NISTIR 5950

Study of Technology for Detecting Pre-Ignition Conditions of Cooking-Related Fires Associated with Electric and Gas Ranges and Cooktops, Final Report

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Executive Summary

A significant portion of residential fires stem from kitchen cooking fires. Existing fire data indicate that these kitchen cooking fires primarily are unattended and most often involve oil or grease. Previous study has determined that strong indicators of impending ignition for several foods cooked on range surfaces are temperatures, smoke particulates, and hydrocarbon gases. The purpose of this experimental investigation was to determine the feasibility of utilizing one or more of these common characteristics of the pre-ignition environment as input to one or more sensor(s) in a pre-fire detection device. This device would detect approaching ignition and allow alarm or shutoff of the range for foods cooked on electric and gas ranges without generating false alarms during a variety of normal, or standard, cooking activities.

The aspect of feasibility explored by the National Institute of Standards and Technology was the physical possibility of differentiating between the characteristics of broad ranges of pre-ignition and normal environments. The ultimate goal of the overall study being conducted by the Consumer Product Safety Commission (CPSC) is to evaluate the overall feasibility of incorporating such a device into ranges that would react with alarm or shutdown to pre-ignition conditions and reduce the occurrence of unwanted kitchen fires without undue disruption of attended cooking. This evaluation of overall feasibility by the CPSC includes consideration of the reasonableness and magnitude of the social and economic costs and benefits in addition to the physical feasibility of a detection system.

In order to evaluate the physical feasibility of a pre-ignition range-fire detector, a substantial number of cooking procedures were examined. Simulations of unattended cooking leading to ignition as well as normal, or standard, cooking procedures that have the potential to mimic pre-ignition characteristics were included in the study. A total of 16 cases consisting of 5 normal, 5 unattended, and 6 that progressed from normal to unattended were tested on a typical electric range with an inactive range hood. To determine the effects of range type and hood status on sensor performance, two cases were repeated with the range hood active and three cases were repeated on a gas range. The total number of variations was 21, and each case was repeated once for a total of 42 tests.

A variety of measurements was made for each test. An aspirated sample probe was used to pump gases to carbon monoxide, carbon dioxide, and hydrocarbon analyzers. Thermocouples provided temperature measurements at locations near the food and in and around the range and range hood. Hydrocarbon-gas sensors of varying sensitivities to different types of hydrocarbon gases were placed on and around the range and range hood to enable evaluation of the response of potential detector components. Household photoelectric and ionization smoke detectors were placed around the room to evaluate the degree of false alarm incidence using these existing technologies.

The following conclusions are based on measurements and observations of combinations of specific ranges, pans, foods, and ventilation so extrapolation to other conditions should be made with caution.

- Measurements confirm that the cooking environment near the range during unattended cooking approaching ignition exhibits significantly higher levels of temperatures,

hydrocarbons, and particulates than the cooking environment produced by most normal, standard cooking procedures.

- Some attended, standard cooking procedures, such as blackening of fish, may produce conditions similar to those conditions approaching ignition because the procedures themselves are purposefully designed to use extreme temperatures.
- Several sensors positioned in certain locations offer high levels of differentiation when used alone. Depending on the setting of the threshold, a majority of cooking cases would appropriately cause alarm or not alarm.
- No single sensor performed faultlessly without the use of modifications of the detection system to account for special attended cooking cases, but one gas sensor on the range hood and a thermocouple contacting the bottom of the cooking pan were most effective.
- Standard household photoelectric and ionization smoke detectors identify pre-ignition conditions well, but generate a significant number of false alarms when used alone for the particular tests conducted.
- A limited effort at algebraically combining three sets of two sensor signals generates more robust differentiation, and for the best pair, pre-fire and normal conditions were clearly separated with the exception of one attended cooking case which would produce a false alarm rather than a failure to alarm.
- Results with impact on detection were insensitive to range type, range-hood status, and pan material.
- Based on the findings of this investigation, pre-fire detection systems for range-top cooking are physically feasible and merit further consideration.

Acknowledgements

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The author wishes to acknowledge the hard work of Roy McLane and Marco Fernandez in preparing and installing the sensors and other laboratory apparatus, Emil Braun in designing the electronics needed for the sensors and detectors, and Michelle King and Marco Fernandez in conducting the experiments. The author also expresses appreciation to Laurean DeLauter, Gary Roadarmel, and others of the NIST Building 205 crew for their help with safety.

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1.0 Introduction

Nearly 3,700 deaths, about 19,000 injuries, and over $4 billion in property damage were caused in 1995 in the United States by over 400,000 residential fires **[1]**. In recent analyses of data collected through the National Fire Incident Reporting System, NFIRS, the National Fire Protection Association has estimated that range/oven appliance fires, a majority of which involve food, average about 20% of all residential fires and are responsible for approximately 20% of the injuries, 5% of the deaths, and 5% of the property loss associated with residential fires **[2]**. Until recently, there was little research directed toward increasing understanding of the pre-ignition conditions of food fires that might be monitored to indicate an incipient fire or of the devices that might be used to detect and act upon such conditions. The objective of this project is to identify pre-ignition conditions and the methods and devices that can be used to detect such conditions and alert, or intervene, to reduce the risk of food fires associated with electric and gas ranges and cooktops and thereby reduce the number of cooking-related fires in homes. The ultimate goal of the overall study being conducted by the Consumer Product Safety Commission (CPSC) is to evaluate the overall feasibility, including cost and benefit, of incorporating such devices into ranges.

1.1 Review of Phase I

The objective was addressed through two major activities in Phase I. The details are provided in the Phase I report **[3]**. In order to identify the pre-ignition conditions, experiments were performed to monitor specific aspects of the environment and how they changed as ignition conditions were approached. Various foods were heated at high settings using electric and gas ranges with the range hood on for half of the tests. Temperatures of the surroundings close to the pan, plume velocity, and laser-attenuation measurements were recorded. A Fourier transform infrared, FTIR, spectrometer was used to determine if the production of any specific gas species was significant. Analysis of the experimental results determined that strong indicators of approaching ignition were high temperatures close to the pan, smoke particulate levels, and hydrocarbon gases. Monitoring one or more of these conditions was deemed promising for successful detection of approaching food ignition. Additional results of the Phase I work were that each of the particular electric and gas ranges tested produced similar ignition signatures for the same foods, but required different heating periods to achieve them, and that the particular range hood used did not have a significant effect on ignition conditions. The Phase I testing focused on three foods: soybean oil, bacon, and table sugar.

The second Phase I activity was the identification of methods, materials, and devices with potential for detecting and responding to pre-ignition conditions. This was accomplished with a literature and patent search which focused on sensing devices and technologies capable of detecting cooking-related conditions as well as control technologies capable of shutting off gas and electric ranges in the event of a detected threat. The bibliographical information on technologies related to these goals was provided with comments regarding their potential usefulness in a kitchen range pre-ignition detection system. The most promising technologies for monitoring the conditions of interest included tin-oxide sensors for hydrocarbon gases and carbon monoxide, scattering- and attenuation-type photoelectric smoke detectors, and thermocouple thermometry. The search also revealed that logical processing of two or more detected signals has been used in other applications and could be utilized for food pre-ignition detection to limit false alarms. Finally, it was determined that control technologies exist that could be used upon the detection of pre-fire conditions for the shutdown and restart of gas and electric ranges.

1.2 Introduction to Phase II

Phase I demonstrated that common signatures of approaching ignition exist for the three foods cooked on electric and gas ranges. Phase II was designed to obtain additional data on cooking cases and practical sensors. The objective of Phase II was to determine whether there is potential for devices, alone or in conjunction with others, to detect approaching ignition and allow alarm or shutoff of the range for foods cooked on electric and gas ranges without generating undue false alarms during a variety of normal and usually safe cooking activities. The term "normal" will be used in this report to describe accepted, standard cooking procedures derived from recipes or range/oven operation manuals. "Normal" will also indicate that the procedure is attended or monitored. The term "false alarm" will generally be used to describe a situation in which a sensor output surpasses an established alarm threshold when normal cooking is occurring rather than unattended cooking, which is heating maintained at a high level beyond standard practice. Additional clarification of these terms will be used as specific situations are described.

The experiments were designed to (1) establish whether or not a set of normal cooking practices and a set of pre-ignition situations generate sufficiently different signatures to discriminate between these conditions, and (2) test a few readily available detection devices with the ability to respond to the signatures identified by (1). The experiments addressed a broad, yet finite, range of common cooking configurations to determine whether there is potential to detect impending food fires. The nature and extent of practical difficulties that might limit the application of certain devices were also assessed.

2.0 Experimental

2.1 General Design

The purpose of these tests was described in the Phase II introduction. In order to accomplish the purpose, a kitchen facility was necessary which included sources of electrical power and natural gas, ranges, range hood, and some means of air flow control. It was also necessary to develop a set of cooking cases and procedures that would reflect a broad range of environments for which the performance of the various sensors could be examined. This section addresses the design of these experimental elements.

2.1.1 Facility Construction

A small, stand-alone laboratory was built for the Phase I testing and was used again for

Phase II. It was located in Building 205, the Large-Fire Facility, at the National Institute of Standards and Technology (NIST). The interior dimensions of the room were: 3.66 m (12 ft) width, 2.44 m (8 ft) depth, and 2.44 m (8 ft) height. Details of the room's construction including a drawing are contained in the Phase I report **[3]**. The same cabinets were retained to reproduce a kitchen environment. Additional access holes were made in the room walls for external supplies of electrical power and natural gas as well as a large amount of sensor wiring. A range hood (described in Section 2.1.2) was installed above the range. The same range-hood ductwork and room exhaust hood and ductwork were used as described for Phase I **[3]**.

Electrical power and natural gas were provided in a similar manner as before **[3]**. The same 220 V house circuit, boosted to 240 V, was used. Additional 120 V electrical cords were added to accommodate the several power supplies needed for sensors, detectors, and heating tapes. A higher capacity rotameter was used on two tests due to a much higher natural-gas demand. The flow was monitored either with the 4.7 L/min (10 SCFH) rotameter used for Phase I or the higher capacity 23.6 L/min (50 SCFH) rotameter. The gas delivery pressure was maintained at 1.7 kPa (7.0 in of water).

2.1.2 Kitchen Ranges and Range Hood

Four different ranges were used in these tests: A - electric with open-coil sheathed heating elements; B - high-output, sealed-burner gas; C - electric smoothtop; and D - down-draft electric slide-in with a grilling attachment. The majority (34) of the tests were conducted on range A, four tests utilized range B, and two tests each were performed on ranges C and D. Each range was 76 cm (30 in) wide. The electric range with open-coil elements had two 15 cm (6 in) and two 20 cm (8 in) burners. The 15 cm and 20 cm burner elements were rated at 1.33 kW and 2.35 kW, respectively, for 240 V electricity. The front set of burners on each range was used for the pan of focus as in Phase I in order to allow comparison with the previous measurements. The larger, higher-output burner was always used for the pan of focus to maximize the food heating rate and minimize the time to ignition. The gas range had two 2.6 kW (9000 BTU/h) burners and two 3.5 kW (12000 BTU/h) burners. The gas range's large burner was on the left in contrast to the right for the electric range. The smoothtop electric range, including the oven and burners, was rated for 11.4 kW at 120/240 V. It was used only for the oven's self-cleaning capability. The down-draft range was used for its grilling and down-draft features, and it was rated for 14.1 kW at 120/240 with a fan capacity of 236 L/s (500 cfm). The grilling attachment was located on the right side of the range.

The range hood was a 76 cm (30 in) wide model made of stainless steel, and it had a 170 L/s (360 cfm) flow capacity. This unit's cost and flow capacity were above average for the range hoods on the market, yet such models were generally available. The hood opening extended 45 cm (18 in) out from the wall and tapered from about 75 cm (29.5 in) wide at the wall to 63 cm (25 in) at the front over the frontmost 24 cm (9 in). It was not in use for most experiments, but was engaged at maximum flow for several experiments in order to determine its effect on the results.

2.1.3 Test Case Cooking Procedures and Parameters

The purpose of this set of experiments was to characterize the environment preceding ignition during simulated unattended cooking and the potential for false-alarm generation during periods of normal cooking. In order to maximize the data available from each test, some tests combined an initial period of normal cooking followed by a period of simulated unattended cooking on high heat. Some normal cooking tests which were not extended to unattended situations were chosen because they ordinarily utilize high heat and/or produce visible and sometimes accumulating smoke. Other tests were similar to the Phase I tests in that they simulated the unattended, high-heating situation from the beginning.

Three parameters were varied in order to establish their effects on the pre-ignition and normal cooking signatures: (1) food type, (2) range type, and (3) hood operation. A wider variety of foods was tested than in Phase I. Industry input was sought to develop a representative set of cooking cases. Although there are nearly an infinite number of cooking situations, sixteen different cases were studied to encompass a sufficiently broad range of cooking activities to ensure that any evidence for a detection window between normal and dangerous conditions was broadly applicable. Gas and electric ranges were of interest because of potential differences in thermal and chemical environments due to the ranges themselves, regardless of the food being cooked, as well as the different temperature-time histories for the same cooking operation. The range-hood status was of interest primarily because a forced air flow has the potential to either enhance the signals generated during normal cooking or weaken those generated during approaching ignition. Any detection system must not be confused by the use or non-use of a range hood. A range hood with 70% greater flow capacity than that used in Phase I was installed in order to answer questions about the effect of a hood having a flow capacity closer to the maximum generally available on the market.

Table 1 describes the sixteen cooking cases tested in Phase II. All single-pan cases used a large, front burner. For all multi-pan cases, the combustible-food pan was located on the large, front burner. This baseline set of tests used the A-type electric range (except for cases 6 and 15 as is explained later). The range hood was inactive to allow for worst-case build-up of cooking products. Cases 1 and 3 are unattended and were selected to establish pre-ignition conditions using the Phase II instrumentation set for the same cases tested in Phase I. Cases 4, 5, 7-9, 11, and 13 were selected to represent normal cooking activities. Cases 7-9, 11 and 13 involve unattended cooking following a period of normal cooking procedures. These cases are designated "normal→unattended" and were designed to provide both normal and pre-ignition data. Cases 1-3, 10, 12, and 14 simulate unattended cooking for the entire duration of the tests. All unattended cases, whether following normal cooking or not, utilize the highest burner setting even if the normal procedure does not prescribe heating on high. This was done to achieve the fastest ignition possible which was deemed the most dangerous situation. Case 6 employs the C-type smoothtop range with the self-cleaning oven feature. Two additional normal cooking cases, 15 and 16, were added based on suggestions from the range industry. Case 15 uses the D-type down-draft grilling range, and case 16 uses the A-type electric range. Cases 1 and 2 were designed to assess effects of differences in cookware material. The number of tests designed to examine cooking behaviors using electric ranges with the range hood off totalled 32 (16 cases,

Table 1. Case description and procedure list.

Cooking Cases	Descriptions	General Procedures
1. Soybean oil (A) (unattended)	500 mL oil in a 26 cm (10 in) diameter stainless-steel (aluminum bottom) frying pan.	Heat on high until ignition.
2. Soybean oil (B) (unattended)	500 mL oil in a 26 cm (10 in) diameter heavy gauge aluminum frying pan.	Heat on high until ignition.
3. Bacon (unattended)	227 g (8 oz) bacon in a 26 cm (10 in) diameter stainless-steel (aluminum bottom) frying pan.	Thaw bacon. Heat on high until ignition.
4. Water - multiple pans (normal)	4 pans: 2.5 L water in 3.8 L (4 qt) stainless-steel (aluminum bottom) sauce pans.	Heat 1 pan of water on high with pan covered, but allowing for pressure release. After water is rapidly boiling, remove cover from pan. Heat the remaining 3 pans and remove the covers one at a time every 20 min after they have reached boiling. Then maintain the boiling another 20 min after all of the covers are removed.
5. Broiled steak (normal)	454 g (1 lb) T-bone steak and 15 mL (1 tbsp) soybean oil in broiling pan.	Thaw meat, preheat broiler for 4 min. Slash meat every 5 cm (2 in). Place broiler such that meat is approximately 8 cm (3.1 in) from the heating element. Broil for 10 min with the door closed. Turn meat and broil for 10 min more with the door partly open.
6. Self-cleaning oven operation with debris (normal)	227 g (8 oz) of raw beef suet.	Divide suet in many (approx. 25) small pieces and distribute evenly in broiler pan. Activate the self-cleaning oven cycle.

Cooking Cases	Descriptions	General Procedures
7. French-fried potatoes in soybean oil (normal→unattended)	227 g (8 oz) frozen french-fried potatoes and 500 mL oil in a 26 cm (10 in) diameter stainless-steel (aluminum bottom) frying pan.	Heat oil to 190 °C (374 °F) on high. Introduce frozen fries to oil. Reduce heat to medium-high and turn fries until done. Increase heat to high until ignition.
8. Macaroni and cheese (normal→unattended)	206 g (7.25 oz) macaroni in 1.42 L (6 cps) water in 2.8 L (3 qt) medium gauge aluminum sauce pan. Additions: 59 mL (4 tbsp) margarine, 59 mL (0.25 cp) skim milk, cheese sauce packet.	Boil water rapidly on high heat. Add macaroni and stir. Boil 9 min. Drain and mix in margarine, milk, and cheese. Place back on burner on high heat.
9. Soybean oil and water (normal→unattended)	1 pan: 500 mL oil in a 26 cm (10 in) diameter stainless-steel (aluminum bottom) frying pan. 3 pans: 2.5 L water in a 3.8 L (4 qt) stainless-steel (aluminum bottom) sauce pot.	Heat oven to 204 °C (400 °F), and heat water on high on three burners. After 9 min, heat oil on high on one burner for 5 min. Decrease heat under oil to medium-low. After 18 min, increase heat under oil to high until ignition.
10. Soybean oil - multiple pans (normal→unattended)	4 pans: 500 mL oil in a 26 cm (10 in) diameter stainless-steel (aluminum bottom) frying pan.	Heat oven to 204 °C (400 °F), and heat oil on high on all burners for 5 min. Decrease heat on all four burners to medium-low. After 15 min, change one burner's heat setting to high until ignition.

Cooking Cases	Descriptions	General Procedures
11. Chicken in soybean oil (normal→unattended)	Approximately 750 g (1.65 lb) of chicken (3 whole legs) in 500 mL soybean oil in a 26 cm (10 in) diameter stainless-steel (aluminum bottom) frying pan.	Heat oil to 190 °C (374 °F) on high. Introduce chicken to oil. Reduce heat to medium and turn chicken every 4 min for 20 min. Increase heat to high until ignition.
12. Chicken in soybean oil (unattended)	Approximately 750 g (1.65 lb) of chicken (3 whole legs) in 500 mL soybean oil in a 26 cm (10 in) diameter stainless-steel (aluminum bottom) frying pan.	Heat oil to 190 °C (374 °F) on high. Introduce chicken to oil. Maintain high heat until ignition.
13. Stir-fry vegetables in soybean oil (normal→unattended)	283 g (10 oz) stir-fry vegetable mix and 50 mL (3.4 tbsp) soybean oil in a 36 cm (14 in) diameter stainless-steel wok with burner ring.	Heat oil to 280 °C (536 °F) on high. Introduce vegetables. Stir vegetables constantly at medium-high heat for 5 min. Increase heat to high until ignition.
14. Stir-fry vegetables in soybean oil (unattended)	283 g (10 oz) stir-fry vegetable mix and 50 mL (3.4 tbsp) soybean oil in a 36 cm (14 in) diameter stainless-steel wok with burner ring.	Heat oil to 280 °C (536 °F) on high. Introduce vegetables. Stir vegetables for 15 s to coat with oil. Maintain heat on high until ignition.
15. Grilled steak (normal)	Grill 454 g (1 lb) T-bone steak on grilling attachment of down-draft range.	Thaw meat, and preheat grill for 5 min. Slash meat every two inches. Place meat on grill. Grill for 5 min, turn meat and grill for 5 min. Repeat.

Cooking Cases	Descriptions	General Procedures
16. Blackened catfish (normal)	Approximately 227 g (8 oz) catfish fillet and 50 mL (3.4 tbsp) melted butter in a 26 cm (10 in) diameter stainless-steel (aluminum bottom) frying pan.	Heat butter to 100 °C (212 °F). Pre-heat pan on high for 3 min. Put melted butter in pan. Place fillet in pan. Sprinkle blackening seasonings on the exposed side. Heat for 2 min, turn and season, heat for 2 min, and remove from heat.

2 tests/case). The initial tests and their repeats were randomized within each range type to minimize systematic errors. Table 2 lists the tests in the order they were conducted. The times listed in Table 2 are discussed in Section 4.1.

Cases 5, 9, and 11 were repeated (an additional two tests each) with the range hood on to evaluate the effects of the range hood's air flow on the measurements. The high-flow-capacity range hood was used with its highest setting for each of these tests. Air flow velocities in the hood were measured with a bidirectional probe [4,5]. Phase I test results were insensitive to the flow induced by a moderate-flow-capacity range hood [3]. Cases 9 and 11 were repeated (an additional two tests each) on the B-type gas range with the range hood inactive to characterize the effects of range type on the measurements. The additional tests to examine these variables totalled 10 (5 cases and 2 tests/case). Figure 1 shows the categories of tests that were conducted.

One additional test was not fully instrumented and therefore is not included in the case list. It characterized the residual heating effect of a deenergized electric burner. A stainless-steel/aluminum-bottom frying pan, like those used for the cooking tests with 500 mL of soybean oil, was placed on the large burner on range A with thermocouples monitoring burner, pan, and food temperatures. At 30 s to 60 s before previously experienced ignition times, the burner was deenergized, and data were obtained regarding thermal inertia and time to temperature decrease. This information about time to temperature decrease was used to ascertain the minimum period preceding ignition required to shut down the range in order to prevent reaching ignition conditions. In other words, this established the latest shutdown time for this test after which ignition would not occur. Only one test was conducted so the results only provide a rough estimate of this time. Additional testing by the CPSC was planned to provide more data on this issue.

2.2 Instrumentation

A variety of instruments was used to characterize the pre-ignition cooking environment. Measurements focused on those aspects showing the most potential from Phase I. Table 3 describes the instrumentation used in the discrimination test series.

2.2.1 Gas Analyzers

A gas-sampling probe was located 23 cm (9 in) above the center of the large burner surface in order to monitor the gases evolved from the cooking process. The probe consisted of a 2.4 m (8 ft) length of 6.4 mm (0.25 in) OD copper tubing. The probe is portrayed in Figure 2. A pump was used to draw gases through the probe to a rack of analyzers. A portion of the unaltered sample passed through a total-hydrocarbon (HC) analyzer. The remainder of the flow passed through a dry-ice trap, a paper filter, and a tube of desiccant, and then into a combination carbon dioxide (CO_2) and carbon monoxide (CO) analyzer. Heating tape was wrapped around the probe from approximately 7 cm (2.5 in) above the probe tip to the sample inlet for the hydrocarbon analyzer. The heating tape was maintained at approximately 50 °C (122 °F) by three variable current supplies in order to limit condensation. The hydrocarbon analyzer was a

Table 2. Experimental test matrix.

Test No.	Range Type	Hood Status	Case No.	Case Description	Normal/ Unattended	$t_{ignition}$, s	t_{normal}, s
1	Electric (A)	Off	1	Oil (stainless steel)	U	608	
2	Electric (A)	Off	3	Bacon	U	605	
3	Electric (A)	Off	12	Chicken (unattended)	U	1849	
4	Electric (A)	Off	5	Broiled steak	N		1528
5	Electric (A)	Off	4	Water	N		4139
6	Electric (A)	Off	7	Fries	NU	1236	735
7	Electric (A)	On	9	Water, oil	NU	2359	1980
8	Electric (A)	Off	11	Chicken (normal)	NU	2668	1520
9	Electric (A)	On	5	Broiled steak	N		1518
10	Electric (A)	Off	13	Stir-fry (normal)	NU		620
11	Electric (A)	Off	16	Catfish	N		480
12	Electric (A)	Off	9	Water, oil	NU	2358	1980
13	Electric (A)	Off	10	Oil (4 pans)	NU	1632	1260
14	Electric (A)	Off	14	Stir-fry (unattended)	U		
15	Electric (A)	On	11	Chicken (normal)	NU	2699	1530
16	Electric (A)	Off	5	Broiled steak	N		1500
17	Electric (A)	Off	3	Bacon	U	561	
18	Electric (A)	Off	2	Oil (aluminum)	U	594	
19	Electric (A)	Off	4	Water	N		4440
20	Electric (A)	Off	8	Macaroni & cheese	NU	3197	945
21	Electric (A)	Off	16	Catfish	N	510	489
22	Electric (A)	Off	7	Fries	NU	1214	705
23	Electric (A)	Off	13	Stir fry (normal)	NU	1157	610
24	Electric (A)	Off	1	Oil (stainless steel)	U	637	
25	Electric (A)	Off	11	Chicken (normal)	NU	2721	1520
26	Electric (A)	Off	14	Stir-fry (unattended)	U	1005	
27	Electric (A)	Off	2	Oil (aluminum)	U	616	
28	Electric (A)	On	9	Water, oil	NU	2409	1980
29	Electric (A)	On	5	Broiled steak	N		1500
30	Electric (A)	Off	10	Oil (4 pans)	NU	1688	1260
31	Electric (A)	Off	12	Chicken (unattended)	U	1858	

Test No.	Range Type	Hood Status	Case No.	Case Description	Normal/ Unattended	$t_{ignition}$, s	t_{normal}, s
32	Electric (A)	Off	9	Water, oil	NU	2379	1980
33	Electric (A)	Off	8	Macaroni & cheese	NU		1016
34	Electric (A)	On	11	Chicken (normal)	NU	2767	1535
35	Gas (B)	Off	9	Water, oil	NU		1980
36	Gas (B)	Off	11	Chicken (normal)	NU	4387	1560
37	Gas (B)	Off	9	Water, oil	NU		1980
38	Gas (B)	Off	11	Chicken (normal)	NU	4170	1580
39	Electric (C)	Off	6	Self-cleaning	N		
40	Electric (C)	Off	6	Self-cleaning	N		
41	Electric (D)	On to off	15	Grilled steak	N		1609
42	Electric (D)	On to off	15	Grilled steak	N		1618

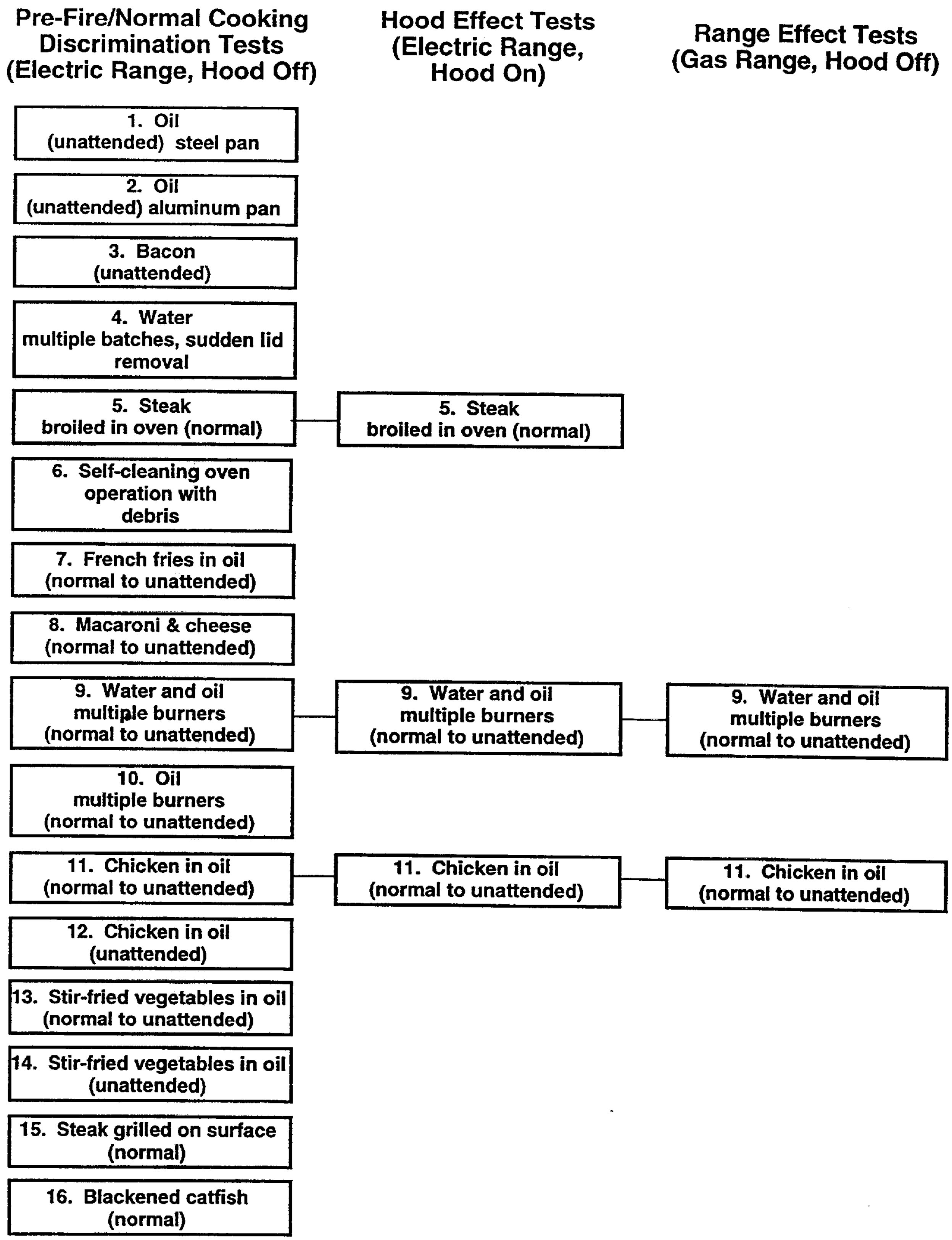

Figure 1. Categories of tests.

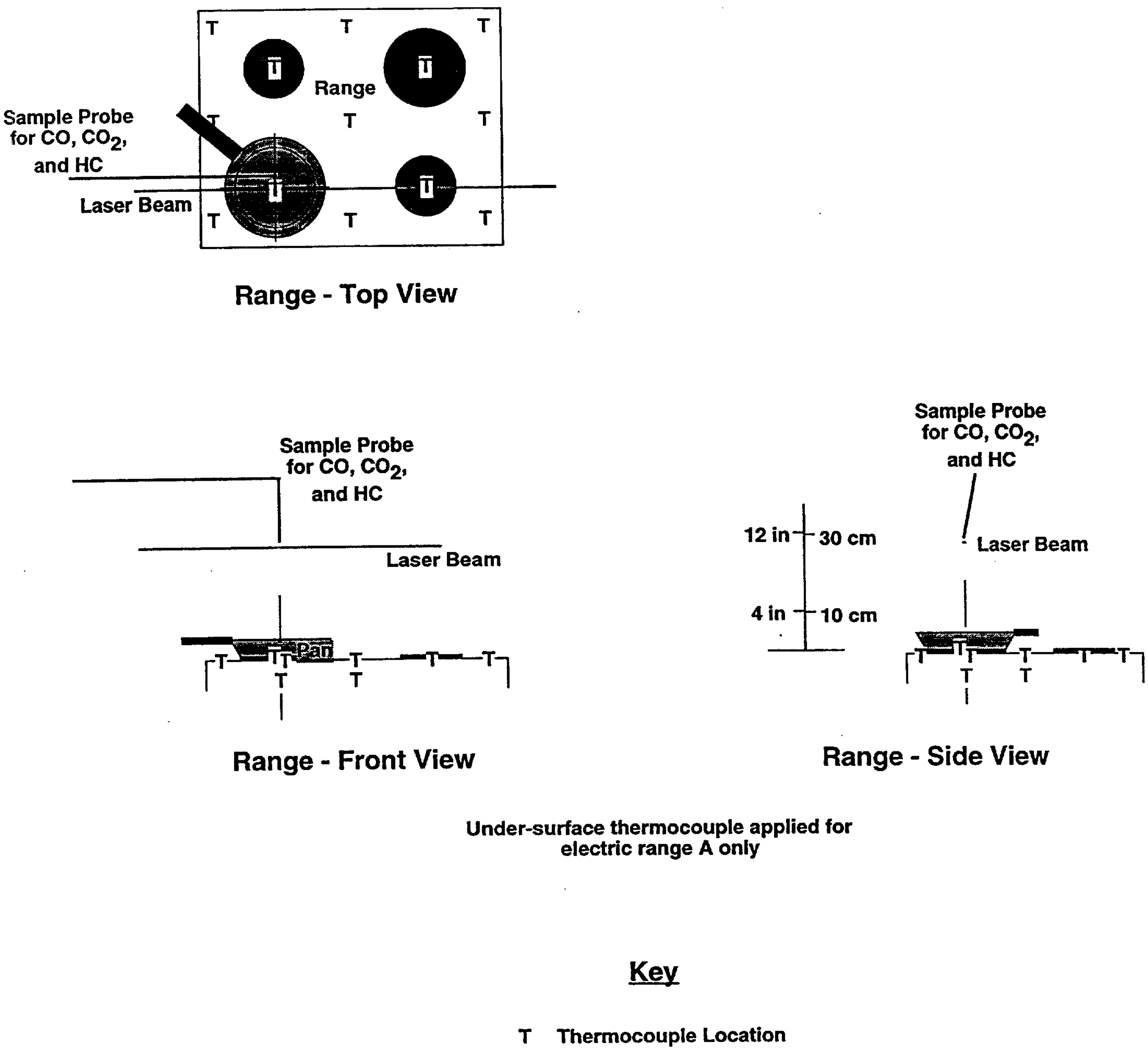

Figure 2. Locations of near-range probes and thermocouples.

Table 3. Instrumentation list.

Instrument	Measurement	Location
Laser (HeNe) and photodiodes	Laser attenuation and scattering by smoke related to relative aerosol mass concentration above cooking area	23 cm (9 in) above burner surface. See Figure 3
Thermocouples	Temperatures	See Figures 2, 3, 4
Total-hydrocarbon analyzer	Hydrocarbon gas volumetric concentration as methane equivalent (only those not condensable < 50°C)	Above hydrocarbon food, see Figure 2
Carbon dioxide analyzer	Carbon dioxide volumetric concentration (dry basis)	Above hydrocarbon food, see Figure 2
Carbon monoxide analyzer	Carbon monoxide volumetric concentration (dry basis)	Above hydrocarbon food, see Figure 2
Bidirectional probe [4,5]	Range-hood duct flow velocity	30 cm (12 in) before last vertical section of duct
Video camera	Visual record of cooking area phenomena	Outside room, focused on cooking region
Data acquisition system	Data collection	Outside room

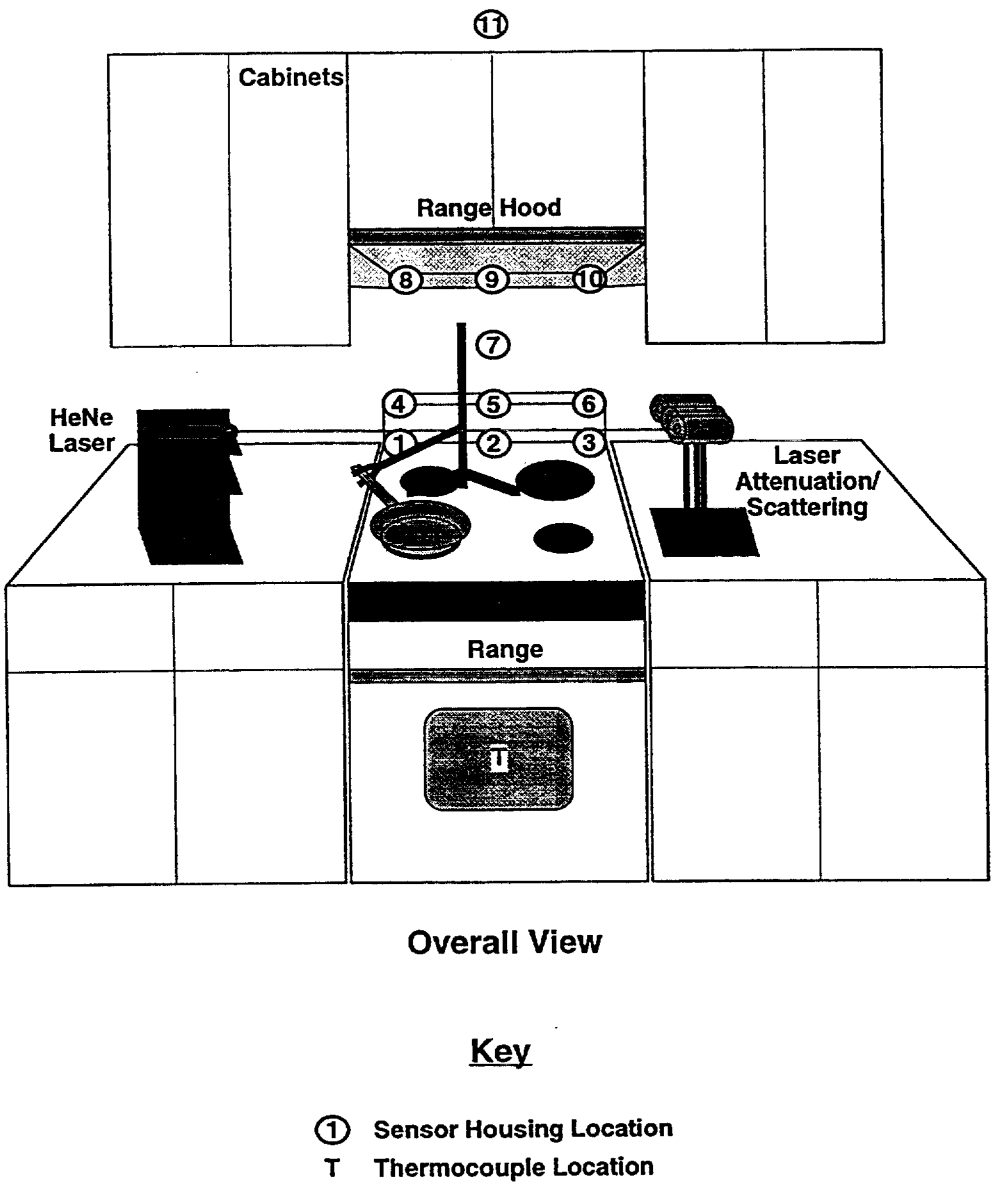

Figure 3. Schematic of near-range configuration, instruments, sensors, and thermocouples.

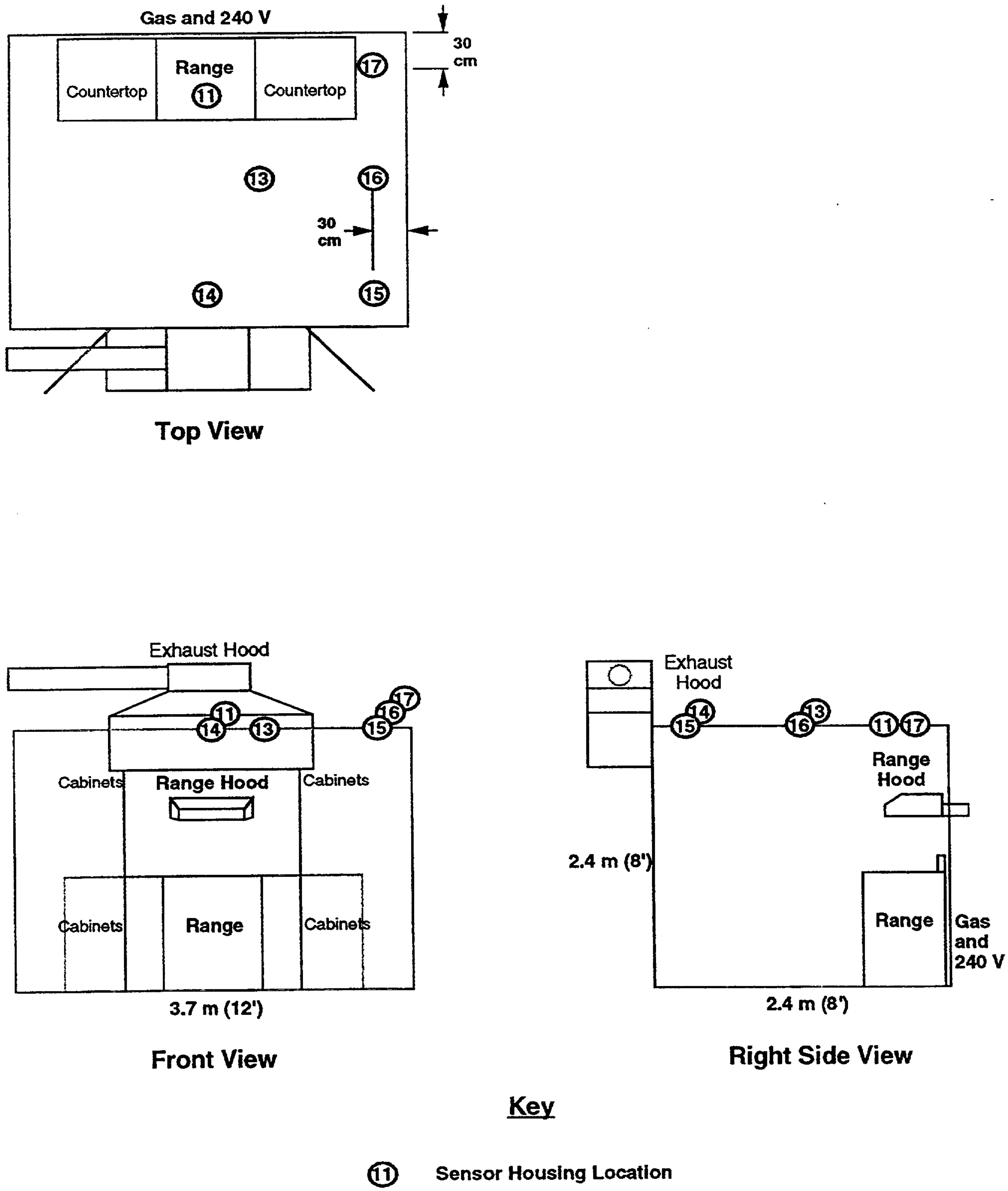

Figure 4. Locations of sensors and thermocouples away from the range.

