FINAL REPORT

on

Development and Manufacturing Assessment
of the
Concentric-Ring Smooth-Top Range Sensor

to:

U.S. CONSUMER PRODUCT SAFETY COMMISSION
(Order Number CPSC-Q-03-1319)

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1.0 EXECUTIVE SUMMARY

The overall objective of this project was to follow up on the developments achieved on CPSC Procurement Order No. CPSC-S-02-1326. The focus of this project was to validate the previous results across all model variations and address issues of manufacturability related to implementation of this system into existing designs.

CPSC prepared a report in 1999 that documented 85,000 fires that occurred annually involving range tops and ovens that were attended by fire departments. Deaths averaged 250 annually along with 4,080 injuries and a loss of $295.6 million in property damage during the four-year period covered in the report. This report clearly shows that unattended operation is a common factor in most of the fires. Further data collected for the 1994 to 1998 period show that 47,200 fires annually originated from food preparation on the cooktop as opposed to the oven. These fires alone resulted in 80 deaths with an additional 2,440 injuries and $134.6 million in property loss annually.

Previous work by CPSC staff demonstrated the potential for range-top sensors to monitor the temperature of cooking pots and thereby to detect an imminent ignition. This work had been carried out on coil-type heating elements and could not be applied to newer smooth-top ranges. AMTI subsequently developed a technique for predicting the onset of a range-top fire using a temperature sensor located under the glass range-top. The present project was intended to verify the applicability of this technique to range-tops made by all manufacturers, and to evaluate its potential manufacturing cost and its impact on cooking performance.

Three commercially available ranges were modified for the purpose of installing the temperature sensor. These ranges were used to test and verify that the sensor approach used in the previous project (CPSC-S-02-1326) was functional across brand lines. Acceptance testing focused on preventing ignition of cooking oil and verification that the sensor technology did not interfere with cooking operations. The results of these tests clearly showed that the sensor and control algorithm did not interfere with normal cooking operations and that it successfully prevented ignition of food on all ranges. An increase in boiling times with large quantities of water was observed as a result of sensor operation. This characteristic was most pronounced when boiling large quantities of water in stock pots having substantially non-flat bottoms.

The manufacturing assessment phase was directed towards identifying the potential manufacturing impact of a sensor-equipped range. AMTI originally intended to work with range and controls manufacturers to determine the impact on cost and manufacturing complexity. As the project developed, we learned that the range manufacturing community was uncomfortable working with us to assess manufacturing impact. This was mainly because of uncertainty surrounding the intellectual property issues. As a result, the manufacturing assessment was based on input from one sensor manufacturer.

2.0 INTRODUCTION AND SUMMARY

Ranges and ovens contribute to a major portion of fires and fire injuries within CPSC's jurisdiction. In 1999, CPSC staff prepared a report[1] documenting the extent of injuries and deaths resulting from cooking-related fires from 1994 to 1996. The data in that report were subsequently updated and refined to include the years from 1994 to 1998[2]. These updated data show that during that period there were 85,000 fires annually involving range tops and ovens that were attended by fire departments. Deaths averaged 250 annually along with 4,080 injuries and a loss of $295.6 million in property damage during the period. Unattended operation is a common factor in most of the fires. The data show that 70,200 fires annually(83 percent) originated on the cooktop as opposed to the oven. These fires alone resulted in an annual average 230 deaths with an additional 3,630 injuries and $263.5 million in property loss annually. Food ignition from the rangetop accounted for 47,200 fires with 80 deaths, 2,440 injuries and $134.6 million in property damage annually, from gas, electric and oil stoves. For electric ranges only, from 1994 to 1998 there were 32,500 rangetop food ignition fires that resulted in 40 deaths, 1,960 injuries and an estimated $104.7 million in property damage.

A four-phase study was conducted by CPSC staff[3]. The objective was to demonstrate the feasibility of developing a temperature-sensing control system for electric ranges to detect pre-ignition conditions, and to lessen the risk of unattended cooking fires. CPSC developed a control system using commercially available thermocouples, and tested it under a variety of cooking scenarios both at CPSC and Good Housekeeping Laboratories. The system was proven capable of preventing ignition in scenarios involving bacon, chicken, and oil. In addition, the system did not interfere with normal cooking operations such as heating of oil or boiling of water. There were some nuisance failures with the system, but given its infancy, the overall performance was very encouraging.

Most of this work had been performed on electric cooktops having coil-type heating elements. The system consisted of thermocouple sensors spring-loaded against the bottom of cooking vessels and a computer control system that modulated power to the electric heaters as the pan-bottom temperature approached ignition conditions. Recognizing that an effective system would have to be applicable to both gas and electric ranges, the CPSC initiated a project at Energy International, Inc. (EI) to demonstrate the technology on gas ranges. The final report[4] documented the performance of two types of temperature-control sensors; pan contact and radiantly coupled. Both sensors were effective at detecting pending range fires under standard test scenarios. Moreover, the radiantly coupled sensor was shown to be more robust and less prone to damage.

CPSC and the Association of Home Appliance Manufacturers (AHAM) contracted a manufacturing feasibility study at Arthur D. Little (ADL) aimed at determining the feasibility and efficacy of modifying range designs to include sensors for preventing range fires. That study indicated that the contact sensor showed considerable promise but would require 2 to 3 years of extensive development and testing to address issues of reliability and durability.

The EI work showed conclusively that the contact-type sensor showed promise in measuring pan

[1] Smith, L. E., Monticone, R., Gillom, B.., "Range Fires – Characteristics Reported in National Fire Data and a CPSC Special Study", U. S. Consumer Product Safety Commission, 1999.
[2] Smith, L. E., Greene, M. A., "Updated Estimate of Range Top Cooking Fires", U. S. CPSC, March 9, 2001.
[3] Johnson, E.L., "Study of Technology for Detecting Pre-Ignition Conditions of Cooking-Related Fires Associated with Electric and Gas Ranges and Cooktops, Final Report", NISTIR 5950, January 1998.
[4] Corliss, J., "Development of a Control System for Preventing Food Ignition on Gas Ranges", 2000

temperature and preventing range fires. Contact sensor performance was summarized in the EI report and International Appliance Technical Conference (IATC) presentation[5] regarding temperature measurement and response and their shortcomings regarding durability. These sensors were first tried on gas ranges in the 1960's and 1970's and after nearly two decades were shown to be capable of tracking pan temperatures, but were not durable enough for practical use as designed at the time--largely due to the fact that the sensor extended above the range grate and was prone to damage.

ADL pointed out that the growing popularity of glass-top electric ranges is increasing the population of ranges that are not adaptable to contact-type sensors. In a later report[6] (2002) ADL discussed concepts that showed promise for a smooth-top electric range including an optical infrared sensor that monitored the pan bottom or a sensor that monitored the bottom of the smooth top. The EI report and IATC paper cited above showed that a radiantly coupled sensor was accurate and fast enough to safely control range fires. Optics, mounted outside of the cooking zone, might be prone to fouling from grease-laden vapors and, consequently, fail over time.

In 2002, CPSC contracted with AMTI[7] to develop and demonstrate a sensor based on monitoring the bottom of the smooth-top glass-ceramic surface. This project concluded with the successful design of a sensor that was based on measurement of the bottom of the glass ceramic, and the implementation of a computer algorithm that essentially predicted the equilibrium pot temperature based on the time rate of change in glass temperature. The sensor that was developed in the 2002 project was based on a type-K thermocouple. The thermocouple was thermally isolated from the radiant and convective environment of the heating element, and held in close thermal contact with the bottom of the glass using spring force.

This sensor was demonstrated under laboratory conditions to work effectively in preventing range fires while not interfering with normal cooking operations. CPSC staff initiated the project that is the subject of this report to further develop the sensor technology, demonstrate it on a variety of ranges, and estimate the potential manufacturing cost and complexity of the approach.

3.0 OBJECTIVE AND APPROACH

The objective of this project was to follow up on the developments achieved on CPSC Procurement Order No. CPSC-S-02-1326. The focus of this project was to validate the results of the previous project across all model variations and address issues of manufacturability related to implementation of this system into existing designs. Specific objectives were to:

- Further develop the shielded-temperature measurement-based control system,
- Examine and document the manufacturing issues, and
- Present results in a detailed final report.

