NIST Technical Note 1986

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U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

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Walter Copan, NIST Director and Undersecretary of Commerce for Standards and Technology

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Investigation of Residential Cooktop Ignition Prevention Technologies

ABSTRACT

Several international standards and regulations regarding residential cooktop ignition prevention have existed for more than a decade. Among these, UL 858 (2014) is the only one that addresses electric coil element cooktops. UL 858 (2017) was recently revised from an oil pass/fail ignition test to include the option of a test that considers the average temperature of a dry (without cooking oil) cast iron pan. If the average pan temperature does not exceed 385 °C for 30 min with the element on its highest power setting, the test result is considered a pass.

A series of experiments were conducted at the National Institute of Standards and Technology (NIST) to examine the effectiveness of cooktop ignition prevention technologies. Several types of commercially available full-scale residential cooktops with integrated ignition prevention technologies were tested. The experiments provided data on the character of the ignition prevention technologies and their performance in terms of prevention of cooking oil ignition.

More than 100 experiments were conducted using both gas and electric cooktops, including 4 propane gas powered cooktops sold in Asia and 1 stove with electric coil heating elements sold in the USA. A retrofit ignition prevention system for electric coil heating elements was also tested. The ignition prevention technologies employed a variety of configurations and engineering designs. Experiments were conducted using four types of cooking vessels. The pans tested were approximately round, about 20 cm to 22 cm in diameter, and 4 cm to 5 cm in depth. The tests followed the UL 858 standard on abnormal cooktop fire hazards, even though UL858 is based solely on an electric coil cooktop technology using either a dry or "wet" (with cooking oil) cast iron pan. Five thermocouples were attached on the bottom of the pans in a cross pattern and the average pan temperature during cooking was monitored. For the experiments involving cooking oil, the incidence of auto-ignition was observed. About half of the experiments were conducted using dry pans and half with small amounts of canola oil.

The results showed that some of the cooktop technologies were more reliable than others in preventing oil ignition and maintaining temperatures below the UL 858 standard's limit temperature criteria. The results demonstrated that residential cooktop ignition prevention technologies can be effective for both electric and gas cooktops.

Keywords: cooking fires; ignition prevention; cooking oil fires; kitchen fires

Disclaimer

Certain trade names or company products are mentioned in the text to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment is the best available for the purpose.

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1. INTRODUCTION

During the five-year period from 2010 to 2014, U.S. fire departments annually responded to approximately 166,000 home fires that involved cooking equipment [1]. The damage caused by these fires included an annual average of 480 civilian deaths, 5,500 civilian injuries, and $1.1 billion in direct property damage. Cooking equipment was involved in 46%, that is almost one-half of reported home fires, 19% of home fire fatalities, and 44% of reported home fire injuries. U.S. Fire Departments responded to more than 450 home cooking fires per day during this period. Cooktops, or ranges, have been involved in most of these cooking fires losses.

Of the reported home fires involving cooking equipment, ranges or cooktops accounted for 62 % of the fires, 88 % of civilian cooking fire deaths, 79 % of civilian cooking fire injuries and 73 % of direct property damage. Use of electric cooktops are associated with a higher risk of cooking fires as compared to gas ranges. Although only 60% of households use electric cooktops, 80% of cooktops involved in reported cooking fires were powered by electricity. Using this information, NFPA reports that the rate of reported fires per million households was 2.6 times higher with electric ranges compared to gas ranges. In addition, NFPA reported that unattended equipment was a leading cause of cooking fire ignitions, accounting for 34 % of all cooking fires. More than half (55%) of the non-fatal civilian cooking fire injuries occurred when the victims tried to fight the fire themselves [1].

Although there has been significant progress in reducing home fire fatalities over the last 30 years, there has been relatively little progress in home cooking fire fatalities. While home fire fatalities have dropped by about one-half over this period, cooking fire deaths have decreased only 4% during the same period [1]. Thus, cooking fires are a significant problem and are unlikely to go away on their own without significant educational and/or technological changes. Recently, a UL 858 standard has been established which requires new electric coil stoves to pass an abnormal cooking test. The test considers the prevention of electric coil cooktop ignition. A recent study was conducted to consider fire suppression technologies that attempt to address cooktop fires [2].

Several international standards and regulations regarding residential cooktop ignition prevention have existed for more than a decade. Table 1 summarizes these standards, listing the country, cooktop type, the year the standard was enacted and the name of the rule. The table also lists the pass/fail criteria of the test method. If a temperature criterion is used, then the value of the temperature is also listed. Among the standards, UL 858 (2014) is the only one that addresses electric coil element cooktops [3]. UL 858 was recently revised from an oil pass/fail ignition test to include the option of a test that considers the average temperature of a dry (without cooking oil) cast iron pan. If the average pan temperature does not exceed 385 °C for 30 min with the element on its highest power setting, the test is considered a pass. The other standards in the table are associated with countries in Asia; all involving gas cooktops. The Asian test methods focus on the temperature of a dry pan heated by the cooktop with the limit temperature between 250 ℃ and 300 °C. This temperature value is significantly lower than the UL 858 dry pan temperature criterion of 385 °C. The standard in China for cooktop ignition prevention (see Table 1) is voluntary [4]. Currently, there are two manufacturers in China that produce cooktops that address the standard [4]. Fire loss statistics provided by the Japanese gas industry indicate that the number of reported gas stove fires in Japan decreased 38 % during the period from 2007 to 2012 [7]. Loss statistics are not available from Korea.

The details of the test methodology are important. Dinaburg and Gottuck [5] and Primaira [6] reported on the development of the basic protocols for conducting standardized ignition prevention cooktop tests and the impact of a number of parameters on the results. Heating of a pan of oil on a cooktop is a complex heat transfer problem, dependent on many variables including the pan's size, material composition, shape, thickness, flatness, and emissivity, as well as the heating source power and its distribution, the cooktop geometry, oil type and amount, and external factors such as ventilation conditions, and so on. Because of the complexity of the cooking heat transfer phenomena, cooktop technologies developed to address one of the standards in Table 1 may not successfully address any of the other standard test methods. The objective of this report is not to compare the various test methods, but instead to evaluate the feasibility of ignition prevention technologies from the US domestic market and international markets, employing test methods based on the UL 858 standard as a point of reference.

This report describes experiments intended to characterize the performance of ignition prevention technologies in a full-scale residential kitchen scenario. This report is broken into several parts. In Section 2, the experimental apparatus and procedure are discussed. In Section 3, the experimental results are discussed. In Section 4, the work is summarized and conclusions are presented. References are provided in Section 5. The Appendix consists of two parts. In the first section, the efficacy of the method used to measure the temperature of Pan A is discussed. In the second section, the emissivity of a used pan is measured.

Table 1. International Cooktop Ignition Prevention Standards [3, 4, 7]

Country	Cooktop Type	Standard (year)	Standard Test		
			Test Method	Pan Material	Temperature Criteria (°C)
South Korea	Gas	Korean Gas Standard AB331 (2011)	pan temperature	not specified *	300
Japan	Gas	Gas Business Act (2008)	pan temperature	aluminum	250
China	Gas	GB 16410-2007 (2007)	oil temperature	not specified	300
USA	Electric Coil	UL 858 (2017)	oil ignition	cast iron	na
		UL 858 (2017)	pan temperature	cast iron	385
		UL 858 (2014)	oil ignition	aluminum	na
*although not formally specified, aluminum is typically used in practice					

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Cooktop Ignition Prevention Technologies

Commercial cooktop ignition prevention technologies for residential electric and gas cooktops are designed either as a retrofit option or as part of a new stove. Cooktop ignition prevention technologies in new residential stoves commonly rely on one type of sensor technology – a bimetal switch that opens an electrical circuit at a critical limit temperature. Placement of the sensor-switch in the cooktop varies by manufacturer design. One of the designs tested for gas stoves placed the bimetal switch in contact with the bottom of the cooking pan, held in place by a spring-loaded assembly directly below the center of the burner as seen in Figure 1. Associated electronics regulated the flow such that a limit temperature was not exceeded. Another design for gas stoves placed the sensor just under the body of the cooktop about 5 cm from the center of the burner as seen in Figure 2. This design shut the flow once a threshold temperature was exceeded. A design used in another manufacturer's electric coil element stoves placed a bimetal switch about 4 cm directly below the center of the coil heating element just above the bottom of the drip-bowl as seen in Figure 3. Associated electronics regulated the power such that a limit temperature was not exceeded.

Figure 1 Gas cooktop with a spring-loaded bimetal switch protruding above the burner center (left). A close-up of the burner and sensor is also shown (right).

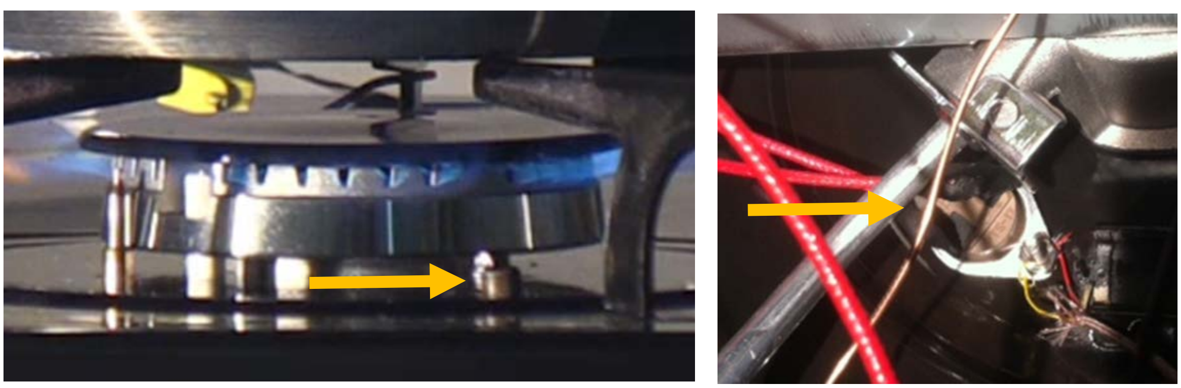

Figure 2 Gas stove with bimetal switch underneath the stove body. A 3 mm diameter total heat flux gauge (positioned at the same distance from the burner center as the switch) is seen protruding above the burner body (indicated by the arrow in the left photo). A view of the stove underbody shows the switch (indicated by the arrow in the right photo), which made physical contact with the stove bottom. For some experiments, a fine gauge bare bead Type K thermocouple (80 µm diameter) was compressed between the sensor assembly and the cooktop bottom.

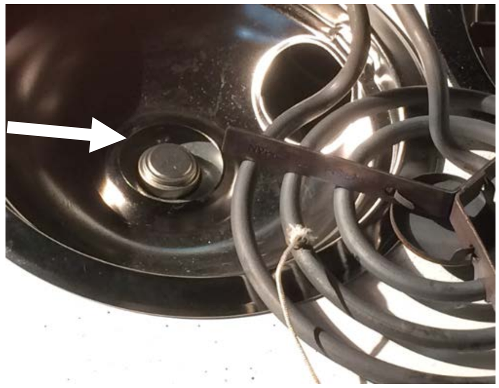

Figure 3 Bimetal switch protruding through the bottom center of an electric stove drip-bowl. The coil heating element with a thermocouple attached to its bottom is also shown.

The technologies selected for study focused on those that would be appropriate for testing using UL 858 (see Table 1) or an analogous method. There are a number of potentially-viable alternate retrofit approaches. One retrofit technology was tested as part of this study. It was designed for electric coil heating elements and used a thermocouple to measure the temperature of the bottom of a metal plate that snugly covered the coil heating element as seen in Figure 4. Electronics regulated the power such that a limit temperature was not exceeded. Experiments were conducted using the smaller heating element only, which had a plate that was 17 cm in diameter.

