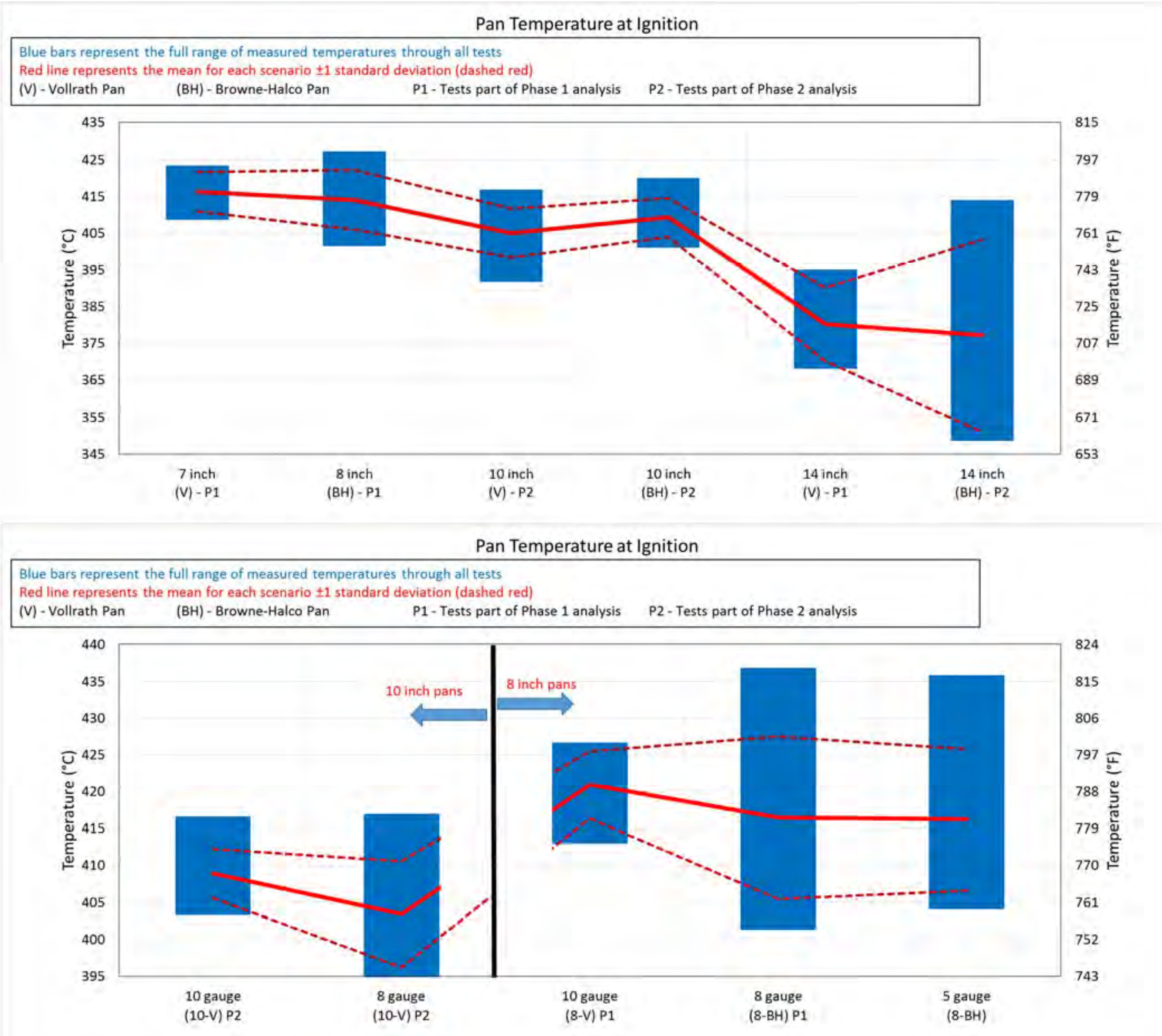


Figure 106 – Average pan temperature at ignition for various pan sizes (top) and thicknesses (bottom)

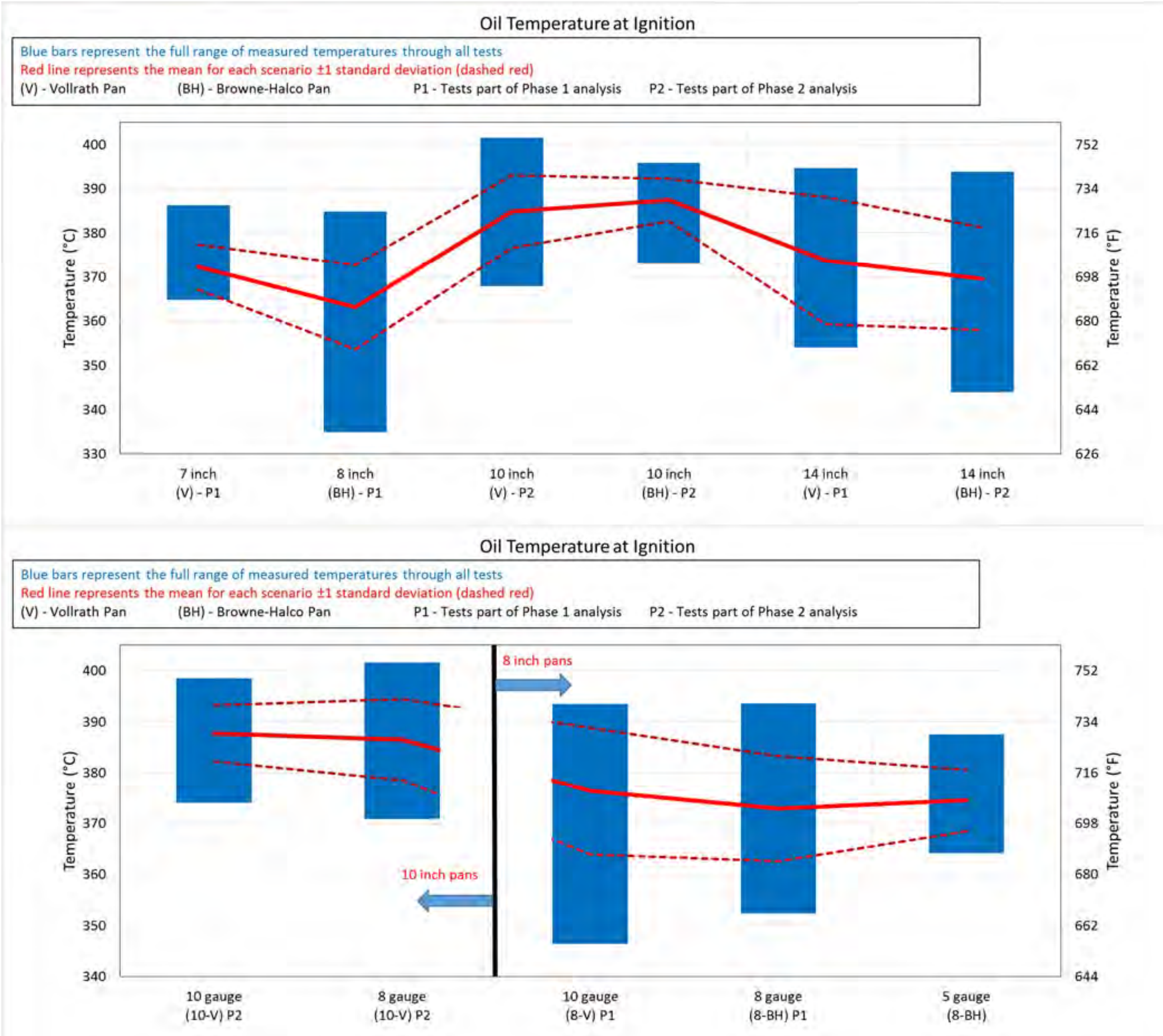


Figure 107 – Average oil temperature at ignition for various pan diameters (top) and pan thicknesses (bottom)

6.10. Pan Warping and Temperature Overshoot

Testing was conducted in Phase 1 to evaluate the ability to warp a pan using thermal cycling. A dry 10 gauge, 8 in. (20 cm) diameter pan was heated on the 8 in. (20 cm) GE electric coil element until the pan temperature measured approximately 400–450°C (750–840°F). All power was then cutoff to the element and the temperature overshoot was measured. When the temperature began to decrease it was dunked into a large water tank to initiate rapid cooling. This process was repeated through 30 heating and cooling cycles. Several of the heating cycles are shown with the measured range power output in Figure 108.

