**UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
WASHINGTON, DC 20207**

Memorandum

Date: DEC 1 8 2003

TO : The Commission
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THROUGH: Patricia Semple, Executive Director PS
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FROM : Jacqueline Elder, Assistant Executive Director
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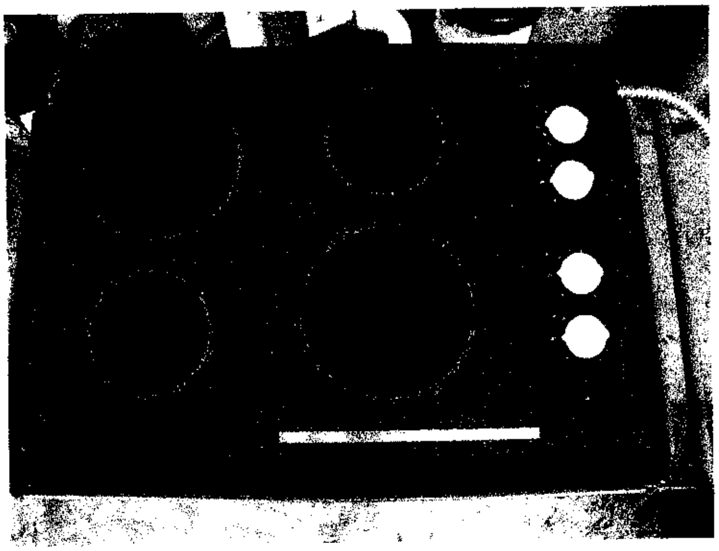
SUBJECT : Contractor Report on Development and Testing of Temperature Sensors for Preventing Cooking Fires on Glass Ceramic Electric Ranges

Attached is a contractor report from Advanced Mechanical Technology, Inc. (AMTI) on the development and testing of sensor and control technologies to address cooking fires on glass ceramic cooktops.[1] This contract was conducted in support of U.S. Consumer Product Safety Commission (CPSC) staff efforts to prevent cooking fires. Each year cooking fires from food igniting inside a cooking utensil cause an estimated 47,200 residential structure fires, claiming 80 lives, injuring 2,440 victims, and resulting in $134.6 million in property loss[2].



The AMTI contract is a follow-up to an FY02 study that was conducted by Arthur D. Little, Inc (ADL, now Tiax, Inc.). The ADL contract was a paper study to identify and assess sensor technologies that could be used on glass ceramic cooktops to detect temperatures that could lead to food ignition. Glass ceramic cooktops, as shown in the photo to the left, consist of a solid sheet of glass ceramic and, therefore, are not compatible with the pan-contact temperature sensors that CPSC staff had previously evaluated

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[1] The U.S. Fire Administration provided the funds for this contract.
[2] Smith, Linda E. and Greene, Michael A.; CPSC staff memorandum, *Updated Estimates of Rangetop Cooking Fires*; March 9, 2001.

NOTE: This document has not been reviewed or accepted by the Commission.
Initial RL **Date** 12/18/03

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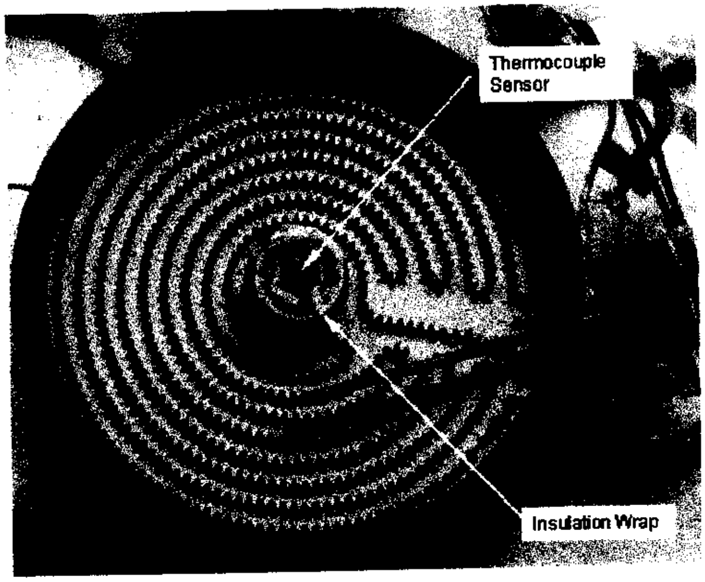
for use on gas and coil-type electric burners to prevent cooking fires.[3,4] The FY02 ADL study[5] identified various sensor and control technologies with potential applicability for use on glass ceramic cooktops. Starting from this point, AMTI explored several methods for accurately detecting or inferring pan temperature from the underside of the glass.



AMTI staff developed a radiantly-shielded thermocouple assembly that was able to track pan temperature. The assembly was installed in the center of the heating element, where there are no elements, as shown in the photo to the left (the rod-shaped thermostatic switch was moved aside to accommodate the assembly). AMTI also developed an algorithm that can be used by a control system to more closely infer the pan temperature. The thermocouple, used in conjunction with the control algorithm, successfully prevented ignition of representative foods but did not affect normal cooking. For example, the system permitted water to be boiled without any increase in the time-to-boil for nearly all of the combinations that were tested.

In support of continuing efforts to promote the adoption of performance requirements in the voluntary standards for ranges to help prevent cooking fires, the CPSC staff will forward this report to Underwriters Laboratories, the standards developer for household electric ranges, and the Association of Home Appliance Manufacturers, the trade association for range manufacturers.

AMTI's results are a significant initial step toward addressing the challenge to develop a system for measuring pan temperature on glass ceramic cooktops.

Attachment

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[3] Lim, H. et al. Study of Technology for Detecting Pre-Ignition Conditions of Cooking Related Fires Associated with Electric and Gas Ranges: Phase III. U.S. Consumer Product Safety Commission, 1998.

[4] Corliss, J. *Development of a Control System for Preventing Food Ignition on Gas Ranges* Energy International, 2000.

[5] Brekken, M., Carbone, P. and Benedek, K.; *An Evaluation of Sensor and Control Technologies to Address Cooking Fires on Glass Ceramic Cooktops*; Arthur D. Little, Inc., 2002.

FINAL REPORT

on

Identification and Evaluation of Temperature Sensors for Preventing Fires on Electric Smooth-Top Ranges

to:

U.S. CONSUMER PRODUCT SAFETY COMMISSION
(Order Number CPSC-S-02-1326)

July 28, 2003

by:

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1.0 EXECUTIVE SUMMARY

The overall objective of this project was to identify sensors that could be used with a smooth-top electric range to sense pending ignition in a cooking vessel and intervene to prevent range-top fires. 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 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.

An off-the-shelf smooth-top electric range was procured for use in this project. The range was modified to incorporate thermocouples and other instrumentation to allow the temperatures of the glass, the heating element, ambient conditions under the glass and the cooking pan to be monitored during various cooking scenarios. A series of baseline laboratory tests were conducted to determine the thermal environment within the heated zone of the range during normal cooking operations such as boiling water and blackening meats. The testing resulted in two significant findings; (1) the emissivity[1] of the cooking pan strongly impacts the operating temperature of the glass, and (2) the thermal time response of the glass cooktop was significantly slower than the response of a typical cooking pot or pan.

The original concept for a fire-prevention control was to radiantly couple a thermal sensor located below the glass to the bottom of a pot. While this was successfully accomplished, it became apparent that, due to wide differences in pan emissivity, the response of the thermal sensor varied widely. In fact, observations taken during a normal cooking operation such as boiling water with a low-emissivity pan (stainless steel, for example) fell within the range of readings taken from a high emissivity pan (cast iron) during an event that concluded with ignition. Thus, a radiant sensor was excluded from further consideration.

Simply measuring the bottom of the glass with a contact temperature measuring device such as a thermister or thermocouple showed promise in the early testing. Because the glass temperature rise significantly lags the cooking pan temperature rise, the response of the control was dependent upon the previous operations conducted on the range and on the existing thermal conditions of the range components at the time that an ignition event is likely to occur. For example, if the range was used to boil water for several minutes, the glass, heating element and the air under the range top would be preheated to a safe but high level. Then, if a pan of oil or other flammable food material was heated to a temperature approaching ignition, simply measuring the temperature of the glass bottom would be sensitive enough to detect pending ignition and interrupt the heat input.

If, on the other hand, the range was initially at room temperature and a pan of flammable food material was heated until ignition, the glass temperature reading would indicate a value well within the normal, safe limits. This was due to the thermal lag of the glass and is a result of the

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[1] Emissivity is a material property that relates how well the material surface radiates heat. A "perfect" surface has an emissivity of 1. Real surfaces have an emissivity less than one. Generally, dark, dull surfaces such as cast iron or flat black painted surfaces have high emissivity while shinny surfaces have a low emissivity. The emissivity of stainless steel is generally about 0.1 while cast iron is about 0.85 to 0.9.

optical/thermal characteristics of the glass itself. The glass is formulated to be fairly transparent to the heat source wavelengths. Thus, most of the radiant heat from the heating element is radiated directly to the pan. The glass is heated from a combination of convection from the air in the heating element space, conduction from the pan itself and absorbed radiation passing through the glass from the heating element and as re-radiation from the pan. Because of the strong radiant coupling between the heater and the pan, pan temperature rises faster than the glass temperature. Once the system has been preheated, glass temperature follows pan temperature fairly closely.

Several attempts were made to create a thermal environment wherein the glass could closely track pan temperature. For example, an effective insulation system was devised to isolate the glass sensor from the environment under the glass. This system consisted of three concentric rings of low-emissivity material (stainless steel) sandwiched with thin ceramic fiber insulation. Further, the glass was machined with a diamond hole saw such that a circular "moat" was formed around the region of the glass that was being sensed. Even with the high thermal isolation of the glass via the moat, glass temperature did not respond rapidly enough. Moreover, the machining operations effectively weakened the glass to the point that it would have failed the Underwriters laboratories (UL) drop test.[2]

All data collected during testing was logged using LabVIEW software. The resulting data files were analyzed for trends in temperature response. After detailed analysis, there appeared to be a solution to the glass response time in the form of a control algorithm that responded to the time-rate-of-change of glass temperature; the first derivative with respect to time. By incorporating a term in the algorithm that was derivative-dependent and adding it to the measured glass temperature, the resulting value closely matched actual pan temperature under all conditions and with all pan sizes and types.

The resulting control system consists of a simple thermal sensor held in contact with the glass bottom and isolated from the heating element with insulation. No machining or other modifications to the glass are necessary. The control simply monitors actual glass temperature, modifies the reading based on the instantaneous derivative, and interrupts power to the range top when the resulting value reaches a dangerous level.

