



CPSC Staff's Statement on Primaira, LLC's Report, "Refinement of Temperature-Limiting Control Systems for Preventing Oil Ignition on Gas and Electric Cooktops"¹
November 2015

The following contractor report titled, "Refinement of Temperature-Limiting Control Systems for Preventing Oil Ignition on Gas and Electric Cooktops," presents the results of research and testing conducted by Primaira, LLC, under Health and Human Services ("HHS") Contract No. HHSP233201400193A.² Primaira performed this work to provide additional information to support development of requirements for the voluntary safety standards for gas and electric ranges to reduce surface cooking fire incidents.

Under the contract, Primaira performed testing and analysis in conjunction with four subtasks that provided additional insight and understanding of control system requirements for pan-temperature limiting. The four tasks were to: (1) determine gas burner/electric element minimum power rating for ignition; (2) optimize gas burner cycling during temperature-limiting operation for the burner control system that Primaira developed under Contract No. GS11T10BJM6060, as reported in [*Pan Temperature-Limiting Control Technology to Reduce Incidence of Unattended Cooking Fires*](#); (3) replace the resistance temperature detector ("RTD") sensor currently used in prototype pan-bottom temperature sensors with less expensive thermistor-type sensors commonly in use in appliance controls; and (4) evaluate the interaction between the existing glass temperature-limiting device and pan temperature-limiting controls in electric, glass ceramic cooktops.

This information will assist CPSC staff as they continue to work with standards developers, the Association of Home Appliance Manufacturers and other interested parties to develop proposals for requirements for reducing the likelihood of igniting food in a pan on a cooktop element. Additionally, this report will be posted on the CPSC website as resource information.

¹ This statement was prepared by the CPSC staff, and the attached report was produced by Primaira, LLC for CPSC staff. The statement and report have not been reviewed or approved by, and do not necessarily represent the views of, the Commission.

² The DHHS Program Support Center executed Contract No. HHSP233201400193A on behalf of U.S. Consumer Product Safety Commission (CPSC) staff in accordance with Modification No. 120 to Interagency Agreement No. CPSC-I-14-0003.



PRIMAIRA

Refinement of Temperature-Limiting
Control Systems for Preventing Oil
Ignition on Gas and Electric Cooktops

Final Report

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Executive Summary

Background

Since 1995, the U.S. Consumer Product Safety Commission (CPSC) has supported work aimed at identifying and mitigating the risks of unattended cooking fires. According to CPSC staff, cooking equipment has accounted for the largest percentage of residential fires since 1999. In 2010, Primaira LLC, under contract to the CPSC, developed a set of prototype sensor and control systems capable of detecting pre-ignition conditions and then controlling heat output for residential gas, electric coil, and glass ceramic cooktops. In 2013, Primaira LLC, under contract to the CPSC, validated the ignition-prevention capabilities and other key performance criteria of the pan-temperature-limiting controls implemented into the gas cooktop.

Objective

The objective of this subsequent project was to continue refinement of the developmental temperature-limiting control systems relative to four areas:

- Determination of gas burner/electric element minimum power rating for ignition;
- Optimization of gas burner cycling during temperature-limiting operation;
- Replacing the RTD sensors currently used in prototype pan-bottom temperature sensors with less expensive thermistor-type sensors commonly in use in appliance controls; and
- Evaluation of the interaction between the existing glass temperature-limiting device and pan temperature-limiting controls in electric, glass ceramic cooktops.

Fire Test Facility

All testing was conducted in Primaira's cooktop fire test facility. This facility consists of a modified 20' ISO Container, with a front area for data acquisition and observation, and a back area with exhaust and fire protection for cooktop fires.

Test Results

Low wattage elements:

The tests demonstrated that 150 mL of oil in a 6" diameter cast iron skillet on a 4" diameter electric coil element with a nominal rating of 600 W can ignite. Ignitions at these low levels of element power occurred with cast iron pans. Tests demonstrated that oil did not ignite with an 8" aluminum pan on a 6" electric coil element nominally rated at 900 W. Tests demonstrated that a 5,000 Btu/hr burner on a gas cooktop did not ignite oil in a pan under any of the test conditions. The lowest wattage element on a glass ceramic cooktop (750 W) was powerful enough to cause

an oil fire. Oil in a 6” cast iron pan on the 750 W element set to “8”, resulting in an average output of 600 W, also ignited on this glass ceramic cooktop element.

Refined gas burner control settings:

Increasing the reduced firing rate from 2,500 to 4,400 Btu/hr in a gas burner control scheme provides benefits of reduced burner cycling and smoother temperature profiles without impacting the ability to avoid a fire.

Thermistor-based sensor:

The relatively low upper temperature limit of low-cost thermistors presents an impediment to their use in a practical pan temperature limiting sensing and control system. A system to maintain the thermistor temperature within its operable range created an unacceptable lag in the control system, making it of little practical use in the current pan temperature limiting control scheme for electric coil elements.

Glass limiter/pan temperature control interaction:

The pan bottom temperature controls were found to be more aggressive than the glass temperature limiter (i.e. the controls limited the glass temperature to a lower level than the manufacturer’s glass limiter did). As such, once the pan temperature control began to control element power, the glass temperature limiter was overridden and did not affect power to the element. However, the glass limiter did engage initially at lower temperatures than the pan bottom temperature control, which under some circumstances, would impact the point at which the pan temperature controller engaged.

The pan bottom temperature controls held the glass to lower temperatures than the limiter did, indicating it may be “glass-safe” to remove the limiter if the pan temperature controls are in place.

Conclusions and Summary Recommendations

The objectives of the project have been met. Additional data has been provided to support the implementation of the pan temperature limiting technology into electric coil, gas and electric glass ceramic cooktops. The testing results highlight boundary cases for sensor implementation.

1. Introduction

Background, Objectives and Approach

Since 1995, the U.S. Consumer Product Safety Commission (CPSC) has supported work aimed at identifying and mitigating the risks of unattended cooking fires. According to CPSC staff, cooking equipment has accounted for the largest percentage of residential fires since 1999. An estimated annual average of 146,700 cooking equipment-related fires during 2009–2011 accounted for 40.5 percent of the average annual estimate of total residential fires for the same period. “The corresponding death estimate is an annual average of 160 deaths, which is 7.1 percent of the average annual estimate of total residential fire deaths. The annual average number of cooking fire injuries for 2009–2011 was estimated to be 3,450, which represents 26.9 percent of the total estimated annual average number of injuries for the same time period. Much of these losses were associated with range and oven fires.” (D. Miller; 2009-2011 Residential Fire Loss Estimates; U.S. Consumer Product Safety Commission Staff Report, 2013).

Researchers at several organizations have reviewed a wide variety of potential hazard detection schemes and have tested the efficacy of some of them in practical test environments. This research has demonstrated that pan-bottom temperatures are reliable indicators of pending ignition that can be exploited to initiate automatic corrective actions to prevent food ignition.

In 2010, Primaira LLC, under contract to the CPSC, developed a set of prototype sensor and control systems capable of detecting pre-ignition conditions and then controlling heat output for residential gas, electric coil, and glass ceramic cooktops. The algorithms for the electric coil, gas, and ceramic glass cooktop controls were refined until all cooking processes for all pan types tested provided results that were equivalent to the cooking performance without the controls activated, while at the same time preventing the pan from exceeding 700 °F. All boil times with the controls were within the standard deviation of the boil test. Cooking performance for sear, blacken, simmer, and sauté modes with the controls active were all equivalent to non-control-active tests. All cooking and temperature-limiting tests were conducted with aluminum, cast-iron, and stainless steel pans of various configurations. However, control system operation was not tested at that time to confirm fire mitigation performance.

In 2013, Primaira LLC, under contract to the CPSC, validated the ignition-prevention capabilities and other key performance criteria of the pan-temperature-limiting controls implemented into the gas cooktop. Baseline ignition testing was conducted for a test matrix consisting of four different gas heating rates, six different pan types, and two oil amounts. These tests were conducted without the controls activated. Validation testing was conducted with the controls activated for 18 tests with the same variables as the baseline tests. Additional performance testing was conducted with warped pans and pans located off-center of the burner. No fires occurred with the pan-temperature controls in use.

In April 2015, safety standard UL 858 for Household Electric Ranges was amended to include a test procedure to evaluate sensors and other devices that will prevent cookware from reaching the ignition temperatures associated with common cooking oils. The amendment will be published in the summer of 2015. This new test procedure applies to electric coil elements with heat outputs higher than 350 W. The test procedure utilizes an uncoated aluminum pan with a diameter one inch larger than the electric coil being tested, and a 0.125" deep layer of Canola oil in the pan. The electric coil is prohibited from igniting the oil when the element is set to its highest power setting during a 30 minute test duration. The effective date for the test has not been set at this time.

2. Project Objective

The objective of this project was to continue refinement of the developmental temperature-limiting control systems that were designed and constructed under Contract GS11T10BJM6060 relative to four areas:

1. Determination of gas burner/electric element minimum power rating for ignition;
2. Optimization of gas burner cycling during temperature-limiting operation;
3. Replacement of the RTD sensors currently in use with less expensive thermistor sensors commonly in use in appliance controls; and
4. Evaluation of the interaction between the existing glass temperature-limiting device and pan temperature-limiting controls in glass ceramic cooktops.

3. Project Equipment/Facilities

The Cooktop Fire Test Facility is shown in Figure 1. We used this facility to conduct the ignition testing referred to in the project task list.



Figure 1: Outside and Inside Cooktop Fire Test Facility

Oil ignition tests were conducted with aluminum, cast iron, and stainless steel skillet with 150 mL (137g) Canola oil, unless otherwise specified. Oil temperatures at 1/16” and 1/8” height from the pan bottom were measured and recorded. Pan temperatures at the pan center, pan radius and halfway between were measured and recorded.

Appendix 1 lists the details of the cooktops and utensils used for testing. Appendix 2 defines the procedures used for testing.

4. Project Tasks

Task 1: Determination of gas burner/electric element minimum power rating for ignition:

In this task, we conducted tests in our Cooktop Fire Test Facility to determine the minimum burner/element power ratings that result in ignition. We tested the smallest element in the coil, the glass ceramic, and gas cooktops with small, medium and large diameter pans to determine if there was a minimum heat input at which there is no concern about ignition. These tests were conducted without the use of pan temperature limiting control systems. They were “baseline” tests in that they characterized the nature of ignitions when no mitigation technique was in use.

The importance of this is that there could be some elements/burners that are inherently ignition safe and would not need a sensor.

Also, on the electric coil cooktop, we tested one pan with multiple oil levels to determine if the amount of oil can increase risk at low input rates.

We used a theoretical model we have developed¹ to simulate the oil heating process, along with our past test results, as a guide to determining the “worst case” pan material and pan sizes for ignition on small elements or burners. This model predicted that small pans on a small element would lose less heat than a larger pan, resulting in higher pan temperatures and shorter times to ignition. Therefore, we would expect a small pan to be a worst case for ignition purposes. The model also indicated that cast iron or stainless pans may be more likely to ignite than aluminum pans, making the non-aluminum cookware a worst case for these tests. Additional tests were conducted to cover these potential worse-case scenarios.

We conducted further testing on three additional cooktop elements to determine whether the oil in a pan reaches the same temperature when heated with a higher wattage element that is cycling as compared to a lower wattage element heating continuously.

Task 2: Determine if a less aggressive turndown is feasible with the gas burner:

The pan-temperature limiting controls for a gas burner cycles the gas flow rate between the nominal rate (defined by the user-defined set point), and a lower, reduced rate. The flame stays lit during the cycling to avoid safety and performance issues of extinguishing and re-lighting the gas flame. The original control system reduced the gas flow to 2,500 Btu/hr when the controls called for a reduction in heat. This heating rate corresponds to the gas flow at the midpoint setting of the burner dial (Set Point 5). However, this heating rate is less than 15% of the maximum input rate (for the test range) of 18,500 Btu/hr. The rate of cycling of the burner could be reduced if the lower heating rate were higher, so the pan cools down less. Less cycling could extend the life of the valve and other switching components, make the firing rate reduction less obvious and smooth the transition from low to high firing rate.

We tested the reduced level at the firing rate determined from Task 1 to be inherently safe and not cause ignitions. The target for the reduced firing rate was 4,000 – 6,000 Btu/hr.

Task 3: Design and test a thermistor-type sensor in the electric coil and gas burner:

We currently have demonstrated the controls with an RTD pan bottom temperature sensor, with the expectation that a thermistor could be a less expensive option for future implementation.

¹ “Analytical Modeling of Pan and Oil Heating On an Electric Coil Cooktop” Primaira LLC, Report prepared for the Fire Protection Research Foundation, July 2014
<http://www.nfpa.org/research/fire-protection-research-foundation/reports-and-proceedings/other-research-topics/analytical-modeling-of-pan-and-oil-heating-on-an-electric-coil-cooktop>

Presently, the operating temperature of the sensor is close to the maximum operating temperature of cost-effective thermistors, so sensor re- design and algorithm adjustment may be necessary to ensure that the thermistor operates within its specified temperature range.

We designed and fabricated a thermistor –based sensor and tested it for efficacy in the electric coil cooktop.

Task 4: Evaluate the interaction between the glass temperature limiter and pan temperature controls in the glass ceramic cooktop:

We conducted a series of tests to determine the nature of the interaction between the existing mechanical glass temperature limiter and the pan-bottom temperature limiting controls. Under conditions that the pan-bottom temperature limiting controls are alone controlling the element, we measured the glass ceramic temperature to confirm that it does not exceed temperature limits set by the existing glass temperature limiter. We disabled the glass temperature limiter, and re-ran a series of control tests to determine whether the response of the system is improved without a dual safety system.

We conducted a series of dry pan tests, no-pan tests, and water boil tests to confirm that neither the pans nor the glass ceramic exceed threshold temperatures without the glass temperature limiter in place.

5. Results

5.1 Threshold Power Levels for Oil Ignition

We conducted a series of tests to identify a threshold input rate for given pan sizes that represents a power input that is inherently safe; that is, the power input level is too low to result in an oil ignition. The initial test matrix for these tests is shown in Table 1.

Table 1: Threshold Power Input Initial Test Matrix

Electric Coil Cooktop: 6" 1300W Element	150 mL Canola oil	• 8" Aluminum Pan
		• 8" Aluminum Pan (set to 8)
		• 10" Aluminum Pan
		• 12" Aluminum Pan
	100 mL Canola oil	• 10" Aluminum Pan
	300 mL Canola oil	• 10" Aluminum Pan
Glass Ceramic Cooktop: 5" 750W Element	150 mL Canola oil	• 8" Cast Iron Pan
		• 8" Aluminum Pan
		• 10" Aluminum Pan
		• 12" Aluminum Pan
Gas Cooktop: 5000 Btu/hr Burner	150 mL Canola oil	• 8" Aluminum Pan
		• 10" Aluminum Pan
		• 12" Aluminum Pan

Figure 2 below illustrates the results of these tests. The oil ignition zone band illustrated in the graph represents the minimum oil ignition temperatures for electric elements (top of the band) and gas burners (bottom of the band). These minimums were determined from the database of ignition tests we have conducted on electric and gas cooktops, for a range of pan sizes, materials, and heating rates.

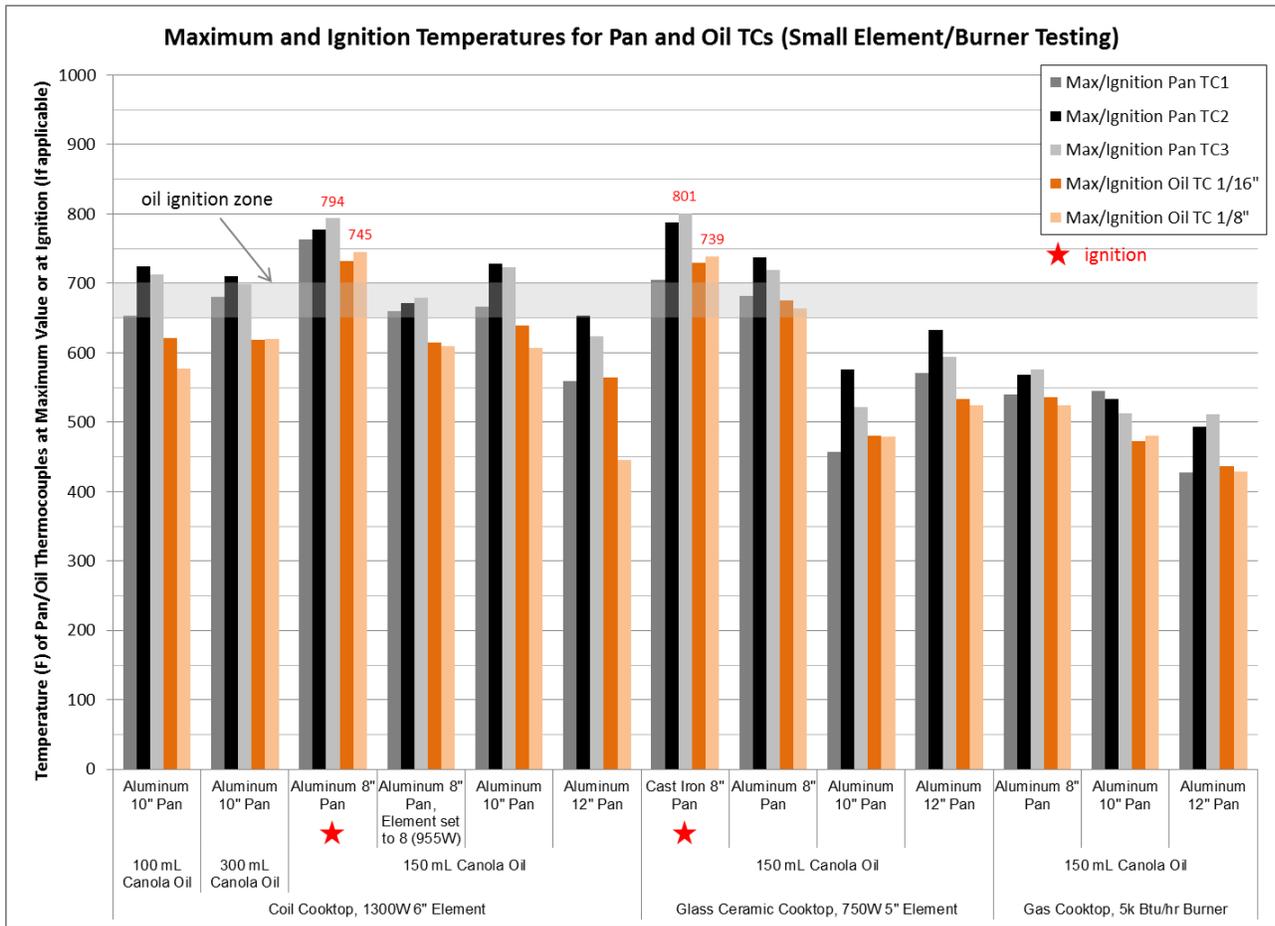


Figure 2: Results of Low Input Rate Testing – Initial Test Matrix

These tests illustrate the importance of pan size when determining the ignition potential of a burner or electric element. Photographs of the pans used and the relationship of the pan size to the electric element or burner size is shown in Appendix 1. The tests conducted on the coil and glass ceramic electric elements resulted in ignition when the element and pan sizes were closely matched. For example, an 8” aluminum skillet with 150 mL Canola oil on the 1300 W, 6” electric coil, set to “High” resulted in ignition while the same amount of oil in 10” and 12” aluminum skillets did not ignite under the same test conditions.

The results for each cooktop are discussed below, in turn. In some cases, we conducted additional tests in order to clarify or explore variables that impacted the results.

5.1.1 Electric Coil Cooktop

Details of the results for the electric coil cooktop are shown in Figure 3.

