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CONSUMER PRODUCT SAFETY COMMISSION
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CPSC/OFFICE OF
THE SECRETARY

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Memorandum

Date: May 22, 2000

TO : The Commission
Sadye E. Dunn, Secretary

THROUGH: Pamela Gilbert, Executive Director PG
Michael S. Solender, General Counsel MSS

FROM : Ronald L. Medford, Assistant Executive Director, RLM
Office of Hazard Identification and Reduction
Andrew M. Trotta, Electrical Engineer, Division of Electrical Engineering AMT

SUBJECT : Contractor Report on Gas Range Control System Development and Testing

Attached is a contractor report on the development and testing of a gas range burner control system. This report was completed by Energy International, Inc. (EI) in support of CPSC staff work to address cooking fires. The Energy International experimental burner control system successfully prevented ignition of cooking materials with minimal impact on normal cooking under the test conditions specified in the contract.

After some final work on its system, EI plans to ship the gas range with the experimental control system to the CPSC Laboratory. CPSC staff will repeat some of the tests to verify that the range still functions as expected and will then send the range to the Good Housekeeping Institute (GHI) for third party evaluation under a wider range of normal cooking scenarios.

This work, in conjunction with a similar effort on an electric range equipped with an experimental burner control system developed by CPSC Laboratory staff, demonstrates potential methods to modify ranges to prevent fires caused by ignition of cooking materials.

Attachment

NOTE: This document has not been reviewed or accepted by the Commission.
Initial ______ **Date** 5/22/00

CPSA 6 (b)(1) Cleared
5/23/00
✓ No Mfrs/Prvtlblrs or
Products Identified
___ Excepted by ______
___ Firms Notified,

Energy International, Inc. Report No. 00-9615-AR9615001

DEVELOPMENT OF A CONTROL SYSTEM FOR PREVENTING FOOD IGNITION ON GAS RANGES

April 2000

Prepared for:

U.S. Consumer Product Safety Commission

Prepared by:

ENERGY INTERNATIONAL, INC.

CPSA 6 (b)(1) Cleared 5/23/00
✓ No Mfrs/PrvtLblrs or Products Identified
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Energy International, Inc. Report No. 00-9615-AR9615001

DEVELOPMENT OF A CONTROL SYSTEM FOR PREVENTING FOOD IGNITION ON GAS RANGES

EXECUTIVE SUMMARY

This project was focused on determining if a surface-contact sensor would be capable of sensing pending fires on gas range tops and demonstrating the technology in the laboratory. Results of the work showed conclusively that a surface-contact sensor touching the bottom of the cooking vessel would indeed be capable of monitoring the pan temperature and preventing fires. In addition, testing in the project showed that the sensor did not interfere with normal cooking operations.

A secondary output of the work was the design and demonstration of a radiantly coupled sensor that should be capable of preventing fires on electric and gas ranges without the reliability risks of an exposed sensor. Moreover, this sensor is compatible with modern gas or electric ranges.

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DEVELOPMENT OF A CONTROL SYSTEM FOR PREVENTING FOOD IGNITION ON GAS RANGES

1. INTRODUCTION

Ranges and ovens contribute to a major portion of fires and fire injuries within CPSC's jurisdiction. According to a report prepared by CPSC staff[1], 86,000 fires involving ranges were attended annually by fire departments from 1994 to 1996. Deaths totaled 245 along with 4,160 injuries and a loss of $292.9 million in property damage. Moreover, the report presents data that clearly show that unattended operation is a common factor in most of the fires.

A four-phase study has recently been completed through a joint-effort between CPSC and NIST[2]. 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. The team 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 scenarios 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.

Work by the CPCS and NIST was accomplished on electric cook tops. 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 this project at Energy International, Inc. to demonstrate the technology on gas ranges.

1.1 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 companies like Robertshaw and Harper-Wyman developed contact probes, usually only connected to one

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[1] 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.

[2] "Study of Technology for Detecting Pre-Ignition Conditions of Cooking-Related Fires Associated with Electric and Gas Ranges and Cooktops, Final Report", Erik L. Johnson, NISTIR 5950, January 1998.

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 poor however because the system was slow to reach cooking temperature and had the requirement for special pans. This was a marketing disadvantage. The temperature sensor was below the surface and out of reach for the consumer. This feature yielded a robust system having the advantage of not being easily damaged.

The other control system, sometimes called "The Burner with a Brain," 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 the bottom of the pan surface. This feature provided consistent sensor-to-pan contact with uneven pans.

The Burner with a Brain 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 meaningful, it was expected 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.

2. OBJECTIVE

The objective of this project was to test and if necessary develop a prototype household gas range burner control system that demonstrated a capability of shutting off or reducing the input of the burner in the event of a pending flare-up or fire without interfering with normal cooking operations.

3. APPROACH

The overall concept for a range controller was to sense pending ignition in the cooking vessel by monitoring its temperature. As this temperature approached a point high enough to ignite the food, the control system reduced heat input sufficiently to maintain the temperature below the ignition point. The critical information needed to develop and demonstrate a control system capable of this was:

- Ignition temperature for cooking oil,
- Interaction of the pan with the burner (impact of the pan material and size on control response), and
- Amount of heat reduction necessary to prevent reaching ignition temperature.

The approach taken to develop this information and demonstrate a control system consisted of four steps:

- Modify a conventional gas range so that it could be controlled with a computer-based data acquisition control system.
- Obtain temperature data for a variety of cooking vessels (saucepans and skillets) of differing sizes and materials while boiling water and heating oil to ignition.
- Create an acquisition and control algorithm that monitored pan temperatures and reduced gas flow to prevent ignition.
- Verify that the controller allowed normal cooking operations to occur without interference (normal cooking operations included boiling water and frying meats).

This section details the individual aspects of the overall approach. Subsequent sections describe the results of the testing and evaluation work; the strategy employed to develop the control system; and the performance of the control system.

There are two practical temperature limits that a cooking vessel experiences during all cooking scenarios of interest. The lower limit is defined by boiling water and the upper limit is defined by the ignition point of oil. Water boiling on a surface has very high thermal contact with the surface, and once water begins to boil, its temperature remains constant. This high heat transfer effectiveness and constant temperature results in a pan temperature close to the water boiling temperature.

With oil, there is a high heat-transfer effectiveness with the pan surface, but less than the water boiling case. When heated to ignition its temperature continues to rise. This is because the boiling temperature of cooking oil is at or above the ignition point. Consequently, a pan filled with oil and heated to ignition will rise in temperature until the oil ignites. The only factor that acts to limit the temperature rise is an insufficient amount of heat to reach the ignition temperature. This is the functional aspect of the range fire prevention control.

3.1 Gas Range Modification

Conventional gas ranges have manual control valves for each burner. The cook adjusts heat input by adjusting gas flow to the burner. There is no mechanism for automatically controlling the gas flow since there are no electric valves on conventional range tops. Consequently, the first task was to modify a conventional range with an electric valve system making it possible for a controller to manage the gas flow.

The control strategy for the gas range had to be different than the strategy employed for the electric range in earlier work. Cycling power to the electric elements through a solid-state relay controlled the electric range used by CPSC. The relay was controlled by a computer with an on-time to off-time ratio designed to produce any desired partial power setting. Gas ranges require an ignition system to light the burner. A control system designed to cycle the burner from full on to off requires that the ignition system operate with every burner-on event. Throttling the burner system to a low enough point to prevent reaching the ignition point simplifies burner operation.

Ideally, in the final control configuration, each burner would be equipped with a multi-stage valve that could be electronically controlled from full flow down to some minimum flow or even to an off position if necessary. As a practical matter, the control system developed in this project was intended to prevent fires on the range top, and not to provide fine flow control. It is not necessary to have a multi-stage valve on each burner. Instead, each burner could be supplied with gas from two sources such that the design maximum input is achieved when both sources are operating and some reduced input results from only one source operating.

An example of this type of control valving is shown in **Figure 3-1**. The primary gas supply to the range top burners is controlled with an orifice such that only a portion of the total flow can be supplied by the primary supply. A secondary electric gas valve can be installed in the location shown. Individual electric valves also supply gas to each burner. When the flow from this second valve is combined with the main gas flow, the total flow is at the design high rate for the range. This overall flow then enters the manual control valve that the operator uses to control the burner input.

When the manual valve is set on "high" and the range is left unattended, a fire could ensue. In that event, the control system would first close the individual electric gas valve for the problem burner. This would lower the heat input to a lower value and hopefully stop the ignition from occurring. If this action were insufficient to prevent the pan temperature from rising too high, the secondary valve would then close stopping all gas flow to the range top and preventing a fire.

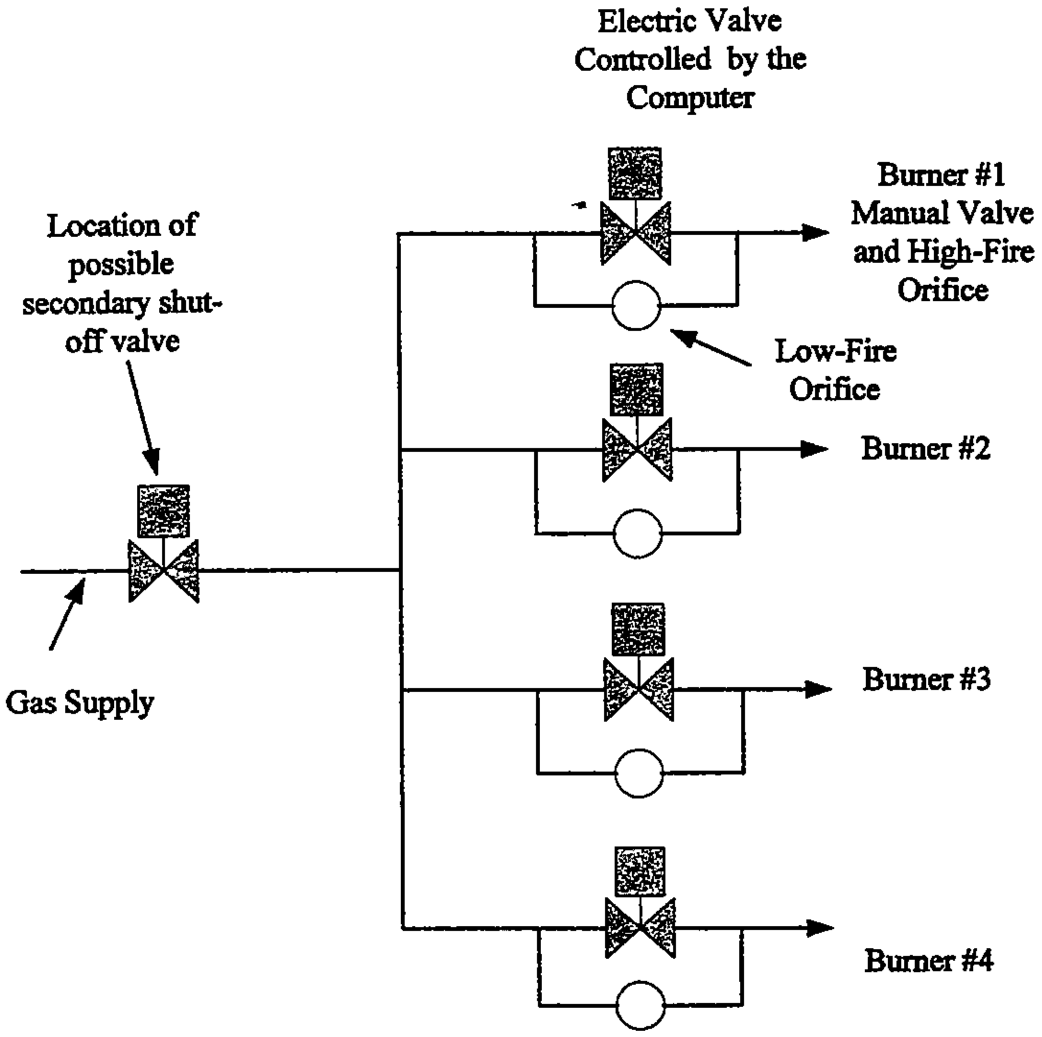

Figure 3-1. Control Piping for the Range-Fire Control System

The valve system used in this project consisted of two valves with adjustable control orifices operating in parallel, but only one burner was modified for testing. Using individual valves and adjustable control orifices enabled the system to be customized according to test results until a satisfactory low-flow condition was determined. The control software shut off the individual burner valve to reduce gas flow to approximately 40 percent of maximum when conditions that could lead to ignition were sensed. The software also had a provision to shut off the secondary valve in the event the pan temperature continued to rise. Throughout the testing, it was never necessary to actuate the second valve. Thus in the final control system, it would only be necessary to provide one electric valve for each top burner.

3.2 Test Matrix

A three-stage laboratory program was adopted to develop the data necessary to program the controller. The stages in the testing program were:

Stage 1: Tests were conducted to determine the lower and upper temperature limits, i.e., the thermal envelope, for the control system. The control temperature limits were established from these data.

Stage 2: Using the control temperatures from Stage 1, additional tests were conducted to investigate the effectiveness of the control system in controlling fires on the range top.

Stage 3: Finally, with the control system in use, tests were conducted to determine the effect, if any, of the control system on the ability of the range to prepare food.