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[3] 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. 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. The 1999 report presents data that clearly show that unattended operation is a common factor in most of the fires. The later data show that 70,200 fires (83 percent) originated on the cooktop as opposed to the oven. These fires alone resulted in an annual average death rate of 230 with an additional 3,630 injuries and $263.5 million in property loss. Ignition of cooking materials from the rangetop accounted for

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[2] UL Standard 858, Sep 01 1993, "Standard for Household Electric Ranges", 14th Edition

[3] Smith, L. E. et al., "Range Fires – Characteristics Reported in National Fire Data and a CPSC Special Study", U. S. Consumer Product Safety Commission, 1999.

47,200 fires with 80 deaths, 2,440 injuries and $134.6 million in property damage annually.

A four-phase study was conducted by CPSC[4]. 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[5,6] 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 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 temperature and preventing range fires. Contact sensor performance was summarized in the EI report and International Appliance Technical Conference (IATC) presentation 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[7] (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

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[4] 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.

[5] Corliss, J., "Development of a Control System for Preventing Food Ignition on Gas Ranges", 2000

[6] Corliss, J., "Development of a Control System for Preventing Food Ignition on Gas Ranges", Presented at the 2002 IATC Conference, Lexington, KY.

[7] "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.

time.

2.1 General Approaches to Smooth-Top Temperature Measurement

Measuring the temperature of the actual smooth top to infer the temperature of the pan has limitations regarding accuracy, response and cooking acceptability. This temperature measurement approach was implemented about 30 years ago and, as outlined in the next section, relied heavily on special pans to closely match the surface of the smooth top. If special pans were not used, the controller would hold the smooth top to a safe temperature as planned, but heat transfer to the pot was limited by the poor contact, resulting in unacceptable cooking results.

In today's smooth-top electric ranges, various heating approaches are employed including electric resistance, halogen bulbs and in some cases, induction coils. If the temperature of the bottom of the ceramic surface distant from the cooking vessel is measured, the measurement location and technique have to be insensitive to the heating effects of the heating elements. This is a challenging and difficult task. If these interferences are properly accounted for via firmware or software, cooking performance should not be impaired.

A temperature sensor imbedded in the smooth top near the cooking surface has the potential to be more accurate. Moreover, if this sensor technology averaged the smooth-top surface temperature over a specific area, variations due to uneven pan contact potentially could be accounted for in the results. A sensor of this type might be imbedded in the surface by sealing into etched grooves, for example.

An infrared sensor approach closely parallels the radiantly coupled approach successfully demonstrated in the EI work and could be successful in the smooth-top range if there is adequate protection from fouling. A sensor that receives radiant energy directly from the pan bottom measures temperature more directly than an overhead optical sensor. Moreover, in the earlier EI work, this approach was shown to be insensitive to the heating effects of the swirling combustion gases around the sensor in the gas-range application. The same approach has the potential to be insensitive to and unaffected by the heating effect of surrounding electrical heating units including halogen, resistance or even induction.

2.2 Historical Residential Range Control Systems

The range industry has implemented schemes intended to control cooking vessel temperature over the years. These control systems were introduced on electric and gas ranges. For example, some of the early ceramic-top ranges required matching ceramic pans and skillets. These pans and skillets were specially produced with their contact surfaces ground flat to give nearly infinite contact between the cook top and the vessel. At nearly the same time, some of the range controls companies developed contact probes, usually only connected to one burner, that allowed accurate temperature control. These units were built during the period from the mid-1960's through the late-1970's.

These systems were discontinued over time for a variety of reasons. The temperature control aspects of the system used on the ceramic-top range worked well. Day-to-day operation was unacceptable, however, because the system was slow to reach cooking temperature and required special pans. This was a marketing disadvantage. The temperature sensor was below the surface and protected from contact by the consumer. This feature yielded a robust system having the advantage of not being easily damaged.

Another type of control system was employed for gas burners. This system did not require a special top or special pans. This enabled it to be more easily adapted to conventional range devices. The system consisted of a shielded, spring-loaded flat disk that had sufficient self-centering capability that the disk would spring up to the pan and be parallel with the bottom of the pan surface. This feature provided consistent sensor-to-pan contact with uneven pans.

The gas burner controller was eventually removed from the market for a number of reasons, not the least of which was its propensity to be damaged. When the burner or heating element was not being used, the sensing disk extended above the electric element or the burner grates. As a result, it was subject to mechanical damage by the user if a pan were to be slid across the surface, hitting the side of the disk and support collar. Differences in pan materials also made it susceptible to inaccuracies. For this system to be useful, it needed to accurately control the pan temperature.

Another problem in the early units was the inability to go into a simmer mode. Since water boils at one temperature, settings near the boiling point of water either produced a full rolling boil or no boil at all. This was later resolved on electric units by having a control that could turn clockwise or counter-clockwise from off. One direction gave standard "infinite switch" control, and the other direction gave temperature control using the sensing system.

3.0 OBJECTIVE AND APPROACH

The objective of this project was to follow up on the promising technologies that were identified in earlier CPSC work and:

- Identify temperature measurement techniques that can effectively measure pan temperature on ceramic glass cooktops,
- Select sensors that can perform this function, and
- Evaluate the sensor's effectiveness in measuring pan temperature against a standard set of tests.

The specific approach used in meeting project objectives involved a series of steps, each with its own objectives and expected outcomes.

The initial work focused on identifying any additional candidate sensors and control approaches based on AMTI's experiences; literature references, especially those from recent CPSC work; and pertinent contacts with industry, instrument suppliers and temperature measurement sensor suppliers. This activity was focused on developing a list of candidate temperature measurement and control options for the electric smooth-top range. Several approaches had already been demonstrated on a heating-element-type electric range and on a gas range, as discussed above. AMTI's initial belief was that the gas-range approaches described above were closely aligned with the requirements of the smooth-top electric range.

The second step progressed in parallel with the background investigations. This step involved performing baseline testing on a smooth-top range. This testing was aimed at determining the control envelope available to the control system for use in preventing range fires while not interfering with the cooking process.

In operation, the smooth-top range exhibits a specific temperature profile through the glass top and on the surface in contact with the cooking vessel depending on the cooking operation being performed. There is a "thermal envelope" of normal operation ranging from a low temperature condition associated with boiling water to a high-temperature condition encountered while sautéing foods, frying and other high-temperature cooking operations. Any control scheme has to be invisible to the cook when the system temperatures are within this range, yet be fast enough to shut down the heat input when temperatures exceed the highest encountered during normal cooking operations. The outcome of this second step was used in defining this working temperature range and gathering data that supported the control algorithm for deciding when to intervene.

The third step involved modification of a range to incorporate the control strategy. The electric range selected for testing in this project was modified to allow a temperature-measurement system to be implemented for testing and evaluation. This modification included a wiring change to the temperature-control function of the range. The as-received range was equipped with a high-input setting and a variety of intermediate settings, depending on knob position. The fire-prevention control system has the capability of overriding the cooking power input function when ignition is pending for any knob position. The modifications made to the test range only involved one of the heated zones; a production unit would necessarily involve all four zones.

The fourth step was to demonstrate range operation under the influence of the ignition-prevention control system. This step involved installing the control scheme, developing the software needed to operate it, and demonstrating the system on the test range. This included demonstrating that the controller did not interfere with normal cooking scenarios and that it did prevent ignition when required.

The fifth step was to provide information necessary to solidify the selection of the control strategy and system. This step involved an analysis of the manufacturing impact of the control system. A key question to be addressed was: What materials and processing will be required to implement this new and different technology into current range production?

4.0 STEP 1. TEMPERATURE SENSOR EVALUATION

Much work has been done to date in evaluating various technologies for measuring temperatures in cooking systems, both as contact sensors and non-contact sensors. Work during 2002 by ADL and Energy International focused strongly on direct contact and radiant sensors. As a practical matter, the range industry is unlikely to incorporate a sensor system that is complex, requires the user to do something to make it work or that will not exhibit the reliability level usually associated with this type of appliance.

These considerations effectively eliminate sensors that are remote from the range such as hood-mounted or side mounted IR sensors. Moreover, sensors that protrude through the glass surface are also effectively eliminated from consideration due strictly to the fact that they would greatly reduce the beauty and functionality of the smooth glass top. Sensors that are deposited on the glass surface in the form of thin films are also likely to not be commercially successful due to the complexity and fragility of the design.

Remaining sensor technologies that could be commercially successful are those that *infer* pan temperature from some other temperature that is directly measured or by a sensor that is specifically tuned to the radiant energy reflected and/or reradiated from the pan itself. A successful system would be one that limits the overall appliance modifications necessary for satisfactory performance.

Based on this assessment, AMTI moved forward with baseline testing using sensors that directly contacted the bottom of the glass surface and with radiantly coupled sensors that were located below the glass.

5.0 STEP 2. BASELINE TESTING

Initial testing was performed with the goal of determining the overall thermal environment under the range top during specific cooking operations. A typical smooth-top cooking surface was procured for the testing. The cooktop that was selected was a counter-top range model and did not include the oven components. Baseline measurements of system temperature profiles through the smooth-top and on the pan bottom during various cooking cycles and events leading up to ignition were measured with this system.

The test cooktop had a bi-metal thermostat above each of the ribbon heaters. These thermostats perform two functions during range operation, one of which has an impact on fire-detection control system function. The first function of the bi-metal thermostat is to sense a rise in temperature within the heating element cavity and switch on a "hot" light that is visible to the user. The "hot" light remains on throughout the cooking cycle and for a period after the element is switched off. This is so that the user knows that any one or more of the heaters has been on recently and that they should not touch the range. The other function of the thermostat is to control the temperature in the heating element cavity to an upper limit. This is accomplished by shutting off power to the element when the element senses a temperature of about 1330° F. As a result, the range-top heaters act as constant-temperature sources instead of constant heat-input sources.

Baseline testing was necessary so that the thermal envelope or range of temperatures expected in normal cooking operations and during conditions leading to ignition could be determined. This was especially important because of the temperature-limiting aspects of the heat source. Because the eventual control strategy was expected to measure temperature at a single point, it was important to know what the highest possible temperature at the measurement location would be in comparison to the temperatures experienced at this location during normal operations. This was critical because the control temperature had to be set high enough such that it was above temperatures seen in normal operation while far enough below the ignition temperature to allow for minor measurement error and thermal inertia.

Testing was begun with 10-inch skillets made from stainless steel, aluminum and cast iron. The overall test matrix used in these experiments is shown in **Table 1**. There were four series of tests performed:

- Heating the skillets to their maximum temperature with no food or water in them to achieve maximum temperatures[8],

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[8] This test series might be considered optional. The gas range testing conducted at EI did not consider these tests because the controller temperature settings are always lower than the oil ignition temperature. The dry-skillet temperature is considerably higher than the ignition temperature.

- Heating to ignition of a small amount of oil (100 ml),
- Heating to ignition with a large amount of oil (500 ml), and
- Boiling of water in saucepans.