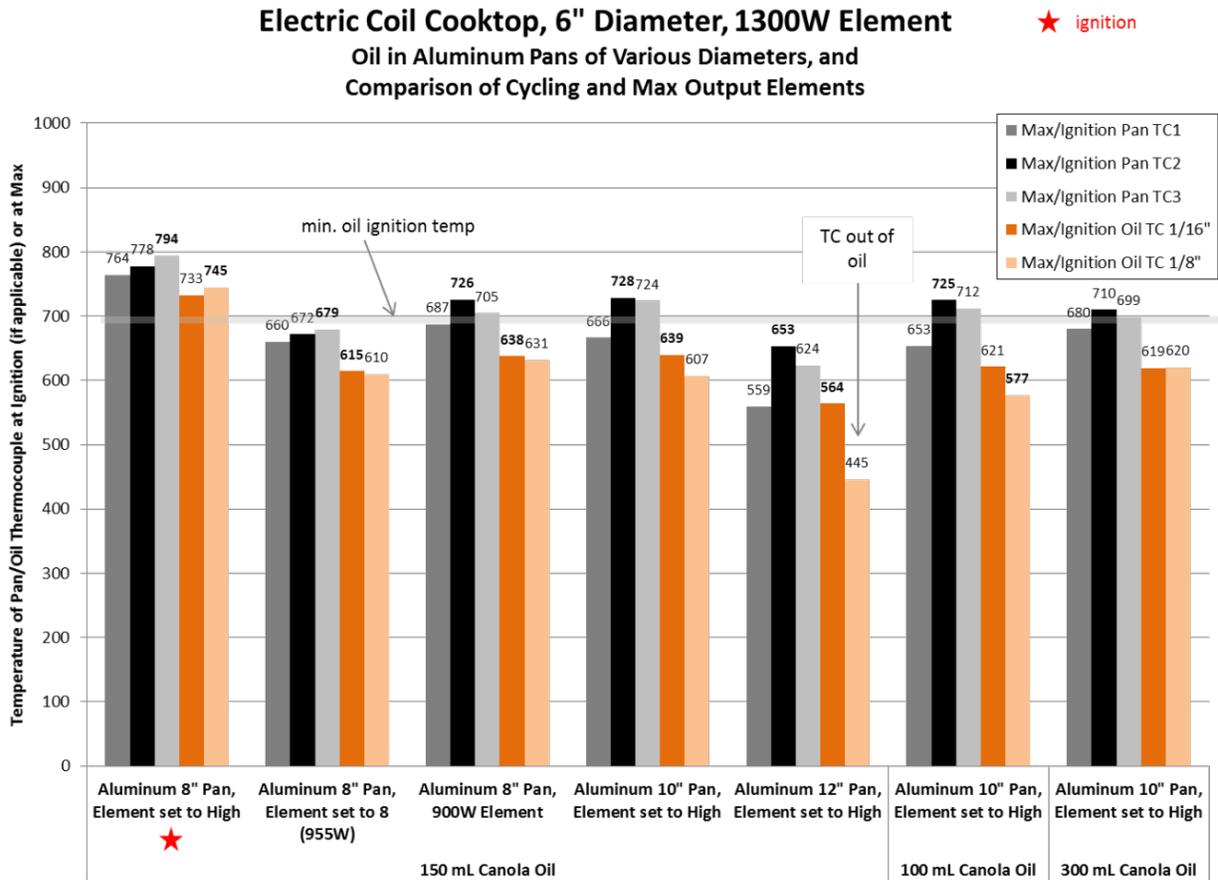


Figure 3: Results of Low Input Testing on Electric Coil Cooktop – Aluminum Pans

In the initial set of testing, an 8" aluminum skillet with 150 mL Canola oil on the 1300 W, 6" electric coil element set to "High" resulted in ignition. This same skillet and oil volume did not ignite when the element setting was reduced to simulate the effect of a lower output element (~955 W, typical of common small elements) of the same size.

The 10" aluminum pan was tested at 1300 W with 100 mL, 150 mL and 300 mL Canola oil. None of these tests resulted in ignition. Variation in oil amount between 100 and 300 mL had minimal impact on pan or oil temperatures.

We repeated the electric coil test at 955 W with a cast iron pan, as theoretical modeling work indicated that cast iron would be a more severe condition than the aluminum pan. Heavy, small pans represent a worst case for oil ignition on electric coil elements as the increased weight leads to better heat transfer from the coil into the pan, and the smaller pan loses less heat to the environment.

As predicted, the oil in the cast iron pan ignited with the element at a set point of “8” (~955 W). We conducted additional tests at set points “6” and “4” with the 8 inch diameter cast iron pan. These results, along with the test result at set point “8”, are shown in Figure 4.

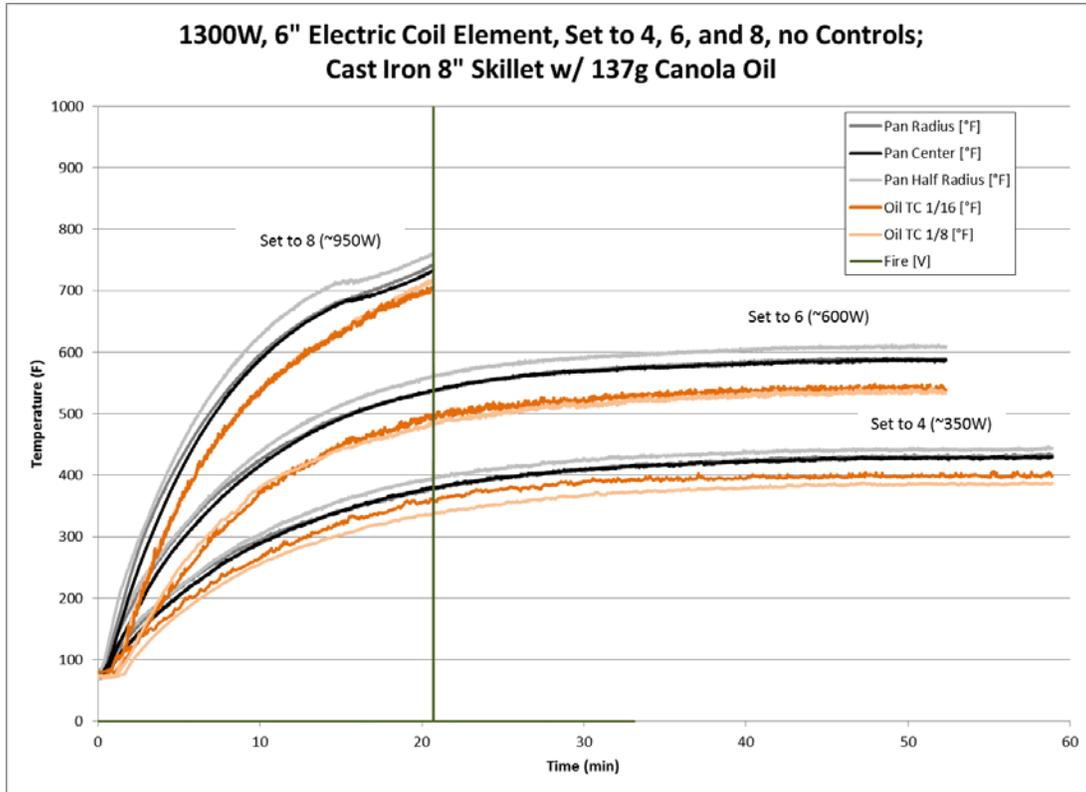


Figure 4: Electric Coil Element Set to “8”, “6” and “4” with a Cast Iron Pan

Figure 5 illustrates the difference between an oil ignition test with an aluminum pan and a cast iron pan on an element set to “8”, corresponding to 955 W. The oil reaches temperatures 100 °F higher with the cast iron pan than the aluminum pan. In this comparison test, there was no ignition (no controls were used) with the aluminum pan, while there was an ignition with the cast iron pan.

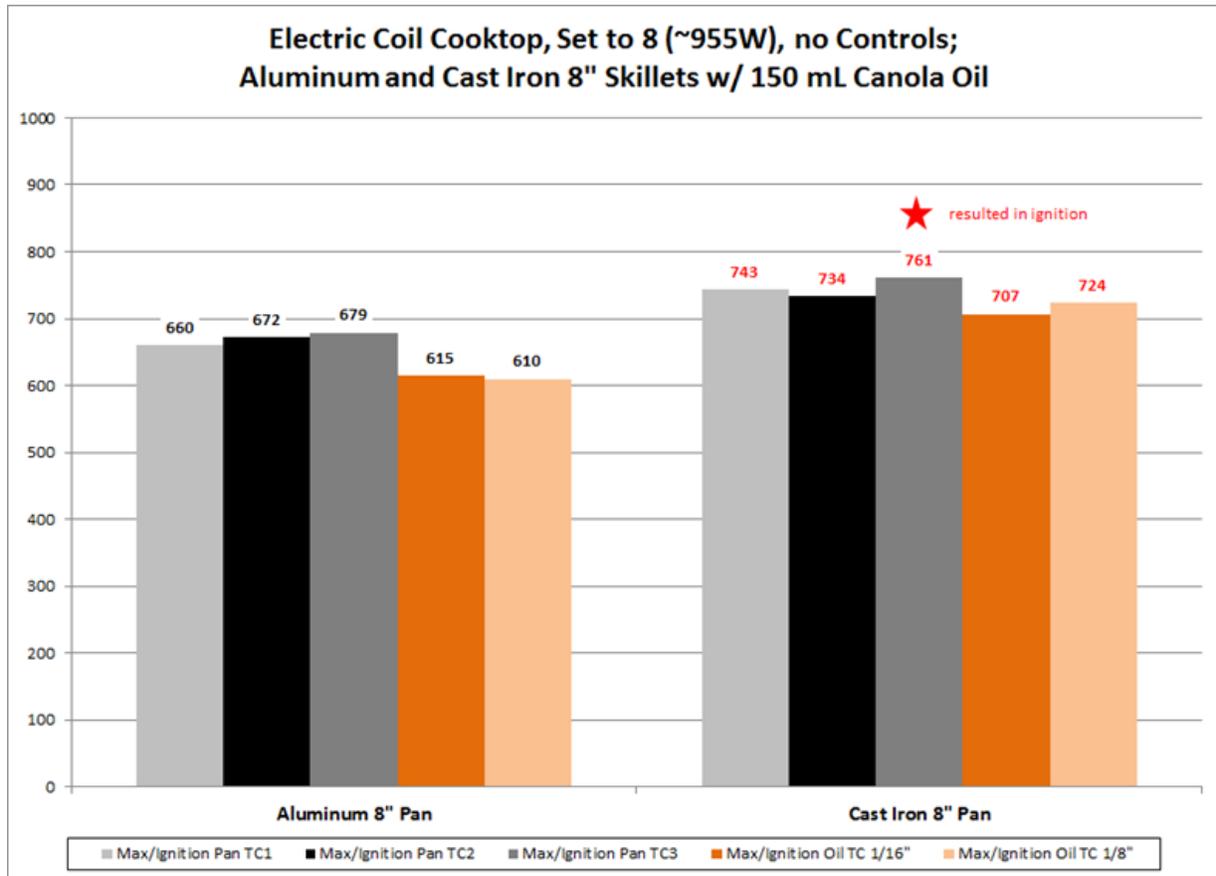


Figure 5: Comparison of Pan and Oil Temperatures, Cast Iron vs. Aluminum, No Controls

We conducted an additional set of tests to compare the ignition characteristics of oil in pans on an element:

- 1) At a reduced power level achieved by cycling a high power element; and
- 2) With a lower, full power rating.

To conduct these tests, we used a portable table stove with two small elements shown below in Figure 6. The element on the left has a nominal rating of 900 W and a measured output of 846 W. The element on the right has a nominal rating of 600 W and a measured output of 560 W.

Photographs of an 8" aluminum pan on the 6" element are in Figure 7 and Figure 8.



Figure 6: Portable Table Stove with Cooking Elements Rated at 900 W and 600 W



Figure 7: 8" Aluminum Pan on 900 W (Rated) Coil Element



Figure 8: Side View of 8" Aluminum Pan on 6", 900 W (rated) Coil Element

The comparison of the temperature profile resulting from an 8" aluminum pan on a cycling element with an average wattage of 955, and an element on continuously at a rating of 846 W is shown in Figure 9. The figure shows that with an aluminum pan, the maximum temperatures reached are close to each other, but the continuous operation of a lower wattage results in a higher temperature than the cycled operation at a higher average wattage.

**Electric Coil, 1300W and 846W 6" Elements, No Controls;
Surface Oil Temperatures for 8" Aluminum Skillet w/ 137g Canola Oil**

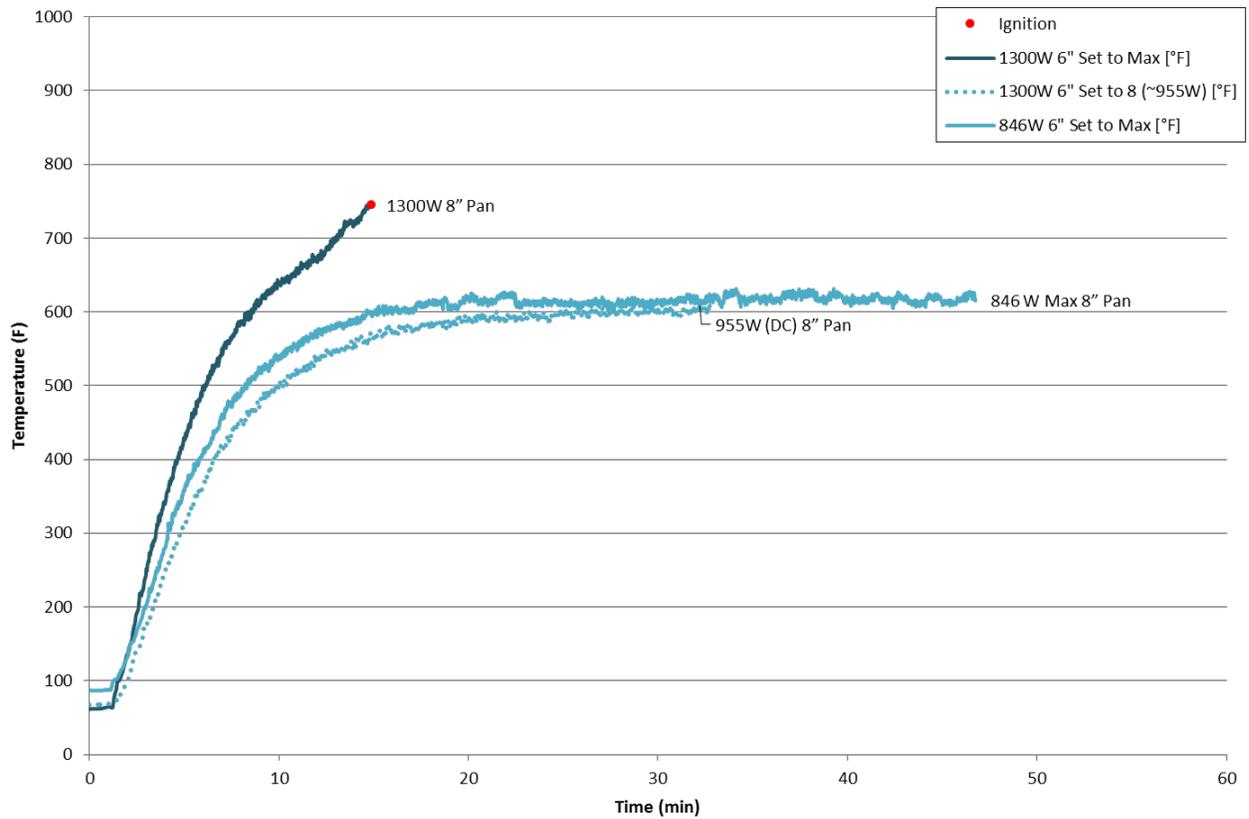


Figure 9: Oil Temperature Profiles in Aluminum Pans: Cycled Elements vs Full Powered Elements of Similar Wattage



Figure 10: 6" Cast Iron Pan on 4" (600 W) Element

We repeated the test for a 6" cast iron pan on a 4" diameter element (600 W rated), compared to this same pan on a 1300 W, 6" element cycled to roughly 600 W average power. (Note the element diameter is different in this comparison.)

Figure 11 shows the oil temperature profiles from cast iron pans heated from roughly 600 W power generated by cycling the 1300 W element compared to having the nominal 600 W element on full power. The graph shows that:

- With 6" cast iron pans, 600 W nominal (560 W actual) will cause an ignition of 150 mL of oil, while 600 W average from cycling a 1300 W element does not result in ignition. (Compare "560 W Max 6" Pan" to 600 W (D.C.) 6" Pan)
- With 6" cast iron pan, 150 mL oil ignited from 560 W continuous input, while 40 mL oil (1/8" oil layer) did not ignite. (Compare 560 W 6" Pan, 1/8" Oil to 560 W Max 6" Pan).
- The smaller amount of oil reached higher temperatures than the 150 mL oil, but did not ignite because it had pyrolyzed and hardened during the heating process.
- Oil in 8" cast iron pan was about 50 °F cooler than in the 6" pan at the same cycled input rate.

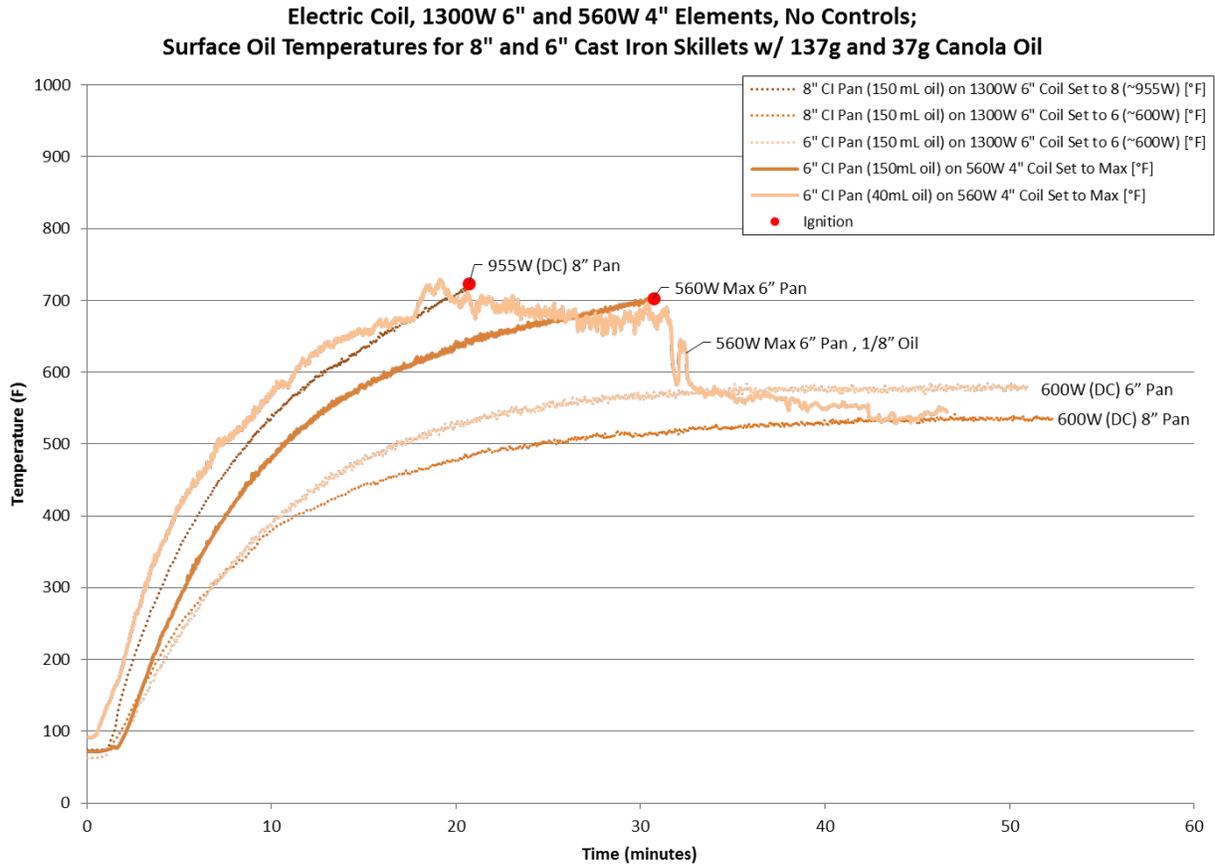


Figure 11: Oil Temperature Profiles for Duty Cycled vs Steady Power

A summary chart of testing conducted to explore cycling versus continuous power heating is shown in Figure 12. The summary shows that a small element at wattages as low as 560 W can ignite oil in a 6" diameter cast iron pan.