The test matrix conducted in Stage 1 was a duplicate of tests conducted by CPSC on electric ranges in most cases. Energy International extended the test matrix to include boiling water in the skillets for direct comparison with temperatures achieved by burning oil in the same skillet. At least two tests and sometimes up to four tests were done for each condition. The Stage 1 tests, shown in **Table 3-1**, were designed to investigate the impact of pan material (in the case of skillets) and pan size (in the case of the saucepans) on sensor output.

Skillets measuring 10-inches in diameter were used in the tests. Four different materials of construction were involved; stainless steel, cast iron, aluminum, and ceramic. In addition, three types of pans usually used for boiling water were included in the tests. These were a 7-quart stainless steel dutch oven or double boiler, 5-quart aluminum saucepan, and a 1-quart stainless steel saucepan. Tests in the skillets involved heating oil to ignition and boiling water. The oil ignition tests were conducted with a plentiful oil supply (500 ml) as might be used for frying potatoes for example, and a limited supply (100-ml) as might be used for frying or browning meats. The saucepan tests were done with boiling water only.

Table 3-1. Selected Tests Conducted to Determine Highest and Lowest Expected Temperatures

Test Scenarios	Cooking Vessel	Procedure
Oil Ignition	10-inch pan - Stainless steel - Ceramic - Light aluminum - Cast iron	Heat 500 ml of oil on high until ignition occurs.
Oil Ignition	10-inch pan - Stainless steel - Ceramic - Light aluminum - Cast iron	Heat 100 ml of oil on high until ignition occurs.
Water Boil	10-inch pan - Stainless steel - Ceramic - 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.

Stage 2 testing also duplicated CPSC tests, and were undertaken to show that the control system, once developed, was capable of limiting the temperature to a safe value below the ignition point. These tests were run in duplicate for repeatability. Specific tests in the series are shown in **Table 3-2.**

Table 3-2. Selected Tests Conducted to Investigate the Ability of the Controller to Prevent Range Fires

Test Scenarios	*Cooking Vessel*	*Procedure*
100 ml of soybean oil	10-inch pan - Stainless steel - Ceramic - Light aluminum - Cast iron	Heat on high until pan temperatures indicate no change for 15 minutes.
500 ml of soybean oil	10-inch pan - Stainless steel - Ceramic - Light aluminum - Cast iron	Heat on high until pan temperatures indicate no change for 15 minutes

The third series of tests, Stage 3, were done to demonstrate that the range burner, when under the control of the flame-prevention system, would be capable of preparing foods in a normal manner without control intervention. Food preparation consisted of frying chicken and bacon. Water boiling was done in the saucepans to demonstrate that the control system would not interfere with this operation either. Specific tests conducted in this series are shown in **Table 3-3.**

Table 3-3. Test Matrix Conducted to Investigate the Effect of the Controller on the Ability of the Range to be used in Food Preparation

Test Scenarios	*Cooking Vessel*	*Procedure*
8 oz. (227 gm) of bacon	10-inch pan - Stainless steel - Ceramic - Light aluminum - Cast iron	Heat on high until pan temperatures indicate no change for 15 minutes.
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.
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.

3.3 Test Set Up

Temperatures at ten locations were monitored continuously during the tests. **Table 3-4** describes the location, number, and purpose of the thermocouples used in the tests.

Table 3-4. Thermocouple Locations and Test Purpose

Thermocouple Location	Number	Purpose
Surface Contact Probe	1	Intended as the primary control thermocouple, used to indicate pan temperature.
Pan Surface	4	Welded to the actual cooking vessel, these thermocouples were used to measure the actual pan temperature. Only the metal pans had thermocouples welded to them.
Pan Contents	1	A thermocouple placed in the fluid being heated indicated the actual content temperature.
Above the Pan	1	This thermocouple was used to sense flame.
Burner Head	1	Used to monitor the temperature of the burner head below the pan.
Spill Pan	1	Monitored the temperature of the sheet metal in the spill area around the burner head.
Grate Finger	1	Attached to the end of the grate, this thermocouple monitored the grate-finger temperature.

Figure 3-2 schematically illustrates the thermocouple locations used in the tests. **Figure 3-2a** illustrates the underside of a metal skillet with 4 thermocouples welded directly to the bottom. Three of the thermocouples were located at a 2-inch radius from the center, and the fourth was mounted at the pan center. The point at which the surface-contact probe contacted the underside of a pan is also indicated. **Figure 3-2b** illustrates the top view of the burner cap where the contact probe and the burner cap thermocouples were mounted, while **Figure 3-2c** shows a side view of the burner with a pan in place. This view shows the remaining thermocouples, including the manner in which the contact probe contacted the underside of the cooking vessel.

3.3 Control Software and Data Collection

In parallel with the experimental effort outlined in Section 3.2, software for the controller was developed in the G (graphical) programming language of LabVIEW[3]. The software written for the project was based on using a single thermocouple to control range burner operation. Usually the control thermocouple was the pan probe. In some tests, alternate thermocouples were used as control. This software also collected data from all input sources and recorded it onto the computer disc for later analysis.

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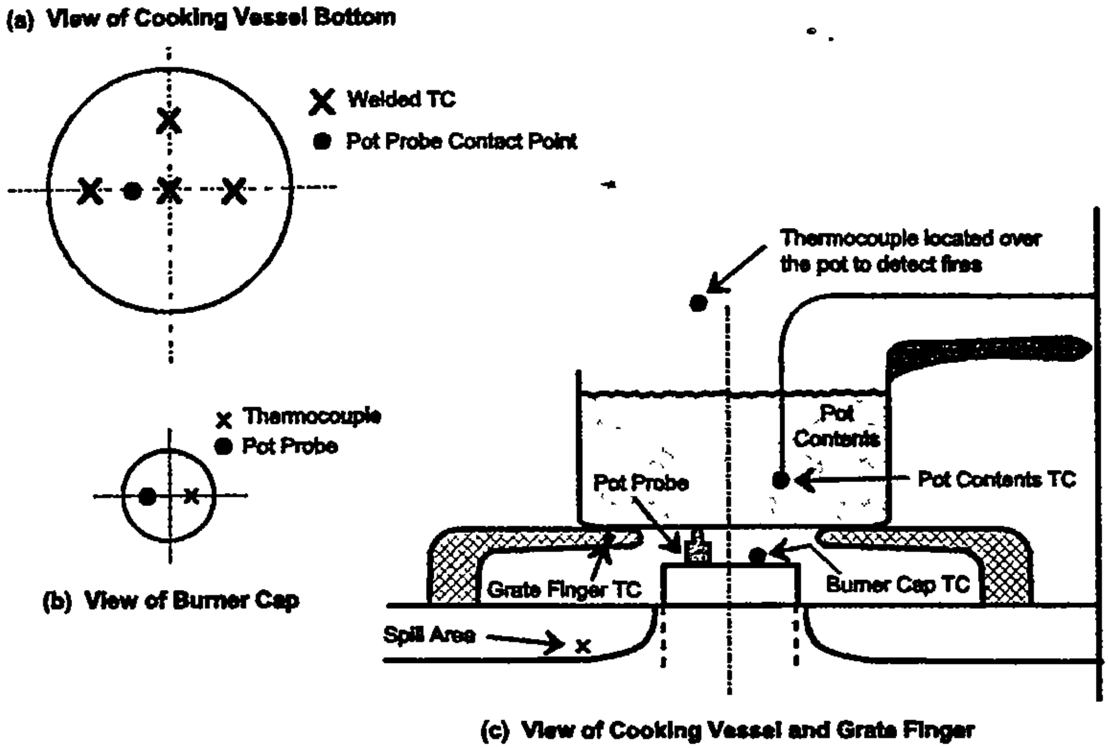
[3] LabVIEW v5.1 was used for the project. The software provider is National Instruments, Austin, Texas.


(a) View of Cooking Vessel Bottom

(b) View of Burner Cap

(c) View of Cooking Vessel and Grate Finger

Figure 3.2 Schematic Layout of Thermocouples Used to Develop the Control System

The control system permitted a maximum and minimum temperature to be specified for the test. The algorithm monitored the control temperature once per second. The burner was ignited and the manual gas valve was set to the maximum input. The pan began to heat as the control software monitored the control temperature. If this temperature was below the minimum, a digital signal was sent from the software (through the PC) to the primary electric gas valve to remain open and maintain the burner on full output. If the control temperature exceeded the lower limit, a digital signal was sent to the range valve to reduce the burner output to low. If the control temperature exceeded the upper limit, a digital signal was sent to the secondary and primary valves to shut the burner off completely and terminate the test. This function was included as an emergency shut off in the event of a run-away situation. This never occurred during testing.

The routine is capable of switching burners from high to low when approaching ignition temperature, then back to high when the control thermocouple reading falls below the lower limit. With the appropriate control temperature setting, the software is capable of producing a steady-state temperature below ignition, and one that does not produce excessive overshoot or undershoot.

4. TECHNICAL DISCUSSION

The US CPSC and NIST conducted a four-phase test to develop a control system for an electric range that prevented ignition of food in the event of unattended cooking. A major conclusion derived from this study was that a cooking vessel contact probe sufficiently tracked the temperature of the vessel and gave reliable feedback to a control system, which in turn prevented ignition of the food. Under the current project, EI/Cleveland investigated the development of similar technology for a gas range. The central issue in developing the technology for a gas range was the difference between the thermal behavior of the electric and gas systems. Gas burners provide rapid heating to the cooking vessel when on and almost no heat when first shut off. Electric elements have a slower rise time to full heat and a more gradual fall-off in heat input when shut off.

Because of the large number of tests conducted in the overall program, only typical results will be presented and discussed in the body of the report. Complete results are included in **Appendix A.**

4.1 Stage 1 – Establishing the Control System Thermal Envelope

4.1.1 General Considerations

The initial tests were conducted to determine the thermal envelope or range of temperatures expected in normal cooking operations and during conditions leading to ignition of the oil. The plan for the eventual control scheme was to base its operation on the temperature monitored by a contact thermocouple in contact with the pan bottom. It was important to know what the highest possible temperature at this 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 selected high enough such that it was above temperatures seen in normal operation while far enough below the critical ignition temperature to allow for minor measurement error and thermal inertia.

There were a few uncertainties associated with the testing that had minor effects on the quality and interpretation of the data. In addition to the normal uncertainties associated with instrumentation error, the test uncertainties included:

- Differing placement of the cooking vessel, from one test to another, on the grate. There was no system in place to guarantee exact placement of the cooking vessel on the grate so that these differences in placement resulted. This affected the location of the surface-contact probe relative to the center of the vessel.

- Differences in location of the temperature sensor used to measure the pan contents. Significant difficulty was experienced in obtaining reproducible pan content temperatures when heating small quantities of oil (100 ml), and when cooking the bacon and chicken.

While these uncertainties are less than ideal during the data analysis, they actually reflect the reality of everyday cooking in a typical household.

4.1.2 Evaluation of the Surface-Contact Probe

CPSC and NIST demonstrated that a surface-contact probe could track the temperature of the cooking vessels and their contents under a variety of cooking scenarios on an electric range. The objective of the current project was to determine if a similar probe could track the temperature of the pan contents when using a gas range.

Data collected from Stage 1 tests were used to determine the ability of the surface-contact probe to represent actual pan temperature. This was done by comparing the readings from the contact probe to the readings from thermocouples welded to the pan bottom. Two general scenarios were considered; boiling water and heating oil to ignition. Moreover, the tests also considered variations in pan shape (skillet, saucepan) and material.

Figure 4-1 shows the general relationship between the surface-contact probe and the pan bottom temperature for the case of boiling water. In all cases examined, the welded thermocouples indicated a temperature closely coupled to the boiling temperature as would be expected. The contact probe always indicated a much higher temperature than the water or the actual pan bottom. This was because the surrounding combustion gas temperature influenced the contact probe more than it was by the pan temperature.

Considering a simple thermal model of the probe, pan, and surroundings, the thermocouple in the contact probe is heated primarily by the combustion gases and the pan bottom. The relationship between the thermal contact resistance (probe to pan), the heat transfer coefficient between the probe and surrounding combustion gases, and the areas of the contact region and probe sections in contact with the gases determines the measured temperature. The probe contact resistance and heat transfer coefficients between the probe sheath and combustion gases were unknown. Assuming that these coefficients are roughly equal, the heat transfer between the probe and its surroundings is a simple ratio of the areas. In this case, the probe area exposed to combustion gases was many times larger than the actual probe-to-pan area. Consequently, the probe would be expected to register a temperature closer to the gas temperature than the pan surface temperature. This was confirmed by inserting a separate temperature probe directly into the flame in the vicinity of the contact probe.

For the water-boiling tests conducted in this series, the contact probe indicated an average temperature of about 478°F. The actual pan temperature as indicated by the welded thermocouples was about 250-260°F. The offset or difference between these readings was approximately 228°F. The temperature indicated by the contact probe was high, but consistent, indicating that the contact probe could reliably track the actual pan temperature even in light of the large offset.