Rosemount Model 400A*. The hydrocarbon measurement was calibrated in terms of the equivalent concentration of methane. The combination CO_2 and CO analyzer was an Infrared Industries Dual Gas Analyzer and used non-dispersive infrared technology. Both CO_2 and CO concentrations were measured from dry gas samples.

2.2.2 Thermocouples

Thermocouples were used to measure temperatures in three general areas: near the food, around the range, and above the range. For the area near the food, thermocouples were placed at the center of each burner and contacted to the pan bottom if a pan was present. The contact was not through permanent fastening, but was ensured by spring loading the thermocouple. For electric range A, the thermocouple was located inside the center coil of the burner element and did not contact the element itself. For the gas range, the thermocouples were also bent in order to contact the pan bottom, and for protection, ceramic tubes were placed around the thermocouples in the vicinity where they passed through the flame. One thermocouple was placed in the food near the center of the pan. The pan and food thermocouples were all Omega model number KMQSS-020(G)-12 [stainless-steel sheathed, 0.51 mm (0.020 in) sheath diameter, K-type (Chromel-Alumel), grounded, 30 cm (12 in) long]. For range A, additional thermocouples were located on the drip pan centered below the burner and on the surface beneath the drip pan centered below the burner.

For the area around the range, thermocouples were placed on the top surface at left, center, and right positions along the front and midway back from the front of the burner area of the range. For range A, a thermocouple was also placed beneath the top surface of the range at the center left to right and front to rear of the burner area. These locations are depicted in Figure 2. A thermocouple was placed on the upper surface inside the oven 5.5 cm (2.2 in) behind the door opening and centered across the oven.

For the area above the range, one thermocouple was placed above the food in the buoyant plume approximately 3 mm (0.1 in) below the end of the sample probe. Thermocouples accompanied each of the sensor-group sites located on or near the range hood as well as those located on the ceiling. These are shown in Figures 3 and 4. A pair of thermocouples were placed on the inside surface of the front edge of the range hood. These thermocouples were Omega model no. SA1-K [30 gauge, 0.25 mm (0.010 in) diameter, K-type (Chromel-Alumel), 91 cm (36 in) long, Teflon insulated, self-adhesive backing]. A thermocouple was also located under each of the left and right filter elements of the hood. These thermocouples and those used at each sensor site and on the range surface were Omega model no. 5TC-GG-(K)-30-(72) [30 gauge, 0.25 mm (0.010 in) diameter, K-type (Chromel-Alumel), 183 cm (72 in) long, glass braid

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*Certain commercial equipment, instruments, or materials are identified in this report to specify adequately the experimental procedure which allows its duplication. Such identification does not imply recommendation, endorsement, or disapproval by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose. Some of the materials or equipment were used in a manner or conditions for which they were not designed.

insulation]. The assortment of thermocouples used for the experiments cost approximately $10 to $30 each.

2.2.3 Laser-Attenuation and Scattering Apparatus

Laser attenuation and scattering measurements were performed in order to monitor the quantity and characteristics of the smoke produced during each test. Laser attenuation is due to light reflection and absorption and is the fraction of initial laser intensity that does not transmit through a cloud of particulates. A laser-attenuation system consists of a laser and a light detector, such as a photodiode, aligned optically so the laser light passes through the medium to be measured and into the photodetector. In Phase I, two laser-attenuation systems were used at two different heights above the burner of interest, 18 cm (7 in) and 28 cm (11 in) **[3]**. For Phase II, only one laser-attenuation system was used at a height of 23 cm (9 in), but in addition to an attenuation measurement, attempts were made to gather light-scattering data at two angles. The He-Ne laser-attenuation and scattering system was arranged such that the beam passed through the axis of symmetry of the pan of focus. The optics were open and accessible rather than self-contained such as in photoelectric smoke detectors. The He-Ne laser was a Melles Griot model number 05-LLR-811 and generated a 1 mW beam. It was mounted on a vertical-translation stand to enable alignment. The laser and photodiode detector are depicted in Figure 3.

Laser-light scattering is the fraction of initial laser intensity that is reflected by a cloud of particulates. Relative scattered-light intensities were measured by two additional photodiodes which were mounted on optical rods and connected to power sources and signal amplifiers. The scattering was measured at 5° and 10° from the forward direction. The photodiodes (Hamamatsu S1337-1010BQ, 100 mm^2 active surface area), operational amplifier circuits, power source box, and mountings with connections for power input and signal output were the same as those used by Pitts et al **[4]** and for Phase I **[3]**. An iris was also placed in front of each photodiode and opened to approximately 4 mm (0.16 in) to reduce the amount of stray light that could reach the photodiodes. For the scattering photodiode detectors, narrow band-pass filters (Melles Griot 03FIL006, 632.8 nm) were installed to only allow light of the laser's wavelength to pass through. The pre-test output of the attenuation photodiode amplifier with unobstructed laser light was 7 V - 9 V.

2.2.4 Video and Photographic Equipment

As in Phase I, a VHS video camera was centered outside of the doorway of the laboratory and focused to capture a view of the cooking scene. Close views were recorded at early stages of heating and wider views were recorded when smoke generation began. A zoom-lens camera was used to take still 35 mm slide photographs of the test area and cooking process.

2.3 Sensors and Detectors

This section describes the readily available gas sensors and smoke detectors which were installed to determine their capability to differentiate between normal and pre-ignition conditions.

2.3.1 Gas Sensors

Criteria were developed for the sensors to be used in the study as part of the Phase I NIST effort. The following list highlights the key sensor selection considerations. These criteria were for test purposes only and are not universal guidelines for sensor selection.

1. Available as a functioning model, even if a prototype.
2. Cost less than $250 for one or $500 for multiple samples.
3. Reusable - not ruined, destroyed, or altered by detection of the pre-ignition signature or by a power off/on cycle.
4. Unobtrusive, with potential for additional miniaturization or installation within/on the range without obstruction of cooking activities, counter space, or hood flows.
5. Include instructions or ready access to consultation with the manufacturer.
6. Have a means of perceiving the pre-ignition signature from a range-mounted location, or if non-range-mounted, require little modification or installation effort.
7. Capable of continuous analog output or an analog alarm signal output.
8. Not susceptible to contaminant accumulation.

Tin-oxide gas sensors were selected from two manufacturers based on these criteria and applied to this investigation. The first, Figaro, markets several Taguchi-type thin-film sensors with sensitivities geared towards specific groups of gases. The sensors used were those marketed as sensitive to general hydrocarbons (TGS813), general alcohols and volatile organic compounds (TGS822), general cooking gases (TGS880), cooking alcohols (TGS882), and water vapor (TGS883). Except for the water-vapor sensor, each of these sensors responded to several gases including methane, carbon monoxide, ethanol, propane, isobutane, and hydrogen, but with different combinations of sensitivities. The gas sensor sensitivities were affected by both temperature and humidity so sensor outputs resulted from combined reaction to levels of the hydrocarbon gas mixture, water vapor, and temperature. The effects of the three variables on sensor output were in the same direction, i.e., increased levels of each variable increased sensor output. Costs for the gas sensors ranged from $10 to $25 each.

The sensors were connected to output circuits and 15 V dc power supplies. The sensors' internal heating elements were supplied with a 5 V heating voltage. Three to six sensors were powered by each power supply. Sensors were placed individually or with one or two others in a sensor housing. The housings consisted of 4.4 cm (1.75 in) long pieces of 7.0 cm (2.75 in) OD bakelite tubing with 0.3 cm (0.12 in) wall thickness attached to a 0.5 cm (0.19 in) thick disk of bakelite at one end with mounting holes for the sensors.

Carbon monoxide sensors were purchased from Capteur Sensors and Analysers, Ltd. These were thick-film tin-oxide sensors (part no. 1C-G-S-0-05-CM-E-07) and came with a filter to eliminate hydrocarbons. Their cost was approximately $70 each. Each CO sensor used a 5 V dc power supply and had its own printed circuit board to regulate the heating element to maintain a constant temperature between 400 °C (750 °F) and 500 °C (930 °F). The sensor's resistance varied depending on the gas concentration, and a simple voltage-divider circuit was constructed to provide an output signal.

The approximate sensor locations are shown in Figures 3 and 4. Table 4 summarizes the sensors used in the discrimination test series. Table 5 is the key for all of the individual sensors

Table 4. List of sensors.

Sensor	Measurement	Location
Thermocouples	Temperatures	See Figures 2, 3, 4
Smoke-particulate sensors (4 ionization and 8 photoelectric)	Voltage representing detector response and transition to alarm state	Several locations. See Figures 3, 4
Gas sensors (tin-oxide type): carbon monoxide, hydrocarbons, volatile organics, cooking gases, cooking alcohols, water vapor	Voltage representing response to contacting gases	Several locations. See Figures 3, 4

Table 5. Identification key for sensors and detectors.

Sensor Group or Designation	Associated Sensors, Detectors
A	General-hydrocarbon sensor General-alcohols (VOCs) sensor
Ah	Same as A with heat resistant cases
B	Total-cooking-gases sensor Cooking-alcohols sensor Water-vapor sensor
C	Total-cooking-gases sensor
D	Carbon monoxide sensor
X	Photoelectric smoke detector
Z	Ionization smoke detector
T	Thermocouple temperature sensor

and sensor groups and types employed in the following tables and figures. The locations of the sensors and sensor groups are depicted in Figures 2-4. Table 6 lists the sensors groups and their relative orientations. Twenty-five sensors were mounted in 16 housings in 11 locations near the range. A site for various sensors was not a single point, but an area where some combination of sensors was clustered. Two of the general sensors were ordered with special heat-resistant housings, and these were placed at site 9 near the majority of food ignitions. The heat-resistant versions cost about $25 each which was about twice as much as the regular models.

2.3.2 Smoke Detectors

The photoelectric-type smoke-detector models used were a type available for household or commercial use. They consisted of a detector module, mounting base, and test cable. The model numbers were Detection Systems DS-250, MB4W, and TC2000, respectively. The base diameter was 16 cm (6.3 in). The plug-in test cable produced an analog voltage signal. The eight detectors were all powered by a single 12 V dc power supply. Alarm signals were also recorded from the photoelectric detectors. These detectors cost about $45 each.

The ionization-type smoke detectors were an inexpensive model ($10-$15 each) designated for home use. The manufacturer donated three of the four units used and provided modification instructions that enabled retrieval of analog responses and alarm voltages without affecting product performance. The ionization-detector diameter was 14.2 cm (5.6 in). The four detectors were each powered by individual 9 V batteries.

Both types of smoke detectors were only used for providing an alarm signal and not for quantitative smoke-obscuration measurements. The detectors were all listed and labeled by Underwriters Laboratories (UL). The detector locations are shown in Figures 3 and 4 and described in Table 6 using Table 5 as the key.

2.4 General Procedure

Each experiment began with no heat applied to the food and ended soon after ignition of the food or upon completion of the cooking procedure. The general steps involved in these experiments are provided in Appendix A. Usually two or three personnel would conduct each test. Because of the frequency with which fires occurred, additional help was often notified when the food was about to ignite. A test log sheet was used to make notes of the times and nature of phenomena and observations. A sample blank sheet is included as Appendix B.

2.5 Data Acquisition, Reduction, and Plotting

Data acquisition, reduction, and plotting were accomplished using the same equipment and software as in Phase I. A more complete description of these processes is included in the Phase I report [3]. A computer, scanner box, and digital voltmeter constituted the data acquisition system. The data system had a capacity of 60 instrument channels and 160 thermocouple channels, but 56 and 42, respectively, were actually used. The data system was capable of scanning the 98 channels at 8 s intervals, which was the setting for most tests, but a few of the

Table 6. Sensor and detector location descriptions.

Site No.	General Location	Sensor Groups	Specific Sensor-Housing Orientation
1	Base of splash panel at left edge of range	C	Centered at nominal site location
2	Base of splash panel at center of range	C	Centered at nominal site location
3	Base of splash panel at right edge of range	C	Centered at nominal site location
4	Top of splash panel at center of range	C	Centered at nominal site location
5	Top of splash panel at center of range	C	Centered at nominal site location
		X	Centered 1.3 cm (0.5 in) above C housing, contacting both 7A and 7B
6	Top of splash panel at right edge of range	C	Centered at nominal site location
7	On rear wall just below range hood at center of range	A	Contacting bottom of range hood with left edge of housing against the plane of range symmetry
		B	Contacting bottom of range hood with right edge of housing against the plane of range symmetry
8	Front of range hood at left edge of range	C	Centered at nominal site location
9	Front of range hood at center of range	Ah	Contacting front edge of range hood with left edge of housing against the 9D housing
		B	Contacting front edge of range hood with right edge of housing against the 9D housing
		D	Contacting front edge of range hood centered on hood
		X	Oriented vertically with base plane along plane of hood front edge and bottom centered over and contacting 9D housing.
10	Front of range hood at right edge of range	C	Centered at nominal site location

Site No.	General Location	Sensor Groups	Specific Sensor-Housing Orientation
11	On the ceiling over front, center of range hood, i.e., above site 9, 46 cm (18 in) from rear wall	A	Contacting the front of 11X with left edge of housing against the plane of range symmetry
		B	Contacting the front of 11X with right edge of housing against the plane of range symmetry
		D	Contacting both 11A and 11B to the front, centered on plane of range symmetry
		X	Centered at nominal site location
13	On the ceiling, centered front to back, 106 cm (42 in) from right wall	X	Centered at nominal site location
14	On the ceiling, centered left to right, 15 cm from front wall	X	Centered at nominal site location
		Z	Contacting 14X to the right, 15 cm (6 in) from front wall
15	On the ceiling, 30 cm (12 in) from right wall and front wall (square)	X	Centered at nominal site location
		Z	Contacting 15X to the right, 30 cm (12 in) from front wall
16	On the ceiling, centered front to back, 30 cm (12 in) from right wall	X	Centered at nominal site location
		Z	Contacting 16X to the right, centered front to back
17	On the ceiling, 30 cm (12 in) from right wall and rear wall (square)	X	Centered at nominal site location
		Z	Contacting 17X to the right, 30 cm (12 in) from rear wall

longer tests utilized 10 s, 12 s, or 30 s time intervals due to the expected slow rates of change of the measured variables.

A data acquisition program developed at the Building and Fire Research Laboratory was used in conjunction with a computer. The program produces data files as follows: ascii test descriptions are placed at the top of the file, followed by digitized background readings, range calibration measurements, and finally the time dependent test data.

The reduction of data was performed with RAPID **[6]** software which was developed at NIST especially for fire tests. More details concerning the use of RAPID are available in the Phase I report **[3]**. RAPID requires an input data file of data collected by the data acquisition system and a program control file which contains the data channel descriptions and command instructions for data analysis. A sample program control file is included as Appendix C. The final output of the reduction process is a file containing the reduced data in columns. This file is readable by a variety of computer plotting and analysis programs. A complete set of the data in electronic form will be available through the CPSC.

Data plotting was performed on a Macintosh Centris 650 with Kaleidagraph version 3.0 software. The use of Kaleidagraph is described in the Phase I report **[3]**. A set of 11 plots was created for each test to visually inspect the time behavior of the measured variables. These plots are attenuation, carbon monoxide, selected hydrocarbons, ionization detectors, photoelectric detectors, site 11 gas sensors, site 7 gas sensors, site 9 gas sensors, temperatures near the food, selected temperatures on the range, and selected temperatures above the range surface. Similar plots for certain tests will be presented as examples in Section 3. Some data smoothing was employed to clarify general trends in the midst of large signal fluctuations. Smoothing is noted on the appropriate plots. A description of smoothing techniques is in the Phase I report **[3]**.

3.0 Results

3.1 General Experimental Results

Selected plots of measured quantities are included in this section with notes regarding particularly interesting features. Primarily, results from baseline tests performed on the electric range A will be shown in this section. A discussion of range and hood effects is provided in Section 4.3. Statistical analyses of the test measurements are provided in Section 4. A small number of tests are used as examples because of the large total number of measurements for each of 42 tests. The trends are typical although there are some variations in detailed behavior and measured values from test to test. Important quantitative differences are addressed in Section 4.

3.2 Gas Concentrations

The results of gas-analyzer measurements for two tests are shown in Figures 5 and 6. Figure 5 is a plot of CO, CO_2, and total-hydrocarbon concentrations versus time for a test of french-fried potatoes cooked in 500 mL of soybean oil. The concentrations of CO and CO_2 were measured on a dry basis (water removed). The concentration unit of parts per million is designated by ppm. The CO_2 concentration increased from an initial background level of 0.1%

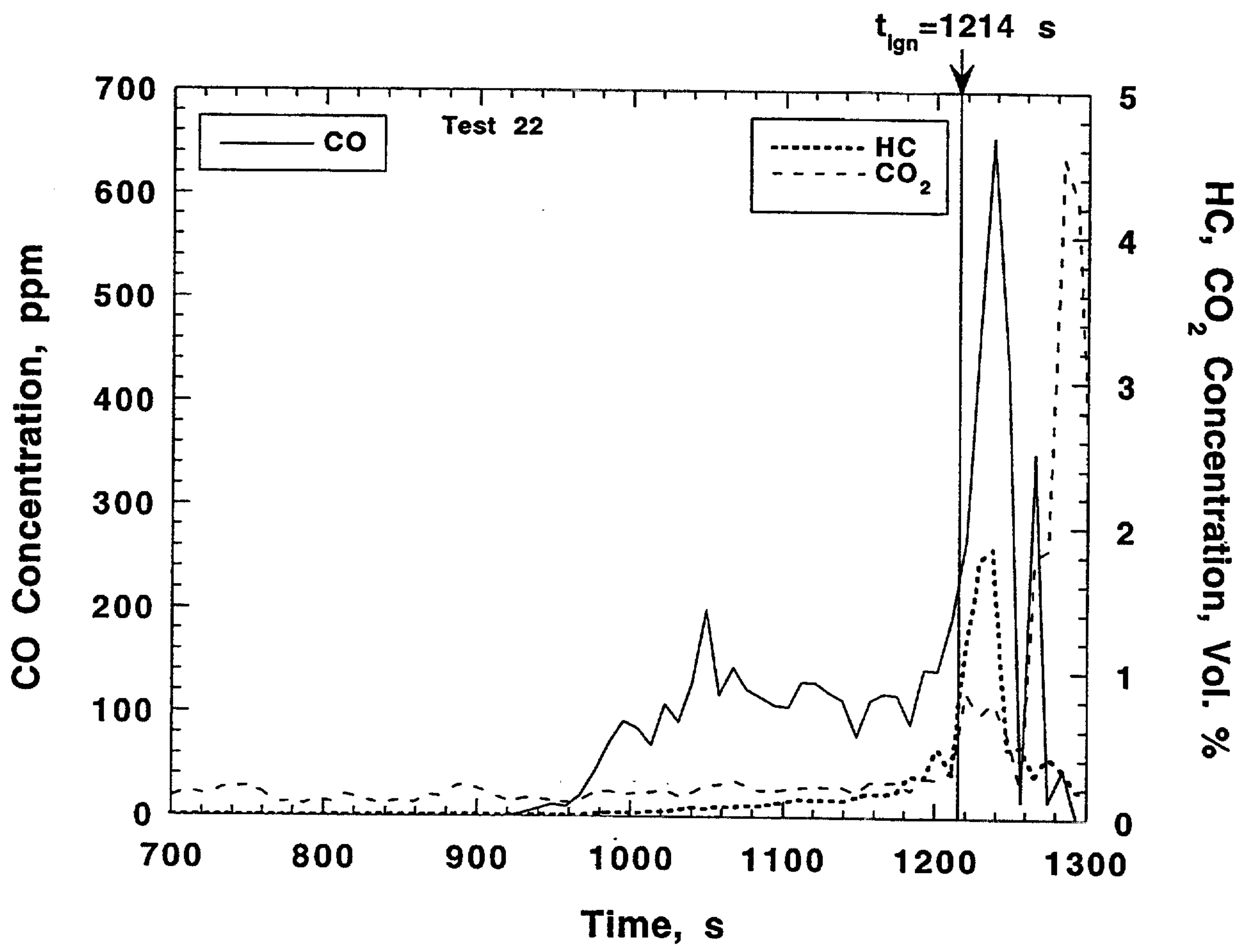

Figure 5. CO, hydrocarbon, and CO_2 concentrations versus time for french-fried potatoes in soybean oil (normal→unattended).

to about 0.3% before ignition. The CO concentration increased from 0 ppm to about 200 ppm with all of the rise occurring in the 300 s preceding ignition. The hydrocarbon concentration increased from 0% to 0.5% over about the same period as CO. After ignition, CO and hydrocarbon concentrations continued to rise because the lid used to smother the fire increased interior pan and food temperatures and thus smoke production. The late peak of CO_2 concentration reflects the use of the fire extinguisher to cool the pan and extinguish reignitions.

Figure 6 shows the corresponding results for a test of blackened catfish. The ignition line appears delayed relative to the analyzer signals because for this particular test, the food ignited about 30 s after the pan was removed from the hot burner and placed on a cold burner away from the gas sampling probe. The CO_2 concentration remained near its background level through 480 s when the pan was removed from the heat. No extinguisher was used so the CO_2 level remained low. The CO concentration increased from 0 ppm initially to about 1200 ppm at 480 s with most of the rise occurring after 380 s. The hydrocarbon concentration increased from 0% to 2% between 240 s and 480 s.

3.3 Gas-Sensor Responses

There are a larger representation of gas-sensor plots included compared to any other sensor type because there were 25 individual gas sensors. The focus of the figures is on those sensors that were located along the plane of symmetry of the range and responded with relative strength. The plots show sensor output voltage versus time. Output voltages have had initial background voltages subtracted from them. The responses of the hydrocarbon- and alcohol-gas sensors at sites 7, 9, and 11 for a test of french-fried potatoes cooked in 500 mL of soybean oil are shown in Figures 7, 8, and 9. The water-vapor and CO-sensor responses for the same sites and test are shown in Figure 10. In each plot, the responses to the introduction of the fries to the hot oil at 285 s are shown. Figure 11 shows the responses of the hydrocarbon sensors at site 9 for a blackened catfish test with no ignition. Figure 12 shows the responses of the hydrocarbon sensors at site 9 for unattended chicken in 500 mL of soybean oil.

3.4 Smoke-Detector Responses

The two kinds of smoke detectors had different cooking condition responses as they reached alarm states. The photoelectric detectors simply changed from a nonalarm zero voltage value abruptly to an alarm-state voltage of 5 V. Figure 13 shows the output signals for all of the photoelectric detectors versus time for a french-fries test. The ionization detectors reacted in a gradual fashion related more closely to the amount of smoke contacting them. When the voltage output crossed zero and became negative, the alarm was activated. Figure 14 shows the output signals for the four ionization detectors for the same french-fries test. Figures 15 and 16 are the corresponding plots of photoelectric and ionization detector outputs for a broiled-steak test.

3.5 Temperatures

The plots of temperature are divided into two categories: near the pan or food, and on the range upward to the range hood.

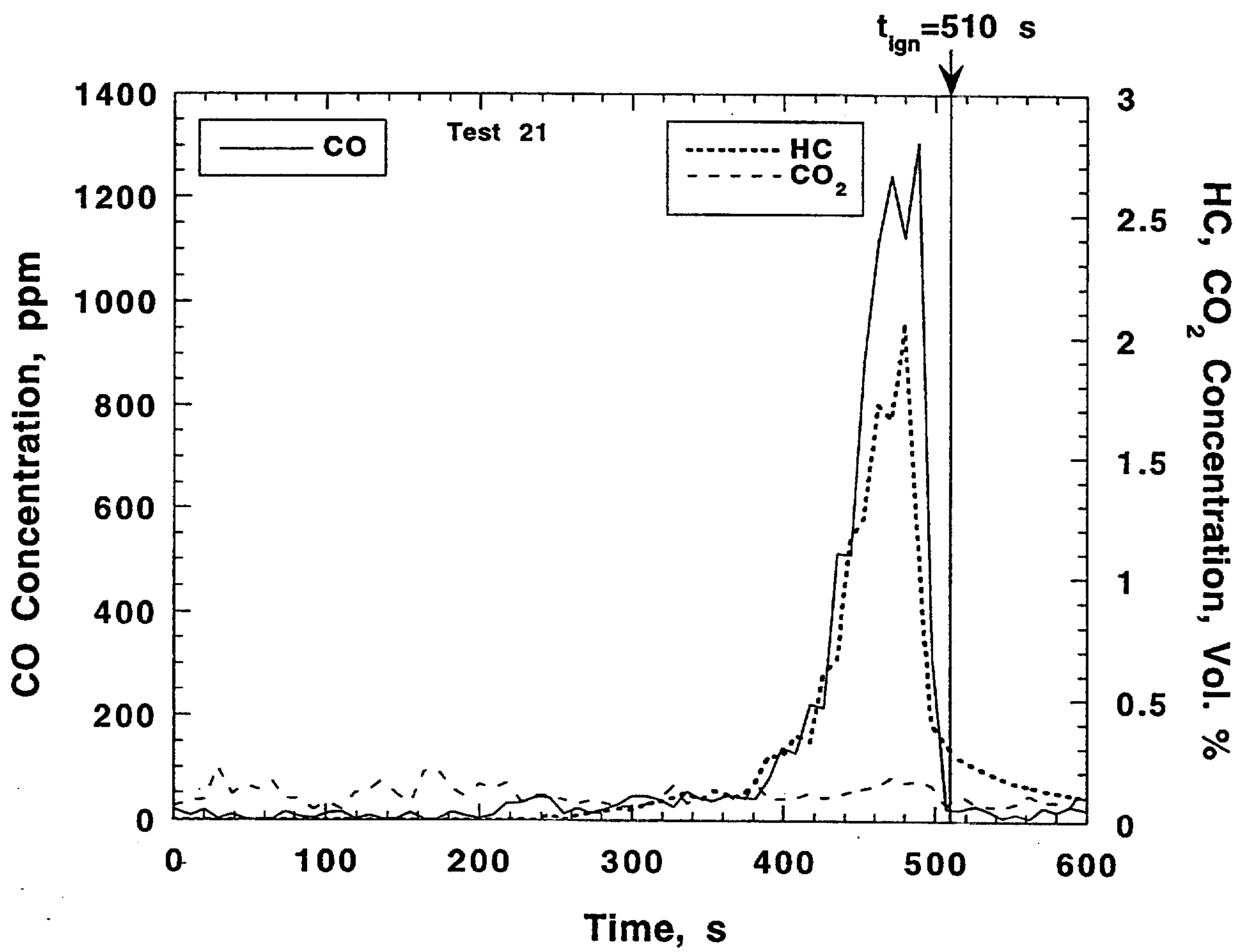

Figure 6. CO, hydrocarbon, and CO_2 concentrations versus time for blackened catfish (normal).

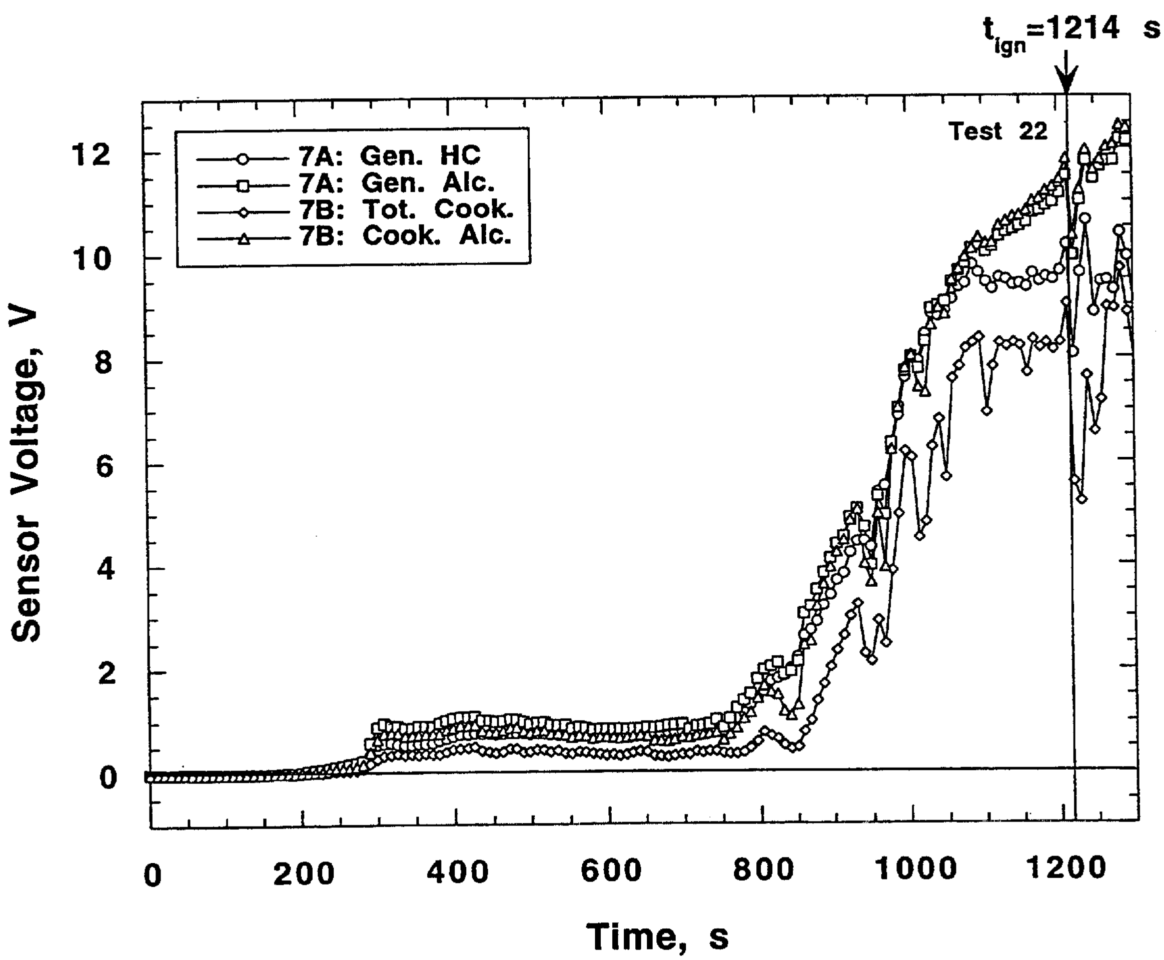

Figure 7. Site 7 hydrocarbon-sensor responses versus time for french-fried potatoes in soybean oil (normal→unattended).

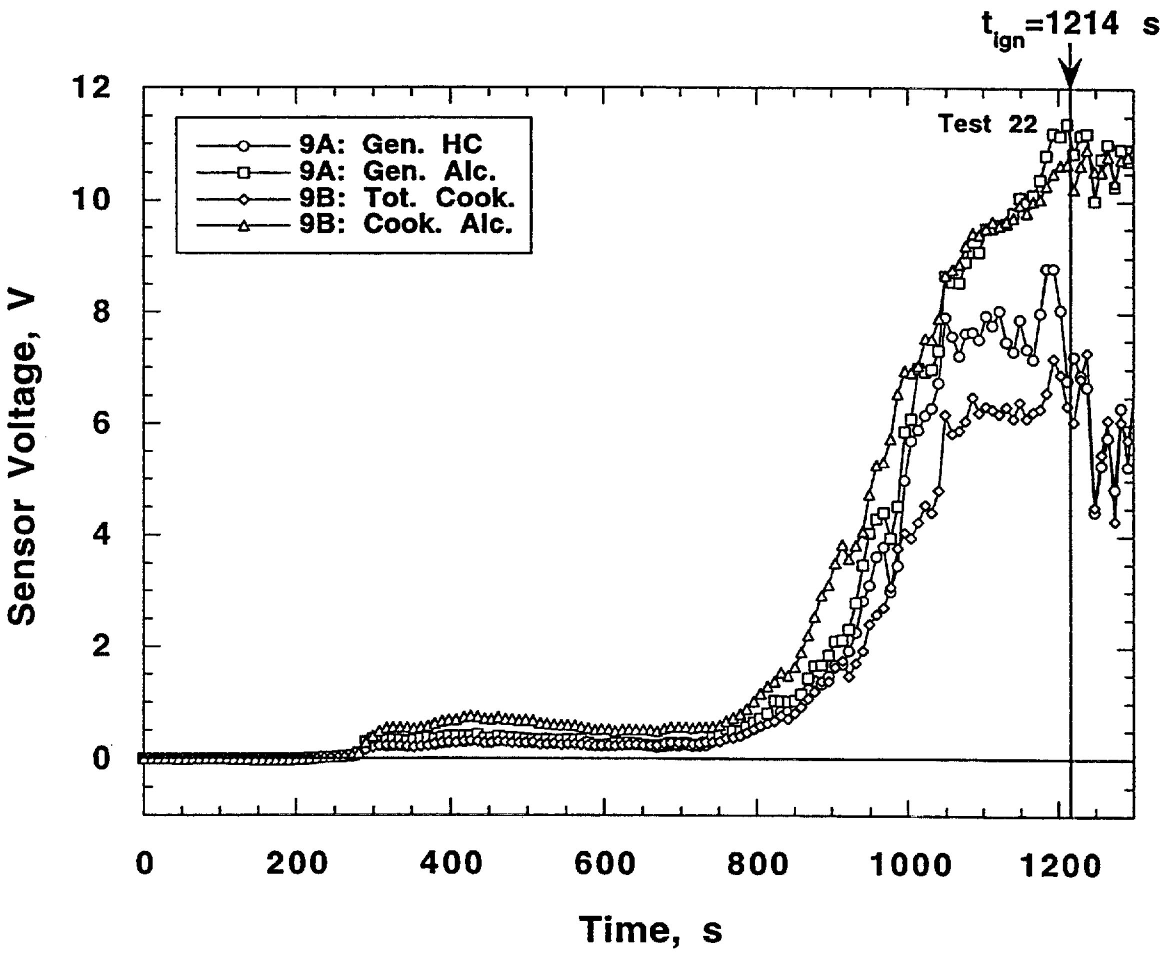

Figure 8. Site 9 hydrocarbon-sensor responses versus time for french-fried potatoes in soybean oil (normal→unattended).

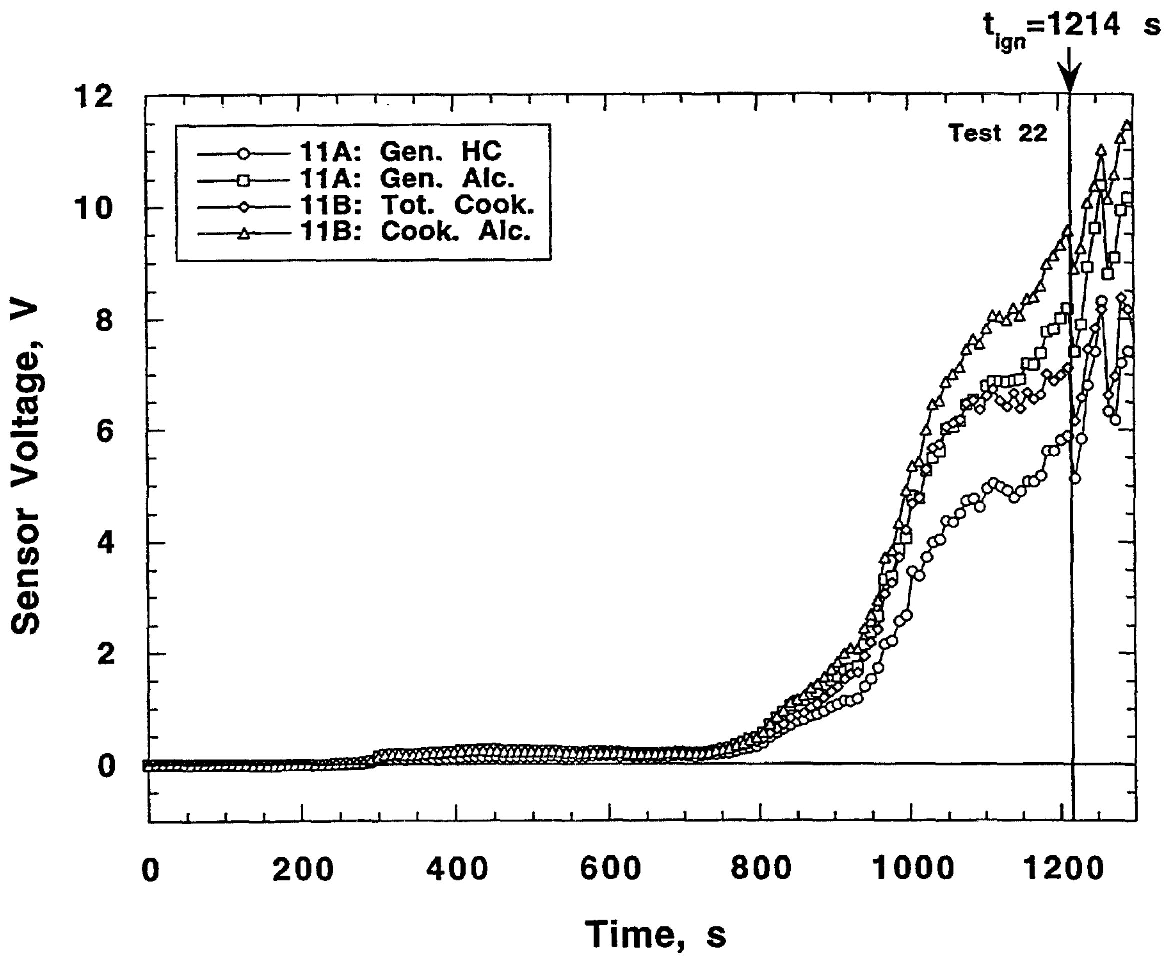

Figure 9. Site 11 hydrocarbon-sensor responses versus time for french-fried potatoes in soybean oil (normal→unattended).

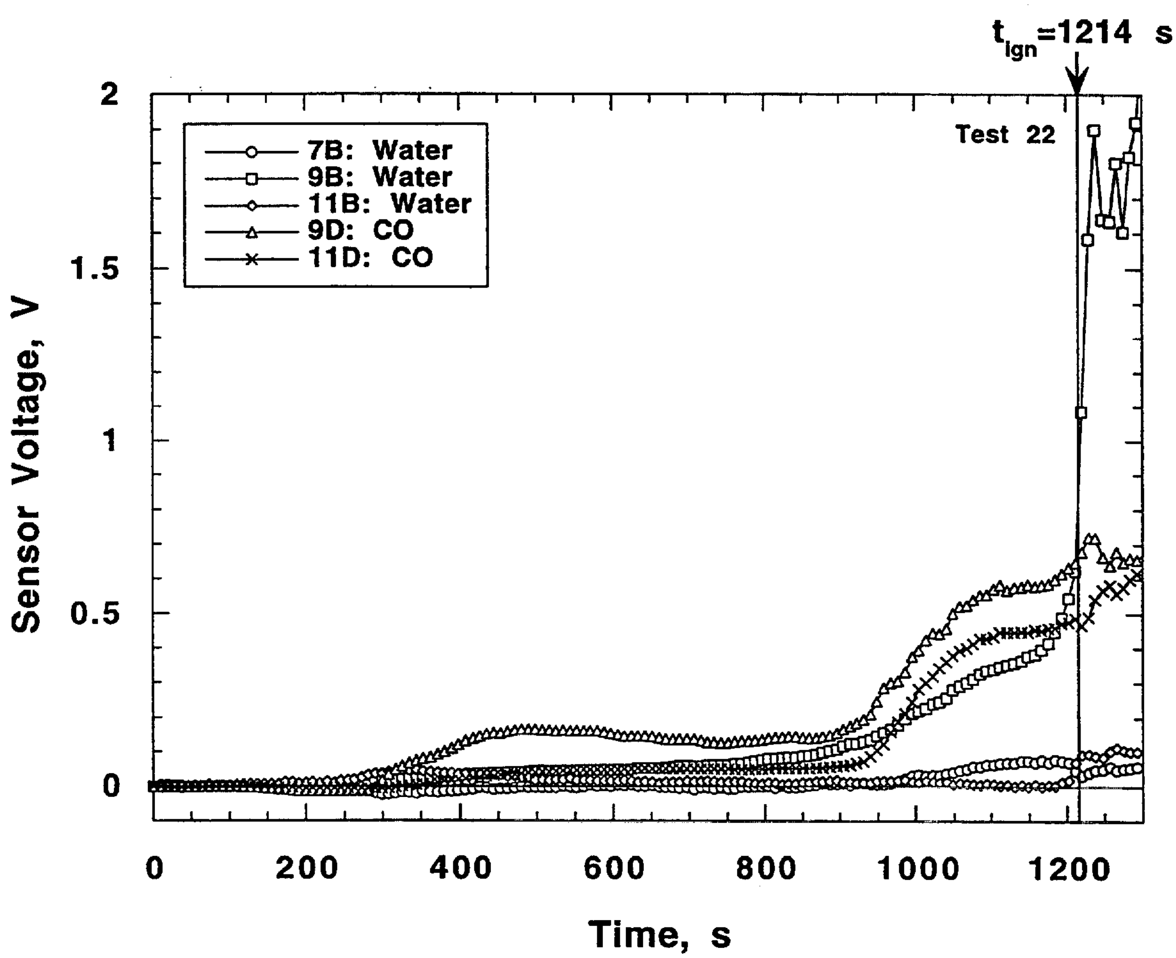

Figure 10. Sites 7, 9, 11 water-vapor and CO-sensor responses versus time for french-fried potatoes in soybean oil (normal→unattended).