As a further test series, water was boiled in the same skillets that were used for ignition tests so that the system temperature profiles obtained were independent of pan shape. Thus, the testing revealed the influence of pan material directly[9]. The test sequence continued with boiling water in saucepans of various sizes to gain an understanding of the effect of pan shape.

Table 1. Selected Tests Planned to Determine Highest and Lowest Expected Temperatures

Test Scenarios	*Cooking Pan*	*Procedure*
Dry Cooking Pans	10-inch pan - Stainless steel - Light aluminum - Cast iron	Heat empty 10-inch skillets until steady-state temperatures are achieved. Terminate the aluminum skillet tests if the aluminum begins to sag or melt.
Oil Ignition	10-inch pan - Stainless steel - Light aluminum - Cast iron	Heat 500 ml of soybean oil on high until ignition occurs.
Oil Ignition	10-inch pan - Stainless steel - Light aluminum - Cast iron	Heat 100 ml of oil on high until ignition occurs.
Water Boil	10-inch pan - Stainless steel - Light aluminum - Cast iron	Heat water on high until temperature reaches 100C (212F); rolling boil is observed.
Boil 6 qt. of water	7 qt. Stainless steel dutch oven	Heat water on high until temperature reaches 100C (212F); rolling boil is observed.
Boil 3 qt. of water	5 qt. Lightweight aluminum saucepan	Heat water on high until temperature reaches 100C (212F); rolling boil is observed.
Boil 2 cups of water	1 qt. Stainless steel saucepan 1 qt. Aluminum saucepan	Heat water on high until temperature reaches 100C (212F); rolling boil is observed.

Data taken in these and all other tests included (1) the temperature on the pan bottom as measured by a thermocouple welded to the metal, (2) the temperature of the smooth-top surface as measured from underneath, (3) digital photographs of the setup, (4) range power consumption information to indicate "burner on" status, (5) the temperature of the bi-metal control rod, and (6) other system temperatures such as room temperature, temperature under the cooktop, etc. All data were acquired by computer using the LabVIEW software and reported in graphical and tabular form.

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[9] Work completed on the gas range system included these additional tests, and the data obtained by eliminating pan shape was invaluable for evaluating control performance.

5.1 Initial Testing with 10-Inch Skillets

The initial series of tests were conducted to measure system temperatures during specific events; boiling water in the skillets, running the range with nothing on the heating zone and operating with dry skillets.

The sensor for this test was a 0.063-inch diameter sheathed type-K thermocouple installed through the heater base and extending to the glass surface. The thermocouple was held against the glass with light spring force. The thermocouple sheath was wrapped in refractory insulation to a thickness of 0.75 inches. This was done to shield the thermocouple from direct thermal radiation. **Figure 1** shows the original-equipment heating element with the bi-metal control rod and the insulated thermocouple inserted from below. The glass top has been removed.

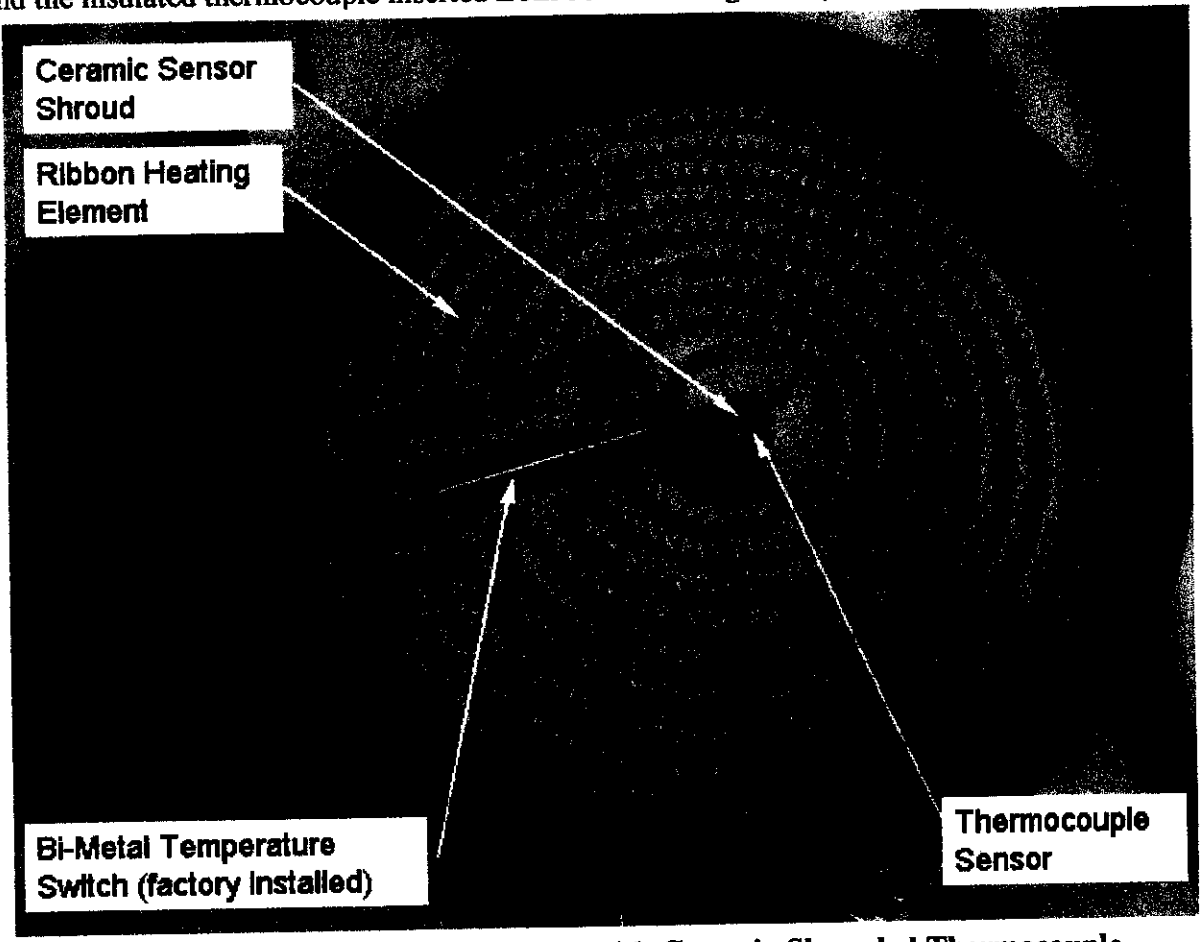

Figure 1. As-Received Heating Element with Ceramic-Shrouded Thermocouple Installed Near the Heater Center.

Figure 2 shows the temperature data collected during initial testing with the stainless steel skillet. The three temperatures shown on the graph are the glass bottom, skillet and the thermostat rod (bi-metal thermostat rod). The rod temperature gives an indication of the general temperature in the space between the heating element and the glass surface. This temperature cycles between about 1160°F and 1220°F due to the action of the high limit switch.

As expected, the lowest temperature measured on the glass occurred when the skillet was used to boil water. Since the heat sink was at a constant and relatively low temperature of 212°F, the overall system temperatures were at the lowest level expected. In the initial period of testing, as shown on the left side of the plot, the sensor temperature reached a steady-state temperature of about 1000°F, and the skillet temperature stabilized at about 220°F. This was typical of all skillet materials tested in this manner. The temperatures observed while boiling water were consistently lower than the temperatures observed for all other conditions. Thus, boiling water in the skillets, and later in the sauce pans, was a reliable method of determining the lowest expected system temperatures.

The highest system temperatures were expected to occur when a cooking pan was being heated to the point of ignition. For simplicity and speed of testing, this condition was initially simulated by heating a "dry" skillet. During tests of this nature, the skillet temperature increased significantly. In the case of the stainless steel skillet observed during this initial test, skillet temperature increased to about 800°F, but the glass bottom sensor temperature only increased by about 120°F.

After the system reached a steady-state temperature while heating a dry skillet, the skillet was removed and the system was allowed to reach steady state. This test showed that the glass temperature dropped significantly when the skillet was removed. Under these conditions, thermal radiation from the heating element passes through the glass and is absorbed in the room. The lower glass temperature is a result of eliminating the back conduction and reflected radiation from the pan. The sensor indicated a steady-state temperature of about 960°F under these conditions.

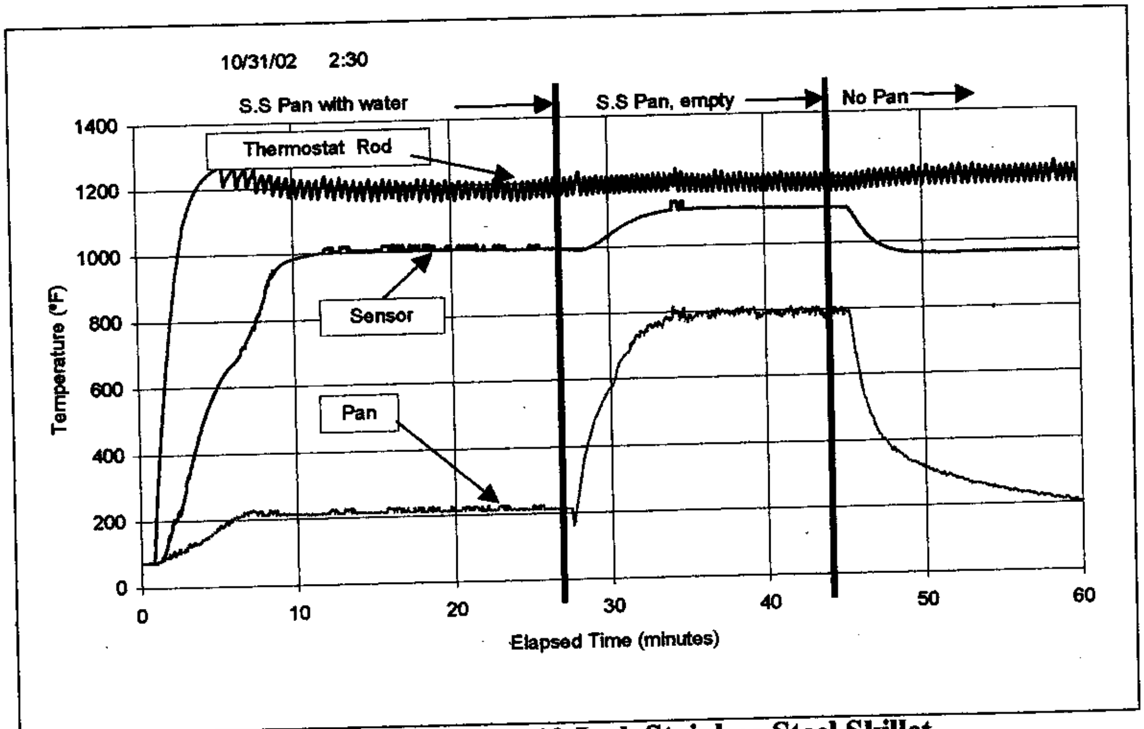

Figure 2. Baseline Test Results with a 10-Inch Stainless-Steel Skillet

This initial baseline testing demonstrated the influence that the specific thermal load had on glass temperature and temperature sensor response. Baseline testing was continued using the aluminum and cast iron skillets. These tests revealed the impact of skillet thermal properties (emissivity and conductivity) and thermal mass.