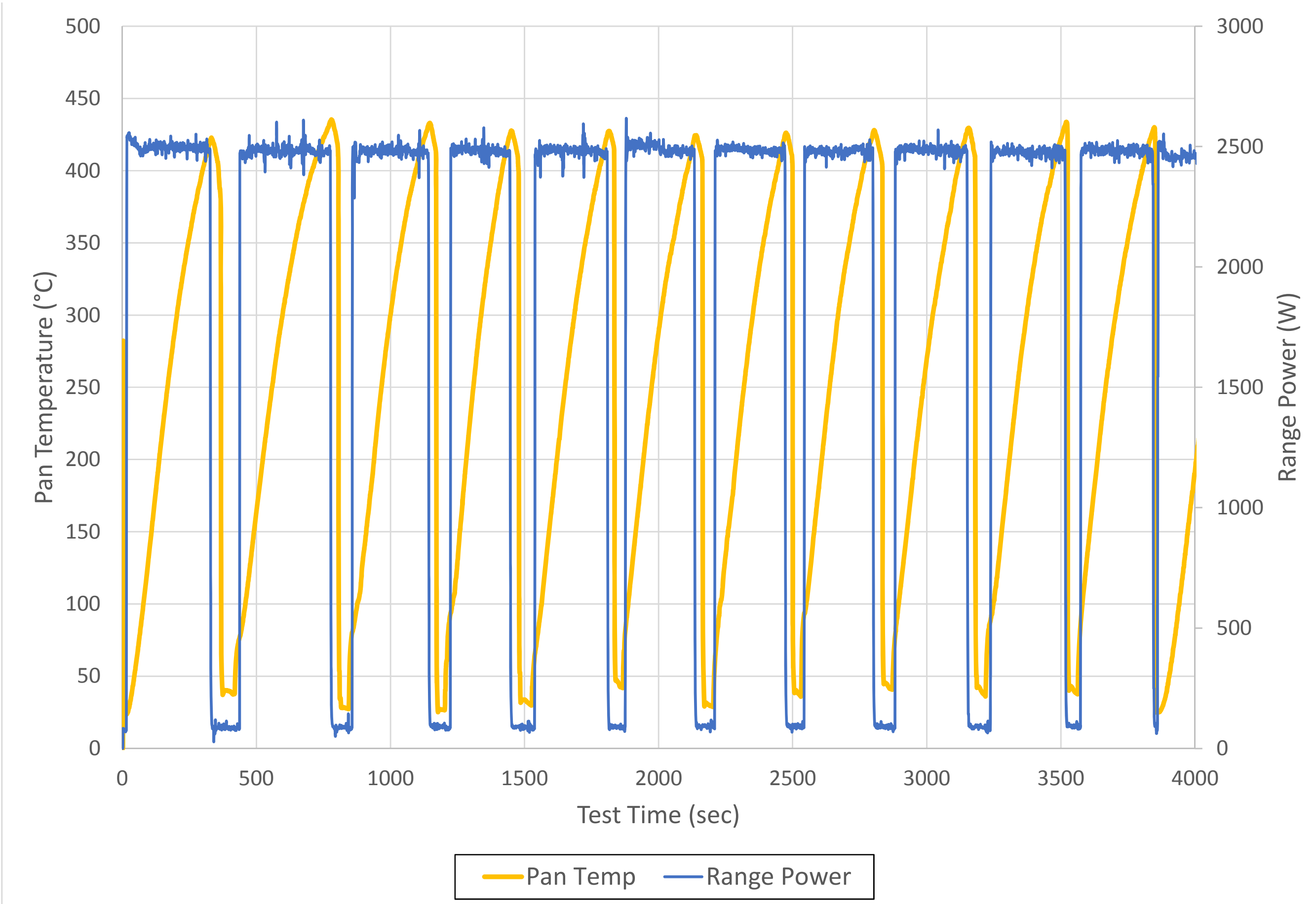


Figure 108 – Pan temperature and range power during rapid heating and cooling

After 30 heating and cooling cycles were conducted, the pan flatness was measured about the center of the pan in a 2 in. (5.1 cm) radius. The maximum deviation measured across this area was 0.058 in. (1.5 mm) This is greater than the 0.006 times the diameter (8 x 0.006 = 0.048 in. (20 x 0.006 = 1.2 mm)) threshold specified in UL 1026 [4]. It is less than the maximum deviation of 0.25 in. (6.4 mm) reported by a UL 858 task group for Technical Feasibility and Performance Goals (TFPG) for implementation of a contact temperature sensing device for range fire prevention [5].

During each cycle, the power was cut to the range and the temperature of the pan allowed to continue rising due to residual thermal gradients between the element and pan surface. This effect is considered a temperature overshoot. A representative pan temperature overshoot is shown in Figure 109.