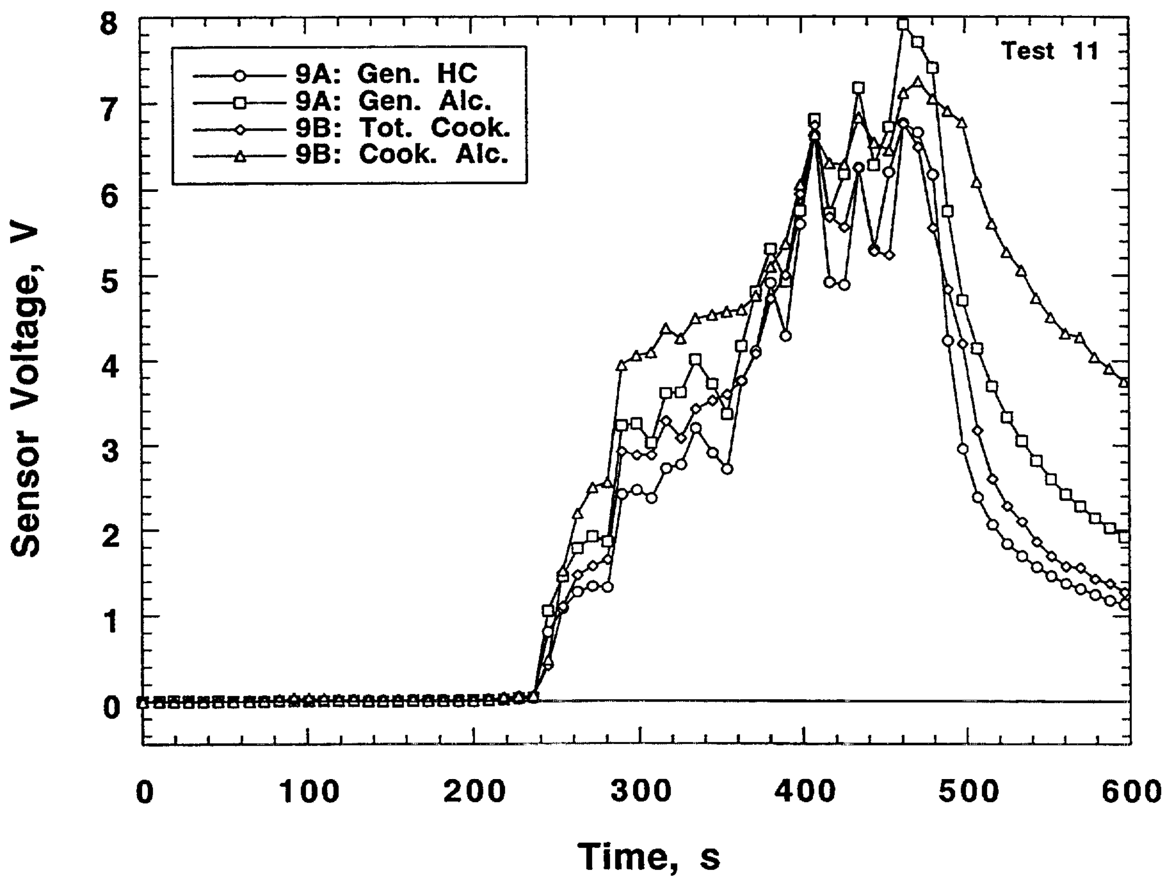

Figure 11. Site 9 hydrocarbon-sensor responses versus time for blackened catfish (normal).

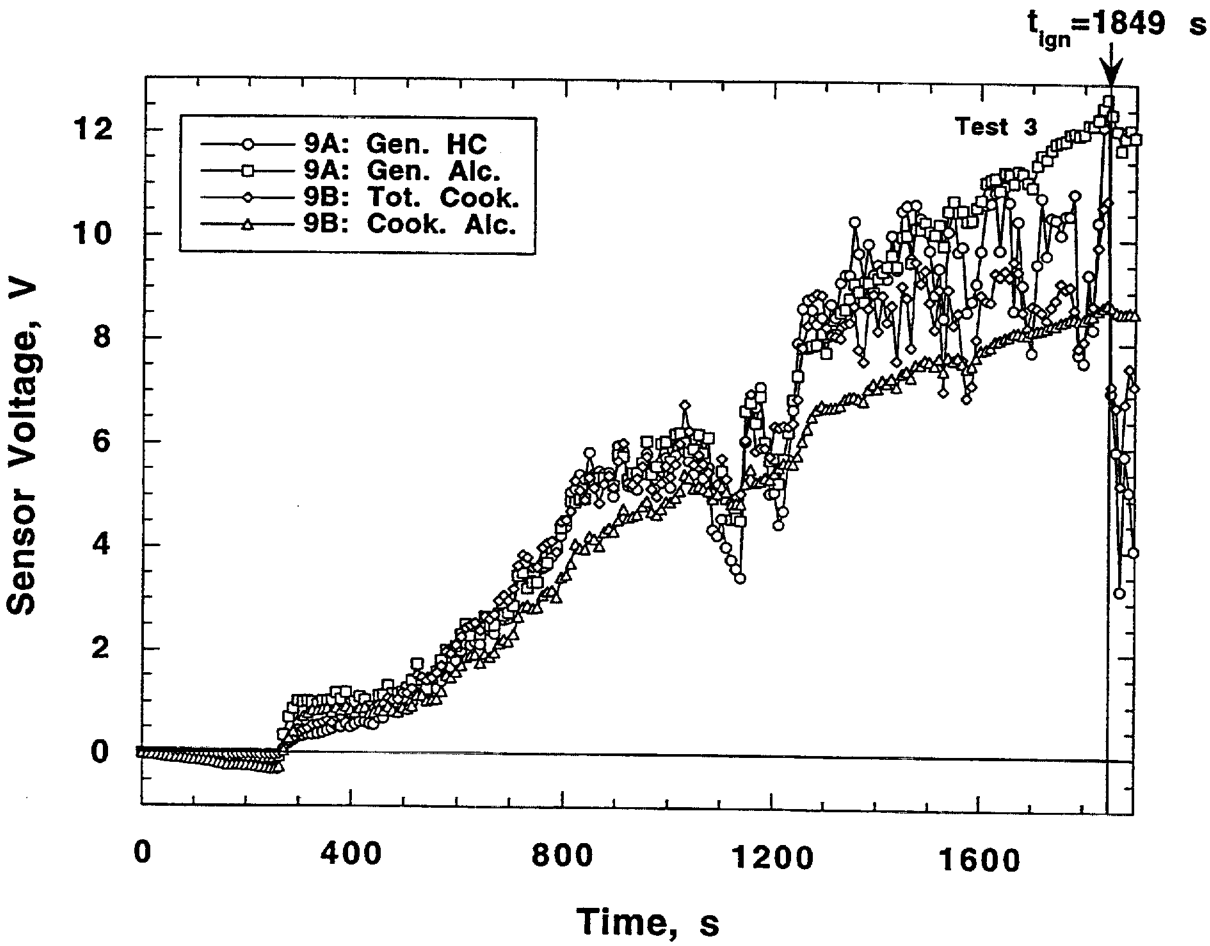

Figure 12. Site 9 hydrocarbon-sensor responses versus time for chicken in soybean oil (unattended).

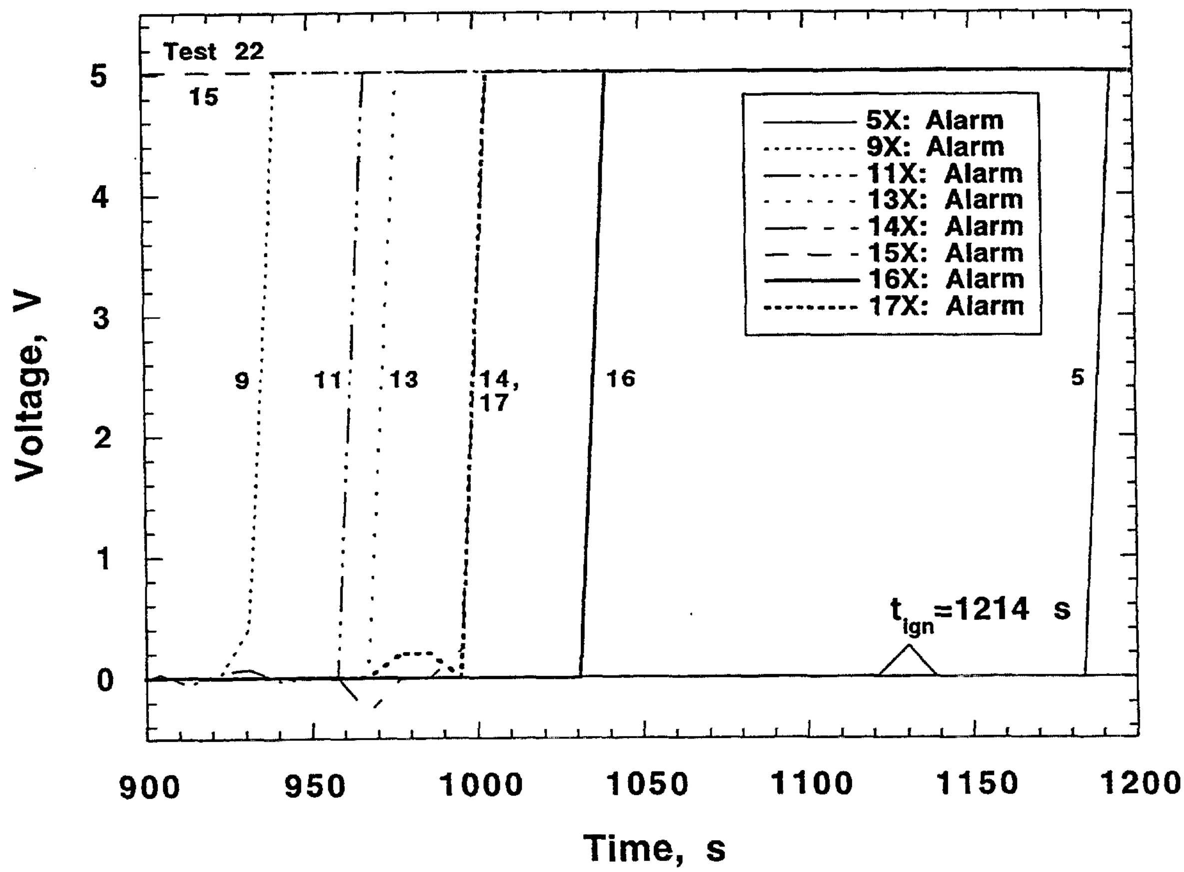

Figure 13. All photoelectric detector alarm signals versus time for french-fried potatoes in soybean oil (normal→unattended).

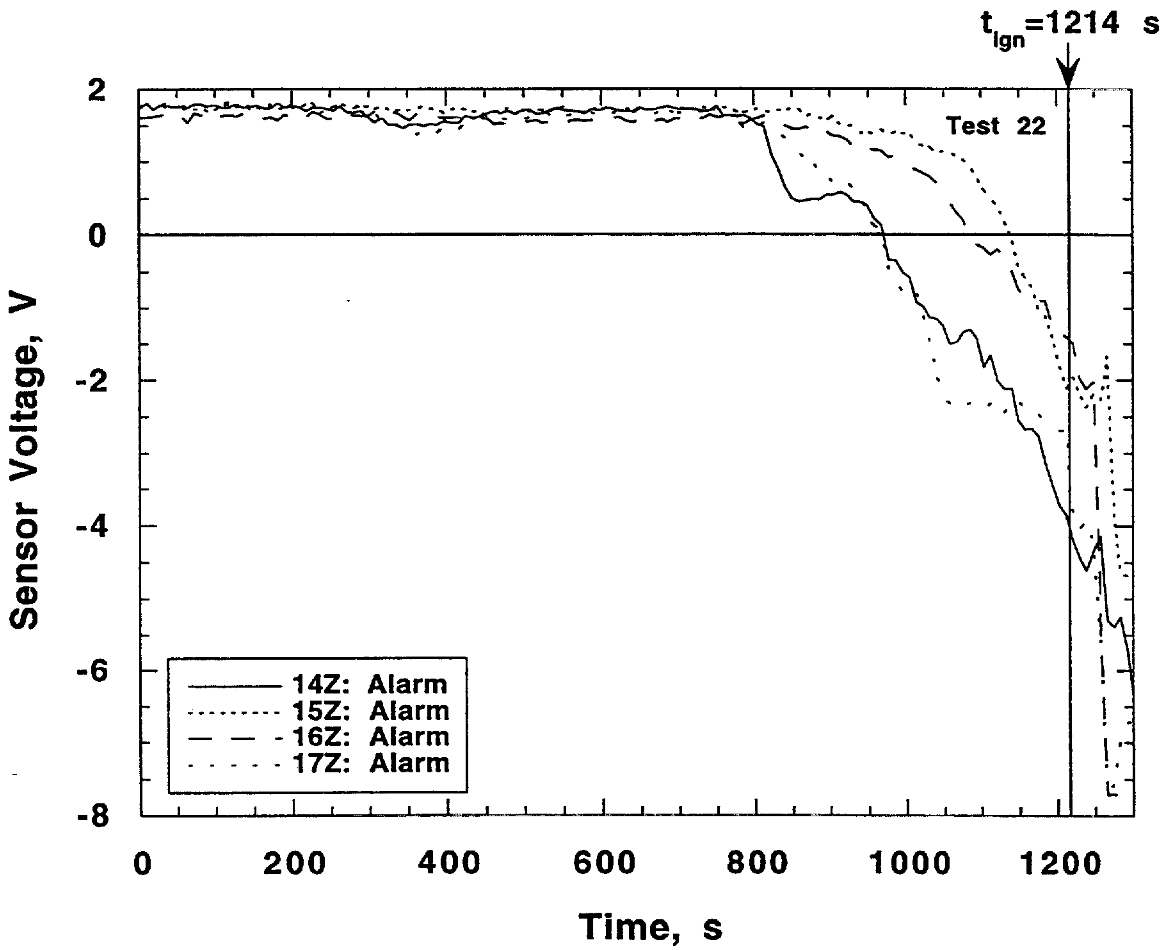

Figure 14. All ionization detector alarm signals versus time for french-fried potatoes in soybean oil (normal→unattended).

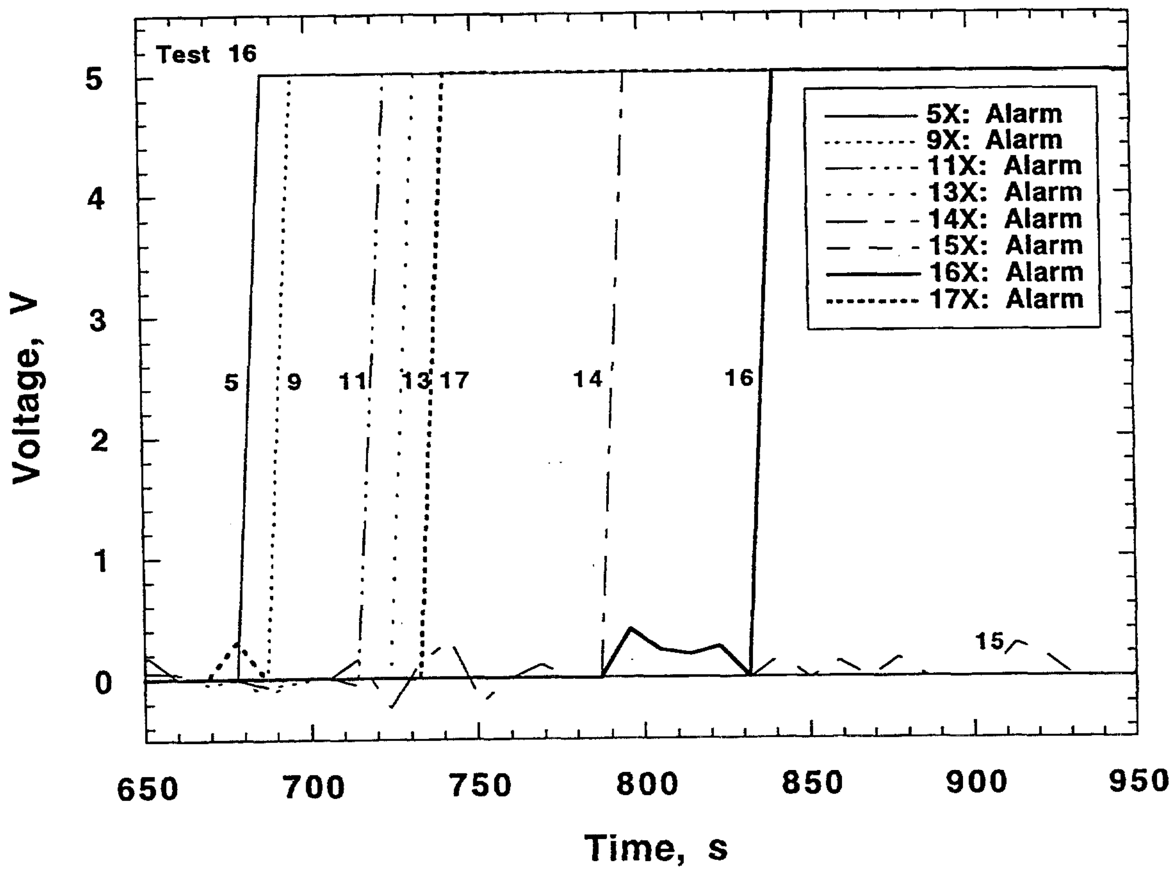

Figure 15. All photoelectric detector alarm signals versus time for broiled steak (normal).

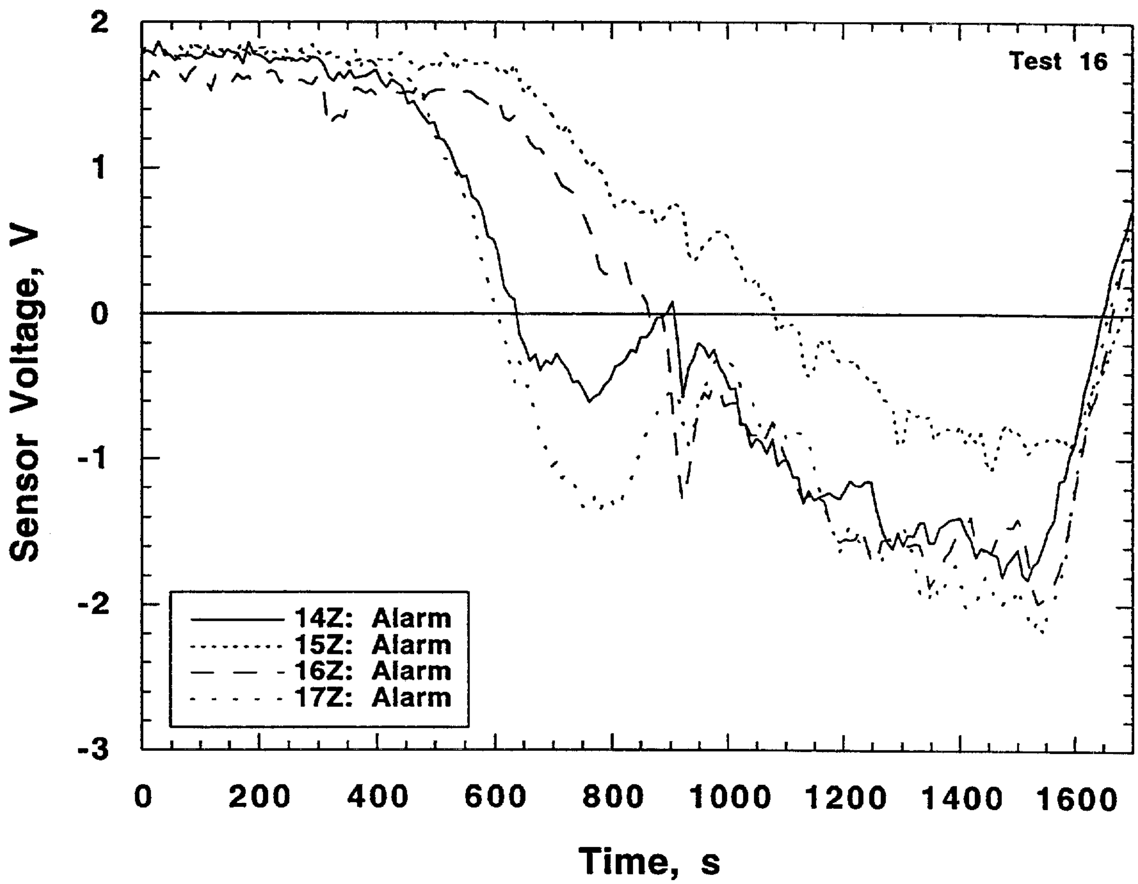

Figure 16. All ionization detector alarm signals versus time for broiled steak (normal).

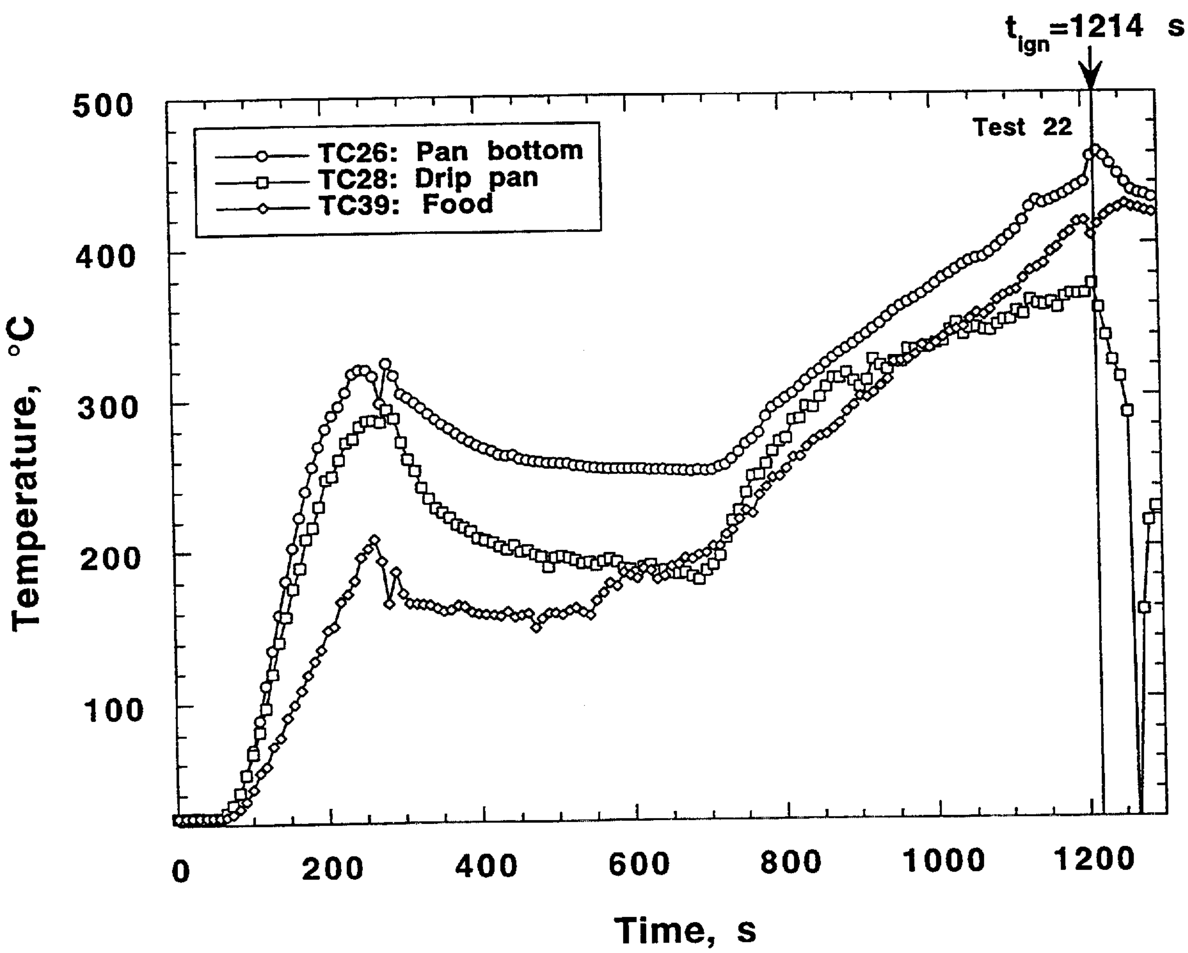

Figure 17. Temperatures near the pan versus time for french-fried potatoes in soybean oil (normal→unattended).

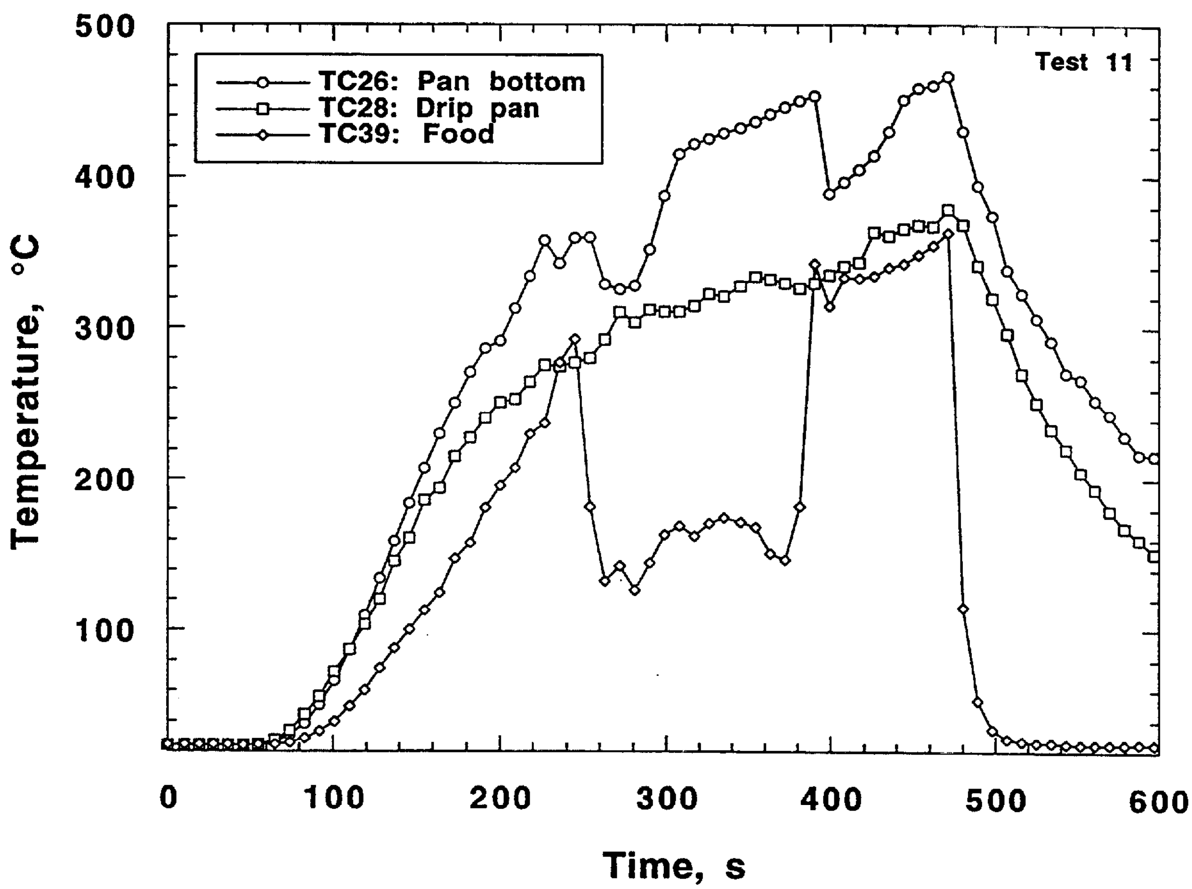

Figure 18. Temperatures near the pan versus time for blackened catfish (normal).

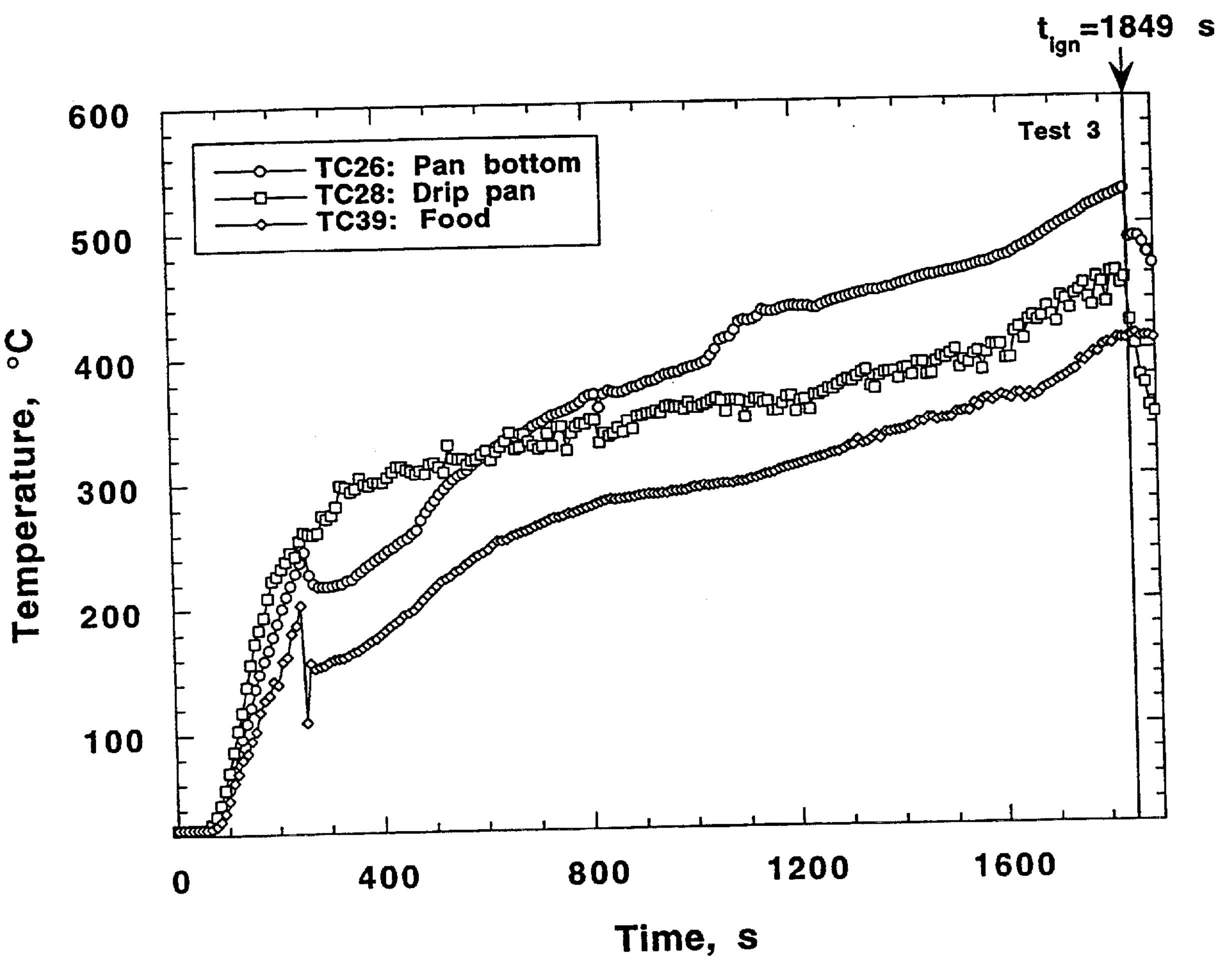

Figure 19. Temperatures near the pan versus time for chicken in soybean oil (unattended).

3.5.1 Pan and Food

Figure 17 shows a plot of three thermocouple responses versus time for a french-fried-potatoes test. Numbered thermocouples and their corresponding locations are described in Appendix C. Thermocouple 26 measured the temperature on the pan bottom. Pan temperatures often increased following ignition because the thermocouple remained in contact with the pan after the lid was put in place which trapped additional heat in the pan and raised its temperature. Thermocouple 26 malfunctioned for portions of tests 24-32. Thermocouple 28 was located near the center of the drip pan under the burner. Thermocouple 39 was located in the food itself. Since the food thermocouple was not fixed in the pan, temperature plots often show fluctuations due to stirring or turning of the food which exposed the thermocouple to relatively colder or hotter local areas. Figures 18 and 19 show the corresponding three temperature-time histories plotted for the cases of catfish and chicken in oil (unattended), respectively. The lower food temperature beginning at about 250 s in Figure 18 was due to the introduction of the fish into the pan.

3.5.2 Range and Range Hood

Figure 20 shows a plot of thermocouple responses versus time associated with the range for a french-fried-potatoes test. Thermocouples 19, 22, and 23 were located on the center of the range surface, at the center of the front edge, and in the right front corner near the focus burner, respectively. Thermocouples 29 and 30 were located underneath the drip pan of the focus burner and underneath the range surface at the center of the range, respectively. The sharp drop in some temperatures after ignition was due to the cold gas from the CO_2 fire extinguisher. Figure 21 shows thermocouple responses from above the range for the same test. Thermocouple 9 was located at site 9 with the gas sensors on the center of the front of the range hood. Thermocouple 35 was located under the right-side hood filter. Thermocouple 40 was located just below the end of the gas-sampling probe. Figures 22 and 23 show results for the same locations as in Figures 20 and 21 except that they were produced by a test of water on three burners with the oven on and oil on the focus burner. Also, thermocouple 31 on Figure 22 shows the additional trace of the oven temperature which exhibited a cycling behavior.

3.6 Laser Attenuation and Scattering

Figures 24 and 25 show laser-attenuation measurements versus time for tests of french-fried potatoes and water and oil, respectively. The circles represent the actual data points, and the curves were generated by partially smoothing the data. A 2% smooth, for example, replaces a data point with a point generated from a least-squares curve fit through the original point and the surrounding 2% of all of the data. Light-scattering measurements were found to be impractical due to very low signal-to-noise ratios.

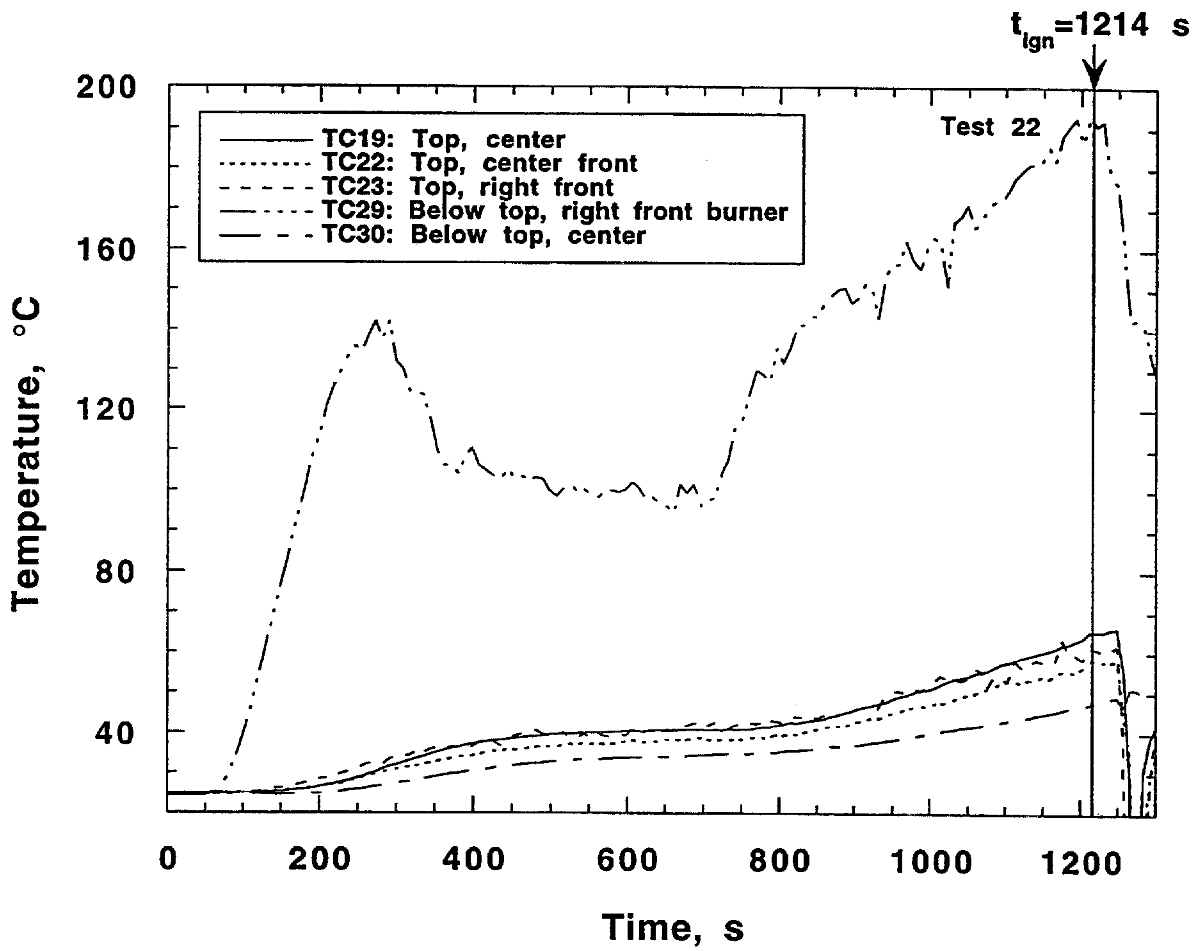

Figure 20. Temperatures of the range versus time for french-fried potatoes in soybean oil (normal→unattended).

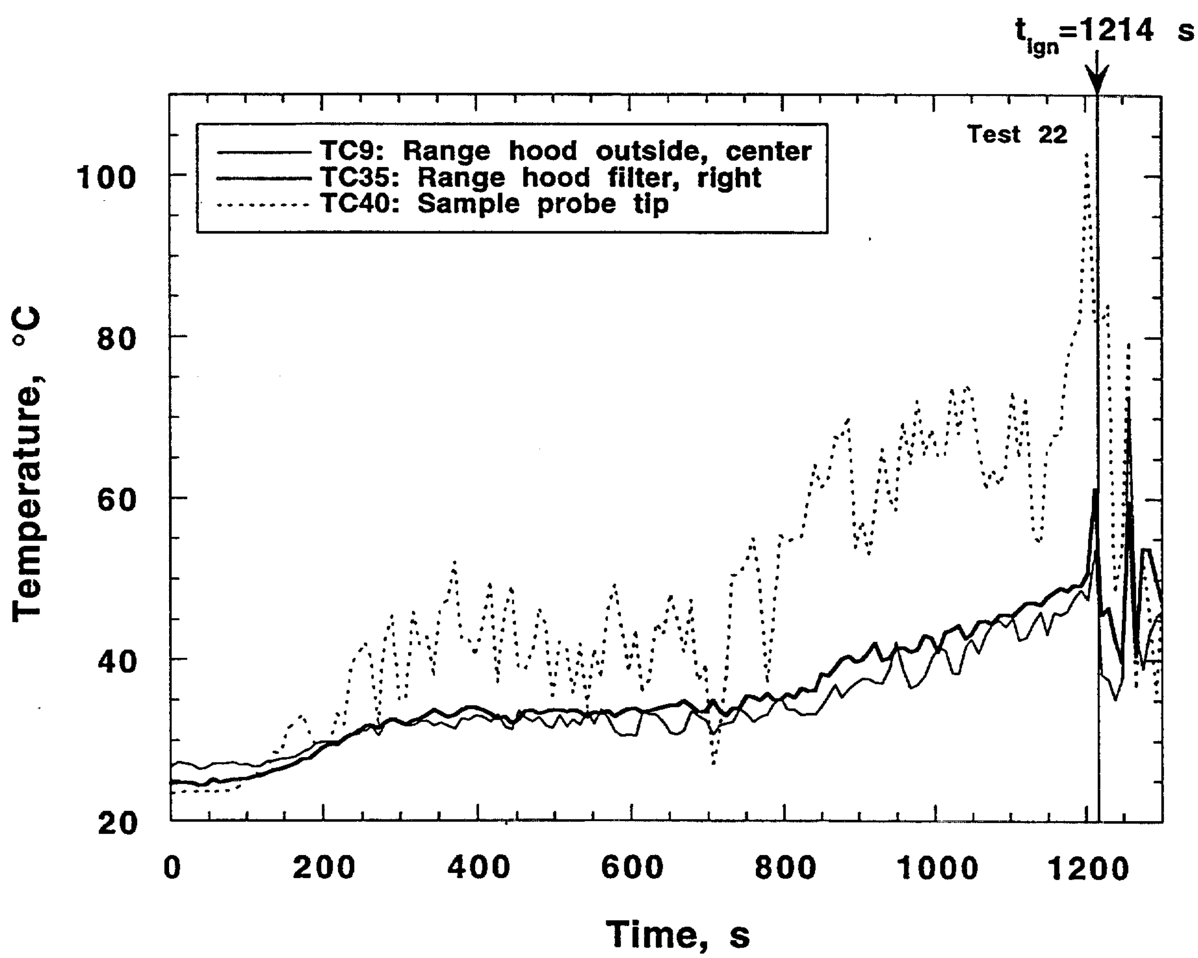

Figure 21. Temperatures above the range versus time for french-fried potatoes in soybean oil (normal→unattended).