The overall thermal response of the system with the three skillet types is shown in **Figure 3**. Testing began in each case with water boiling, then the skillet was heated in a dry condition. The sensor in all of these cases was a 24-gauge type-K thermocouple. A small "divot" was ground into the underside of the glass and the thermocouple was bonded to the glass with high-temperature, thermally conductive epoxy. This was done to eliminate any variation that might have occurred with the spring contact of the thermocouple. Also, the thermocouple was insulated from the thermal environment under the glass with high-temperature insulation.

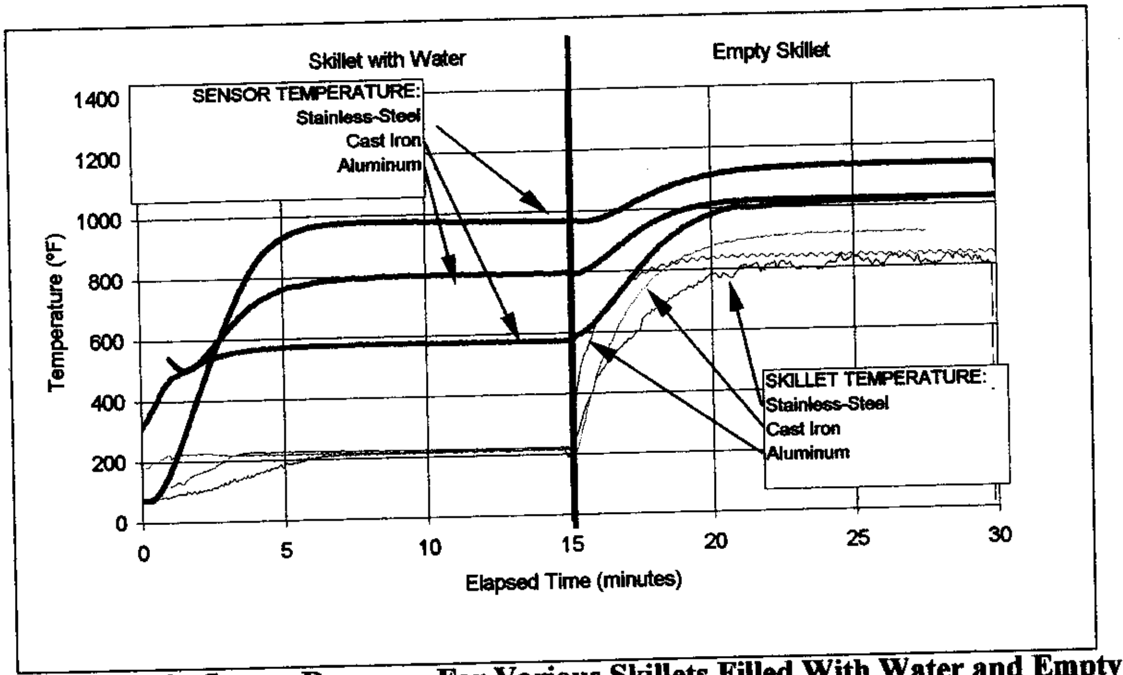

Figure 3. Sensor Response For Various Skillets Filled With Water and Empty.

Figure 3 shows that the response of the temperature sensor is quite different depending on skillet material. The sensor indicated a temperature range from about 580° to 960°F while boiling water in the skillets. This results from the emissivity differences between pan materials and is a result of reflected radiation heating the glass material. Even though the pan temperature is at a steady-state temperature close to water boiling temperature, the glass temperature varies widely. When low-emissivity skillet materials are being heated, heat flow from the heating element to the skillet is mainly by conduction from the air above the heating element through the glass. High emissivity skillets, such as cast iron, are strongly coupled with the radiation from the heating element and conduction plays a lesser role. This results in lower glass temperature.

When skillet temperature is allowed to rise to a steady-state level more indicative of pending ignition (simulated by a dry skillet), all temperatures rise as expected. Because the overall system temperatures begin to approach the limiting temperature imposed by the bi-metal temperature switch, the glass temperature begins to rise closer to that of the skillet temperature. Even under the much higher temperature conditions, radiant heat exchange plays an important role in determining glass temperature. The cast-iron skillet results in a lower glass temperature than the stainless steel skillet although the temperature spread is much less than that observed with a lower temperature heat sink. For example, in these cases, the sensor indicated an increase of about 170°F for the stainless-steel skillet, 220°F for the aluminum skillet, and 440°F for the cast-iron skillet.

An effective fire-prevention sensor system would have to allow the glass temperature to rise to the level experienced while boiling water with any cooking vessel, yet prevent the temperatures from rising to levels experienced when ignition is pending. **Figure 3** clearly indicates the conundrum faced with a system that simply monitors glass temperature. The highest temperature experienced with a high-emissivity pan when approaching ignition is very nearly the same as the glass temperature developed during a normal cooking operation when using a low-emissivity pan. There is not enough of a temperature difference between operating regions to allow a simple and reliable temperature-based system to operate.

5.2 Radiantly Coupled Sensor

Baseline testing was continued using the same skillets but with a different type of temperature sensor. This sensor was designed to be more radiantly coupled to the pan than the simple thermocouple bead.

The radiant sensor consisted of a blackened copper disk with a thermocouple brazed to it. The disk was 0.25-inch diameter and 0.1-inch thick. It was positioned under the glass within the heating element environment and was in light contact with the glass. The sensor disk was shielded from radiation and convection heat transfer by a copper tube packed with ceramic insulation. The copper tube extended below the heating element region and was covered with refractory insulation on the surface that was within the heating zone. Thus, any heat that was conducted through the outer insulation would be shunted to the cooler air below the heater via the copper tube. Any heat not shunted via the tube would be insulated from the radiation target by the additional refractory packing within the tube. By reducing overall heat transfer to the sensor element, the sensor was expected to more closely detect the cool pan temperature.

Figure 4 shows the temperature response of this radiantly shielded temperature sensor when using a stainless-steel skillet. Because the radiation from the low-emissivity stainless-steel skillet was the weakest, this skillet was used for evaluating sensor performance. The goal was to find a sensor configuration that would show a stronger response to skillet temperature and, thus, operate at a lower temperature while boiling water. If this could be accomplished, the overall spread between ignition conditions and normal cooking would be increased, and a fire-prevention system could be designed.

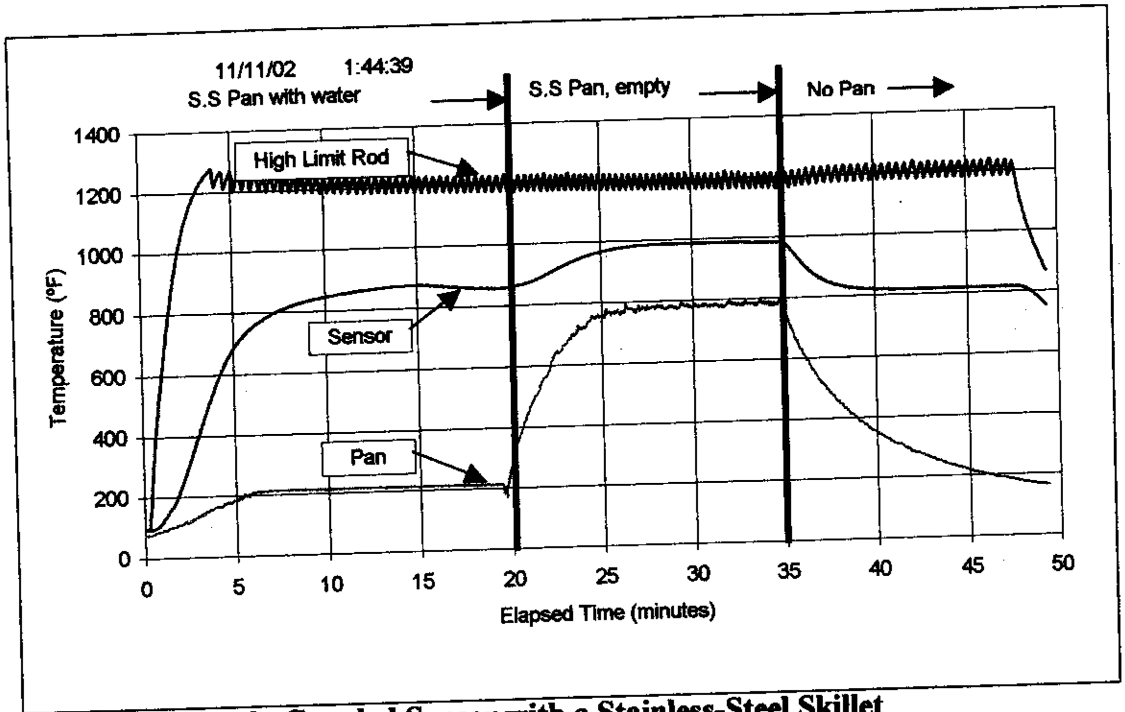

Figure 4. Radiantly Coupled Sensor with a Stainless-Steel Skillet

The spread in indicated temperature using this sensor with and without water in the skillet was about 115°F. This was quite similar to the results observed with a simple thermocouple bead in contact with the glass. However, because of the enhanced thermal protection offered by the copper shunt system, overall sensor temperature levels were approximately 240°F less than in the baseline thermocouple test. Based on this observation, a conclusion was reached that the glass at the region where temperature was being measured had to be more thermally isolated from the rest of the system.

6.0 STEP 3. RANGE MODIFICATION AND TESTING

Based on the results of preliminary baseline testing, it became clear that a successful sensor would have to be well isolated from the rest of the range system and that the glass area being sensed would also most likely have to be isolated. The following series of tests was begun in an effort to provide better thermal isolation for the under-glass temperature sensor.

6.1 Sensor Isolation Modifications

The first modification made to the sensor was to increase the center sensor insulation to reduce the direct radiation heat transfer from the heating element. The center of the heating element base was bored out to allow a much larger thermal shield (1.5-inch diameter) to be installed. A spring-loaded thermocouple was fed through the center of the insulation barrier and allowed to intimately contact the glass surface. A small divot was machined into the glass so that the thermocouple bead was closer to the pan bottom. This divot extended through half the glass thickness, or about 0.083 inches.