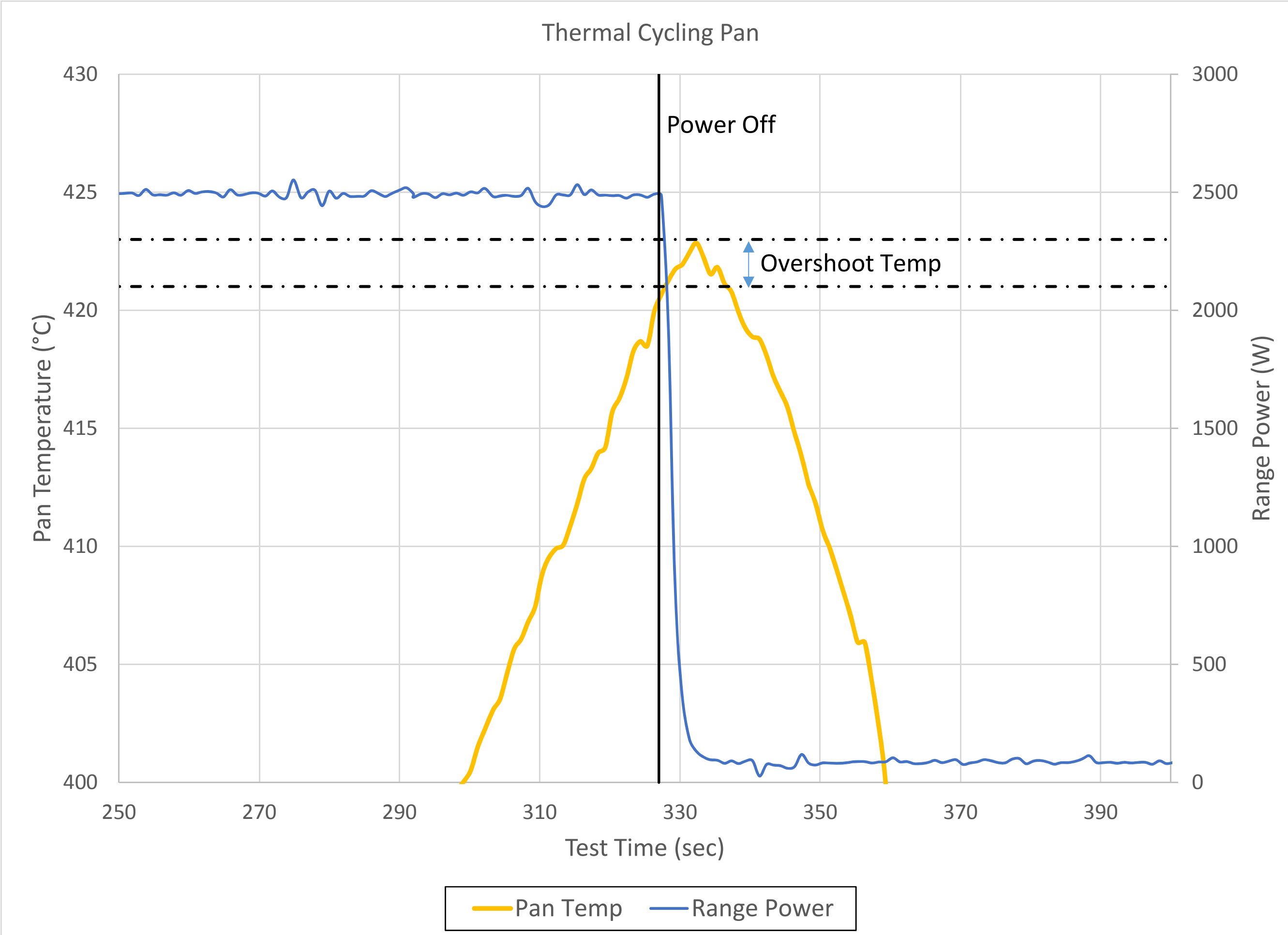


Figure 109 – Pan temperature overshoot when range power cycled off

Temperature overshoots were generally observed to vary between 1–11°F (1–6°C) and occurred over 3–10 seconds. The magnitude of the overshoot was typically increased with reduced pan temperatures. At lower pan temperatures, the residual temperature gradient between the element surface and the pan surface was increased, and the temperature overshoot would be greater in magnitude. The greatest overshoots were observed for pan shutoff temperatures of approximately 715°F (380°C). At lower pan cutoff temperatures, the overshoot may be further increased.

7. GLOBAL TEST CORRELATIONS

The preceding sections have compared the results of numerous tests by isolating variables. In order to focus the analysis within each section, only select tests were considered. Several trends were observed to occur in many test series. For example, the available time windows between the measurement of 1.6%/ft (5%/m) smoke and ignition and between an average pan temperature of 300°C (572°F) and ignition were found to correlate well with the total heating time to ignition. In addition, the average pan and oil temperatures at ignition were often found to decrease with increasing total heating time to ignition. This section combines the analysis from all test variables and attempts to identify and quantify these global correlations observed across all tests.

For most test scenarios conducted, the total heating time to ignition was found to correlate well with the variable conditions, such as element power, pan size and shape, pan mass and thermal properties, and oil depth and volume. The total heating time was also found to correlate well with the calculated minimum heating time to ignition (a linear combination of the pan and oil mass, specific heat capacity), temperature at ignition, and the total element power input.

Other test metrics characterizing potential challenges to prevention devices, such as the time windows for pan temperature or smoke activation, pan and oil temperatures at smoke production and ignition, were either correlated to the total heating time to reach ignition or showed minimum response at all. The only other variable found to impact these metrics, was the % FFA of the oil used for testing. While this was not found to impact the ignition temperatures, oils with low % FFA were found to produce smoke at higher temperatures and provide a shorter potential window for activation by smoke detection technologies.

For calculation of the global correlations, all Phase 2 tests have been included in the analysis. The Phase 1 tests were neglected due to the lack of repeated tests and the use of less responsive oil temperature measurements. The Phase 2 tests included evaluation of all the variables (without all the scenarios) included in Phase 1 and resulted in both the fastest and slowest ignition among all tests. A description of each test scenario (1–16) is provided in Table 2 in Section 5.3. The correlation of the heating time to reach ignition with the calculated minimum time to ignition (which combines most pan/element variables) is shown in Figure 110. The calculation of the minimum time to ignition is discussed in Section 5.4.6 and shown in Eq. (2).

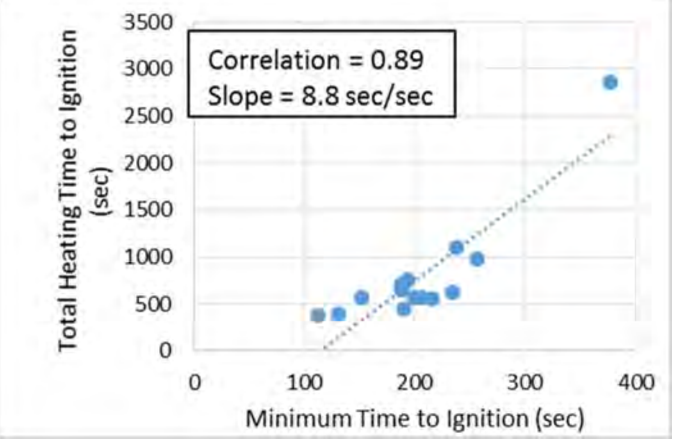


Figure 110 – Correlation between the measured time to ignition and the calculated minimum ignition time for all Phase 2 tests

The minimum heating time to ignition is a calculated variable that incorporates a number of pan/element/oil factors. In order to further improve the calculated ignition time, a correction factor has been empirically developed to account for the difference in size between the pan (*D*) and the element (*B*). The correction factor was calculated using Eq. (3), for pan and element sizes in inches.

$$F = \frac{B + Abs(B - (D - 2.5))}{2.25} \qquad \textbf{Eq. (3)}$$

When the minimum ignition time is multiplied by the correction factor, the estimated ignition times are much closer to the actual ignition times, and the correlation is improved. This correlation is shown in Figure 111 along with a line of equality (calculation of the exact ignition time). The calculated times are slightly shorter than the actual times to ignition as shown by the curve falling above the line of equality. This is likely due to the influence of other variables such as the conductivity of the pan, the pan flatness, and the pan stability. However, cursory attempts to develop combined correlations incorporating these variables were not successful and are beyond the scope of this project.

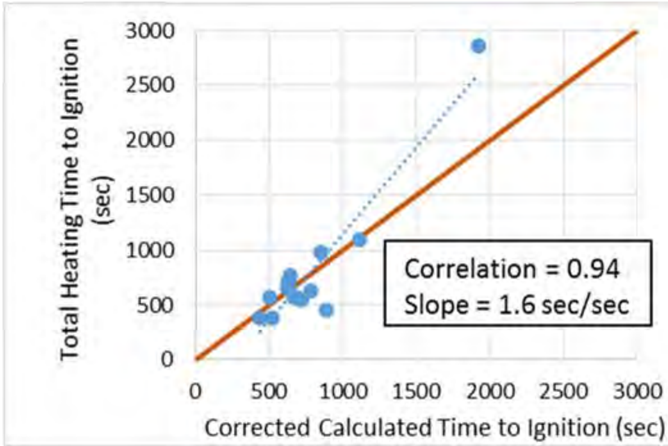


Figure 111 – Correlation between the corrected measured time to ignition and the calculated ignition time for all Phase 2 tests

The measured pan and oil temperatures at the time of ignition correlated negatively with the total heating time to reach ignition. Longer tests generally ignited with lower measured pan and oil temperatures. The actual curves appeared to be asymptotic, reaching minimum temperatures at the longest tests conducted. The pan and oil temperatures and estimated curve fits are shown in Figure 112. Pan temperatures were found to decrease by approximately 2.1°C (3.8°F) per minute of heating to ignition for times between 381 and 1095 seconds, with a strong correlation in this range of -0.85. The pan temperature stopped decreasing with increased test length and approached an asymptote at approximately 377°C (711°F). Oil temperatures also decreased with increasing heating time to ignition by approximately 0.9°C (1.6°F) per minute of heating time between 381 and 1095 seconds. The correlation is not as strong as the pan temperatures, with a moderate correlation of -0.48 measured. The oil temperature at ignition also asymptotes for longer tests, reaching an approximate minimum of 370°C (697°F) for the longest tests conducted. The equations used to calculate the curve fits are based on the minimum and maximum times to ignition and pan and oil temperatures. They are shown in Eq. (4) and Eq. (5) for the pan and oil temperatures, respectively. The correlations were developed to investigate the averages from all the tests to try to understand the trend. In order to use the data for design of a minimum possible temperature should focus on the lower error bounds shown in the plots.