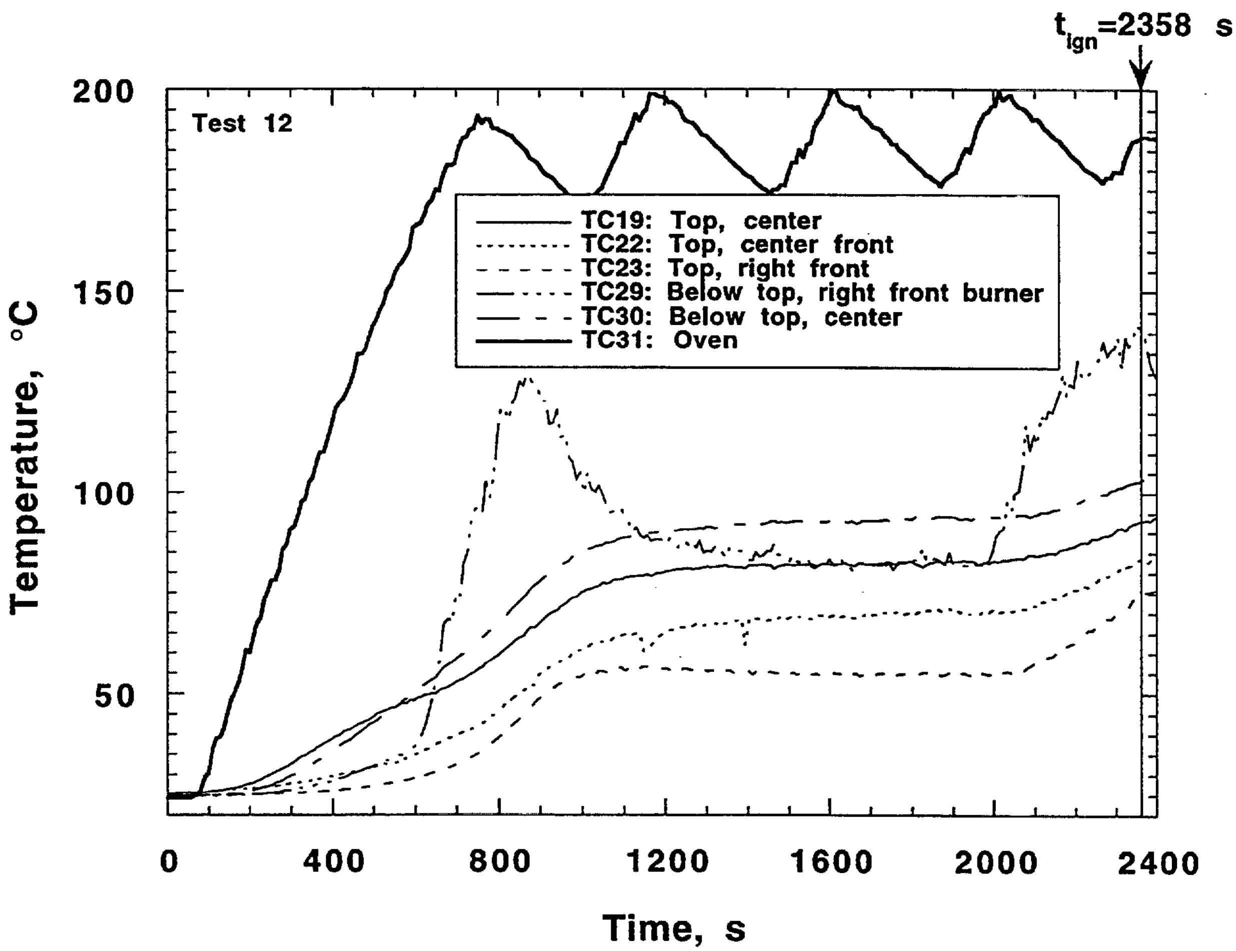

Figure 22. Temperatures of the range versus time for water and oil (normal→unattended).

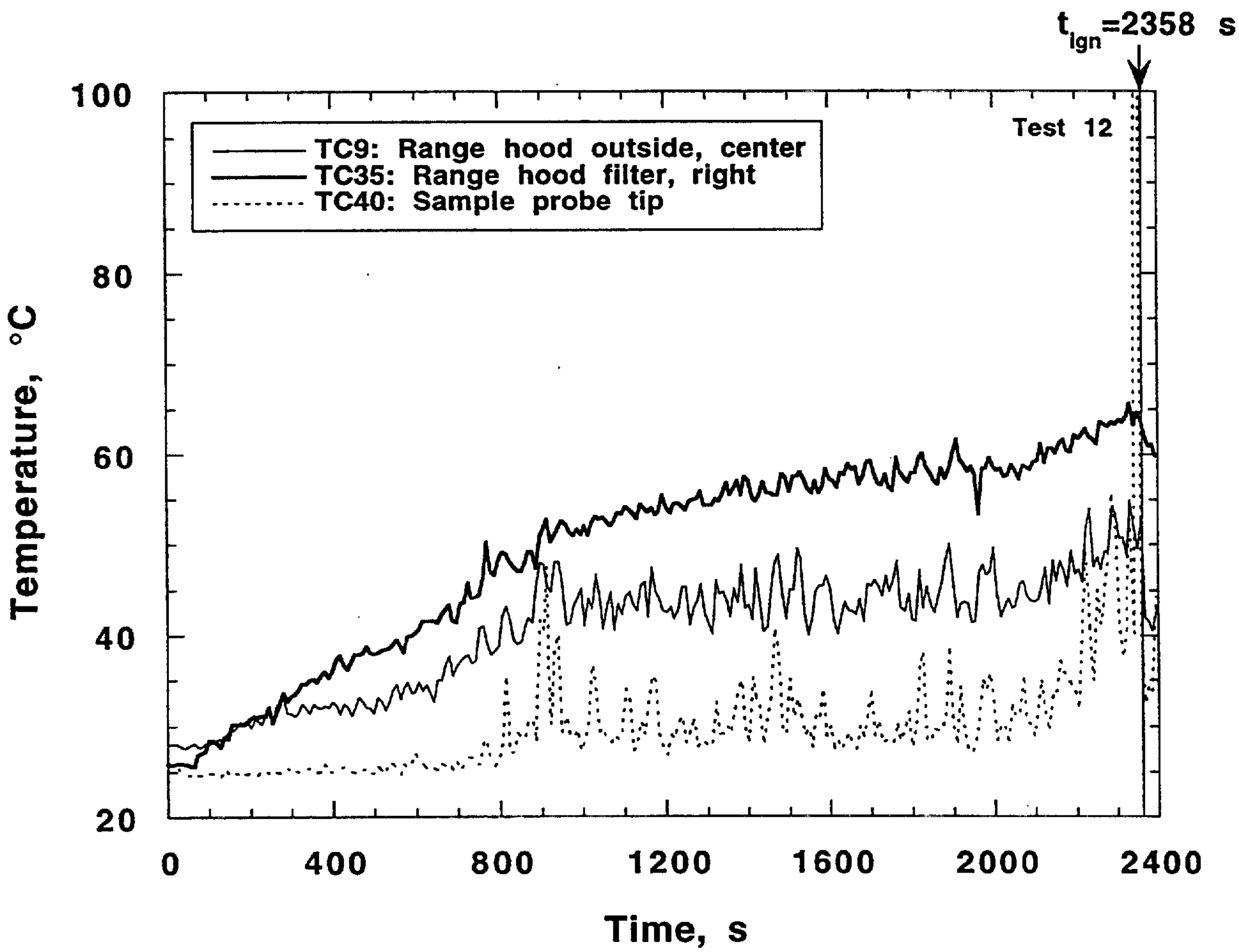

Figure 23. Temperatures above the range versus time for water and oil (normal→unattended).

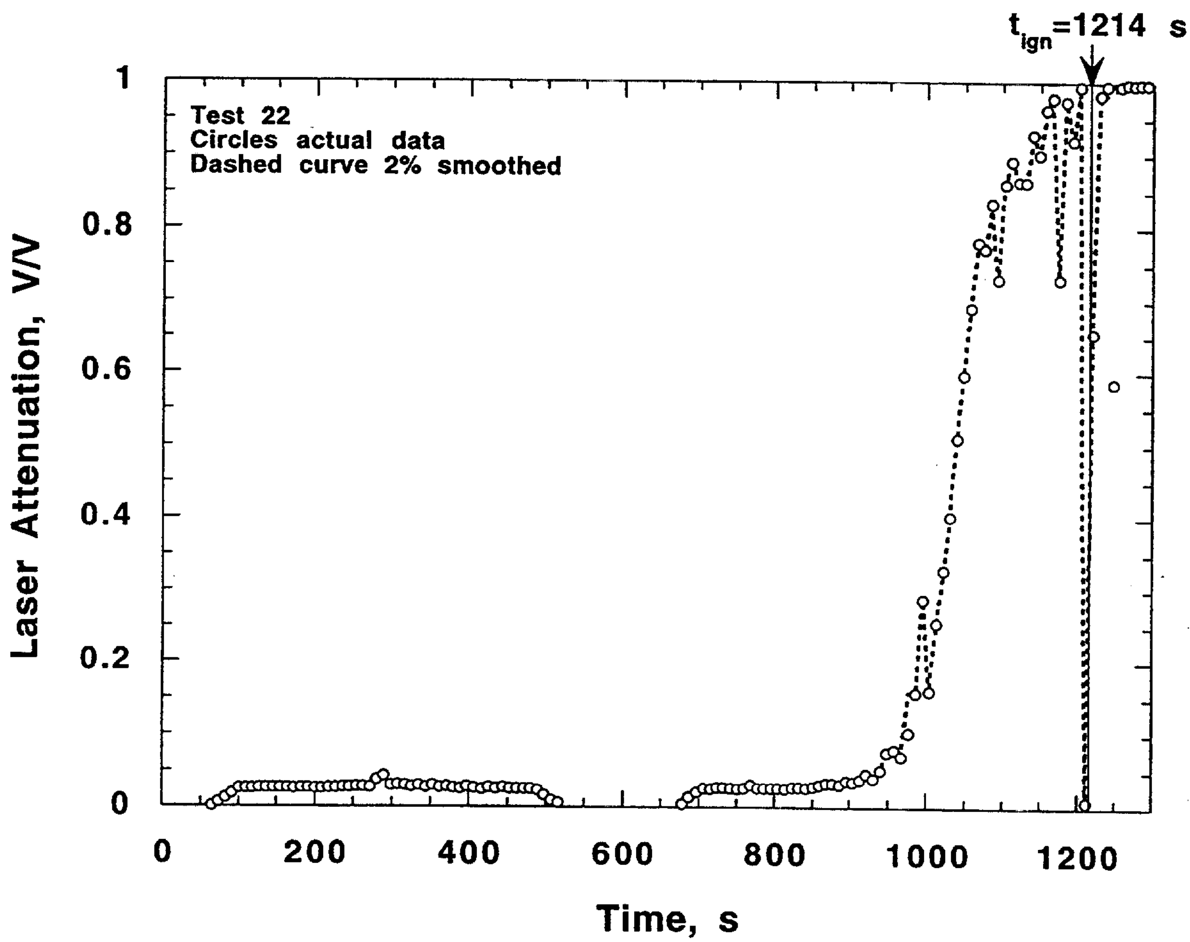

Figure 24. Laser attenuation versus time for french-fried potatoes in soybean oil (normal→unattended).

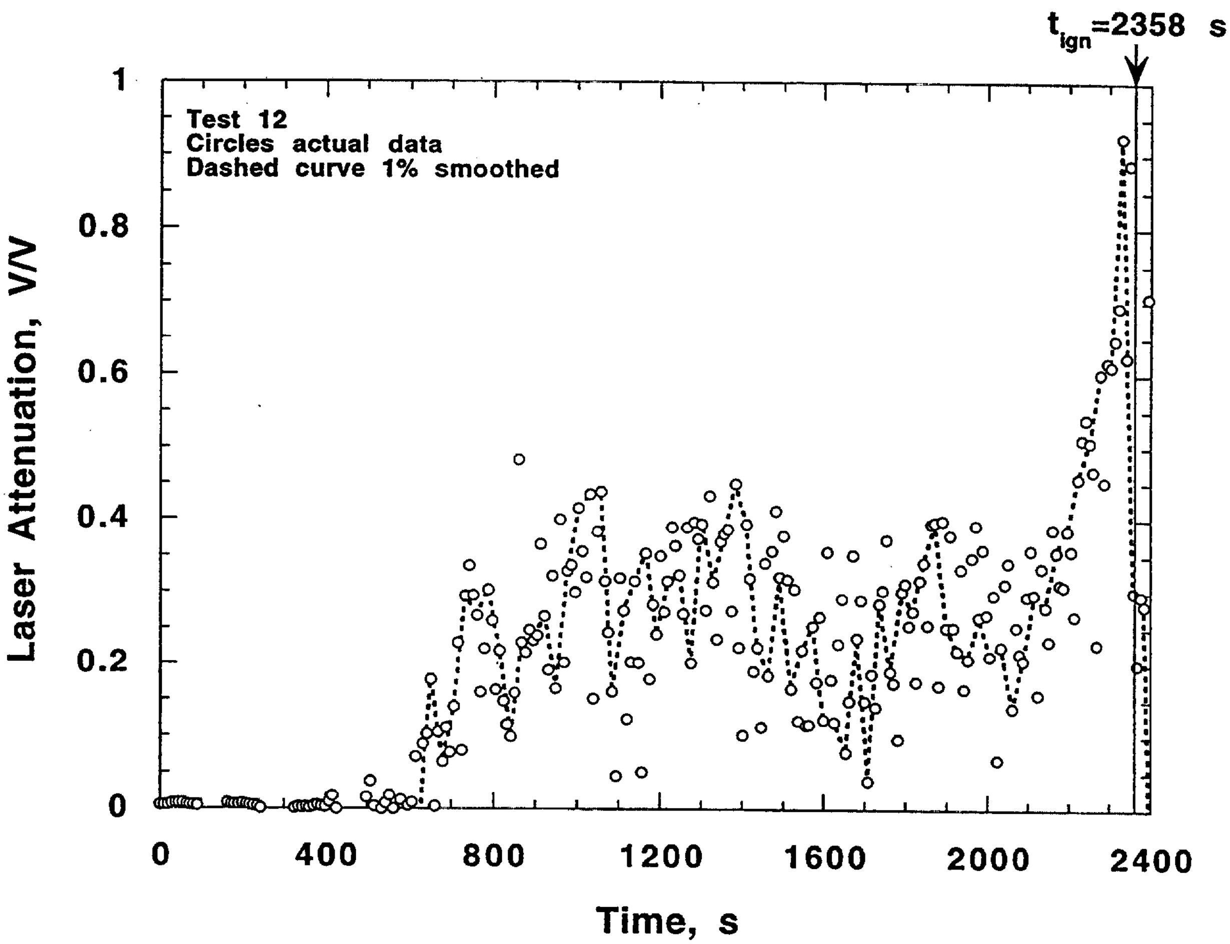

Figure 25. Laser attenuation versus time for water and oil (normal→unattended).

3.7 Recorded Images

The videotape recordings provide considerable qualitative and quantitative details concerning the tests. The instants of ignition are clearly defined, allowing more exact times and modes of ignition to be determined. The recordings are also useful for characterizing the depth and thickness of the smoke layer for each experiment.

A total of 120 slide photographs were taken for this experimental series. The slides portray the experimental apparatus, cooking phenomenon, and pre- and post-test images of the food.

4.0 Analysis and Discussion

4.1 Analysis Techniques

Table 2 lists the tests and their corresponding designations as normal, unattended, or both. Depending on the designation, times for ignition and times chosen as normal are listed as well for each test. The normal times are when the heating period of a test was concluded or when the unattended portion of a test began. A few unattended tests (10, 14, 33, 35, and 37) did not lead to ignition, but the times when heating was stopped were used as ignition times. These tests were among those performed for the cases of stir-fry vegetables, macaroni and cheese, and oil and water (with the gas range). This was done because the levels of smoke and/or melting of metal were judged sufficiently undesirable or potentially dangerous enough to warrant designating the situations as alarm-worthy.

The normal and ignition times were used for each test to perform analyses. Since the identification of a detection window, or distinct difference between normal and ignition conditions, for all tests is the objective, the maximum measured values during the normal cooking periods and the minimum measured values in the 30 s (and sometimes 60 s for comparison) preceding ignition were calculated for every variable. In figures to follow, these are designated by "nMax" and "i30Min", respectively. The minimum was the data point of least value of typically three or four points from the 30 s period. The normal maximum values were the highest levels that occurred during normal cooking. Minima and maxima were used rather than averages in order to capture the sensor signals that would be employed by an actual detection system including noise or fluctuations inherent in the measurements. Table 2 lists the normal and ignition times used for the data analysis.

Unless otherwise stated, all of the minima are from the 30 s preceding ignition. Thirty seconds was chosen as the pre-ignition time of primary focus based on the cooling-lag test on electric range A which indicated an 11 s delay before food and pan-bottom temperatures began to decrease after power was cut off. Figure 26 shows the pan-bottom and food temperatures versus time for the cooling-lag test. Thirty seconds provides nearly 20 s of additional time preceding ignition as an added safety factor.

Most of the measurements showed that the variables sensed did not generate signals that would be useful inputs for a pre-fire detection system. They showed insufficient or no differentiation between normal and pre-fire conditions so they have no potential as detection

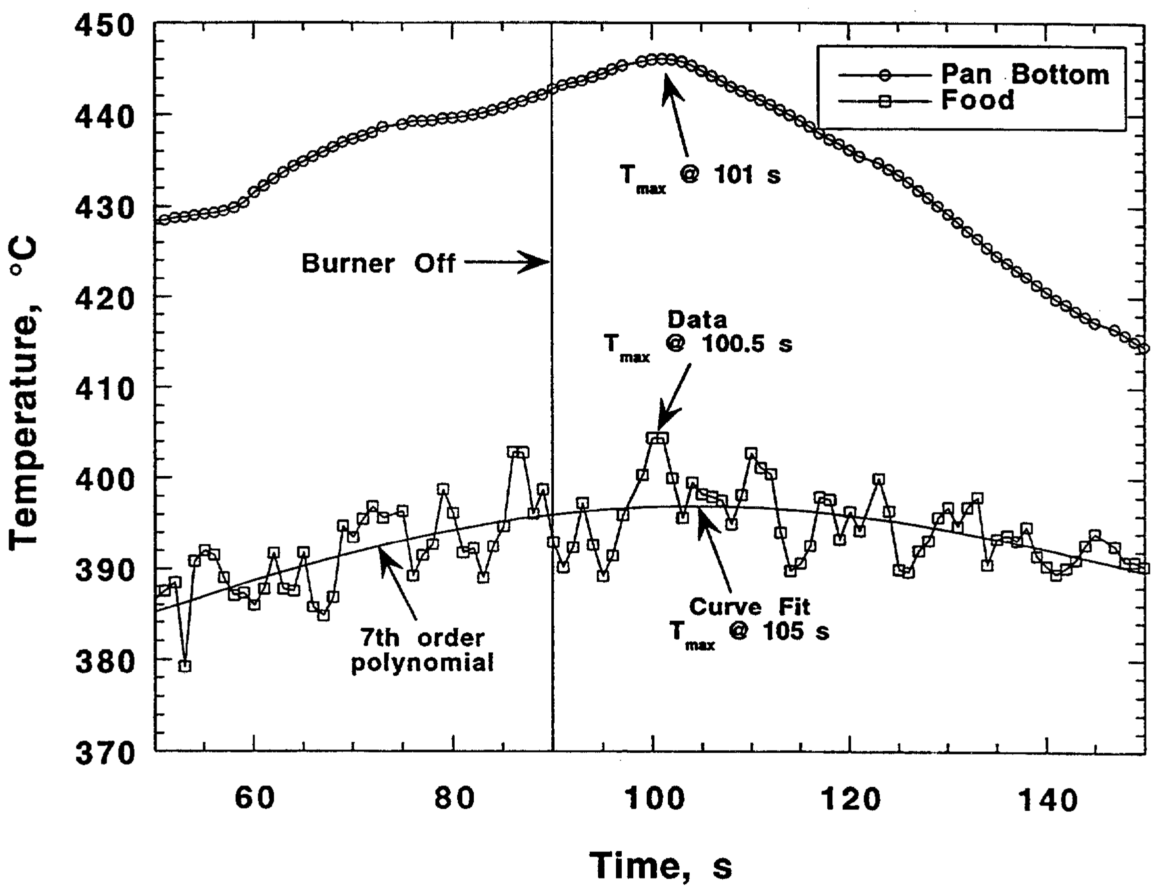

Figure 26. Pan-bottom temperature and food temperatures versus time for cooling-lag test of 500 mL oil on the type-A electric range.

devices at their specific locations. Instruments such as the laser-attenuation system and gas analyzers are not candidates for detector components because of their bulk and expense. The focus of analysis, therefore, was placed on the sensors located along the plane of symmetry of the range to see if single sensors alone could successfully provide coverage across the width of the range. Less focus was given to sensors off of the plane of symmetry because a detection system requiring localized coverage by 2 or 4 sensors of each type would be prohibitive due to higher costs and complexity. Performance results for gas sensors, thermocouples, and smoke detectors are summarized in Sections 4.2.1 through 4.2.4.

4.2 Detection Potential of Devices

The following list of questions was generated through discussions between NIST, CPSC, and range-industry representatives. The questions reflect important considerations in the evaluation of the detection success and implementation potential of the devices.

1. Does detection occur with sufficient time for the actuation of a shutoff device and cooling of the area so ignition cannot occur?
2. Does the device function consistently with the range hood on and off?
3. Does the device fail to respond to normal conditions, or not generate false alarms?
4. Can the device be exposed to a kitchen environment, especially contaminants, with a rate of deterioration in performance consistent with 20 years of range life expectancy?
5. What is the probable capability in reducing food fires?
6. How easily can the device be incorporated into a new range/cooktop?
7. Is the device useful as a retrofit, as a new component, or as an external independent device?
8. What is the cost of the device as purchased, and what might be the mass produced costs, costs for range installation, or costs for modification as retrofits available from manufacturers or suppliers?

Points 1-5 are addressed in the following sections, and the NIST study especially focuses on points 1-3. Points 6-8 should be dealt with through the engineering development of a detection system.

4.2.1 Gas Sensors

Figures 27 and 28 are examples of sensor outputs that were found not to be especially useful for discriminating between normal and pre-ignition conditions. Figure 27 shows the normal maxima and pre-ignition minima for the total-cooking-gas sensor at site 6, which was located behind the focus burner on the splash panel of the range. On the plot, the individual test numbers are on the independent axis. Since the gas burner of focus was located on the opposite side of the range from the primary electric burner, data from the site 4 sensor replaced the site 6 data for the gas-range tests. The signals were generally weak with no clear separation between normal and pre-ignition conditions. This result was due to the relatively low height of the sensor above the range surface which prevented exposure to the majority of the cooking gases.

Figure 28 shows the response of the CO sensor located on the range hood at site 9. The regions of maximum normal points and minimum ignition points overlap substantially. For an

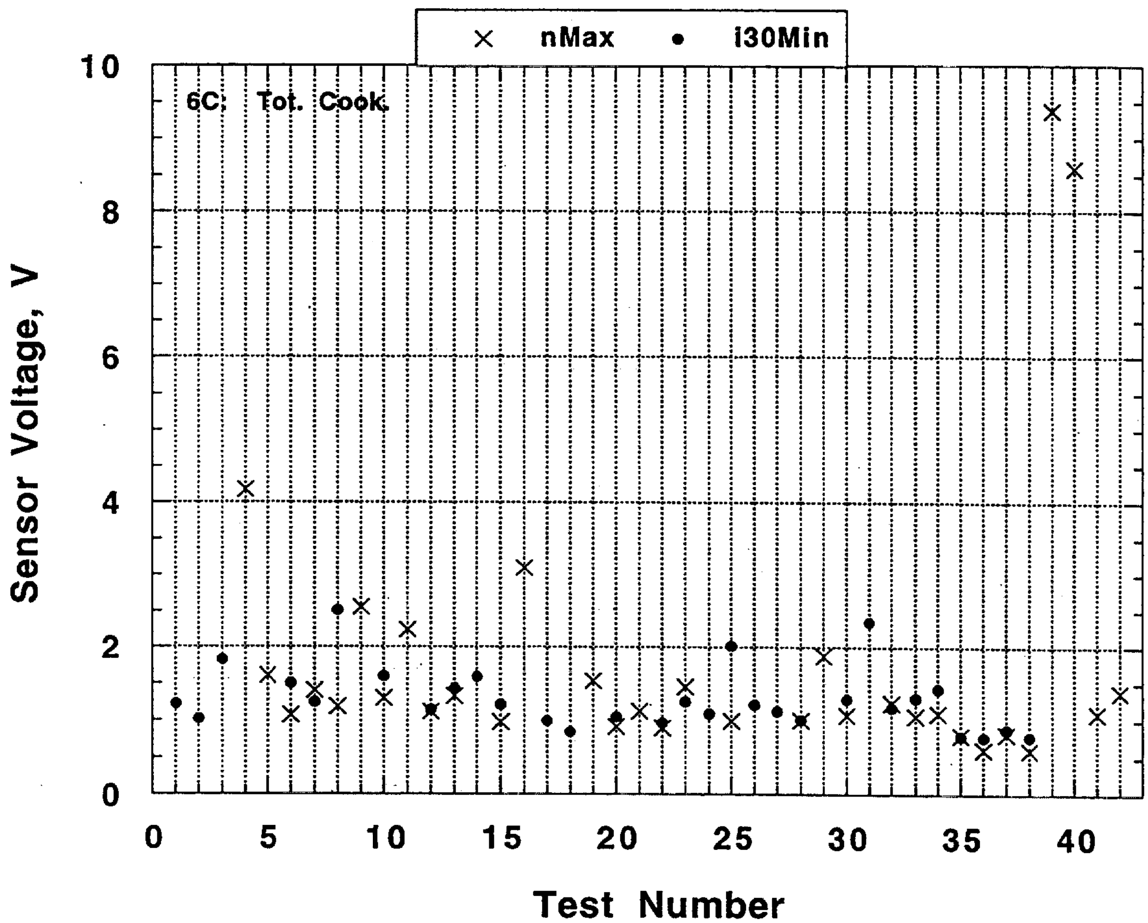

Figure 27. Site 6 total-cooking-gas sensor maximum normal and minimum ignition output 30 s before ignition versus test number. Data for the gas-range tests (35-38) are from the site 4 total-cooking-gas sensor.

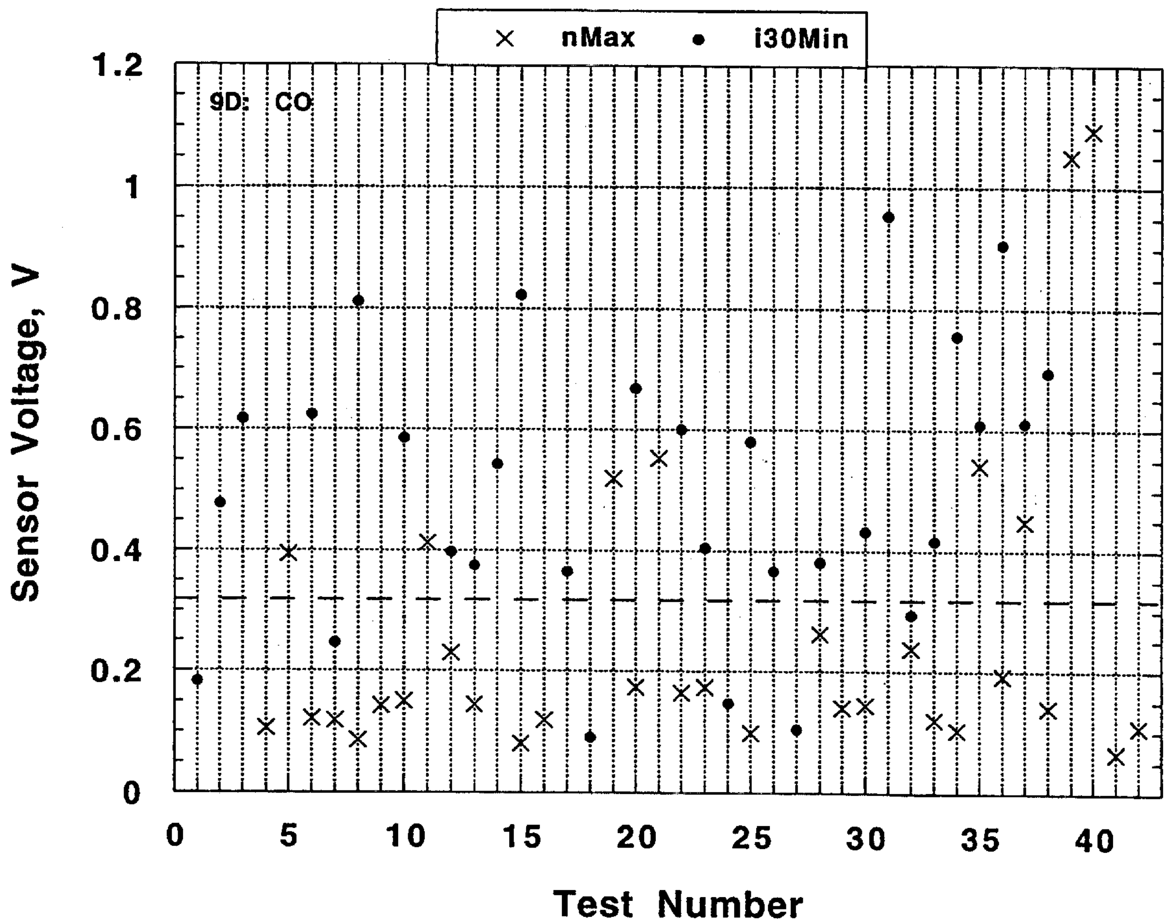

Figure 28. Site 9 carbon monoxide sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

alarm threshold of 0.32 V, the sensor generated a 25% false-alarm rate and 20% failure-to-alarm rate. This sensor, while in one of the best locations for exposure to plume gases, did not show significant enough differences between normal and pre-ignition CO levels to make it a good candidate for a detection system.

Figure 29 shows the results for the site 10 total-cooking-gas sensor. Since the gas burner of focus was located on the opposite side of the range from the primary electric burner, data from the site 8 sensor replaced the site 10 data for the gas-range tests. For an alarm threshold of 4.8 V, the sensor generated a 19% false-alarm rate and a 7% failure-to-alarm rate.

Some false alarms occurred for cases that may be characterized as special which has an impact on the performance characterization of each sensor. The tests have been separated into categories reflecting these special cases in Table 7. Table 7 is a chart which lists the sensors discussed in this section and the section on thermocouples, their associated figures, their assigned alarm thresholds, and their false-alarm and failure-to-alarm rates based on the thresholds. The following paragraphs discuss the information in Table 7 and its interpretation.

The thresholds in Table 7 were selected with an effort to minimize both false alarms and failures to alarm, but the chosen values are not the only valid settings nor are they necessarily the best. For the alarm columns in Table 7, the numbers in parentheses are the percentages reflected by the test numbers that are listed. The percentages were calculated by dividing the number of incidents of false alarm or alarm failure (failure to alarm) by the total numbers of opportunities for each. These totals are 32 for false alarms and 30 for failures to alarm and reflect the number of tests or portions of tests that were normal and unattended, respectively.

The special cooking-case columns in Table 7 are steak, fish, cleaning, and other. The blackened-fish case is an inherently attended cooking procedure for which a temporary deactivation (with automatic reactivation) of the detection system by the operator could prevent disruption of cooking by range shutdown. Another solution to special attended cooking cases could be motion detector technology which could confirm that a process is indeed attended. Broiling of steak and the self-cleaning oven cases are operations that don't utilize the range surface and are also not a threat for ignition. Inclusion of an input to the detection system algorithm indicating that the oven is in use for broiling or self-cleaning could prevent these activities from being disrupted. In the "other" category, cases 5, 10, and 19 appear for some sensors. Case 10 is stir-fry vegetables which is another inherently attended cooking procedure which could be protected from disruption as described previously. Cases 5 and 19 are multiple pans of boiling water. The reason that these normal cases generated higher readings was that oil residue from previous tests was not completely removed from the burners and produced some smoke for several minutes in the early heating period. If this occurred in a real kitchen, the prevention of the production of smoke could be considered a positive situation, and the shutdown of the range would alert the operator that debris should be cleaned from a burner.

Additional columns in Table 7 are for "real" false alarms, and "real" and "other" failures to alarm. The tests listed under the "real" columns could not be accounted for in the ways that oven broiling and cleaning and attended cooking could be. Therefore the "real" tests represent deficiencies in the ability of particular sensors to differentiate between normal and pre-ignition conditions. The "other" instances are considered in the discussion of specific sensor results. Based on the preceding explanations of the table, the gas sensors already discussed did not

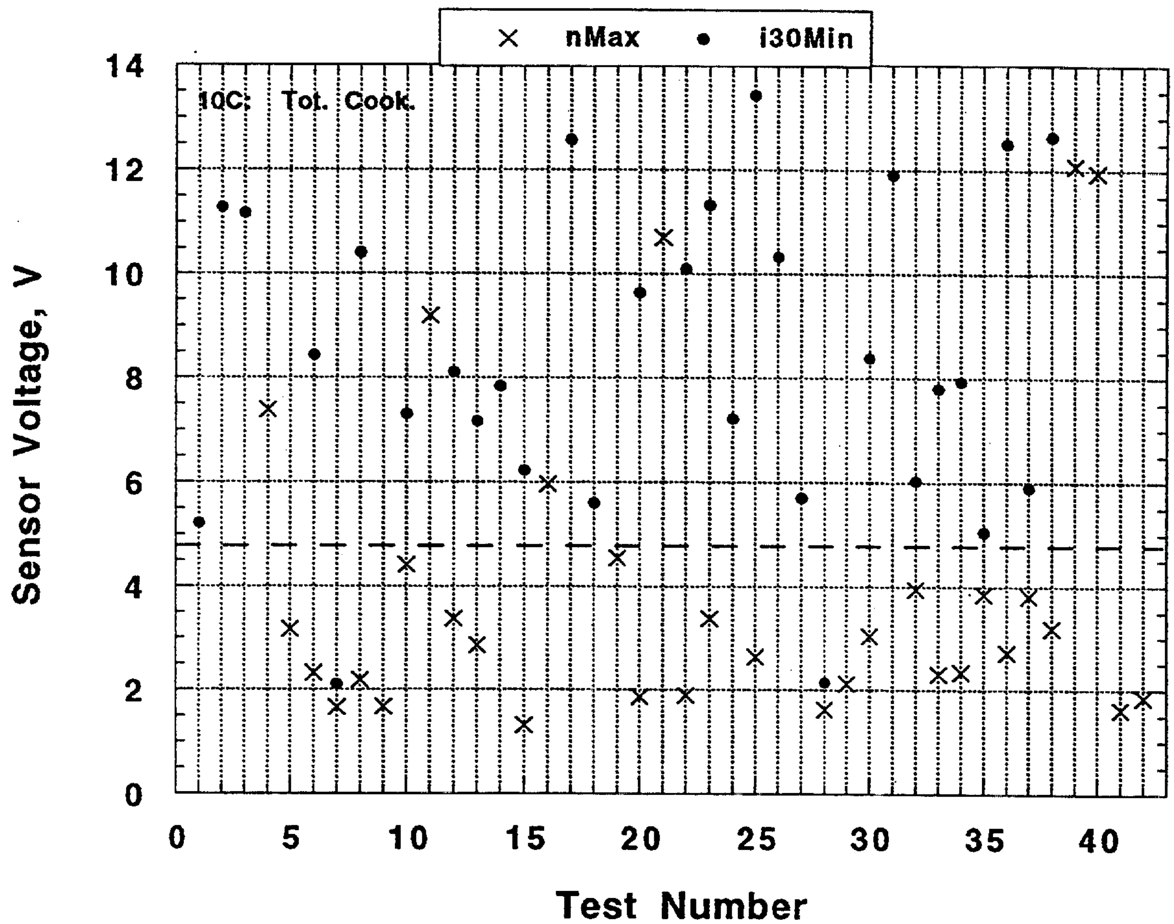

Figure 29. Site 10 total-cooking-gas sensor maximum normal and minimum ignition output 30 s before ignition versus test number. Data for the gas-range tests (35-38) are from the site 8 total-cooking-gas sensor.

Table 7. Selected sensors' false-alarm and alarm-failure performance for 42 tests

Fig. No.	Sensor	Thresh-hold	Tests with False Alarms					Tests with Alarm Failures	
			Real (%)	Steak (%)	Fish (%)	Cleaning (%)	Other (%)	Real (%)	Other (%)
28	9D Carbon Monoxide	0.32 V	35,37 (6)		11,21 (6)	39,40 (6)	5,19 (6)	1,7,18,24, 27,32 (20)	
29	10C Total Cooking	4.8 V		4,16 (6)	11,21 (6)	39,40 (6)		7,28 (7)	
30	7A General Alcohol	3.5 V	35,37 (6)	4,9,16, 29 (13)	11,21 (6)		10,19 (6)		
31	7B Cooking Alcohol	3.3 V	35,37 (6)	4,9,16, 29 (13)	11,21 (6)		10,19 (6)		
32	9A General Hydrocarbon	2.5 V	34 (3)	16 (3)	11,21 (6)	39,40 (6)		7,35[$] (7)	
33	9A General Alcohol	3.1 V		4,16 (6)	11,21 (6)	39,40 (6)		7,35[$] (7)	
34	9B Total Cooking	2.7 V		4 (3)	11,21 (6)	39,40 (6)		7,35[$] (7)	1 (3)
35	9B Cooking Alcohol	3.5 V			11,21 (6)	39,40 (6)	19 (3)		
36	11A General Hydrocarbon	1.7 V		4 (3)	11,21 (6)	39,40 (6)		7,35[$] (7)	

Fig. No.	Sensor	Thresh-hold	Tests with False Alarms					Tests with Alarm Failures	
			Real (%)	Steak (%)	Fish (%)	Cleaning (%)	Other (%)	Real (%)	Other (%)
37	11A General Alcohol	3.0 V		4 (3)	11,21 (6)	39,40 (6)		7,35[$] (7)	
38	11B Total Cooking	2.2 V		4,16 (6)	11,21 (6)	39,40 (6)		7,35[$] (7)	
39	11B Cooking Alcohol	3.5 V		4 (3)	11,21 (6)	39,40 (6)		7,35[$] (7)	
40	T19	50 °C	5,7,12,13,19,28, 30,32,35,37 (31)	4,9,16, 29 (13)	11 (3)	39,40 (6)		17 (3)	
41	Tpan (30 s)	340 °C	12 (3)		11,21 (6)		19 (3)		
42	Tpan (60 s)	340 °C	12 (3)		11,21 (6)		19 (3)		23 (3)
43	Tpan X 7A Gen. Alc.	1500 V°C			11,21 (6)		19 (3)		
44	Tpan X 7B Cook. Alc.	1500 V°C			11,21 (6)		19 (3)		
45	Tpan X 9B Cook.Alc.(30 s)	1400 V°C			11,21 (6)		19 (3)		
46	Tpan X 9B Cook.Alc.(60 s)	1400 V°C			11,21 (6)		19 (3)		

[$] Test 35 did not proceed to ignition and therefore did not produce a true failure to alarm.

perform as poorly as first stated. The site 9 CO sensor generated 6% false-alarm and 20% failure-to-alarm rates. The site 10 total-cooking-gas sensor generated 0% and 7% rates, respectively.

The responses for the best gas sensors at sites 7, 9, and 11, which were the three major sites on the range's plane of symmetry, are presented in the following figures. These sensors showed significant differentiation between normal and pre-fire conditions. None of the gas sensors produced complete separation of the conditions sufficient to allow its use as a single detector that would have both acceptable false-alarm and failure-to-alarm rates unless the special cases were considered in the detection scheme. The site 9B cooking-alcohol sensor was most effective, and with the use of modifications to the detection system to account for special attended cooking cases would perform perfectly.

Figures 30 and 31 are for gas sensors at site 7. Figure 30 shows the site 7 general-alcohol sensor's normal maxima and ignition minima for each test. An alarm threshold set at 3.5 V would not produce any failures to alarm, but 12 instances of false alarms would have occurred in the 42 tests. Some of the false alarms are special cases as have been noted. The sensors would have alarmed for all of the broiled-steak tests, the self-cleaning-oven tests, the blackened-catfish tests, and some of the stir-fried-vegetable and multiple-water tests. The remaining tests that would produce false alarms are 35 and 37 which are both water-and-oil tests heated on the gas range. No failures to alarm would be generated by this sensor. Figure 31 shows the compiled test results for the site 7 cooking-alcohol sensor. With a threshold set at 3.3 V, the identical set of false alarms would occur as for the site 7 general-alcohol sensor with the same reasoning.

Figures 32 through 35 are for site 9 gas sensors. Figure 32 shows the general hydrocarbon-gas sensor's responses. For a threshold set at 2.5 V, two water-and-oil tests, 7 and 35, would result in failure to alarm. Test 35, however, did not proceed to ignition, and the data point results from the time when heating was stopped so only one failure to alarm is authentic. Catfish tests 11 and 21, steak test 16, self-cleaning tests 39 and 40, and normal-to-unattended chicken test 34 would all produce false alarms. Figure 33 shows the plot for the general-alcohol sensor at site 9. With a threshold of 3.1 V, this sensor would perform very similarly as the site 9 general-hydrocarbon sensor. The differences would be a false alarm for steak test 4 and no false alarm for chicken test 34. Figure 34 shows the plot for the site 9 total-cooking-gas sensor. With a threshold of 2.7 V, it would perform just as the site 9 general-alcohol sensor except steak test 16 would not produce a false alarm. Figure 35 shows the responses of the cooking-alcohols sensor at site 9. This sensor would produce no failures-to-alarm with an alarm threshold of 3.5 V. The only false alarms would occur for catfish tests 11 and 21, self-cleaning oven tests 39 and 40, and water test 19 with the smoking oil on the rear burner. This gas sensor had the best performance of the site 7 and 9 sensors discussed thus far.