Tests were performed to characterize the performance of this sensor configuration. The sensor temperature response was closer to the pan temperature than the earlier baseline testing using a smaller diameter insulation system. However, results showed that the better-insulated sensor still did not provide the sufficiently large temperature overlap that would be required for a functional fire-prevention sensor.

To further isolate the sensor from the heating element radiation, the sensor was insulated with a series of concentric stainless-steel tubes acting as radiation shields (see **Figure 5**). Three tubes were installed concentrically with a small air gap between them. This configuration resulted in improved sensor response as compared to that using ceramic insulation. Results, shown in **Figure 6**, show that the sensor response was shifted downward by about 100°F over the best ceramic insulation system used. The results also show that the temperature spread between pan materials was insufficient for a reliable sensor to be designed.

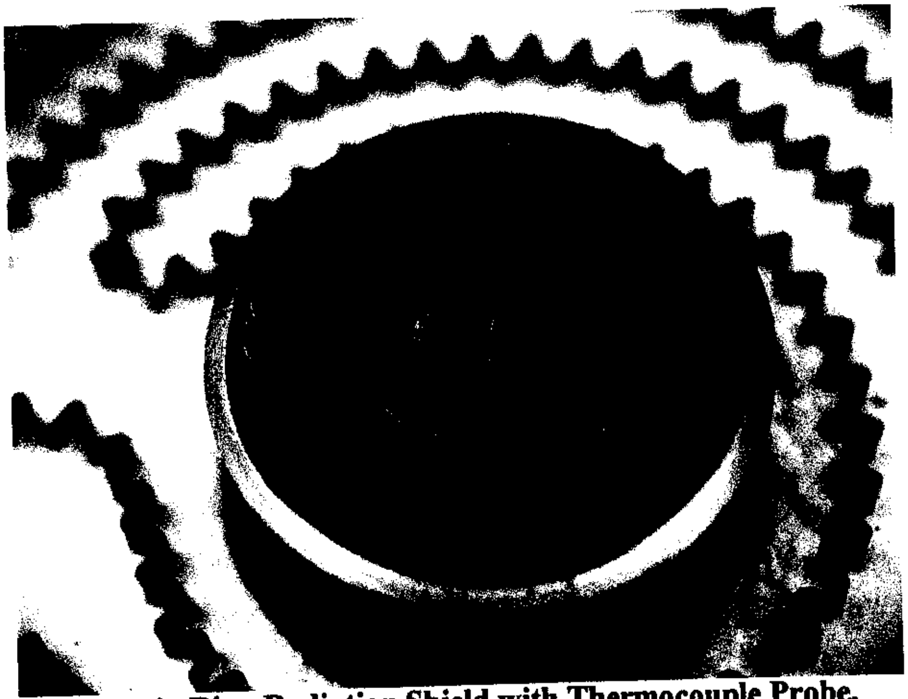

Figure 5. Concentric-Ring Radiation Shield with Thermocouple Probe.

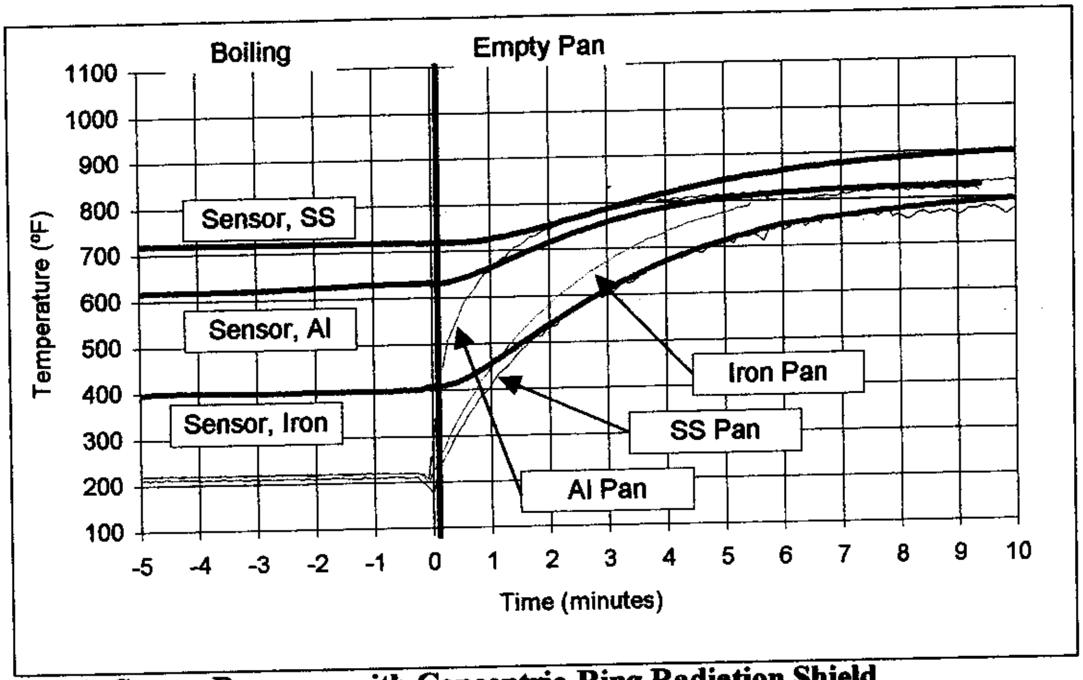

Figure 6. Sensor Response with Concentric-Ring Radiation Shield.

6.2 Oil Ignition Tests Using the Well-Isolated Glass Sensor

Oil ignition tests were performed for each of the 10-inch skillets while sensing glass temperatures with a thermocouple that was isolated from the heating effects using the concentric tube system. The skillets were filled with 100ml of soybean oil and heated until ignition occurred.

Figure 7 shows the sensor response from these tests. For all skillets, the oil-ignition temperature was about 770°F, as expected. The sensor indication at ignition was 690°F for both the cast iron and stainless steel skillets, and 740°F for the aluminum skillet. If a control system was designed with a pan-limiting temperature of 700°F, the sensor temperature set point would have to be between 610° and 630°F based on data shown in **Figure 6**. This sensor set point would effectively prevent the skillets from reaching oil-ignition temperatures, but would prevent the stainless-steel pan from reaching a temperature sufficient to boil water.

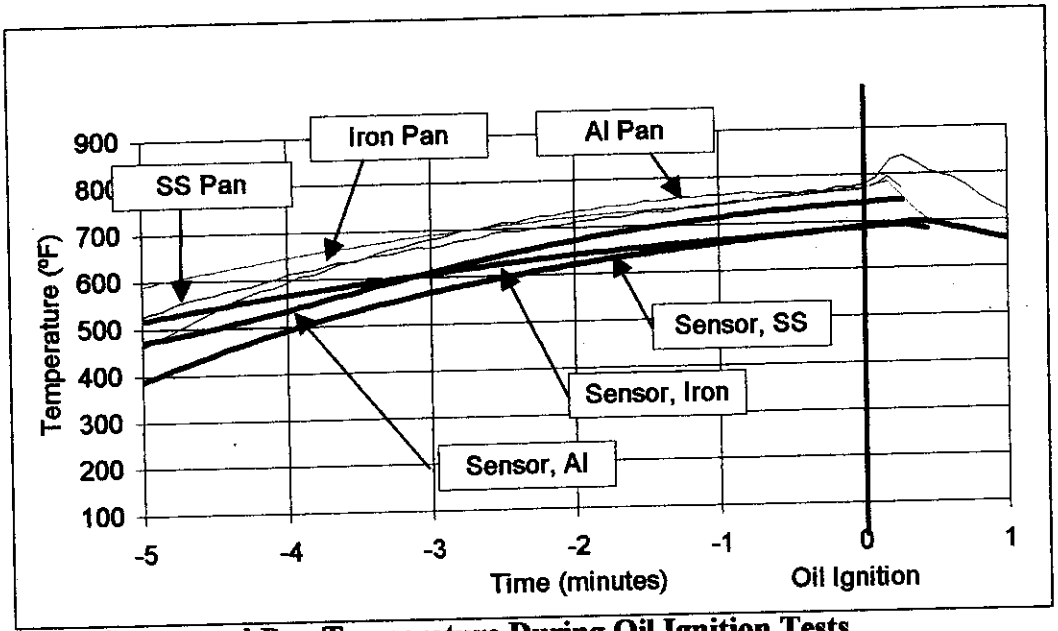

Figure 7. Sensor and Pan Temperature During Oil Ignition Tests.

Improved sensor performance was thought to be possible by further isolating the region of the glass where the temperature was measured.

6.3 Glass Thermal Isolation Modifications

There are a variety of test standards that the glass smooth-top range must pass that involve the structural integrity of the glass itself. Modifications to the glass are likely to cause the glass to fail these tests[10]. Pertinent sections of the US and Canadian standards that are involved include:

Ball drop test UL 858 (USA)
Each glass/ceramic panel is to be subjected to the impact produced by dropping a steel sphere, 2 inches (50.8 mm) in diameter and weighing 1.18 pounds (535 g), through a distance of 20.25 inches (514 mm). The test is to be conducted with the panel at room temperature.

Ball drop test CSA C22.2 - 61 (Canada)
A steel ball having a mass of 0.53 kg (50 mm in diameter) shall be dropped from a height of 355 mm onto the glass surface while it is in a cold condition. The test shall be repeated 5 times with the point of impact varying in each drop. The six drops shall be repeated on a heated surface after the elements have been energized for 15 min with switches set to high. The cooktop shall not become a hazard as specified in Clauses 4.4 and 4.25.

Pan dropping test UL 858 (USA)
Glass/ceramic panel is to be subjected to ten impacts produced by dropping a 3.96 pound (1.8 kg) weight through a distance of 6 inches (152 mm). The weight is to be shaped as a cooking utensil, is to have a flat bottom, and is to have a diameter of 4.25 to 5.125 inches (108 to 130 mm) with a corner radius of 3.125 inches (9.5

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[10] Private conversation with Christiane Baum, Applications Manager, Schott HomeTech North America

mm). Each panel is to be subjected to ten impacts, and are to be equally distributed over the panel. The weight is to be dropped so that it strikes the panel as flatly as possible. The test is to be conducted with the panel at room temperature.

Thermal Shock Test UL 858 (USA)
The cooking surface of a glass/ceramic-top appliance shall not crack or break when tested as follows: The largest surface unit is to be operated for 1/2 hour at its maximum heat setting. Then, 500 cubic centimeters of water at room temperature is to be poured over the hottest area of the cooking surface.

Modifications to the glass were carried out in light of the above drop tests for the purpose of determining what, if any, modifications would be feasible in a satisfactory control system. The goal of these modifications was to thermally isolate a portion of the glass in the cooking zone so that the temperature at the isolated section better tracked the cooking operation. It was assumed that if there was a successful and promising configuration, a glass design capable of passing the drop tests, while difficult, might be possible.