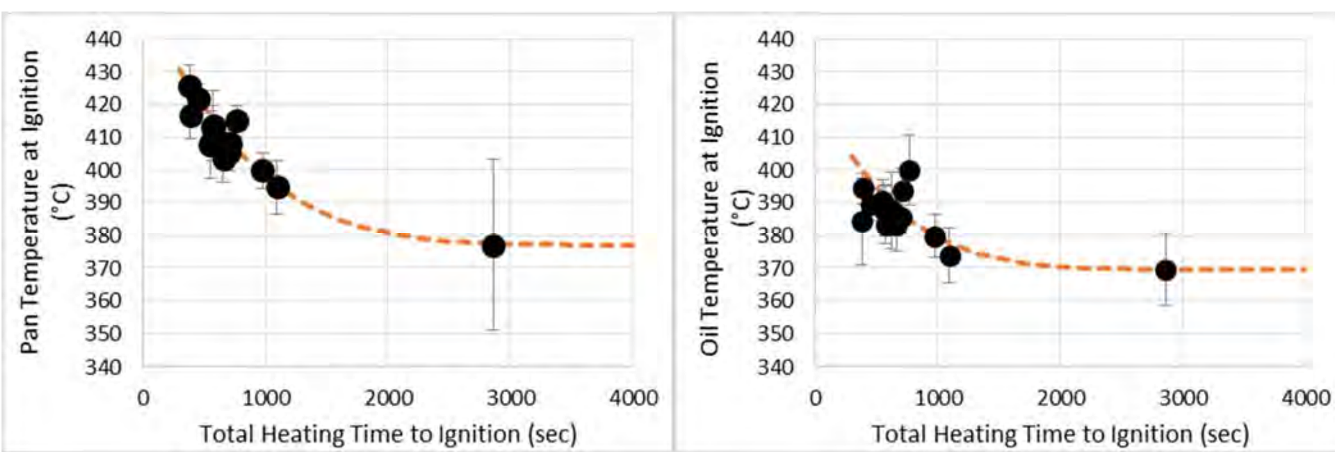


Figure 112 – Correlation between the total heating time to ignition and the pan and oil temperatures measured at ignition

$$Pan\ Temp\ at\ Ignition\ (°C) = \left[1 - \operatorname{atan}(t_{ign} - 381)\right]^3 [426 - 377] + 377 \qquad \textbf{Eq. (4)}$$

$$Oil\ Temp\ at\ Ignition\ (°C) = \left[1 - \mathrm{atan}(t_{ign} - 381)\right]^4 [400 - 370] + 370 \qquad \textbf{Eq. (5)}$$

The time windows between a fixed pan temperature threshold (300°C (572°F) and ignition and between a smoke obscuration threshold (1.6%/ft (5%/m)) and ignition scaled proportionally with the total heating time to ignition across all tests conducted. These values are representative of potential activation windows for prevention devices measuring either pan temperatures or smoke concentrations. Shorter time windows indicate more challenging fires to prevent. Decreasing the total heating time reduces the available operating time for these devices. If the thresholds are shifted, the total available time can be increased or decreased, but remain proportional to the total ignition time. The correlations for the pan and temperature thresholds are shown in Figure 113.

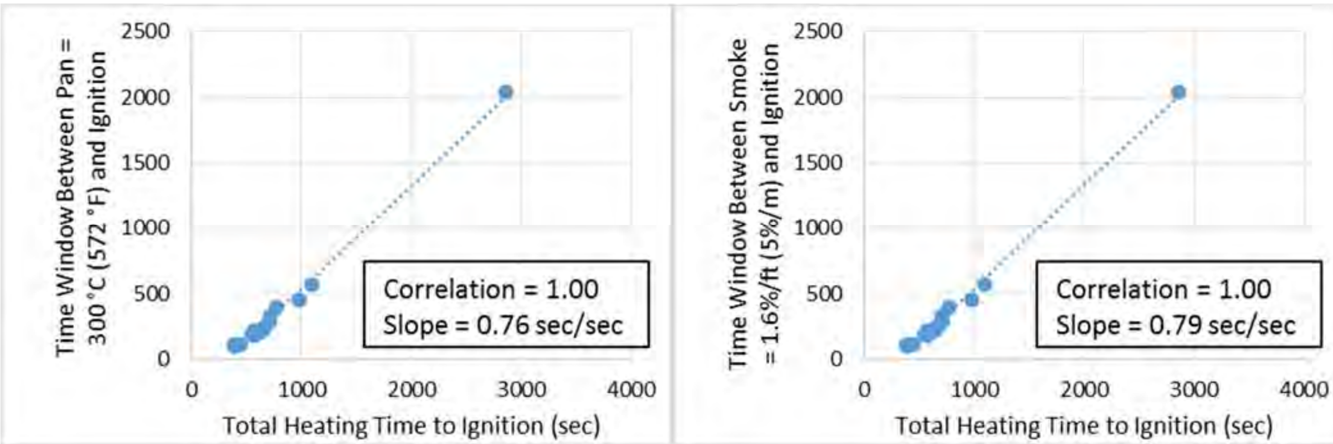


Figure 113 – Correlation between the total heating time to ignition and time windows for activation of fixed pan temperature or smoke obscuration thresholds

In general, the challenge for detection for any device can be linked to the total heating time required to reach ignition. By decreasing the total test time, the available operating windows are shortened and the margin of safety between operation and ignition is reduced. The total test time can be reduced by:

- Decreasing the volume of oil used for testing
- Sizing the pan to match the element diameter
  - 8 in. (20 cm) pans heated fastest on 8 in. (20 cm) element
  - 8 in. (20 cm) pans ignited faster than either smaller or larger pans
- Increasing the element power output
- Using a flatter and more stable pan
- Using a pan with less mass and lower specific heat capacity
- Using a pan with greater conductivity

Challenging scenarios are not only the fastest to reach ignition, however. Tests with slower heating times to ignition had lower measured pan and oil temperatures at ignition than fast tests and very flat temperature slopes. The average pan and oil temperatures decreased by approximately 2.1°C (3.8°F) and 0.9°C (1.6°F) per minute of additional heating time to reach ignition, respectively. Both pan and oil temperatures were found to reach asymptotes for the longest tests at approximately 377°C (711°F) and 370°C (697°F), respectively. Depending on the technology, these reduced temperatures at ignition may present additional challenges to prevention devices.

8. COMPARISON OF TEST INSTRUMENTATION

A large number of instruments were used to measure the pan and oil temperatures, effluent temperatures, and smoke obscuration for these characterization tests. For creation of a test standard, the total number of devices can likely be reduced. In order to identify the best locations for instrumentation, the individual measurements from each test have been compared to the overall average values. The devices that best represent the average should be included in the standard tests, and all other instrumentation should be removed.