Figures 36 through 39 show the results for the site 11 gas sensors. For the general-hydrocarbon sensor results shown in Figure 36, many of the ignition voltages are much lower than for previous sensors and are close to the main body of normal-cooking maxima. A threshold of 1.7 V would produce the same set of faults as the total-cooking-gas sensor at site 9. Figure 37 shows that a threshold of 3 V would produce the same results for the general-alcohol sensor as the site 11 general-hydrocarbon sensor. Other threshold values could be chosen which would

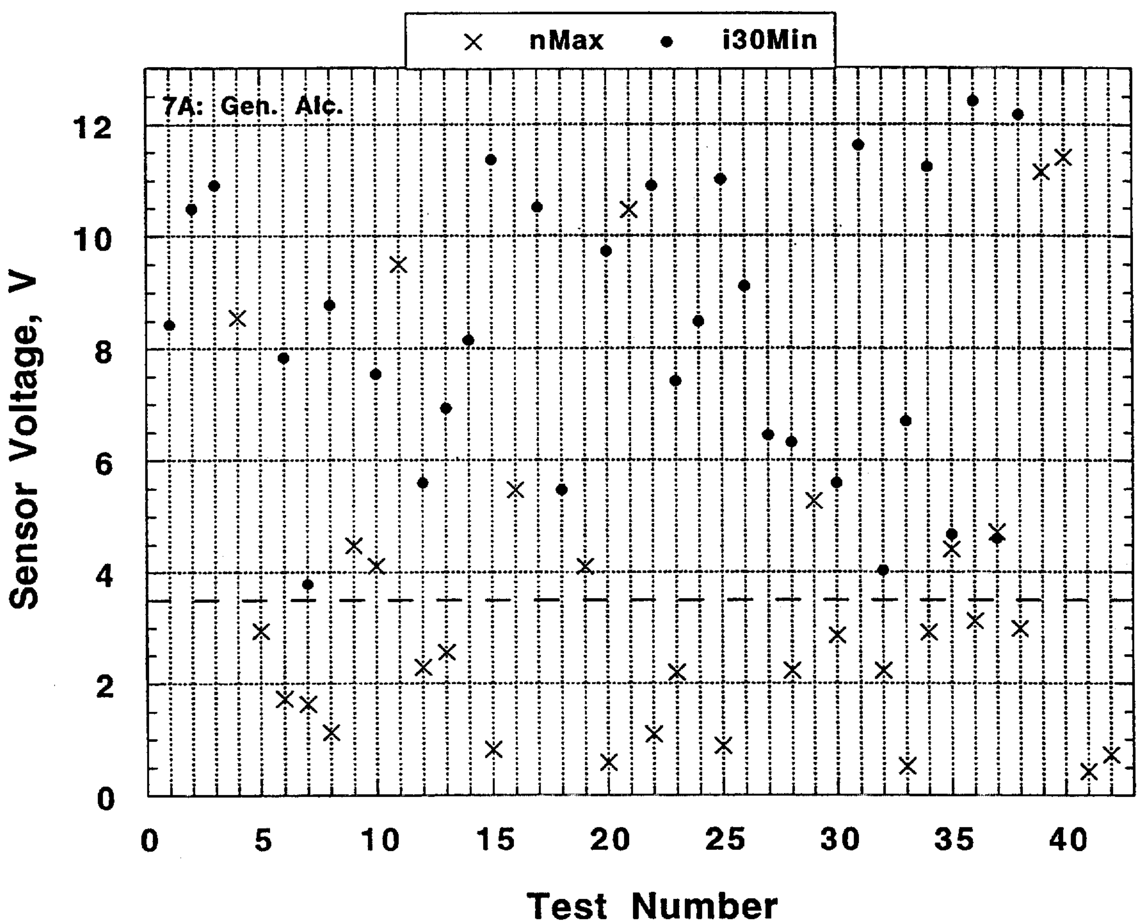

Figure 30. Site 7 general-alcohol sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

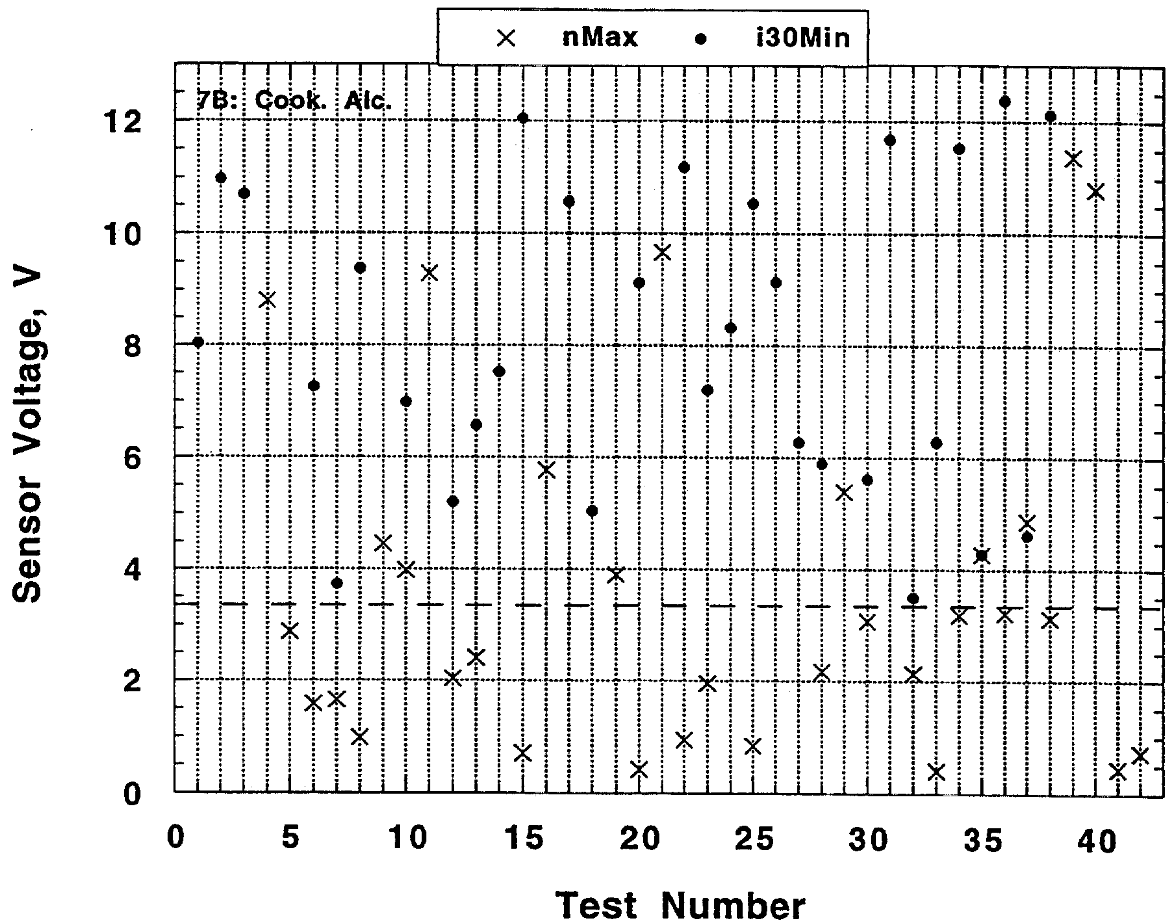

Figure 31. Site 7 cooking-alcohol sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

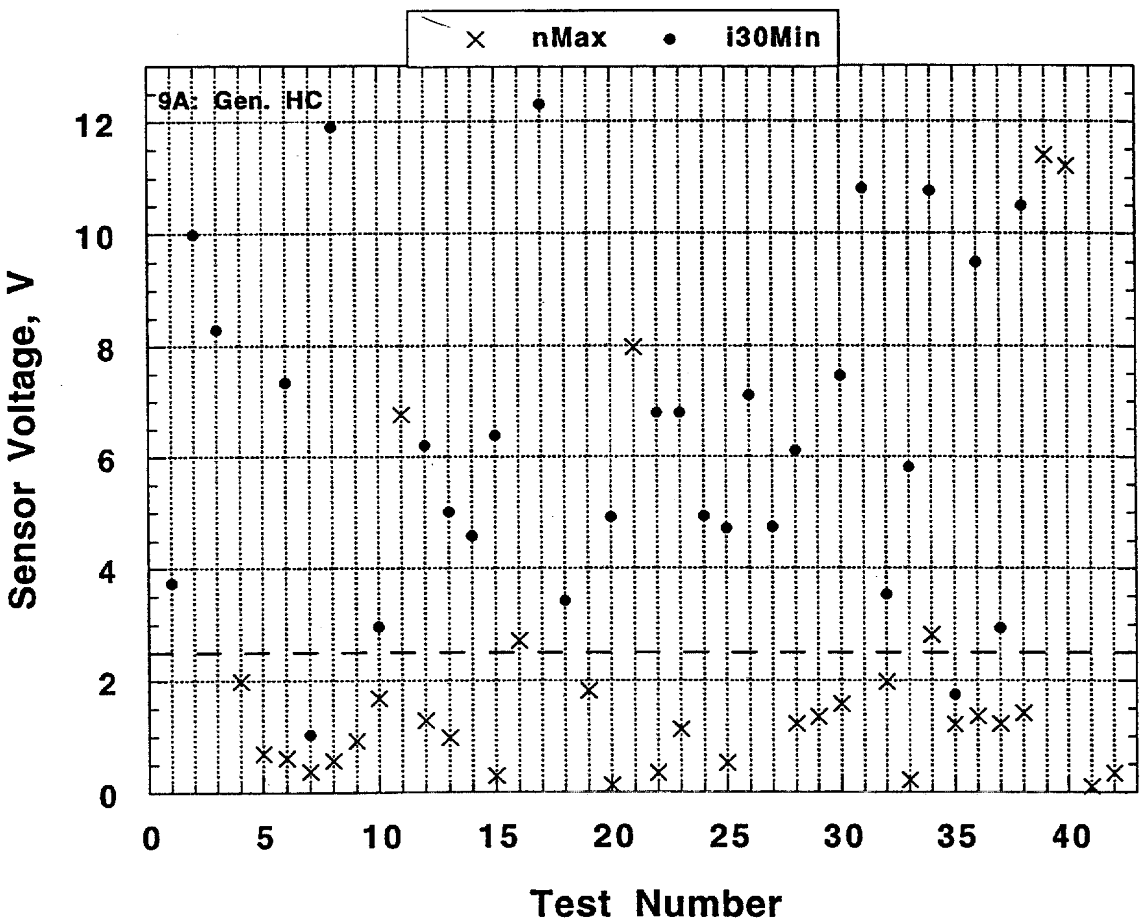

Figure 32. Site 9 general-hydrocarbon sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

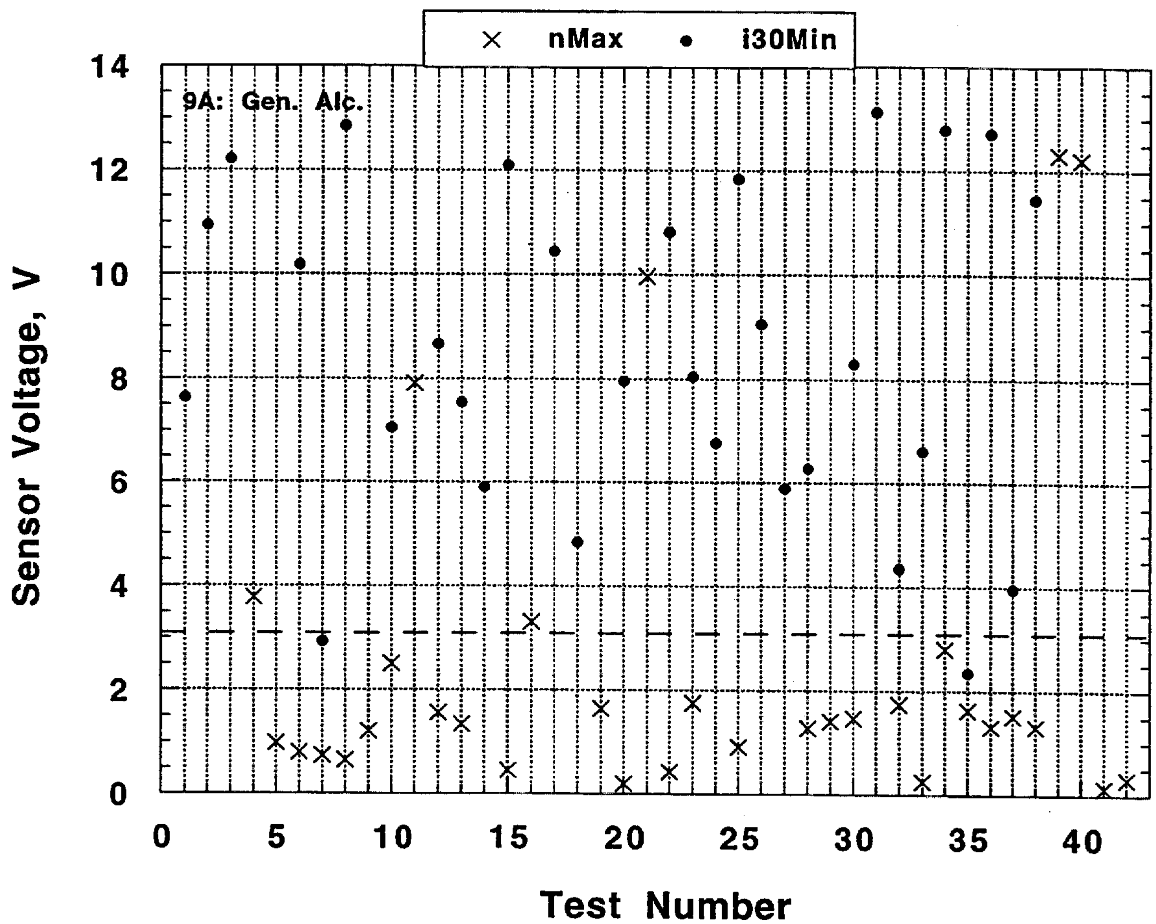

Figure 33. Site 9 general-alcohol sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

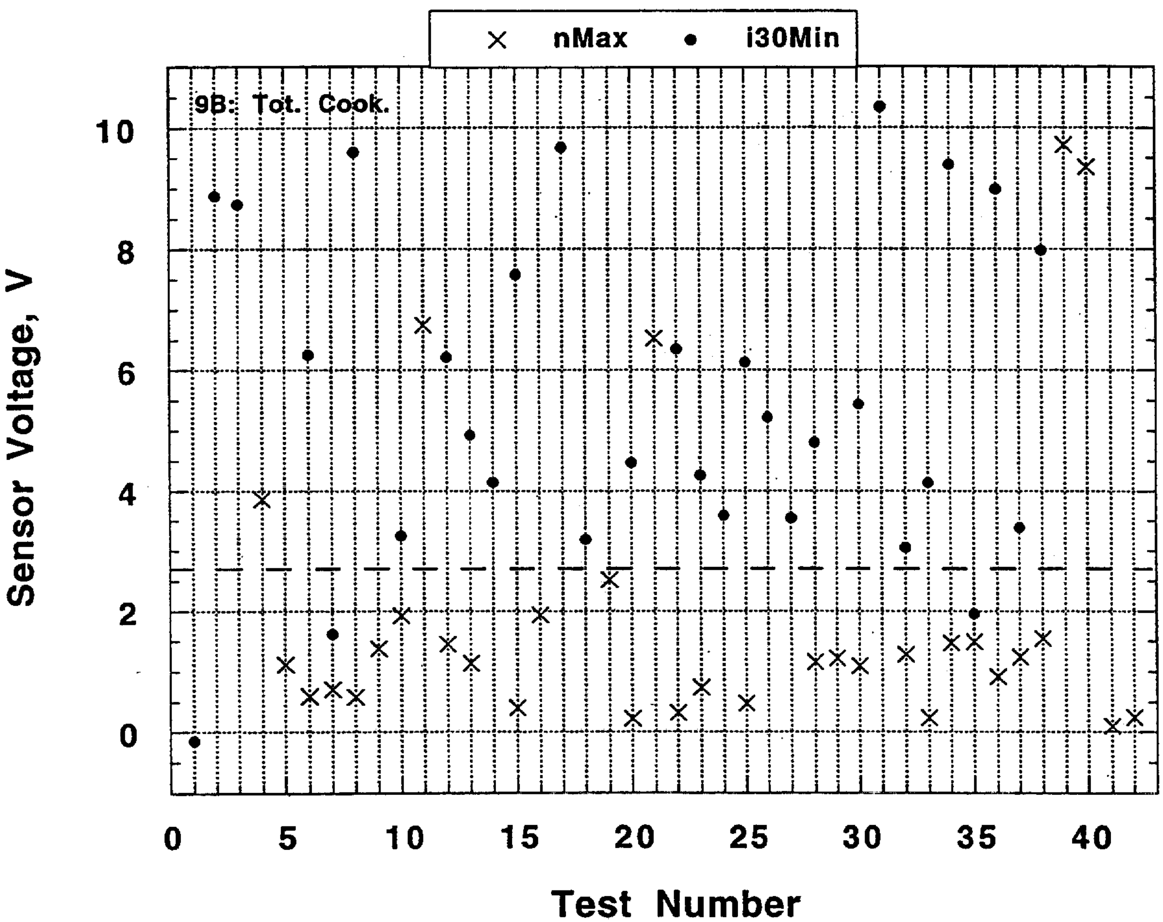

Figure 34. Site 9 total-cooking-gas sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

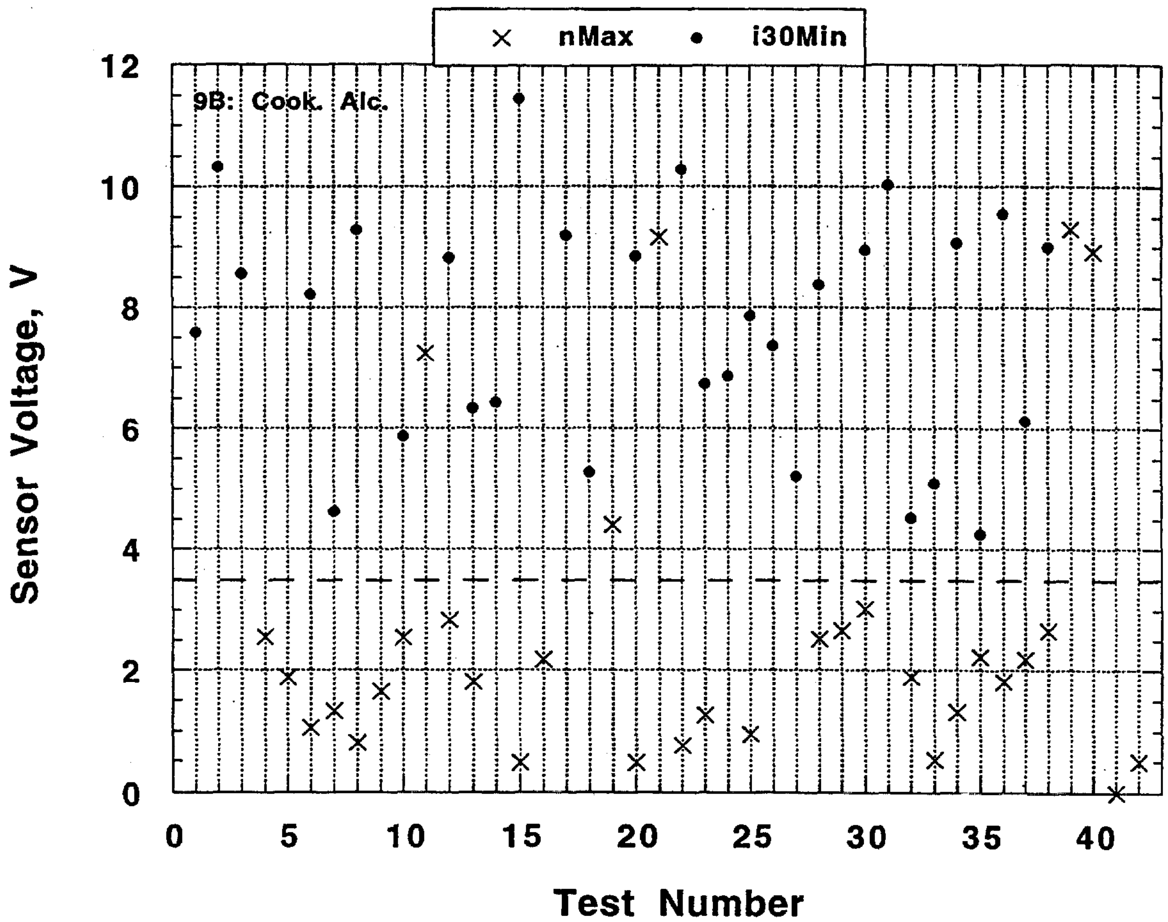

Figure 35. Site 9 cooking-alcohol sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

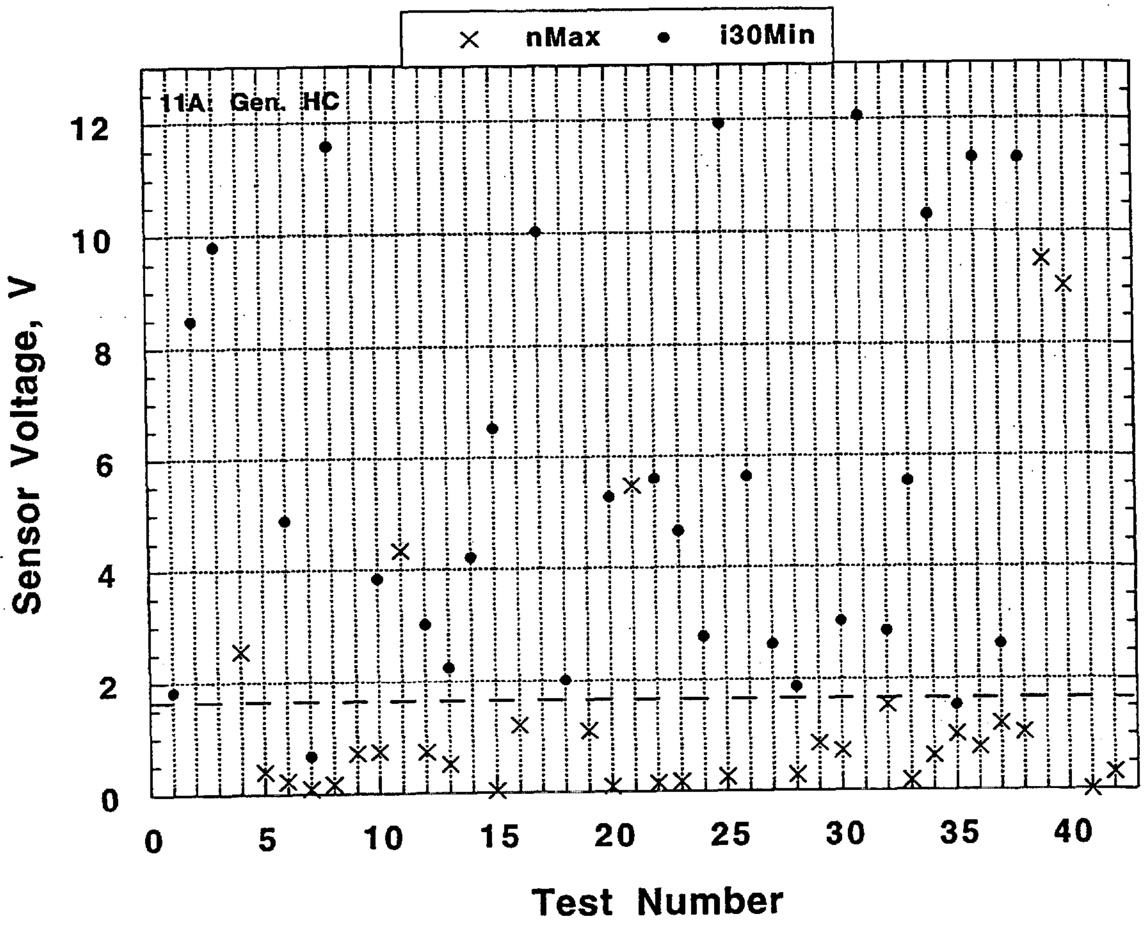

Figure 36. Site 11 general-hydrocarbon sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

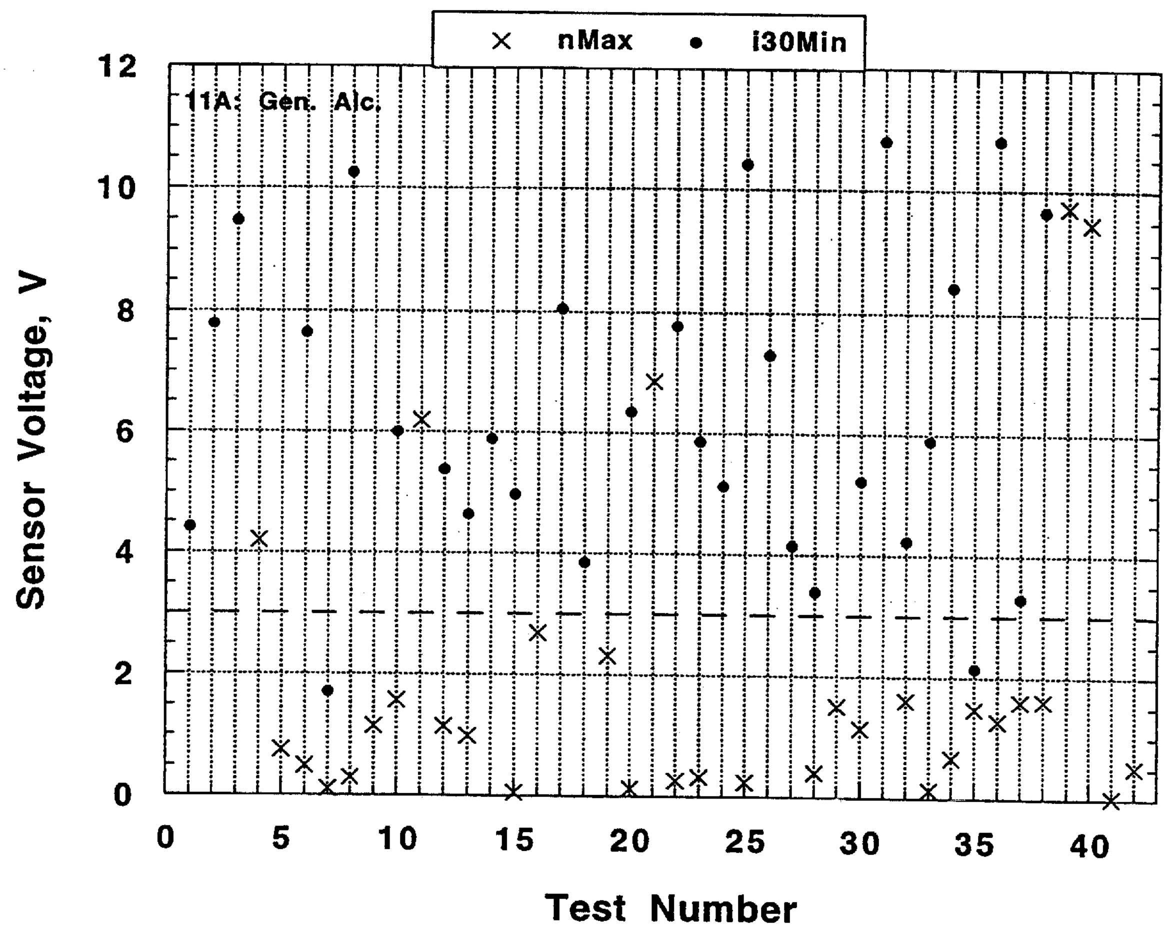

Figure 37. Site 11 general-alcohol sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

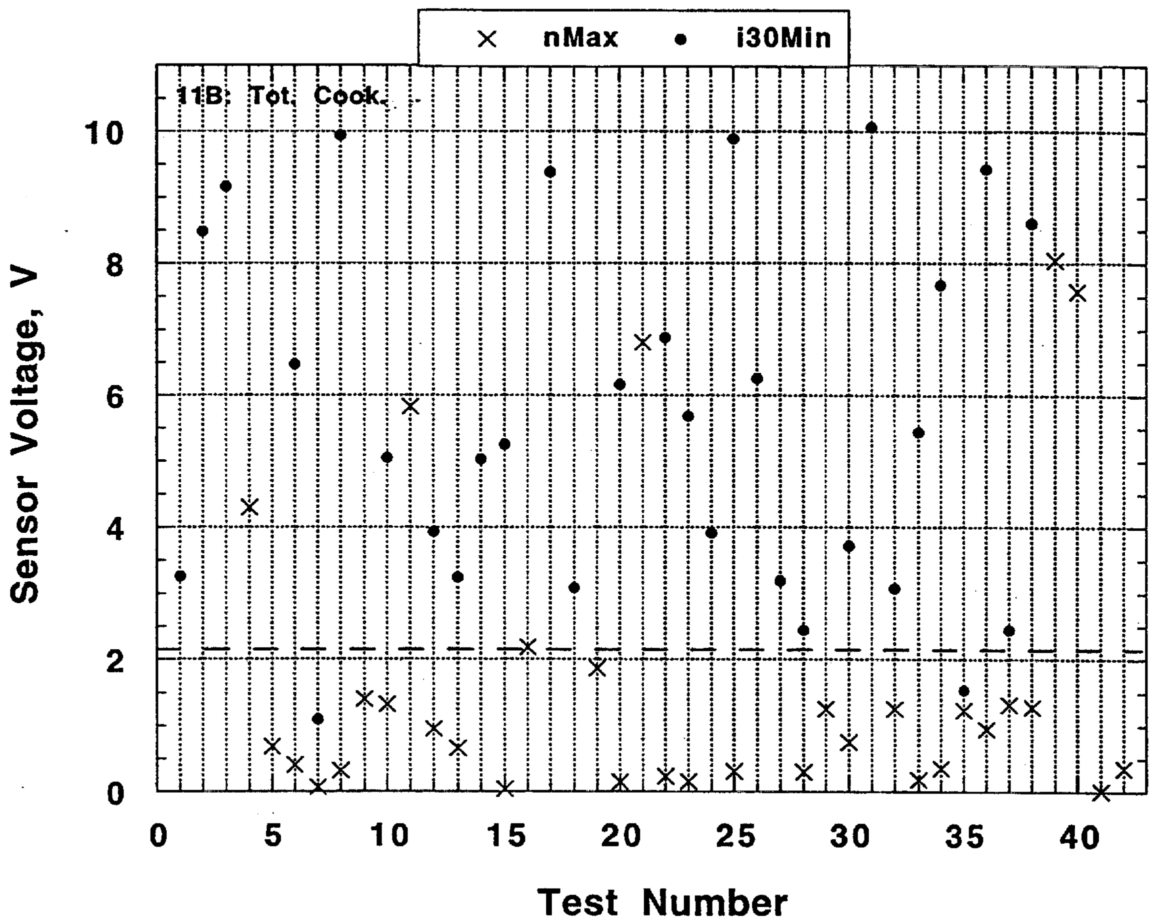

Figure 38. Site 11 total-cooking-gas sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

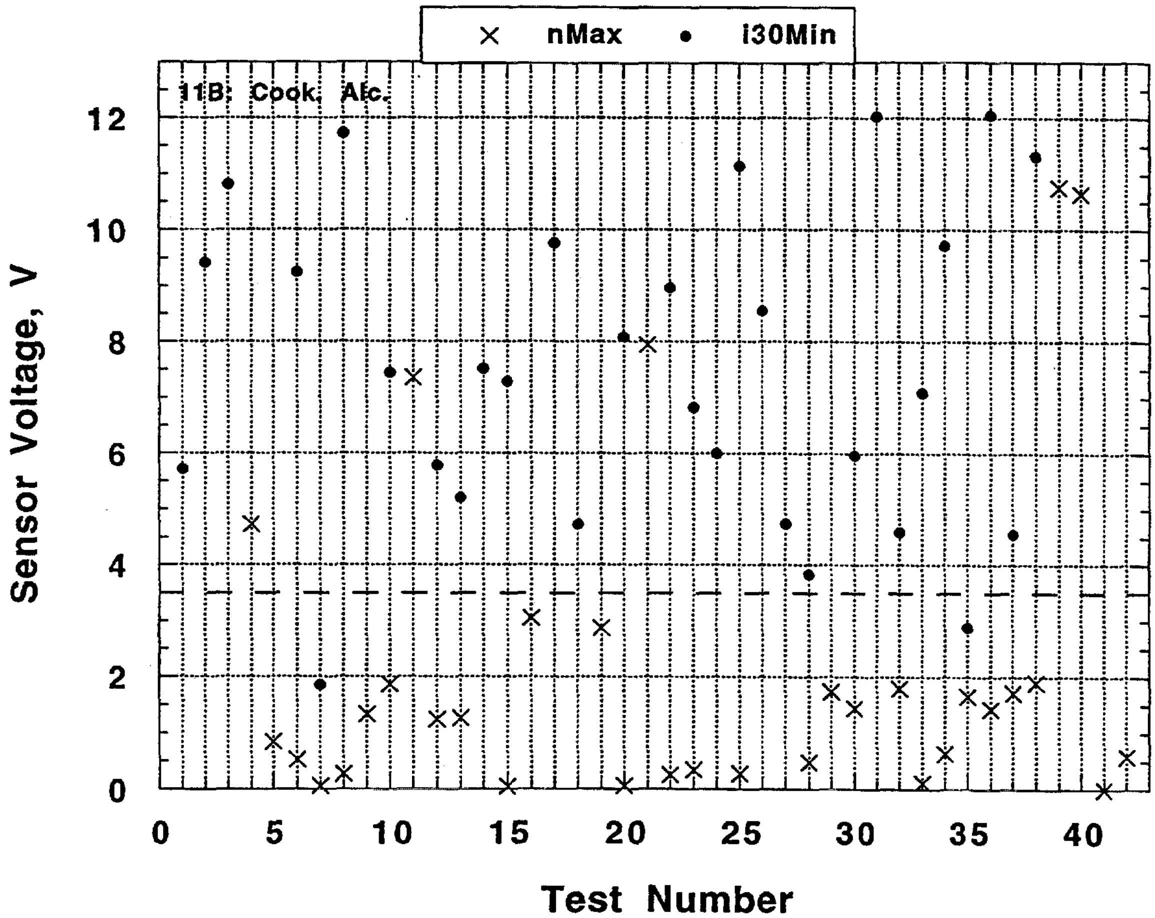

Figure 39. Site 11 cooking-alcohol sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

shift the relative proportions of failures-to-alarm to false alarms. The plot of the responses of the total-cooking-gas sensor in Figure 38 shows that it also would generate the same set of successes and failures as the previous two sensors if an alarm threshold of 2.2 V were used. Figure 39 is the plot for the cooking-alcohol sensor at site 11. If a threshold of 3.5 V is selected, this sensor performs like the other site 11 gas sensors. The responses of the site 11 gas sensors were similar, but the two alcohol sensors produced slightly higher ignition minima and clearer separation from the main group of normal maxima that make them slightly better candidates for detector components.

The gas sensors used in this study were very rugged and consistent throughout the study. The exposure of the gas sensors near the range, especially at sites 9 and 10, to grease and oil aerosols and smoke was extensive during most of the cooking cases and was thus repeated for most of the 42 tests. The self-heating of the sensors was sufficient to drive off accumulated contaminants and allow continued consistent performance during the entire test series. The harsh treatment of these sensors during this series of tests should translate into years of normal cooking exposure, and their robustness is a positive attribute.

4.2.2 Thermocouples

While many thermocouples showed trends of increasing temperature versus time, only the pan-bottom thermocouple provided adequate distinction between normal and pre-ignition temperatures for multiple tests. Figure 40 shows the response for the site 19 thermocouple which was located at the center of the range surface. The temperature at site 19 did not provide clear contrast between normal and pre-ignition conditions. Table 7 lists the site 19 thermocouple alarm rates as 31% false alarm and 3% failure to alarm. The thermocouples near the heating burner produced the highest range of temperatures and therefore provided the best differentiation. While food temperatures were monitored since ignition is most closely tied to the temperature of the potential fuel and surfaces contacting it, it is impractical to implement food or inside-pan temperature measurements as part of a detection system because they would require action by the cook. The next most logical, useful temperature measurement would be underneath the pan bottom.

Even though food temperatures were measured in this study, they did not provide a good signal differentiation between normal and ignition conditions because of the movement of the thermocouple during cooking and the existence of localized relatively hot and cold spots within the food. Figure 41 shows results for the thermocouple located at the center of the pan bottom. Some of the duplicate experiments did not produce valid temperature measurements for this thermocouple, but all of the cooking cases are represented by at least one test. For a threshold set to 340 °C (644 °F), the pan-bottom thermocouple would generate four false alarms and no failures to alarm. The false alarms would occur for the catfish tests, 11 and 21, water-and-oil test 12, and water test 19. The test 19 result can be discounted as a false alarm because the data point reflects the period after which the water boiled dry in the focus pan. Such a situation would be appropriate for range shutdown. Figure 42 is the same as Figure 41 except that the minima are for the 60 s before ignition. The results are very similar to those for 30 s with the addition of only one alarm failure. The pan-bottom thermocouple alone is nearly a completely

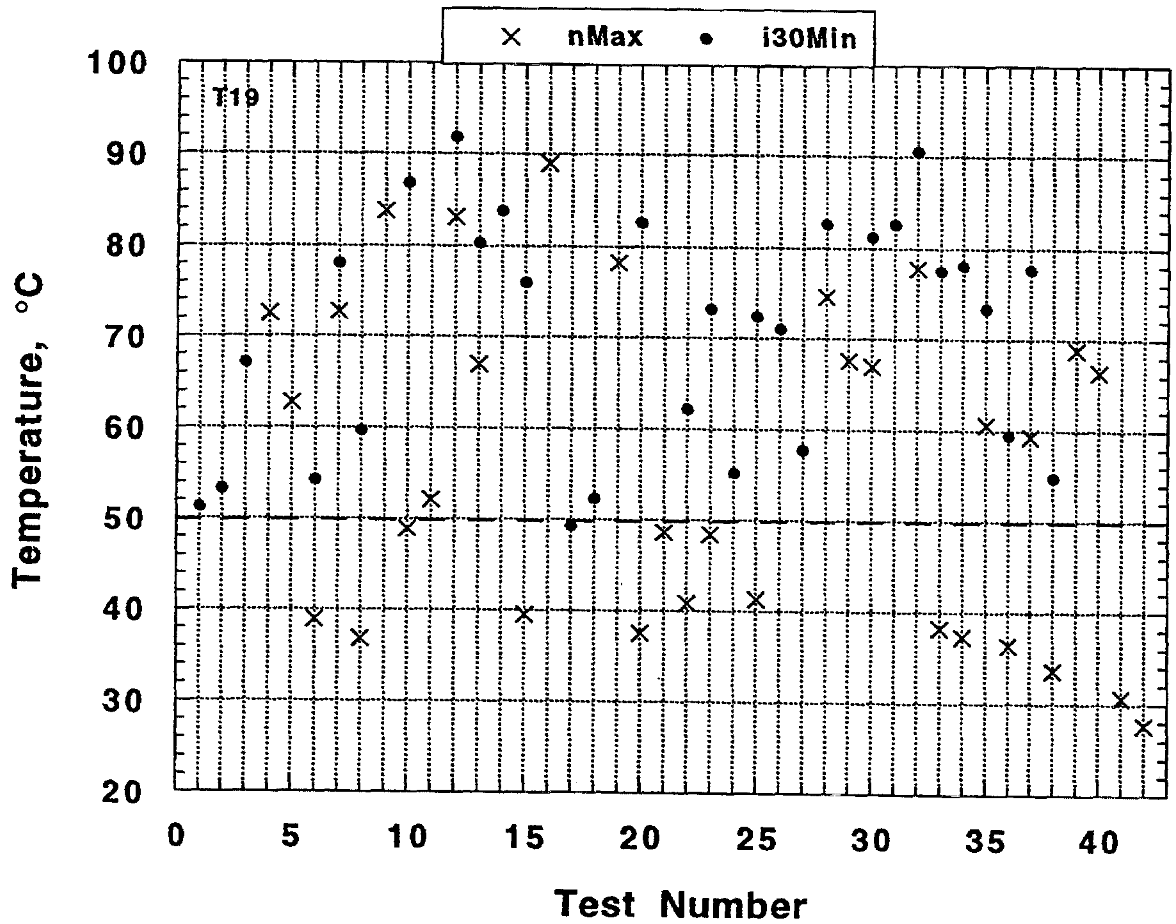

Figure 40. Site 19 thermocouple temperature maximum normal and minimum ignition output 30 s before ignition versus test number.

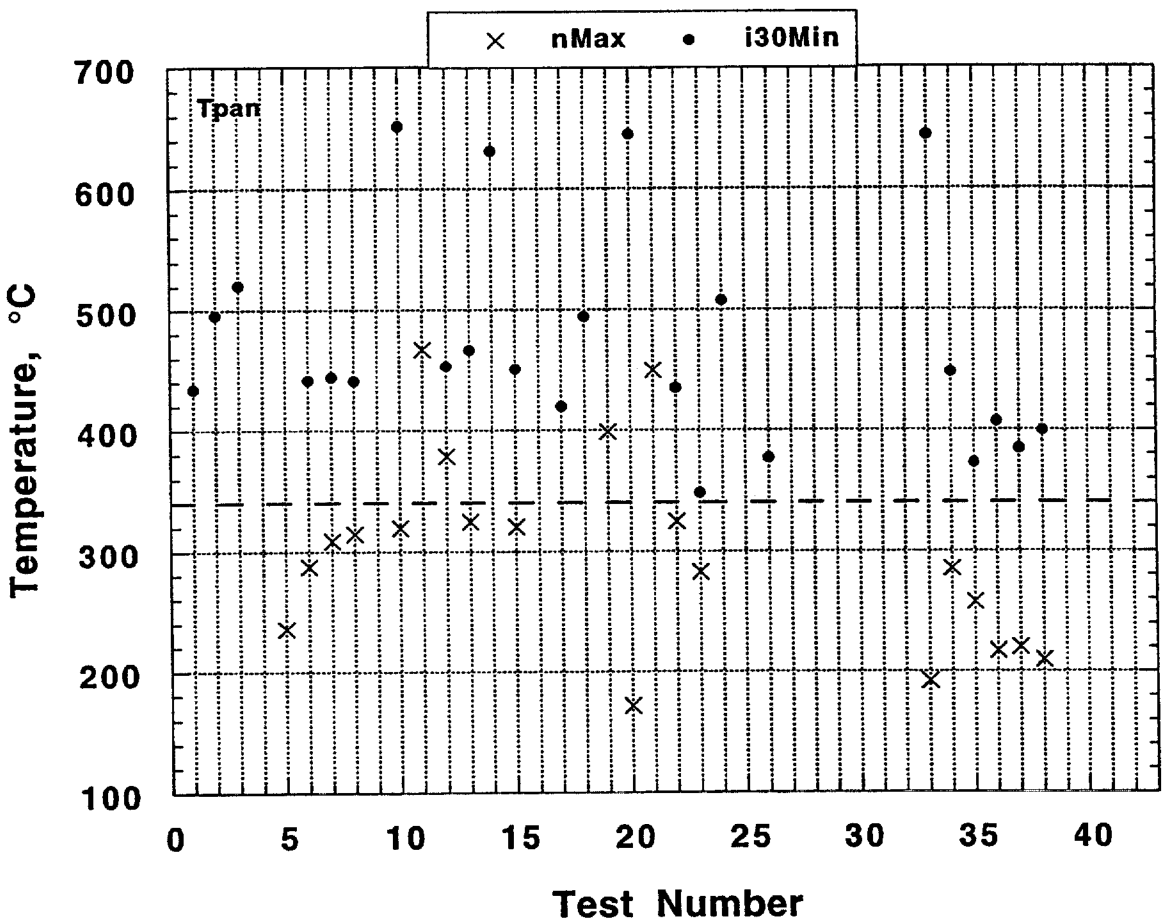

Figure 41. Focus-burner pan-bottom temperature maximum normal and minimum ignition output 30 s before ignition versus test number.