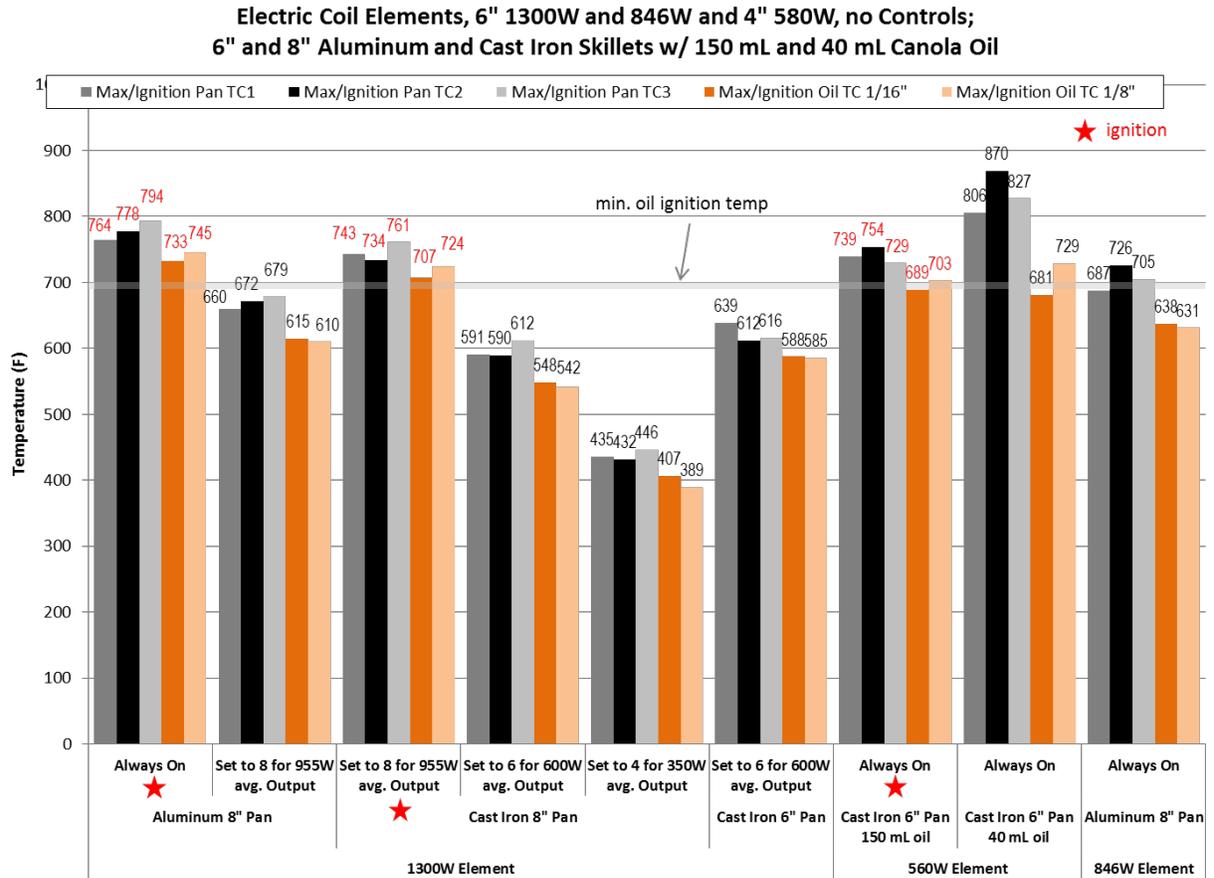


Figure 12: Summary of 8" and 6" Pan Tests at Low Average Power

5.1.2 Glass Ceramic Cooktop

On the glass ceramic cooktop 5" diameter, 750 W element set to "9" (the highest setting) an 8" cast iron skillet with 150 mL Canola oil resulted in ignition. An aluminum 8" skillet tested under the same conditions produced oil temperatures that did not result in ignition. The oil temperatures in the 10" and 12" aluminum skillets were 250°F - 300°F below the ignition risk zone. In addition, we reduced the average wattage to 600 W, by setting the element to "8" (the next highest setting). At this average power level, (600 W), oil in a 6" cast iron pan ignited. Details of these results are shown. We did not further reduce the cycled wattage as we could not identify a glass ceramic cooktop with an element rated between 350 and 650 W to confirm the cycled result with a full wattage element. A scatter plot showing a recent survey of glass ceramic cooktop element wattage plotted as a function of element diameter is shown in Figure 14. For this survey we tabulated the element wattages and the corresponding element diameters for the glass ceramic cooktops offered by 6 major appliance manufacturers. The data was

obtained from each manufacturer’s website and product descriptions. The smallest cooking element found was 700 W. (There are some warming elements available at less than 350W.)

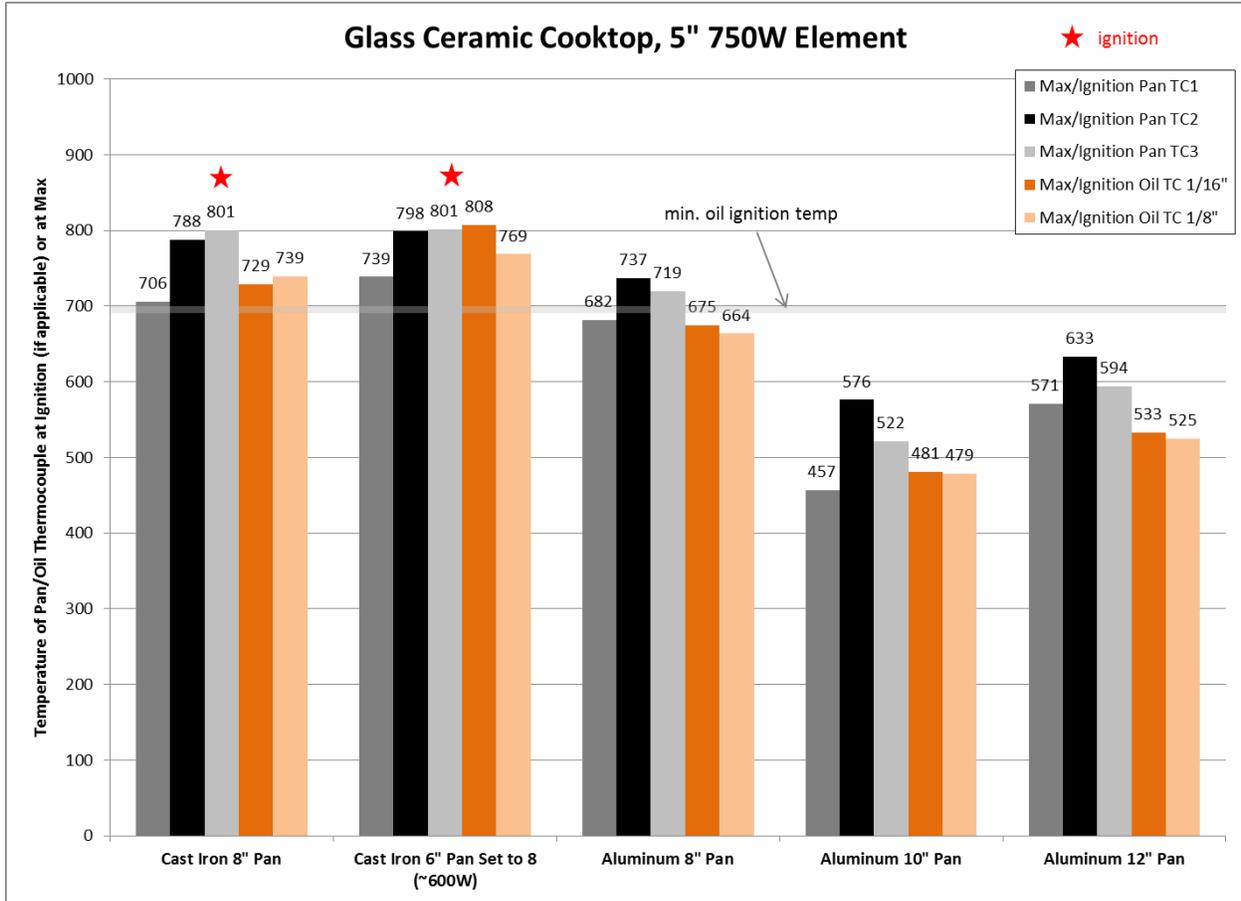


Figure 13: Results of Low Input Testing on Glass Ceramic Cooktop

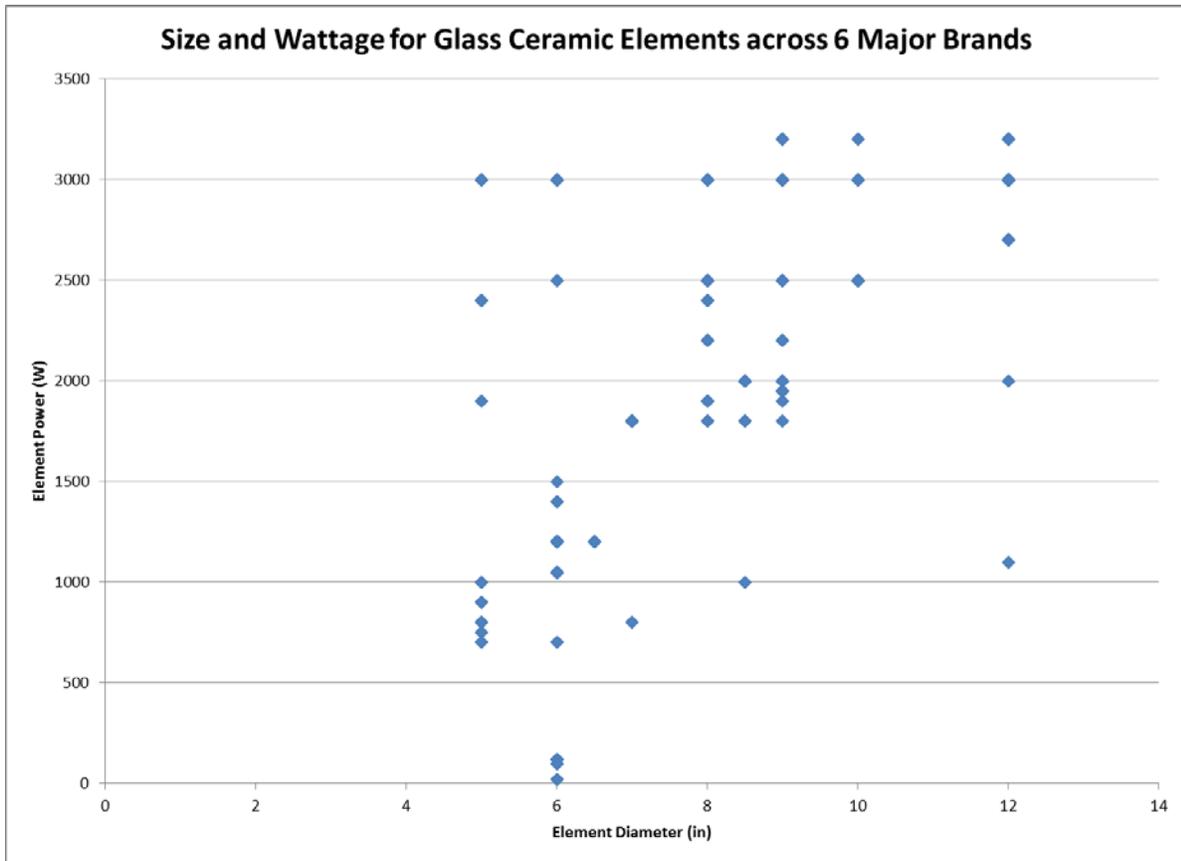


Figure 14: Scatter Plot of Glass Ceramic Cooktop Element Wattage and Diameter

5.1.3 Gas Cooktop

None of the tests conducted on the 5,000 Btu/hr gas burner resulted in ignition. The maximum recorded oil temperature in an 8” stainless steel skillet came close to the ignition region for oil ignition on gas burners, but did not ignite. Oil temperatures reached in an 8” aluminum skillet with 150 mL Canola oil were well below the 670°F ignition risk zone for gas burners. Details of these tests are shown in Figure 15. The ignition results will be dependent on gas burner design, grate design, and pan size as the efficiency of the burner (and therefore the heat into the pan) is strongly affected by these characteristics.

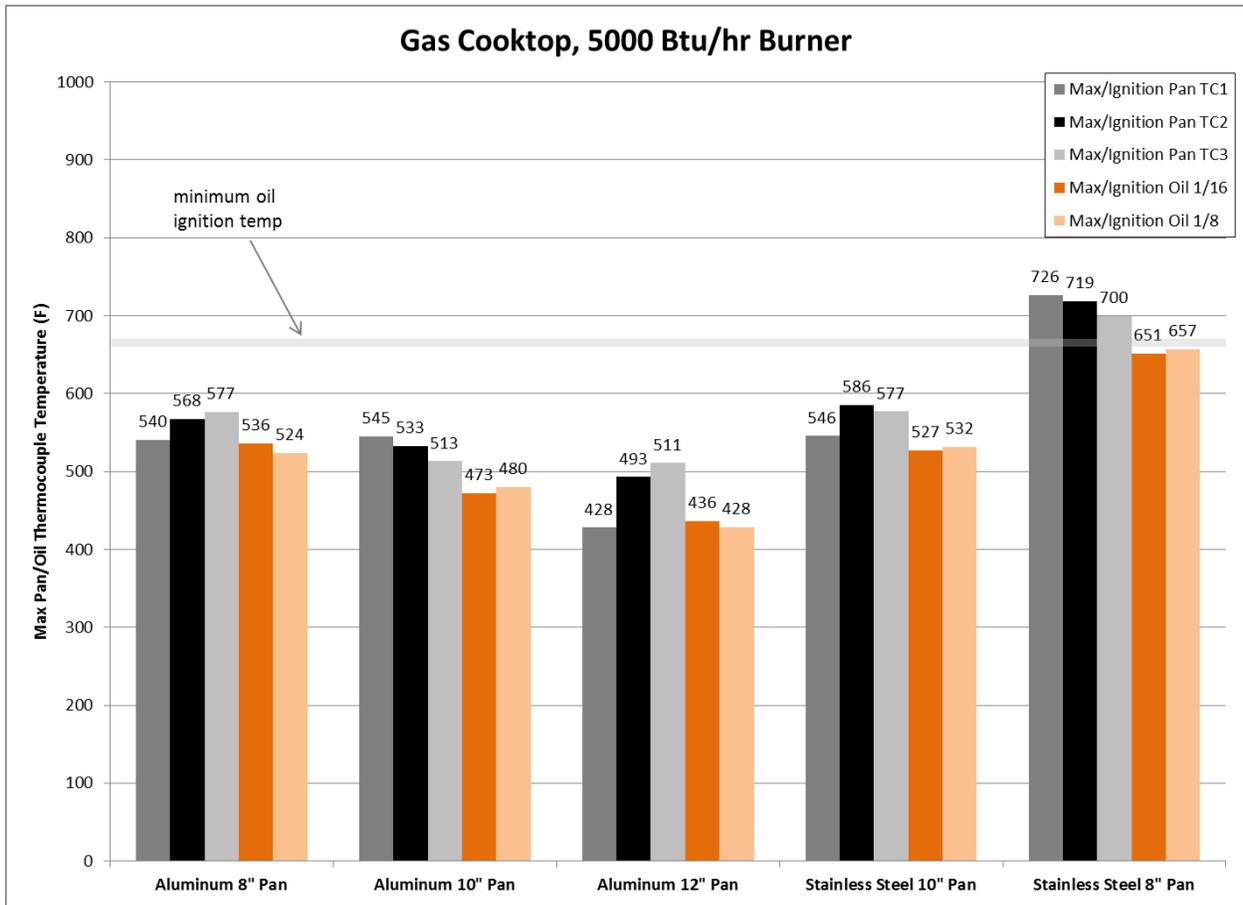


Figure 15: Results of Low Input Rate Testing on Gas Cooktop

For comparison, we include the results of tests conducted for the CPSC in 2013 under Contract #HHSP233201300146A for stainless steel, cast iron and aluminum pans with Canola oil heated on an 8,000 Btu/hr gas burner. None of these tests resulted in a fire or oil temperatures in the oil ignition zone, but all the pans were 10" in diameter at that time, which would be expected to result in lower temperatures than 8" pans, which more closely match the burner size. The oil temperature results shown in Figure 16 show that stainless steel could be a worse case pan material for a gas burner.

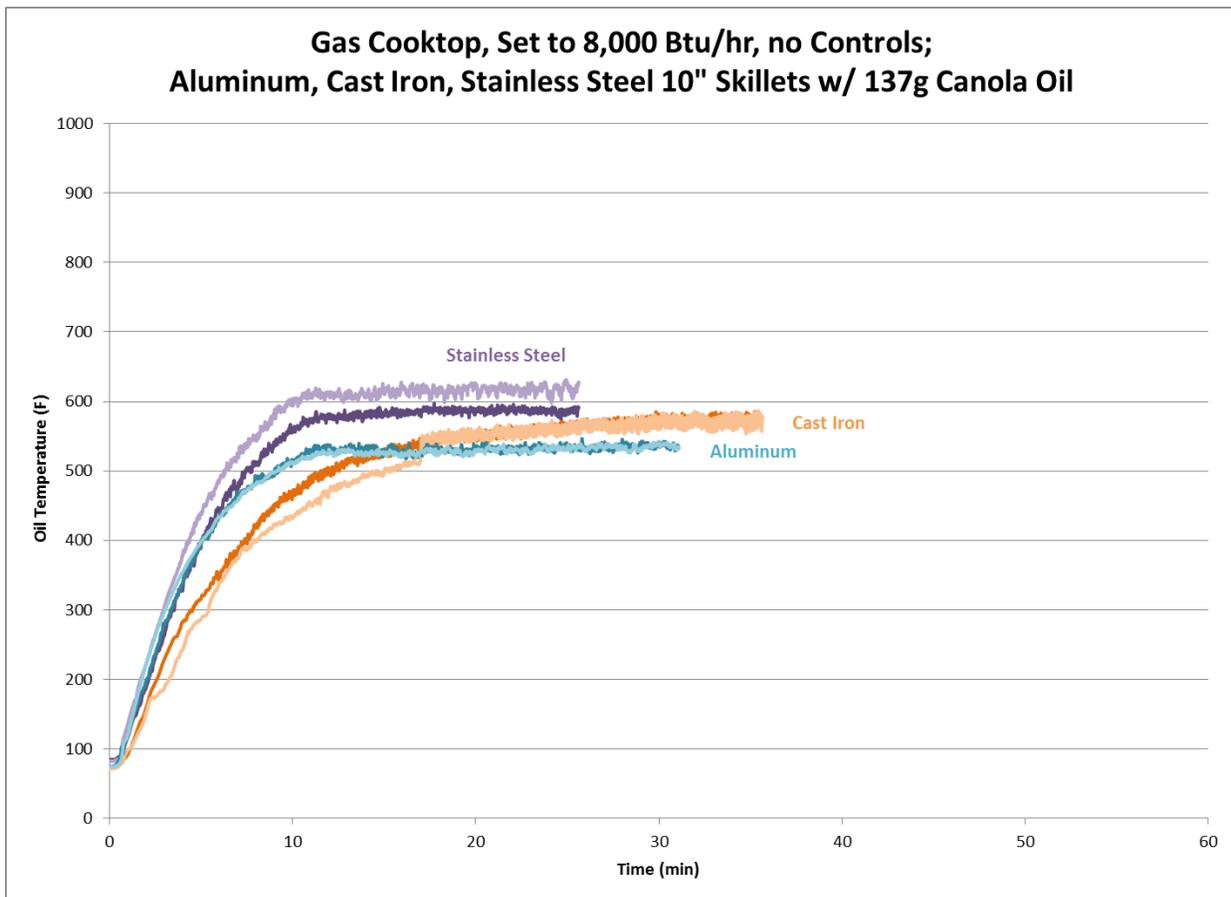


Figure 16: Oil Temperatures Reached From 8,000Btu/hr Burner on Gas Cooktop

Figure 17 compares the 10” stainless steel and aluminum pan results at 8,000 Btu/hr to the 8” and 10” aluminum pan results at 5,000 Btu/hr. This comparison shows that the oil temperature in a 10” pan at 8,000 Btu/hr will be similar to the oil temperature in an 8” pan at 5,000 Btu/hr.