In the case of heating the oil to ignition the contact probe and welded thermocouples registered roughly equivalent temperatures. A typical plot is shown in **Figure 4-2**. This figure shows that the contact probe tracks the actual pan temperature very closely. The contact probe data demonstrated that this sensor could be effectively used as an indicator of pending ignition. The temperature indicated by the probe when approaching ignition was considerably higher than the temperature indicated during normal cooking. Such a wide spread should make it possible to

Figure 4-1 Typical Water-Boiling Test Data

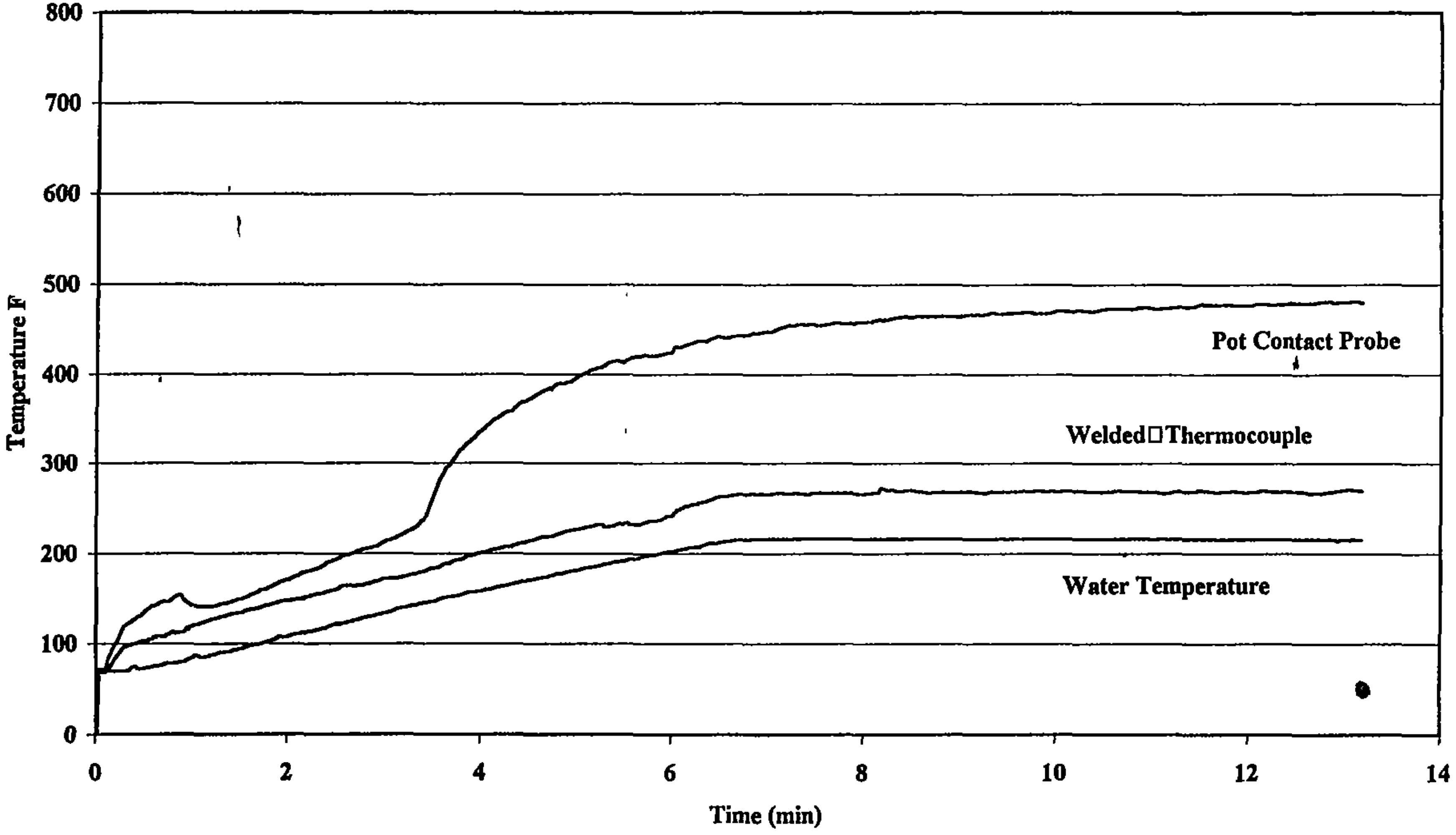
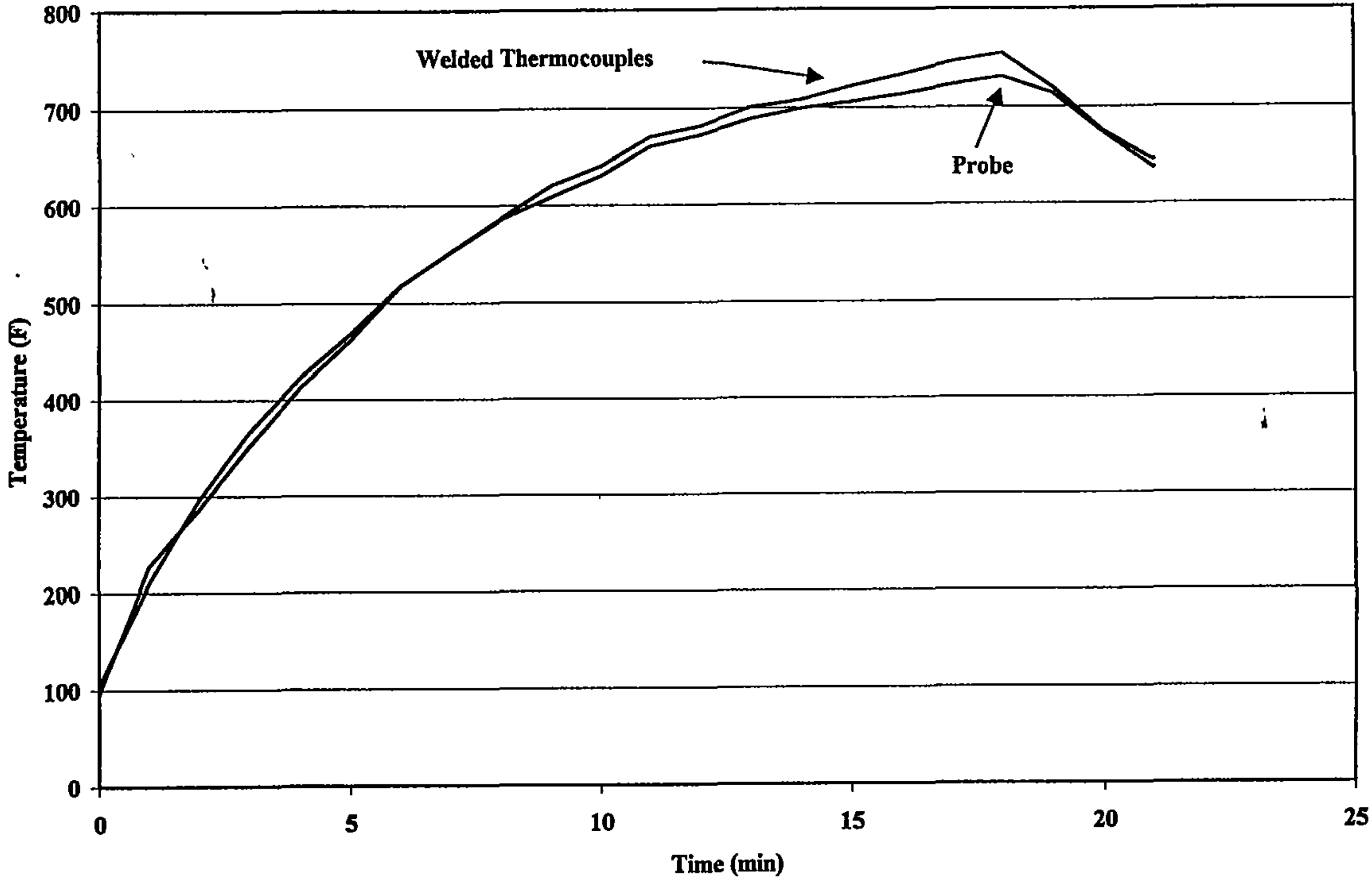


Figure 4-2 Typical Oil-Ignition Test Data



select a single temperature below the ignition point yet far enough above the normal temperature readings to prevent fires.

An effective control system has to be set to react to a sensor temperature that is below the critical temperature for ignition yet above the temperature expected in normal cooking. Contact probe output for several water boiling and oil ignition tests is shown in **Figure 4-3**. These data include tests in the 10-inch skillets and the saucepans. The probe readings for the ignition tests are clearly higher than the readings from the water boiling tests. There is considerable scatter in the readings as would be expected from the variations in pan materials and sizes represented by the data in **Figure 4-3**. The important point is that there is a range of temperatures from a low of 550°F to a high of about 650°F that was never experienced by the probe. This is the temperature range for the control that was selected.

4.2 Development of the Control Algorithm

After collecting data on the key system temperatures during water boil and oil ignition with different cooking vessels, these data were analyzed to determine where to set the control value so that fires would be prevented without interfering with normal cooking. As part of the data analysis, all tests were grouped into two categories - water boiling tests and oil ignition tests. (See **Table 4-1.**)

The results discussed previously indicated that the contact probe could be used to track the temperature of the cooking vessel bottom, which in turn automatically tracks the temperature of the vessel contents. In the case of boiling water, the contact probe reading averaged 478°F with a standard deviation about this average of 11 percent.

Table 4-1. Contact-Probe Data from all Water Boiling and Oil Ignition Tests.

Quantity	Boiling Water (F)	Igniting Oil (F)
Maximum temperature	550	750
Minimum temperature	420	610
Average temperature	478	688
Standard deviation (from average)	53	47
% deviation	11	7

* Water boiling data were taken after reaching steady state

** Oil ignition data were taken just prior to ignition

Clearly, in order for the software controller not to interfere with normal cooking, the lower limit of the thermal envelope should be above 478°F. In the case of heating oil to ignition, the average contact-probe temperature reading (at the point of oil ignition) was 688°F, with a standard deviation about this average of 7 percent[4]. The range of temperatures expected to occur

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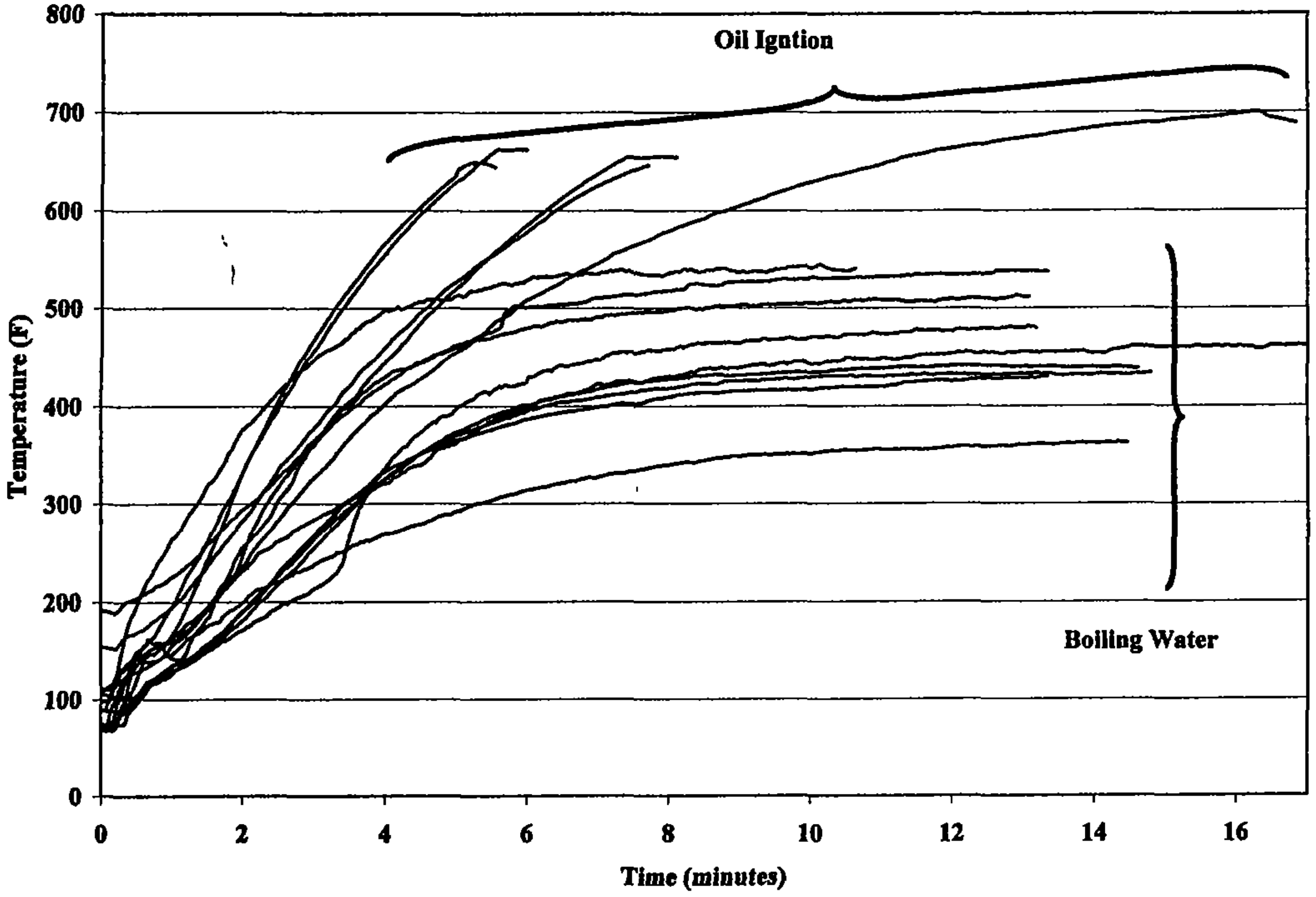
[4] The low standard deviations for the contact probe temperature reading in the case of boiling water and heating oil to ignition provided a level of confidences in the averages.