[5] Corliss, J., "Development of a Control System for Preventing Food Ignition on Gas Ranges", Presented at the 2002 IATC Conference, Lexington, KY.
[6] "An Evaluation of Sensor and Control Technologies to Address Cooking Fires on Glass Ceramic Cooktops", Final Report, Order No. CPSC-S-01-1193, February, 25, 2002, Arthur D. Little, Inc.
[7] "Identification and Evaluation of Temperature Sensors for Preventing Fires on Electric Smooth-Top Ranges", Final Report, Order Number CPSC-S-02-1326, July 28, 2003, Advanced Mechanical Technology, Inc.

AMTI's approach to meeting project objectives involved a series of steps, each with its own objectives and expected outcomes.

The initial focus was on determining the specific temperature sensor technology to be used. This had a significant impact on cost and system integration, since a sensor technology that is compatible with existing or planned cooktop control systems should be the least expensive to implement. In the work conducted on Order No. CPSC-S-02-1326, AMTI used type-K thermocouple sensors as this facilitated all temperature measurements. Our focus was on determining the thermal behavior of the system, measuring temperatures at various points in the cooktop, and developing software for temperature control and fire prevention. The method of sensing cooktop temperature was not important for the laboratory work conducted under the contract. Cooktop temperature could have been sensed with a resistance temperature device (RTD) or a thermistor instead of a thermocouple. In this continuation effort, the other temperature measuring technologies, and associated electronics, were considered with an eye towards manufacturability, cost and integration with existing controls on the ranges.

The next step was to consider a self-test system for the controls. The algorithm that was developed in the earlier work was based on a thermal sensor that was providing accurate and reliable inputs. A practical production system will require that the sensor system[8] include diagnostics to self-calibrate and self-test to determine if it is working properly. A non-functioning control will have to notify the user of a problem and possibly provide some kind of diagnostic signal for a service technician.

Next, the system was design-optimized for lowest potential manufacturing cost and simplicity. This step involved specifying components and materials to ensure compliance with appropriate codes and standards, and estimating the cost for including the pan temperature sensing technique on all glass ceramic electric cooktops and ranges.

A working model of the control system was installed on various cooktop models and evaluated for effectiveness. This included conducting tests as described in Attachment A[9] of the solicitation to demonstrate that (1) the system prevents ignition of food materials and (2) that the system does not interfere with normal cooking operations.

4.0 STEP 1. IDENTIFY AND FINALIZE TEMPERATURE MEASUREMENT TECHNOLOGY

In the previous range sensor project, a type-K thermocouple was used as the glass surface-temperature probe. This method was selected because it offered flexible configurations, rugged probes and a wide variety of available shapes and sizes. However, thermocouple probes require specialized electronic circuitry not currently in use by the range industry to evaluate temperature. The relative expense of the additional electronics was thought to pose a barrier for this technology.

An evaluation of sensor types to accomplish the same type of glass-surface temperature measurement was performed. The sensor requirements were:

[8] For the purposes of this report, the sensor system includes the sensor, attachment and/or orientation with respect to the glass, and the data processing system or electronics.

[9] Description of Proposed Test Conditions to Evaluate A Temperature Measuring System for Preventing Food Ignition on Electric Ceramic Glass Ranges and Cooktops.

- Inexpensive sensor
- Inexpensive electronics (if required)
- Rugged construction
- Reliable operation
- Good match for the temperature range
- Familiar technology to the range industry
- Fast responding
- Measurement area is small
- Ability to be shielded from radiant heat directly from the element
- Vibration resistant

Ranges that utilize temperature sensors for oven cleaning and baking operations rely on resistance temperature devices (RTD's) for temperature measurement. These devices utilize a platinum alloy as the sensing element. The principle of operation is that platinum has a large and linear change in electrical resistance with respect to temperature, and this resistance change is measured to interpret temperature.

Two common configurations of platinum RTD's are wire-wound and thin film. The wire-wound design uses a long strand of platinum wire wound around a central core, usually resulting in a cylindrically shaped probe. These probes are manufactured in a range of sizes. The smallest probes are around 1/16-inch in diameter, and about 1/2-inch in length. The smallest practical size is limited by the manufacturing process of winding small-diameter wire. Larger probes are not as strictly limited in size. Wire-wound probes are used in range ovens to sense oven temperature. They are well suited for measuring a large cavity because they average the temperature measurement over the entire sensing surface.

Thin-film RTDs operate on the same principle, but use integrated-circuit fabrication techniques to produce very small sensors. Instead of using wire, the platinum is deposited onto a substrate to form a long, thin conductive path. The conductive path can be very short, and thus a very compact sensor is the result. This compact size results in very fast response times because of the high surface-area-to-volume ratio and because the platinum element and the measuring surface are separated by a very thin, high thermal-conductivity ceramic substrate. RTDs have a near linear output (resistance change) in response to temperature change. Thin-film RTDs were chosen for this sensor application because they have fast response time, are compact, can withstand temperatures up to 600ºC, and are familiar to the range industry as oven temperature probes.

The specific sensor used on this project was a thin-film RTD purchased from Omega Engineering. **Figure 1** shows typical dimensions for an Omega Engineering platinum RTD element part number F3105. The sensor is a resistance-type device, and it requires a constant-current power supply and a wheatstone bridge to detect resistance changes.

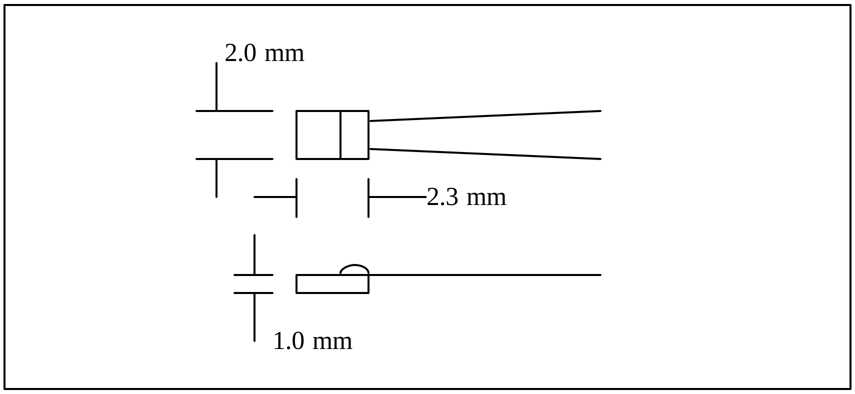

Figure 1. Omega Engineering Thin-Film RTD Sensor

5.0 STEP 2. MANUFACTURE TEMPERATURE SENSORS

Three temperature sensors were manufactured for use in the project. The design was based on the same concept that was successfully demonstrated in the previous project. An insulating cylinder consisting of ceramic insulation and stainless-steel tubing was constructed to insulate the sensor. The RTD sensor was positioned at the top of this tube and held in contact with the bottom of the glass using the spring pressure of the heating-element assembly.

Figure 2a shows a sectional view of the RTD sensor assembly, and **Figure 2b** shows a dimensioned sketch of the sensor assembly. The RTD and insulating cylinder were sealed against the glass using a compliant, high-temperature disk gasket about 1.5-inches in diameter. A small relief was cut into the gasket to accommodate the thickness of the sensor element, and a small hole in the gasket center provided a pathway for the sensor wires.

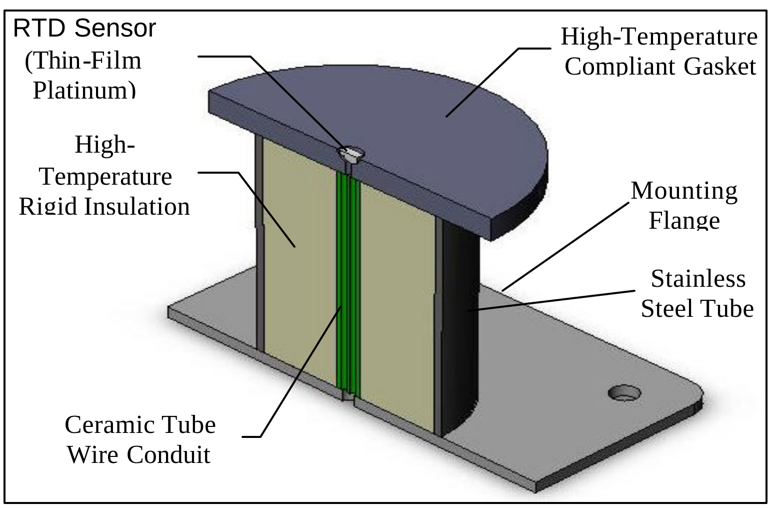

Figure 2a. RTD Sensor Design Detail

Below the gasket, a rigid ceramic tube having two passages was used to protect the sensor wires and provide structural support for them as they passed through the sensor assembly. This ceramic tube was wrapped in high-temperature ceramic insulation, and pressed into a one-inch diameter, thin-walled stainless-steel tube.