The average differences between each measurement location and the average value over all tests conducted are shown in Table 18. The average temperature or smoke obscuration was calculated for each second during each test, and the difference between individual points was calculated and averaged throughout the duration of the test from heating to ignition. These average differences are shown in the table. As shown, there was almost no variation (<1°C, <1%/ft) between the smoke meters and the effluent thermocouples located in the hood. This shows that the effluent was uniform within the hood above the range.

There is also almost no variation between the average oil temperature and the oil temperatures measured slightly above and below the half oil depth. Averaged over all tests, the temperature slightly above the half depth had zero difference, and the temperature slightly below was increased by 1°C (1.8°F), variation below the accuracy of the thermocouples used during testing. The variation in the oil temperatures was greater laterally than by depth. In general, either oil TC 1 and or oil TC 3 measured slightly higher or lower than the average by 3–5°C (5–9°F), and the center thermocouple generally tracked the average best. It is recommended for simplicity that a single center thermocouple placed at the half oil depth be used for subsequent oil temperature measurements. It should be inserted as close to the half oil depth as reasonable, but as long as it remains within the oil and does not touch the pan it should provide sufficient accuracy.

Greater variability was observed for the pan temperature measurements. On average, pan TC1 (located closest to the handle) measured the highest, and pan TC 3 (farthest from the handle) measured the lowest temperatures. This was true for all scenarios except for 3, 8, 9, 14, and 16. These tests all used different pans than the baseline tests, which used the Vollrath 10 in. (25 cm), 8 gauge aluminum pan. This pan was found to lean slightly towards the handle due to the torque applied by the handle mass and the slightly curved pan bottom. The pans used in Scenarios 3, 8, 9, 14, and 16 either settled at different angles, had convex shaped bases, or extended well beyond the base of the element compared to the baseline pan.

Table 18 – Average variation between individual measurements and test averages for comparison of instrumentation

See Table 2 in Section 5.3 for description of test scenarios	Pan Temperatures			Oil Temperatures					Effluent Temperatures				Smoke Obscuration	
	Pan TC1 (°C)	Pan TC2 (°C)	Pan TC3 (°C)	Oil TC1 (°C)	Oil TC2 (°C)	Oil TC 3 (°C)	Above Half Oil Depth (°C)	Below Half Oil Depth (°C)	EF1 (°C)	EF2 (°C)	EF3 (°C)	EF4 (°C)	Meter 1 (%/m)	Meter 2 (%/m)
Scenario 1	11	1	-12	-6	3	3	0	0	1	0	0	-1	-1	1
Scenario 2	9	1	-10	-6	2	4	0	0	0	0	0	0	0	0
Scenario 3	5	-5	0	-4	3	1	0	0	0	0	0	1	0	0
Scenario 4	12	1	-13	-5	2	4	0	0	0	1	0	0	-1	1
Scenario 5	10	1	-11	-6	3	3	0	0	0	0	0	0	-1	1
Scenario 6	10	1	-12	-4	3	1	0	0	0	0	0	0	1	-1
Scenario 7	7	-3	-4	-3	3	3	0	-3	0	0	0	0	0	0
Scenario 8	6	-8	4	-3	1	2	0	0	0	0	0	0	-1	1
Scenario 9	11	-16	5	-2	3	-1	0	-1	0	0	0	0	-1	1
Scenario 10	5	-1	-4	-4	2	0	-1	2	0	0	0	0	-1	1
Scenario 11	7	-3	-4	3	-4	8	-3	-5	-1	0	1	0	1	-1
Scenario 12	0	0	0	5	-2	4	-2	-5	0	0	0	0	1	-1
Scenario 13	10	2	-12	-4	1	2	0	0	0	0	0	1	0	0
Scenario 14	5	-14	8	-5	0	5	1	0	0	0	0	0	-1	1
Scenario 15	-1	0	1	-4	2	1	0	0	0	0	0	1	0	0
Scenario 16	-31	27	4	-5	3	3	0	0	1	0	-1	0	-1	1
All Phase 2 Tests	6	-2	-5	-3	2	3	0	-1	0	0	0	0	0	0
All Phase 1 Tests	6	-1	-4	-5	3	-1	-1	3	0	0	0	0	-1	1
All Tests	7	-2	-5	-4	2	1	0	1	0	0	0	0	-1	1

For tests conducted with very large pans (Scenario 16), the center pan temperature was an average of 27°C (49°F) greater than the test average. This was due to the reduced temperatures at location 1 and 3 where the pan did not contact the element. It is believed that the center temperature is most representative of the actual pan temperatures in this case, despite its difference from the average.

The other tests showing the largest disparity between the center temperature and the average were Scenario 9 (16°C (29°F) below average) and Scenario 14 (14°C (25°F) below average). Scenario 9 was conducted using the cast iron pan which had a slightly convex base, reducing contact between the center of the pan and the element, reducing the center pan temperature. Scenario 14 was conducted with the low end stainless steel pan, and it is unclear why the center temperature was reduced for this case. Considering all other test cases, however, the center pan temperature remained within 10°C (18°F) of the average pan temperature and provided a good estimate of the average. The center measurement should be sufficient for characterization of standard tests.

9. RECOMMENDATIONS FOR TEST STANDARD

One intent of a standard test is to provide a realistic test condition that bounds other likely hazardous conditions. Therefore, a device that can prevent the standardized scenario can reasonably be expected to prevent most other potential fire scenarios. The use of combustible cooking oils for testing was selected because it presents the greatest potential hazard, and should bound other cooking fire scenarios. This analysis was conducted in order to identify the cooking oil scenarios that would present the greatest challenge to potential prevention devices. In addition, recommendations are provided for demonstrating that an acceptable test has been run, and performance guidelines for evaluating prevention devices.

9.1.1. Test Scenarios

In order to determine the conditions presenting the greatest challenge, three potential types of detection devices have been considered. These theoretical devices, and the situations that cause them the greatest challenge, include:

- Pan temperature measurement with fixed pan temperature threshold
    - Shortest time windows between fixed pan temperatures and ignition
    - Lowest pan temperatures at ignition
- Pan temperature measurements incorporating algorithm (e.g., rate-of-rise)
    - Smallest or largest slope of pan temperature approaching ignition
    - Shortest time window between fixed pan temperatures and ignition
    - Lowest pan temperatures at ignition
- Smoke concentration sensor
    - Shortest time window between production of smoke and ignition
    - Lowest total amount of smoke produced before ignition

With regard to selection of an oil, canola oil was found to produce smoke at the highest temperatures (275–280°C (527–536°F) on average), and reach ignition in the same time and same temperatures (or slightly faster) as the other oils. These aspects would provide the greatest potential challenges, and therefore canola oil was selected for continued testing. Although only tested once, the peanut oil used in Phase 1 also heated quickly and produced smoke at high temperatures, comparable to the canola oil tested. However, canola oil is deemed more representative of products found in homes than peanut oil, and it was selected for continued testing.

No systematic variations in ignition or smoke temperatures were observed between commercial and consumer grade oils, or between various brands of oils tested. Oil temperatures measured when smoke obscuration reached 1.6%/ft (5%/m) varied by as much as 30°C (54°F) for repeat tests conducted with different oil brands, and oil temperatures measured at ignition varied by as much as 10°C (18°C). However, these variations occurred randomly and could not be attributed to any particular oil brand, with each brand producing both above and below average results for various test scenarios. It should be sufficient to select the oil type and purchase wherever available.