Figure 4-3. Comparison of Pot Contact-Probe Temperatures when Boiling Water and when Heating Oil to Ignition Using Various Cooking Vessels



when performing normal cooking operations or up to ignition is in the range of 478°F to 688°F. Thus, the operating envelope for the control system is in this range.

Given the establishment of the thermal envelope, the next task was to choose a single, relatively well-rationalized point within the envelope that would serve as the control temperature. The goal was to find a point high enough to allow normal uninterrupted cooking, while at the same time being low enough to prevent oil ignition. A control temperature at the midpoint of the operating envelope, 590°F, was selected and Stage 2 tests were initiated to determine the ability of the control to prevent ignition of the pan contents when the burner was on the highest setting and unattended.

4.3 Stage 2 – Preventing Ignition

The first series of tests conducted with the controller was the oil ignition series. Results from these tests are shown in **Figures 4-4a, 4-4b, 4-4c,** and **4-4d. Figures 4-4a** and **4-4b** show the results of heating 100 ml of oil in a 10-inch aluminum pan and cast iron pan respectively. As shown in **Figure 4-4a**, once the contact probe temperature reading exceeded 590°F, the burner valves were set to the lower input value (approximately 40 percent of the maximum input). This occurred at roughly 4.25 minutes into the test, and the temperatures indicated by the contact probe and a thermocouple in the oil were observed to decrease soon thereafter. After the temperature indicated by the contact probe dropped below 590°F, the controller signaled the gas valve to return to maximum gas flow. The contact probe again reached a reading of 590°F, and the process was repeated.

Figure 4-4a shows that the oil temperature variations lagged behind the contact probe. The frequency of the valve cycling in this case was relatively high, while the amplitude of the contact probe temperature cycling profile was relatively low. This behavior is characteristic of systems with low thermal inertia.

Figure 4-4b shows typical results when heating a small amount of oil in a 10-inch cast iron skillet. The difference between these two results demonstrates the differences between pan thermal properties. The cycling frequency of the burner is significantly lower than that for the aluminum pan, and the amplitude of the temperature profiles is larger. This result is characteristic for a system with large thermal inertia. Even with the overshoot shown in **Figure 4-4b**, the oil temperature never approached a value near the point where ignition could occur.

The control system effectively prevented fires in the same skillets with 500 ml of oil. The specific thermal behavior was considerably different as shown in **Figures 4-4c** and **4-4d**. The key difference in this set of tests, as compared to the 100-ml tests, is the larger volume of oil. The results are similar, but the larger oil volume results in a slower response time. For example, the temperature change curves have less steep slopes, and the cycling frequency is lower, indicating greater thermal inertia.

In summary, for all the tests conducted (see additional data in **Appendix A**), the oil temperature never approached the ignition temperature when the control system was active. Moreover, water boiling was unaffected by the control in all tests conducted. These data are also shown in **Appendix A**.

Figure 4-4a. Control System Test with 100-ml of Oil in a 10-Inch Aluminum Skillet

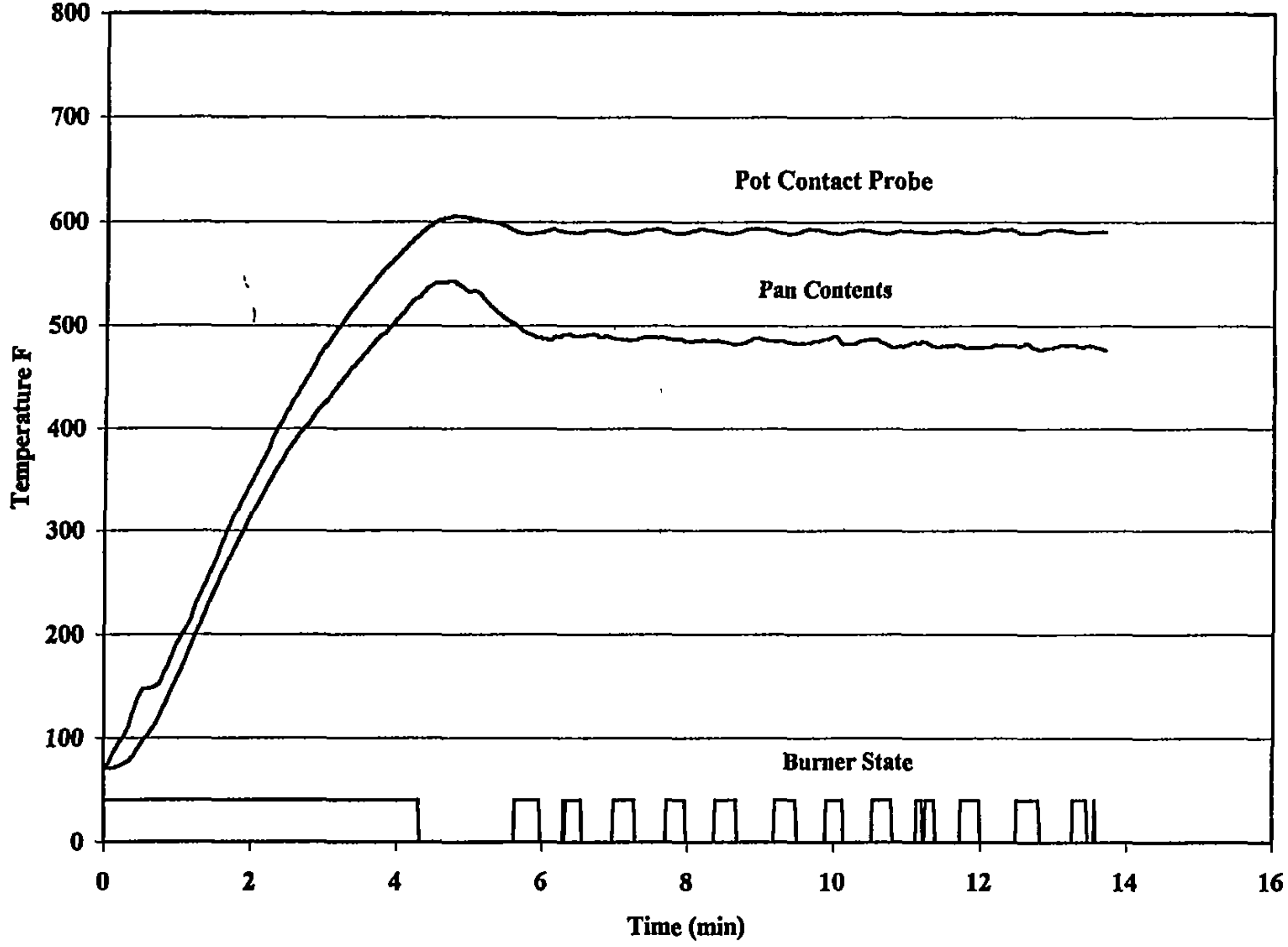


Figure 4-4b. Control System Test with 100-ml Oil in a 10-Inch Cast Iron Skillet

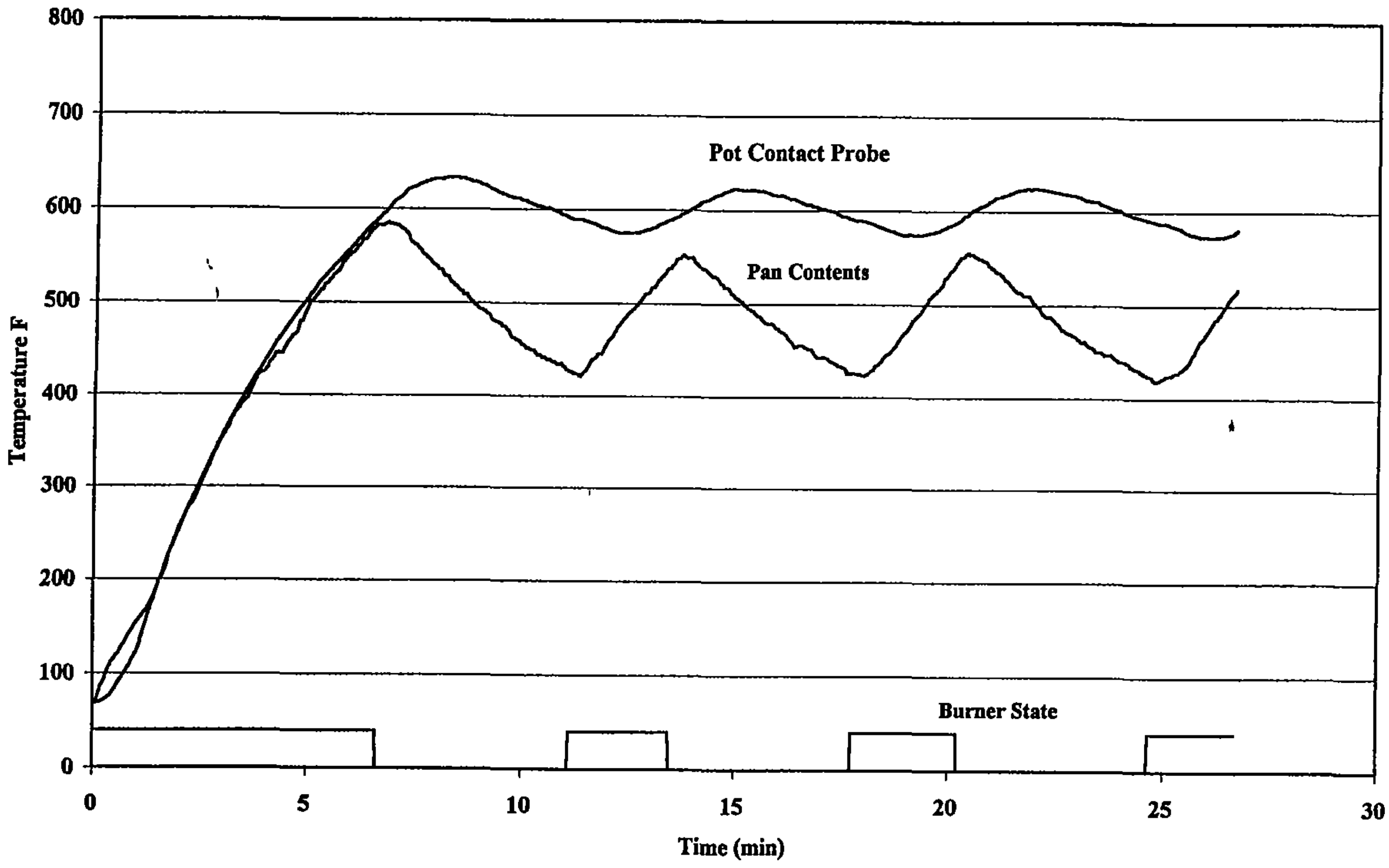


Figure 4-4c. Control System Test with 500-ml of Oil in a 10-inch Aluminum Skillet