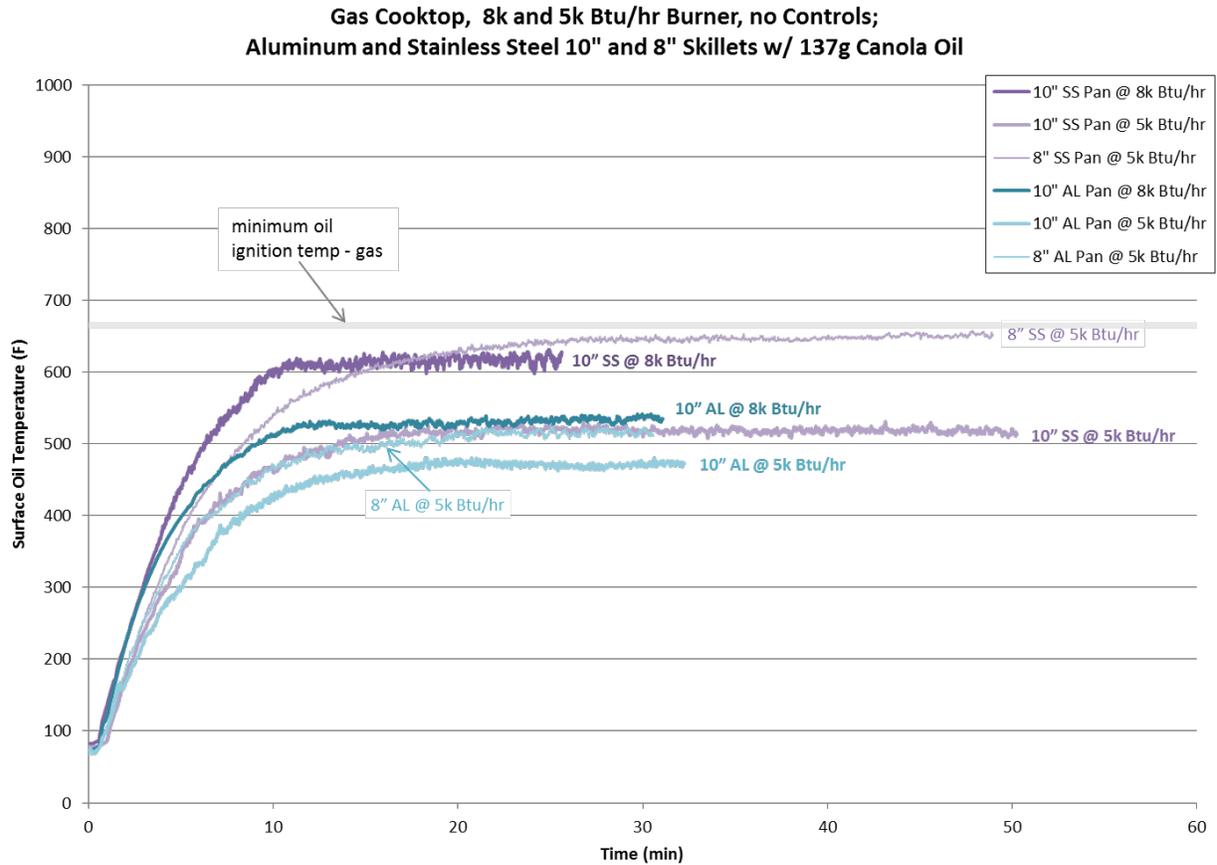


Figure 17: Oil Temperatures Reached From 5,000 and 8,000 Btu/hr Gas Burners

Similar plots of oil temperature profiles from electric cooktops are included in Appendix 3.

5.1.4 Summary

The tests demonstrated that a 600 W electric coil element can cause a fire in a cast iron pan with 150 mL Canola oil. Tests also demonstrated that a 750 W element in a glass ceramic cooktop that is cycling at 600 W will also ignite oil in a cast iron pan. Tests demonstrated that a 5,000 Btu/hr burner on a gas cooktop did not light oil in a pan under any of the test conditions. It is noted that oil ignitions on gas burners will be influenced by burner design, grate height and other factors in addition to heat output. The design factors impact burner efficiency and therefore total heat that is transferred into the pan.

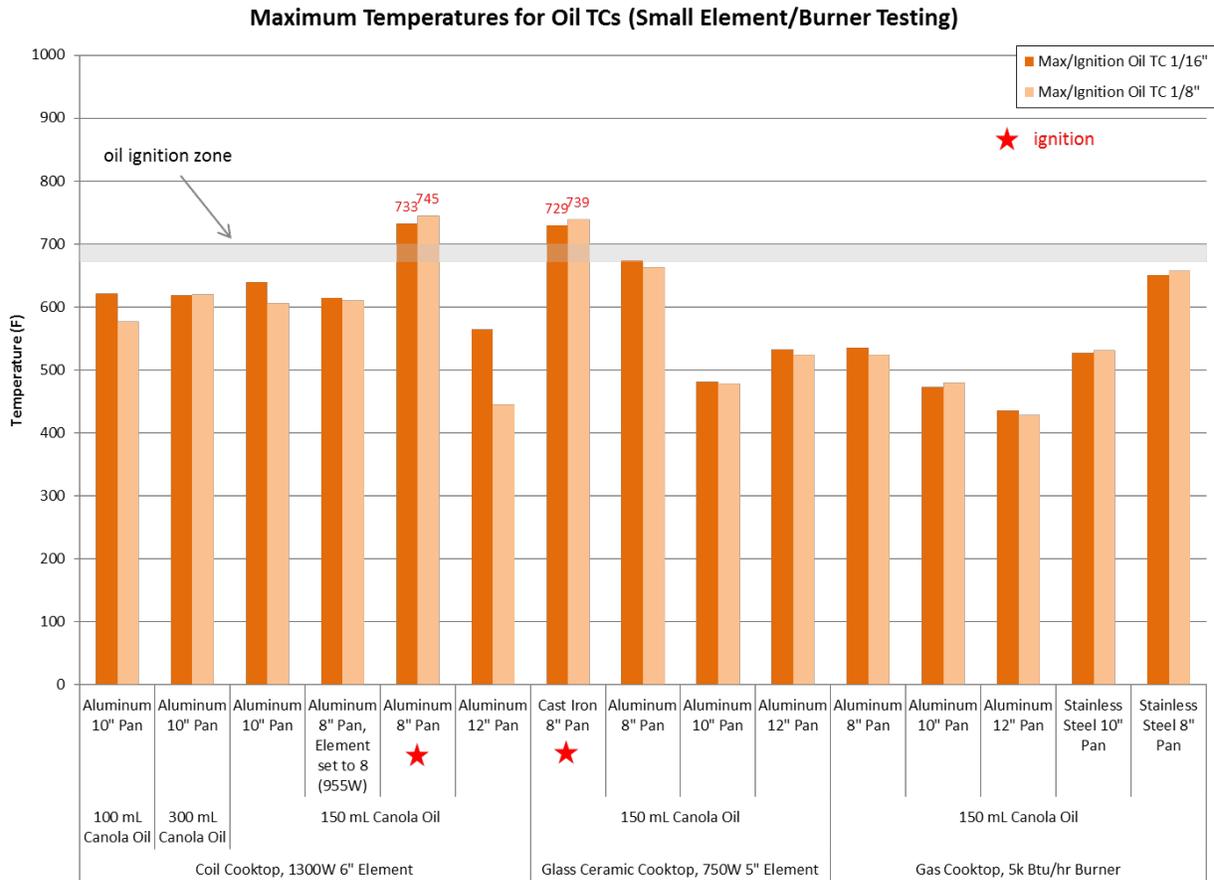


Figure 18: Summary Oil Temperature Results for 8", 10" and 12" Pans on All Cooktops

Figure 18 summarizes the maximum oil temperatures reached for tests conducted on all cooktops with 8", 10" and 12" pans.

5.2 Refinement of Gas Burner Controls

Our approach to pan temperature limiting with the gas burner involves turning the burner down from the input rate set by the user to a lower flow rate set by a flow restrictor in a bypass gas line. The operation of a solenoid valve switches the gas from one line to another based on the control algorithm. Our testing was conducted with a gas burner rated at 18,500 Btu/hr with our integrated pan temperature limiting sensor and control system. The burner and sensor configuration is shown in Figure 19.



Figure 19: Gas Cooktop Sensor Configuration

The total number of on/off cycles of the gas valve to maintain a set point temperature is dependent on the level of the reduced gas flow rate. We characterized the cycle rates of the control system that was using the standard control algorithm defined in CPSC Contract HHSP233201300146A, and a stainless steel pan in “dry cook”, i.e. there was no oil in the pan during the testing.

We characterized the number of on/off cycles that occurred in a 20 minute period. When the low input rate of the gas was 2,500 Btu/hour, the gas valve opened or closed 22 times times in a 20 minute period. The operation of the valve reduced to 13 times in this time frame when the input rate of the gas was 4,400 Btu/hour. At 7,500 Btu/hr there was only one switch of the valve (to off), but the pan continued to rise in temperature beyond the limits to prevent an oil fire. Clearly there is a trade-off between number of gas valve cycles and the gas input rate at the reduced flow setting. The relationship between gas valve cycles to maintain the set point temperature and the flow rate of the reduced gas setting is shown in Figure 20.

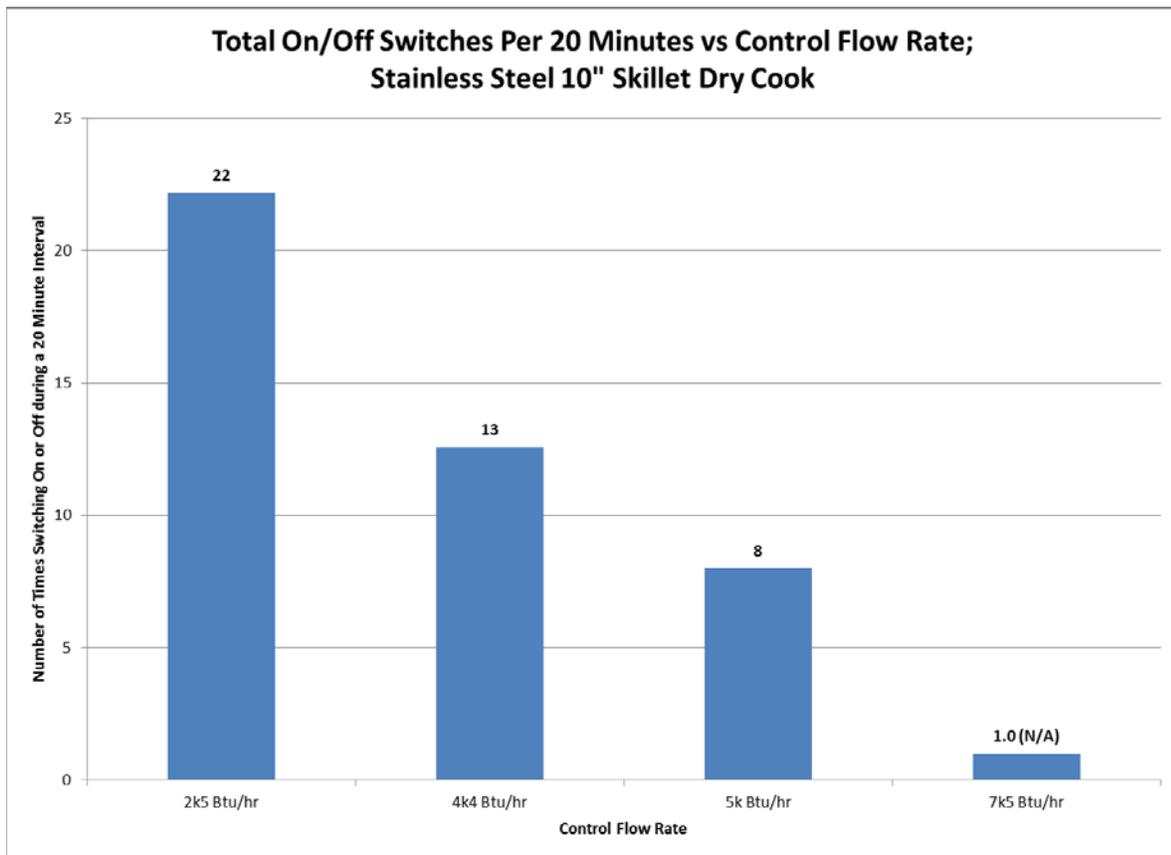


Figure 20: Relationship between Gas Flow at the Reduced Rate and Gas Valve Cycles

5.2.1 Testing to Define Upper Limit to Reduced Gas Flow Rate

There are limits in allowing the reduced rate to creep too high. At 7,500 Btu/hour, the oil ignites in a 10” stainless steel pan. At 5,000 Btu/hr, the oil did not ignite, but it reached 710°F after an extended test that degraded the oil. Higher volumes of oil could have led to an ignition.

5.2.2 Ignition Testing

Based on the result at 5,000 Btu/hr, we chose 4,400 Btu/hr as the preferred input rate to use for the reduced rate of the gas cooktop. The previous reduced rate was 2,500 Btu/hr.

We conducted the following ignition tests on the gas cooktop using 4,400 Btu/hr as the reduced input rate:

- Aluminum 8” skillet w/ 150 mL Canola oil
- Aluminum 8” skillet w/ 300 mL Canola oil
- Cast Iron 8” skillet w/ 150 mL Canola oil

- Cast Iron 8” skillet w/ 300 mL Canola oil
- Stainless Steel 8” skillet w/ 150 mL Canola oil
- Stainless Steel 8” skillet w/ 300 mL Canola oil

No ignitions occurred in any of these tests, as shown in Figure 21, below. In all these tests, the nominal input rate of the gas burner was 18,500 Btu/hr.

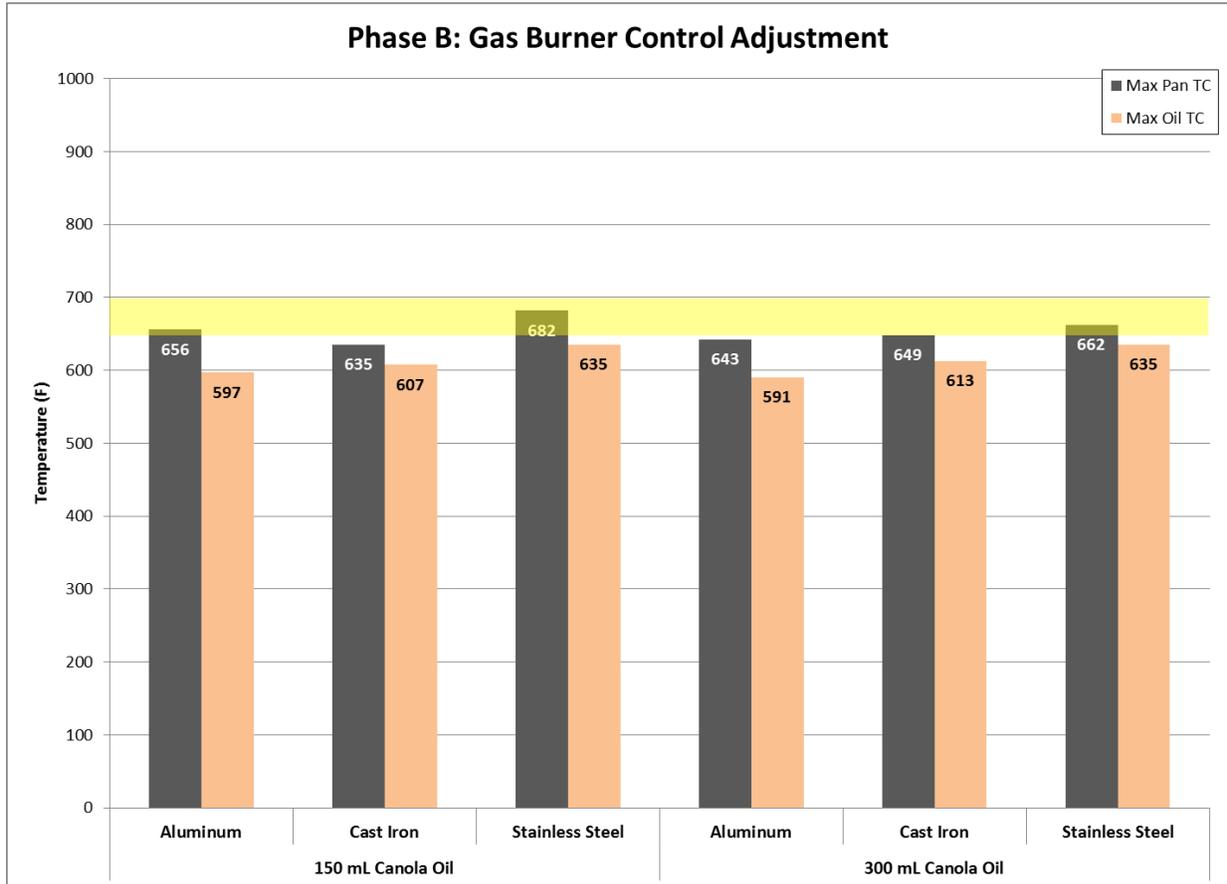


Figure 21: Maximum Pan and Oil Temperatures Reached on Gas Cooktop using 4,400 Btu/hr for Control (Reduced) Input Rate

5.2.3 Summary

Increasing the reduced firing rate from 2,500 to 4,400 Btu/hr provides benefits of reduced burner cycling and smoother temperature profiles without impacting the ability to avoid a fire.

5.3 Thermistor-Type Sensor Feasibility Assessment

The objective of this element of the program was to assess the feasibility of using a low-cost thermistor to effect pan temperature limiting control.

In our previous work we have demonstrated the pan temperature limiting controls using a RTD-based sensor. RTDs are robust sensing elements with highly linear characteristics, very little sensor-to-sensor variation, and broad operating temperature ranges (up to 450 °C (840 °F) or 600 °C (1110 °F), depending on RTD class).

However, in the long term a thermistor-based sensor could offer a lower cost solution. On the other hand, the control points for the pan temperature limiter are close to the maximum operating temperature of cost-effective thermistors, so sensor design and control parameters/algorithms need to be modified to accommodate this approach.

The objective of this element of the program was to design and fabricate a thermistor-based sensor (using only low-cost thermistor options), modify control parameters accordingly and conduct control testing to establish feasibility.