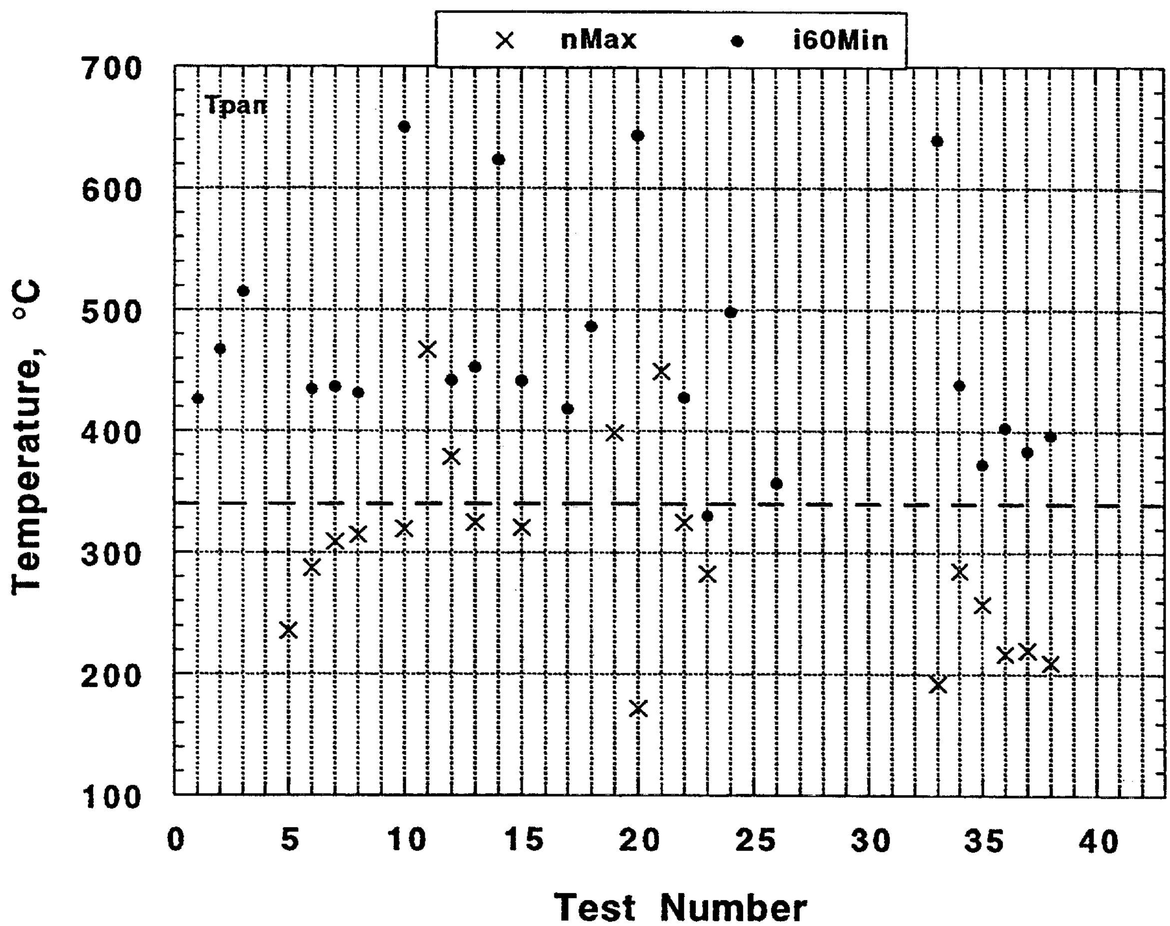

Figure 42. Focus-burner pan-bottom temperature maximum normal and minimum ignition output 60 s before ignition versus test number.

effective detection device, and it yielded comparable results to those of the best gas sensors.

It should be noted that the pan-bottom thermocouple did deteriorate after 24 tests under the repeated elevated heating conditions and periodic bending. Further study of the application of thermocouples or other methods of temperature measurement would be necessary to optimize temperature sensing for reliability and durability.

4.2.3 Combinations of Sensors

Since even the sensors with the best results would still alarm falsely for some attended or oven operations, combinations of various sensors were examined in order to determine if two sensors working together would provide improved differentiation. It was also of interest to determine if combined signals could prevent the nuisance alarms for the special cases and thus make the use of overrides and oven sensors less necessary. The thermocouple that performed best as a discriminator between normal and pre-ignition conditions was the pan-bottom thermocouple. Several gas sensors that performed similarly included the general- and cooking-alcohol sensors at site 7 and the cooking-alcohol sensor at site 9. The approach chosen to characterize the effectiveness of combining two detector responses was one of the simplest possible i.e., the multiplication of two signals. Rather than multiplying the data first and selecting maxima and minima from the generated data, a different method was employed. This method of multiplying the sensor data provides the most conservative, or worst-case, results. The already established minima and maxima from the pertinent data channels were multiplied. The effect of this was to provide a maximum limit for the combined normal maxima and a minimum limit for the combined pre-ignition minima. The plots generated from this method of combination show the closest overlap or smallest separation of normal and pre-ignition conditions. If the data had been multiplied before selecting new minima and maxima, the results would be even more promising than those that are discussed.

Figures 43 - 45 show plots of combined normal maxima and ignition minima for the pan-bottom thermocouple and three selected chemical sensors for each test. Note that the triangles and open circles represent substitute data that result from combining the sensor data from the tests for which the pan-bottom thermocouple malfunctioned with the functioning-thermocouple results from the duplicate tests for those cases.

Figure 43 is a plot of the results of combining pan-bottom temperature and the site 7 general-alcohol sensor voltage. A distinct gap with only a couple exceptions exists from 1400 to 1600 V°C between the normal and pre-ignition data points. Data from water test 19 has already been described as anomalous since the pan boiled dry. The only remaining exceptions are those from the blackened-catfish tests. Figure 44 is a plot of the result of combining the pan-bottom temperature and the site 7 cooking-alcohol sensor voltage. A gap between the conditions exists from 1400 to 1600 V°C as well. Figure 45 is the corresponding plot for the pan-bottom temperature and site 9's cooking-alcohol sensor. This combination produces a gap from 1200 to 1500 V°C. The condition discrimination produced by these combined-sensor signals is better than those generated by the best single sensors. Figure 46 is the same as Figure 45 except the 60 s before ignition criteria were used to generate the minimum pre-ignition signals. The results are very similar with only a slight decrease in the spread between the normal and pre-ignition

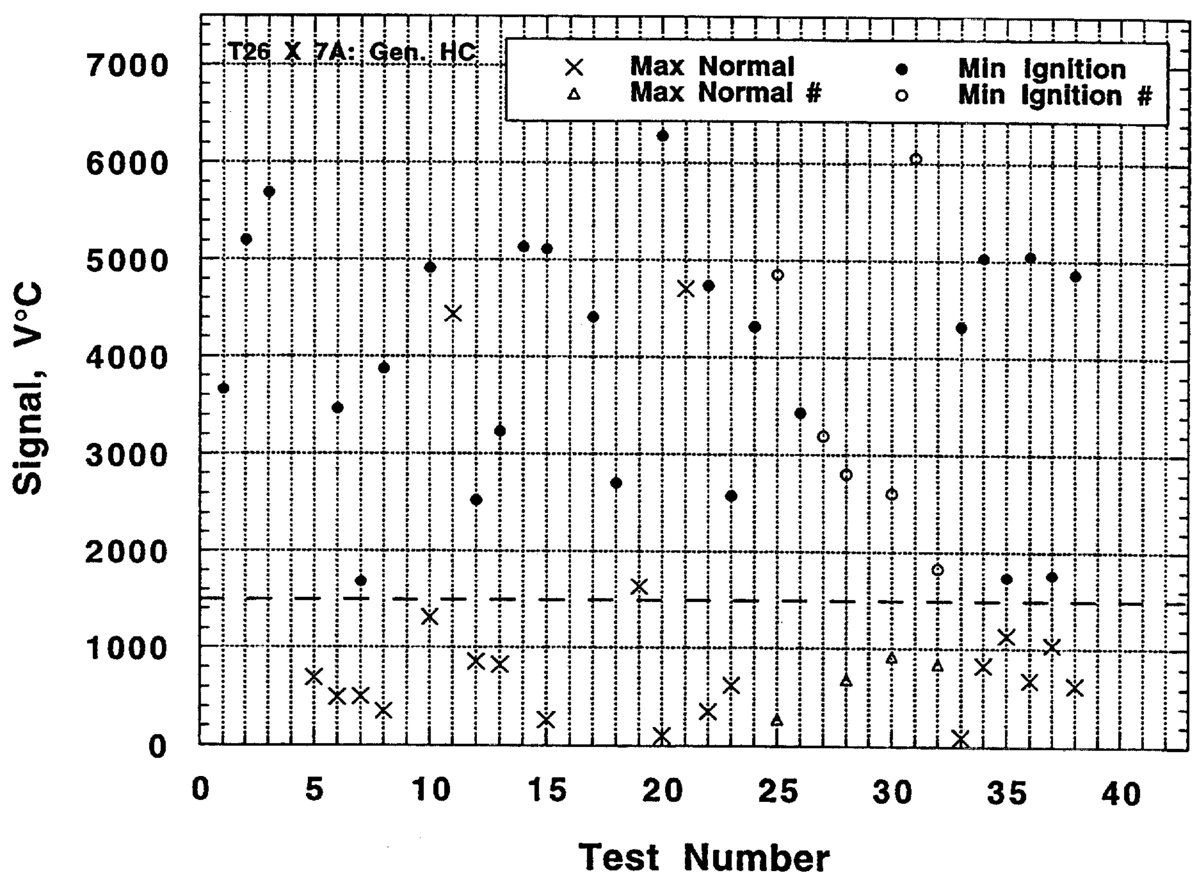

Figure 43. Focus-burner pan-bottom temperature multiplied by site 7 general-alcohol sensor voltage maximum normal and minimum ignition output 30 s before ignition versus test number. # signifies the results from substitute thermocouple data.

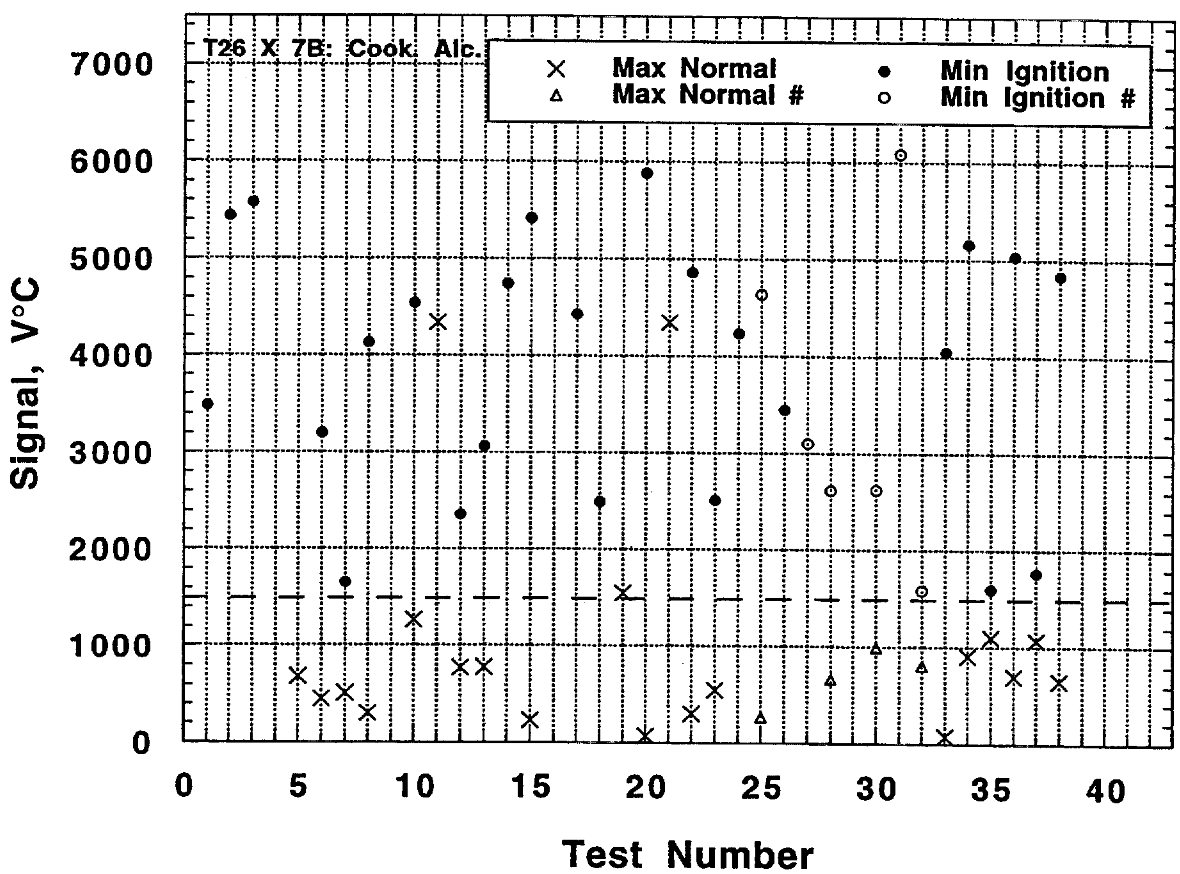

Figure 44. Focus-burner pan-bottom temperature multiplied by site 7 cooking-alcohol sensor voltage maximum normal and minimum ignition output 30 s before ignition versus test number. # signifies the results from substitute thermocouple data.

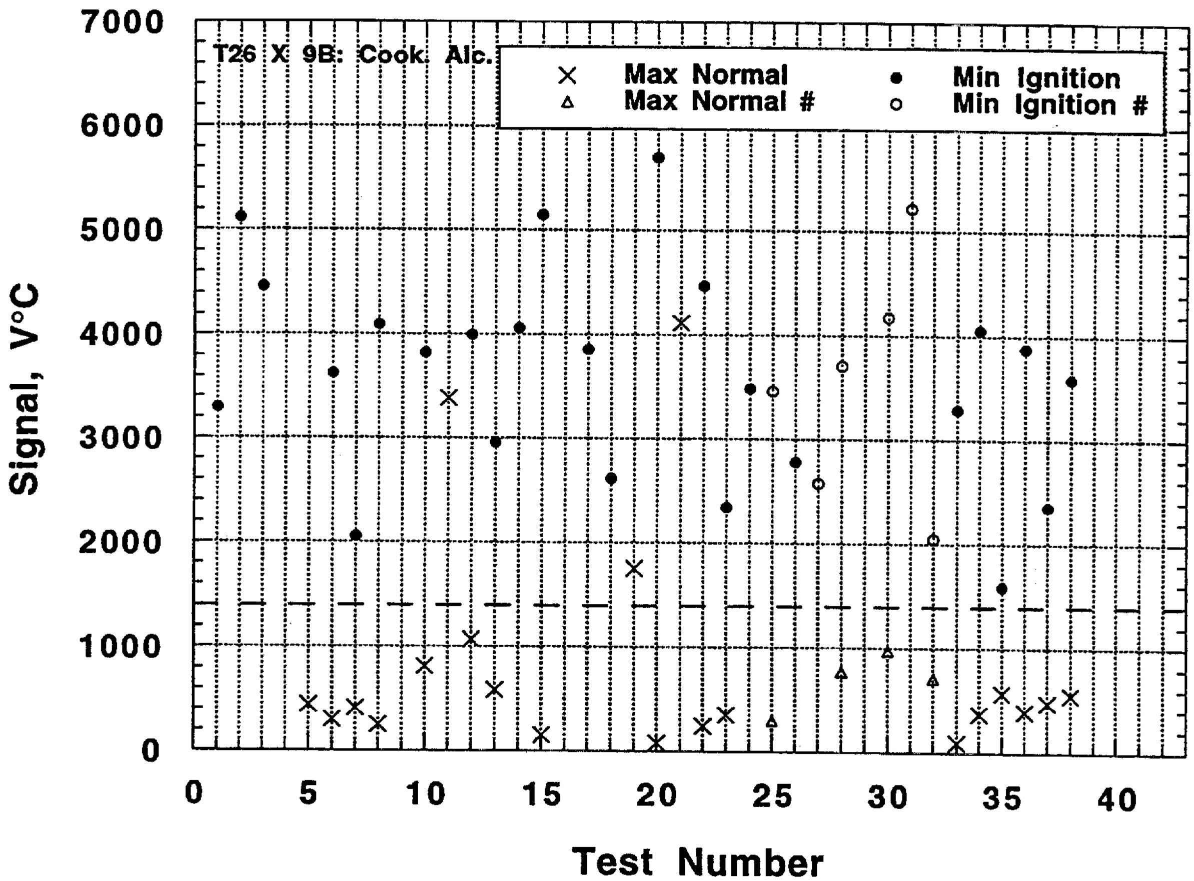

Figure 45. Focus-burner pan-bottom temperature multiplied by site 9 cooking-alcohol sensor voltage maximum normal and minimum ignition output 30 s before ignition versus test number. # signifies the results from substitute thermocouple data.

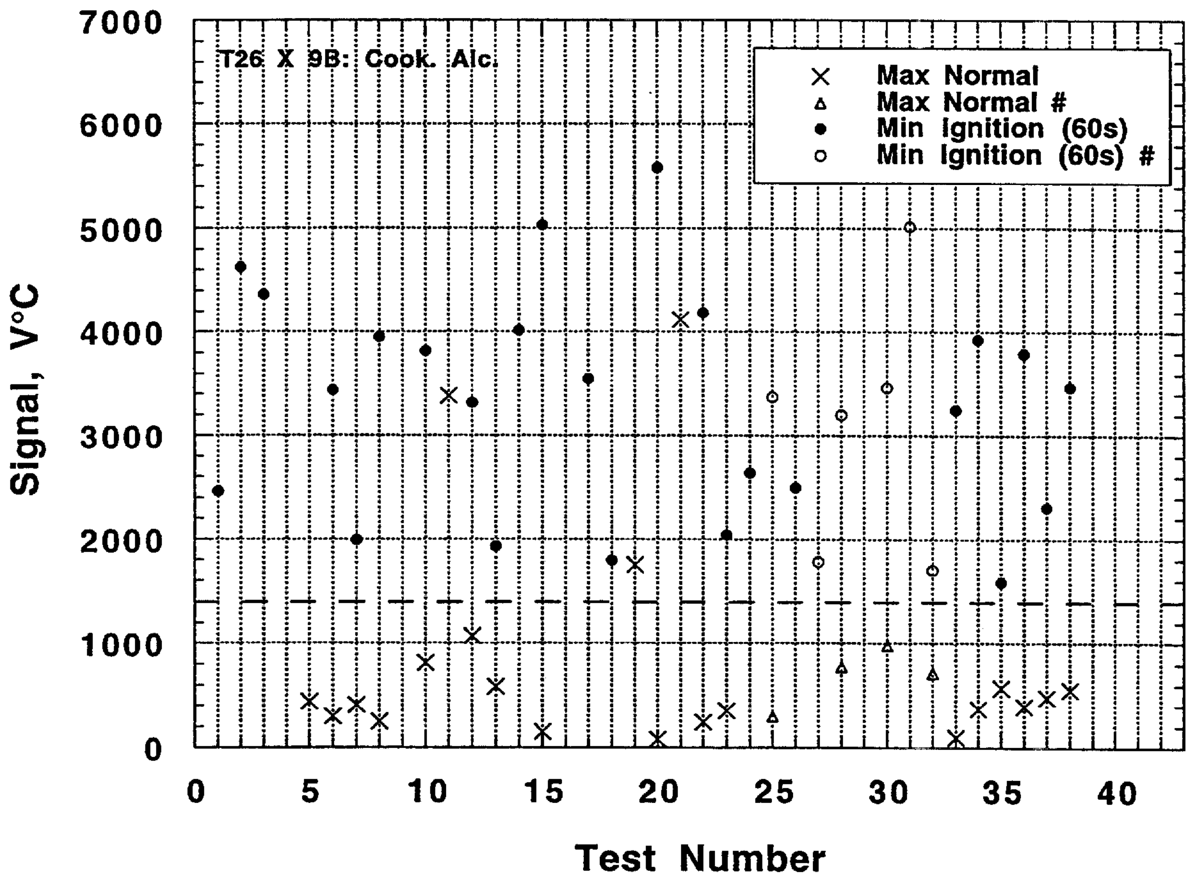

Figure 46. Focus-burner pan-bottom temperature multiplied by site 9 cooking-alcohol sensor voltage maximum normal and minimum ignition output 60 s before ignition versus test number. # signifies the results from substitute thermocouple data.

points. The significance of the cooking of the blackened food as a cause for false alarms must be judged in terms of the proportion of cooking it constitutes and the degree of inconvenience suffered by a consumer. As discussed previously, application of additional sensor or consumer inputs and logic circuitry could eliminate the problem of false alarms during attended cooking operations.

A more sophisticated, higher order analysis of combinations of sensors is likely to produce an even more reliable detection algorithm. Investigation of alternative sensors and locations around the range is also likely to improve upon those that were selected and tested in this study. The sophistication of current electronic capabilities such as temporary deactivation, motion detection, and oven-use monitoring can also aid in preventing false alarming, especially in view of the attended or controlled nature of several of the most difficult cases experienced in this study.

4.2.4 Smoke Detectors

This section discusses the alarm times generated by photoelectric and ionization smoke detectors at sites 5, 9, 11, and 13-17. Figure 47 is a plot of the average alarm time in seconds versus the individual photoelectric smoke detectors. The earliest alarming detector on average was at site 9 which was located just at the front of the range hood. The site 11 detector was the next most sensitive and was located at the ceiling directly above sites 9 and 10 and close to the impingement area of the smoke plumes. The detector at site 5, on the wall under the hood behind the range, was on average the next to respond. Sites 13, 14, 16, and 17 alarmed at similar times, and site 15's photoelectric smoke alarm was the slowest to respond, probably because its location was most distant from the smoke source.

Figure 48 shows the ratios of alarm times to normal times for the photoelectric detectors at sites 5-13 plotted versus test number. Data points are scattered on each side of the horizontal dashed line indicating a ratio value of one. Points falling below the line represent false alarms because the alarm time was less than the time of the end of the normal-cooking period. Points above the line represent acceptable alarms because they occurred after the normal portion of a test. Figure 49 shows the ratios of alarm times to ignition times versus test number for the same detectors. For this plot, points above the line represent failures to alarm because the alarm time was later than the ignition time. Points below the line represent successful alarming before ignition. Note that no cooling-lag time or safety margin was subtracted from the ignition times. Figures 50 and 51 are plots similar to Figures 48 and 49 except they pertain to the remaining photoelectric smoke detectors at sites 14-17.

Table 8 lists all of the smoke detector sites for both detector types with their failure and success rates. Each column list the number of instances of success or failure followed by the corresponding percentage in parentheses. Four of the eight photoelectric smoke detectors were completely successful at alarming before ignition. Two additional ones may have been as successful, but each began one test in alarm mode and provided no information. Only the detectors at sites 5 and 15 failed to alarm for a few tests. The reason the photoelectric detector at site 5 sometimes failed to respond is most likely because of its position on the back wall, relatively near the range surface where little of the plume smoke passed or accumulated. The detector at site 15 may have failed to alarm two times because Site 15 is the most distant from

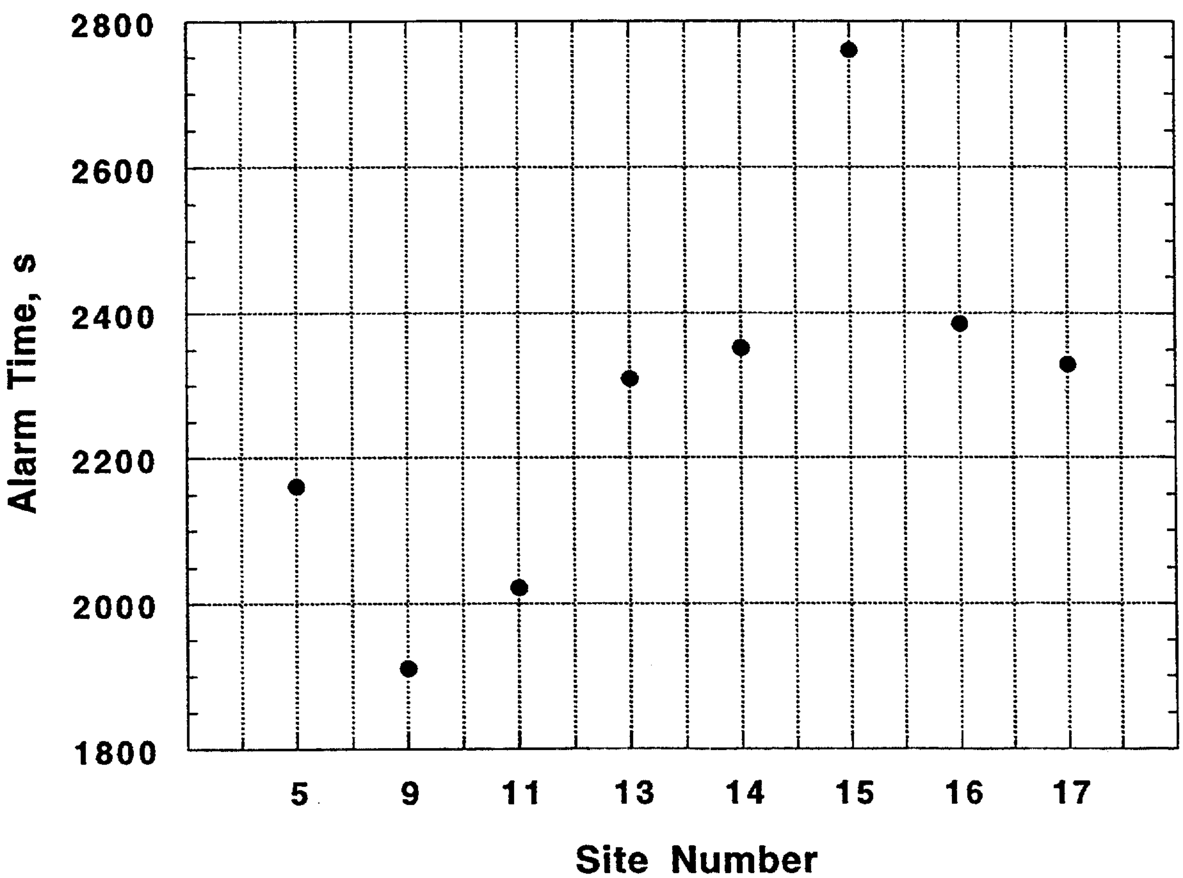

Figure 47. Average photoelectric smoke-detector alarm time for all tests versus site number.

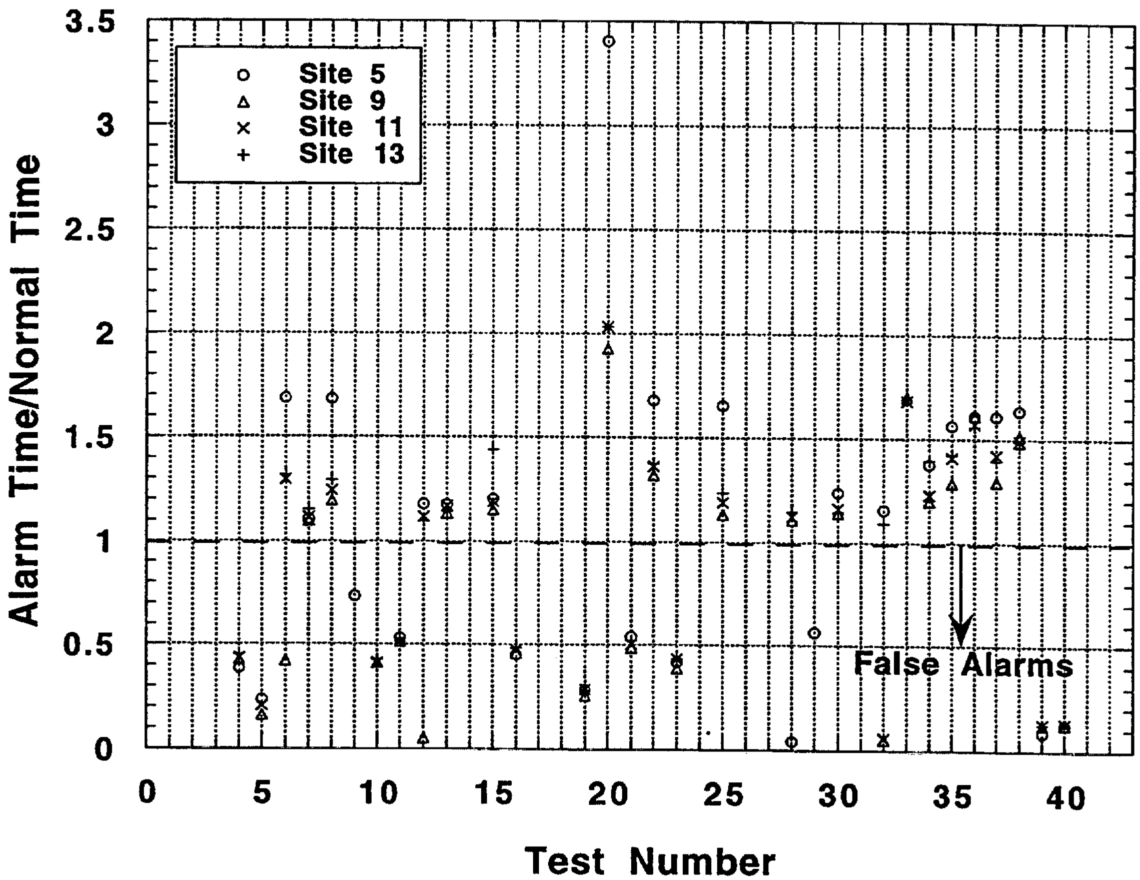

Figure 48. Sites 5-13 photoelectric smoke detectors ratio of alarm times to normal times for all tests versus test number.

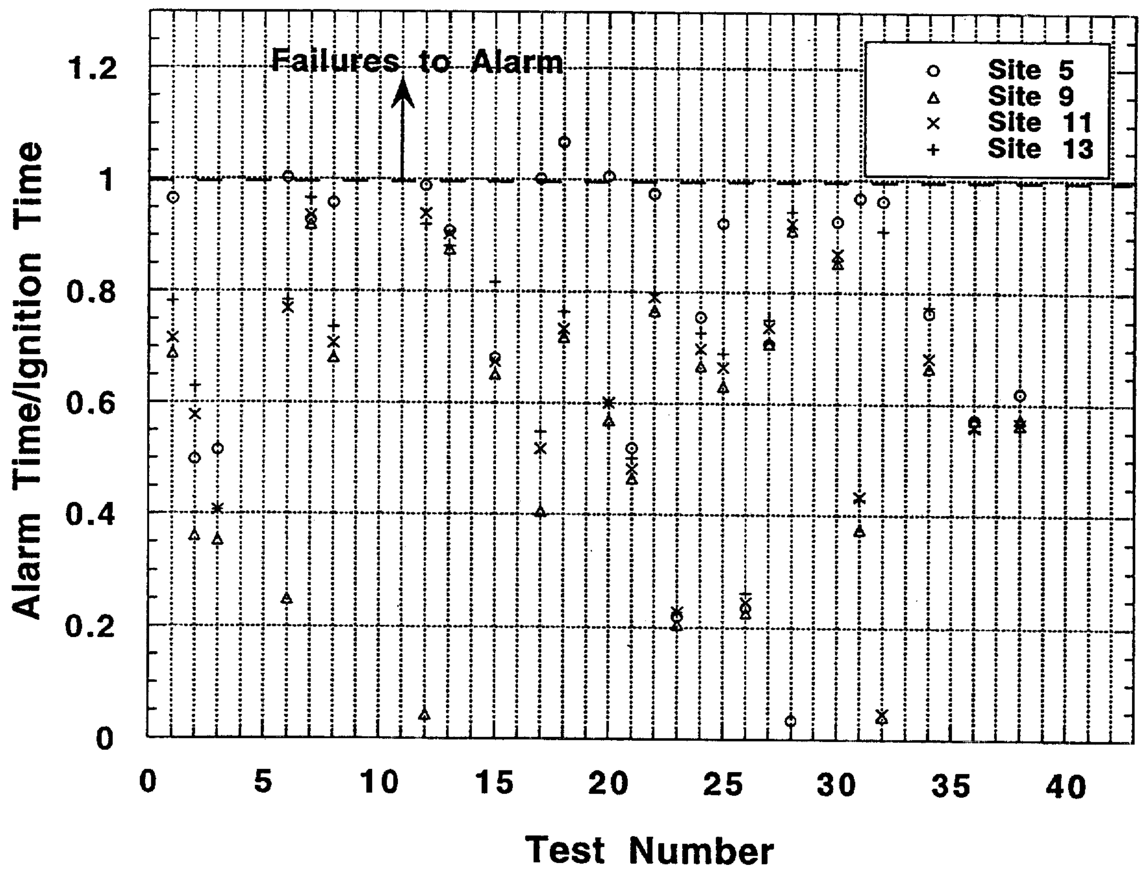

Figure 49. Sites 5-13 photoelectric smoke detectors ratio of alarm times to ignition times for all tests versus test number.

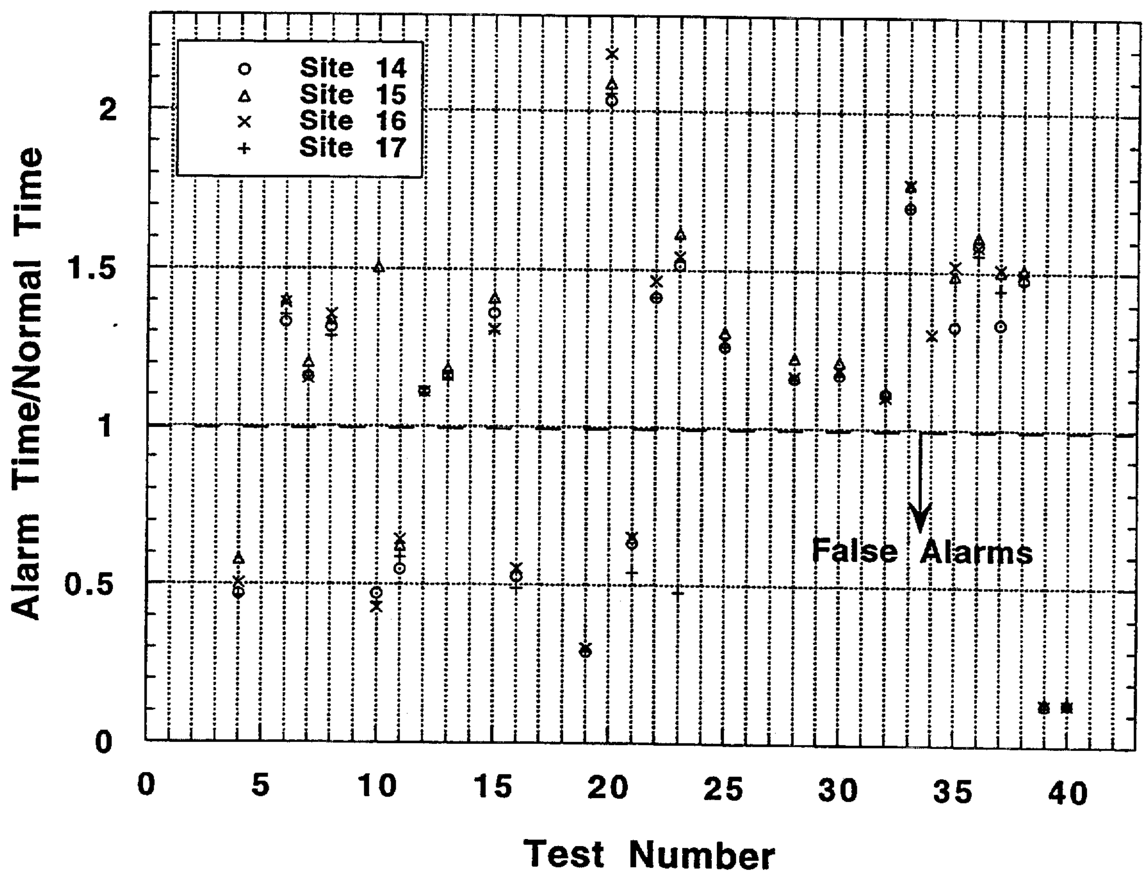

Figure 50. Sites 14-17 photoelectric smoke detectors ratio of alarm times to normal times for all tests versus test number.

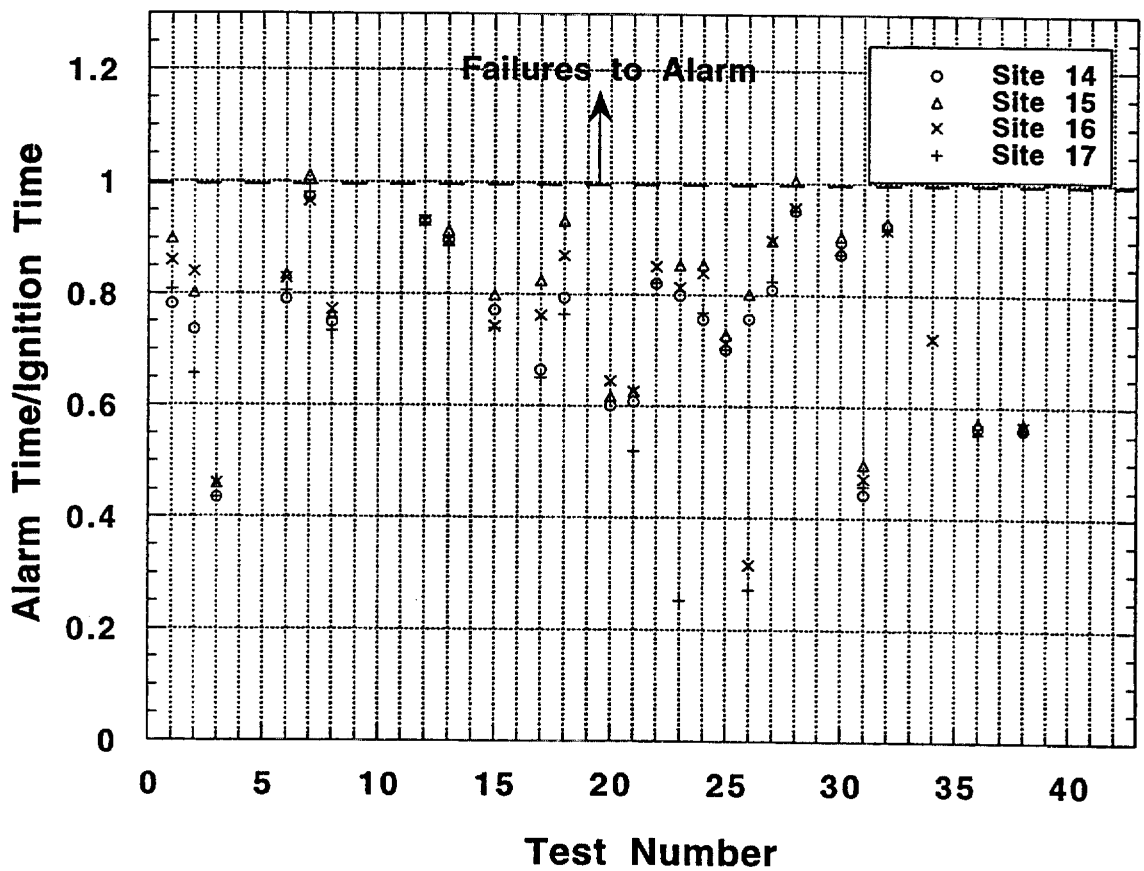

Figure 51. Sites 14-17 photoelectric smoke detectors ratio of alarm times to ignition times for all tests versus test number.