There are other commercially available, potentially viable, retrofit technologies that were not tested in this study. They include one type that uses a motion sensor to depower a stove during unattended cooking. Another technology uses a timer, depowering the stove after a set amount of time. A third approach involves depowering the stove when a smoke alarm sounds. These alternate technologies would not necessarily be tested for approval using the test methods listed in Table 1.

Figure 4 Bottom and top view of a retrofit technology composed of a thermocouple sensor to measure the temperature of the bottom of a metal plate that covers the coil heating element. Regulating electronics installed under the stovetop are not shown.

2.2 Test Apparatus and Procedure

Eighty tests were conducted following the basis of the test methods described in the UL 858 standard. The experimental test matrix varied three parameters involving 4 pan types, 6 stove types, and whether the pan was wet or dry (48 conditions). Following UL858, five thermocouples were attached to the inner bottom of the pan in a cross-like pattern configured as shown in Figure 5. The average transient temperature was monitored and its maximum value noted. The occurrence of ignition, or its prevention, was tested with the pan filled with 50 g, such that the oil was about 3 mm (or 1/8 in) deep in the20 cm diameter pans tested here ("wet pan tests"). All wet pan tests were conducted with canola oil following UL 858. To check the consistency of the results, a number of the tests were repeated 2 or 3 times.

The four types of pans used in the tests are described in Table 2, which provides information on the pans' shape, outer diameter, depth, material, wall thickness, mass, and flatness. Unless otherwise noted, the uncertainty specified in Table 2 and throughout this report represents the standard deviation of repeat measurements. The values in the table were determined by measurements on several pans of each type. All four pans were approximately round with nominal diameters of 20 cm. Two pans were made of aluminum, one of cast iron, and one of stainless steel. One of the aluminum pans had a hard-anodized, dark surface. The other aluminum pan had a bright, shiny surface. Pan B´ was identical to Pan B except its underside was coated with a thin layer of black paint. Pan flatness was measured using an optical level to determine the difference in the level on either end of the pan bottom.

Figure 5 shows the thermocouple layout and photos of Pans A, C, and D. Thin type K thermocouples (0.5 mm diameter) were used. Thermocouples were attached by spot welding to Pan C and D's cast iron and magnetizable stainless-steel surfaces and by peening to Pan B's aluminum surface. The accuracy of the thermocouple measurement was ± 2 °C as specified by the manufacturer [8].

Table 2. Test Vessel Summary. *

Pan	Shape	Diameter** (cm)	Depth (cm)	Material	Wall (mm)	Mass (g)	Flatness (degrees)	Features
A	round	19.7 ± 0.2	3.9± 0.2	aluminum	2.8 ± 0.1	501.3 ± 0.4	0.1 ± 0.1	hard-anodized surface
B	round	21.7 ± 0.2	4.4± 0.2	aluminum	2.9 ± 0.1	540.9 ± 1.0	0.2 ± 0.1	shiny surface
B´	round	21.7 ± 0.2	4.4± 0.2	aluminum	2.9 ± 0.1	542.7 ± 1.0	0.2 ± 0.1	black bottom
C	nominally round	20.0 ± 0.2	4.4± 0.2	cast iron	3.5 ± 0.5	1473 ± 26	0.2 ± 0.1	irregular surface
D	round	20.0 ± 0.2	3.2± 0.2	stainless steel	2.8 ± 0.1	778 ± 12	0.3 ± 0.1	5 layers*** smooth surface

* represents one standard deviation of repeat measurements
** inner diameter at rim (or lip) of pan
*** uses 18/10 stainless steel inside pan and magnetic grade stainless steel on pan bottom

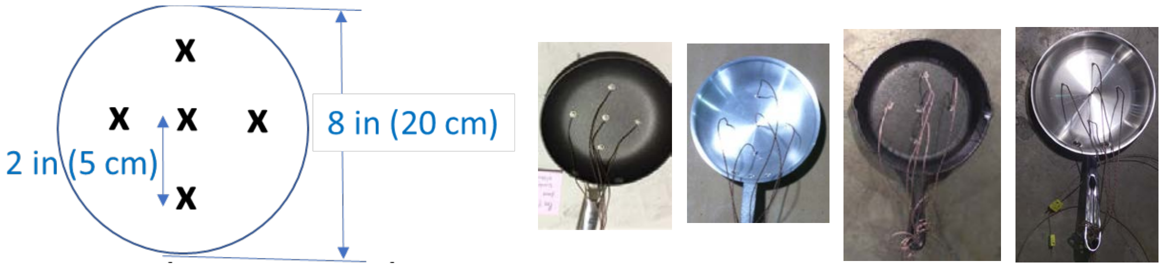

Figure 5 Drawing of the thermocouple layout marked by Xs (left) and photos (right) of the round, nominally 20 cm diameter Pans A, B, C, and D, which were made of anodized aluminium, aluminium, cast iron, and stainless steel, respectively. Thermocouples were attached by use of a screw/washer assembly (Pan A), peening (Pan B), or spot welding (Pans C and D).

A different procedure was used to mount thermocouples onto Pan A where the thermocouple bead was snugly compressed under a small (6-32) screw/washer assembly that was drilled and tapped into the bottom of the pan (see Pan A in Figure 5). This approach was selected because (1) Pan A was composed of aluminum for which spot welding was not practical and (2) peening thermocouples occasionally led to spurious results - sometimes in the middle of the experiment, presumably due to imperfect contact with the pan surface. The Appendix of this report presents the results of two sets of experiments that considered the efficacy of this measurement method. The results showed that the screw/washer thermocouple assemblies can provide a reasonable measure of pan temperature albeit with a time lag of about 5 s compared to the peened thermocouples and an increased measurement uncertainty of approximately 2 °C.

An informal survey of used residential pots and pans indicates that the pan bottoms come in various configurations and states of appearance, some shinier and some darker than others, as seen in Figure 6. Section 6.2 of the Appendix describes measurements on a used pan that show that the emissivity coefficient on visibly dark portions of its bottom surface was equal to 0.997 for temperatures from about 90 °C to 200 °C. On the other hand, the emissivity coefficient for polished or shiny aluminum is known to vary from about 0.04 to 0.06 for temperatures as large as 600 °C [9]. To demonstrate the complexity of the heat transfer process in controlling the oil ignition phenomena, a number of experiments considered the effect of the emissivity of the pan bottom on the maximum pan temperatures and the incidence of oil ignition. In these experiments, the bottom of Pan B, a shiny aluminum pan, was sprayed with a thin coating of high-emissivity black paint (ε=0.94) [10] as a limiting case. The results of these experiments are discussed in Section 3.4 below.

Figure 6 Photo of the bottoms of used residential cooking pans.

For all the experiments, the burners were set to their highest power setting and the burner power was monitored. Experiments were conducted in a quiescent environment and placed under an exhaust hood to remove heat and combustion products. The gas stove experiments were conducted using consumer grade propane with a minimum specified purity of 90 %. The experimental configuration is shown in Figure 7. A propane cylinder was connected to a volume displacement flow meter with a temperature and an absolute pressure sensor. The secondary pressure regulator was adjusted per stove manufacturer specifications. The configuration for the electric cooktop experiments was nearly identical. The electric stoves were connected to 240 V and the coil elements were set to their highest power setting.

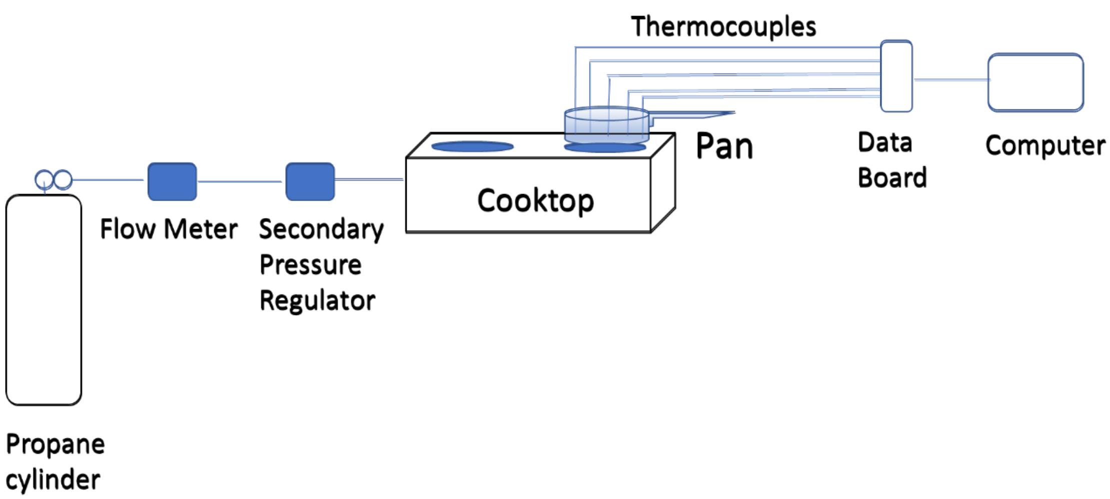

Figure 7 Experimental configuration for the gas stove experiments.

Table 3 describes various aspects of the ignition prevention cooktop systems including information on the burner power and the ignition prevention sensor. The nominal burner power is listed in the table based on the volume flow measurement for the gas cooktops and on the measured current draw for the electric cooktops. For the gas burners, the table lists the stove inlet pressure, which was based on manufacturer specifications.

Table 3. Cooktop burner systems, stove type, gas stove inlet pressure, stove power, power cycle and sensor type.

Stove	Stove Type	Pressure (kPa)	Power (kW)	Power cycle	Sensor Type
1	Electric coil	---	1.2	on/off	bi-metal switch 4 cm below heating coil
2	Electric coil	---	1.4	on/off	thermocouple attached to plate
3	Propane gas	2.0	2.5 *	high/low	spring-loaded bi-metal contact switch
4	Propane gas	2.0	3.0 **	high/low	spring-loaded bi-metal contact switch
5	Propane gas	2.8	2.6	on/off with manual reset	under-stove “hidden” bi-metal switch
6 ***	Propane gas	2.8	2.6	on/off with manual reset	under-stove “hidden” bi-metal switch

* low flow mode power was 0.6 kW
** low flow mode power was 0.4 kW
*** highly similar to Stove 5, but with a different sensor design

The stoves tested in this study were designed to regulate cooktop heating automatically to prevent auto-ignition, while at the same time enabling user cooking preferences. Power regulation in each of the stoves was configured differently as summarized in Table 3. For Stoves 1 and 2, the power was modulated from fully on to completely off and then back to fully on. For Stoves 3 and 4, the gas flow was modulated from high to low flow and then back to high flow. Stoves 3 and 4 had different low flow values, while the high flow values were very similar. For Stoves 5 and 6, the gas flow was completely stopped and had to be manually reset once the flow was stopped.

The experimental procedure involved the following steps. The pan was centered on the burner. For tests using oil, the volume of oil was measured and the oil was carefully introduced into the pan to avoid spillage. The data acquisition system was initiated and the cooktop element or burner was energized to its highest level. Tests were typically conducted for 20 min to 30 min, or until the oil ignited. After a test, any residual canola oil was discarded and new oil was used in the next test. If ignition did occur, the experiment was continued until the oil was completely consumed.

In some experiments using Stoves 1 and 6, calibrated, water-cooled, total heat flux gauges, 12 mm and 3 mm diameter, respectively were used to measure the total heat flux near the sensor. For Stove 6, the heat flux gauge was positioned at the same distance from the burner center as the underbody sensor and is seen protruding above the burner body (indicated by the arrow in the left photo). Figure 2 shows the stove underbody with the sensor highlighted by an arrow (right photo), which made physical contact with the stove bottom. For some experiments using Stove 6, a fine gauge (80 μm) bare bead Type K thermocouple was compressed between the switch assembly and the Stove 6 cooktop, which allowed monitoring of the sensor temperature and determination of the temperature at the time of fuel flow shut-off. For Stove 1, the heat flux gauge was positioned at the location of the limit sensor directly below the center of the heating coil.