5.3.1 Implementation Considerations

There are two important differences between low-cost thermistors and the RTDs we have been using in the cooktop sensor to date:

- (1) thermistors have a lower maximum operating temperature
- (2) thermistors have a highly non-linear thermal response characteristic, i.e., small increases in temperature produce logarithmic decreases in resistance

Cost-effective thermistors have a maximum operating temperature of approximately 300 °C (570 °F), which is considerably lower than that of the RTDs we have been using to date. Thermistors that can operate at maximum temperatures comparable to these RTDs are significantly more expensive than the RTDs themselves, so the potential cost advantage of switching to thermistors is lost. The practical implication of this upper temperature limit is that we must design a sensor body that allows the thermistor to operate at temperatures some way below the pan temperature while still providing a fast enough response to be useful in a temperature limiting controller.

Thermistors have a highly non-linear thermal response characteristic. Figure 22 shows a representative variation of thermistor resistance with temperature. Note the y-axis of the graph is a logarithm axis.

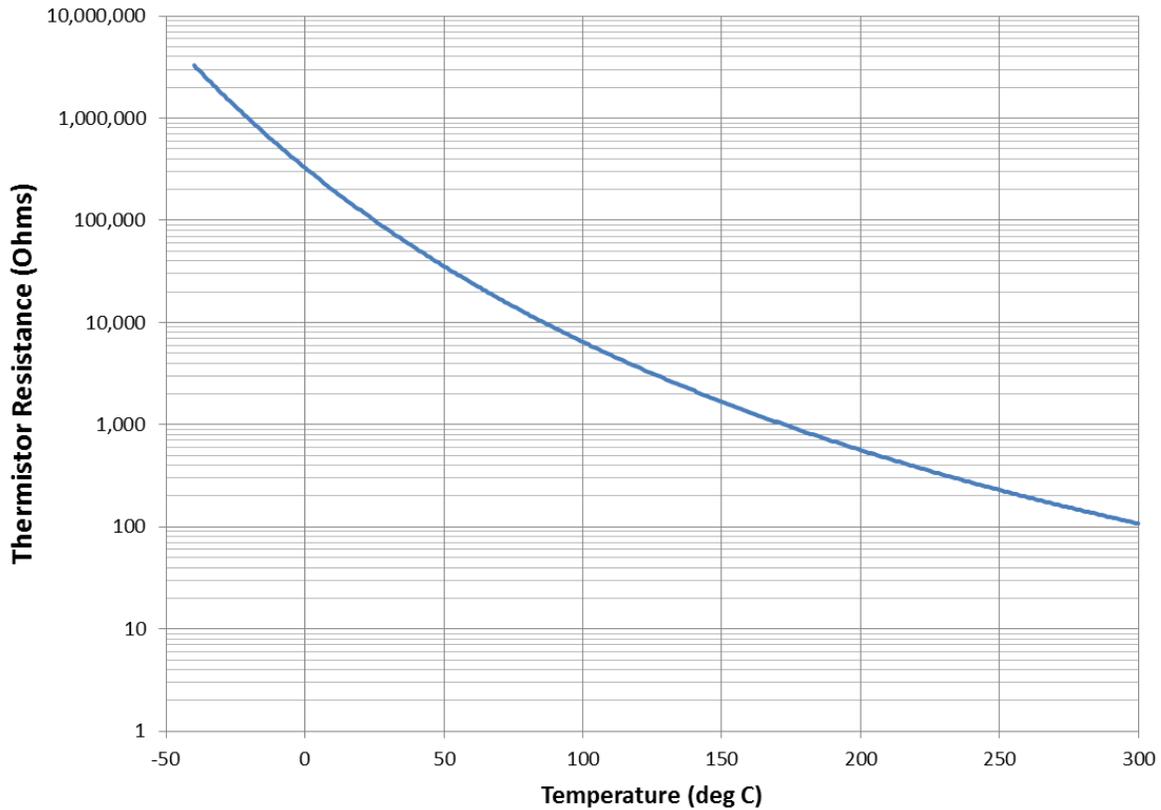


Figure 22: Representative Thermistor Resistance Curve

The general approach to using a thermistor as a temperature measuring device in an electronic control application is to set up a voltage divider in which the thermistor, as a variable resistor, generates a variable voltage as its temperature varies, and then to bias and linearize this voltage over a preferred temperature range.

5.3.2 Sensor Housing Design

We adapted the design of the previous RTD sensor housing to incorporate layers of Fiberfrax insulation between the sensor cap (which contacts the pan bottom) and the thermistor. The design is illustrated schematically in Figure 23. The insulation provides some thermal resistance between the pan bottom and the sensor and allows the thermistor to operate within its normal operating temperature range while still providing a responsive signal of pan temperature for control purposes.

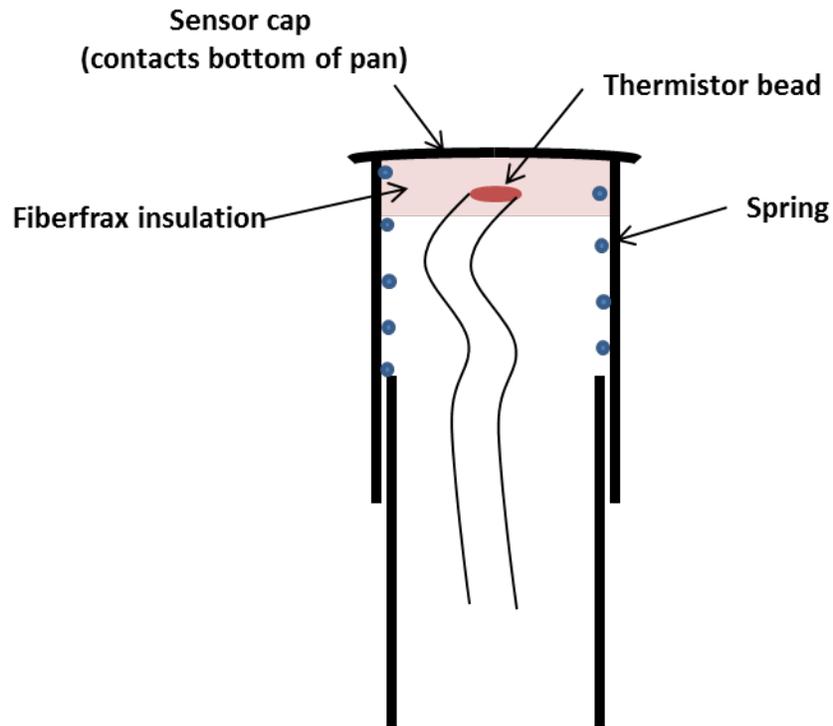


Figure 23: Schematic Illustration of Thermistor Sensor Design

5.3.3 Integration into Control System

We designed a circuit to bias, linearize and scale the variable thermistor voltage to output voltage levels in the 0 – 5 V range between 150 C and 300 °C and to interface to the PLC that we use to control the cooktop. The circuit design is illustrated in Figure 24 below.

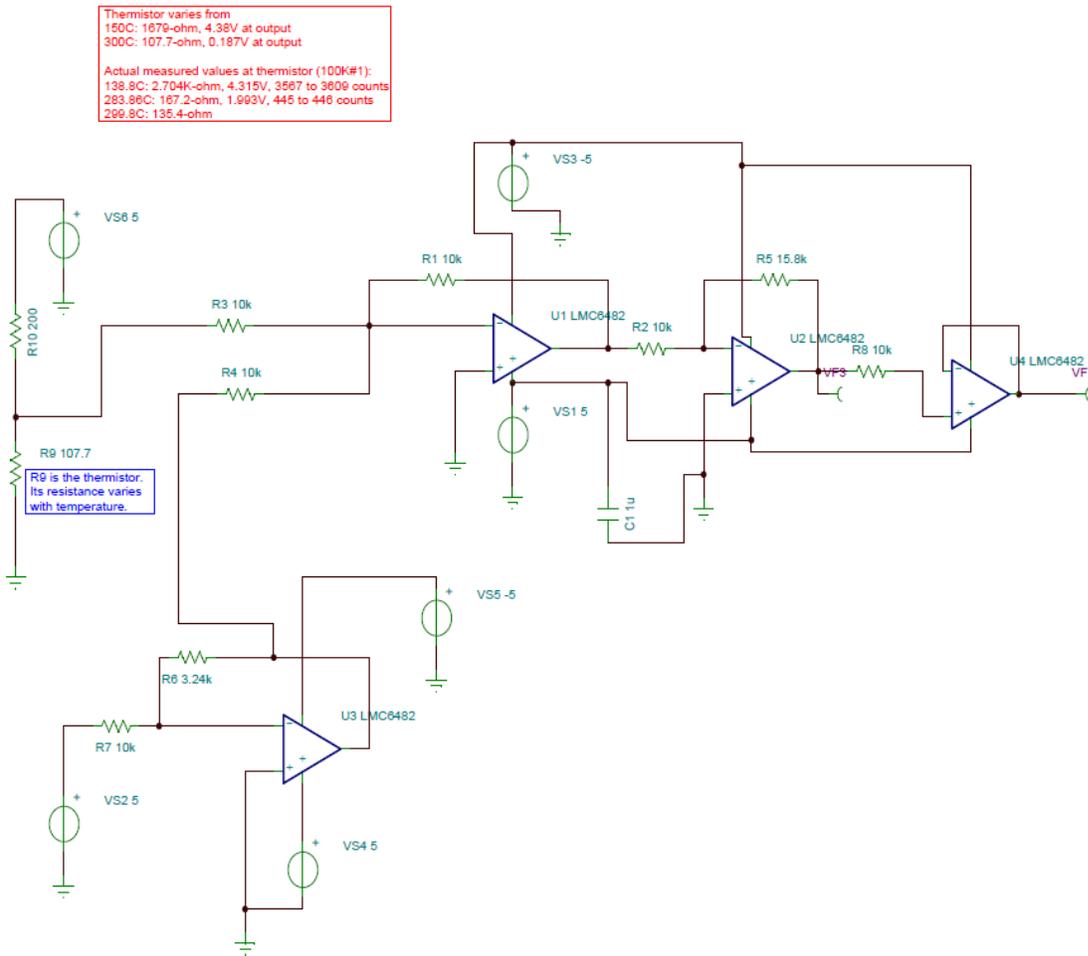


Figure 24: Thermistor Signal Conditioning Circuit

5.3.4 Calibration

We calibrated the thermistor sensor against reference thermocouples in order to check the linearity of the input circuit in the temperature range of interest. The circuit components were chosen such that we have a useful thermistor signal above approximately 150 °C (300 °F). There is little change in PLC input voltage below this temperature level. A typical thermistor calibration is shown in Figure 25 – we were able to obtain highly linear voltage signals in the temperature range of interest.

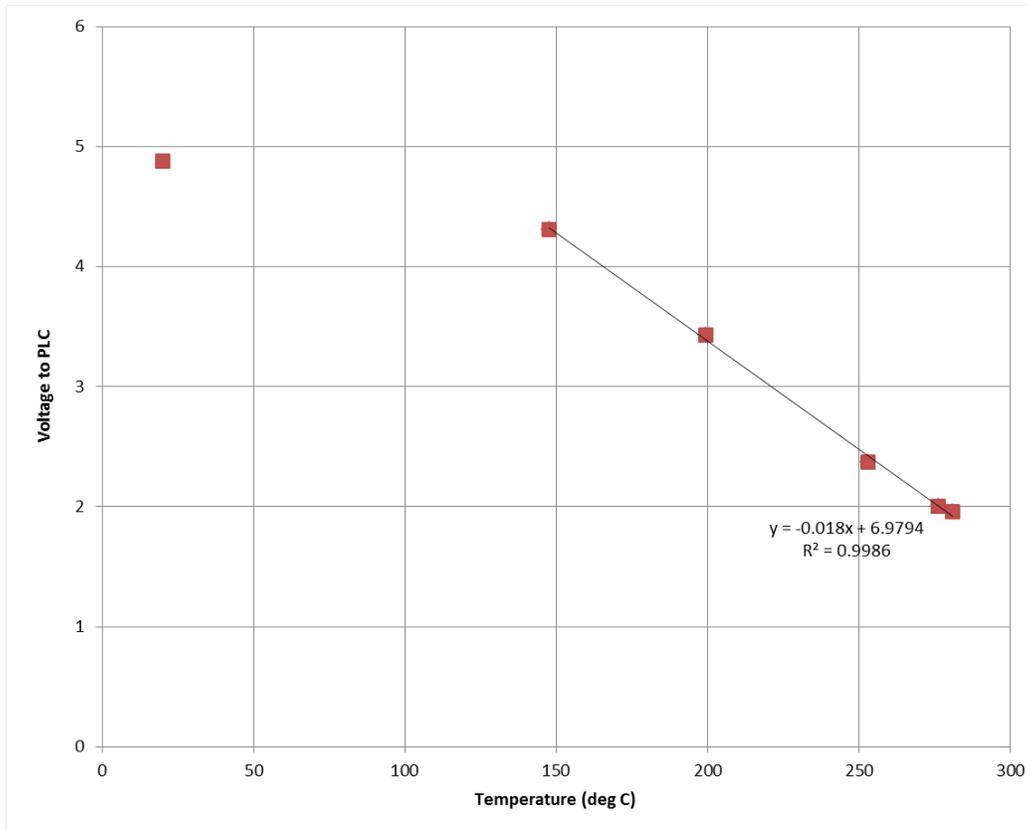


Figure 25: Typical Thermistor Calibration Curve, Showing Region of Linearization

5.3.5 Sensor Characteristics

We started by conducting dry cook tests to understand the thermistor sensor characteristics and to make sure that the maximum operating temperature of the thermistor was not exceeded. The temperature data in Figure 26 and Figure 27 for dry cook tests with a 10” cast iron pan on an 8” electric coil element at two different heat input settings, are representative of what we observed in general.

As the data show, initial indications were that the thermistor operates within its design temperature envelope while still providing useful data to prevent pan over-temperature leading to oil ignition. However, as expected, we observed a lag between the sensor thermistor response and the pan response.

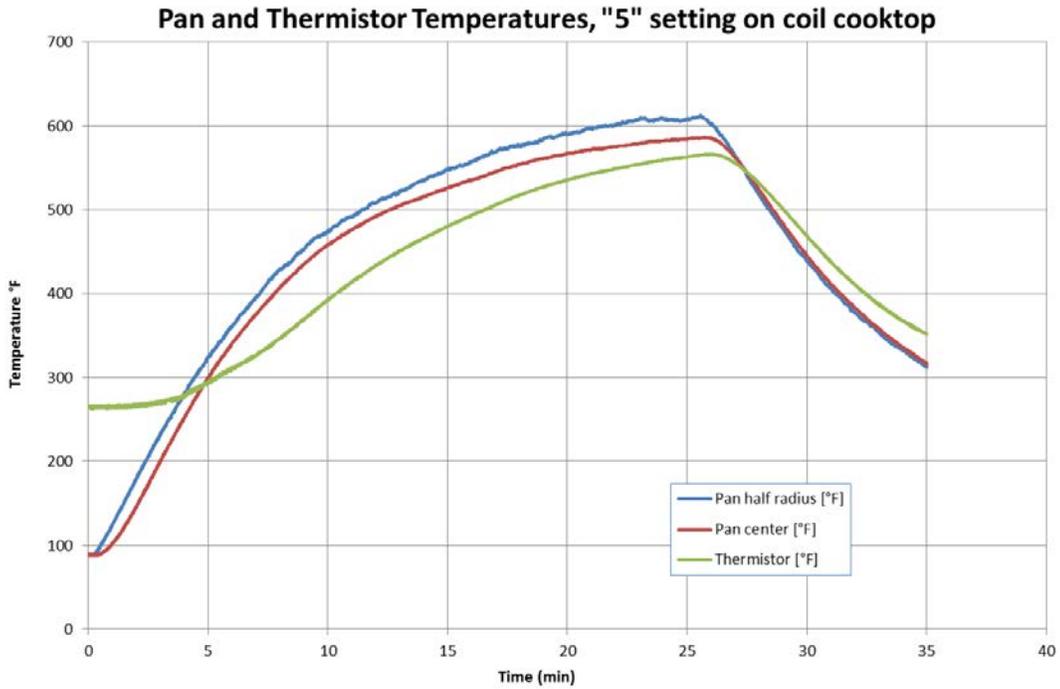


Figure 26: Pan and Thermistor Temperature Data for Dry Cook with 10” Cast Iron Pan on 8” Electric Coil at Setting 5. (Element shut off after approximately 27 minutes).

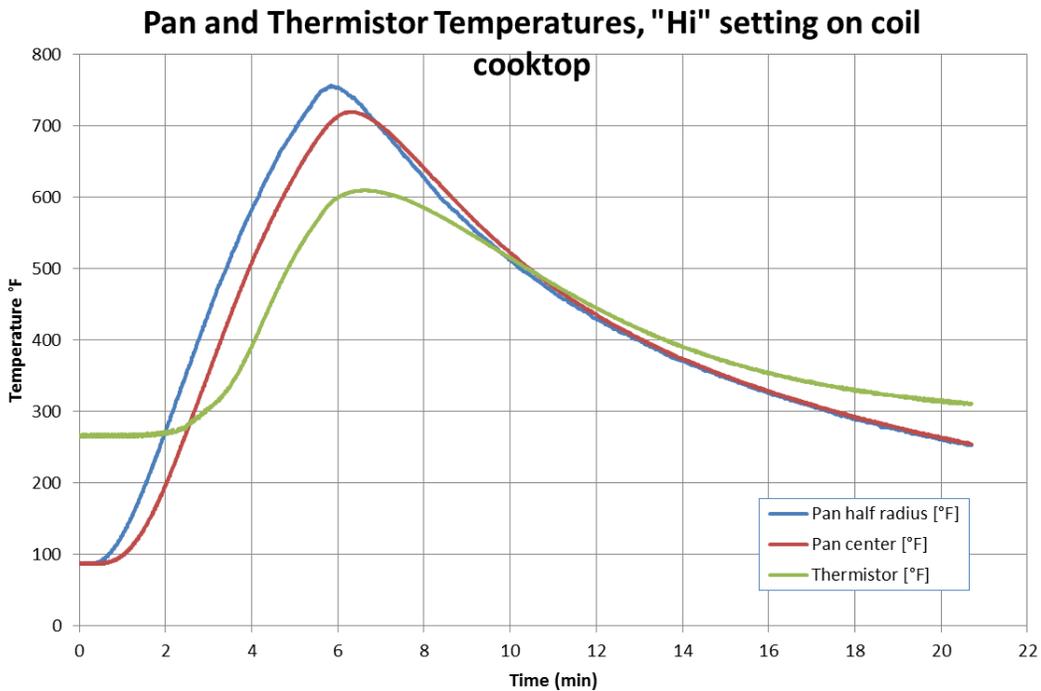


Figure 27: Pan and Thermistor Temperature Data for Dry Cook with 10” Cast Iron Pan on 8” Electric Coil on High. (Element shut off after approximately 5.5 minutes).

Further testing was conducted for a variety of pan types and heat input rates. The initial performance characteristics for the thermistor sensor are summarized in Figure 28, where the indicated thermistor temperature is plotted as a function of the pan center temperature for a variety of pan types and heating rates.