Table 8. Smoke detectors' false alarm and alarm failure performance for 42 tests

Condition	Unattended (Ignition)			Normal		
Site Number	**Alarm Successes (%)**	**Alarm Failures (%)**	**Pre-test Mal-functions (%)**	**Non-alarm Successes (%)**	**False Alarms (%)**	**Pre-test Mal-functions (%)**
Photoelectric Smoke Detectors						
5	22 (85)	4 (15)	0 (0)	20 (62)	12 (38)	0 (0)
9	26 (100)	0 (0)	0 (0)	19 (59)	13 (41)	0 (0)
11	26 (100)	0 (0)	0 (0)	21 (66)	11 (34)	0 (0)
13	26 (100)	0 (0)	0 (0)	23 (72)	9 (28)	0 (0)
14	25 (96)	0 (0)	1 (4)	23 (72)	8 (25)	1 (3)
15	21 (81)	2 (8)	3 (12)	24 (75)	5 (16)	3 (9)
16	26 (100)	0 (0)	0 (0)	24 (75)	8 (25)	0 (0)
17	25 (96)	0 (0)	1 (4)	22 (69)	9 (28)	1 (3)
Total	*197 (95)*	*6 (3)*	*5 (2)*	*176 (69)*	*75 (29)*	*5 (2)*
Ionization Smoke Detectors						
14	23 (88)	3 (12)	0 (0)	19 (59)	13 (41)	0 (0)
15	16 (62)	10 (38)	0 (0)	25 (78)	7 (22)	0 (0)
16	22 (85)	4 (15)	0 (0)	22 (69)	10 (31)	0 (0)
17	23 (88)	3 (12)	0 (0)	18 (56)	14 (44)	0 (0)
Total	*84 (81)*	*20 (19)*	*0 (0)*	*84 (66)*	*44 (34)*	*0 (0)*

the smoke source and on average, its photoelectric detector responded slowest as shown in Figure 47. The site 15 photoelectric detector experienced the fewest false alarms which is consistent with its distance from the smoke source and delay in reacting to the smoke.

Figure 52 is a plot of the alarm times for the various ionization detectors plotted in the same way as Figure 47 was for the photoelectric detectors. Four detectors were employed. Site 14 responded the earliest on average. Although it was not the closest to the range, it was located at the point where the accumulated smoke flowed out of the room into the exhaust hood. The site 17 detector was the next fastest and was the closest detector to the range. The detectors at sites 15 and 16 had comparable alarm times with those of site 15, again slightly slower in agreement with results for the photoelectric detectors.

Figure 53 shows the ratios of alarm times to normal times for the ionization detectors at sites 14-17 plotted versus test number. The data are plotted in the same manner as for the photoelectric detectors in Figures 48 and 50. Figure 54 shows the ratios of alarm times to ignition times versus test number for the same detectors. This plot is similar to Figures 49 and 51. Table 8 lists the ionization smoke detectors and their failure and success rates. Of the ionization detectors at sites 14-17, the one at site 15 failed most often to alarm before ignition which is the same result as for the photoelectric detectors. Similar to the relative success of the site 15 photoelectric detector, the site 15 ionization detector experienced the fewest false alarms of all of the ionization units. The detectors at sites 14 and 17 produced twice as many false alarms as the one at site 15.

The totals in Table 8 for each detector type indicate that these particular photoelectric detectors on average were about 16% more effective than the ionization detectors in alarming prior to ignition conditions and were about 4% more effective in not alarming for normal conditions. This is reasonable since the photoelectric smoke detection technique is more sensitive than the ionization technique to the relatively large soot particles produced by pyrolysis of hydrocarbon materials such as food [7]. In conjunction with other inputs such as temperature or a gas measurement, it might be possible to create a reliable detection system using a standard smoke detector. Of the two detector models compared in this study, the photoelectric model would be the better choice to incorporate into a system. Smoke detectors of decreased sensitivity would probably demonstrate better performance regarding false alarms, but the detrimental effect on failures to alarm might counter any improvements.

4.3 Effects of Cooking-Environment Variables

It is important to examine the possible effects of changes in the cooking environment on the signals that might be used for distinguishing normal and pre-fire conditions. The variables discussed in this section include the food and cooking method, the type of range, the use of the range hood, and the pan material. Most of the figures in this section plot a sensor signal versus time before ignition. This method of presentation allows the period just preceding ignition to receive greater focus. Only data up to the time of ignition are plotted.

4.3.1 Food and Cooking Method

The effects of food type have been addressed in the previous sections through the

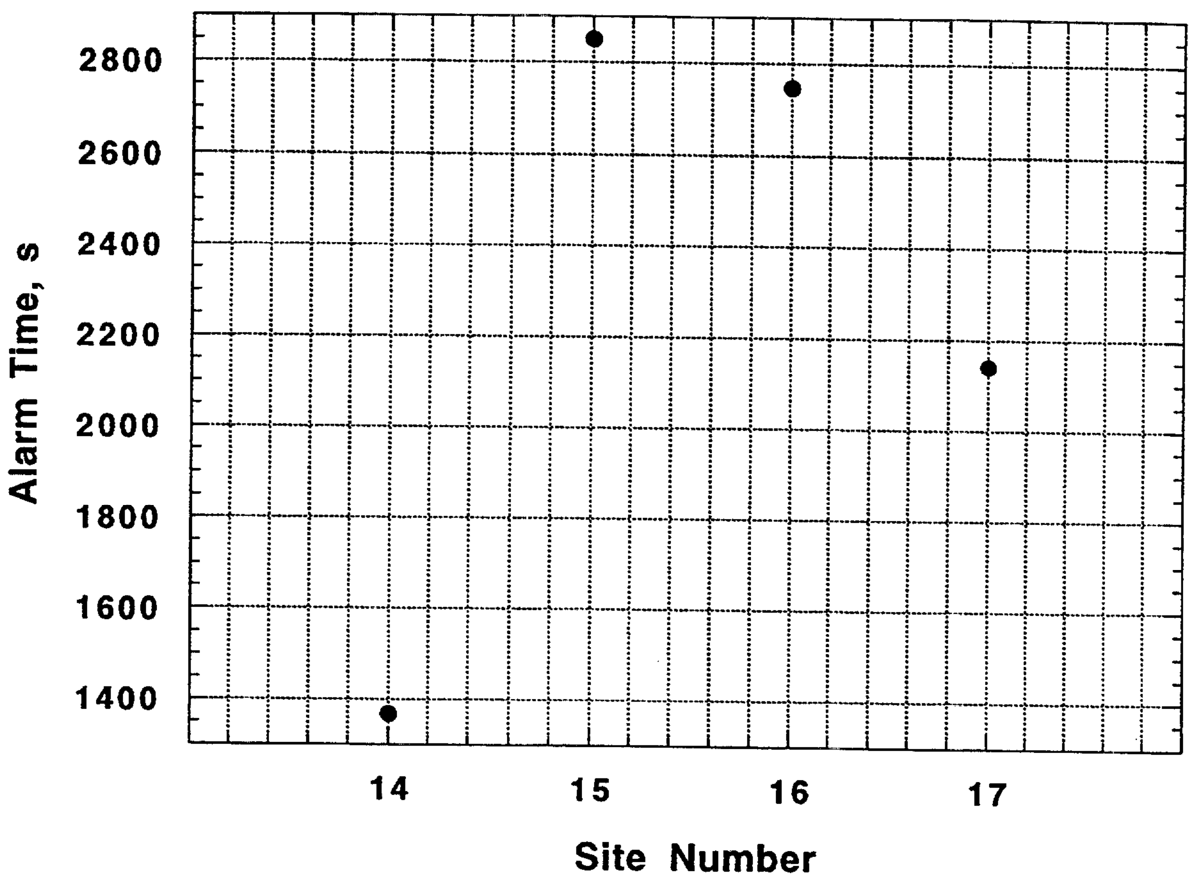

Figure 52. Average ionization smoke-detector alarm time for all tests versus site number.

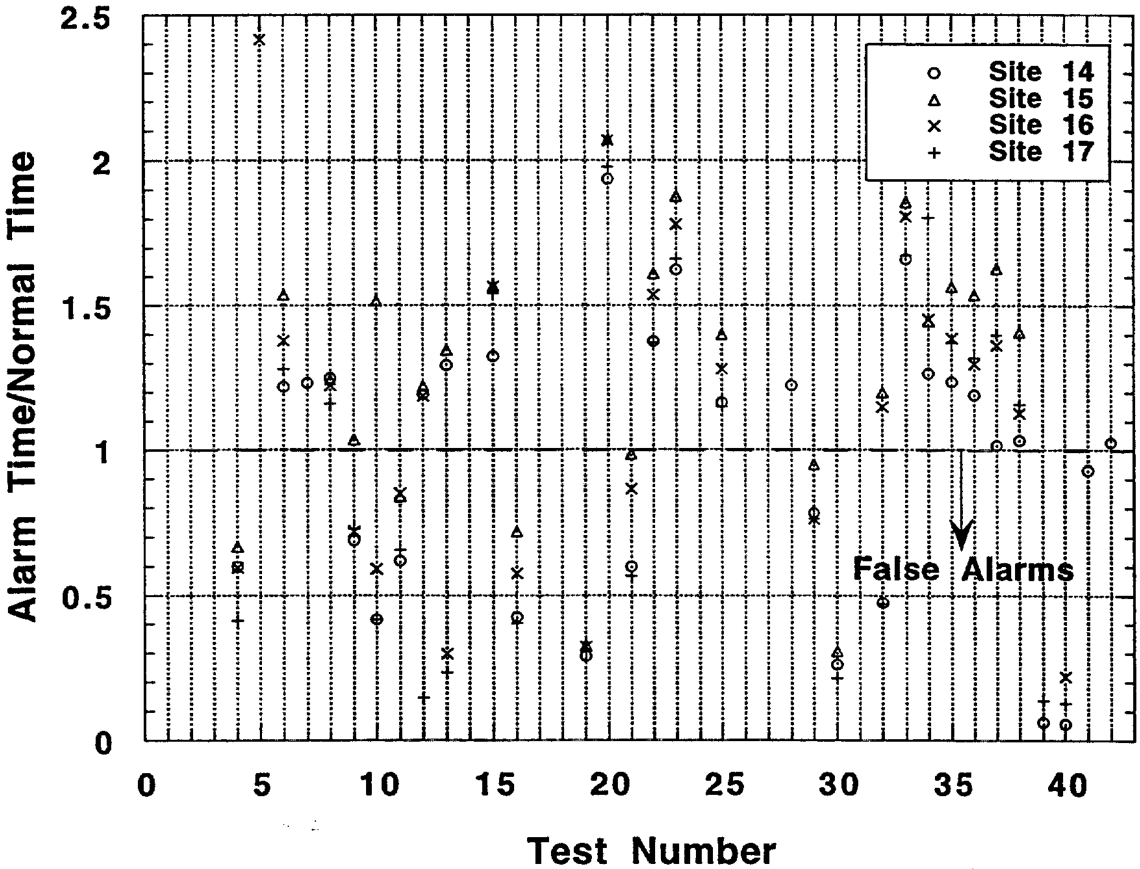

Figure 53. Sites 14-17 ionization smoke detectors ratio of alarm times to normal times for all tests versus test number.

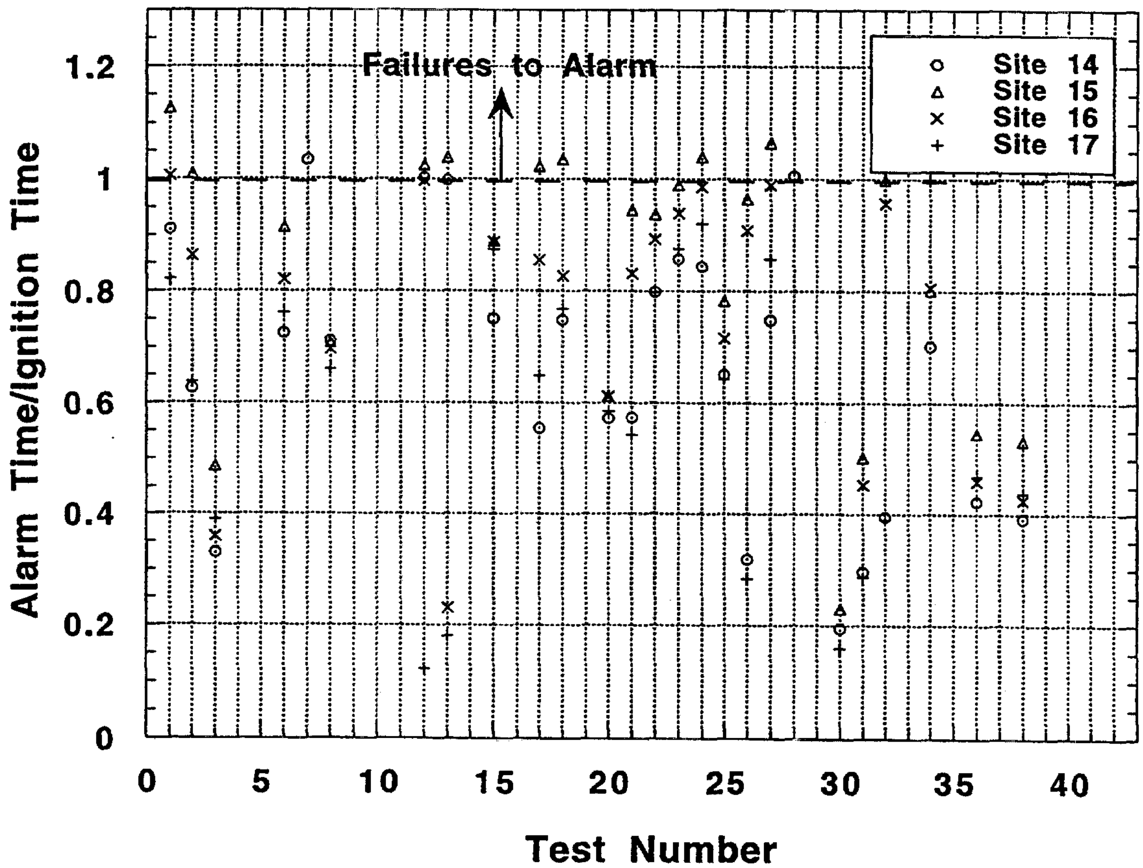

Figure 54. Sites 14-17 ionization smoke detectors ratio of alarm times to ignition times for all tests versus test number.

scatter plots showing normal and pre-ignition measurements. The wide range of variation across the 42 tests is indicative primarily of the differences in food and cooking method. Some differences due to range type, range-hood status, and pan material are superimposed on the basic differences, and the influence of these variables are addressed in the next sections.

4.3.2 Range Type

Four different ranges were utilized for this set of experiments. Ranges C and D, the smoothtop and down-draft, were used to address the special cases of self-cleaning ovens and grilling, respectively. The majority of tests were performed on electric range A. A couple of the range-top cooking cases tested on range A were also tested on gas range B to establish similarities and differences for different range types. The cases tested on both electric and gas ranges were chicken-in-oil (normal) and water and oil. All of these tests were conducted with the range hood off.

Figure 55 is a plot of the pan-bottom temperature versus time before ignition for the chicken and oil case that progressed from normal to unattended cooking for tests performed on both ranges. The temperatures during the normal-cooking period of the tests vary by 60 °C (140 °F) to 120 °C (250 °F). The electric-range temperatures varied between the two tests as well by about 60 °C (140 °F) during the normal period. The gas-range temperatures were very similar throughout the tests and nearly indistinguishable for the last 2000 s before ignition. For the last 300 s, the electric-range tests resulted in nearly identical temperature curves as well. The pan-bottom temperatures on the electric range reached maxima of 450 °C (840 °F) and 470 °C (880 °F). The pan-bottom temperatures on the gas range reached maxima of 400 °C (750 °F) and 410 °C (770 °F). Using absolute temperatures and comparing to the lower values from each pair of tests, these variations in pan-bottom temperature at ignition are 2.7% and 1.5% for electric and gas, respectively.

Figure 56 is a plot of the Site 9 general-alcohol sensor response versus time before ignition for the same test on both ranges. Both of these tests show excellent reproducibility. The rate of increase of the signal during the unattended period of the tests on the electric range is about a factor of two greater than the rate for most of the unattended period for the tests on the gas range. The rate of increase for the gas-range tests does increase to match that of the electric-range tests in the last 300 s to 500 s before ignition. All of the tests experienced ignition within ±5% of a sensor output of 12.7 V.

Figure 57 shows laser attenuation versus time before ignition for the same chicken test for both electric and gas ranges. While each signal averages approximately 95% attenuation near ignition, the signal for gas cooking rises over 1800 s, and the signal for electric cooking rises over only about 900 s.

The comparison of the tests performed on the different ranges indicates the following effects of range type. At ignition, the pan temperatures for the electric range are 5% to 11% higher than for the gas range. The signals for the gas sensor at ignition do not seem to be affected significantly by the range type. The laser-attenuation signal approaching ignition is also insensitive to range type. All of the signals are stretched in time for the gas range relative to the electric range. The relative differences observed in heating times to ignition for these particular

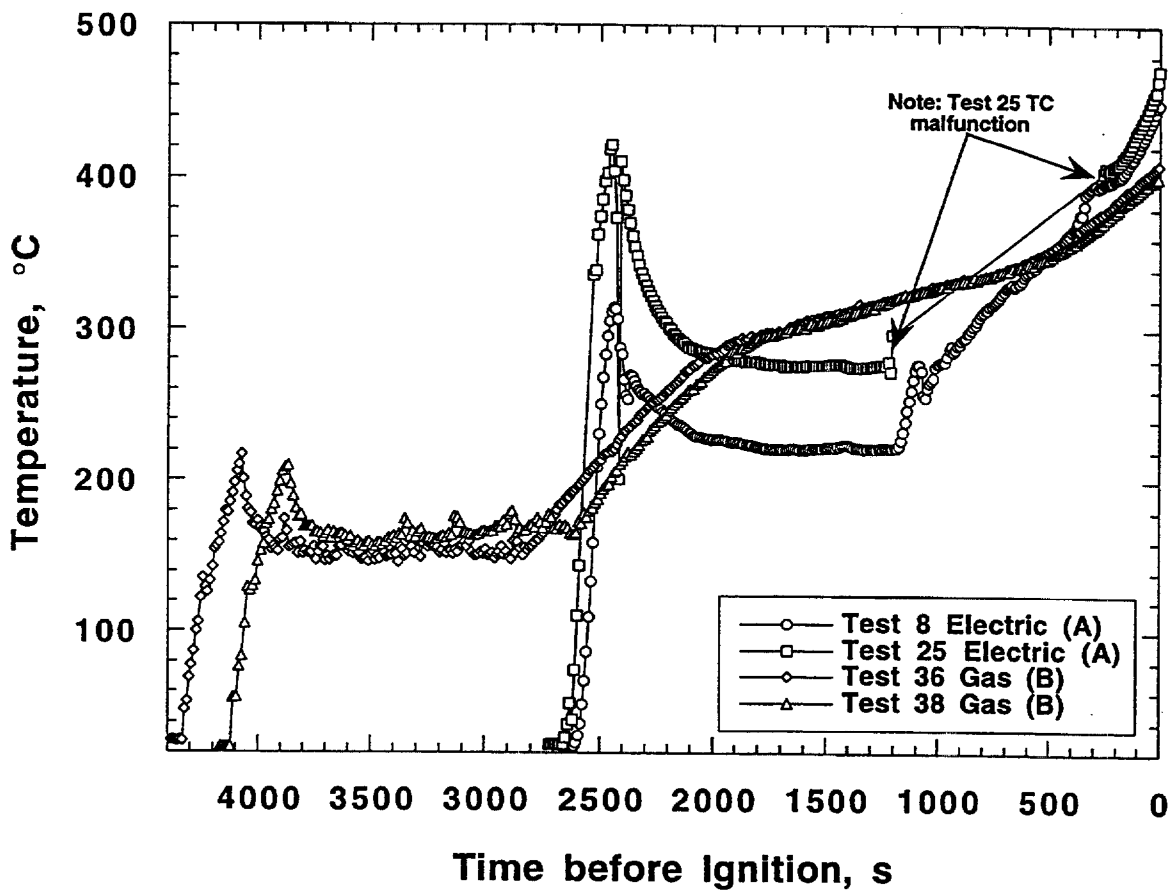

Figure 55. Pan-bottom temperature versus time before ignition for chicken in oil (normal→unattended) for the electric (A) and gas (B) ranges.

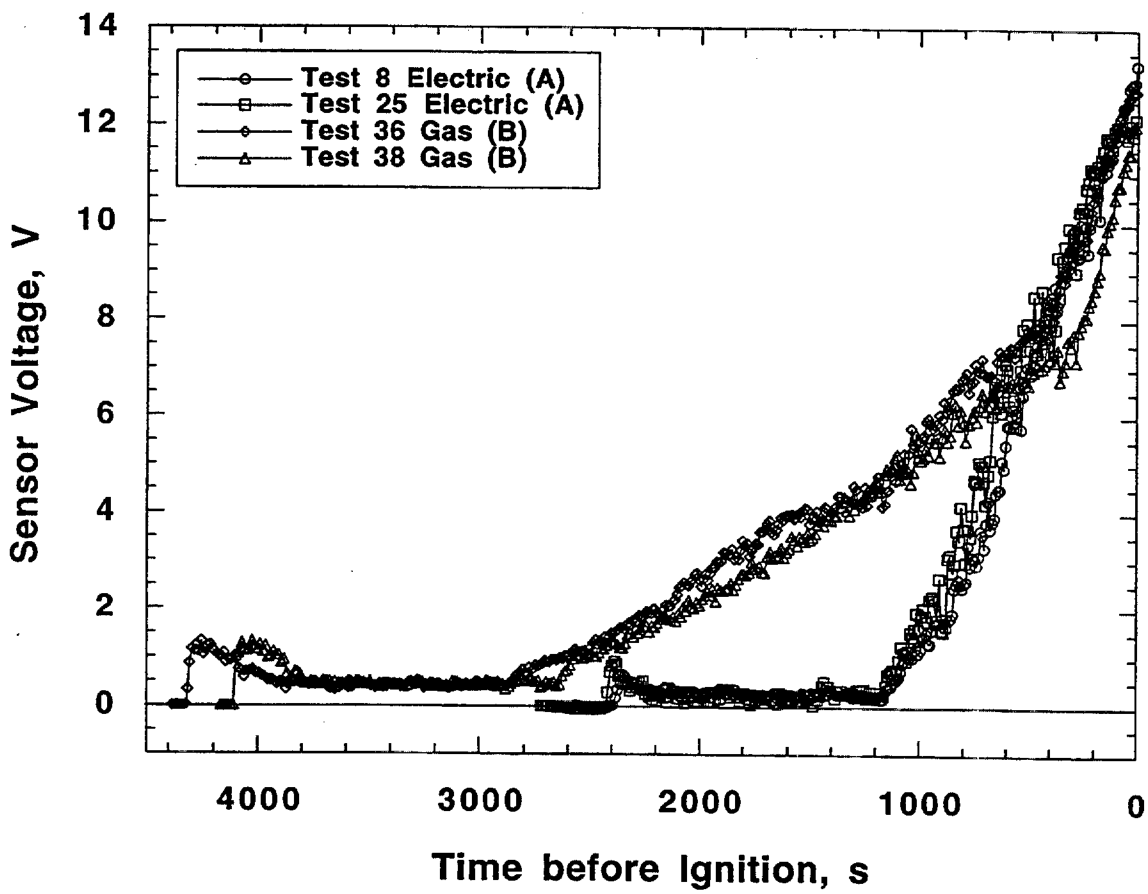

Figure 56. Site 9 general-alcohol sensor response versus time before ignition for chicken in oil (normal→unattended) for the electric (A) and gas (B) ranges.

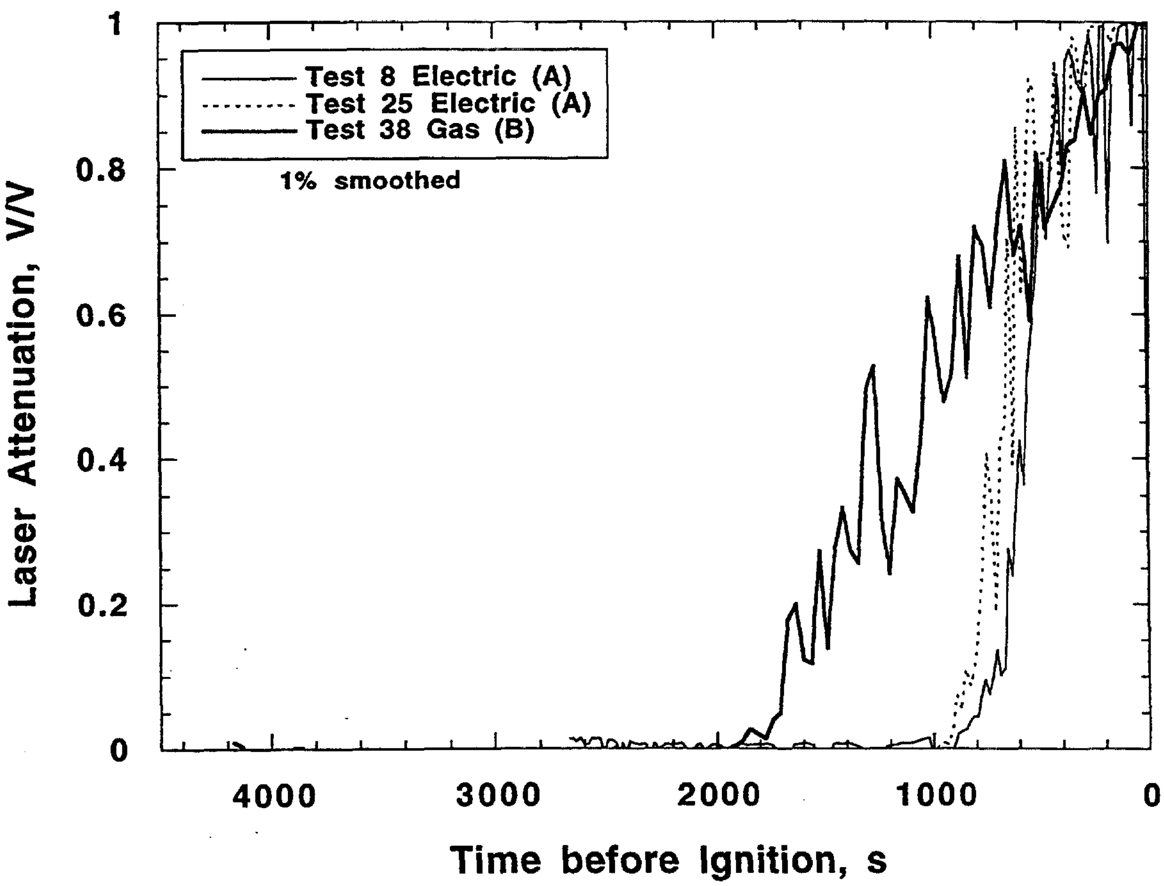

Figure 57. Laser attenuation versus time before ignition for chicken in oil (normal→unattended) for the electric (A) and gas (B) ranges.

ranges may be different for other gas and electric ranges because of the various heating-power ratings available.

4.3.3 Range-Hood Status

The range hood was inactive for the majority of the tests. For the three cases of chicken and oil (normal), broiled steak, and water and oil, additional tests were conducted with the range hood active to establish whether the range hood affected the signatures of normal and pre-fire conditions. This study of the effects of range-hood status were conducted on electric range A only.

Figure 58 is a plot of the site 9 general-alcohol sensor output versus time before ignition for each of the hood-status comparison tests of water and oil. During the normal-cooking period up to about 500 s before ignition, the two hood-on signals were somewhat lower, probably due to the dilution effect of excess air drawn into the hood. After 1100 s and throughout the rest of the tests, no clear distinction can be made between the two conditions. Variations in the magnitude of signal fluctuations were exhibited by both types of tests.

Figure 59 is a plot of the site 9 general-alcohol sensor output versus time for each of the hood-status comparison tests of broiled steak. The data are plotted versus time and not time before ignition because there was no ignition for the tests. For these tests, it is clear that those with the hood on generally produced a much lower sensor voltage than those with the hood off. After the first 800 s of one of the hood-off tests, the output did decrease to the level of the hood-on test outputs. If the maximum signal is deemed most important, then for the broiled steak, a decrease in signal of about 60% was caused by the use of the range hood. Since this is a normal cooking operation, this effect is not detrimental, but would be helpful for condition discrimination if it only affected normal cooking and not pre-fire situations.

Figure 60 is a plot for the same sensor as the previous two plots, but for tests of chicken in oil (normal). For this case, there was no apparent effect on the sensor signal from the hood status. The signals followed the same trends and had the same magnitudes during both the normal-cooking (until 1150 s before ignition) and unattended periods of the tests.

Figure 61 is a plot of the maximum normal and minimum 30 s pre-ignition voltages produced by the site 9 general-alcohol sensor for the water-and-oil, broiled-steak, and chicken-in-oil cases that were tested on the electric range with the range hood on and off. This plot shows the differences from test to test as well as between those conducted with the hood on and those with the hood off. A decrease of between 40% and 60% of normal signals due to hood use is apparent for the steak and water-and-oil cases, but not for the chicken case. The effect of the hood status is unclear for the water-and-oil case since the average signal decreased by about 30% for the case with the hood on compared to the hood off, but one hood-on test produced a greater signal than a hood-off test. The ignition levels for the chicken tests were unaffected by range-hood status.

Similar to the findings of the Phase I experiments, pre-ignition conditions are not significantly or clearly affected by range-hood status [3]. Since this study looked at normal cooking activities as well, the effect of range hood on those conditions could be identified in some cases. The decreasing effect on normal conditions was favorable to a detection system

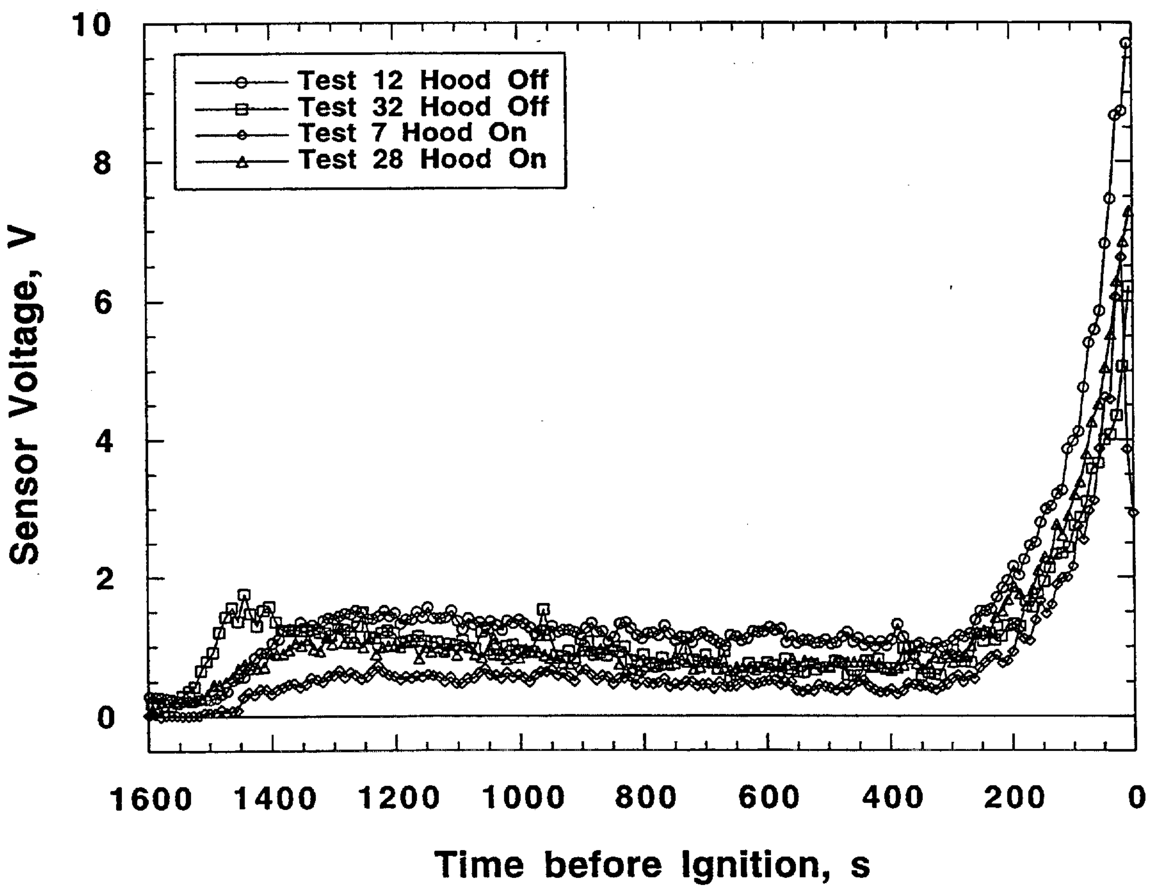

Figure 58. Site 9 general-alcohol sensor response versus time before ignition for water and oil (normal→unattended) for the electric (A) range with the hood on and off.

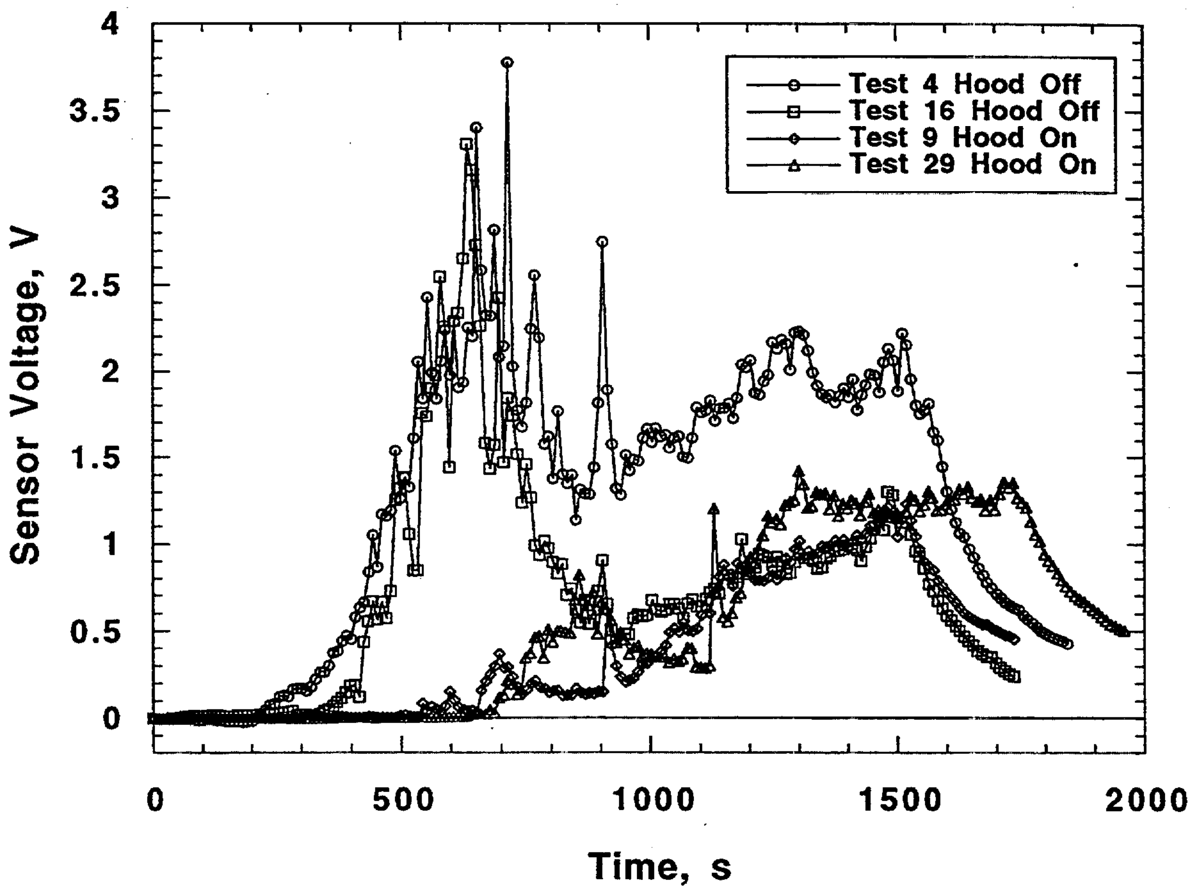

Figure 59. Site 9 general-alcohol sensor response versus time for broiled steak (normal) for the electric (A) range with the hood on and off.

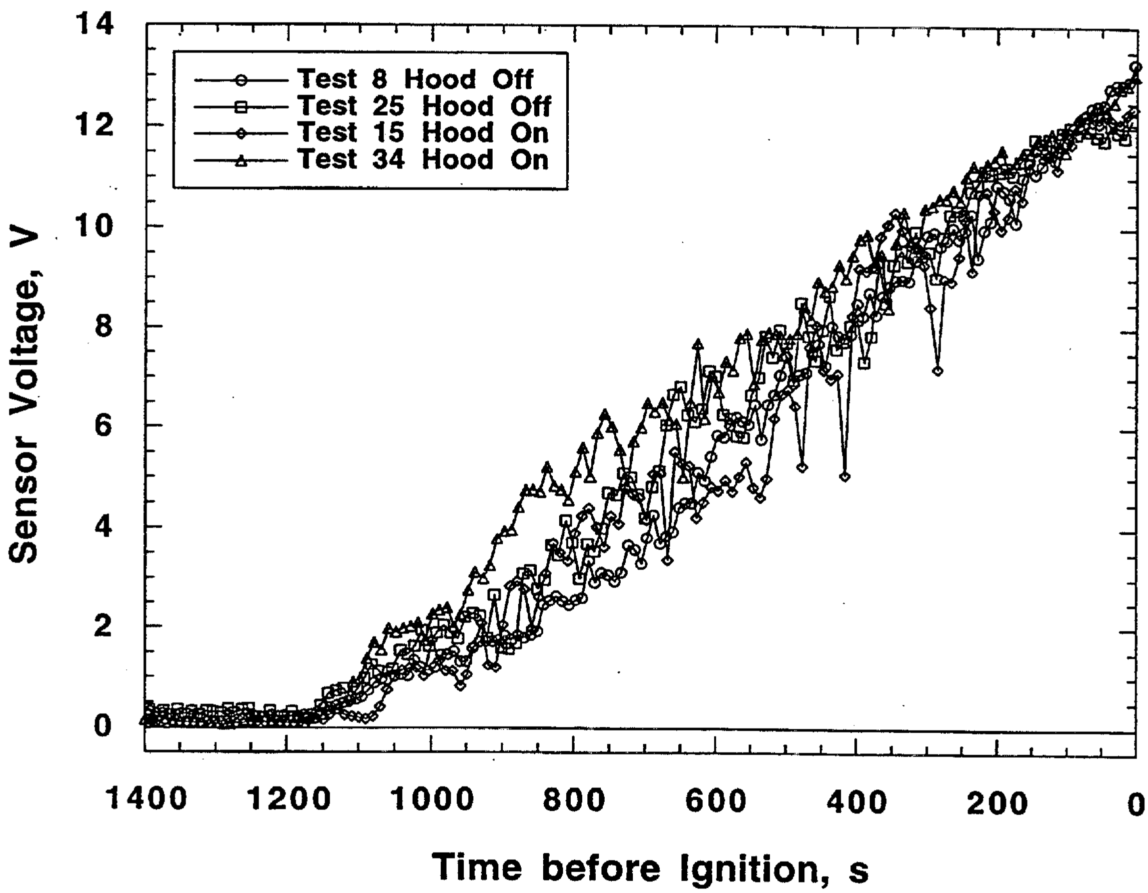

Figure 60. Site 9 general-alcohol sensor response versus time before ignition for chicken (normal→unattended) for the electric (A) range with the hood on and off.

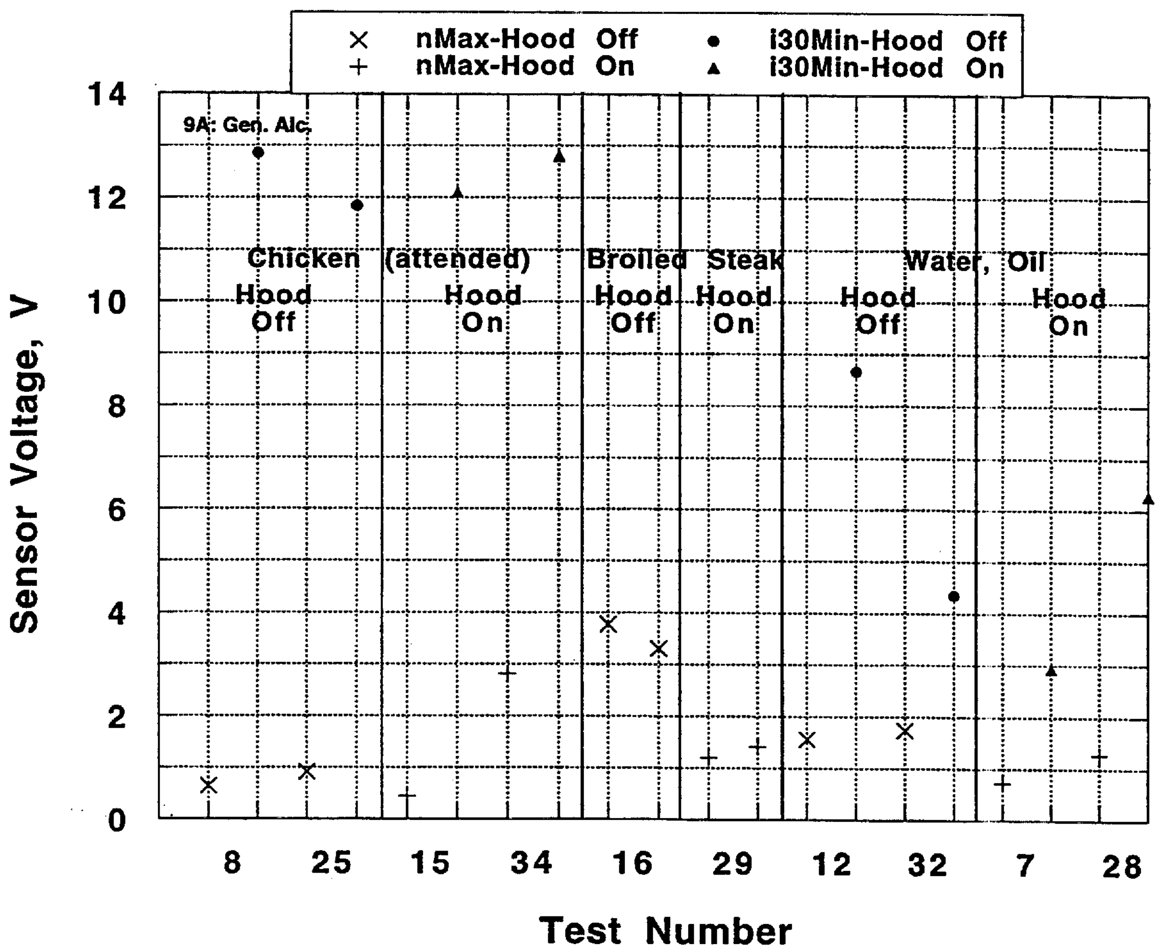

Figure 61. Site 9 general-alcohol sensor responses versus test number for water and oil, broiled steak, and chicken in oil (normal) for the electric (A) range with the hood on and off.

because it tended to increase the difference between normal and pre-ignition conditions. These effects were only determined for the typical electric range. The down-draft experiments for grilled steak utilized a more powerful fan than that of the range hood. Nearly all of the gaseous or aerosol cooking products were captured by the down-draft fan even on its medium setting, thus making detection of any conditions resembling pre-fire impossible.