3. RESULTS

3.1 Observations

There was little to note in terms of observations when experiments were conducted using a dry pan. When oil was tested, and as the pans and the oil temperature began to increase, a vapor cloud with a smoke-like appearance was generated above the liquid oil. Initially, the vapor was difficult to see without bright light illumination. As the pan temperature increased, the vapor became more visible. When autoignition did not occur, a large fraction of the oil was left in the pan. If autoignition and subsequent fire occurred, the oil burned until the fuel was depleted and the fire self-extinguished. An amount of residue in the form of soot was often present on the bottom of the pan. Figure 8 shows Pan D (stainless steel) after a test using canola oil.

Figure 8. Black soot residue left inside Pan D (stainless steel) after Test 87 using Stove 6.

3.2 Electric Cooktop Systems

Figure 9 shows the transient temperature measurement for the five pan thermocouples (TC1 to TC5) on dry Pan B heated by Stove 1 during Test 36. The transient temperature of the electric heating element (TC6) is also shown in Figure 9. The TC6 temperature profile was an indication that the heating coil element was being powered (increasing temperature) or not powered (decreasing temperature). There was a lag of 5 s to 15 s between the response of the coil heating element and the average temperature of the pan bottom. For the experiment, the data acquisition was started and background was taken for 60 s, then the cooktop power was turned-on. The temperatures on the pan bottom tracked each other to within about 10 °C, increasing steadily for the first 300 s and then cycling off and on as the coil heating element was depowered and powered. Figure 10 presents the average and standard deviation of the same data presented in Figure 9. The maximum of the average pan temperature over the duration of the experiment (over all temperature cycles) was 372 °C (as indicated in the figure), which occurred 800 s after powering the stove during the fifth power-on cycle. After 500 s, the average temperature in the pan was regulated between 336 °C and 372 °C. The standard deviation of the pan temperatures was less than 10 °C throughout the experiment as shown in Figure 10.

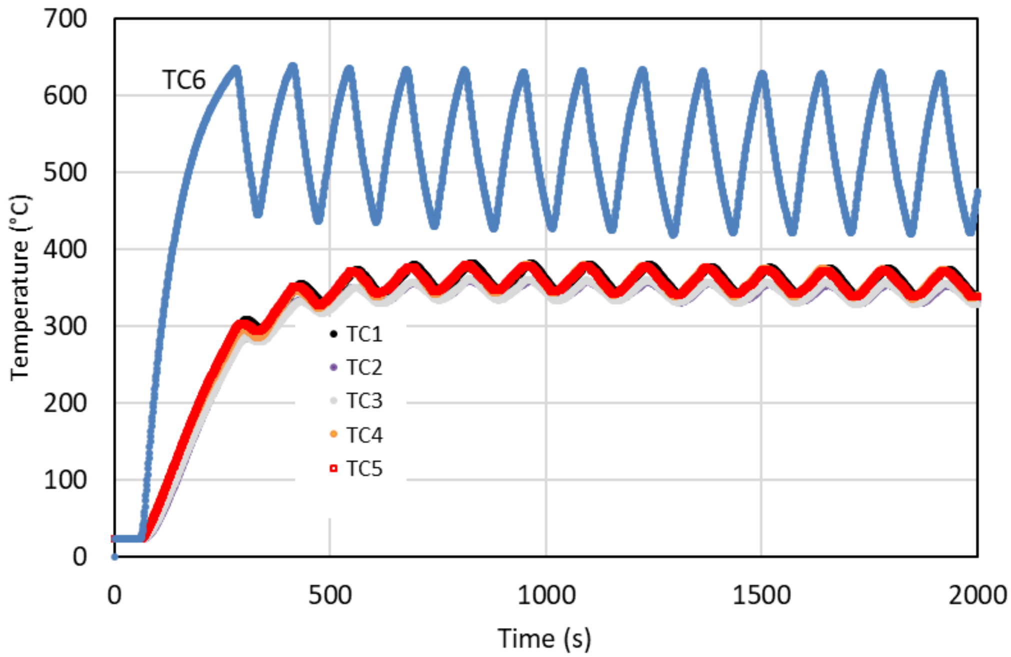

Figure 9 Transient thermocouple temperature measurements (TC1 to TC5) on the bottom of dry Pan B and on the electric heating element (TC6) on Stove 1 during Test 36.

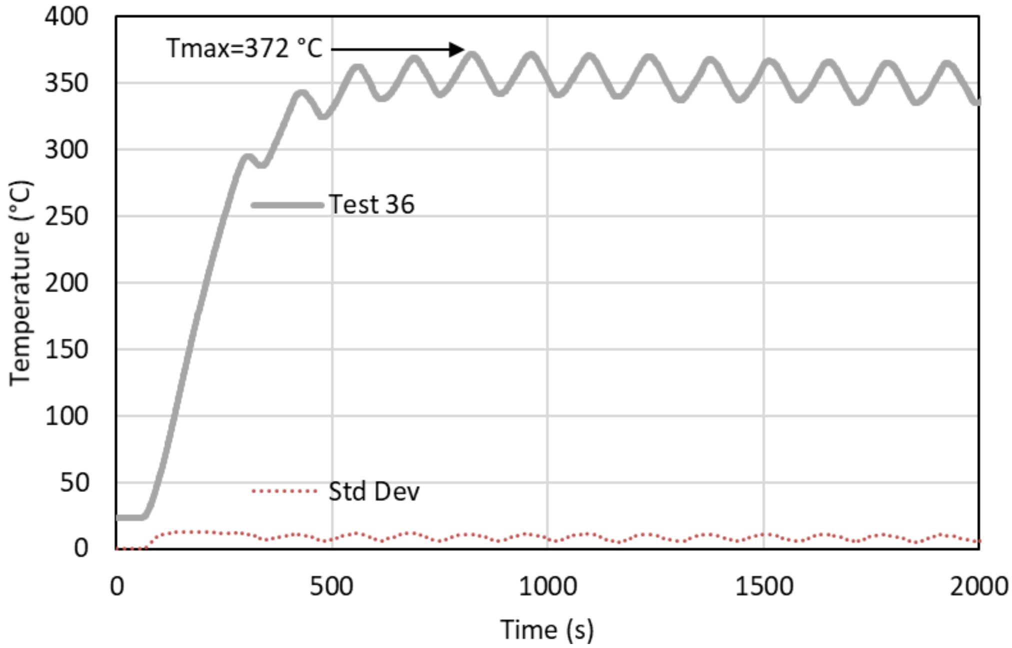

Figure 10 Time-average and standard deviation of temperature measurements of thermocouples TC1 to TC5 on the bottom of dry Pan B on Stove 1 during Test 36.

Figure 11 shows trends similar to Test 36 for Tests 8, 64, and 66, which were repeat dry pan experiments using Pan A on Stove 1. The maximum temperatures for the three tests were 396 °C, 408 °C, and 412 °C, respectively, yielding an average of 404 °C and a standard deviation of 8 °C (or 2 %). Considering all the electric cooktop tests reported here, the average standard deviation of the temperature maxima for the repeat tests was 8 °C.

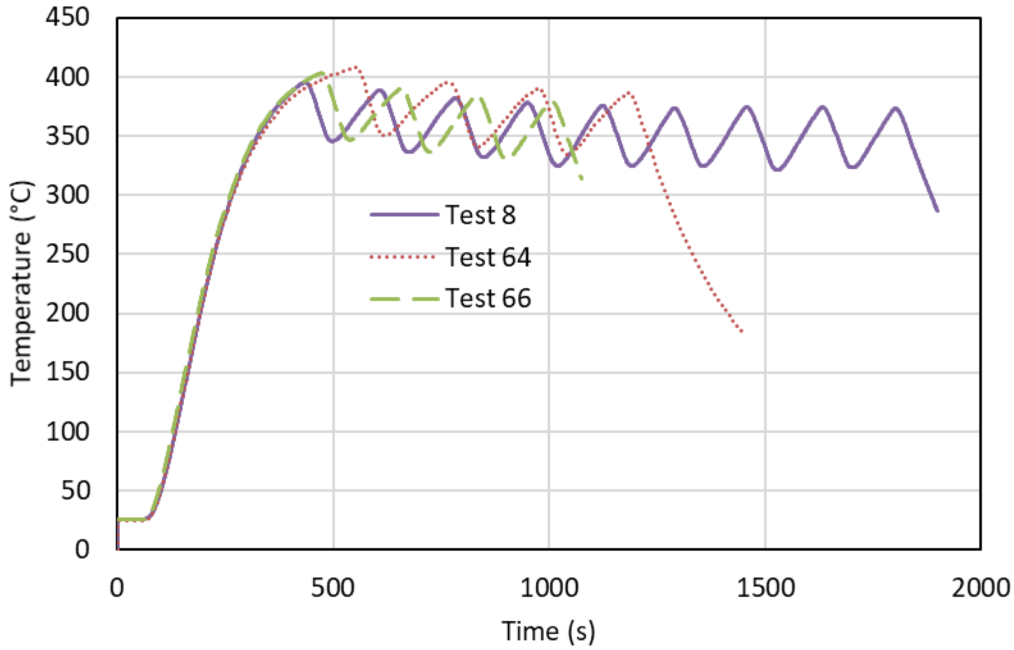

Figure 11 Time-averaged thermocouple temperature measurements on the bottom of Pan A on Stove 1 during repeat Tests 8, 64, and 66.

Figure 12 compares the results of the time-averaged thermocouple temperature measurements in Pan A on Stove 1 during Test 62 (dry pan) and Test 82 (wet pan). In both tests, the maximum pan temperature occurred on the first temperature cycle with the wet pan maximum about 15 °C smaller than the dry pan maximum. On average, the wet pan temperature maxima were 26 °C and 15 °C smaller than the dry pan maxima for Stoves 1 and 2, respectively, likely due to evaporative cooling by the hot canola oil.

Table 4 summarizes the electric coil cooktop experimental results for Pans A – D using Stoves 1 and 2 and if ignition occurred (during the wet pan tests). The table presents the maximum average pan temperatures for each stove – pan combination. The average of the standard deviations of the repeated experiments for the individual tests was about 2 % (or 8 °C) on average. Ignition was not observed to occur during any of the wet pan experiments. The average of the temperature maxima for each of the stoves is listed at the bottom of the table for both the dry and wet tests, which is a convenient way to compare the performance of the stove ignition prevention technologies. The average of the temperature maxima determined for Stove 2 was more than 100 °C lower than those tested using Stove 1 - for both the wet and dry tests. The average of the temperature maxima in the wet pan tests for each of the stoves was smaller than those of the dry pan tests, but the difference was not significant (to a 95 % confidence level) based on the results of a statistical t-test (P=0.3012 and 0.1829 for Stoves 1 and 2, respectively,) [11]. Consideration of the results shown in Table 4 indicate that both stoves using dry Pan C would have passed the UL 858 temperature criteria test. The other dry pans are not expected to meet the UL 858 temperature limit as only cast iron is specified in the UL858 test method.