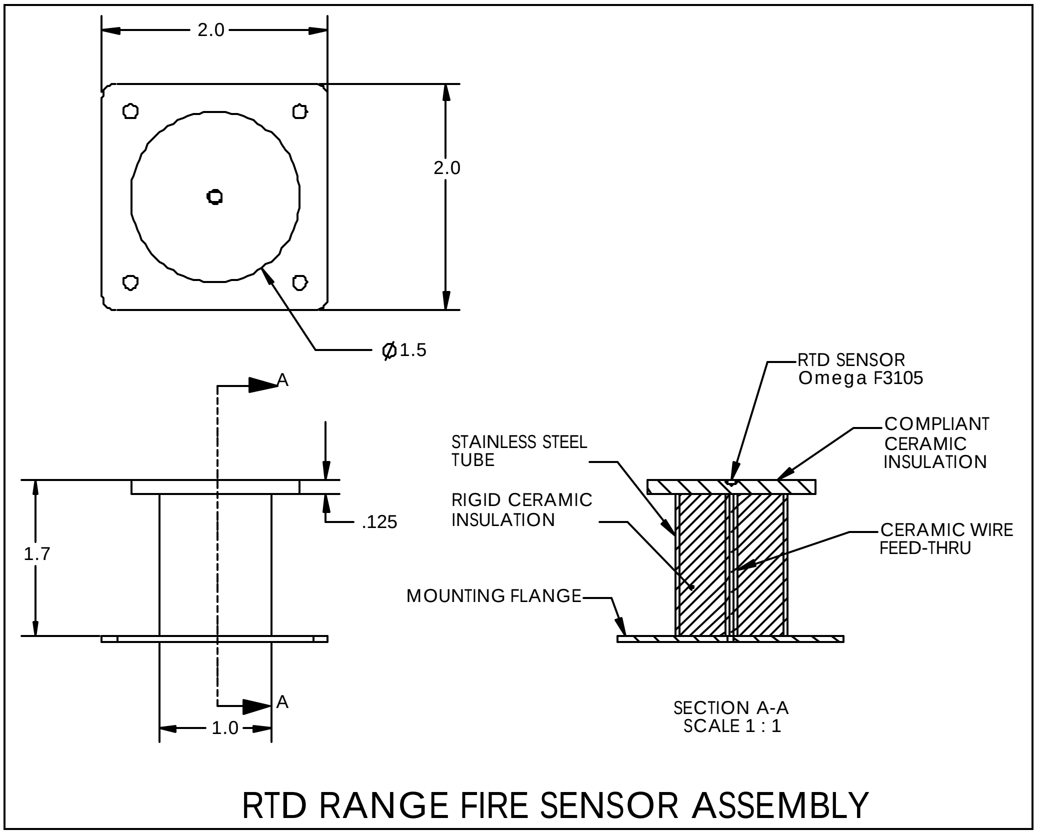

Figure 2b. RTD Sensor Detail Drawing

6.0 STEP 3. OBTAIN AND MODIFY TEST RANGES

Three commercially available ranges were purchased for the project. Two of the ranges used identical heating-element designs and the other had a slightly different heating-element design. In all cases, a temperature-limit thermostat was positioned across the center of the heating-element assembly. The temperature-limiting sensor was shifted off center to accommodate the installation of the fire-protection sensor. In two cases, the ribbon element itself also had to be moved slightly to make room for the sensor assembly. **Figure 3** shows the range heating elements before modification.

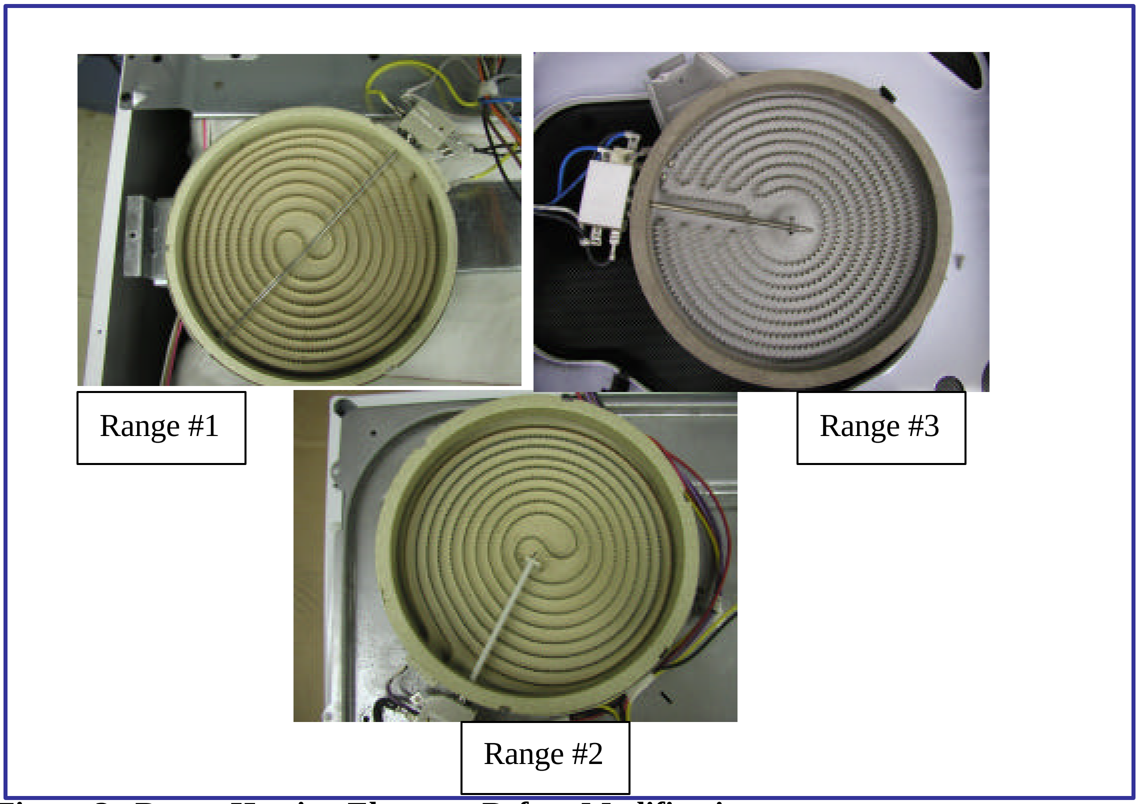

Figure 3. Range Heating Elements Before Modification

The sensor assembly was installed in the center of the element, through a 1-inch diameter hole that was machined through the heating-element assembly. The attachment flange on the sensor assembly was fastened to the heating element pan with screws.

It is important that the temperature sensor be in good thermal contact with the glass surface so that accurate temperature readings can be made. It is also important that the sensor RTD element be isolated from the hot air and radiation in the heating-element environment. This was accomplished by spring loading the sensor element against the glass and incorporating a flexible gasket at the sensor-glass contact. The spring force that was used for loading the sensor came from the same spring system that is incorporated in the heating-element assembly. This dual use of parts results in a zero cost addition for the sensor suspension system. Wires from the sensor were routed under the heating-element section of the range and out to the data-acquisition system.

Figure 4 shows a schematic illustration of the sensor assembly installed in the element tray and **Figure 5** shows a typical heating element with the sensor installed and the temperature-limiting thermostat relocated.