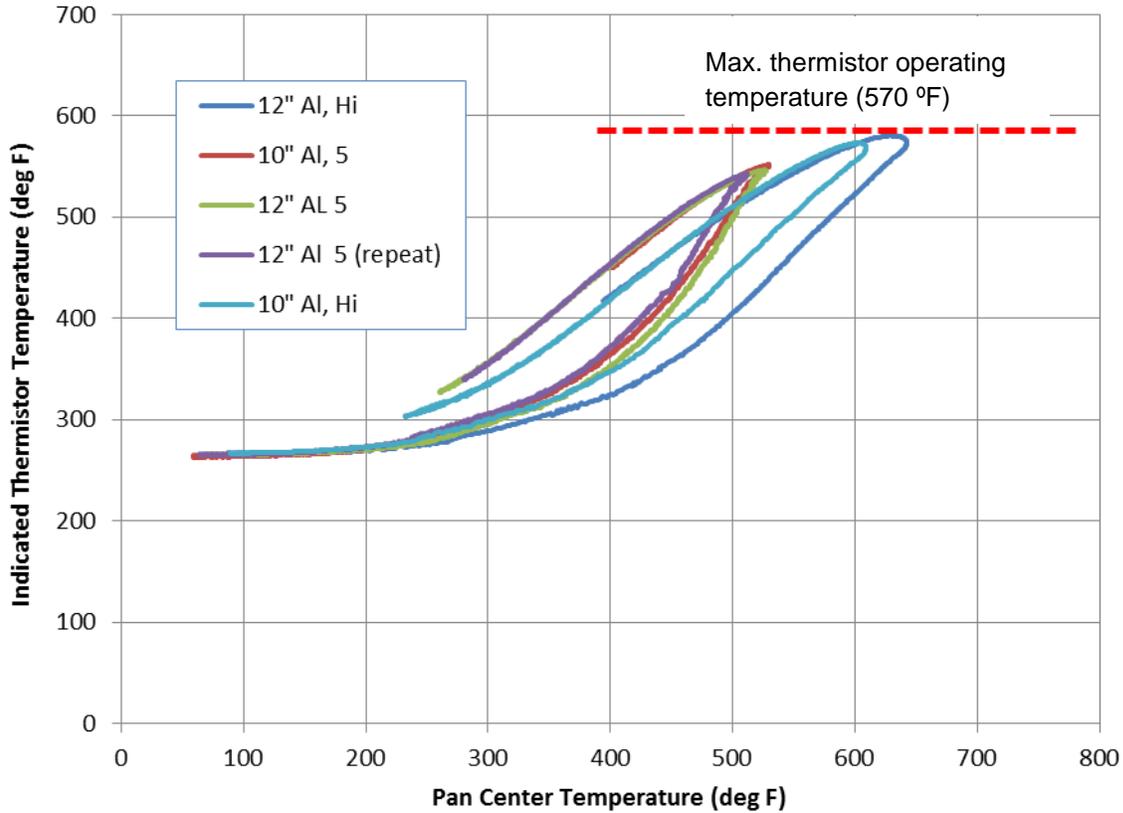


Figure 28: Indicated Thermistor Temperature as a Function of Pan Center Temperature for Various Pan Types and Heating Rates

The thermistor operating temperature is limited to 300 °C (570 °F). However, we need to sense pan temperatures considerably in excess of 570 °F. The data for the initial sensor build shown in Figure 28 suggests that the sensor is too limited in its pan temperature range. In order to increase the upper limit of pan temperatures at which the sensor would provide useful data, we re-built the sensor with additional insulation between the sensor cap and the thermistor bead. The two different sensor characteristics are compared for the case of a 10” cast iron pan (dry-cook) in Figure 29.

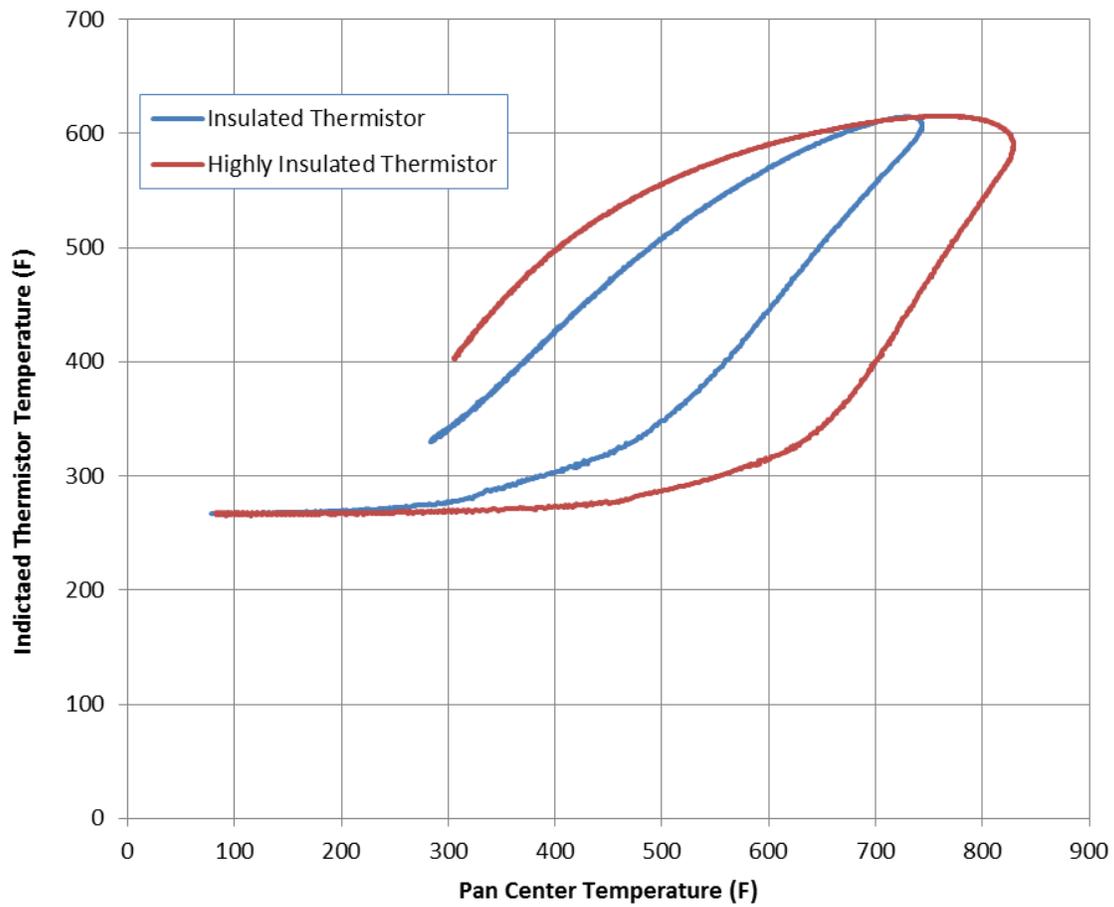


Figure 29: Impact of Additional Insulation on Response Characteristics of Thermistor Sensor

As intended, the operating range of the thermistor has been increased to higher pan temperatures by adding insulation between the sensor cap and the thermistor bead. However, the response time of the thermistor has been affected: there is now even more of a lag between pan and thermistor response.

5.3.6 Control Performance

Initial pan temperature control trials with the highly insulated thermistor sensor showed poor control characteristics compared to the previous RTD characteristics. The requirement to limit the maximum sensor temperature by adding insulation is the reason for the less than desirable characteristic. For example, Figure 30 below shows the initial temperature control for a 10” cast iron pan on the electric coil element using the highly insulated thermistor sensor.

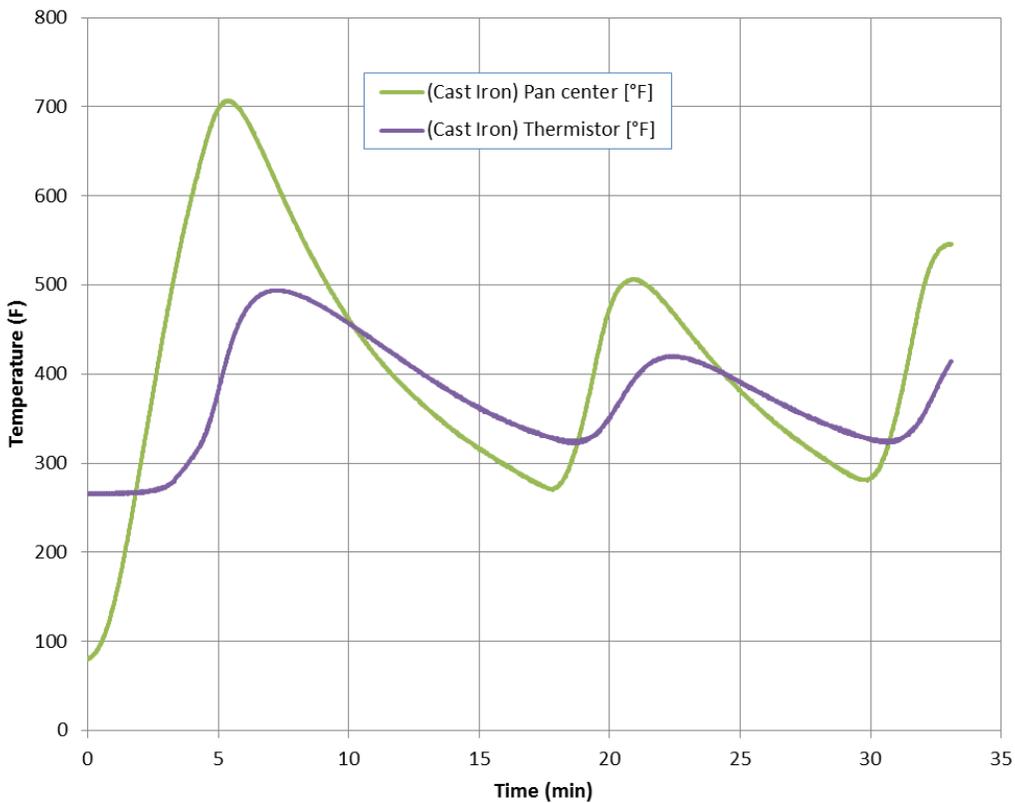


Figure 30: Dry-Cook Control of a 10” Cast Iron Pan on an Electric Coil Element using the High-Insulated Thermistor Sensor

It was necessary to effect control at a relatively low indicated thermistor temperature (~330 °F) in order to prevent the pan temperature exceeding 700 °F. Once the power cycled off, the pan started cooling but the thermistor kept getting hotter, eventually exceeding the pan temperature significantly. This is due to heat transfer from the hot cast iron pan to the insulated sensor body. It took an unacceptably long time for the thermistor temperature to drop and the power to cycle

on, at which point the pan had cooled significantly. This control behavior is in marked contrast to that achieved with the RTD sensor which is closely coupled to the pan temperature.

Similar behavior was observed for a much lower thermal mass aluminum pan, see Figure 31. In this case as well, the slow response of the thermistor sensor to temperature changes caused large swings in controlled pan temperature with a long time period (approximately 10 minutes).

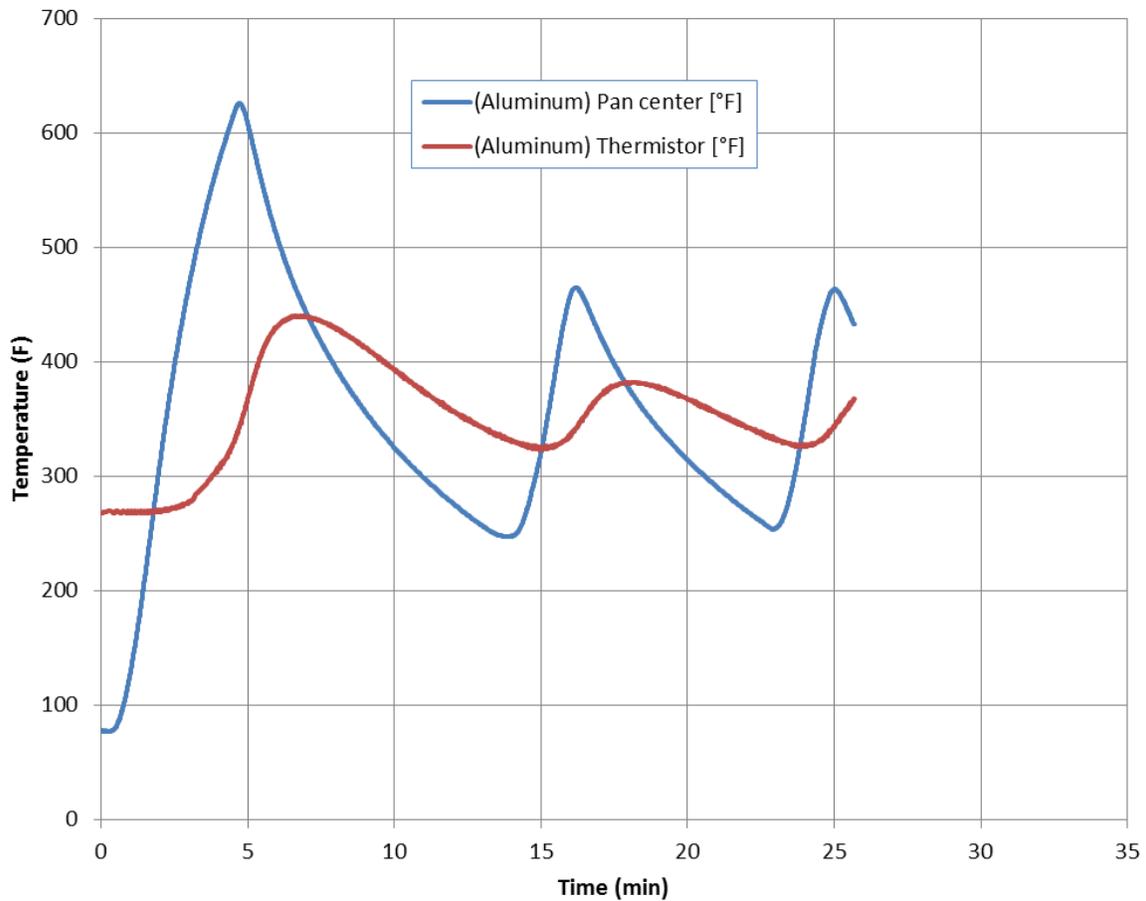


Figure 31: Dry-Cook Control of a 10” Aluminum Pan on an Electric Coil Element with the Highly-Insulated Thermistor Sensor

The sensor housing was modified to improve the responsiveness of the thermistor to changes in pan temperature. This was done by removing several layers of Fiberfrax insulation between the thermistor and the top of the sensor housing (the part that contacts the pan bottom). Responsiveness was improved, as can be seen in the comparative thermistor and pan temperature data in Figure 32, but pan temperature control was still problematic.

The less-insulated sensor (shown in red) responded faster than the highly-insulated sensor (blue), and its control cycle time (from power off to power on again) was much shorter. However, the need to activate control at a relatively low temperature (less than 350 °F) in order to prevent pan over-temperature on the initial heat-up led an inability to control the pan to a sufficiently high temperature. In fact, once again, the controlled pan temperature on average ended up being below the thermistor temperature.

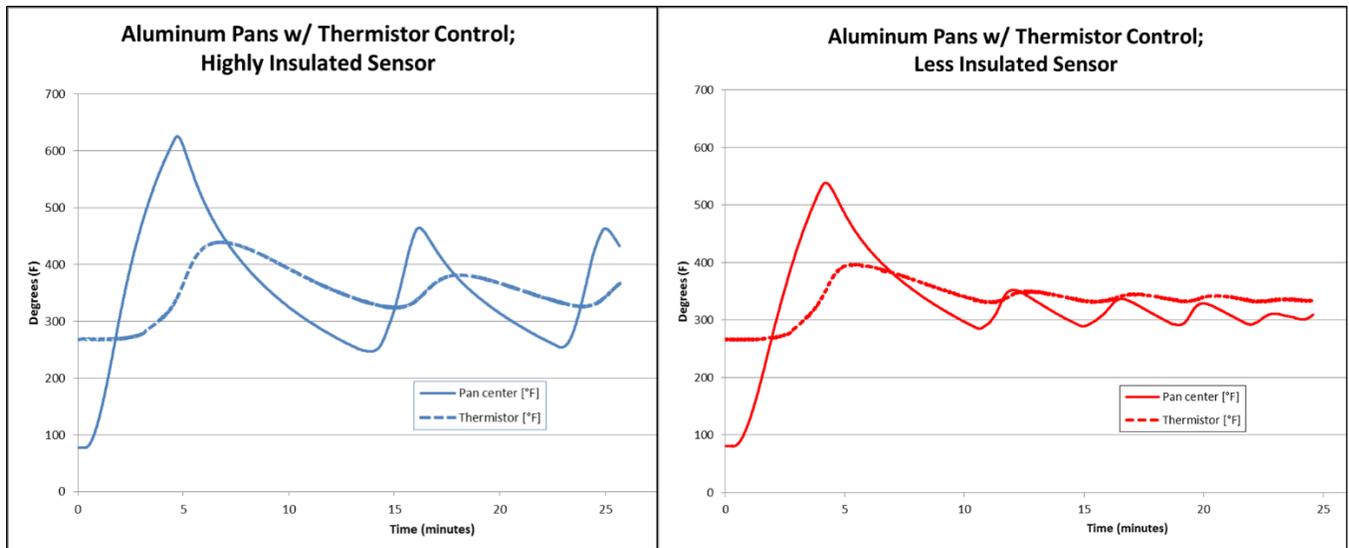


Figure 32: Pan Center Temperatures and Thermistor Temperatures for Two Different Sensor Body Arrangements

5.3.7 Summary

The relatively low upper temperature limit of low-cost thermistors presented an impediment to their use in a practical pan temperature limiting sensing and control system. A system to maintain the thermistor temperature inside its operable range created unacceptable lag in the control system to be of practical use in the current pan temperature limiting control scheme for electric coil elements.

While we do not exclude the possibility that a successful implementation could be developed in due course, it is apparent from the results obtained herein that a considerable development effort

would be required in order to overcome this hurdle, possibly requiring significantly more complex algorithm development and testing in addition to sensor body design and optimization.

5.4 Interaction of Glass Limiter and Pan Temperature Controls

We conducted a series of tests to determine the nature of the interaction between the existing mechanical glass temperature limiter and the pan-bottom temperature limiting controls. We monitored the glass ceramic temperature in 3 tests conditions under three operating controls: with only the glass limiter operating, with the pan-bottom temperature limiting controls plus the glass limiter, and with only the pan-bottom temperature limiting controls. We tested each control approach with a dry cook, a boil test and with no pan or pot on the element (bare glass).

All testing was conducted using the 3200 W power boil element in a, 36” smooth top cooktop.

The relative positions of the glass limiter and the RTD sensor are shown in Figure 33. The glass limiter was bent slightly to accommodate the centrally located RTD.

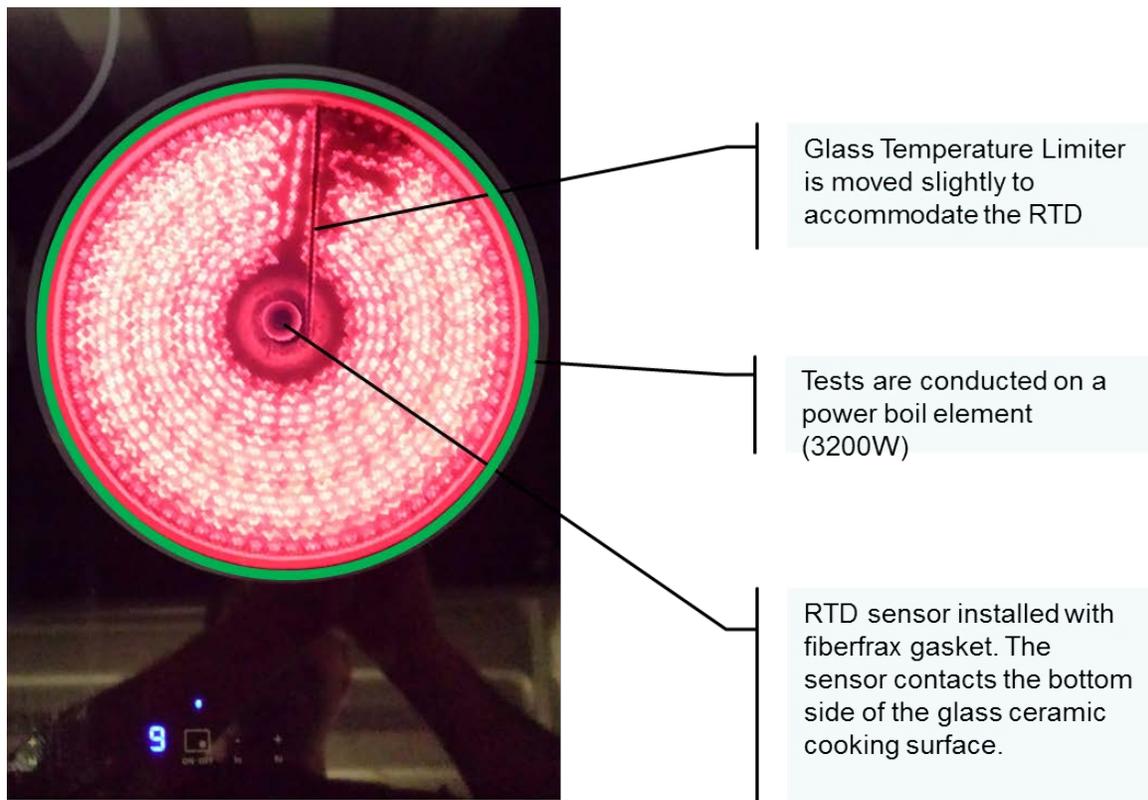


Figure 33: Sensor and Limiter Locations in 3200 W Element of Glass Ceramic Cooktop

This testing may open options for offsetting the cost of controls in the glass ceramic cooktop with the removal of the limiter. It may also offer an approach to further refine the pan-bottom temperature limiting controls without the complexity of the glass limiter operation.