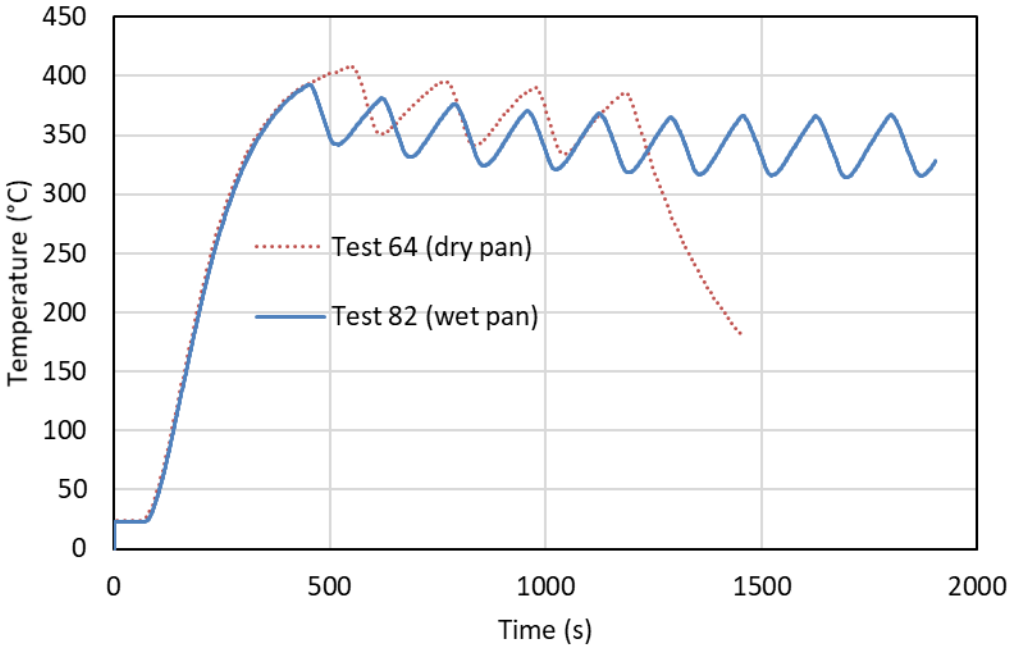

Figure 12 Time-averaged thermocouple temperature measurements on the bottom of Pan A on Stove 1 during Test 64 (dry pan) and Test 82 (wet pan).

Table 4. Electric Cooktop Results. The measured dry and wet pan temperature maxima for Pans A – D heated on Stoves 1 and 2. The average standard deviation for each of the individual electric cooktop test results listed in the table was 2 % (or about 8 °C). The occurrence of oil ignition for the wet pans is noted. For each of the stoves, the average and standard deviation of the maximum pan temperatures among the various pans are listed.

	Dry Pan T_{max} (°C)	
Pan	Stove 1	Stove 2
A	405	268
B	382	278
C	363	226
D	383	295
T_{avg}	384 ± 18	267 ± 29

	Wet Pan			
	Stove 1		Stove 2	
Pan	T_{max} (°C)	Ignition	T_{max} (°C)	Ignition
A	393	No	267	No
B	335	No	250	No
C	285	No	227	No
D	405	No	264	No
T_{avg}	355 ± 56		252 ± 18	

3.3 Gas Cooktop Systems

The results for gas cooktop Stoves 3 and 4 (see Table 5) were qualitatively similar to the electric cooktop results. Figure 13 shows the time-averaged thermocouple temperature measurements in dry Pan A heated on Stove 4 during repeated Tests 23 and 26. The average of the temperature maxima was about 271 °C. Figure 14 shows the high and low fuel flow burner flames during an experiment with dry Pan A on Stove 4. The modulated fuel flow consistently provided a 2.5 kW burner flame in the high-power mode and about 0.6 kW in the low power mode, with the modulation maintaining the pan temperature below its target limit temperature. Stove 3 was similarly engineered, consistently providing a 3.0 kW burner flame in its high-power mode and 0.4 kW in its low power mode.

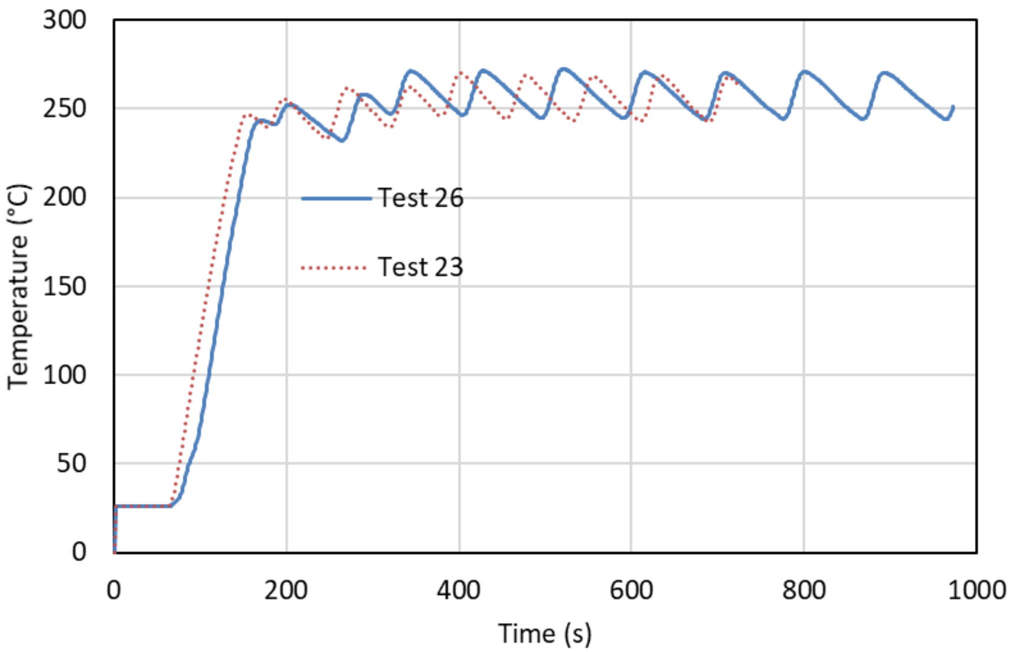

Figure 13 Time-averaged thermocouple temperature measurements on the bottom of dry Pan A heated on Stove 4 during repeat Tests 23 and 26.

Figure 14 High (left) and low (right) fuel flow burner flame modes during experiment with dry Pan A on Stove 3.

Figure 15 shows analogous results for the time-averaged thermocouple temperature measurements in Pan B with 3 mm (1/8 in) of oil heated on Stove 4 during repeat Tests 69 and 71. The average of the temperature maxima was about 268 °C and oil ignition did not occur for any of the oil experiments using Stoves 3 or 4. Considering all the gas cooktop tests reported here, the average standard deviation of the temperature maxima for the repeat tests was 14 °C (or 4 %).

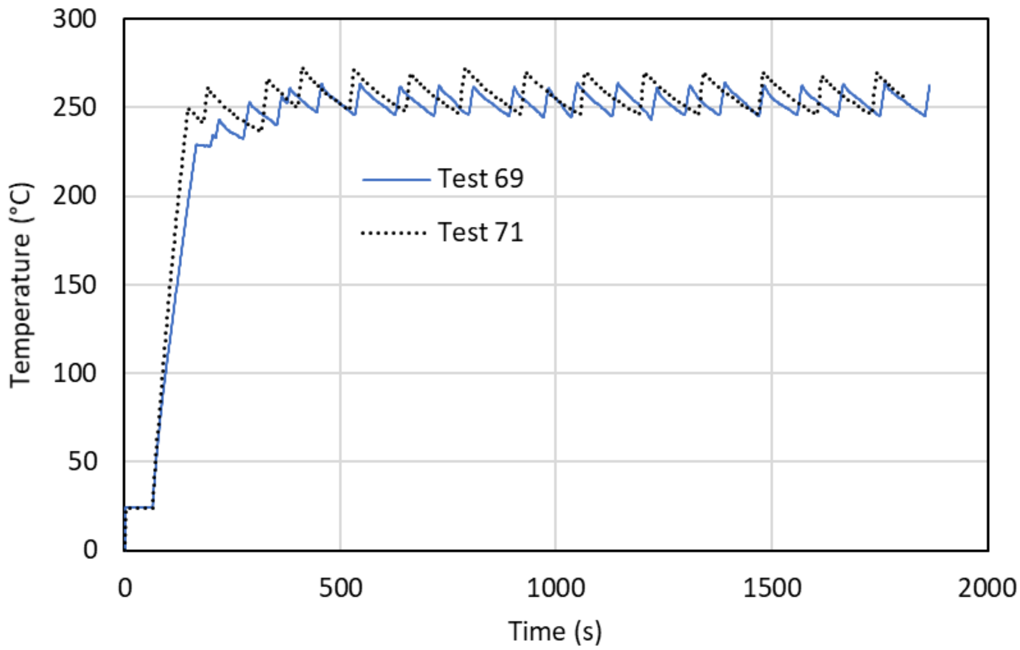

Figure 15 Time-averaged thermocouple temperature measurements on the bottom of Pan B with 3 mm (1/8 in) of oil heated on Stove 4 during repeat Tests 69 and 71.

The results for gas cooktop Stoves 5 and 6 (see Table 5) were qualitatively different than the results for Stoves 1 - 4. Stoves 5 and 6 were designed to shut-off once a critical temperature limit was obtained and could only be reset manually. Figure 16 shows the transient thermocouple temperature measurements in wet Pan B with 3 mm (1/8 in) of oil heated on Stove 6 during Test 90. The temperature at the limit sensor is also shown. The oil ignited at about 420 s into the experiment and continued to burn until the fuel was consumed about 120 s later. The cooktop burner shut-off at 840 s into the experiment when the thermocouple at the limit sensor TC7 was approximately 191 °C. Experiments using the various pans on Stove 6 showed that the limit sensor consistently shut-off the cooktop burner fuel flow when the temperature was 193 °C ± 3 °C. Similar results were observed for the limit temperature on Stove 5, which was not unexpected since Stoves 5 and 6 were highly similar in terms of the stove and ignition prevention technology design.

Figure 17 shows the time-averaged thermocouple temperature measurements in wet Pan B with 3 mm (1/8 in) of oil heated on Stove 6 during repeat Tests 60 and 90. Oil ignition occurred during both experiments, when the average pan temperature was about 400 °C. The propane flow to the cooktop

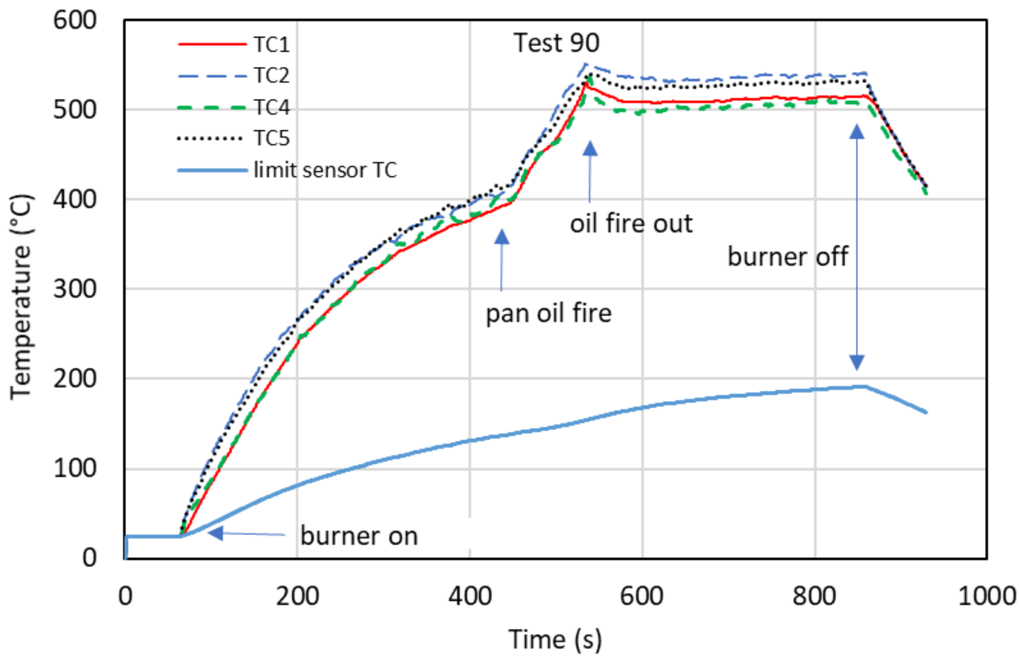

Figure 16 Transient thermocouple temperature measurements (TC1 to TC5) on the bottom of wet Pan B with 3 mm (1/8 in) of oil heated on Stove 6 during Test 90. The measured limit sensor temperature is also shown.