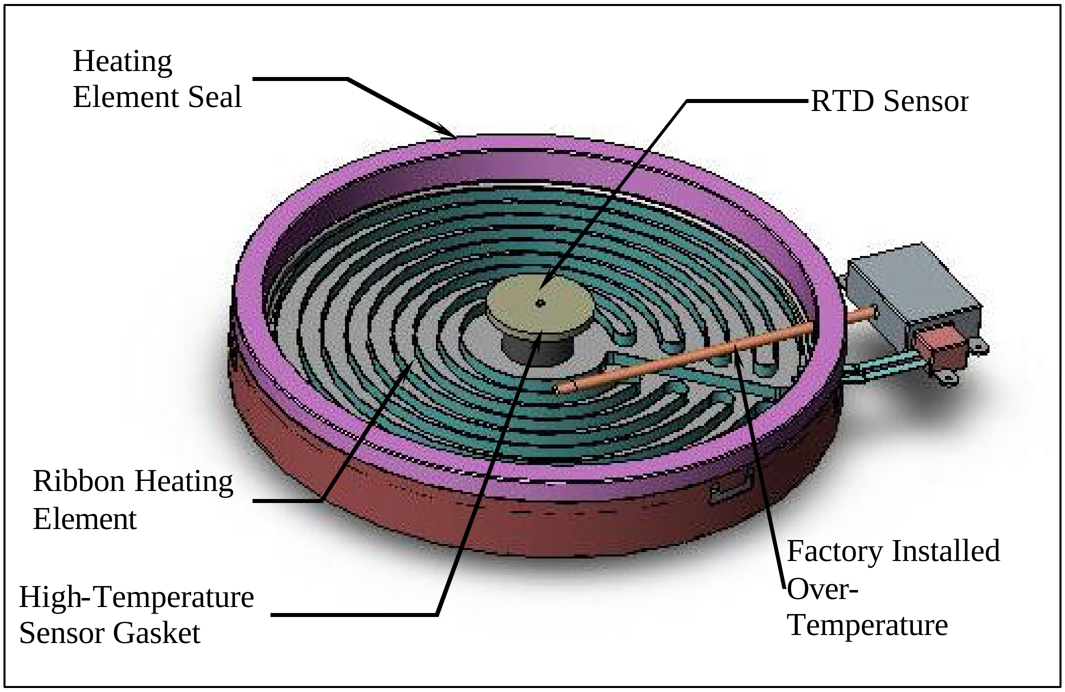

Figure 4. Typical Sensor Installation in a Heater Assembly

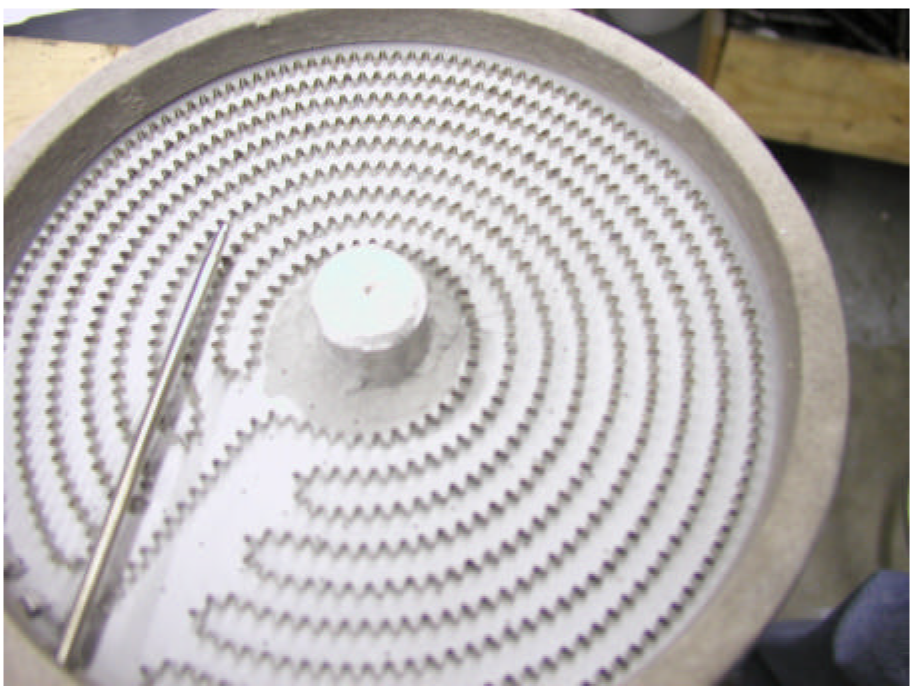

Figure 5. Modified Heating Element Assembly

7.0 STEP 4. CONDUCT STANDARD COOKING MATERIAL IGNITION TESTS

The objective of the testing was to determine if the control system was capable of preventing ignition of cooking materials on each of the ranges while not interfering with normal cooking operations.

In this task, a series of tests was performed using commercially available residential cookware. The cookware used in the tests is listed in **Table 1**. These tests were intended to demonstrate that the control system did not interfere with normal cooking operations and that it was effective at preventing a fire during unattended cooking.

The test matrix used during this task is shown in **Tables 2** and **3**. During these tests, the system temperatures, including the pan bottom and food contents, and the sensor output were monitored using PC-based control software, LabVIEW. The same software was used to actively control the system heat input in response to critical temperatures, and to prevent ignition. (See Appendix A for a description of the control system software.)

Data collection included the temperatures of the pan bottom and pan contents at a sampling interval of four seconds during each test using data from contact-type thermocouples. The response of the temperature sensor and all other pertinent data (time, room temperature, etc.) were simultaneously collected. During each scenario, the cooktop was videotaped using a standard analog 8mm recorder to document the physical conditions during each test (e.g., smoke accumulation and ignition).

Table 1. Descriptions of Cooking Utensils to be Used in Testing*

Reference	Examples of Available Utensils
Stainless Steel Skillet	10” stainless steel skillet with aluminum core
Light Aluminum Skillet	10” lightweight nonstick aluminum fry pan
Cast Iron Skillet	10-½” cast iron skillet
7 qt SS Dutch Oven	7-quart stainless steel Dutch oven with aluminum core
1 qt SS Sauce Pan	1-quart stainless steel sauce pan with aluminum core
3 qt. Aluminum Sauce Pan	3-quart nonstick aluminum saucepan with porcelain-enamel exterior
1 qt. Aluminum Sauce Pan	1-quart nonstick anodized aluminum saucepan

*These utensil descriptions are taken from the solicitation, Appendix A.

Two types of tests were conducted to demonstrate the control function; high heat input (**Table 2**) and water boiling (**Table 3**). During the high-heat tests, the controller allowed the skillet and its contents to rise to the upper allowable limit before the heat input was reduced.

Table 2. High-Heat Cooking Scenarios*

Cooking Scenarios	Cooking Vessel	Procedure
Empty Pan	10-inch skillet - Stainless steel - Light aluminum - Cast iron	Heat on high until pan temperatures indicate no change for 15 minutes; test may be terminated if aluminum pan begins to deform.
100 ml of soybean oil	10-inch skillet - Stainless steel - Light aluminum - Cast iron	Heat on high until ignition or pan temperatures do not change for 15 minutes.
500 ml of soybean oil	10-inch skillet - Stainless steel - Light aluminum - Cast iron	Heat on high until ignition or pan temperatures indicate no change for 15 minutes.
8 oz. (227 gm) of bacon	10-inch skillet - Stainless steel - Light aluminum - Cast iron	Heat on high until ignition or pan temperatures indicate no change for 15 minutes.
500 ml of soybean oil, 750 gm of chicken	10-inch skillet - Stainless steel - Heavy aluminum - Cast iron	Heat oil on high to 190°C (374°F). Introduce chicken to oil. Reduce heat to medium and turn chicken every 4 min for 20 min. Increase heat to high and continue until ignition or pan temperatures indicate no change for 15 minutes.

*From Appendix A of the solicitation.

Table 3. Boiling Water Scenarios*

Cooking Scenarios	Cooking Vessel	Procedure
Boil 6 qt. Of Water	7 qt. SS Dutch oven	Heat water on high until temperature reaches 100°C (212°F) or rolling boil is observed.
Boil 1 qt. Of Water	3 qt. aluminum saucepan	Heat water on high until temperature reaches 100°C (212°F) or rolling boil is observed.
Boil 2 cups of water	1 qt. SS saucepan 1 qt. aluminum saucepan	Heat water on high until temperature reaches 100°C (212°F) or rolling boil is observed.

* From Appendix A of the solicitation.

Baseline tests were run to determine operating characteristics of each range and pan-type combination. A control algorithm was used to predict the steady-state pan temperature based on the first derivative of sensor temperature with respect to time. There is a time constant in the algorithm that has a fixed value. Preliminary baseline testing was done to establish the time constant for each range, with the objective being to find a common time constant.