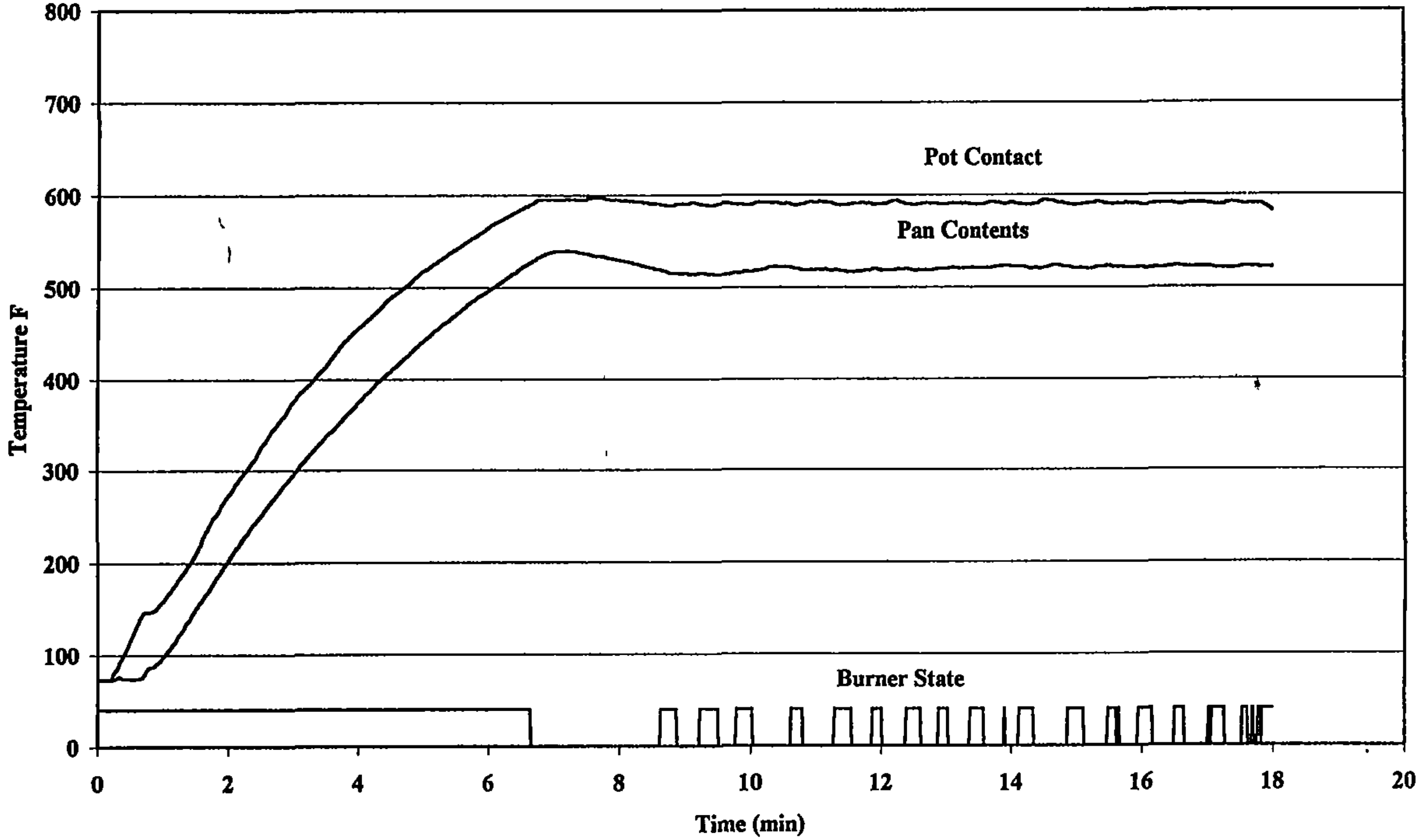
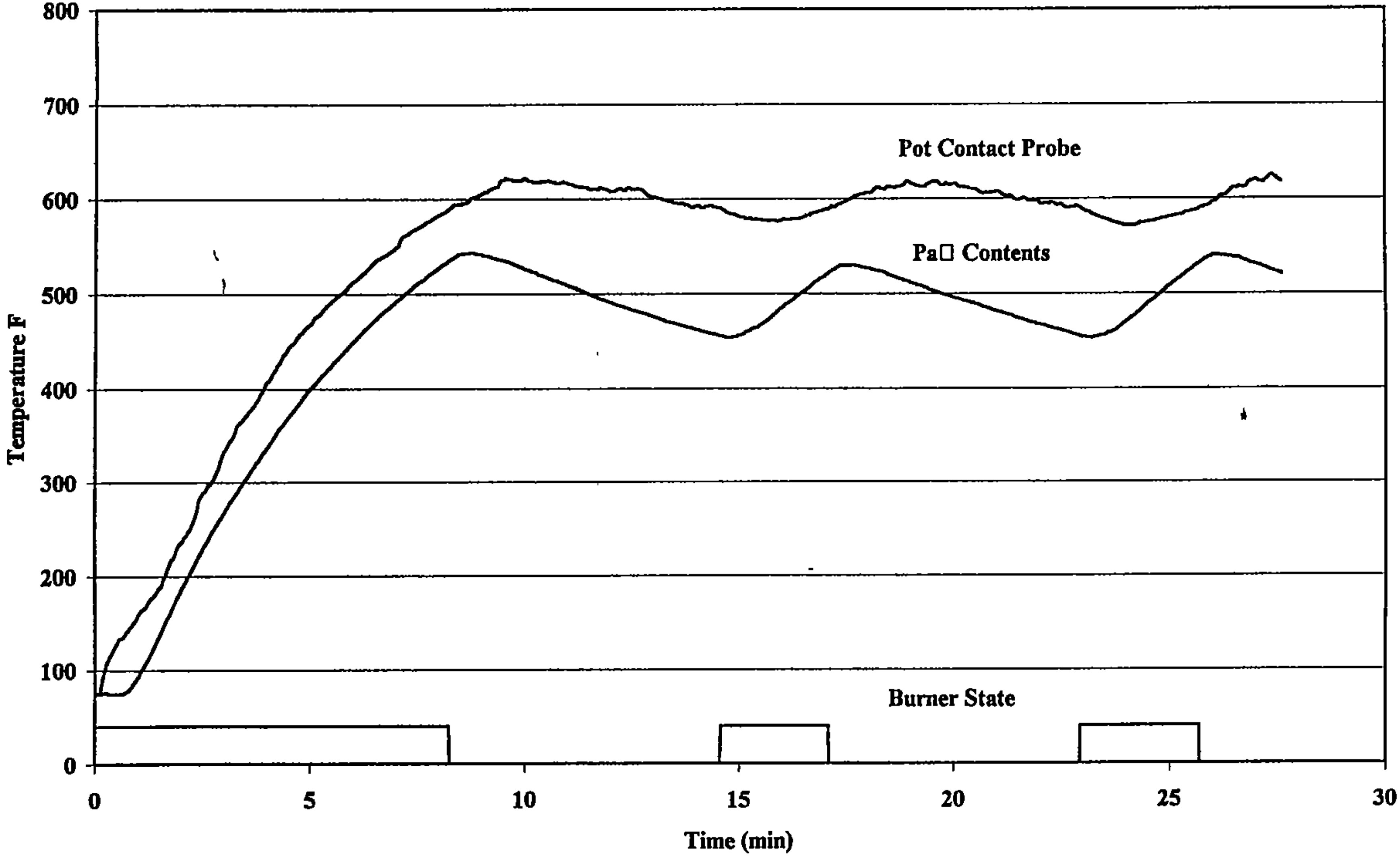


Figure 4-4d. Control System Test with 500-ml of Oil in a 10-Inch Cast Iron Skillet



4.4 Stage 3 – Effect of the Control System on the Quality of Prepared Foods

This series of tests were focused on preparing two types of foods in the skillets while the control system was active and set to 590°F contact probe temperature. The objective was to determine if the control would interfere with the cooking operation by sensing a high temperature and causing the heat input to be reduced when not intended. Two foods were prepared including bacon and chicken.

4.4.1 Preparing Bacon

Figures 4-4e and **4-4f** present selected results from the cooking 8oz of bacon in 10-inch aluminum and cast iron vessels. The characteristics of the temperature profiles are remarkably different for the two pan types. **Figure 4-4e** shows the results of cooking bacon in a 10-inch aluminum skillet with the control system active. The control response as indicated by the contact-probe fluctuation is similar to results obtained in the 100-ml oil tests described above. **Figure 4-4f** shows the results of cooking bacon in a 10-inch cast-iron skillet. These results are similar to the 100-ml oil heating experiments described above as well. In both cases, the bacon was cooked to beyond completion without interference by the control system, and without ignition.

4 4.2 Preparing Chicken

This series of tests were conducted to investigate the impact of controller function on cooking chicken. **Figures 4-4g** and **4-4h** present selected results from cooking 750 mg of chicken in 500 ml of oil, using 10-inch aluminum and cast iron skillets. Overall, the findings for this series of tests is similar to that for bacon, although there is some difference between the frequency of temperature cycling, as well as of amplitude of the temperature profiles (a function of the type of food being cooked). In all cases the controller did not interfere with the cooking of the chicken.

4.5 Investigation of Alternate Control Points

The contact probe was demonstrated to be a viable control sensor approach during the experiments conducted in this program. The range industry has applied this approach in the past to gas ranges with the intent of controlling boiling and over temperature. The results, while encouraging, were not successful due to the fragility of the sensor in its extended (no pan on the grate) position. Energy International examined other temperature sensor locations during this work in an attempt to find a location that could be used as a temperature indicator while at the same time providing a means to make the sensor more rugged. Three alternate locations were considered; the spill pan, grate finger, and the burner head.

Figure 4-4e. Control System Test with 8-Oz of Bacon in a 10-Inch Aluminum Skillet

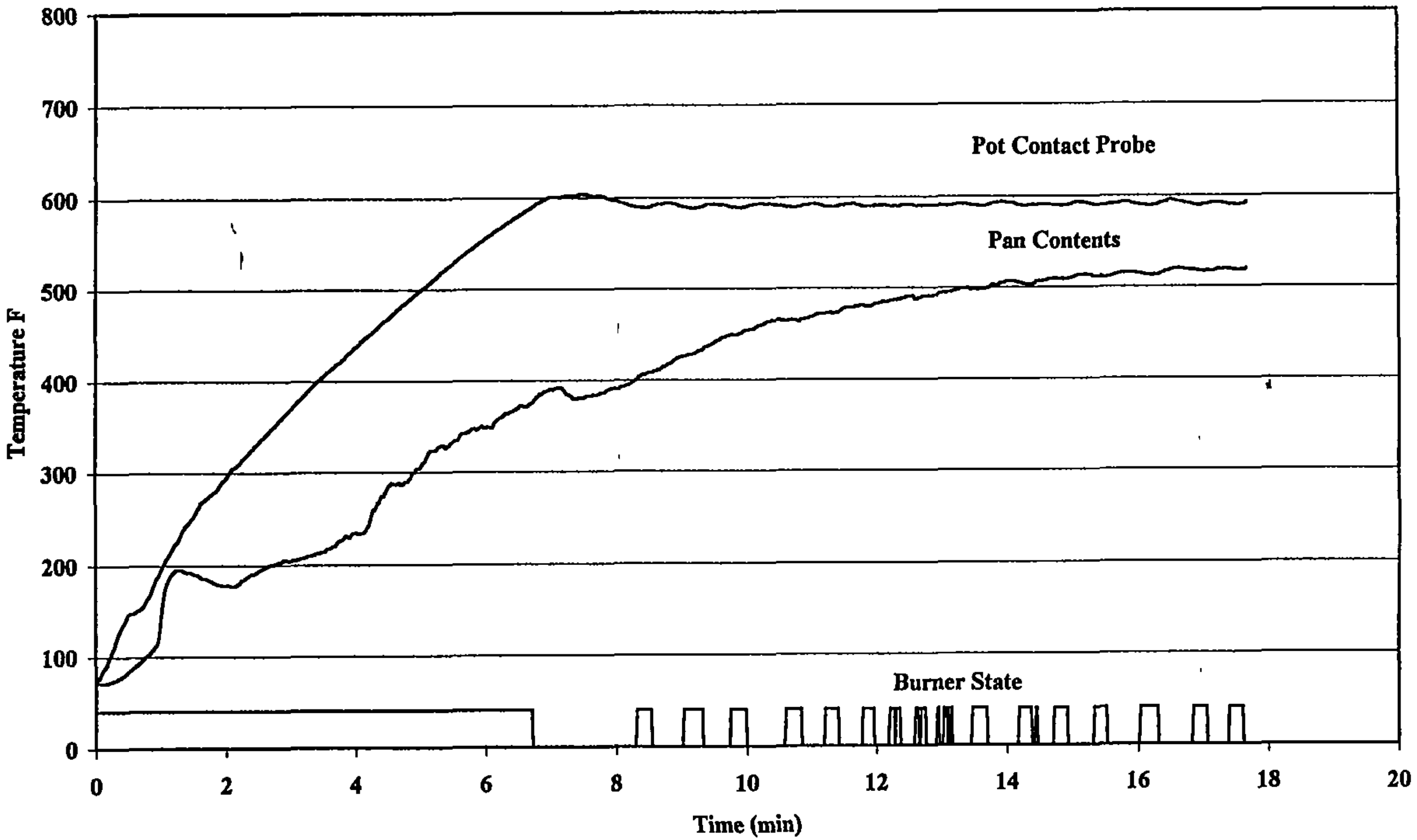


Figure 4-4f. Control System Test with 8-Oz of Bacon in a 10-Inch Cast Iron Skillet