Tests having the fastest heating time to reach ignition also had the shortest time windows for smoke or pan temperature activation, the highest slopes approaching ignition, and the lowest amount of total smoke production. Conversely, tests having the longest total time to ignition had the lowest pan temperatures at ignition and lowest slopes in temperature rise. In order to properly challenge all devices, it is recommended to conduct one short and one long heating test for standardized evaluation.

Among the scenarios tested, the fastest tests included the use of the low end stainless steel pan on the 3000 W glass ceramic top range with ¼ in. (6.4 mm) of oil. These tests reached ignition in an average of 381 seconds (371–395). Comparably, the use of the same pan on the 2600 W coil element cooktop reached ignition in an average of 385 seconds (375–406). These two test conditions represent the only tested condition with heating times of less than 7 minutes. When the threshold is extended to 8 minutes, the cast iron pan on the glass ceramic top range with ¼ in. (6.4 mm) of oil and the Phase 1 fresh canola oil and peanut oil tests (with 8 in. (20 cm) pan on 2600 W coil) are included as well.

The longest tests conducted involved the use of the 14 in. (36 cm) pan. Of the five tests conducted with this pan, four ignited in less than an hour of heating with times ranging from 1199 to 3488 seconds (20–58 minutes). These tests were highly variable in total ignition time and pan and oil heating rates. When tests between 15–20 minutes were considered, this included the use of the 10 in. (25 cm) aluminum pan on the glass ceramic top range with ¼ in. (6.4 mm) of oil and on the electric coil range with ½ in. (12.8 mm) of oil.

The “fast” tests reaching ignition in less than 8 minutes, the “slowest” tests taking longer than 20 minutes, and the “slow” tests taking between 15–20 minutes to ignition are summarized in Table 19. The maximum and minimum pan and oil temperatures and smoke obscuration obtained from each ignition time group are shown in Figure 113.

Table 19 – Test scenarios found to provide fast, slow, and slowest ignition times

	Test ID	Pan			Oil		Range		Ignition Time	
		Size In. (cm)	**Material**	**Mass g (lb)**	**Type**	**Depth In. (mm)**	**Type**	**Power W**	**sec**	**min**
FAST	P1-5	8 (20)	Aluminum	622 (1.4)	Canola	0.25 (6.4)	Coil	2600	464	7.7
	P1-6								475	7.9
	P1-7	8 (20)	Aluminum	622 (1.4)	Peanut	0.25 (6.4)	Coil	2600	465	7.8
	P2-16	10 (25)	Stainless Steel	694 (1.5)	Canola	0.25 (6.4)	Coil	2600	406	6.8
	P2-17								375	6.3
	P2-18								383	6.4
	P2-28	10 (25)	Stainless Steel	694 (1.5)	Canola	0.25 (6.4)	Glass ceramic	3000	379	6.3
	P2-29								371	6.2
	P2-30								395	6.6
	P2-31	10 (25)	Cast Iron	977 (2.2)	Canola	0.25 (6.4)	Glass ceramic	3000	437	7.3
	P2-32								452	7.5
	P2-33								458	7.6
Slow	P2-25	10 (25)	Aluminum	817 (1.8)	Canola	0.25 (6.4)	Glass ceramic	3000[1]	1026	17.1
	P2-26								1137	19.0
	P2-27								1109	18.5
	P2-25a								1109	18.5
	P2-37	10 (25)	Aluminum	817 (1.8)	Canola	0.50 (12.8)	Coil	2600	986	16.4
	P2-38								974	16.2
	P2-39								974	16.2
Slowest	P1-27	14 (36)	Aluminum	1717 (3.8)	Canola	0.25 (6.4)	Coil	2600	1398	23.3
	P1-28				Soybean				1199	20.0
	P2-43			1808 (4.0)	Canola				2230	37.2
	P2-44								3488	58.1
	P2-45								DNI[2]	

1 – Power was cycled on/off by glass break sensor, average power approximately 2000 W
2 – DNI (did not ignite) after 1 hour of heating

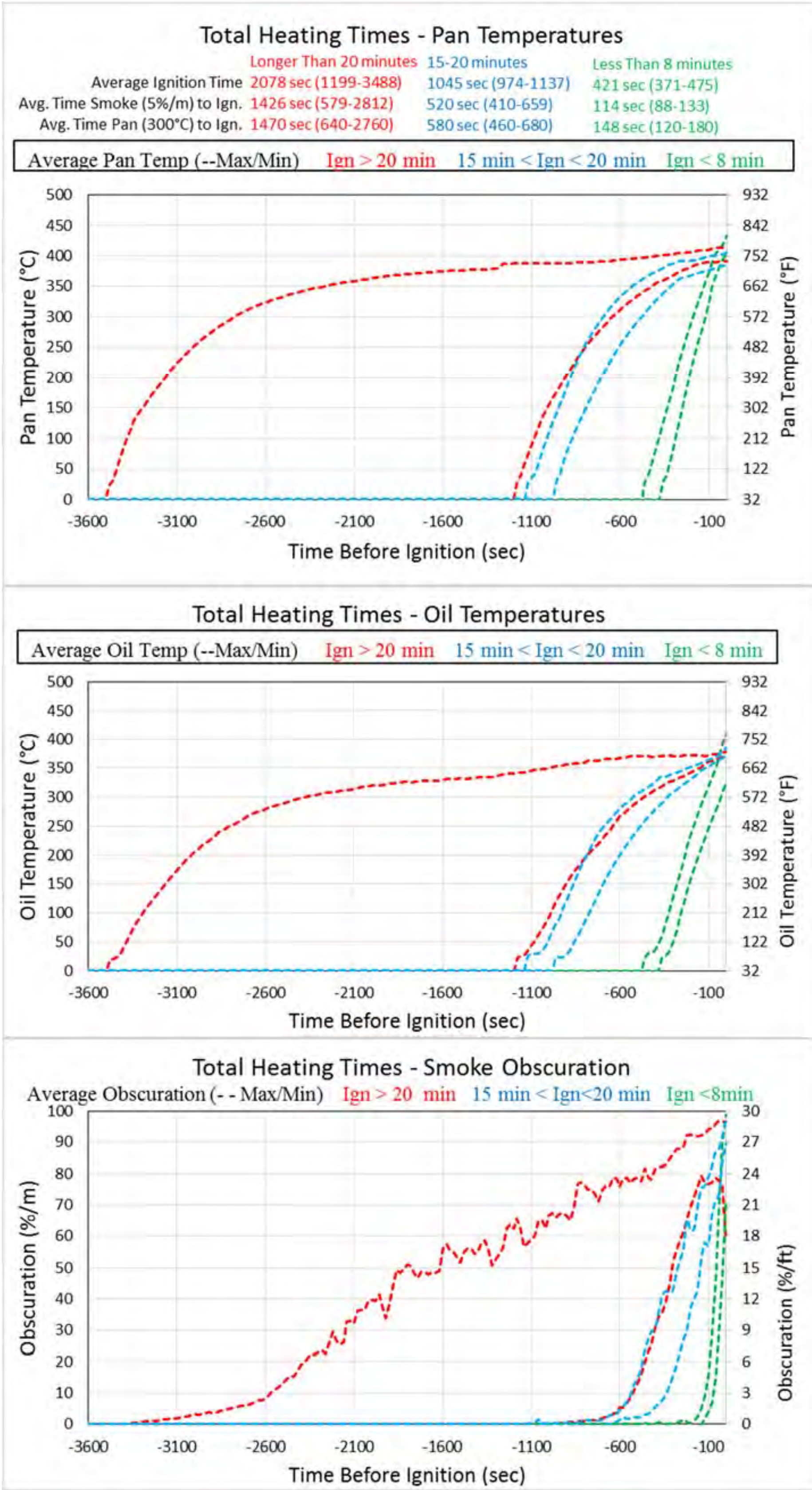


Figure 113 – Pan and oil temperatures and smoke obscuration curves for fastest and slowest ignition times among all tests

The specific test conditions provided above and in Table 19 should be considered as guidelines for achieving fast and slow tests, but other combinations of variables will likely produce comparable test results. Many combinations of test variables (pan, range, oil) should be able to produce fast and slow tests.