To do this, each of the three pan types was heated empty and with about 500mL of water. Both the pan and the range were at room temperature at the beginning of the test. The transient temperature readings from the sensor and pan were captured using the data-acquisition system.

Figure 6 shows the results from one of the baseline tests. This test was conducted with an empty stainless-steel skillet. The pan and sensor temperatures were measured directly, and the predicted steady-state temperature was calculated based on the following equation:

$$T_{PREDICTION} = T_{SENSOR} + M \cdot \frac{\Delta T_{SENSOR}}{\Delta time}$$

The value M was determined by solving the equation at a pan temperature of 700ºF. For all of the ranges, the M value was 60 seconds. The derivative was evaluated over a six-second time interval but since the maximum allowable temperature in the control software was set at 750ºF, the water boiled without interruption.

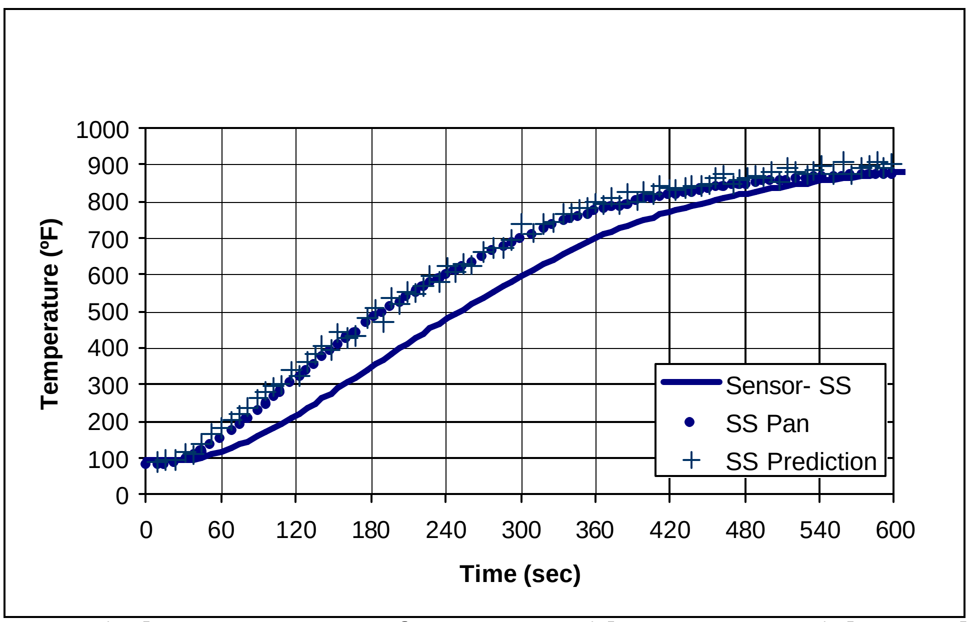

Figure 6. Typical Sensor Response for a Range with an Empty Stainless Steel Skillet.

Figure 7 shows the algorithm response for the same stainless-steel skillet filled with about 500 mL of water. Note that the algorithm does not track the pan temperature exactly in this case but since the maximum allowable temperature in the control system software was set at about 750ºF, the water boiled without interruption.

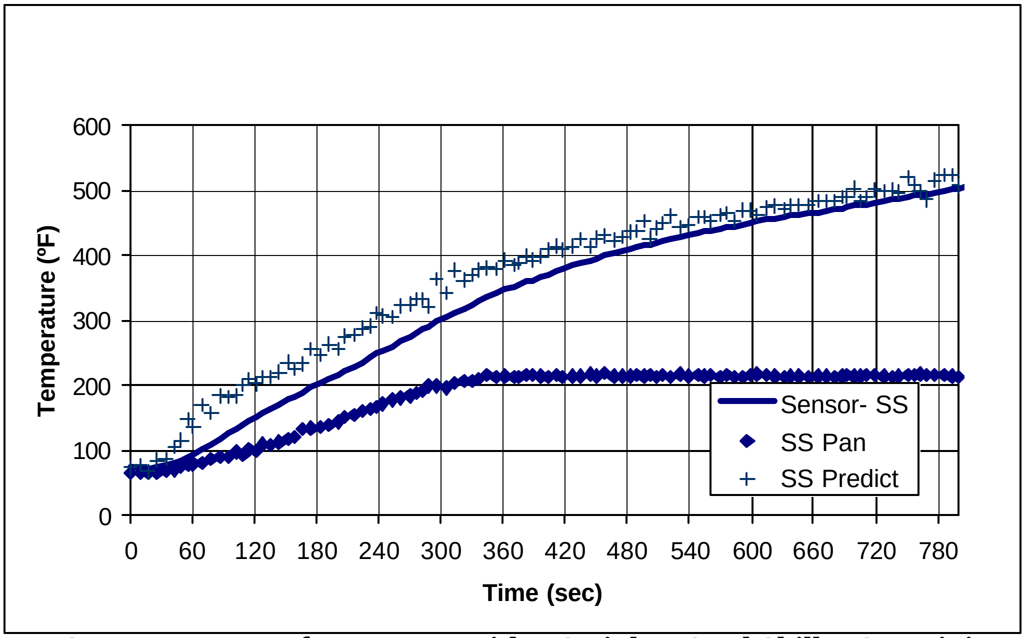

Figure 7. Sensor Response for a Range with a Stainless Steel Skillet Containing 500 mL of Water.

7.1 Preliminary Oil Ignition Prevention Tests

After the derivative-control coefficients were determined, the algorithm function was confirmed with an oil test. 100mL of soybean oil was placed in the stainless steel skillet and heated on high for 15 minutes. **Figure 8** shows the results. For this test, the sensor algorithm maximum temperature was set at 700ºF and the derivative constant was 60 seconds.

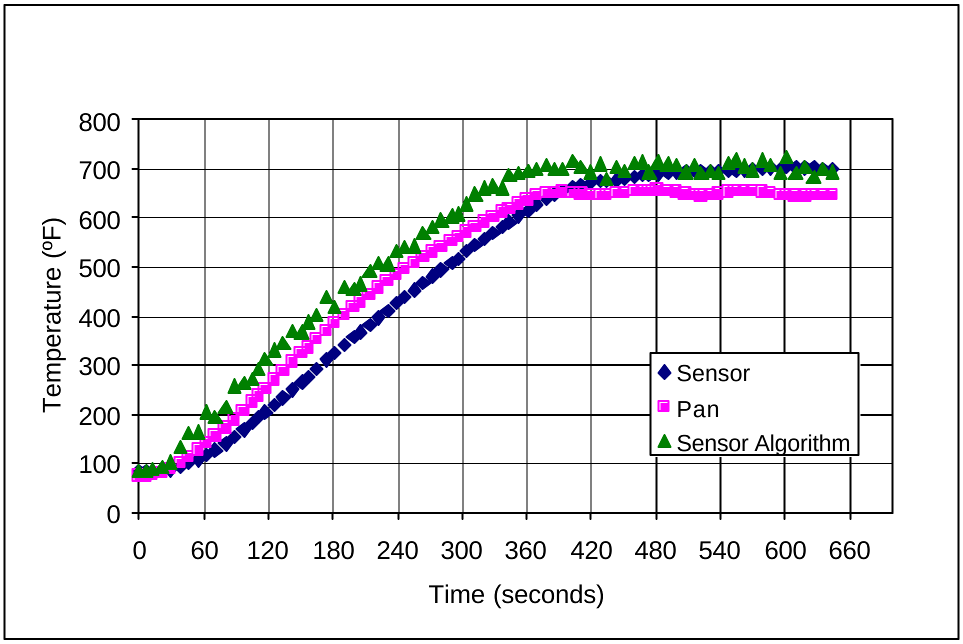

Figure 8. Stainless-Steel Skillet with 100mL Soybean Oil

7.2 Boiling Water Tests

The next step in the test series was to verify the ability of the range to boil 6 quarts of water without significant interference from the fire-protection control. A 7-quart stockpot was filled with 6 quarts of water and brought to a boil on all three ranges with the control turned on.