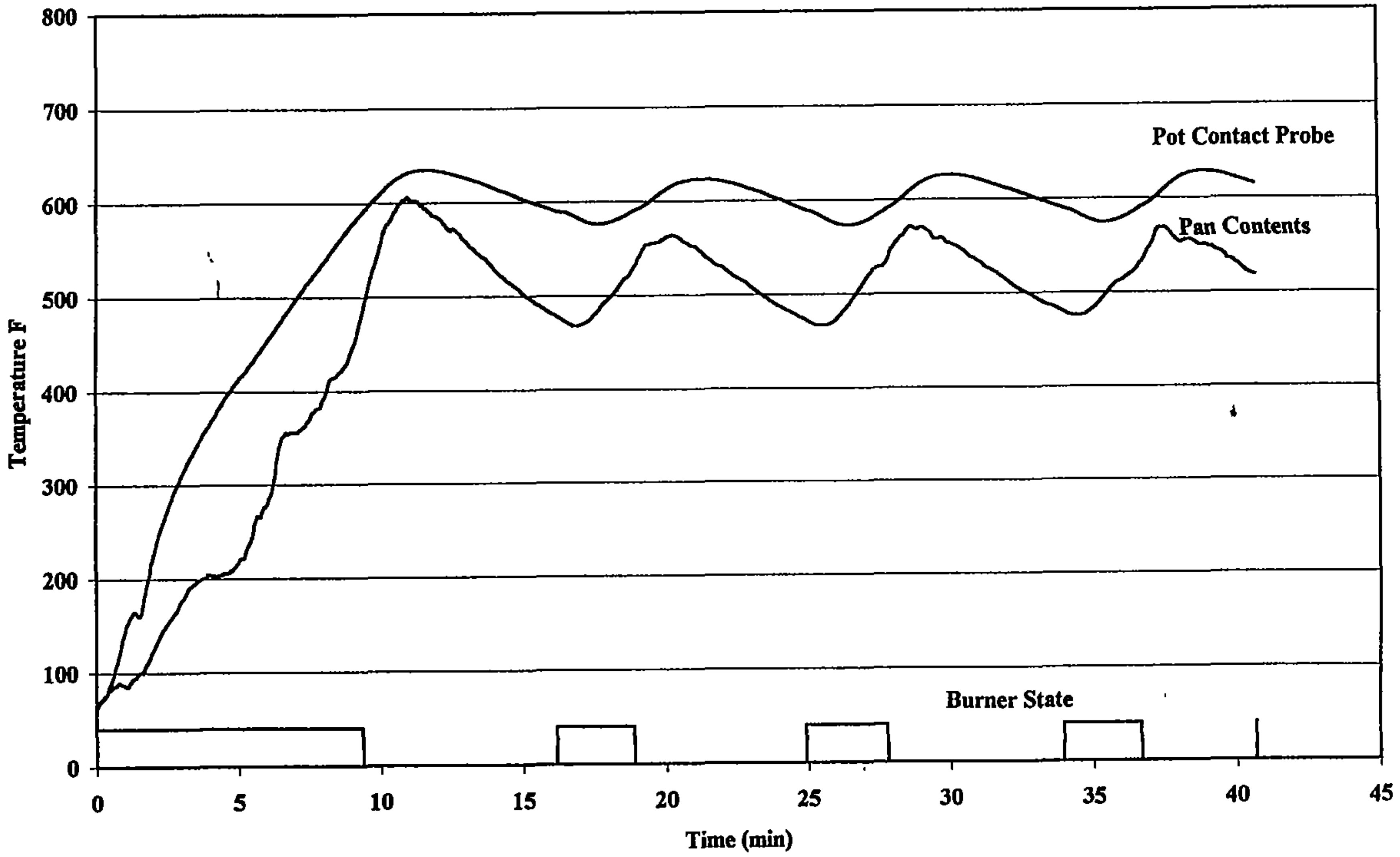


Figure 4-4g. Control System Test with 750-mg of Chicken in a 10-Inch Aluminum Skillet

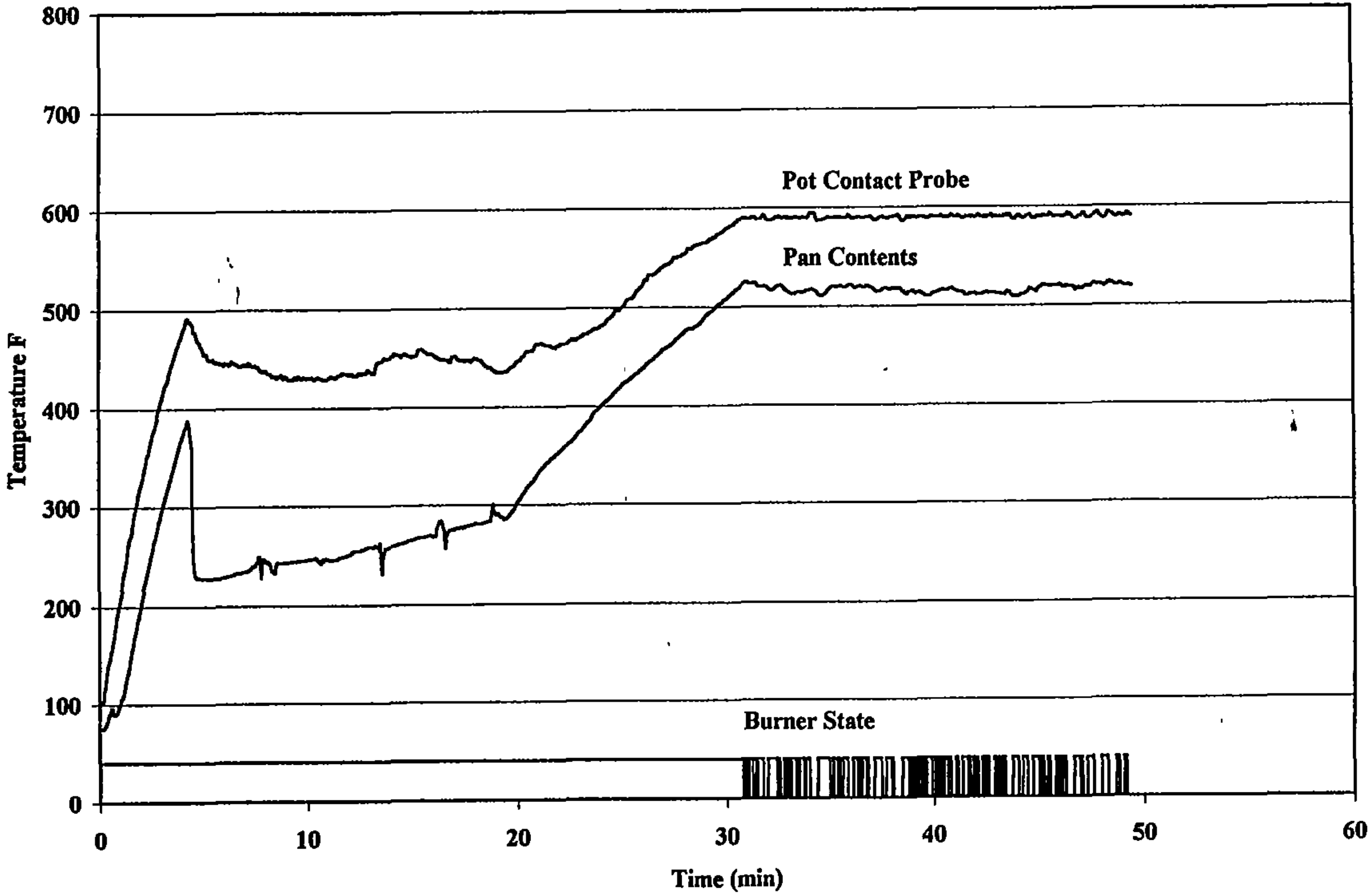
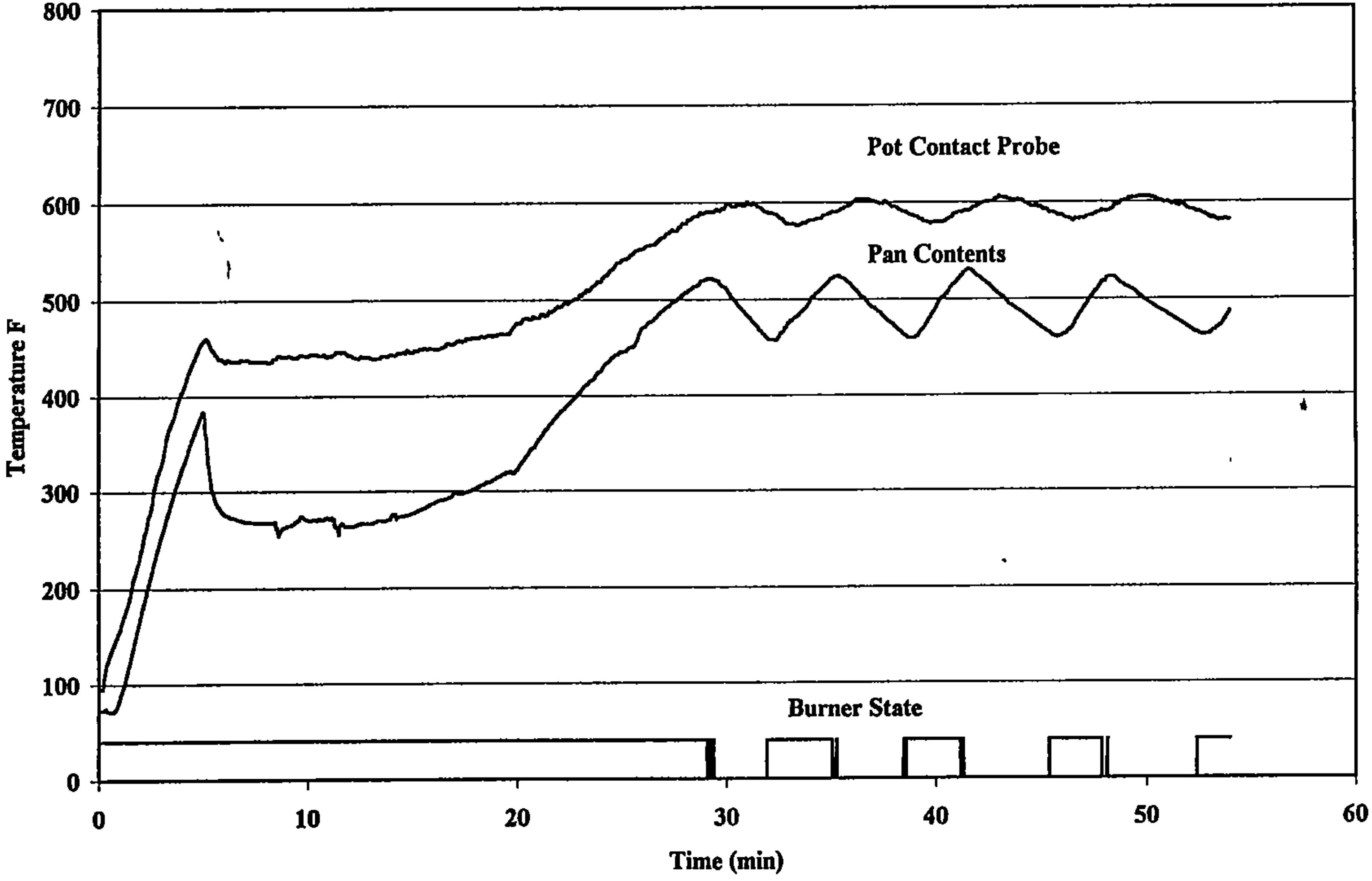


Figure 4-4h. Control System Test with 750-mg of Chicken in a 10-Inch Cast Iron Skillet



The spill pan temperature was measured with a thermocouple permanently attached to the sheet metal. This could be easily accomplished in production, and the attachment point could be under the range top out of view and in a relatively safe location.

The grate-finger sensor was a thermocouple permanently mounted on the tip of one of the grate fingers on the range. This sensor could be routed through a hollow finger and down below the range top for ruggedness. The sensing grate finger would have to be attached to the range top and be non-removable to prevent damage, but the rest of the grate casting could be removable for cleaning.

The burner head was the third location used for the tests. This thermocouple was mounted on the center of the burner head. The burner head temperature is influenced by radiation from the pan bottom and the inrush of cool air and fuel from below. The control strategy plan was that the radiation would dominate the thermal response of the burner head and that it might be an adequate indicator of pan bottom temperature.

Overall results from these experiments are shown in **Table 4-2.** These data are for the skillets and include all four types of materials. The contact-probe data are shown for comparison with the data from other locations. The testing with oil ignition and water boiling showed that the control point having the greatest spread in readings between the two extreme points would provide the most reliable data for the control. In this case, the contact probe is clearly the best choice. The unanswered question however is how much spread is good enough and do the other control points work as well?

The data in **Table 4-2** show that the grate finger provides a temperature difference half that of the contact probe. The burner cap and drip pan temperature swings are even less. At first glance it would appear that the contact probe should be selected, but with further investigation, it also appears that the alternate locations would be equally effective.

Table 4-2. Comparison of Temperature Readings from the Alternate Points with the Contact-Probe Reading

Pan Type	Contact Probe		Grate Fingers		Burner Cap		Drip Pan	
	Boiling Water	Burning Oil	Boiling Water	Burning Oil	Boiling Water	Burning Oil	Boiling Water	Burning Oil
Cast Iron	425	690	690	875	485	660	400	520
S/S	455	701	725	855	455	577	428	503
Aluminum	425	730	710	845	520	775	430	475
Ceramic	440	700	690	885	465	617	390	554
Average	436	705	704	865	481	657	412	513
High/Low	455	690	725	845	520	577	430	475
Differential		235		120		57		45

4.5.1 Modified Burner Cap – Radiant Sensor

The primary driver for investigating alternate control points was to find a way to incorporate pan temperature measurement into a range with a system that could be simple to manufacture and reliable in the field. A surface contact probe was investigated and found to be reliable in measuring the pan temperature, but was believed to be unreliable mechanically in the field.

The grate-finger thermocouple showed promise in testing, but might be troublesome in the field since it was sensitive to changes in the flame pattern that resulted from changing the burner from high to simmer manually. There is no doubt that a grate finger and probe configuration could be engineered to eliminate this problem, but the fact remains that the instrumented grate finger would have to be permanently attached to the range.

The burner cap showed promise until the data were carefully analyzed. This temperature was observed to rise when the burner was shut off and drop when the burner was turned back on. This behavior results from the cooling effect provided by the incoming air and fuel. These fluctuations were not controllable or predictable and it was felt that some conditions could occur in the field where the burner cap temperature would falsely indicate pending ignition. This would cause the controller to interfere with the cooking process.

The drip pan temperature tracked cooking pan temperature somewhat, but was not sufficiently different when boiling water or heating oil to merit further consideration as a control point. Moreover, spills and accumulated dirt might cause even greater insensitivity to pan temperature over time.