Due to the variability in the 14 in. (36 cm) pan tests, it may be desirable to run a “slow” (15–20 minute) test as the test standard, or find other means for lengthening the test duration while maintaining tighter repeatability, such as increasing the depth/volume of oil used.

9.1.2. Demonstration of Acceptable Test

Regardless of the test conditions used to achieve the desired ignition times, the standard tests should fall within the bounds of the pan and oil temperature and smoke profile curves shown above for each time grouping. If the device to be tested relies only on temperatures measured at the pan/oil/range level, there should be no need to construct the collection hood and measure smoke production from the test source. In addition, when constructing the hood it should not be necessary to instrument with temperature or gas measurements, as these measurements did not provide significant additional data regarding the approach to ignition.

As discussed in Section 8.0, the pan and oil temperatures need only be measured at the center of the pan and the center depth of the oil. The oil temperature should remain below the oil surface and not contact the base of the pan, but slight variations in depth from the half oil depth (e.g., ± 1/16 inch for ¼ inch oil depth) should not significantly impact the measurements.

While the characterization tests were all run to ignition, this should not be necessary for demonstration of an acceptable test in standardized testing. All tests that were run in Phase 2 (most responsive TC measurements) ignited at center oil temperatures greater than or equal to 350°C (7662 °F), with the lowest center oil temperature measured at 374 °C (795 °F) for the aluminum pan on the glass ceramic top range.

The shortest time window between the time the center oil temperature reached 350°C (662°F) and ignition was 29 seconds, for the canola oil tested in the cast iron pan on the 3000 W glass ceramic top range. If standardized scenarios are run until the center oil temperature reaches 350°C (662°C), it should be possible to demonstrate sufficient alignment with the previous tests without having to deal with the increased hazards resulting from ignition.

If the element is shut off at the time the oil temperature reaches this threshold, the test data can then be aligned using this point as time zero. The measured maximum and minimum pan and oil temperatures, and smoke obscuration for the fast, slow, and slowest tests conducted are shown in Figure 114.

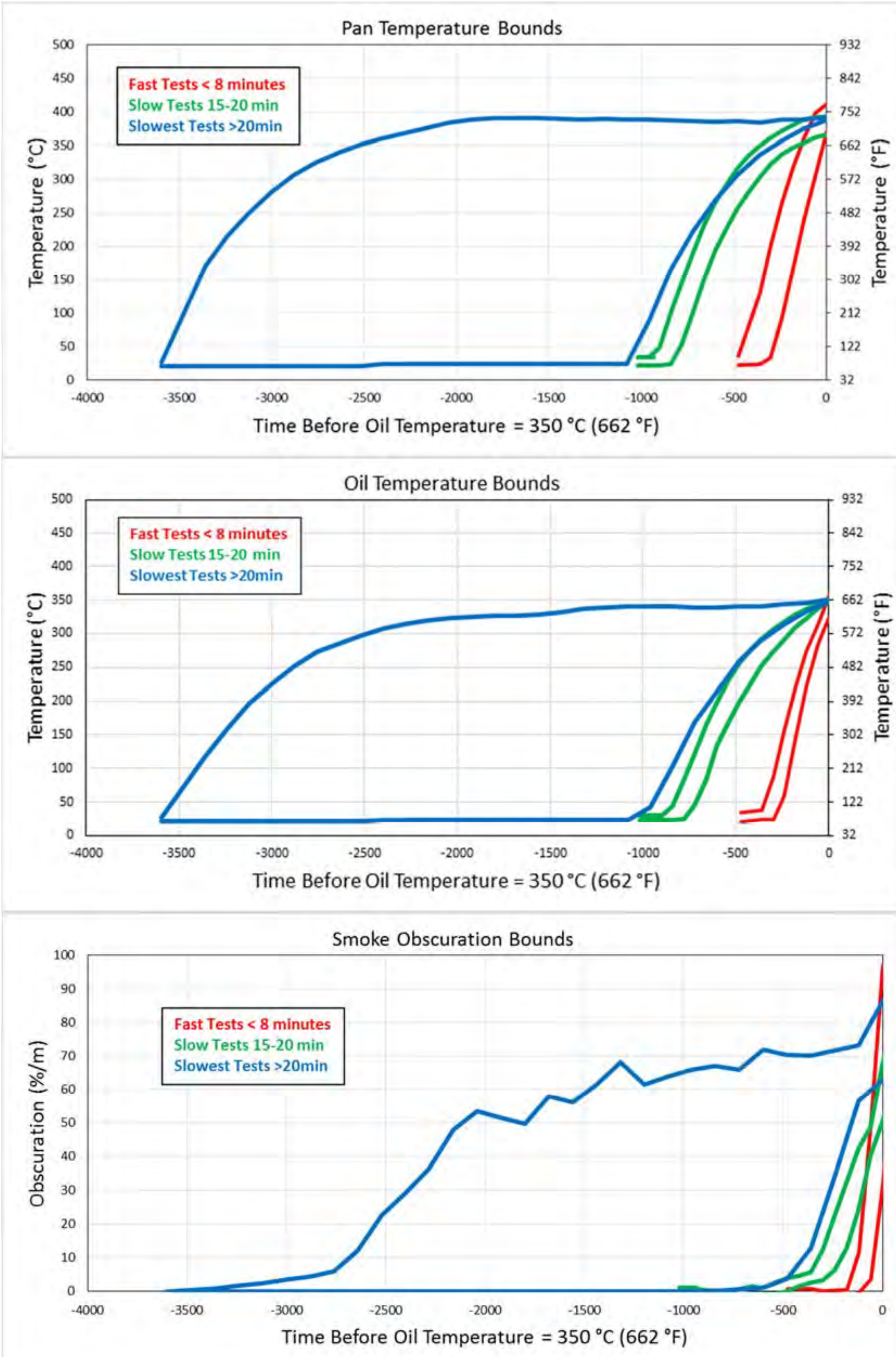


Figure 114 – Pan and oil temperatures and smoke obscuration bounds aligned to a measured oil temperature of 350°C (662°F)

There is some overlap in curves between the slow and slowest tests. The desired standard test could select between these two types of tests, or require both. Both time boundaries would provide a moderate scenario between the extremes for additional prevention confidence.

If a prevention device cannot be disabled or isolated from the range during testing, it may be possible that an oil temperature of 350°C (662°F) cannot be reached to verify test acceptability. If this is the case, a test should be run until the prevention device activates. The pan and oil temperature and smoke (if applicable) curves should then be plotted with the start of heating aligned within the bounds of the initial times for the fast, slow, or slowest tests shown above. The same alignment time must be provided to all curves uniformly, and different start times should not be applied to demonstrate acceptable pan, oil, or smoke curves separately. If the growth profiles can be contained within the bounds of the curves up until the prevention device activates, this should be sufficient demonstration of an applicable test. Baseline tests should be repeated in triplicate to demonstrate alignment with the desired test boundaries.

If smoke is not used as a prevention criteria by the device under test, there is no reason to measure smoke during testing and demonstrate consistency with the above smoke test criteria. If smoke is to be used as an activation criteria, it must be demonstrated that the test setup produces smoke within the boundaries shown above using the same 4 ft x 4 ft (1.2 x 1.2 m) enclosed collection hood. If this can be verified, the hood should then be removed and the same range/pan/oil should be tested within a mock kitchen with operable exhaust hood. The design of this kitchen space, the configuration and flow rates of the exhaust hood, the installation location of the proposed sensor, and the expected smoke obscuration profiles have not been defined. Additional effort will be required before these aspects of a test standard can be defined.