5.4.1 Tests with Glass Limiter Only, Controls Only, and Both Together

We conducted the set of nine tests and show the results below.

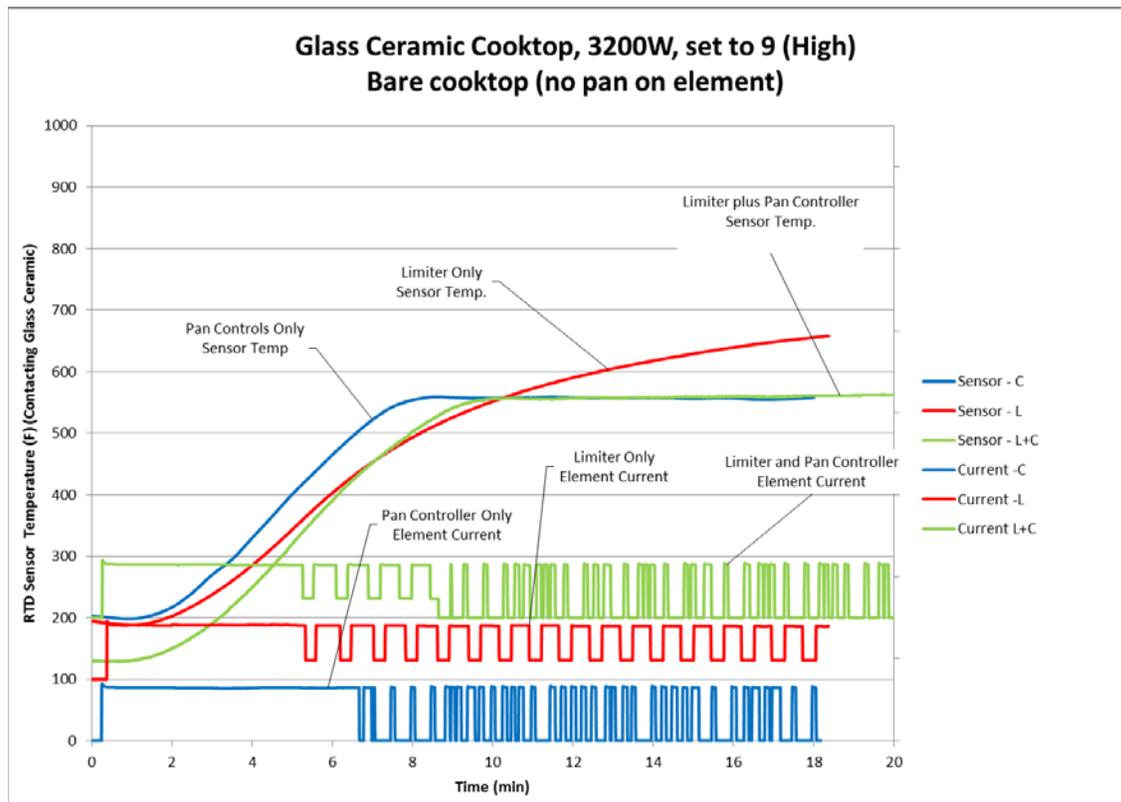


Figure 34: Bare Cooktop: Limiter Alone, Control Sensor Alone, Limiter plus Control

Figure 34 shows that the pan-bottom temperature controller will limit glass temperatures to levels at or below the levels set by the glass limiter. All measurements were made on the glass surface at the center of the element using the pan bottom sensor in close contact with the underside of the glass ceramic.

Tests were conducted for durations of approximately 20 minutes.

The action of the glass limiter shuts off one ribbon element of the two-element hob. When the limiter has engaged, there is still a total of 4.4 amps, or over 1100 W of power from the element. When the pan temperature limiting controls engage, the total power to both elements is completely shut off. The pan-bottom temperature sensor limited the glass temperature (with a bare cooktop), whereas with the limiter alone, the rate of rise of the glass temperature was reduced, but the glass temperature did not reach a limit by the end of the test.

The use of the limiter in conjunction with the pan-bottom temperature sensor did not further limit the glass temperature compared to the limit established by the pan-bottom sensor alone.

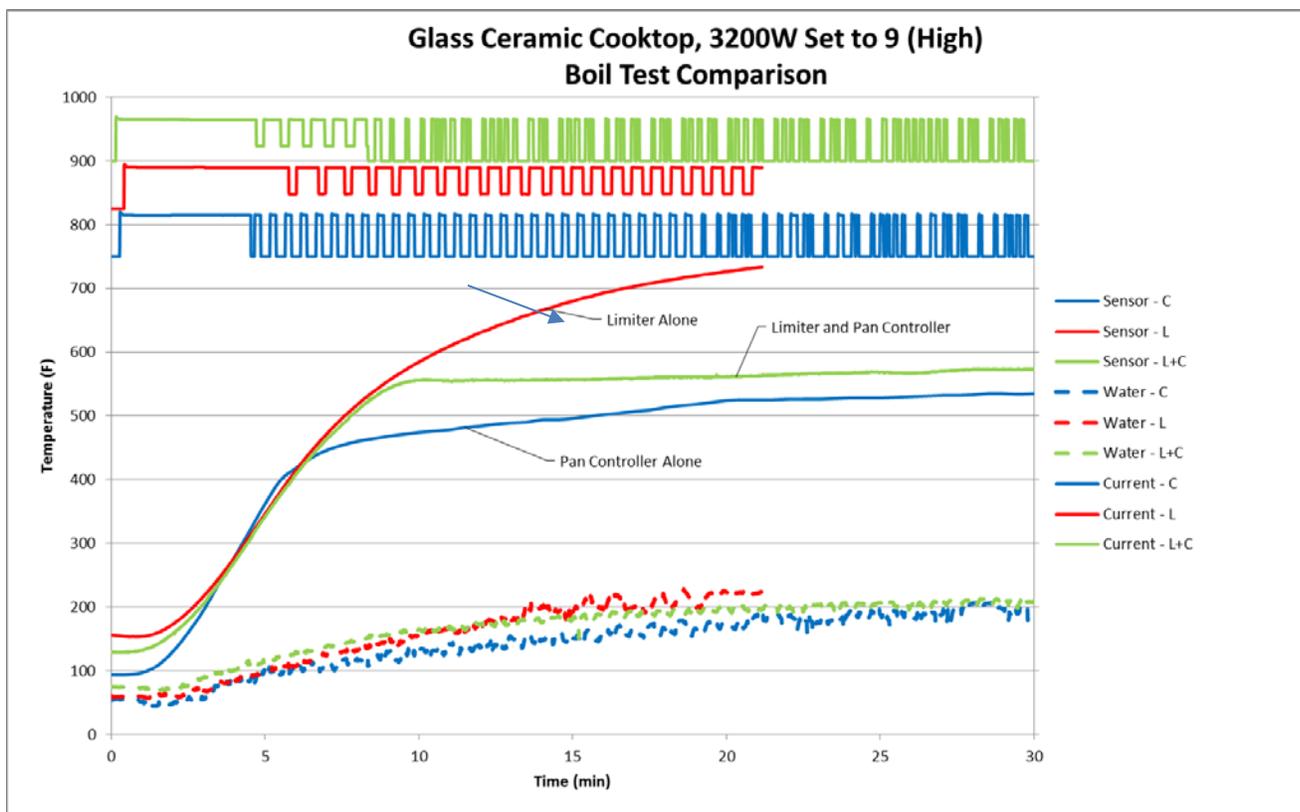


Figure 35: Water Boil: Limiter Alone, Control Sensor Alone, Limiter plus Control

The pan-bottom temperature sensor alone will protect the glass in water boil operation, as shown in Figure 35. The combination of the limiter and the pan temperature controls may have resulted in a slightly less aggressive control than with the pan control alone, as the limiter did engage earlier than the pan temperature controller in this case. The total power input with the limiter

engaged is greater than the power input with the controls engaged. Ultimately, the pan temperature limiting controls are more aggressive than the limiter, effectively overriding its use.

Results of dry cook tests in an empty, 10” cast iron skillet are shown in Figure 36.

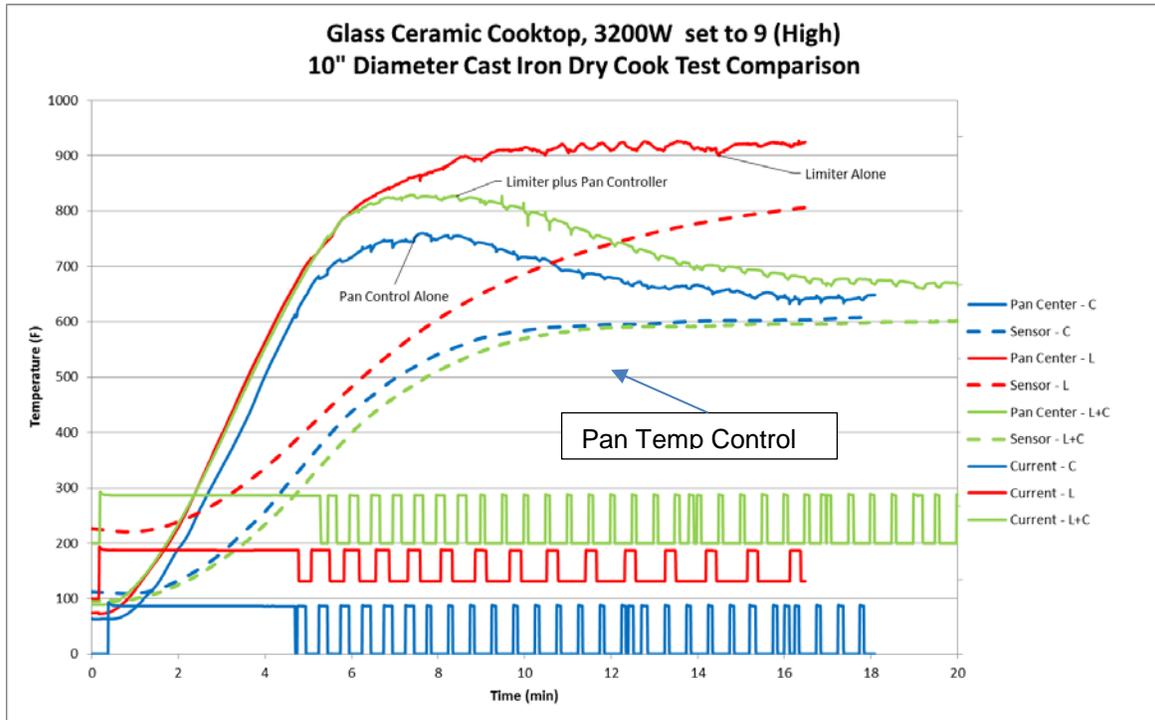


Figure 36: Dry Cook: Limiter Alone, Control Sensor Alone, Limiter plus Control

Once the pan-bottom temperature controls were engaged, these controls effectively overrode the glass limiter

5.4.2 Summary

The pan bottom temperature controls are more aggressive than the glass temperature limiter. As such, once the pan temperature control begins to control element power, the glass temperature limiter is completely overridden and does not affect power to the element.

The pan bottom temperature controls hold the glass to temperatures less than what the limiter establishes, indicating it may be “glass-safe” to remove the limiter if the pan temperature controls are in place.

6. Conclusions

Low input rate elements:

Oil ignition occurred in pans on electric coil elements with outputs as low as 560 W. We did not observe any oil ignition with pans on a 5,000 Btu/hr gas burner, but this result could differ for a different burner design or grate design that resulted in a higher heat transfer efficiency from the burner to the pan. Oil in a cast iron pan on a 750 W element in a glass ceramic cooktop ignited, as did oil in this element set to a duty cycle corresponding to 600 W average output.

Ignitions occur on small elements when the pan size is closely matched to the element size, maximizing the ratio of heat input to heat losses from the pan.

Higher reduced rate for gas burner control:

Increasing the reduced firing rate from 2,500 to 4,400 Btu/hr provides benefits of reduced burner cycling and smoother temperature profiles without impacting the ability to avoid a fire. While 5,000 Btu/hr burner output did not result in an ignition by itself, having 5,000 Btu/hr at the reduced rate was insufficiently low to allow the pan to cool down from higher temperatures as part of a control cycle.

Thermistor-based sensor

The principal conclusion reached after this effort is that the relatively low upper temperature limit of low-cost thermistors presents an impediment to their use in a practical pan temperature limiting sensing and control system. While we do not exclude the possibility that a successful implementation could be developed in due course, it is apparent from the results obtained herein that a considerable development effort would be required in order to overcome this hurdle, possibly requiring significantly more complex algorithm development and testing in addition to sensor body design and optimization.

Glass limiter/pan temperature control interaction

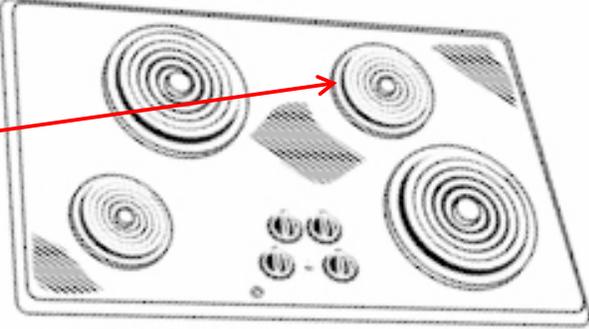
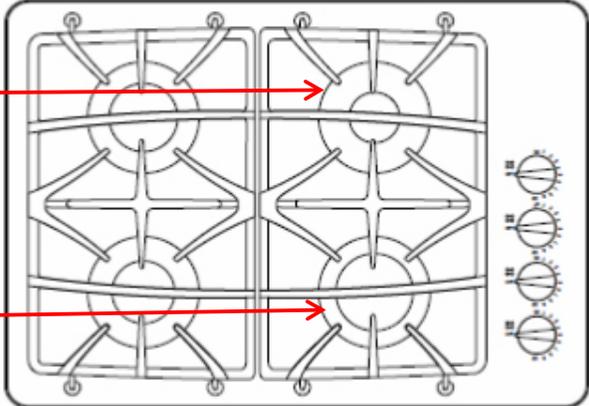
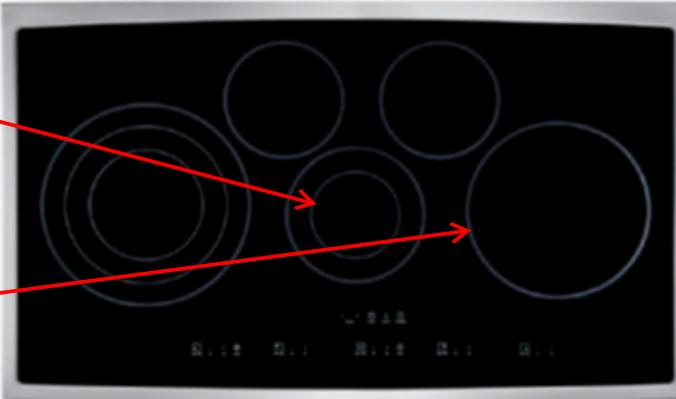
The pan bottom temperature controls are more aggressive than the glass temperature limiter. As such, once the pan temperature control begins to control element power, the glass temperature limiter is completely overridden and does not affect power to the element.

The pan bottom temperature controls hold the glass to temperatures less than what the limiter establishes, indicating it may be “glass-safe” to remove the limiter if the pan temperature controls are in place.

APPENDIX 1

Cooktops and Utensils Used for Testing

Three cooktops and specific hobs used for testing.

Cooktop Type	Element/Burner Wattage or Btu/hr, Size	Diagram
Coil	1300W 6"	
Gas	5k Btu/hr	
	18k5 Btu/hr	
Glass Ceramic	750W 5"	
	3200W 9"	

Utensils used for testing

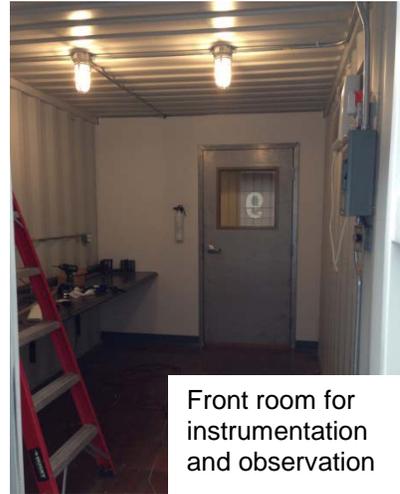
material	size	rim diameter / base diameter				
SS	8"	8" / 5.75"				
	10"	10.5" / 7"				
AL	8"	8" / 6"				
	10"	10" / 7"				
	12"	12" / 8.5"				
CI	6.5"	6.5" / 5.5"				
	8"	8" / 6.5"				

Appendix 2

Test Procedures

Facility:

An oil ignition test has been fabricated in a 20' ISO Container, with a front area for data acquisition and observation, and a back area with exhaust and fire protection for cooktop fires.