A robust sensing location that would work with both electric and gas ranges would be attractive to manufacturers when considering how to approach the need for a flame safeguard control on ranges. The burner cap, radiant-receptor concept was reexamined in light of a potential to be used for both electric and gas ranges. A hollow, thermally isolated sensing element was attached to the burner cap as shown in **Figure 4-5** and used as a control point.

Key elements of the concept shown in **Figure 4-5** are that the sensor is designed to have the radiant portion of the sensor located in close proximity to the pan bottom but not in contact. A thermocouple is mounted to the underside of the top section to read temperature. The top of the sensor close to the pot is also thermally isolated from the sides so that any effect of heating from combustion products is minimized. This design approach would also minimize an error introduced by radiation from the underside of the heating elements on an electric range.

The radiant sensor could easily be used for both gas and electric ranges since it works as a true radiant coupling with the pan bottom and can be easily configured to be in the center of the grate or heating coil. Moreover, the sensing element lies just below the grate or heating element top surface and out of harms way when no pan is on the range. Wires for the thermocouple could be fed into the sensor from below the range top making the design robust and lessening the potential for damage by the user. It could even be possible to incorporate a liquid capillary tube instead of an electronic sensor and have the system operate a gas valve or electric switch to reduce heat input to the pan.

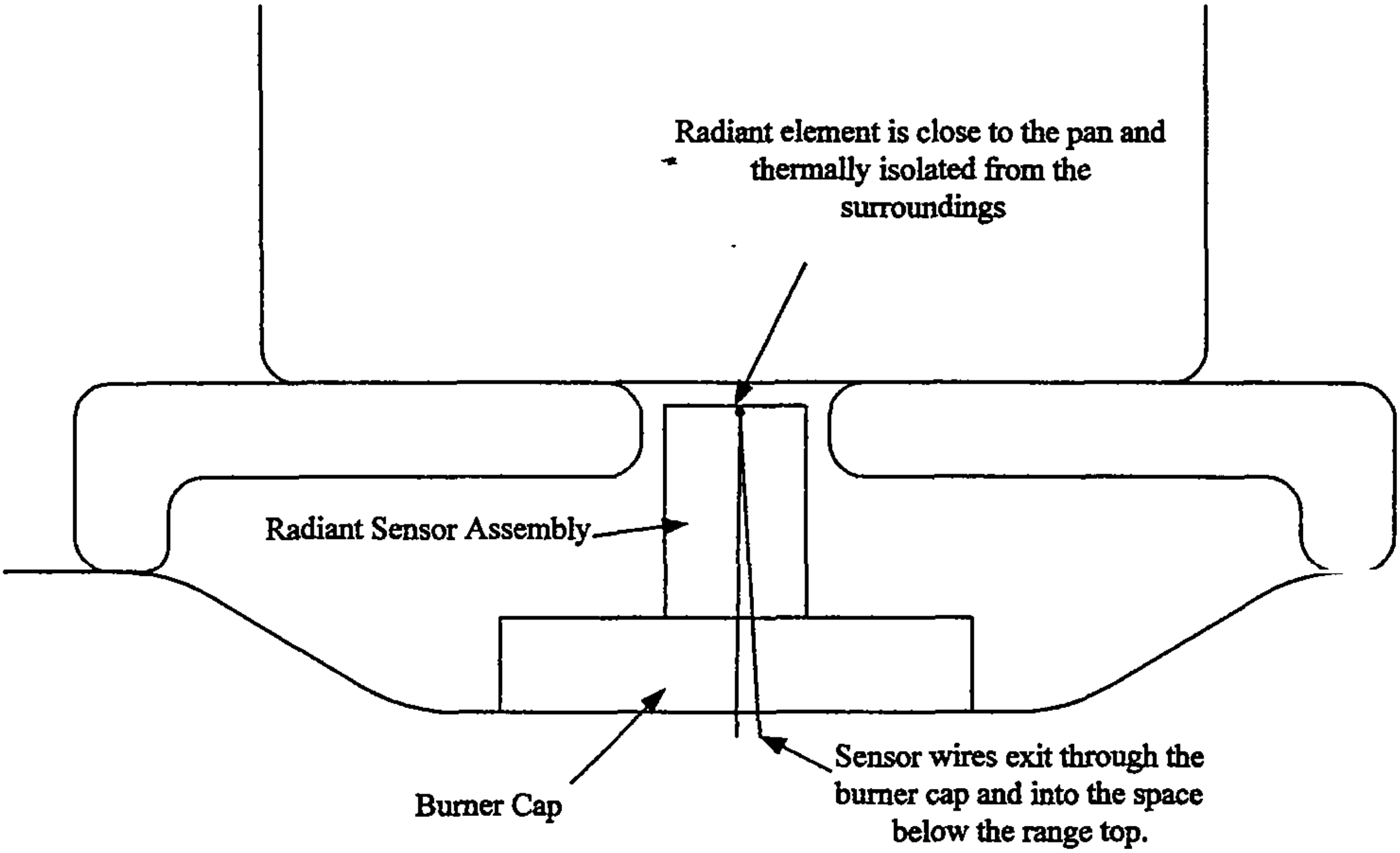


Figure 4-5. Radiantly Coupled Sensing Element

The simple water boiling and oil heating experiments were repeated with the new sensing element. A 10-inch aluminum skillet was used in the tests. **Figures 4-6** and **4-7** show the temperature profiles that resulted. The radiant sensor performed much like the surface-contact probe. The sensor temperature reading during boiling water was about 400°F. The sensor was incorporated into the computer control system as the control point with the control temperature set to 590°F as with the surface-contact probe. **Figure 4-7** shows the temperature profile obtained. No ignition occurred and the sensor performed satisfactorily.

5. CONTROL SYSTEM COST ESTIMATE

Because the control system did not evolve into a detailed design, an accurate cost estimate is not possible. Discussions were held with a major appliance controls manufacturer to determine the range of costs for the controller. If the final embodiment of the electronic system is a surface-contact thermocouple and primary gas valve, the cost for the control was estimated to be in the range of $5 to $7 per burner or $20 to $28 cost added for the range.

Figure 4-6. Water-Boil Test with a 10-Inch Aluminum Skillet Using the Radiant Sensor

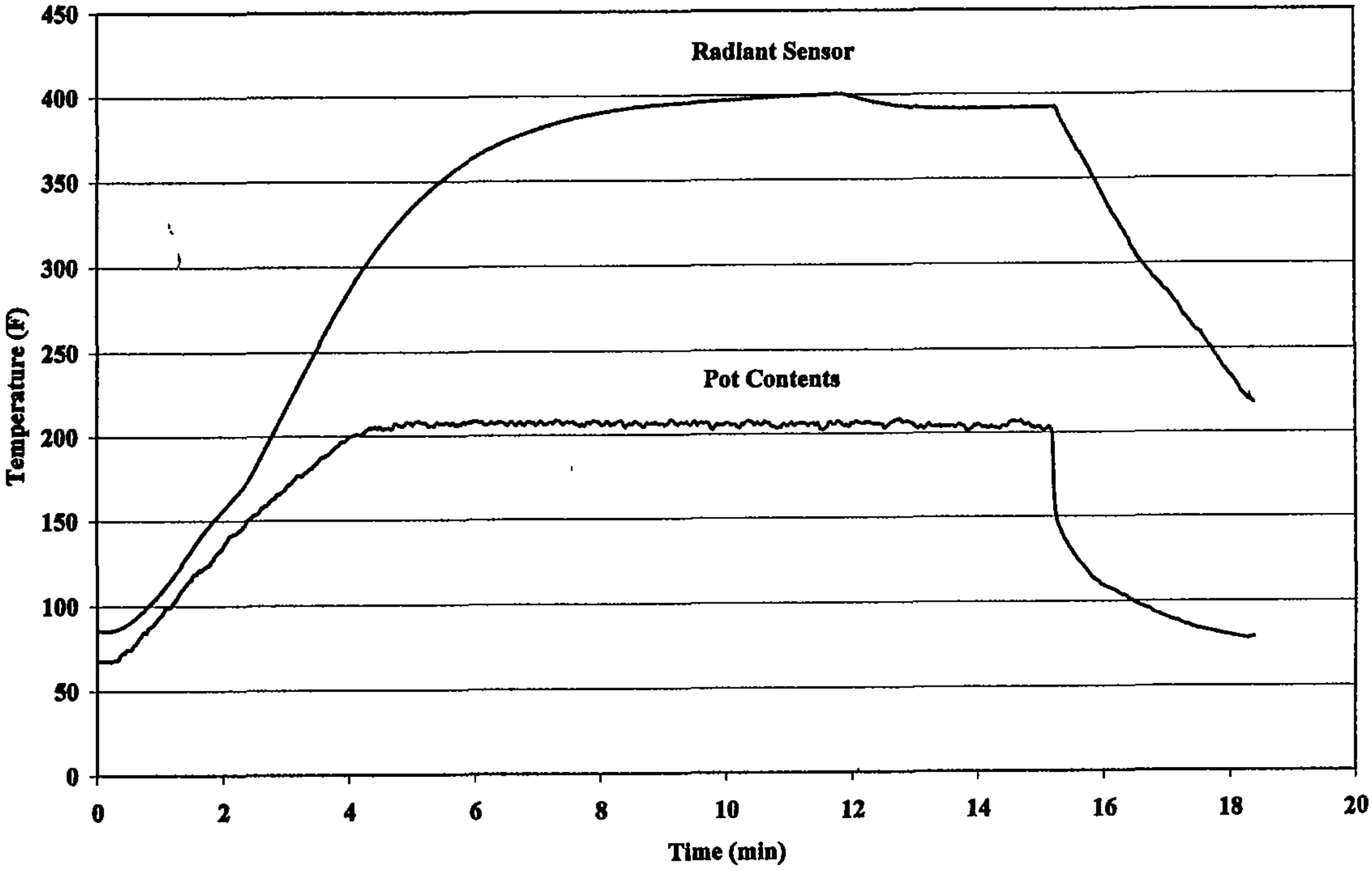
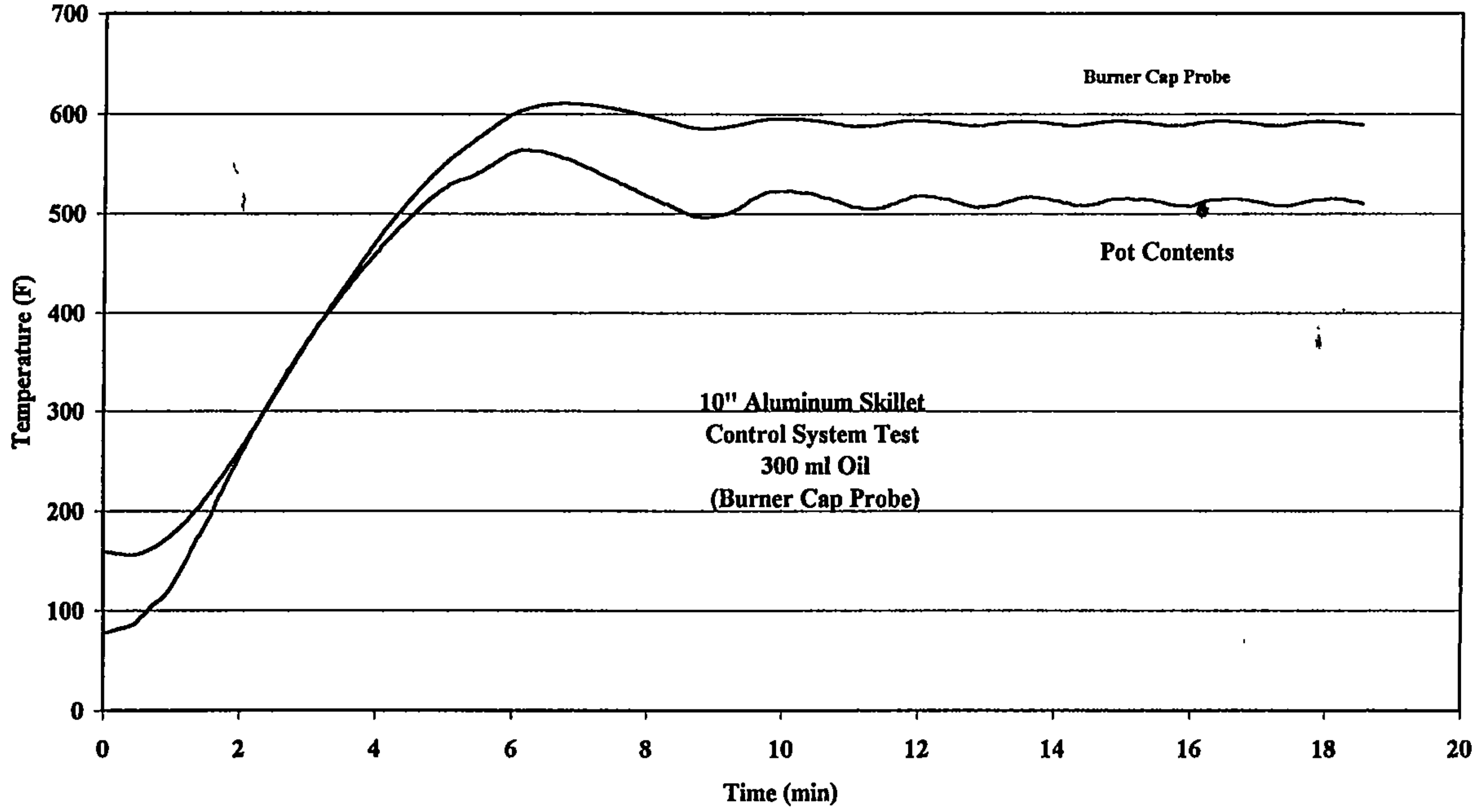


Figure 4-7. Oil-Ignition control Test with a 10-Inch Aluminum Skillet Using the Radiant Sensor for Control



6. CONCLUSIONS AND RECOMMENDATIONS

Based on work conducted during this project, the following conclusions were reached:

1. The surface-contact probe approach tested by CPSC on electric ranges also works effectively on gas ranges to prevent fires.
2. The surface-contact probe also permits normal cooking operations such as boiling water and browning meats without interference.
3. Alternate points on the range top are also available for use in monitoring temperatures that can in turn be used to represent the temperature of the pan.
4. It is possible to develop a radiantly coupled sensor that effectively prevents fires, limits exposure to damage, and is adaptable to both electric and gas ranges.