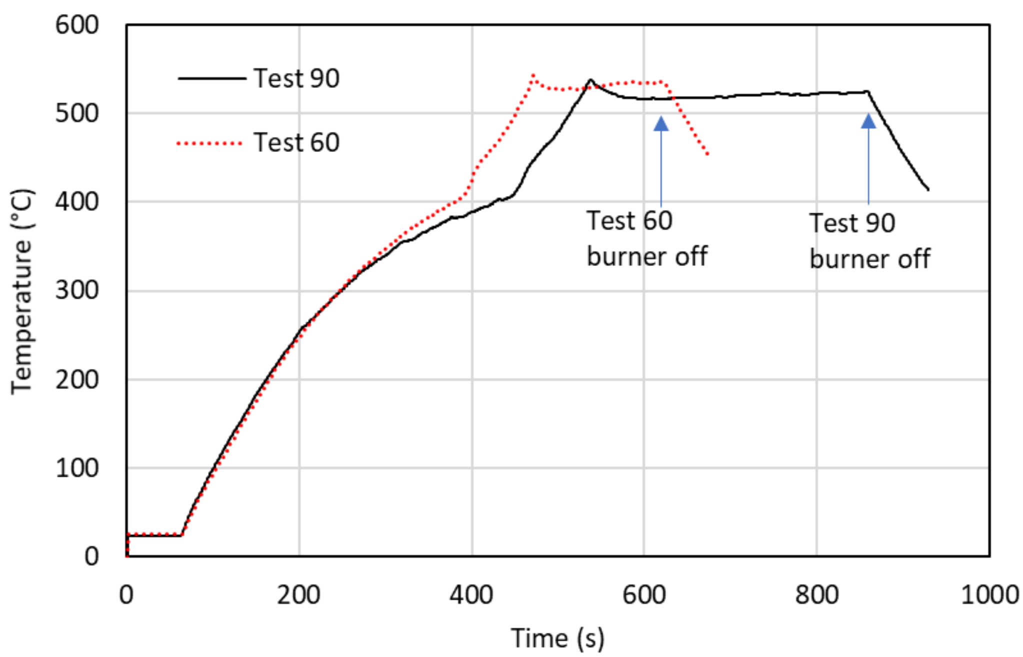

Figure 17 Time-averaged thermocouple temperature measurements on the bottom of wet Pan B with 3 mm (1/8 in) of oil heated on Stove 6 during repeated Tests 60 and 90. A change in the slope of the temperature profiles occurred in both tests, when the oil ignited as the pan temperatures were about 400 °C.

was automatically shut-off only after the oil was completely consumed by the fires.

Table 5 summarizes the gas cooktop results. The table lists the maxima of the time-averaged thermocouple temperature measurements on wet and dry Pans A – D heated on Stoves 3 – 6. Ignition of the cooking oil during the wet pan experiments is noted in the table. The results showed that oil ignition occurred for every type of pan tested when Stoves 5 and 6 were used, but did not occur when Stoves 3 and 4 were used. The table also lists the average and standard deviation of the maximum pan temperatures for each of the stove systems. The average of the temperature maxima in the wet pan tests for both Stoves 3 and 4 were within a few degrees of their respective dry pan tests, whereas for Stoves 5 and 6, the average of the temperature maxima in the wet pan tests were somewhat smaller than the respective dry pan tests. The differences in the maximum averaged wet and dry pan temperature were not significant (to a 95 % confidence level) based on the results of a statistical t-test (P=0.5411, 0.2953, 0.3445, and 0.3673 for Stoves 3 - 6, respectively) [11]. Consideration of the results shown in Table 5 for dry Pan C (cast iron) indicate that Stoves 3 and 4 would have passed the UL 858 temperature criteria test, but that Stoves 5 and 6 would not have passed. The wet Pan C tests are consistent with these results with ignition occurring when Stoves 5 and 6 were tested, but not occurring when Stoves 3 and 4 were tested. Stove 4 had the lowest maximum temperatures for both wet and dry conditions, followed by Stove 3, and then Stoves 5 and 6, which had very similar temperature results.

Table 5. Gas Cooktop Results. The maxima of the time-averaged thermocouple temperature measurements on the bottom of wet and dry Pans A – D heated on Stoves 3 – 6. The average of the standard deviation for each of the repeat gas cooktop experiments was 4 % (or 14 °C). The occurrence of oil ignition for the wet pans is noted. For each of the stoves, the average and standard deviation of the maximum pan temperatures among the various pans are listed.

Pan	Dry Pan T_{max} (°C)			
	Stove 3	Stove 4	Stove 5	Stove 6
A	300	271	395	373
B	305	270	405	507
C	270	255	464	445
D	290	260	360	328
T_{avg}	291 ± 15	264 ± 8	406 ± 43	413 ± 79

Pan	Wet Pan							
	Stove 3		Stove 4		Stove 5		Stove 6	
	T_{max} (°C)	Ignition	T_{max} (°C)	Ignition	T_{max} (°C)	Ignition	T_{max} (°C)	Ignition
A	300	No	266	No	475	Yes	458	Yes
B	295	No	268	No	527	Yes	525	Yes
C	287	No	258	No	393	Yes	389	Yes
D	299	No	253	No	415	Yes	440	Yes
T_{avg}	295 ± 6		261 ± 7		452 ± 60		453 ± 56	

3.4 Emissivity and Heat Transfer Effects

A few experiments were conducted to examine the importance of pan emissivity on the maximum pan temperature and the propensity of oil ignition. For these experiments, the temperature and ignition results for Pan B were compared to those using Pan B', which was identical to Pan B except its bottom was painted with a high emissivity black paint (ε=0.94 ± 0.1 [10]; also see Table 2). The nominal thickness of the coating was estimated as 30 μm based on the pan bottom surface area, the mass of the dry paint, and the density of dry paint [12]). While aluminum is a very good conductor, dry paint is not [12]. Consideration of the Biot Number (Bi) for the thin paint layer and the highly conductive, aluminum, pan bottom shows that each component is thermally thin (Bi << 1) and temperature can be assumed to be constant throughout the paint/aluminum assembly, signifying negligible insulative behavior [13].

The first experiment considered the performance of Pan B′ with 50 g of oil on Stove 6. Three repeat experiments (Tests 61, 65, and 91) were conducted resulting in the transient average pan temperatures shown in Figure 18. Stove 6 shut-off the burner fuel flow in Tests 61 and 65 when the maxima of the average pan temperatures were 390 °C and 395°C, respectively. These tests were analogous to Tests 60 and 90 (see Figure 16 and Figure 17) that used Pan B. Although ignition occurred in Tests 60 and 90 when the pan had a shiny bottom, it did not occur during Tests 61 and 65, when the pan bottom was painted with the highly emissive black paint. Ignition did occur in Test 91 (one of the three repeat tests using Pan B′) about 530 s into the test when the average pan temperature was 397 °C (see Figure 18). The difference in the onset of ignition may have been due to room currents, the exact placement of the pan on the heating coil, or other inadequately controlled processes that influenced heat transfer during testing.

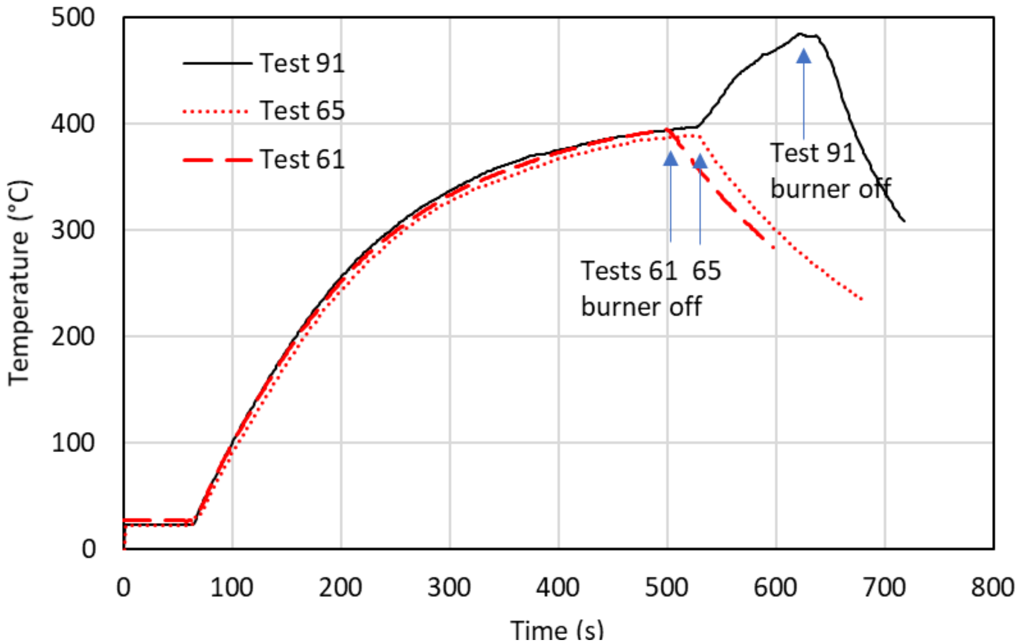

Figure 18 Time-averaged thermocouple temperature measurements on the (inner) bottom of wet Pan B′ with 3 mm (1/8 in) of oil heated on Stove 6 during repeat Tests 61, 65, and 91. The arrows indicate the time when the stove system shut the burner fuel flow.

Figure 19 shows the transient thermocouple temperature measurements (TC1 to TC5) in wet Pan B′ with 3 mm (1/8 in) of oil heated on Stove 6 during Test 91. The measured temperature between the stove underbody and the limit sensor is also shown. The oil ignited at about 530 s and was totally consumed at

580 s (see Figure 19). Only later, at about 620 s, did the stove shut-off the burner fuel flow. The temperature near the limit sensor obtained a maximum of about 195 °C at about the same time.

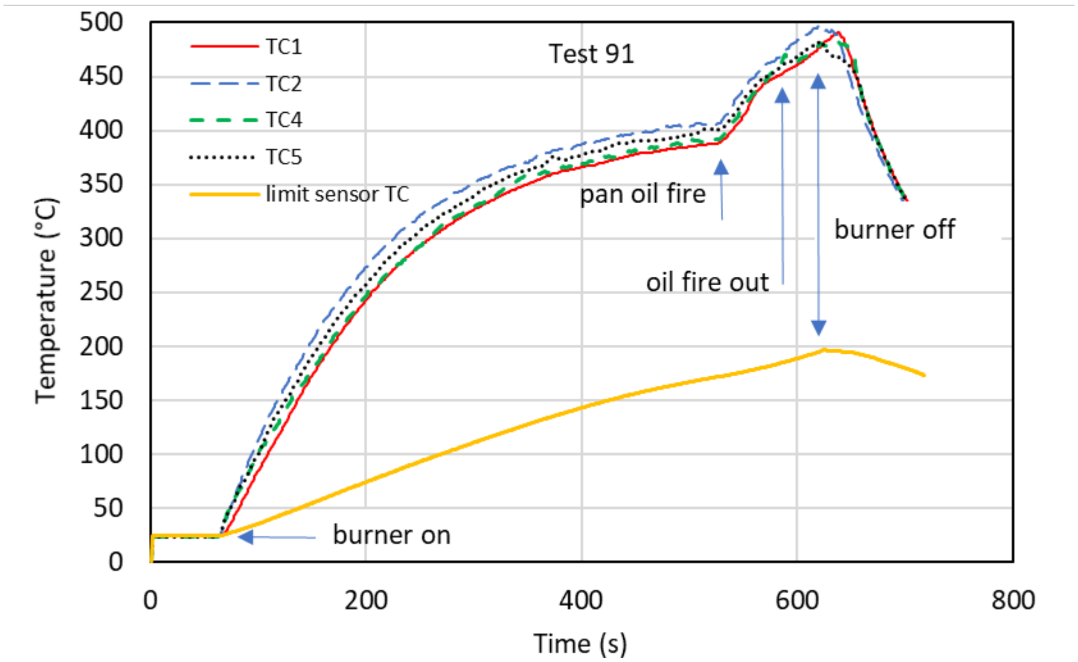

Figure 19 Transient thermocouple temperature measurements (TC1 to TC5) in wet Pan B´with 3 mm (1/8 in) of oil heated on Stove 6 during Test 91. The measured limit sensor temperature is also shown.