The glass used on these cook-tops has a transmissivity of about 70 to 80 percent for thermal radiation wavelengths in the range of 1000 to 2500 nm. This is the region where the heating element emits most of its radiation. There is a lower transmissivity peak (40 to 50 percent), between 3500 and 4000 nm. At all other wavelengths, the transmissivity is close to zero. Radiation from the cooking vessel is at temperatures that should result in long-wave radiation and should, thus, be able to heat the glass. By insulating the measured portion of the glass from the rest of the glass and blocking this portion from direct heating element radiation, the glass temperature in this location was expected to approach an equilibrium temperature closer to that of the pan temperature. It was believed to be critical that lateral heat conduction from other areas of the glass be prevented to maximize sensor sensitivity. It was postulated that creating a thermal break between the two glass sections would significantly reduce this conduction path.

A diamond core drill was used to cut a small circular groove in the glass surrounding the sensor location. Groove dimensions were 1-inch diameter, 0.10-inch depth, and 0.03-inch width. A close up photograph of the groove is shown in **Figure 8**. This groove effectively thinned the glass cross section along the path of lateral heat conduction. This was done so that the circular section of glass around the sensor would thermally communicate with the pan more closely and respond faster, resulting in a sensor temperature closer to the pan temperature.

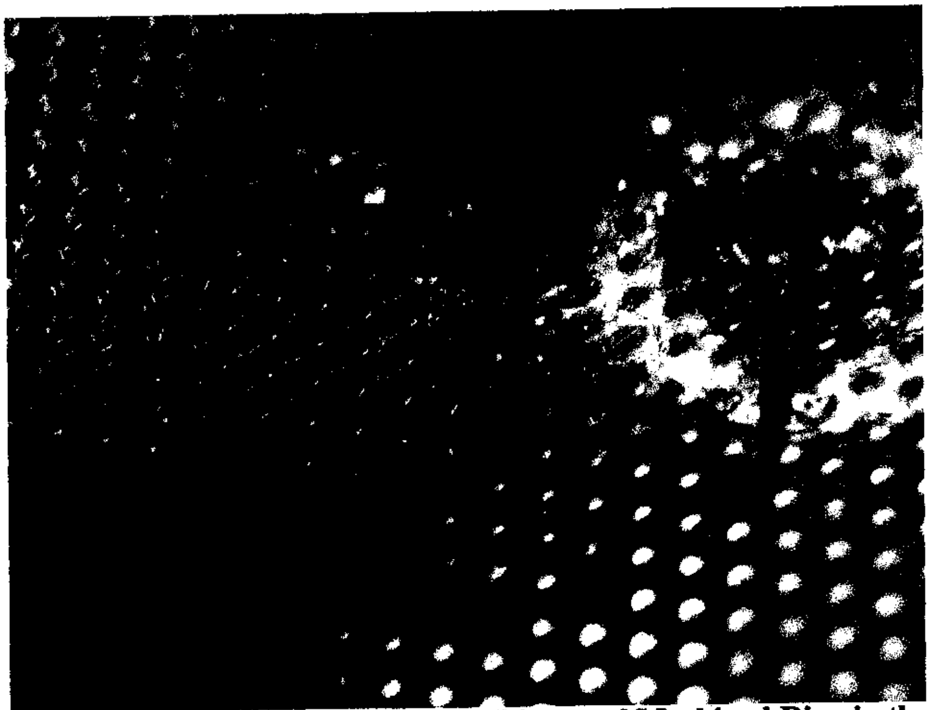

Figure 8. Photograph of the Thermocouple Divot and Machined Ring in the Underside Glass Surface. (The Divot Outside of the Ring Was Used in Other Tests.)

The results of tests based on isolating the sensor and not the glass showed that the sensor response was influenced by heating from the element itself and by heat conduction through the glass thickness. Isolating the sensor was an improvement; but during high heat-transfer situations such as boiling a large quantity of water, the heat conducted through the glass thickness skewed the sensor response.

Testing with the machined ring and concentric sensor radiation shields revealed an improvement in sensor response and temperature spread as shown in **Figure 9**. For the stainless-steel pan, the sensor temperature registered about 650°F while boiling water compared to about 700°F without the machined ring. When heating the stainless-steel skillet in the dry condition, the sensor registered a steady-state temperature that was only about 10°F lower than the actual pan temperature. During previous tests without the thermal break, the sensor temperature was 100°F higher than the actual pan surface temperature under the same heating conditions.

These results indicate that if a sensor was designed with a temperature limit of about 670°F, the system would allow the stainless-steel pan to boil water and also prevent the cast-iron pan from exceeding a temperature of about 720°F and the aluminum pan from exceeding about 700°F. This temperature setting would prevent all pans from reaching the oil-ignition temperature of about 760°F, and appeared to be a viable solution from a thermal point of view. However, the necessary modification to the glass would likely result in failure of the drop tests.

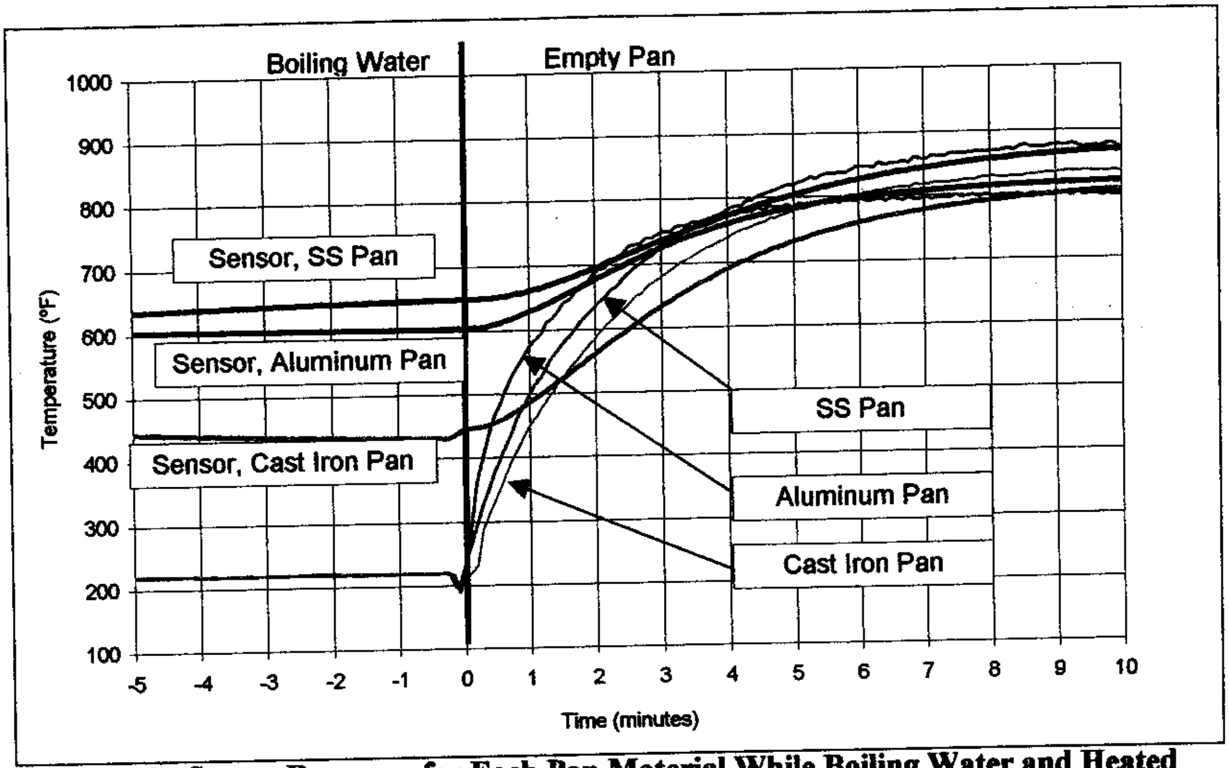

Figure 9. Sensor Response for Each Pan Material While Boiling Water and Heated While Dry with the Machined Ring and Concentric Ring Radiation Shield

6.4 Cold-Start Testing

Most of the test results discussed above involved a series of tests conducted throughout the day with initial range temperature for each test being dependent on prior test schedules and range operation. Testing to this point was focused on steady-state conditions; in effect, the range was preheated for many of the tests. Although the test results at steady state are valid regardless of initial temperature conditions, the transient response of the range glass top and pan materials are important considerations. This series of tests was designed to investigate how the range would respond to heating oil to ignition from a cold start.

Figure 10 shows a typical temperature response under cold-start conditions. In this case, the data are for a stainless-steel skillet filled with 100 ml of soybean oil. The machined isolation groove and thermocouple divot are part of the sensor system along with the concentric cylinder radiation shield.

A simplified LabVIEW control system was implemented for these and subsequent tests. The control system sensed temperature using the radiantly shielded thermocouple and had an output signal that was capable of shutting off electrical power to the range element when the temperature exceeded the set point. An adjustable dead band was included in the algorithm so that the heater would not short cycle.

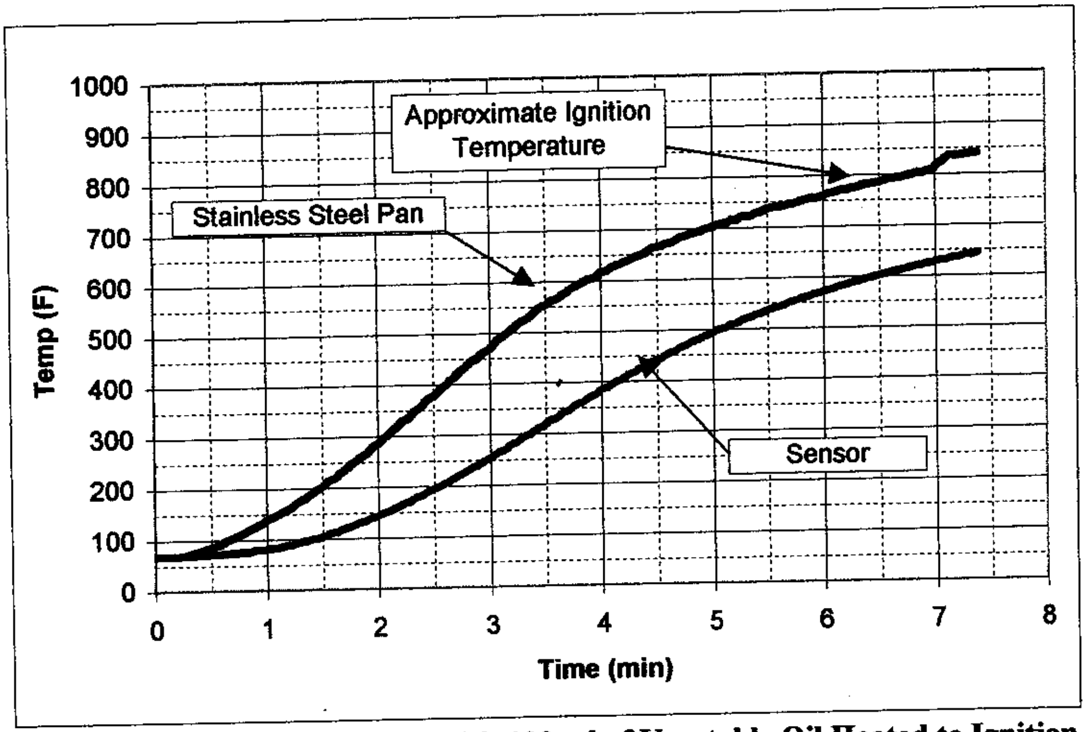

Figure 10. Stainless-Steel Skillet With 100 ml of Vegetable Oil Heated to Ignition

The plot shows that the pan and glass temperatures continuously rise until the pan reaches ignition temperature (~750°F). There was no evidence of control-circuit intervention during this test because the glass did not reach a steady-state temperature. At all times leading up to ignition, the glass temperature was considerably below the control-system set point (650°F).