9.1.3. Prevention Device Performance Criteria

After an acceptable test setup has been demonstrated, the prevention device should be installed and activated and the exact test condition repeated. If the device has not activated by the time the oil temperature reached 350 °C (662°F), or allows the oil to reach this threshold after activation, the test should be manually ended and the device considered unacceptable. This maximum threshold temperature has been selected because no ignitions occurred prior to this threshold in the tests conducted. If desired, a lower maximum threshold could be selected. In this case, the demonstration of an acceptable test could also be shifted to provide better alignment with the desired threshold.

Useful data for selection of an oil temperature threshold is provided in Table 20. In addition to the tested data, potential thresholds are provided from a Japanese gas range standard [6,7], a series of cooktop temperature limited tests conducted by Primaira [8], and an existing temperature limited device [9]. As shown, the oil temperature threshold of 350 °C (662 °F) would provide a minimum of 29 seconds before ignition for the tests conducted with corresponding pan temperatures ranging from 365-407 °C (689-765 °F). For the phase 2 tests utilizing the final recommended instrumentation, ignitions did not occur until the oil temperatures reached 374-406 °C (705-763 °F) and pan temperatures reached 385-432 °C (725–810 °F). Based on the available test data a threshold in the range of 300 to 350 °C (572 to 662 °F) should be sufficient for prevention of ignition. If a more conservative threshold is desired, such as 250 °C (482 °F) oil temperature, the minimum time to ignition increases to 130 seconds and the resulting pan surface temperatures decrease to 263-312 °C (505-594 °F). An oil temperature threshold of 300 °C is currently used by the Japanese Industrial Standard (JIS) 2103 and 2093 [6,7].

Table 20 – Data for selection of oil temperature maximum threshold

Temperature at Ignition (Center TC Only)				
Location	Min [°C (°F)]		Max [°C (°F)]	
Pan	385 (725) – Test P2-18		432 (810) Test P2-26	
Oil	374 (705) - Test P2-25a		406 (763) - Test P2-32	
Oil Temperature Threshold (Center TC only)	**Minimum Remaining Time To Ignition**		**Pan Temperature Range (Center TC only)**	
	[sec]	[Test]	Min [°C (°F)]	Max [°C (°F)]
250 °C (482 °F)	130	P2 - 28	263 (505)	312 (594)
300 °C (572 °F)	85	P2 - 29	316 (601)	360 (680)
325 °C (617 °F)	60	P2 - 31	342 (648)	388 (730)
350 °C (662 °F)	29	P2 -32	365 (689)	407 (765)
Representative Existing Temperature Criteria for Prevention Devices				
Japanese Standard JIS 2103, 2093 [6,7]				
Limit oil temperature to 300 °C (572 °F) on gas range				
Primaira Cooktop Temperature Control Study [8]				
Limited temperature of pan bottom to 371°C (700°F)				
Safe-T-Element™ Temperature Limiting Device [9]				
Limit temperature of cast iron plate to 350 °C (662 °F) Pan and oil temperatures would also remain below this threshold				

In order to simplify the analysis, no other criteria beyond the oil temperature threshold should be included for verification of an acceptable mitigation device test result. Additional limits should not be imposed on the pan temperature or smoke concentration. If the device can prevent the measured oil temperature from exceeding this threshold, it should be considered sufficient prevention performance.

A minimum pan temperature threshold should also be applied to prevent against potential nuisance activations and ensure the device allows for realistic cooking to be performed. Based on a previous assessment of cooking practices, some high temperature cooking operations may require pan bottom temperatures of 246–289°C (475–550°F) and food temperatures from 232–260°C (450–500°F) [10]. A minimum activation temperature threshold in this range should also be considered for evaluation of prevention devices. For example, a fire prevention technology should not limit an oil temperature below 250°C (482°F).

In addition to a minimum temperature threshold, it should be demonstrated that the inclusion of the prevention device does not alter the heating rate from the baseline tests. The pan and oil temperature growth curves obtained with the device installed should not deviate from the test conducted without the device up until the prevention device has activated (within some defined bounds of error).

For example, for a fast heating test conducted without a prevention device and average pan temperature slope of 54°C/min (97°F/min) may be observed. This would be within the bounds of an acceptable test as shown in Figure 114 in Section 9.1.2. A prevention device is then installed and found to activate when the pan temperature equals 350°C (662°F), but the pan temperature slope is decreased to 20°C/min (36°F/min). This may not be considered an acceptable test result, even though the device prevented ignition within the minimum and maximum pan temperature limits. This device could drastically increase the time required to cook food. Limits should be placed (e.g., 10%) on the reduction in heating rate of the pan/oil compared to the base line testing.

If a device can: 1) operate after the desired minimum oil temperature is reached; 2) operate before the maximum oil temperature is reached; and, 3) does not drastically reduce the heating rate measured without the device present, it should be considered acceptable. These three criteria would be required for achieving a passing test result.

9.1.4. Summary of Recommendations

Based on the characterization tests conducted, the following requirements for conduct of a standardized test are recommended.

- Instrumentation
  - Single welded 24 gauge, type K thermocouple welded to the center of the top surface of the test pan
  - Single Inconel sheathed, grounded bead, type K 0.010 in. (0.25 mm) thermocouple inserted into the oil at half the oil depth near the center of the pan
  - 632 mm red 5 mW laser mounted in a 4 ft x 4 ft (1.2 x 1.2 m) collection hood centered over the test pan at a height of 3 ft (0.9 m) above the range with photodiode sensor
    - Only necessary if prevention device under test (DUT) utilizes smoke measurements for activation
    - Entire collection hood only needed if fire prevention system utilizes smoke
- Test Setup
  - Any combination of range/pan/oil that can reach ignition:
    - In less than 8 minutes
    - In greater than 20 minutes (15–20 may be considered instead)
  - Must demonstrate pan and oil temperatures within the bounds developed (see Figure 114) up to a pan temperature of 375°C (572°F)
    - Need not run test to ignition to verify acceptable test condition
    - Must conform with smoke bounds only if fire prevention system utilizes smoke for activation
    - If prevention device cannot be disabled or removed from range, pan/oil/smoke curves must align up to the activation point of the device
    - Recommend using conditions already tested, but if the applicability of a certain prevention technology limits the selection of ranges or pans, other conditions may be demonstrated acceptable
- Device Performance
  - Device must not activate before a predetermined oil temperature has been reached
    - For example, 250°C (482°F) based on potential oil temperatures for high temperature cooking
    - Some cooking may be performed with food temperatures as high as 260°C (500°F) [10]
  - Device must not activate after a predetermined oil temperature has been reached
    - Should prevent temperature, even with overshoot after cutting power from range
    - 300 to 350°C (572 to 662°F) may be appropriate

    - This range is based on the results of the characterization tests. No test ignited within 29 seconds of reaching 350 °C
    - An existing Japanese pan temperature limiting device specifies a maximum of oil temperature of 300°C (572°F), rather than a minimum [6,7]
    - Primaira cooktop temperature limiting study use a pan bottom temperature of 371°C (700°F) without an ignition occurring [8]
    - Safe-T-Element™ limits the plate surface to 350 °C (707 °F), oil temperature therefore also limited below this threshold [9]
  - Device must not reduce the pan or oil heating rate from the baseline test by greater than specified threshold
    - This number should be selected to limit the impact of prevention devices on cooking performance and heating rates
    - For example, 10%, but a greater or smaller acceptable margin may be considered

10. REFERENCES

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