Staffing and Safety:

- Two people attend fire testing at all times
- Outer door to control room is open during all testing
- Safety glasses/shield are always used when in burn room
- Fire-resistant gloves/face shield stored in control room
- Respirator/face shield/gloves used when extinguishing fire

Initial Preparations:

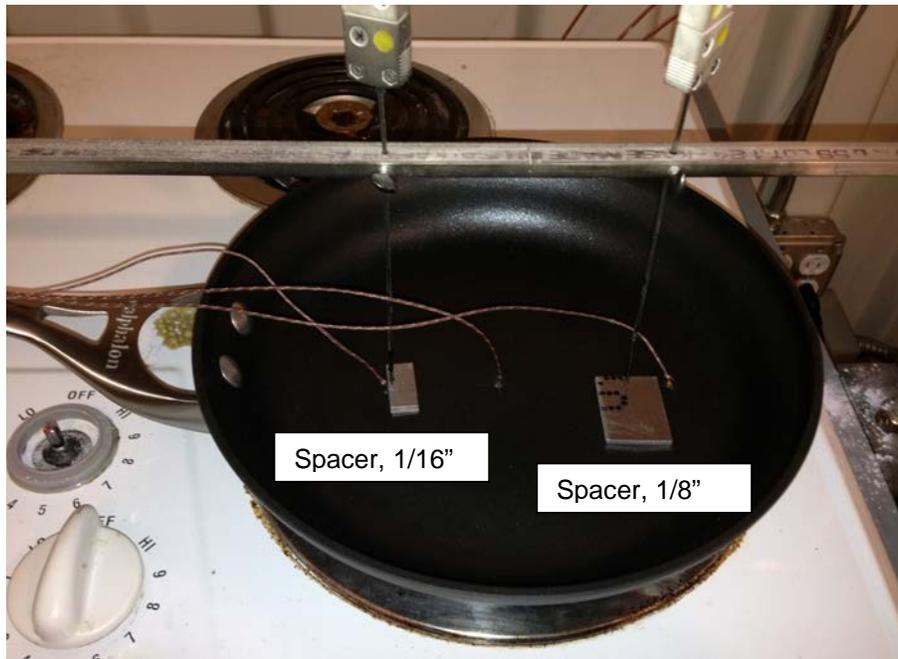
- Fill tared container to 137 grams of Canola oil (corresponds to 150 mL) for low oil tests, 915 grams of Canola oil (corresponds to 1 Liter) for high oil tests
- Fill scoop with Purple K
- Confirm that circuit breaker to cooktop is in OFF position. If not, turn circuit breaker to OFF position so no electric power is available to cooktop

Cooktop/DAQ Preparations in Burn Room:

- Place selected pan on element, check that all thermocouples are plugged in to correct terminals in the Interface Box



- Place spacers of specified thicknesses in pan, under oil thermocouples

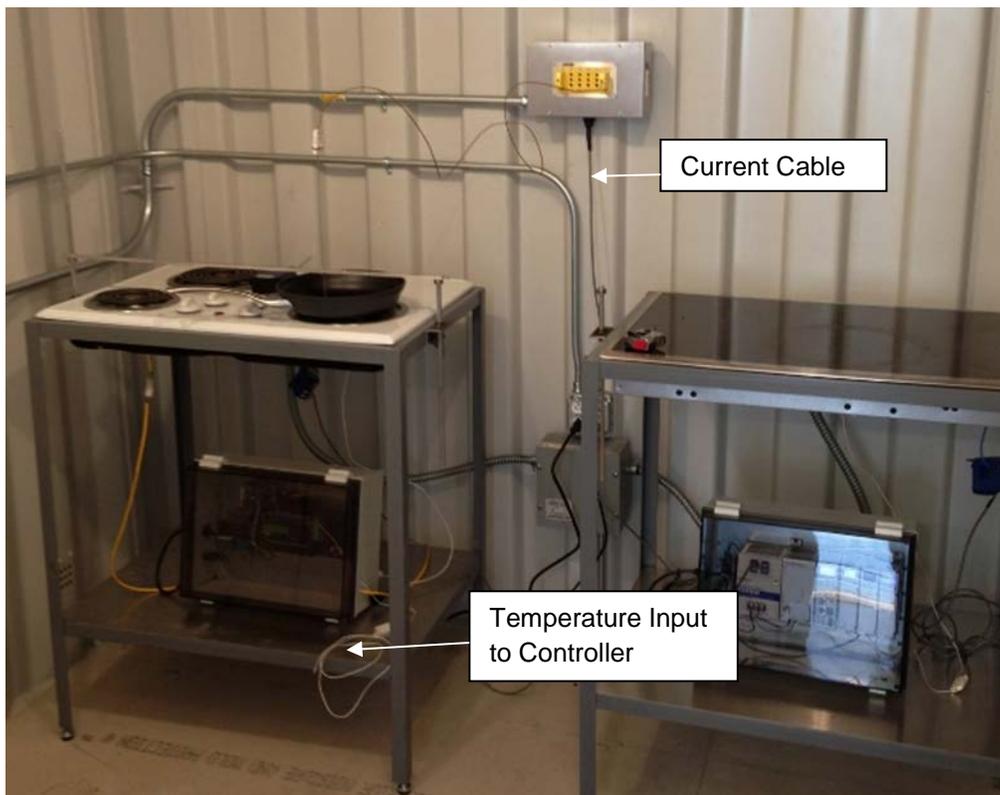


- Position thermocouples, hold with set screw, and remove spacers



- Add measured oil to pan, using scraper to get as much out as possible out of the measuring bowl

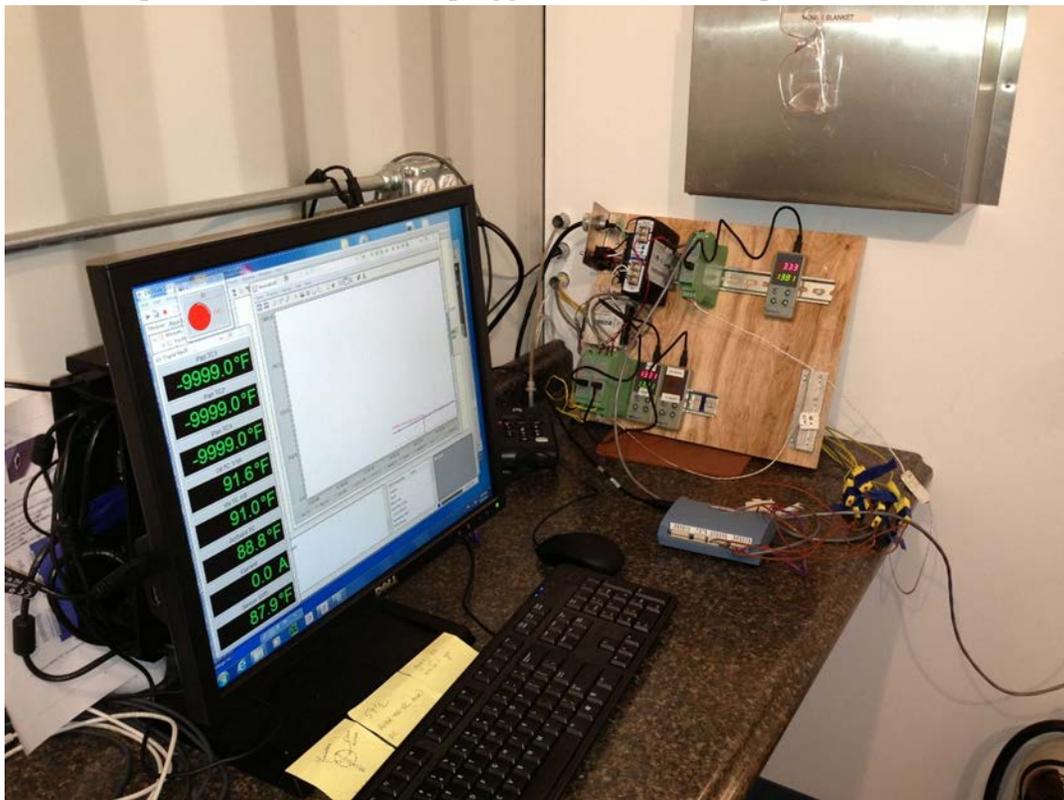
- Plug appropriate RTD cable (from coil or ceramic cooktop) into Interface Box
- If conducting a baseline fire test, plug ambient temperature RTD into control input to prevent controls from registering temperature increase
- Plug current cable of appropriate cooktop into Interface Box



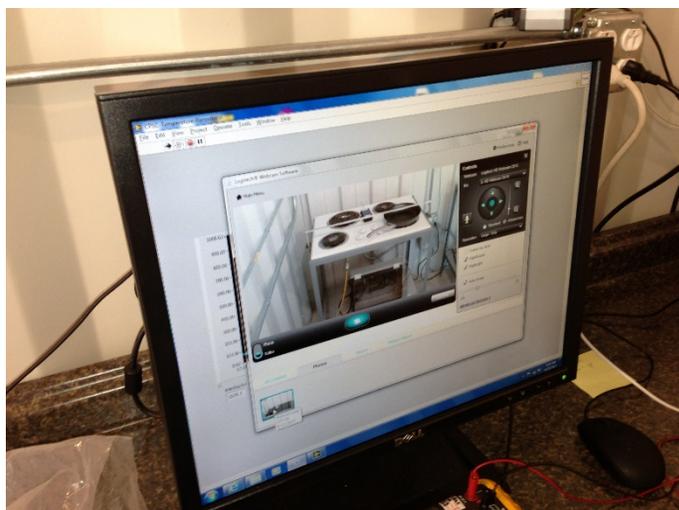
Test Startup:

- Turn exhaust fan in Burn Room to “ON”

- Open DasyLab® Data Acquisition Software, start file and make sure that all thermocouples and RTD cords are plugged into the correct places



- Open web cam, connect proper USB (gray for electric coil, white for glass ceramic), start recording video



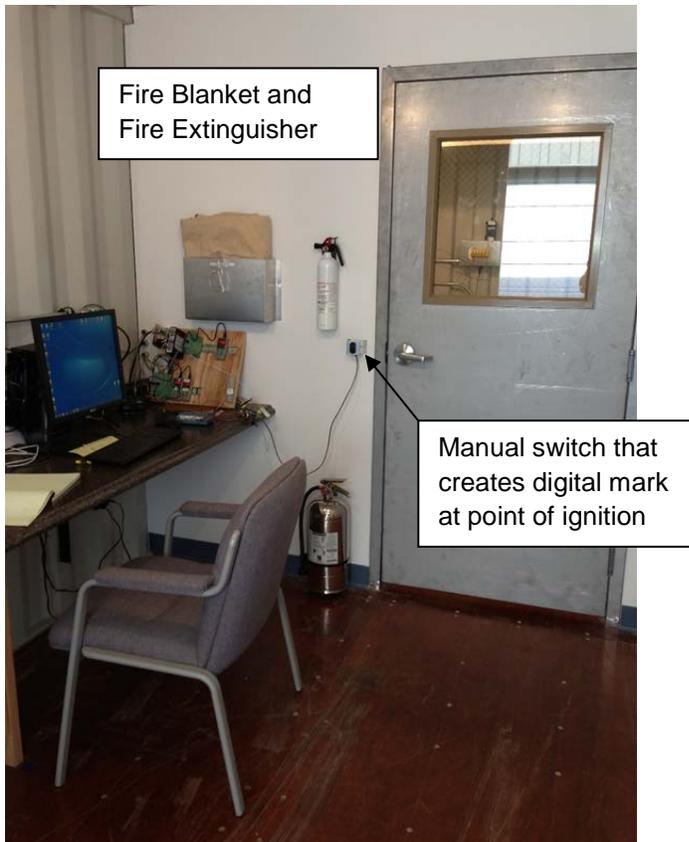
- Record test conditions, ambient conditions, date, time in lab notebook
- Begin data logging in DasyLab®

If Electric Cooktop:

- Flip circuit breaker to cooktop to “ON” position
- Enter Burn Room
- Display white board with written test conditions in view of video camera
- Turn cooktop dial or set cooktop power to setting defined by the test plan
- Leave Burn Room and close door

If Gas Cooktop:

- Turn ball valve in gas line to cooktop to “ON” position
- Enter Burn Room
- Display white board with written test conditions in view of video camera
- Turn cooktop dial to “light”, confirm ignition of burner, then set gas flow to the output setting defined by the test plan
- Leave Burn Room and close door



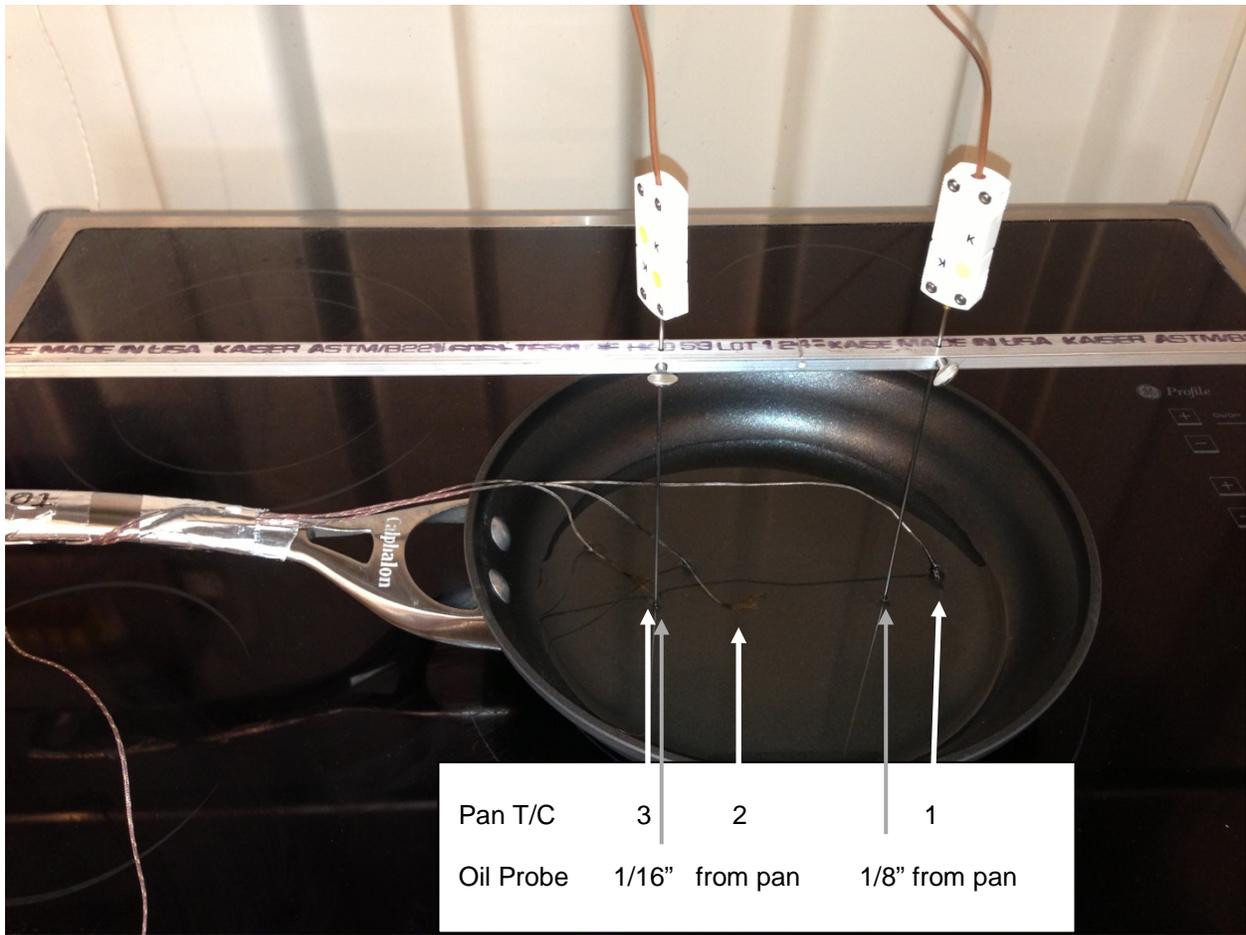
Test Operation:

- Watch pan for signs of smoke and ignition

- When oil ignites, make DAQ mark with switch (Operator 1)
- Shut off power to cooktop using circuit breaker (if electric cooktop) or ball valve (if gas cooktop) (Operator 2)
- Turn fan on high (Operator 2)
- Open door (Operator 1)
- Extinguish fire by pouring scoop of baking soda or Purple K onto pan (Operator 2)
- Leave Burn Room (Operator 2)
- Close door until smoke diminishes (Operator 1)

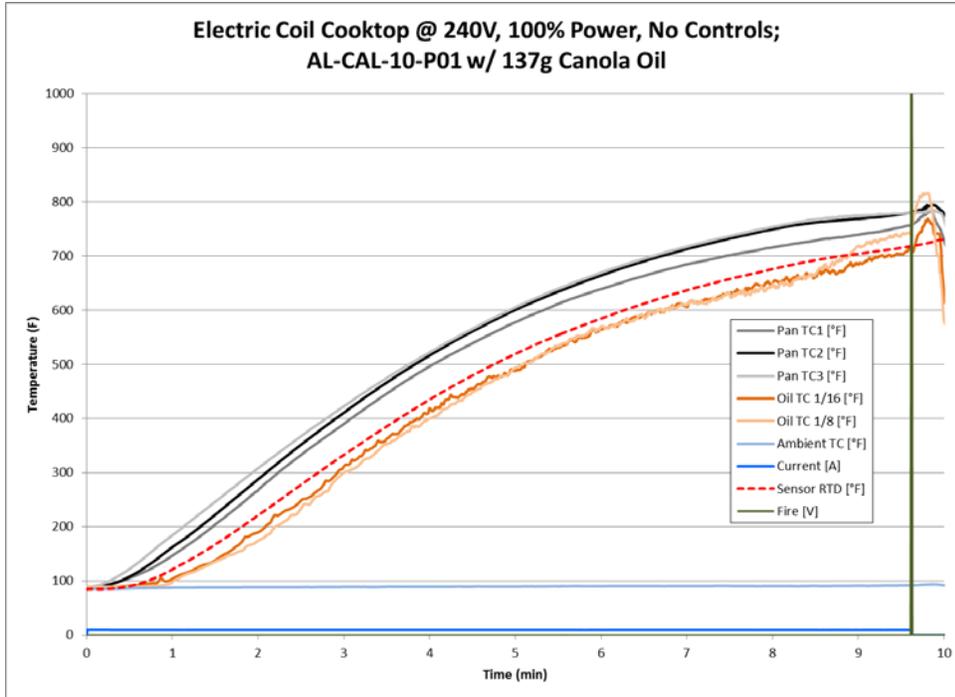
Data Recorded:

- Test number/test conditions are written on white board and held in front of video camera to record conditions
- Date/time and ambient conditions are recorded in lab notebook
- Relevant test conditions recorded in notebook include: pan material, size, manufacturer; oil amount, power level, cooktop type, test type (baseline or with controller running)
- Data extracted from temperature profiles:
 - Oil temp (2), pan temp (3) and RTD temp at ignition
 - Time to ignition
 - Temperature difference between higher and lower oil temperature prove throughout test

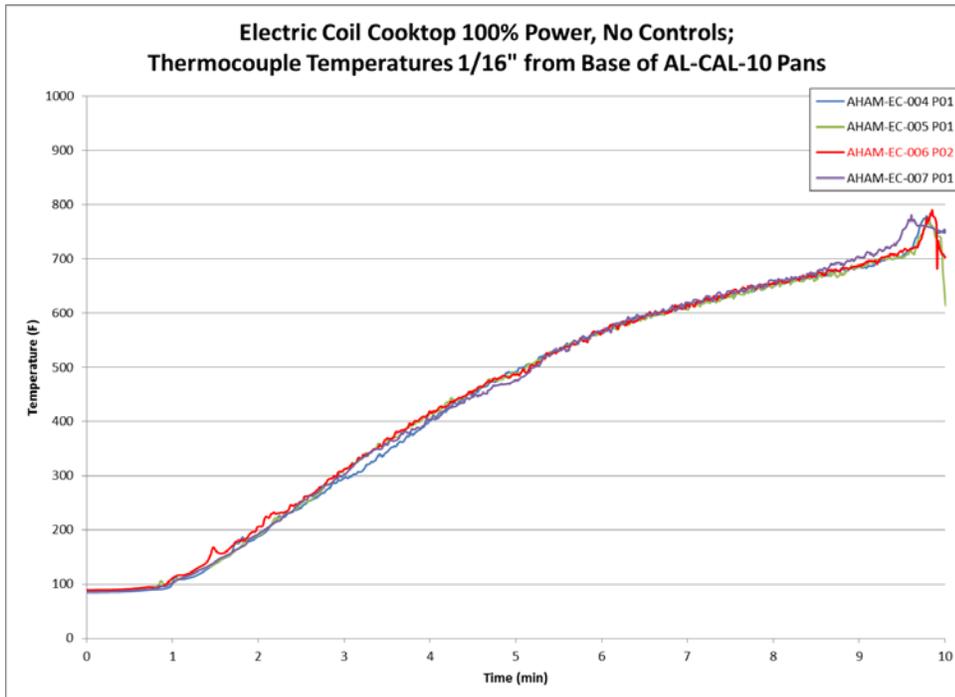


Sample Data:

- Sample temperature profile for one fire test



- Sample aggregate temperature profiles for one oil depth (1/16") over 4 repeats



Appendix 3
**Time Temperature Profiles for Oil Ignition Tests on
Small Electric Elements**