These results confirmed that the glass response time is much slower than that of the pan and contents. Data gathered from all testing were analyzed, and a specific trend was detected. The analysis related the actual pan temperature to the indicated glass temperature as measured by the contact thermocouple and the first derivative of the contact thermocouple reading. This analysis led to the development of an improved control algorithm.

7.0 STEP 4. CONTROL SYSTEM IMPLEMENTATION AND DEMONSTRATION

The primary data used in developing the control system algorithm consisted of (1) duty cycle of the heating element (% "on" time), (2) readings from additional glass temperature sensors located outside the machined groove area, and (3) analyses of the data in the form of calculated first and second derivatives of the sensor temperature. Observations of the data revealed that the glass temperature rise behaved like a first-order exponential temperature rise from a constant temperature source. The governing equation for this transient response is:

$$h_r \cdot A_s \cdot (T_\infty - T) = \rho \cdot V \cdot c \cdot \frac{dT}{dt}$$ **Eq 1**

Where:

h_r = heat-transfer coefficient

A_S = the heat-transfer surface area

ρ = density of the glass

V = volume of the glass

c = the heat capacity of the glass

T_∞ = the source temperature (also the asymptotic temperature as $t \rightarrow \infty$)

The left side of the equation represents the net temperature-dependent heat flux applied to the glass and the right side represents the heat stored in the glass as a function of time. Rearranging and solving for T_∞, the equation becomes:

$$T_\infty = T + \frac{\rho \cdot V \cdot c}{h_r \cdot A_s} \cdot \frac{dT}{dt}$$ **Eq. 2**

The solution to this differential equation is:

$$\frac{T - T_i}{T_\infty - T_i} = 1 - e^{\frac{-t}{\tau}}$$ **Eq. 3**

Where the time constant τ is defined as:

$$\tau = \frac{\rho \cdot V \cdot c}{h_r \cdot A_s}$$ **Eq. 4**

Using **equation 2**, the final steady-state temperature of the glass can be predicted while the glass is warming up based on the instantaneous glass temperature and its instantaneous first derivative.

Previously, it was determined that a steady-state glass temperature of about 650°F was an acceptable control set point. The algorithm computes the steady-state final temperature and activates the control accordingly. The time constant for the glass was experimentally found to be about 7 minutes (420 seconds):

$$T_\infty = T + 420 \cdot \frac{dT}{dt} \qquad \textbf{Eq. 5}$$

The algorithm was first tested with a dry stainless-steel skillet heated to a high temperature while dry while under the control of the computer system. **Figure 11** shows these results (control set point was 650°F for this test). The data clearly show that the control algorithm can track the skillet temperature better than the sensor alone does. This result was repeatable for all pans.

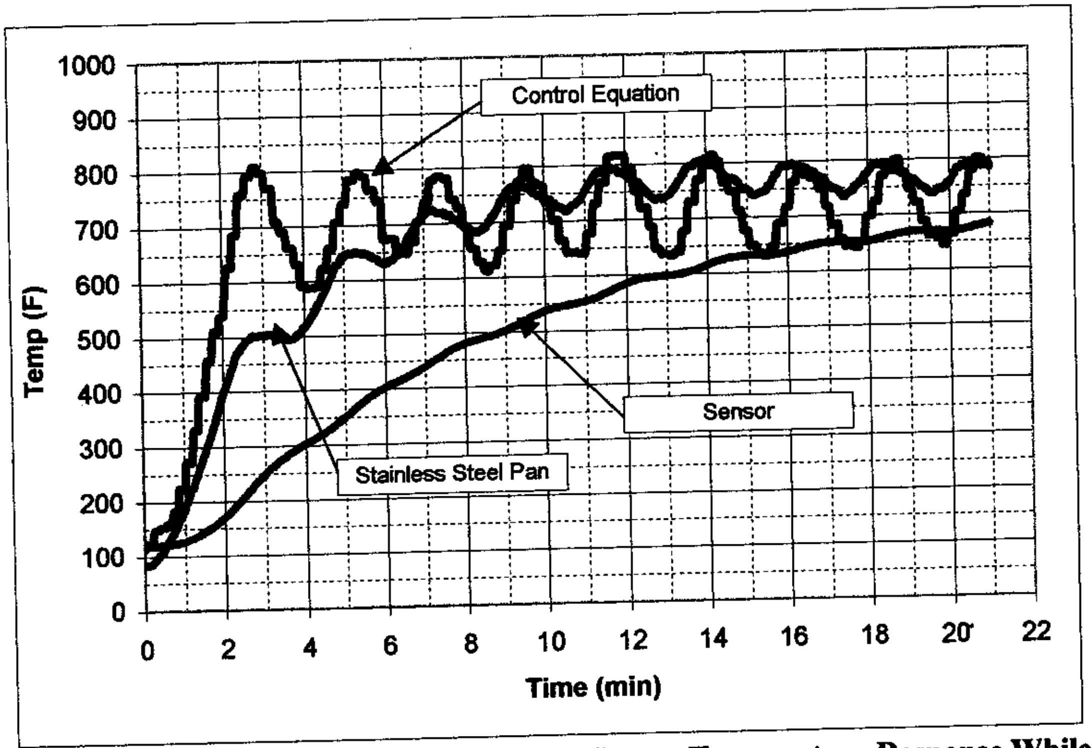

Figure 11. Empty Stainless-Steel Skillet and Sensor Temperature Response While Using the Derivative Control Equation

7.1 Control Algorithm Demonstration Under Actual Cooking Scenarios

Table 2 lists the oil ignition and cooking scenario tests that were performed with the modified control scheme. During the oil tests, no ignition occurred. All the 10-inch skillets were able to successfully boil water without interference from the controller. The 7qt. Dutch oven was able to reach and maintain a rolling boil, but the control interrupted the element at about 10 minutes, which caused an increase in boiling time of about 5 minutes. Chicken and bacon were successfully prepared in all of the skillets without interference from the control system. The smaller pots boiled water without a problem.

Table 2. Test Matrix Planned to Investigate the Effect of the Controller on the Ability of the Range to be used in Food Preparation

Test Scenarios	*Cooking Vessel*	*Procedure*	*Result*
8 oz. (227 gm) of bacon	10-inch pan - Stainless steel - Light aluminum - Cast iron	Heat on high until pan temperatures indicate no change for 15 minutes.	SS pan: No Fire, Max pan temp: 383°C (720°F) Aluminum: No Fire Max pan temp: 360°C (680°F) Cast Iron: No Fire Max pan temp: 394°C (740°F)
500 ml of soybean oil, 750 gm of chicken	- Stainless steel pan - Cast iron skillet - Heavy aluminum pan	Heat oil on high to 190C (374F). Introduce chicken to oil. Reduce heat to medium and turn chicken every 4 minutes for 20 minutes. Increase heat to high and continue until pan temperatures indicate no change for 15 minutes.	SS pan: No Fire Aluminum: No Fire Cast Iron: No Fire
Boil 6 qt. of water	7 qt. Stainless steel dutch oven	Heat water on high until temperature reaches 100C (212F); rolling boil is observed.	Rolling boil in 28 minutes (25 minutes without control)
Boil 3 qt. of water	5 qt. Lightweight aluminum saucepan	Heat water on high until temperature reaches 100C (212F); rolling boil is observed.	Rolling boil in 10 minutes, no activation of sensor control
Boil 2 cups of water	1 qt. Stainless steel saucepan 1 qt. Aluminum saucepan	Heat water on high until temperature reaches 100C (212F); rolling boil is observed.	SS pan: Not tested Aluminum pan: Rolling boil in 7 minutes, no activation of sensor control

7.2 Sensor Installation Simplification

All the tests discussed above were performed with the sensor placed in the center of the heating element and with the modified glass cooktop (divot for the thermocouple bead and a groove machined into the glass to isolate the sensor). With the success of the more sophisticated control algorithm, the possibility existed that the glass did not need these modifications.

The radiantly-shielded thermocouple was relocated to a cooktop section that was in the as-received (unmodified) condition. The thermocouple was pressed against the glass using light spring pressure. The outer diameter of the sensor assembly was 1.5-inches. A 0.125-inch thick gasket made from insulation material was placed between the end of the insulation assembly and the lower glass surface to eliminate any hot air infiltration and to allow for some minor thermal movement of the components.

Figure 12 shows the modifications to the heating element cavity. First, the factory installed temperature control rod was shifted from the center to the side. This was done so the space in the center of the element could be used for the fire-prevention sensor. Next, the insulation at the center of the element housing was bored to a diameter of about 1.5-inch. A "jelly roll" of thin stainless-steel foil (0.005-inch thick) and ceramic blanket insulation (0.1-inch thick) was inserted into a 1.5-inch diameter stainless steel tube; this assembly was installed into the center of the heating element. The sensor thermocouple was fed through the center of the jelly roll and pressed against the lower glass surface.