Measurements characterizing the temperature for Stove 6's limit sensor is shown in Figure 20 for Tests 86 (wet Pan D), 87 (wet Pan C), 88 (dry Pan B), 90 (wet Pan B) and 91 (wet Pan B´). These experiments were conducted under very different conditions, varying the pan type as well as the presence, or absence, of cooking oil (wet or dry pan). As expected, the measured limit threshold temperatures were quite similar, equal to 194 °C ± 4 °C, which was related to the unit design and placement of the ignition prevention limit sensor. The temperature profiles for these tests are also shown in Figure 20, where the arrows indicate the times of fuel shut-off to the burner for each of the tests. After fuel shut-off, the temperature at the limit sensor dropped. The pan temperatures at the time of burner fuel shut-off had a much larger variation (equal to 472 °C ± 57 °C) than the temperature at the limit sensor when the burner power was shut-off during the five experiments (± 4 °C) shown in Figure 20.

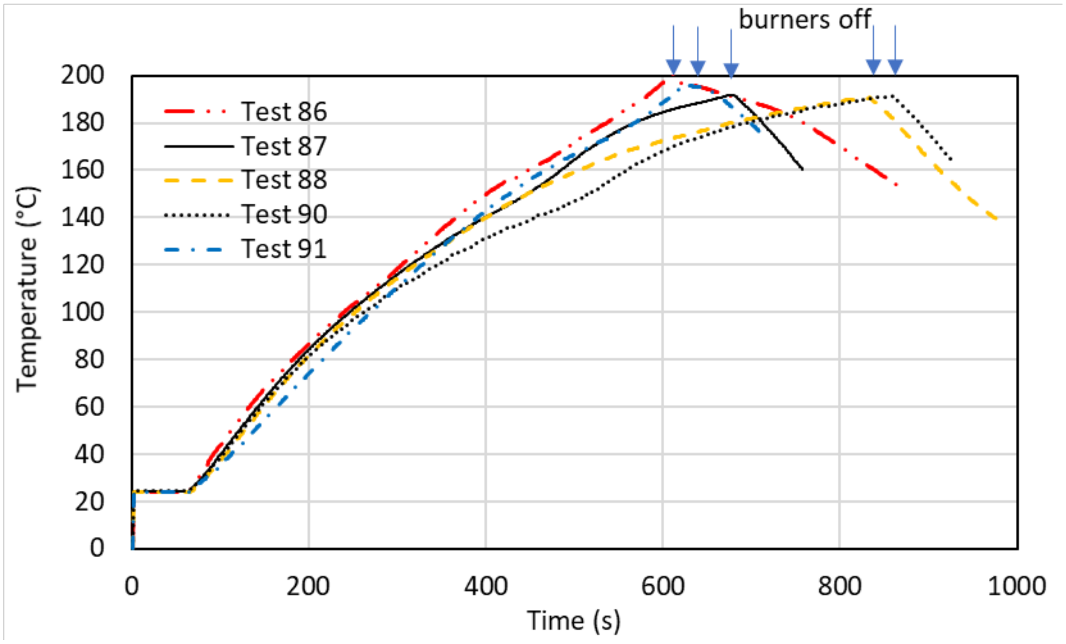

Figure 20 Thermocouple measurement of limit sensor temperature during Tests 86, 87, 88, 90, and 91 for pans heated on Stove 6. The arrows indicate the time when the stove shut-off the burner fuel flow, which occurred at about the temperature maxima.

This can be seen in Figure 21, where the average pan bottom temperatures for pans heated on Stove 6 during Tests 86, 87, 88, 90, and 91 are shown. The limit sensor failed to shut-off the fuel flow to the burner until after oil ignition in the wet pan tests (Test 88 used a dry pan). Figure 21 shows that the average pan temperature in Test 86 increased even after the burner fuel flow was shut-off. In Tests 86 and 90, the fire continued to burn after the burner fuel flow was shut, whereas in Tests 87 and 91, the fire had completely consumed the fuel before the burner fuel flow was shut. When the burner fuel flow was shut in Test 90, the fire was decreasing in size; in Test 86, the fire was still near its peak and the fire provided sufficient heat flux back to the pan to raise its temperature - even in the absence of a burner flame. The video record of the experiment shows that the fuel flow to the burner was shut-off at about 610 s in Test 86 and that the pan fire continued to burn until the oil was fully consumed at about 810 s.

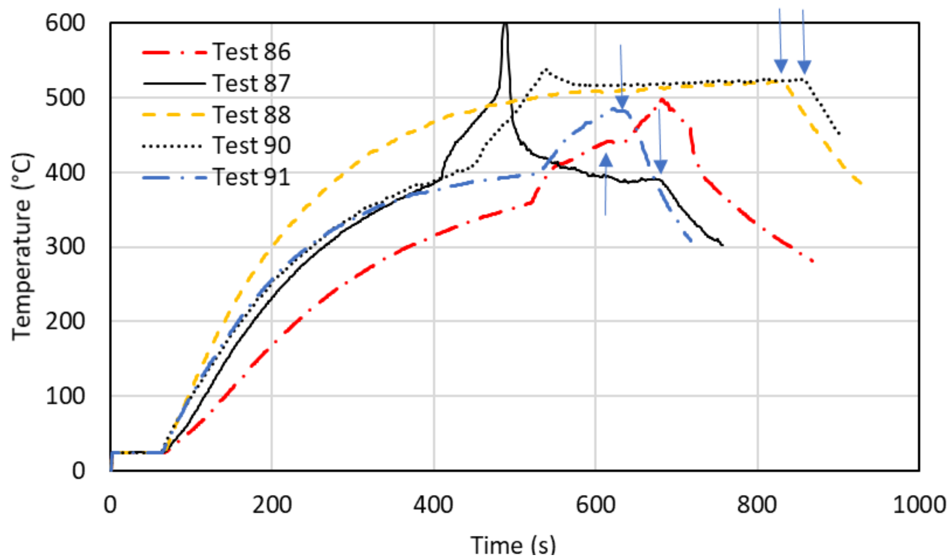

Figure 21 Averaged thermocouple temperature measurements on the bottom of pans heated on Stove 6 during Tests 86, 87, 88, 90, and 91. Oil fires occurred in all tests except Test 88. The arrows indicate when the fuel flow to the burner was shut for each test.

Figure 22 shows the transient heat flux incident on the cooktop near the limit sensor during Test 86. In the figure, the heat flux increased until about 610 s, when the limit sensor activated and the burner fuel flow was shut-off. Trends in the heat flux curve followed the pan temperature shown in Figure 21. The photos in Figure 22 document the experimental scenario at key times.

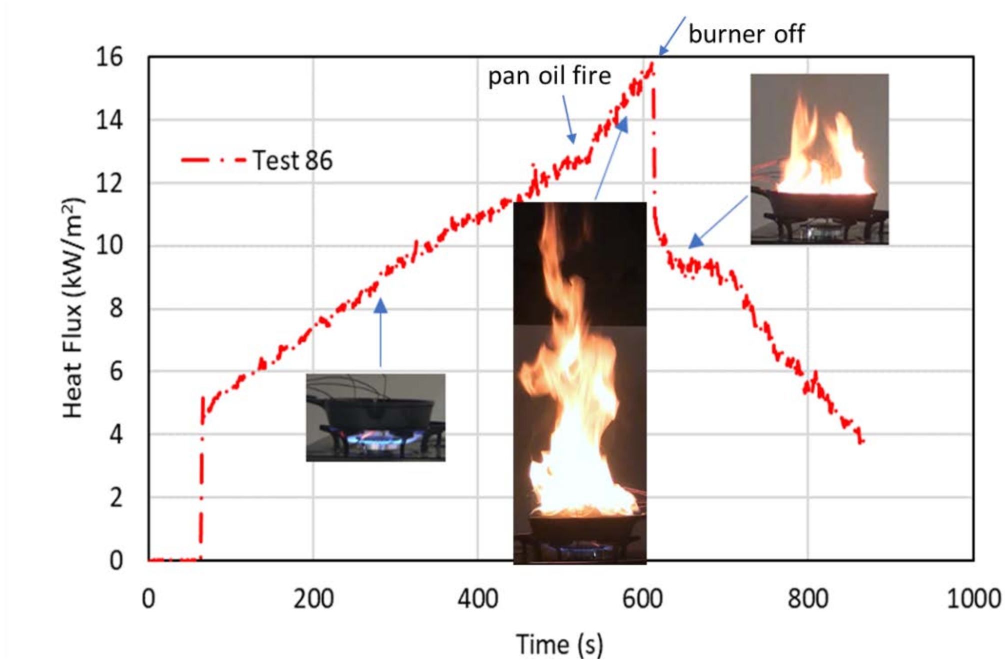

Figure 22 Transient heat flux incident onto the cooktop body near the limit sensor position during Test 86 for Pan D with 50 g of cooking oil heated on Stove 6. Images of the cooktop at 300 s, 580 s, and 650 s are also shown.

Figure 23 compares the transient heat flux incident onto the cooktop body near the limit sensor position during Tests 86, 87, 88, and 90 for pans heated on Stove 6. The heat flux results shown in Figure 23 roughly follow the trends corresponding to the average pan temperatures shown in Figure 21 – when the burner flame was on, the heat flux to the cooktop body increased and when the burner flame was cut, the heat flux decreased. The pan was shielding the heat flux gauge from the fire, so the heat flux at the cooktop only slowly increased as the pan temperature increased. It was the burner flame that dominated heat transfer to the heat flux gauge and the limit sensor.