Boiling times using the as-received (new) pot with the control active were longer when compared to the same test without the control. The boil time was about 30 minutes without the control and about 50 minutes with the control. The reason for this is that the control algorithm cycles power to the heating element when the predicted temperature based on the algorithm is at the limiting set point. The set point needed to prevent ignition is 750°F, and this is reached during the heat-up time for a large quantity of water. The root cause of longer boiling time was proved by monitoring the sensor temperature readings while boiling water in the 7-quart stock pot with the control inactive. In this case, the sensor temperature reading was around 1000ºF while the water was heating. Since the control limit necessary to prevent ignition is about 750ºF, the control system began to cycle the heating element power before it reached the higher temperature.

Not all cooking pans showed the same characteristics regarding system temperatures with and without the control system being active. Two different cooking vessels were compared; the 7-quart stock pot and a 10-inch skillet from the same manufacturer. Both of these pans were stainless steel with an aluminum core.

The first test was with the 7-quart stock pot (about 10-inches in diameter) filled with 6 quarts of water. The control system was turned "off", and the steady-state sensor temperature of the sensor was about 1000ºF for all ranges. The skillet, which was also about 10-inches in diameter, was filled with water. The steady-state sensor temperature in this case was 600°F.

The two pans are the same type of construction (aluminum core, clad with stainless steel on both sides) and similar diameter. The difference between the two pans was their cooking surface flatness. The skillet was within 0.005 inches of being flat (it was slightly concave). The bottom of the stockpot was concave with the center being approximately 0.060 inches higher than the rim.

To measure the effect of pan flatness on sensor response, a stainless-steel stockpot was ground flat and tested by boiling 6 quarts of water to establish a baseline. The pot was then dented using a hydraulic press, first to about 0.055 inches in the center and then to about 0.080 inches. This was done to observe any impact of pan concavity on boiling times.

Results of these tests are shown in **Table 4**, and clearly indicate that pan flatness is an important parameter in boiling large quantities of water on a smooth-top range with a fire-prevention control system active. For example, the boiling time for the "perfectly" flat pot was the same with or without the control at 23 minutes. The pot was thermally well-connected to the glass surface as evidenced by the nearly equal sensor temperature reading. Thus, the control system has little if any effect on boil times if flat pots are used.

The boiling times listed in **Table 4** are slightly faster than the boil times stated previously. This is because these tests were run from a "hot start" instead of from room temperature. To do this, the range top was heated to steady-state by boiling water in a cooking vessel before the instrumented test pot of water was placed on the element. This was done so that all tests were performed from similar starting conditions, and it eliminated the time required to warm up the glass and other components.

When the pot was dented by 0.055 inches, boiling time increased by 13 minutes when the control was active. The boil time was about the same with the control inactive whether or not the pot was dented. The temperature inside the heating element zone as evidenced by the sensor temperature reading increased markedly when the dented pot was used to boil water without the control. Because the control works to limit this temperature to a safe level (under 750°F), heat transfer to the dented pot was reduced resulting in increased boil time.

Increasing the dent to 0.080 inches had very little effect on boil time with the control off or on. The data show that the boil times were nearly the same with the larger indentation. This indicates that the amount of denting might not be as significant as the mere presence of a dent.

Table 4. Boil Times for Flat and Dented Stockpots.

Pan Configuration	Boil Time, minutes		Sensor Temperature at Boiling	
	With Control	Without Control	With Control	Without Control
Flat	23	23	728	703
0.055" Depression	37	24	735	1001
0.080" Depression	39	23	746	1068

7.3 Detailed Oil Ignition Prevention Tests

The objective of this series of tests was to prove that the control system could prevent fires on all of the ranges. Each of the three skillets used in testing was filled with 100mL of soybean oil and placed on an element of the range with the input setting on HIGH. All three ranges were used in the tests with all three skillet types. A total of nine tests was conducted.

Figure 9 shows a sample set of data from the tests. For the first few minutes, the range components and skillet warm up. After this warm-up period, the control begins to cycle the power to the heater element. At the control temperature of 750ºF, the skillet surface temperature is about 660ºF and the oil temperature is around 580ºF. **Table 6** lists the temperatures that were measured during all of the testing in this series.

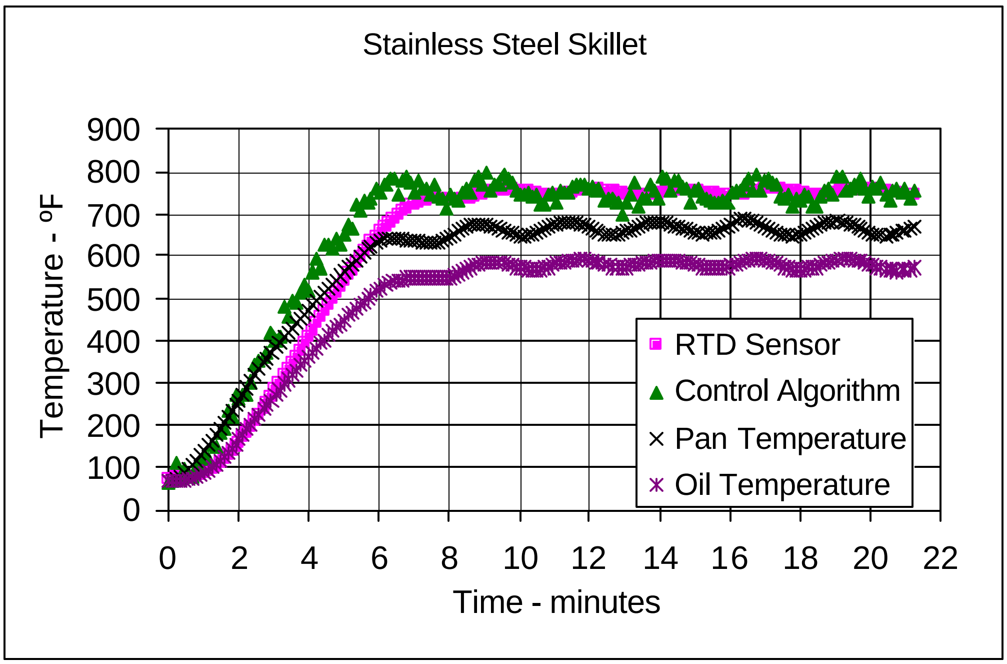

Figure 9. Temperature versus Time Plot for 100mL oil Test with the Stainless-Steel Skillet

Table 5 shows that the oil never reached ignition temperature (about 700ºF). In fact, the oil was mostly below 600ºF during all tests, which suggests that the set point could have been increased somewhat. Increasing the control set point temperature would be helpful in boiling water in dented pans by allowing the glass to reach a higher temperature, but the increase could only be about 50ºF.

Table 5. Average Steady-State Temperatures During Oil Tests.

Range #1			
Skillet Material	**Sensor**	**Skillet**	**Oil**
Stainless Steel	751	664	578
Cast Iron	755	620	525
Aluminum	752	605	527
Range #2			
Skillet Material	**Sensor**	**Skillet**	**Oil**
Stainless Steel	748	680	611
Cast Iron	756	584	519
Aluminum	749	639	537
Range #3			
Skillet Material	**Sensor**	**Skillet**	**Oil**
Stainless Steel	752	634	567
Cast Iron	762	581	518
Aluminum	753	588	502

7.4 Food-Cooking Tests

The objective of this series of tests was to verify that the range sensor control did not interfere with the normal cooking of food. The two tests conducted in this series were:

1. Heat 8oz. (227gm) of bacon on high in each of the skillets (aluminum, cast iron, and stainless steel) until ignition or, if ignition does not occur, heat until a steady temperature occurs for 15 minutes.

2. Heat 400mL soybean oil on high until it reaches a temperature of 190ºC (374ºF), introduce 750 gm (1.7 lb) of chicken and reduce heat to medium. Turn the chicken every 4 minutes for 20 minutes. Increase the heat to HIGH and continue until ignition occurs or, if ignition does not occur, heat until there is 15 minutes of no change in temperature.

Both the bacon and chicken-cooking tests experienced no interference from the control system while cooking. The skillets during the bacon tests were able to reach over 400ºF before the control took over, and cooking proceeded to completion. **Figure 10** shows temperature data from a typical test. This test began with the range at room temperature.