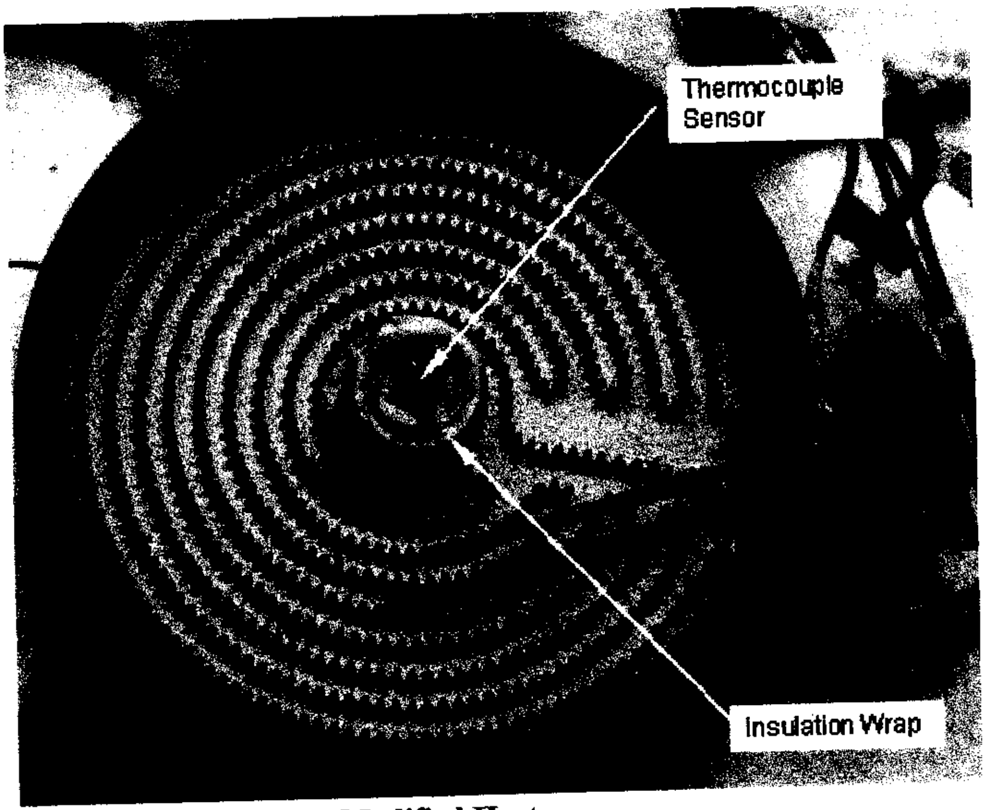

Figure 12. Photograph of the Modified Heater.

Several tests were performed to evaluate the new system dynamics and determine the control algorithm parameters. These were:

1. Cold start, empty pan test:
   - Starting from a cold surface causes the glass to heat up for the maximum amount of time, allowing the time constant of the glass to be determined.

2. Pan temperature control test:
   - The pan temperature, as measured by a thermocouple welded to the pan surface, was used to control the element cycle rate. This control was achieved using the LabVIEW software. Power to the heating element was controlled to limit the pan temperature to 750°F. The resulting sensor temperature was recorded for each pan. The lowest temperature measured for the three pans was used as the maximum sensor set point value.

3. Water boil test:
   - All three pans were used to boil water. The sensor output was monitored during

each test. The highest of the three temperatures measured was used for the minimum sensor set point value.

4. Oil ignition test:

   - 100ml of oil were placed in each of the pans and, using the parameters determined in the previous tests, the control algorithm was activated. The test was run until it was clear that the oil would not ignite, and the pan had reached a steady state temperature.

5. 6 qt. water boil test:

   - With the control algorithm active, 6 quarts of water were brought to a rolling boil in the stainless-steel stockpot. The impact of control interference on boil time was noted for comparison to boil times without the control system being functional.

Results:

After determining the glass time constant and the minimum and maximum sensor temperatures, the control system was implemented with the following parameters:

Control Algorithm Temperature Set Point	730°F
Time Constant	180 seconds
Deadband	10°F

Figure 13 shows an example of the control system managing the element power to prevent the pan from reaching the oil ignition temperature. For the first four minutes of the test, the control algorithm followed the pan temperature closely. After about four minutes, the control algorithm began limiting the heat input to the element to prevent oil ignition. After about twelve minutes, the glass had reached a steady-state temperature. Results from the cast iron and aluminum oil tests were similar to those for the stainless steel test.

As with the previous sensor configuration that involved modifying the lower glass surface, the control algorithm did interrupt the boiling of 6 quarts of water in the stainless steel stockpot. **Figure 14** shows a plot of the stockpot test with the control system active. After about 23 minutes, the controller cycled the element on and off when the pot was about 216°F. At this time, water was lightly boiling on the bottom of the pot. The pot temperature continued to rise to about 219°F and, at 31 minutes, achieved a rolling boil. The reduction of heat input during the last part of the boil test resulted in about a 5-minute increase in rolling boil time as compared to the non-controlled boil test.

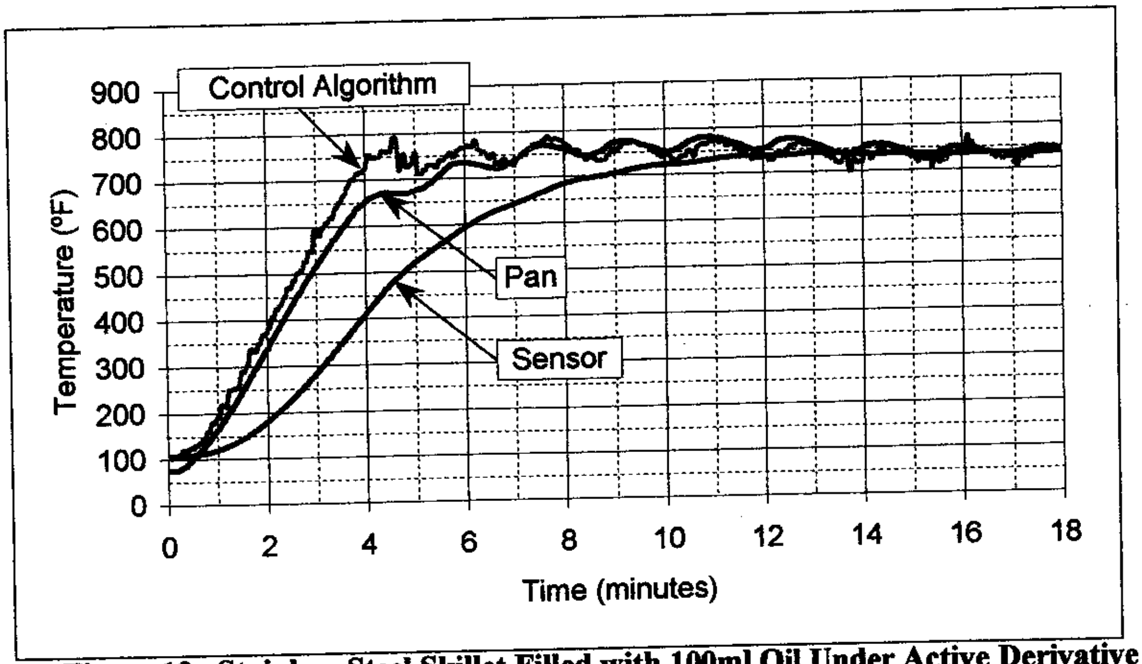

Figure 13. Stainless-Steel Skillet Filled with 100ml Oil Under Active Derivative Control.

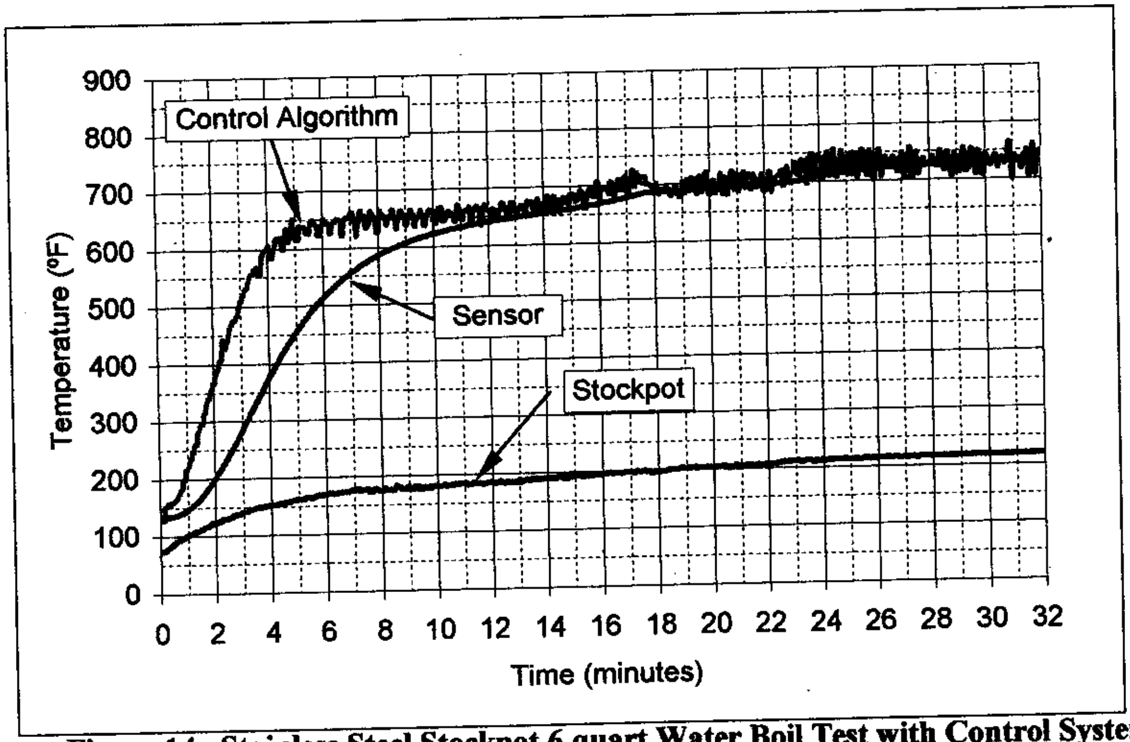

Figure 14. Stainless Steel Stockpot 6 quart Water Boil Test with Control System Active. Rolling Boil at 31 Minutes.

8.0 STEP 5. MANUFACTURING ISSUES

The work on this task was incomplete as a result of schedule limitations. Some general observations regarding manufacturing issues were made based on work performed during the program. Once more complete system design specifications have been defined, cost estimates can be developed.

The control system necessary for monitoring the range and intervening to prevent ignition is simple and should be relatively low cost. Actual computer power required is minimal owing to the simplicity of the algorithm. Any stand-alone range with a self-clean oven would likely have sufficient capacity on the already-present computer to carryout the control function.

Ranges with smooth tops, but without the on-board computer already installed, would have to be redesigned to incorporate the control computer and software.

Sensors for the temperature measurement could be thermocouples, RTDs or thermistors. Each heating zone would not require its own computer for the control function. This could be done by multiplexing. Each heater would require a solid-state relay or contactor to intervene in response to control outputs.

9.0 RECOMMENDATIONS

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

1. The control scheme, impacts on manufacturing and cost impacts should be discussed with range and control manufacturers.
2. A new formulation for the smooth-top range glass was introduced near the end of this project period. Testing under ignition and normal operating conditions should be undertaken with this new glass to verify that the algorithm is functional with the new glass.
3. Further testing and analysis should be conducted to discover any weaknesses in the control algorithm and to fine tune it for robust performance with a variety of range designs.