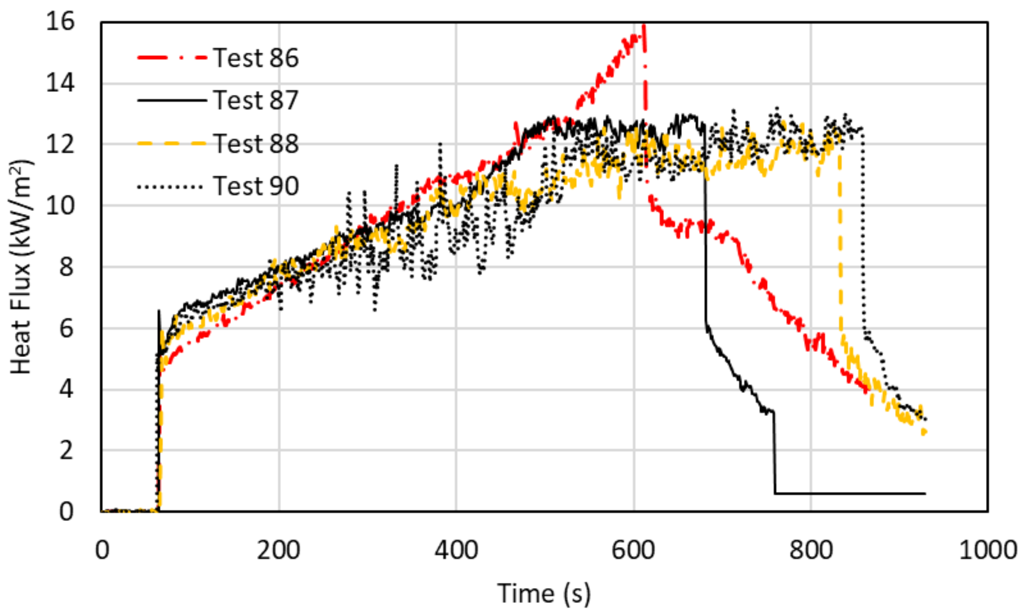

Figure 23 Transient heat flux incident onto the cooktop body near the limit sensor position during Tests 86, 87, 88, and 90 for pans heated on Stove 6. Oil fires occurred in all tests except Test 88.

The effect of the emissivity of the pan bottom on the average maximum pan temperature was tested on stove 1, an electric cooktop (see Figure 3), using dry Pans B and B′. Figure 24 shows that the average measured maximum temperature of Pan B (shiny bottom) was almost 40 °C less than that of Pan B' during an analogous experiment. Heat flux measurements directly below the middle of the heating coil near the position of the limit sensor were about 20 % less for Pan B′ (black bottom) as compared to Pan B (shiny bottom). The temperature difference was attributed to the relatively larger reflection of radiation associated with Pan B which caused the limit sensor to cut the power when the pan temperature was lower. This result confirmed that a small change in the test conditions can make a significant difference in heat transfer to the limit sensor and the performance of the technology.

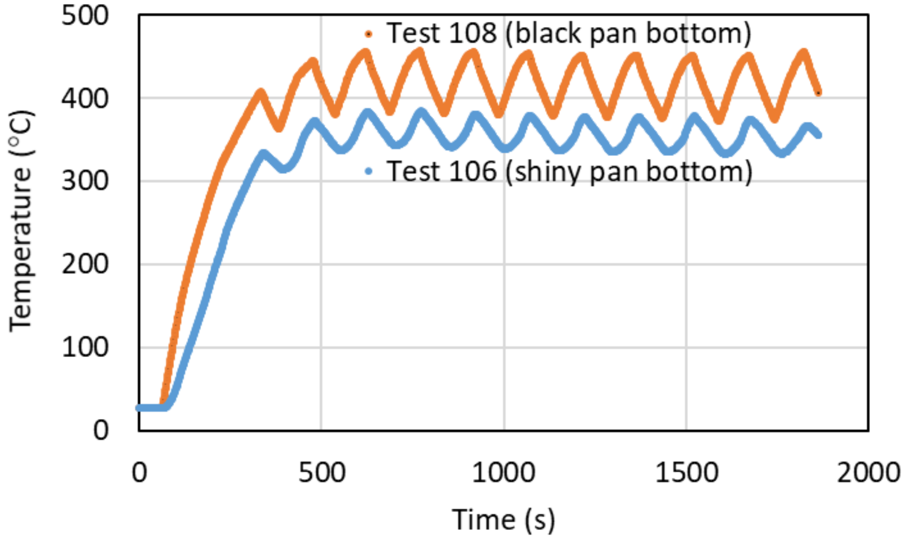

Figure 24 Averaged thermocouple temperature measurements on the bottom of dry pans B and B' heated on Stove 1 during Tests 106 and 108.

4. SUMMARY AND CONCLUSIONS

In summary, a series of cooking experiments were conducted to examine the effectiveness of commercially available cooktop ignition prevention technologies. Several types of full-scale residential cooktops with integrated ignition prevention technologies were tested. The experiments provided data on the characteristics of the currently available ignition prevention technologies and their performance in terms of ignition prevention of cooking oil fires. More than 100 experiments were conducted using gas and electric cooktops, including four propane gas powered cooktops sold in Asia and one stove with electric coil heating elements sold in the USA. One retrofit ignition prevention system for electric coil heating elements was also tested. The ignition prevention technologies used a variety of configurations and engineering designs. Experiments were conducted using four types of cooking vessels.

The pans tested were approximately round, about 20 cm to 22 cm in diameter, and 4 cm to 5 cm in depth. The tests followed the UL 858 standard on abnormal cooktop fire hazards. Although the UL858 standard is specific to electric coil element cooktops using dry cast iron pans and "wet" aluminum pans, tests were conducted for a variety of pans types using stoves that were powered by electric coil elements and propane gas. Five thermocouples were attached on the bottom of the pans in a cross pattern and the average pan temperature during cooking was monitored. For the experiments involving cooking oil, the incidence of auto-ignition was observed. About half of the experiments were conducted using dry pans and about half were conducted on pans that held small amounts of canola oil.

The results showed that the electric coil cooktop ignition prevention technologies tested in this study met the UL858 standard by reliably maintaining the temperature of dry cast iron pans below the UL 858 standard's limit temperature criteria and preventing ignition in pans with a small amount of canola oil.

The results also showed that some residential cooktops can prevent oil ignition in a variety of pan types, although some other cooktop types cannot do so, the difference presumably due to specific design details.

Positioning a limit sensor under the stove body may be a viable strategy, but the cooktop systems tested here (Stoves 5 and 6) did not prevent oil ignition for a variety of pan types. Engineering modification of the stoves' sensor design may be able to address this matter.

The exact type of limit sensor and its location on a cooktop is important as the heat transfer processes associated with cooking fires depend on many variables. The importance of the emissivity of the pan bottom was tested on two cooktops and was shown to play a significant role in heat transfer, pan temperature and probability of ignition. This result showed that small changes in the test scenario can make a significant difference in heat transfer to the limit sensor, depending on the details associated with the configuration-specific heat transfer processes interacting between stove heat source, the limit sensor, and the pan. Due to the complex nature and configuration specific heat transfer processes associated with heat transfer on a cooktop, further study would be useful in the development of robust ignition prevention technologies.

5. REFERENCES

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6. APPENDIX

6.1 Pan A Temperature Measurement Method

Thermocouples were mounted onto Pan A by snugly compressing the thermocouple bead under a small (6-32) screw/washer assembly that was drilled and tapped into the bottom of the pan (see Pan A in Figure 5). This configuration was tested since peening thermocouples to the pan surface occasionally led to spurious measurements results presumably due to incomplete contact. Two sets of experiments were conducted to test the efficacy of this approach. Figures A1 – A3 show the experimental results.

In the first set of measurements, the inside of Pan A was painted with a thin coat of black paint with a well-characterized high-emissivity black paint with ε=0.94 ± 0.01 as specified by the manufacturer [10]. Pan A was placed on top of an electrically heated hot plate and static temperature measurements were made as the plate was heated to a target temperature from room temperature to about 300 °C. The measurements compared the thermocouple mounted under the screw/washer assembly to a non-contact temperature measurement using an infrared thermal imaging camera (TIC). The TIC used here was a 160 pixel by 120 pixel uncooled microbolometer focal plane array sensitive in the 7.5 µm to 13 µm wavelength range [14]. The TIC software converts measured radiance to a temperature at each pixel allowing determination of the temperature at a spot in the field of view. The manufacturer specified TIC measurement accuracy is ± 2 °C [14], which is the same as the manufacturer specified thermocouple accuracy [8].

The TIC was focused on the pan surface within 1 cm of the thermocouple associated with the screw/washer assembly with the TIC emissivity set to the emissivity of the surface coating (0.94 ± 0.01 in this case). Figure A1 compares the results of temperature measurements using the thermocouples compared to temperature measurements using an optical thermal imaging camera. The size of the uncertainty bars in the figures are smaller than the symbols. The results demonstrated that the TIC and thermocouple measurements agreed within the combined experimental uncertainties.

The second set of experiments compared dynamic temperatures measured using the thermocouple mounted screw/washer assemblies to 24 and 30 gauge thermocouples that were peened within 4 mm of the screw/washer assemblies on the pan surface. Figure A2 compares the temperatures measured by the thermocouple pressed under the screw/washer assembly to a 24 gauge peened thermocouple at the center of Pan A on Stove 1. The same data presented in Figure A2 is also shown in Figure A3. Figure A3 plots the transient temperature difference between peened thermocouples and adjacent thermocouples under the screw/washer assembly. Consideration of the peak pan temperatures (see Figure 11) shows that the time-averaged difference between the peened and screw/washer assembly thermocouples was approximately 2 °C. This can be considered an additional measurement uncertainty when using the screw/washer assembly in the determination of the pan temperature. In addition, the time varying temperature profiles showed that there was a 5 s time lag on average for the screw/washer assembly thermocouples compared to the peened thermocouples. This result was not surprising considering the thermal inertia of the mass of the screw/washer assembly. It should also be noted that care had to be taken in drilling and tapping screw threads using this approach to ensure that the holes were sufficiently tight to prevent oil from flowing through the holes during “wet” experiments when the pan contained oil.

In summary, the measurements suggest that use of the screw/washer thermocouple assembly can provide a reasonable measure of pan temperature albeit with a larger combined expanded uncertainty than the peened thermocouples, determined here to be approximately 2 °C. While the measurement approach using a screw/washer assembly provided a reasonable measure of pan temperature, it had a larger uncertainty and a significant time lag when compared to the peened thermocouples.

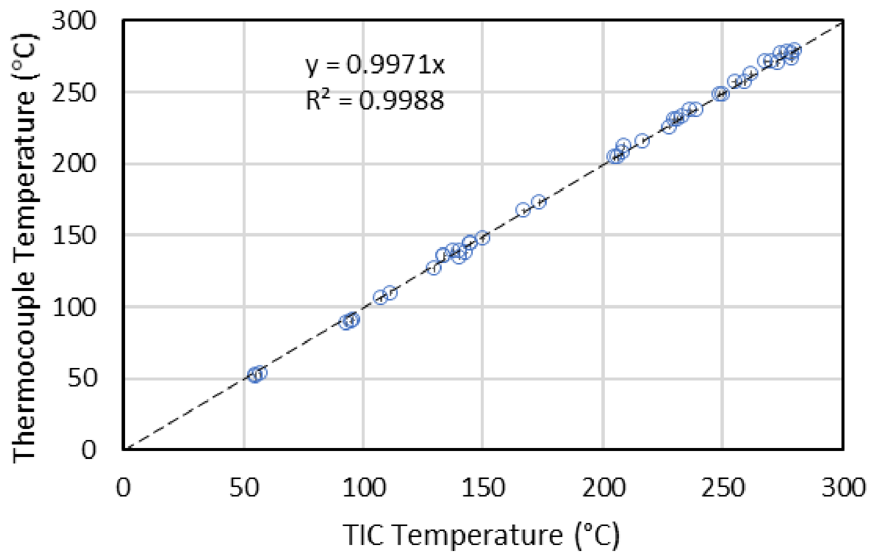

Figure A1 Comparison of thermocouple and thermal imaging camera (TIC) temperature measurements for Pan A on a hot plate.