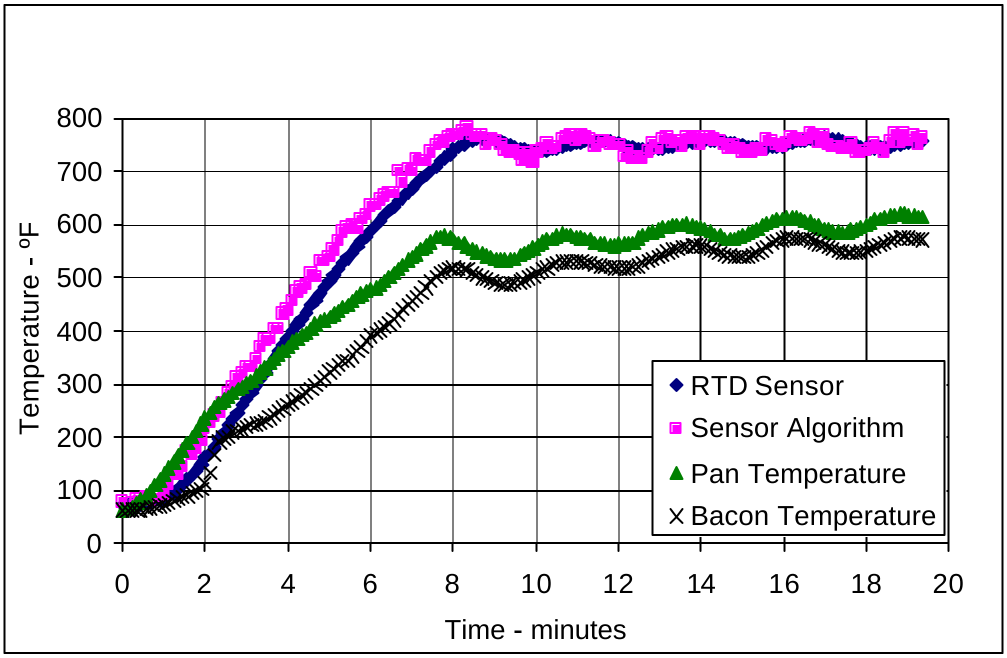

Figure 10. Temperature Plot Obtained During Cooking of 8oz Bacon in a Stainless-Steel Skillet for Range # 2

In the first eight minutes, the pan and contents warm to the maximum temperature without interruption from the sensor control. At this point, the contents of the pan were above 500ºF. During the next 10 minutes of the test, the pan heated up slowly to about 600ºF. After this time, the pan temperature leveled out and became steady without ignition. This is typical of all the bacon tests.

A plot of the typical results from the chicken-cooking tests is shown in **Figure 11**. In the first eight minutes of the test, the contents of the pan were allowed to reach 190ºC (374ºF) as prescribed by test protocol. The heat input was lowered to MEDIUM and the chicken pieces were turned every four minutes for 20 minutes. During this time, the sensor temperature dropped to about 650ºF, and there was no interference with heat input. The range was then turned up to HIGH until the temperature stabilized or until ignition occurred. For all tests, the temperature of the pan contents peaked between 400ºF and 600ºF and no oil ignition occurred.

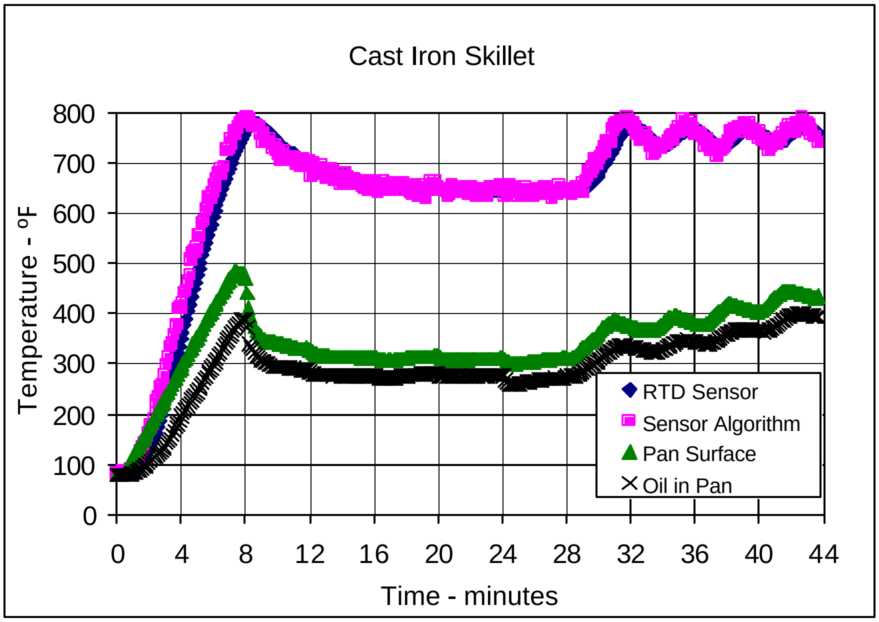

Figure 11. Typical Chicken Cooking Test Results for Range # 2

8.0 STEP 5. DEVELOP MANUFACTURING COST ESTIMATES

This task was focused on developing a cost estimate for the range-control system and further developing the system to include diagnostics in case of sensor failure. AMTI attempted to contact range manufacturers and controls suppliers to assist in this task. No manufacturer was willing to get involved with the project except for a sensor manufacturer. Consequently, the cost estimates for electronics are based on AMTI experience and cost estimates for the sensor are based on conversations with that manufacturer.

Most slide-in and free-standing ranges with electronic controls for the oven use RTD sensors and control circuitry. The diagnostic most needed for these temperature sensors is open-circuit or short-circuit failure. The RTD circuitry interprets resistance as temperature by using a resistance-measuring circuit. A Wheatstone bridge is the most common approach.

Because the circuit is functioning on the basis of resistance, it is quite simple to include a conditional test in the software to signal a failure in the event of very high resistance (open circuit) or unrealistically low resistance as in the case of a short circuit. Consequently, the diagnostics needed for this aspect of the device are within the software.

A successful sensor should also be self-calibrating. It is not possible to actually calibrate the sensor in the field because there is no reliable reference temperature. It would be possible to conduct a start-up self test to determine if the sensor is in good contact with the glass. The RTD could be excited with a small electrical current upon startup causing its temperature to rise. If it is in good thermal contact with the glass, this temperature rise would be less than if it were floating free from the glass. It would be important to first read the sensor temperature to determine that it was at a low point, then to conduct the test for a short time period to measure the temperature rise.

Self-calibration testing was not done during this project. It should be included in a more detailed production design and development project.

Because the range/oven combination already has a circuit for RTD sensors, the basic computational components are already in place. This control would require that the inputs be increased from 1 to 5 and that the circuit be multiplexed. This would not present a difficult technical challenge because the required sampling rate is so low. A new circuit would have to be designed and produced and new software would have to be developed. Cost increase of the control circuit and related changes in the computer would be minimal.

The greatest original equipment manufacturer (OEM) cost increase would be due to the inclusion of additional sensors and wiring. We believe that each sensor assembly could be produced for a cost in the range of $2.00 to $4.00 complete with RTD, insulation and wire. There would be additional costs involved in wiring the control sensors into the circuit board. Potentially an additional $5.00 in manufacturing cost would be involved for each range. Thus, based on our expert judgment and without input from range manufacturers, the cost increase is expected to be in the range of $13.00 to $21.00 for a four-element range with these controls.

Drop-in ranges without ovens are another matter. These units typically do not have electronics on board. This feature would have to be added, and we estimate that this would involve an OEM cost increase of an additional $5.00 to $10.00 for the circuit board and related power supply.

9.0 CONCLUSIONS AND RECOMMENDATIONS

This project showed that the under-glass temperature approach successfully prevented range fires from unattended cooking on all test ranges and with all test foods and cooking vessels. The control approach did not interfere with normal cooking operations involving preparing meats and boiling small quantities of water. The sensor and control did interfere somewhat with boiling large quantities of water, especially in pans with dented bottoms. The time to reach a rolling boil in these cases was lengthened by several minutes.

Based on the findings of this project, the following recommendations are made:

- Conduct endurance testing per UL Standards Technical Panel for Household Electric Ranges, STP 858, recommendations.
- Some range manufacturers asked if the sensor approach could be used to control temperature to lower levels than ignition. This would add value to the range, and testing should be done to confirm this. Tests should be conducted with the LabView control system set to a much lower temperature to determine if the power to the surface heating elements can be controlled such that skillet temperature holds steady at some lower setting.
- Sensor manufacturers should be included in further development testing. Their inputs regarding self-calibration in this application should be sought. The self-calibration routine summarized above should be evaluated along with other self-calibration ideas that are suggested by manufacturers.