Based on these conclusions, the following recommendations are made:

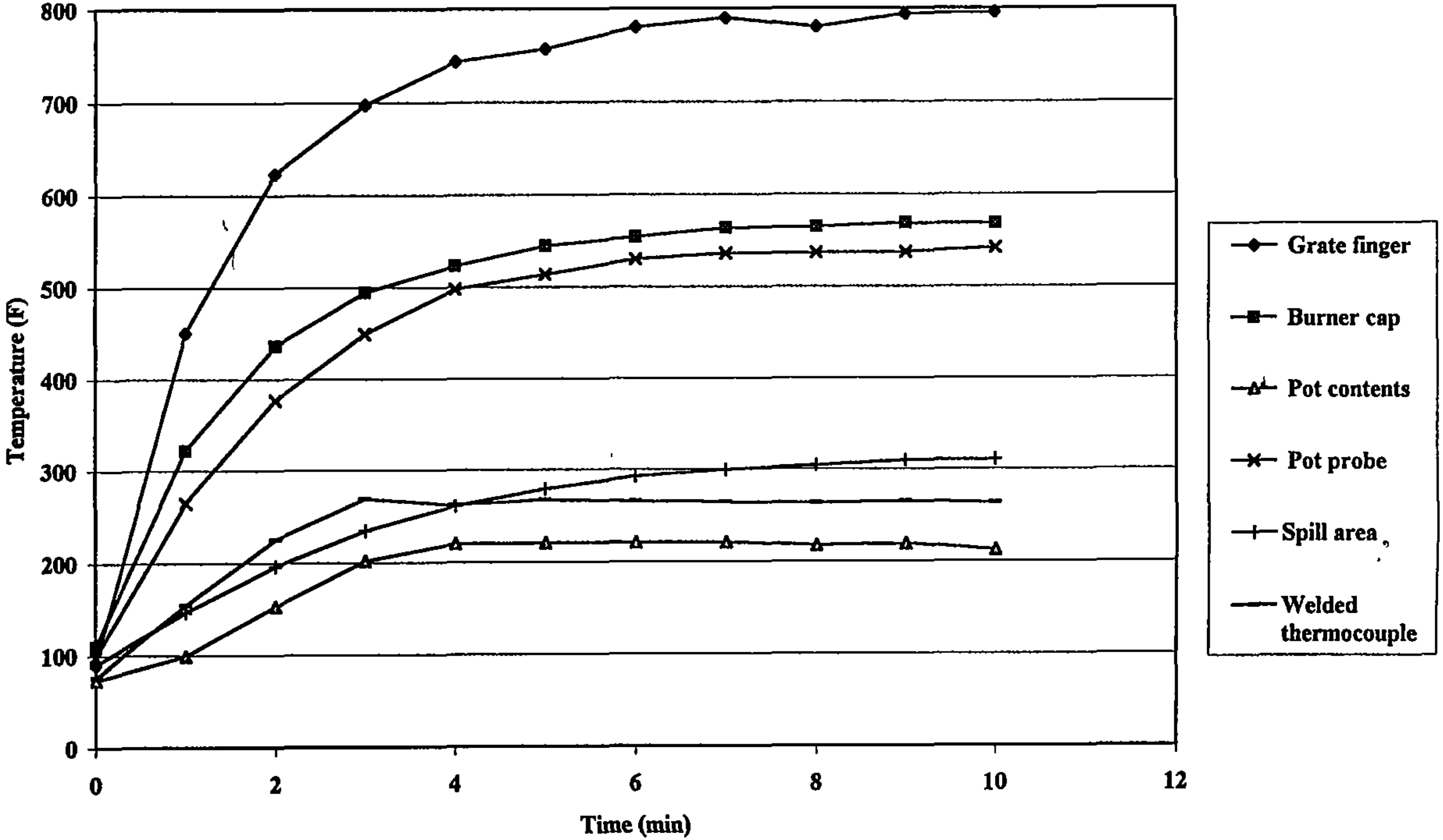
1. CPSC should work with range manufacturers to refine the radiantly coupled sensor.
    - The design of the sensor actuator should be investigated to include electronic means such as thermocouples, thermistors, or RTD's and mechanical actuators for valves or switches.
2. A refined cost estimate should be developed and used in a cost effectiveness evaluation.

Appendix A

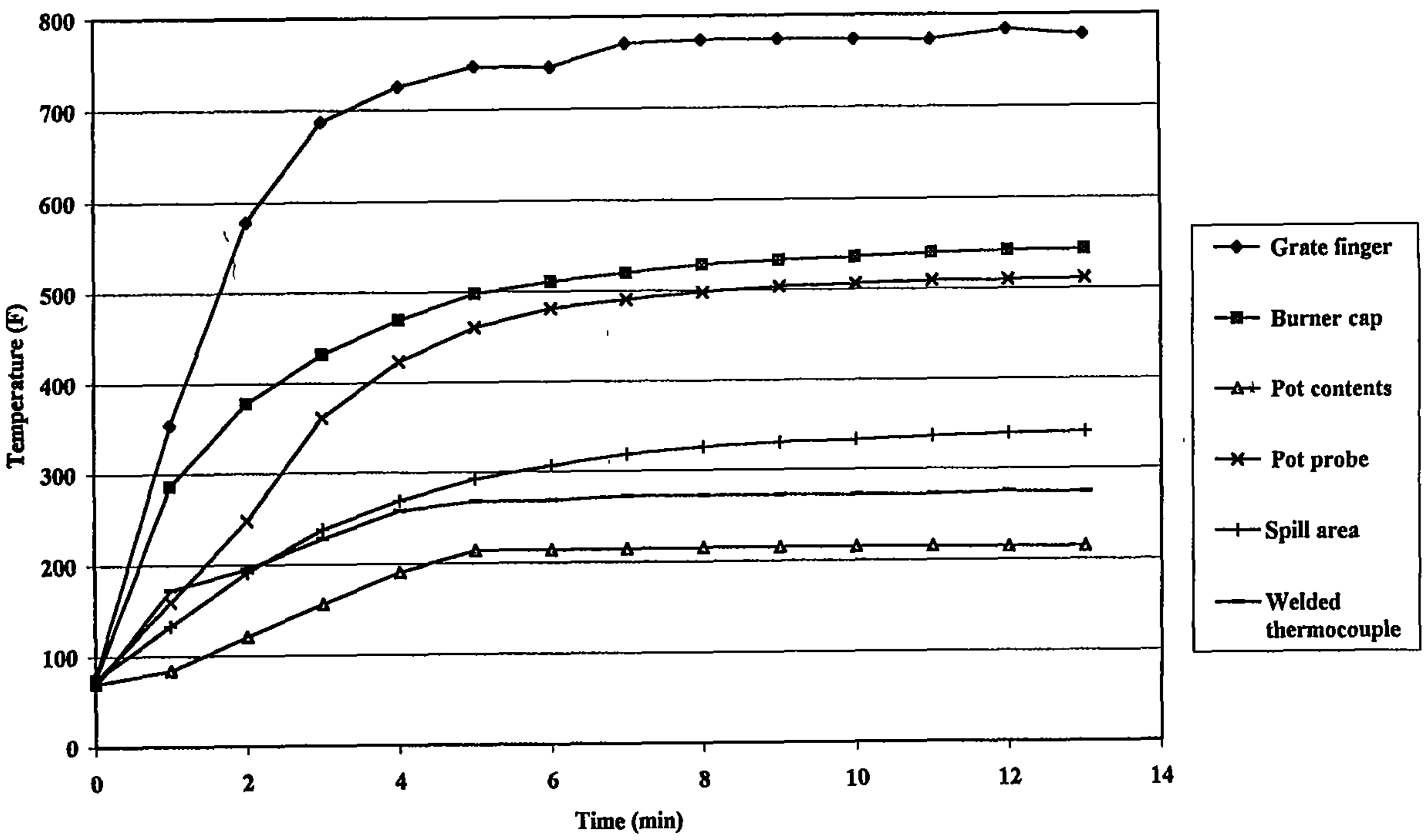
Test Data

This Appendix contains all of the test data gathered during the project. The data are arranged according to the type of test being conducted; water boiling, oil ignition, and operation of the control system under normal cooking scenarios.

1 Quart Aluminum Pot
Water Boil Test



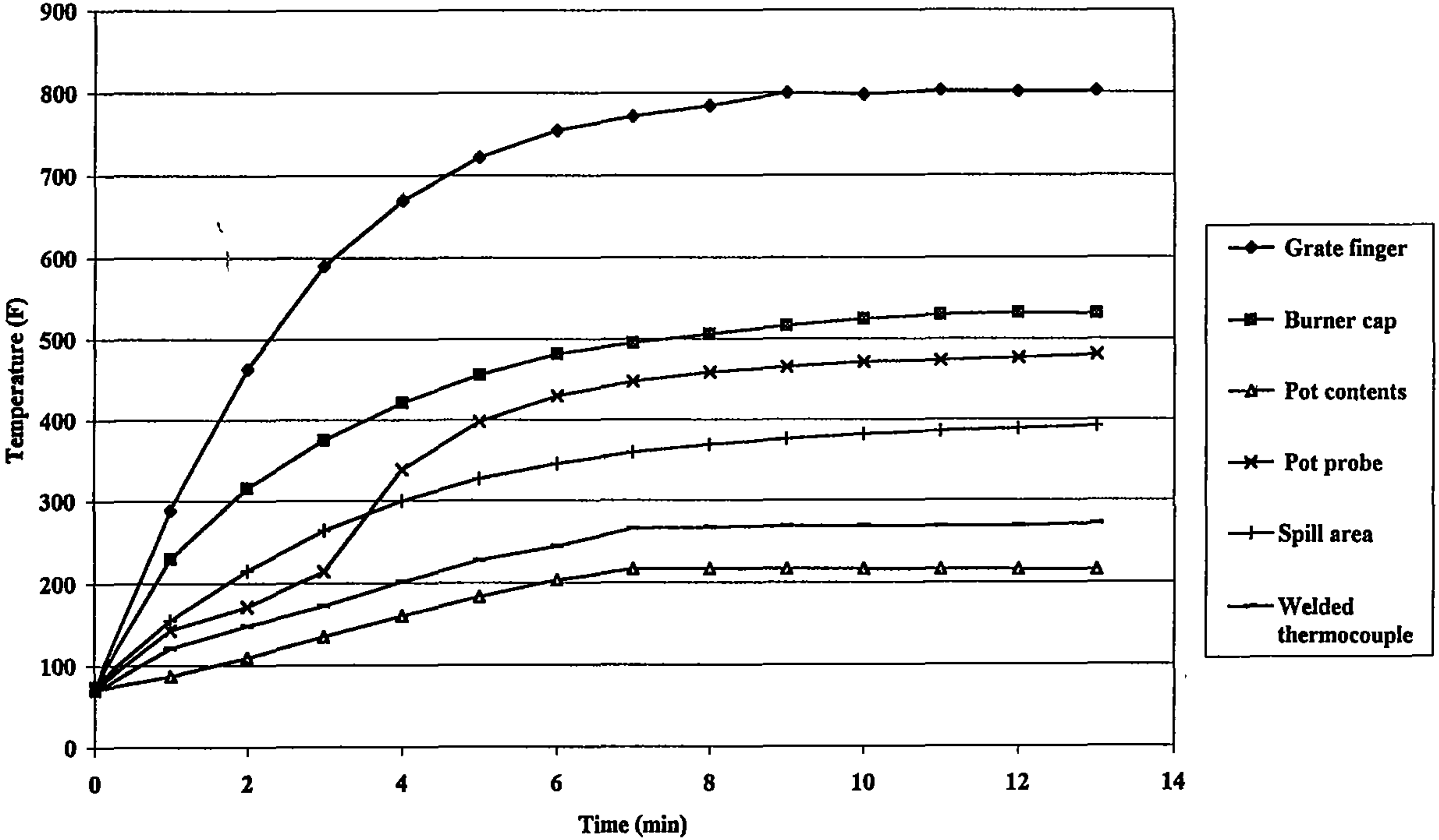
test57a.xls



1 Quart Stainless Steel Pot
Water Boil Test

test60a xls

5 Quart Aluminum Pot
Water Boil Test



Test 58a.xls