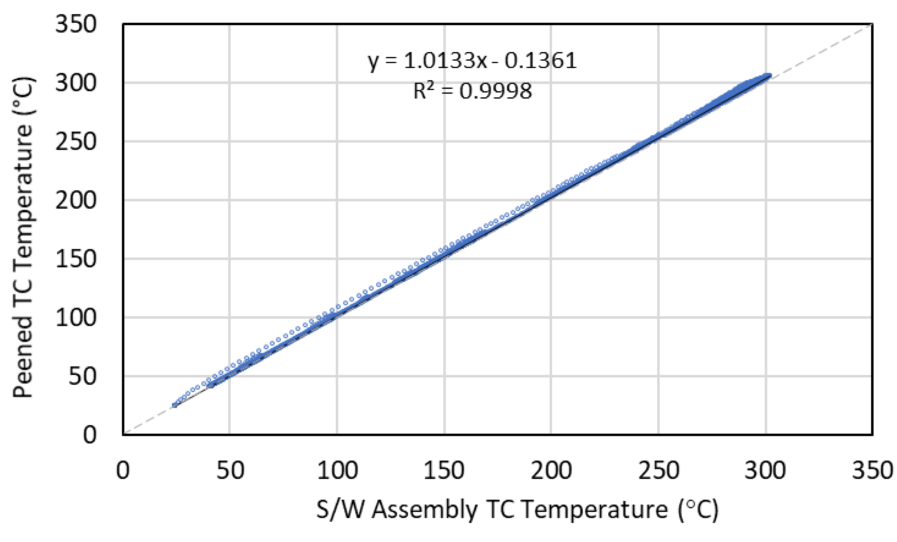

Figure A2 Comparison of temperature measurements of a peened thermocouple and a thermocouple pressed under a screw/washer assembly at the center of Pan A on Stove 1. The difference between the two temperature measurements is shown in the next figure (labelled as "TC1P24").

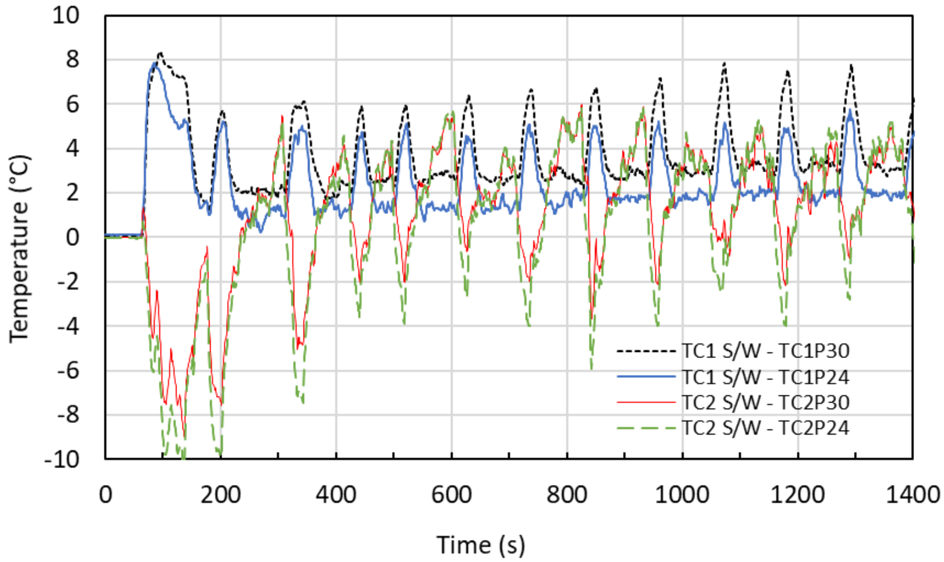

Figure A3 Difference in the temperature measured by peened thermocouples and a thermocouple pressed under a screw/washer assembly on Pan A on Stove 1.

6.2 Pan Surface Emissivity Measurement

The emissivity of the bottom of a used pan was determined using a thermal imager camera (TIC) following ASTM E1933-14 [15]. The apparatus is shown in Figure 24. The pan was heated to elevated temperatures (as high as 200 °C as measured by a thermocouple) using an industrial heat gun. The pan surface temperature was measured by a TIC and compared to the temperature measured by a Type K thermocouple secured to the pan. The TIC had a field of view (θ in the figure) of 25° with a manufacturer specified accuracy of 2 °C. The TIC was focussed on a spot on the pan surface less than 1 cm from the thermocouple bead. The local pan emissivity was determined by adjusting the emissivity setting on the TIC until the spot temperature measured by the TIC approached the value measured by the thermocouple. This approach was tested using a pan with a well-characterized emissivity. Half of the aluminium bottom of a 23 cm pot was coated with a thin layer (32 μm ± 1 μm) of black paint of known emissivity (ε = 0.95 ± 0.01) and a thermocouple was peened to the pot bottom. Setting the TIC emissivity to 0.95, Figure 25 shows images of the heated pot bottom in the visible and infrared (IR). Analysis of the IR image showed that the measured TIC temperature within 1 cm of the thermocouple bead was uniform to within ± 0.5 °C.

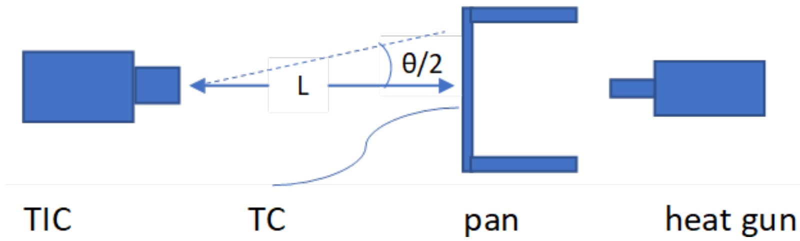

Figure 25. Schematic diagram of the measurement of pan emissivity with a thermal imaging camera (TIC), peened thermocouple (TC), pan, and heat gun. The TIC was focussed on the pan's bottom surface located at a distance L.

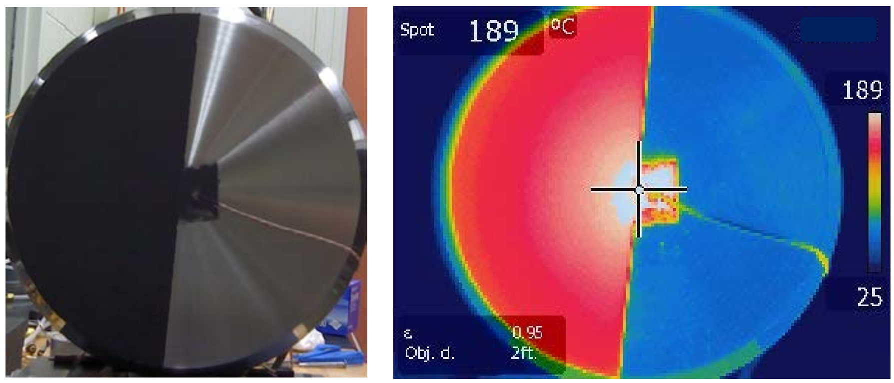

Figure 26. Visible (left) and IR (right) images of a 23 cm diameter stainless-steel pot with an aluminum-clad bottom convectively heated by an industrial heat gun with the pot 0.6 m from the thermal imager. The left half of the surface was coated with a thin layer of high emissivity (ε = 0.95 ± 0.01) black plaint. In the IR image, the TIC measured a spot surface temperature of 189 °C 3 mm from the thermocouple bead at the location between the cross-hairs.

The temperature of the bottom surface of the pot was measured by the TIC and the thermocouple as its temperature was varied by changing the heating gun power setting and its distance to the pot. The ratio of the temperatures measured by the TIC and the thermocouple was nearly constant, yielding a standard deviation of 0.35 % over the temperature range from about 90 °C to 200 °C. The ratio was treated as a calibration factor for the measured TIC temperature in the determination of sample surface emissivity, which was a refinement of the ASTM 1193 test method.

A used 25 cm diameter stainless steel pan obtained from the field was selected for emissivity determination. This pan was selected because it had a thin layer of dark material not unlike other pans observed in an informal survey of residential pots and pans. A thermocouple was spot welded in the middle of a dark section on the pan bottom as seen in Figure 27, which presents visible and IR images of the pan as it was convectively heated using the configuration shown in Figure 24. The pan bottom was located 0.3 m from the thermal imager. The measured TIC temperature within 0.5 cm of the thermocouple bead was uniform to within ± 0.5 °C. In the IR image in Figure 27, the TIC measured a spot surface temperature of 119 °C at the location between the cross-hairs in the image which was positioned within 5 mm of the thermocouple bead. The local pan emissivity was determined by adjusting the emissivity setting on the TIC until the spot temperature measured by the TIC approached the value measured by the thermocouple. Figure 27 shows the measured emissivity for the used pan as a function of pan temperature. The results show that the average emissivity across this temperature range was $0.997\,^{+\,0.003}_{-\,0.021}$ where the uncertainty is reported as the combined expanded uncertainty with a 95 % confidence interval. The uncertainty is asymmetric because the emissivity cannot exceed a value of unity. The main finding is that the surface emissivity of a used cooking pan can be very large.

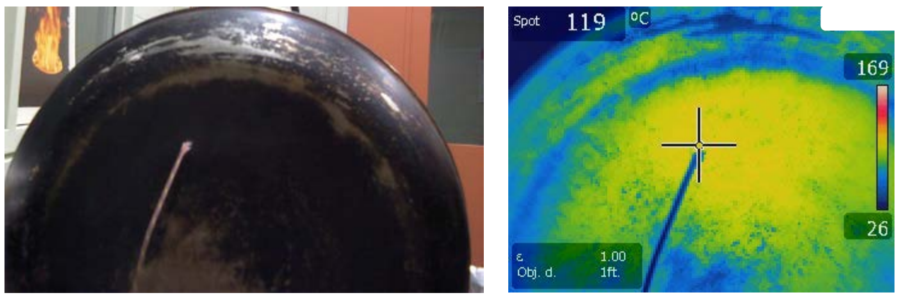

Figure 27. Visible (left) and IR (right) images of the 25 cm diameter used stainless steel pan convectively heated by an industrial heat gun. A portion of the surface was coated with a thin layer of dark material, while sections of the surface were shiny. The pan bottom was located 0.3 m from the thermal imager. In the IR image, the TIC measured a spot surface temperature of 119 °C at the location between the cross-hairs in the image which was positioned within 5 mm of the thermocouple bead.

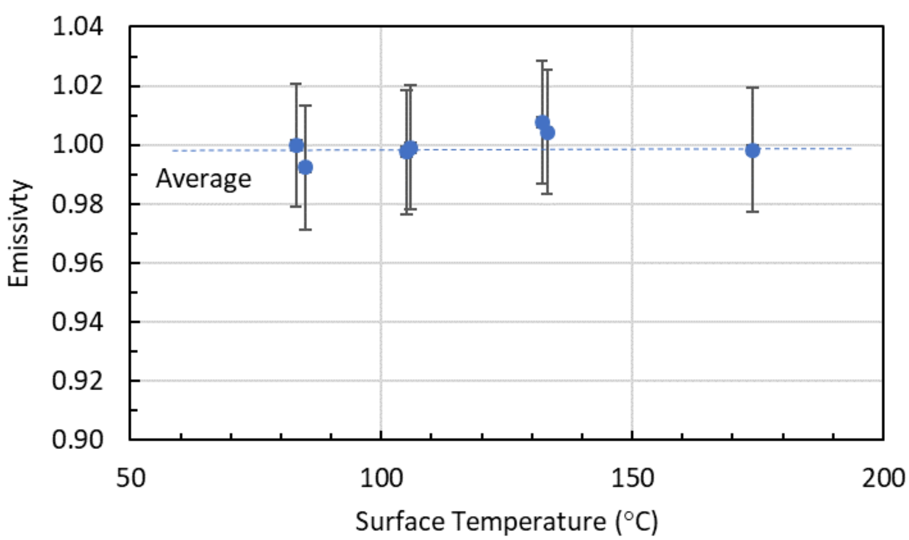

Figure 28. Local surface emissivity of the used 25 cm diameter stainless steel pan measured using a thermal imaging camera in the configuration shown in Figure 24. The thermal imager was located 0.3 m from the pan. The standard deviation for each data point and the average emissivities for all the data are shown.