APPENDIX A

LABVIEW SCREEN CAPTURE AND LOGIC FLOW DIAGRAM

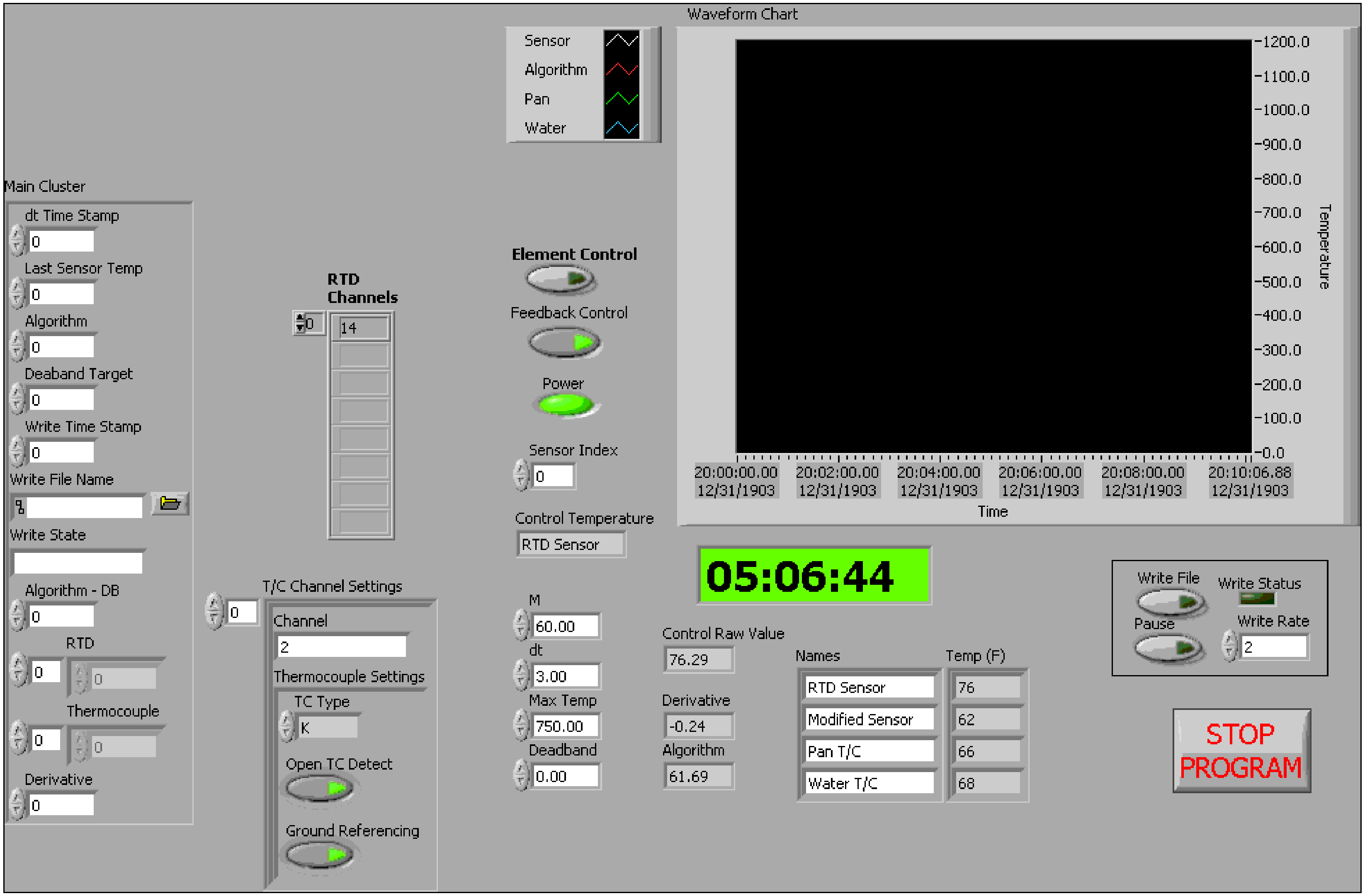

Figure A1. Front Panel of LabVIEW Temperature Control Program

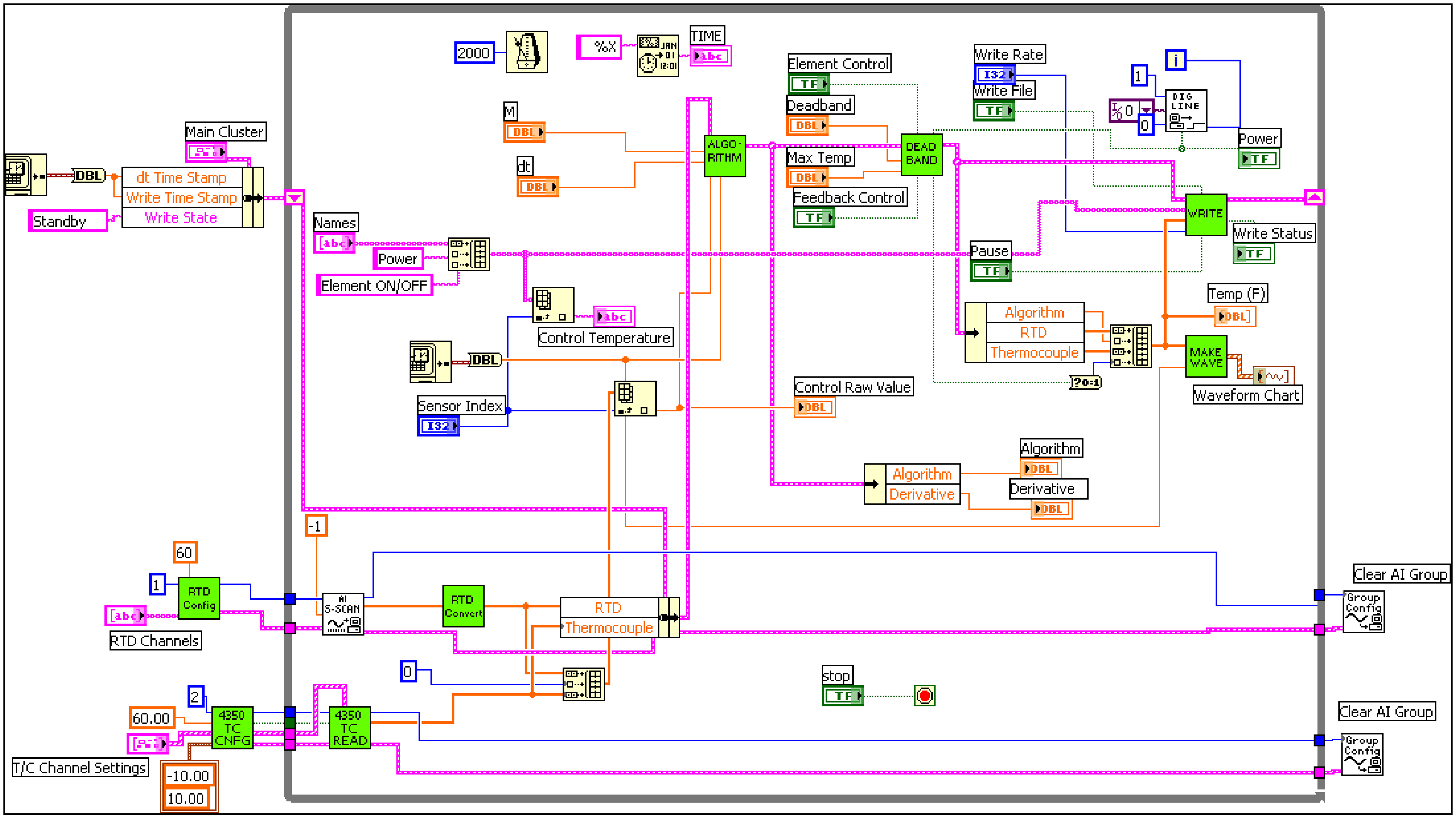

Figure A2. Block Diagram of LabVIEW Temperature Control Program.