4.3.4 Pan Material

Two cases of cooking 500 mL of soybean oil were tested on the electric (A) range with two different frying pans. One pan was made of stainless steel with an aluminum bottom and the other was all aluminum. A few Phase I experiments indicated that aluminum pans required significantly longer periods of time for their contents to reach ignition temperatures. This finding was investigated further in this test series.

Figure 62 shows a plot of food temperature versus time before ignition for the soybean-oil tests using each type of pan. Note that the thermocouple in test 24 occasionally malfunctioned. The temperature increases of the stainless-steel-pan tests lagged the increases of the aluminum-pan tests by about 50 s. Apart from the timing difference, the slopes and magnitudes of the results from the two types of tests were nearly identical. The ignition times for the aluminum tests averaged 18 s shorter, yet it is not clear whether this is a pattern because one of the steel tests had an earlier ignition time than one of the aluminum tests. Figure 63 shows a plot of the site 9 general-alcohol sensor response versus time before ignition for the same tests. No clear difference is apparent between the pairs of tests.

This preliminary evaluation of the differences between two types of cookware does not support the finding from Phase I. While the pans in the current study behaved very similarly, aluminum pans in Phase I had different behaviors [3]. Some further investigation that is planned by the CPSC should clarify the effects of pan mass, geometry, and material on the timing of ignition behavior, yet because of the similar conditions at ignition shown thus far, it is unlikely that pan variations would impact the ability of sensors to discriminate between normal and pre-fire conditions.

4.4 Reproducibility

It is important to establish the degree of consistency of results both between the two experimental series (Phase I and Phase II) that were conducted and within each experimental series. The following sections address the reproducibility of certain measurements from series to series and test to test.

4.4.1 Measurement Uncertainty

Uncertainties were not calculated for every measured variable because of the varied degree of differentiation provided by each variable. Uncertainties are addressed for the most useful measurements found in the study. The approximate uncertainty associated with the data was calculated from the output of the sensors during the period when background data was recorded

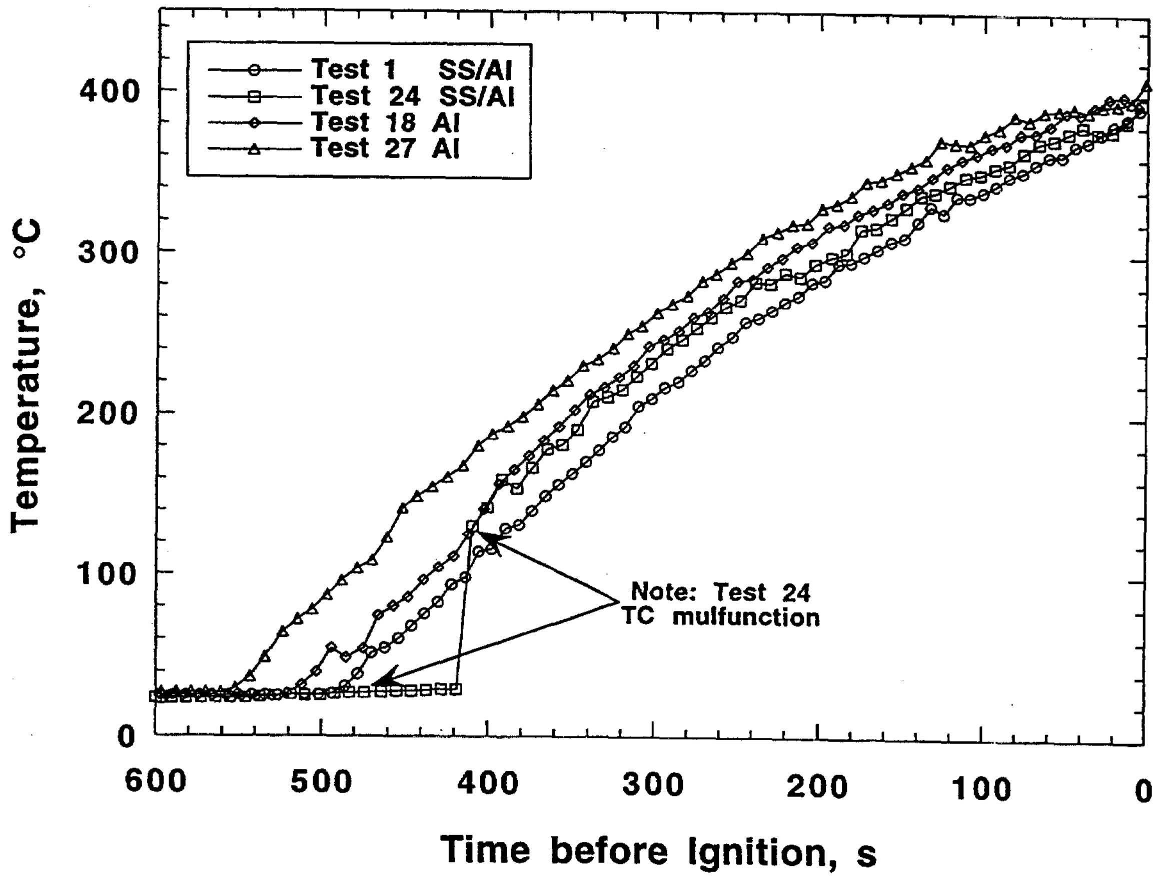

Figure 62. Food temperature versus time before ignition for soybean oil (unattended) on the electric (A) ranges in aluminum and stainless-steel pans.

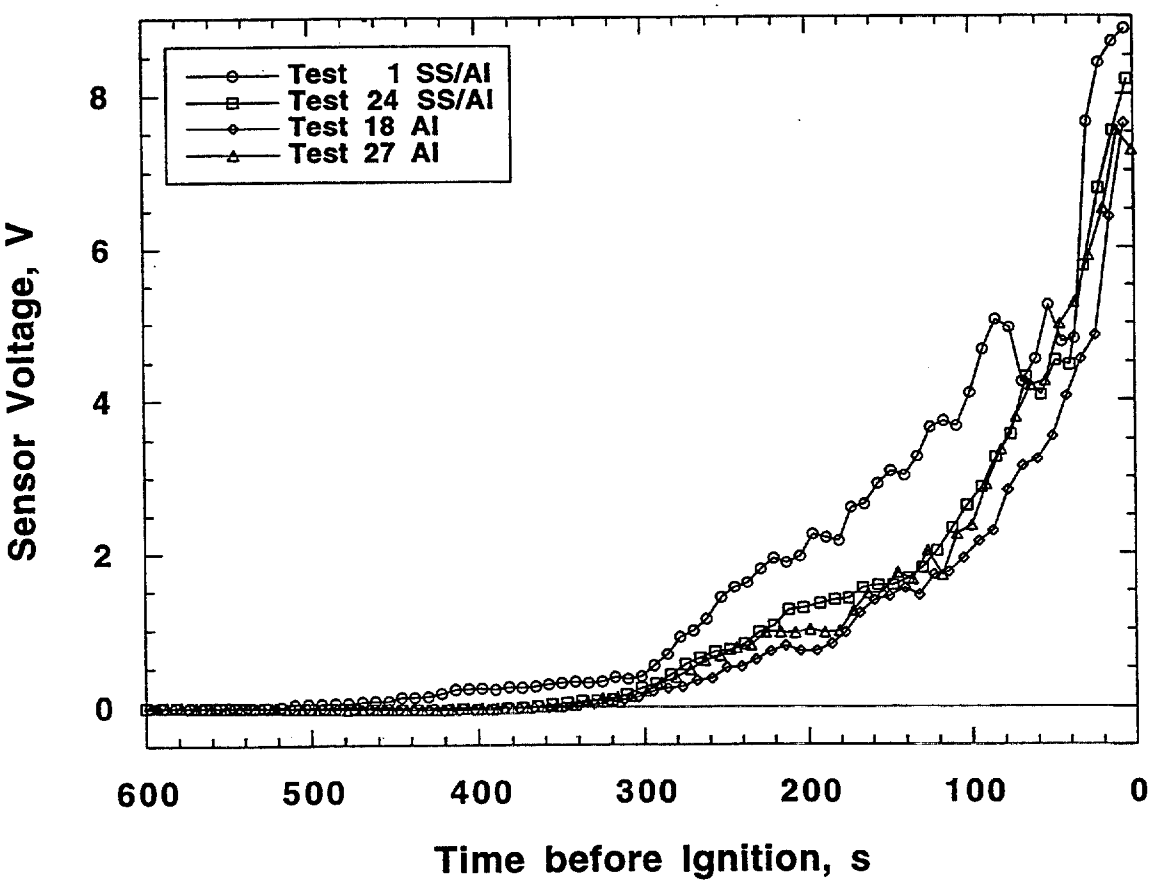

Figure 63. Site 9 general-alcohol sensor response versus time before ignition for soybean oil (unattended) on the electric (A) ranges in aluminum and stainless-steel pans.

and before any cooking began. The environment around the sensors during this period was stable which allowed estimation of the measurement noise associated with the sensors themselves. The maximum uncertainty in the gas-sensor output was less than ±0.1% based on two standard deviations. Uncertainty for the temperature measurements was between ±2 °C and ±3 °C based on the manufacturer's specifications. Due to the scope of the testing, only two tests of each case were performed which did not allow statistical analysis of the maxima, minima, and other points of comparison for tests of a given cooking case, but the plots themselves essentially perform a similar function since they show the spread of data and separation between the sets of maximum normal and minimum ignition values. The range of variation of signals from different cooking cases can be seen in the scatter of the data.

4.4.2 Consistency Between Phase I and II Results

Figure 64 shows a plot of food temperature versus time before ignition for soybean-oil tests conducted on the "A" electric range for both series of experiments. The tests have similarly shaped temperature-time curves, but the Phase II tests are somewhat compressed in time. The final difference in time to ignition is about 100 s with the Phase I test requiring 15% longer to reach ignition than the Phase II tests. The temperature magnitudes are the same at ignition so there would be no impact of the differences in heating rate on pre-fire detection based on temperature.

Figure 65 shows laser-attenuation signal versus time before ignition for the same oil tests from both experimental series. The heights of the laser beams were different for each phase so the signals cannot be directly compared. The Phase I testing resulted in data for two heights, and the beam height during Phase II was halfway between these so the average of the Phase I results should be roughly comparable to the Phase II results with the assumption of a linear correlation of attenuation with height. Except for the longer time required for the Phase I signals to increase relative to the Phase II signals, the trends and magnitudes of the tests are similar. Again, the differences here are in heating rate only and are inconsequential to feasibility of detection based on exceeding thresholds of monitored conditions.

4.4.3 Consistency Within Phase II Results

Reproducibility within the Phase II results has already been shown in some plots such as Figures 55 and 56. In this section, the maximum normal and minimum 30 s pre-ignition levels of signals needed for distinguishing the conditions are inspected to establish reproducibility. In Figure 66, the site 9 general-alcohol sensor responses are plotted versus cooking case number for those tests performed on electric range A with the hood off. Repeated tests are plotted together for each type of case. A typical variation of ignition levels is about 1 V between repeated tests, as observed for cases 1-3, 7, and 10-12. Each pair's variation is between 5% and 20%. A larger difference is seen in case 9 (4 V or 50%). Normal level variations were on the order of 1 V or less except for the self-cleaning oven, case 16 (2 V or 25%).

Figure 67 shows the pan-temperature maxima and 30 s minima versus case number. For the cases with two sets of data, pre-fire minimum variations were 10 °C (20 °F) for case 7 and

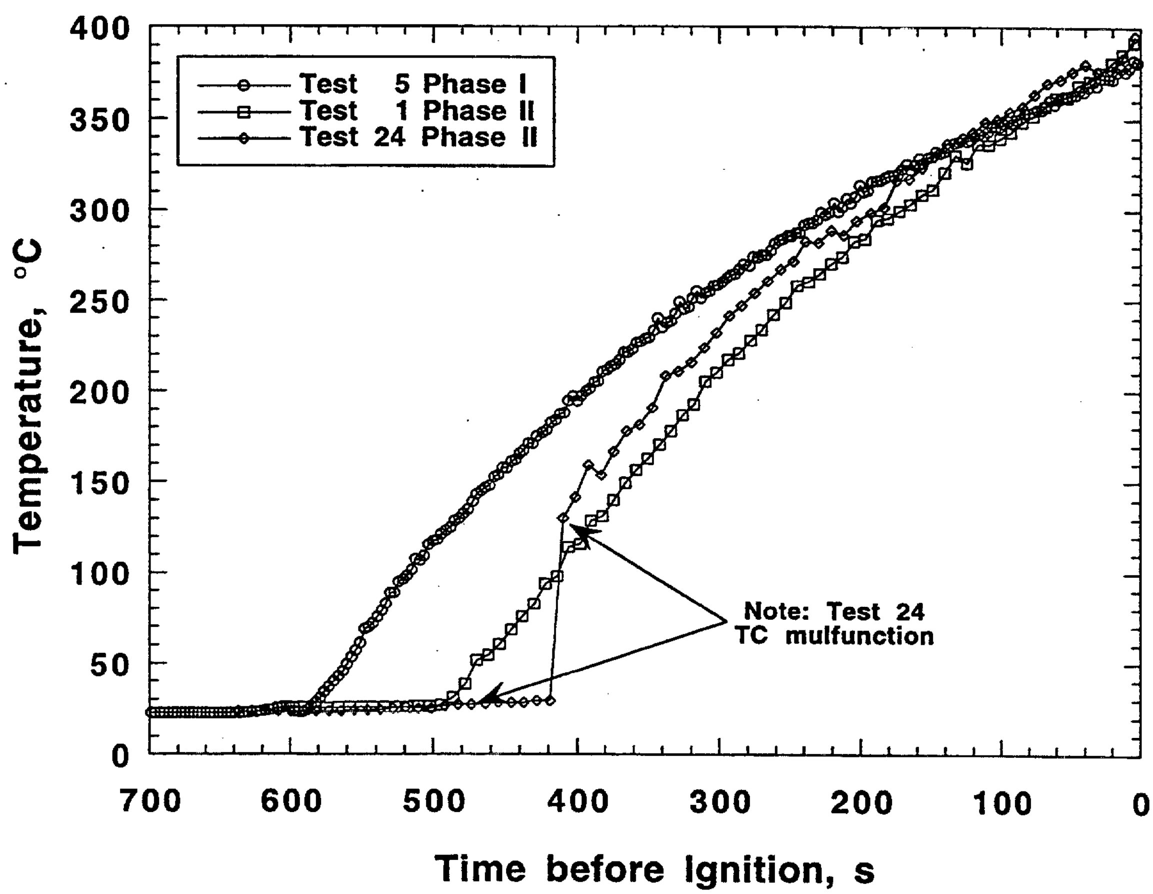

Figure 64. Food temperature versus time before ignition for soybean oil (unattended) on the electric (A) range for Phase I and Phase II.

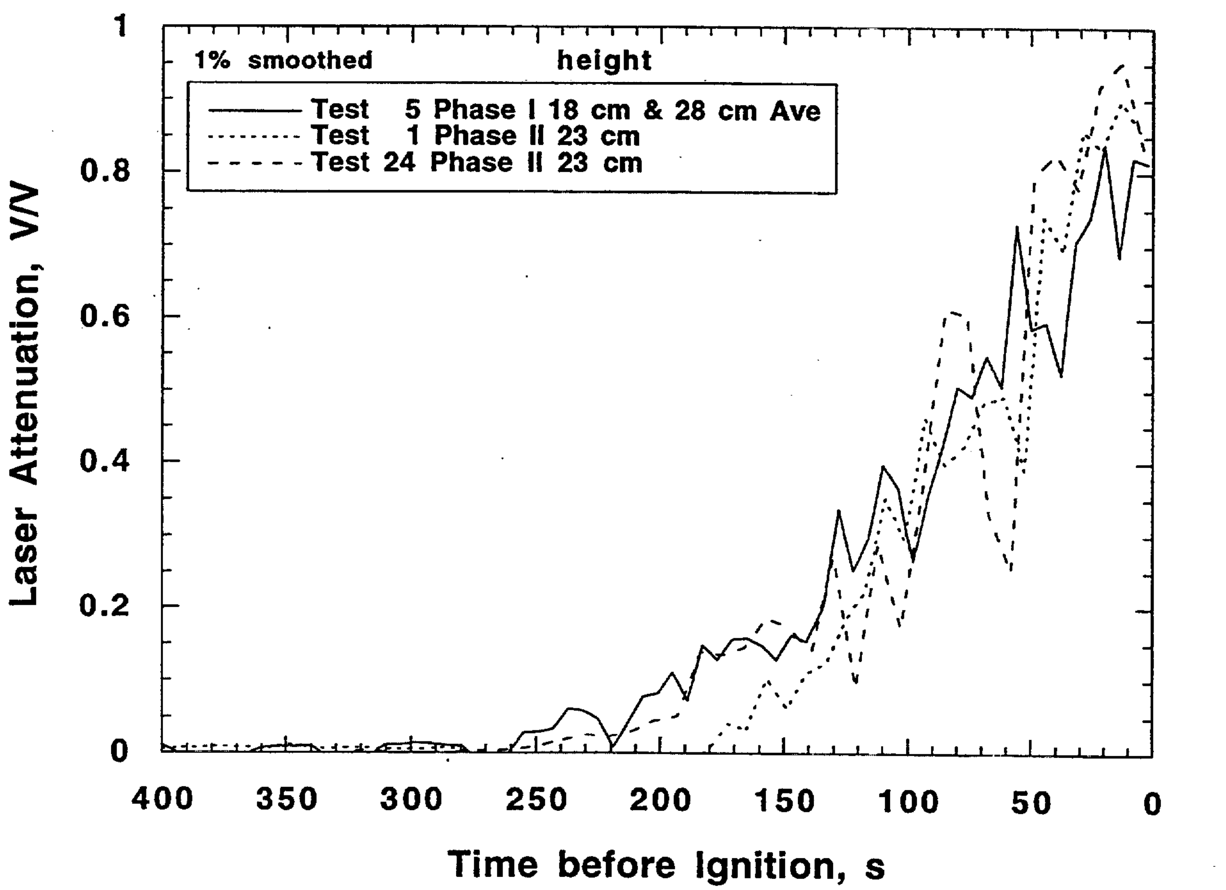

Figure 65. Laser attenuation versus time before ignition for soybean oil (unattended) on the electric (A) range for Phase I and Phase II.

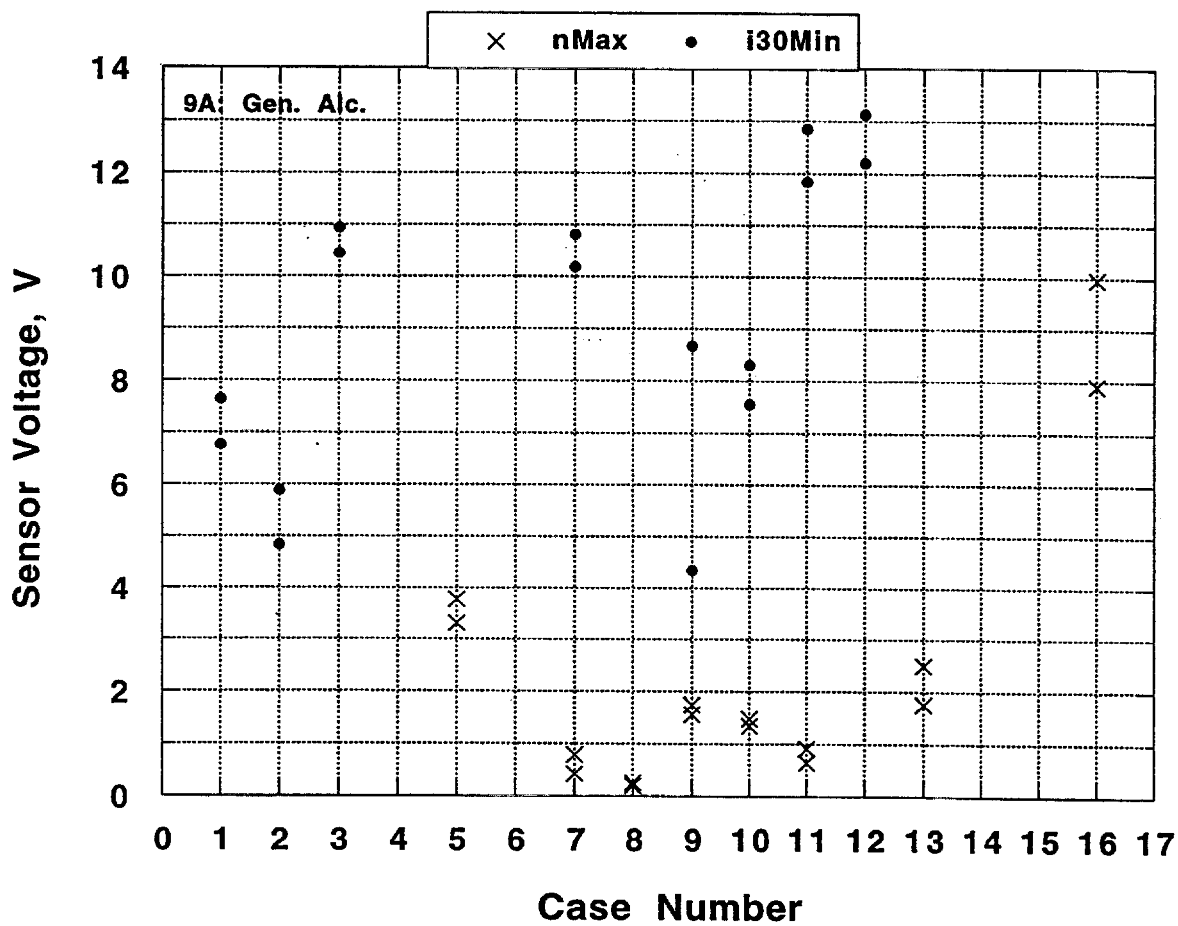

Figure 66. Site 9 general-alcohol sensor maximum normal and minimum ignition output 30 s before ignition versus cooking case number for tests using the electric (A) range and inactive hood.

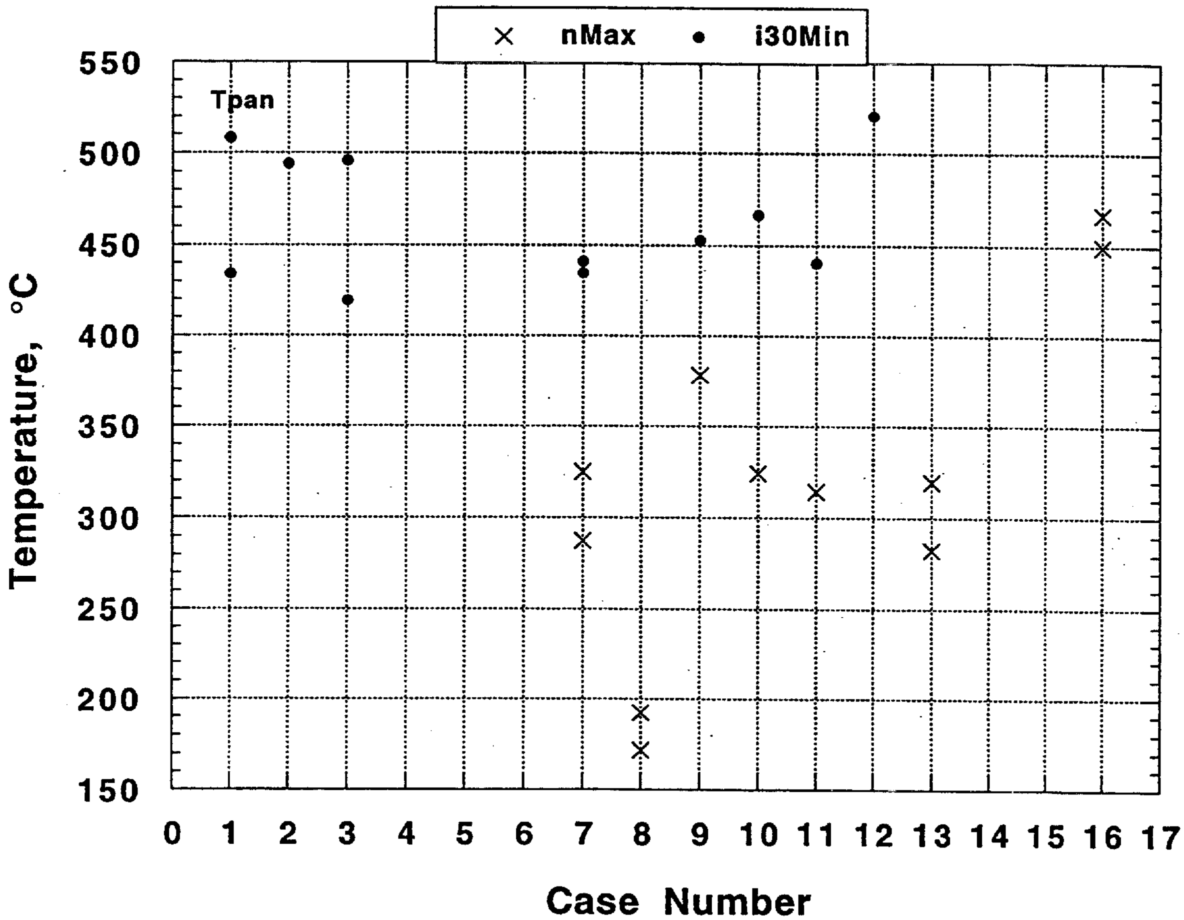

Figure 67. Pan-bottom temperature maximum normal and minimum ignition output 30 s before ignition versus cooking case number for tests using the electric (A) range and inactive hood.

80 °C (140 °F) for cases 1 and 3. The normal-condition pairs varied by 25 °C (45 °F) to 40 °C (70 °F) for cases 7, 8, 13, and 16.

Figure 68 shows the heating times to ignition for replicate tests of four cases of unattended cooking. The times have been normalized by the longer ignition time of the two repeated tests. The variations range from 0.5% for case 12 to 8% for case 3 with an average of about 5%.

The measurements made in the tests of this experimental series were generally reproducible. The gas-sensor voltages generally varied between 5% and 20% and averaged about 15% with one outlier. The pan-temperature variations ranged from 1% to 12%. The heating time to ignition varied from 0.5% to 8% with an average of about 5%. Measurement reproducibility is sufficient to ensure that conclusions concerning the possibility of distinguishing pre-fire and normal cooking conditions are insensitive to experimental variation.

5.0 Summary and Conclusions

5.1 Summary

Results from an experimental series of 42 tests of 16 cases of normal and hazardous range-top cooking activities have been reported. The tests were conducted to determine whether differences between conditions produced by normal, standard cooking operations can be distinguished from pre-fire conditions. The existence of a significant difference between normal and pre-fire conditions is essential for the feasibility of a range-cooking pre-fire detection system. To characterize the differences between the two sets of conditions, maximum sensor signals from periods of normal cooking were compared to the minima of the same type of signals generated during the 30 s prior to food ignition. Several individual sensor signals performed with moderate success. Pairs of sensors with signals that best differentiated between normal and pre-fire conditions were combined through simple multiplication which resulted in even better performance. Sensitivity of the results to range type, hood status, and pan material were examined. Consistency of the results with those from previous research and from test to test were also assessed.

5.2 Conclusions

The following conclusions are based on measurements and observations of combinations of specific ranges, pans, foods, and ventilation so extrapolation to other conditions should be made with caution.

- Measurements confirm that the cooking environment near the range during unattended cooking approaching ignition exhibits significantly higher levels of temperatures, hydrocarbons, and particulates than the cooking environment produced by most normal, standard cooking procedures.
- Some attended, standard cooking procedures, such as blackening of fish, may produce conditions similar to those conditions approaching ignition because the procedures

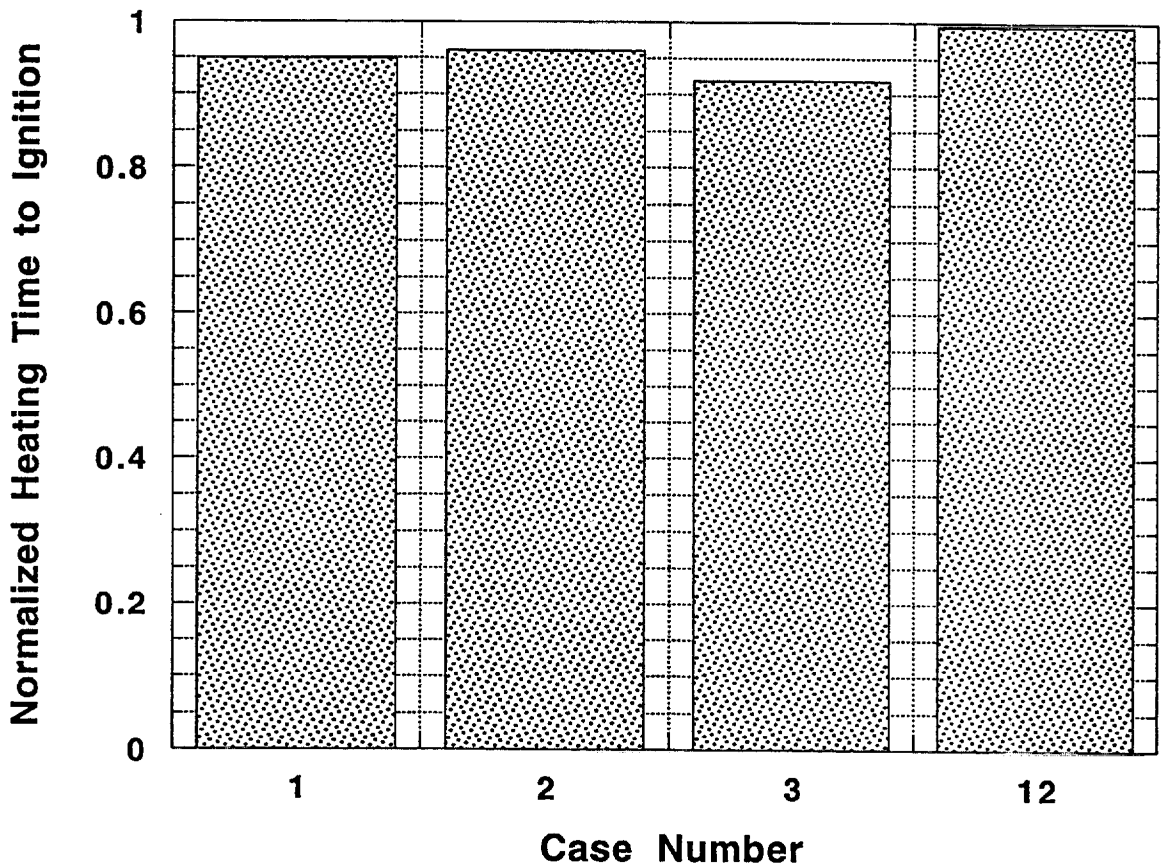

Figure 68. Heating time to ignition versus cooking case number for tests using electric (A) range and inactive hood.

themselves are purposefully designed to use extreme temperatures.

- Several sensors positioned in certain locations offer high levels of differentiation when used alone. Depending on the setting of the threshold, a majority of cooking cases would appropriately cause alarm or not alarm.
- No single sensor performed faultlessly without the use of modifications of the detection system to account for special attended cooking cases, but one gas sensor on the range hood (site 9B cooking-alcohol sensor) and a thermocouple contacting the bottom of the cooking pan were most effective.
- Standard household photoelectric and ionization smoke detectors identify pre-ignition conditions well (95% and 81%, respectively), but generate a significant number of false alarms (29% and 34%, respectively) when used alone for the particular tests conducted.
- A limited effort at algebraically combining three sets of two sensor signals generates more robust differentiation, and for the best pair, pre-fire and normal conditions were clearly separated with the exception of one attended cooking case which would produce a false alarm rather than a failure to alarm.
- Results with impact on detection were insensitive to range type, range-hood status, and pan material.
- Based on the findings of this investigation, pre-fire detection systems for range-top cooking are physically feasible and merit further consideration.

5.3 Suggestions for Future Work

The following points are provided for parties interested in advancing research in the area of kitchen range pre-ignition detection.

- The use of additional technology such as an oven-use sensor, a temporary deactivation switch (with automatic reactivation), or a motion detector could eliminate all of the difficult cooking cases studied.
- Increasing the sophistication and/or decreasing the sensitivity of standard smoke detectors may allow their use in the kitchen for detection of pre-ignition conditions.
- More study is needed of alternative sensor technologies, e.g. electrochemical and fiberoptic, to determine if they behave comparably or better than those studied for this project. Durability and reliability need to be investigated for all potential sensor types.
- Variation of sensor locations may provide marginal improvement of sensor performance.
- Additional combinations of two or three sensors or detectors should be investigated since they may produce more rigorous detection and decrease false alarms for normal cooking procedures.

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7.0 Appendices

Appendix A. General Test Procedure

1. Turn on the sensor power supplies to ensure sensor stabilization by the test start.
2. Ignite the afterburner system and then turn on the room exhaust hood fan.
3. Make sure the duct above the range-hood exhaust is open.
4. Turn on the range hood if required for the particular experiment.
5. Change date and test identification labels attached to the front of the range.
6. Plug in and energize all power cords and strips.
7. Prepare all instruments for operation.
   a. Data acquisition powered, program running, tests specifics input.
   b. Bi-directional probe on and plugged in.
   c. One HeNe laser and three photodiodes powered and aligned.
   d. Check/replace hydrocarbon analyzer filter, water trap media, and desiccant.
   e. Video camera powered and focused, cassette loaded, test labeled, time displayed.
   f. Slide camera loaded.
8. Measure the masses of pan components and food separately and together and record.
9. Place the appropriate amount of the food to be cooked (well-thawed and/or stored at room temperature) in the pan.
10. Carefully center the pan on burner and position the bottom-measuring thermocouple.
11. Make sure the pan handle is secured.
12. Place food temperature measuring thermocouple at proper location.
13. Make sure lid can be used on pan without interference from thermocouple.
14. Check range-surface thermocouples.
15. Take zeros of the instruments, check for anomalies.
16. Span instruments, check for anomalies.
17. Record sensor responses to span gases and N_2.
18. Check for conformity to safety guidelines, especially fire extinguisher proximity.
19. Begin experiment with a 5 s countdown and start two stopwatches, data acquisition system, and video camera.
20. Take 1 minute of background data.
21. With a 5 s countdown to 1 minute, turn the appropriate burner(s) on and adjust setting(s).
22. Observe the behavior of the food, recording important observations and times on the log sheet. A blank log sheet is included as Appendix B.
23. Upon ignition, cover pan with lid to extinguish fire and turn off burner using the external circuit breaker (electric range) or valve (gas range). Use a CO_2 extinguisher if necessary (being careful not to blow the lid off of the pan).
24. Continue the experiment at least 5 minutes after the fire is extinguished or the cooking procedure is completed for background data.
25. After extinguishment, wait sufficient time before removing lid to prevent reignition.
26. After the pan has cooled sufficiently for safe handling, weigh the pan, food, and lid together. For water, measure remaining volume.
27. Clean pan(s) and test area.

The following safety rules were used to prevent injury to test personnel.

1. No personnel are permitted in the laboratory enclosure after significant smoke begins to be produced and a layer of smoke begins to develop unless breathing apparatus are utilized.
2. All personnel conducting or observing the experiment must wear appropriate safety equipment including safety shoes and safety glasses or goggles.
3. Visitors must not enter the lab during a test.
4. At least one fire extinguisher is to be positioned near the doorway.
5. Fire extinguishers are checked for sufficient charge before each test.

Appendix B. Sample Test Log Sheet

CPSC Range-Cooking Fire Pre-ignition Detection Series

TEST ID CPSC96 Date / /1996

Pan Information

Size ________ cm (in)
Type/Number ________
Material ________
Mass Measurements:
- Pan ____ kg
- Lid ____ kg
- Pan+Lid ____ kg
- Pan+Lid+Food (before) ____ kg
- Pan+Lid+Food (after) ____ kg
- Other masses ____ kg

Range Type: Electric/Gas/Grill
Hood Active: YES / NO

Food Summary

Substance ________
Scenario Number ________
Initial Volume ________ ml
Remaining Volume ________ ml
Initial Mass ________ kg
Remaining Mass ________ kg

Experiment Operators

		Instrument(s)
Marco Fernandez	☐	
Rik Johnsson	☐	
Michelle King	☐	
Randy Shields	☐	

Clock Time @ 0

Time(min)	Comments/ Observations	Voltage/Gas Flow Readings	Photos Time #	Temps Time °C
0	DATA ON - BACKGROUND			
1	BURNER ENERGIZED			
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
	IGNITION			
	FIRE EXTINGUISHED			
	DATA OFF			

Additional Notes:

Appendix C. Data Analysis - Sample Program Control File

```
   0   0   0   0  20   1   0   0
   4   1   1   1   0   5
NIST/CPSC Pre-Ignition Detection Series: CPSC9601 12JUN96 Scenario 1: Soybean
Oil, SS Frying Pan, Hood Off
   00 1Time  Elapsed time                                           (s)
   01 2LScat1HeNe laser & photodiode, scattering 5 deg. from forward  (V)
   02 2LTran HeNe laser & photodiode, transmission                  (V)
   03 2LScat2HeNe laser & photodiode, scattering 10 deg. from forward (V)
   04 2CO    Carbon monoxide analyzer, Span 0.3% = ___V          (Vol. %)
   05 2CO2   Carbon dioxide analyzer,  Span 6.0% = ___V          (Vol. %)
   06 21C    Site 1:  Base splash panel, lt          ¦Total cooking
   07 22C    Site 2:  Base splash panel, ctr         ¦Total cooking
   08 23C    Site 3:  Base splash panel, rt          ¦Total cooking
   09 24C    Site 4:  Top splash panel, lt           ¦Total cooking
   10 25C    Site 5:  Top splash panel, ctr          ¦Total cooking
   11 25Xsig Site 5:                                 ¦Photoelectric
   12 25Xalm Site 5:                                 ¦Photo. alarm
   13 26C    Site 6:  Top splash panel, rt           ¦Total cooking
   14 27Ahc  Site 7:  Mid splash panel & hood, ctr   ¦Gen. hydrocarbons
   15 27Aalc Site 7:                                 ¦Gen. alcohols
   16 27Btot Site 7:                                 ¦Total cooking
   17 27Balc Site 7:                                 ¦Cooking alcohols
   18 27Bwat Site 7:                                 ¦Cooking water
   19 28C    Site 8:  Range hood, lt                 ¦Total cooking
   20 29Ahhc Site 9:  Range hood, ctr                ¦Gen. hydrocarbons
   21 29AhalcSite 9:                                 ¦Gen. alcohols
   22 29Btot Site 9:                                 ¦Total cooking
   23 29Balc Site 9:                                 ¦Cooking alcohols
   24 29Bwat Site 9:                                 ¦Cooking water
   25 29D    Site 9:                                 ¦Carbon monoxide
   26 29Xsig Site 9:                                 ¦Photoelectric
   27 29Xalm Site 9:                                 ¦Photo. alarm
   28 2HC    Hydrocarbon analyzer,     Span ___% = ___V          (Vol. %)
   29 210C   Site 10: Range hood, rt                 ¦Total cooking
   30 211Ahc Site 11: Ceiling above range hood, ctr  ¦Gen. hydrocarbons
   31 211AalcSite 11:                                ¦Gen. alcohols
   32 211BtotSite 11:                                ¦Total cooking
   33 211BalcSite 11:                                ¦Cooking alcohols
   34 211BwatSite 11:                                ¦Cooking water
   35 211D   Site 11:                                ¦Carbon monoxide
   36 211XsigSite 11:                                      ¦Photoelectric
   37 211XalmSite 11:                                      ¦Photo. alarm
   38 213XsigSite 13: Ceiling, 30 cm from ctr lt wall      ¦Photoelectric
   39 213XalmSite 13:                                      ¦Photo. alarm
   40 214XsigSite 14: Ceiling, 30 cm from ctr front wall   ¦Photoelectric
   41 214XalmSite 14:                                      ¦Photo. alarm
   42 214ZsigSite 14:                                      ¦Ionization
   43 214ZalmSite 14:                                      ¦Ion. alarm
   44 215XsigSite 15: Ceiling, 30 cm from rt, front walls  ¦Photoelectric
   45 215XalmSite 15:                                      ¦Photo. alarm
   46 215ZsigSite 15:                                      ¦Ionization
   47 215ZalmSite 15:                                      ¦Ion. alarm
   48 216XsigSite 16: Ceiling, 30 cm from ctr rt wall      ¦Photoelectric
   49 216XalmSite 16:                                      ¦Photo. alarm
   50 216ZsigSite 16:                                      ¦Ionization
   51 216ZalmSite 16:                                      ¦Ion. alarm
```

```
 52 217XsigSite 17: Ceiling, 30 cm from rt, back walls   |Photoelectric
 53 217XalmSite 17:                                      |Photo. alarm
 54 217ZsigSite 17:                                      |Ionization
 55 217ZalmSite 17:                                      |Ion. alarm
 56 2Vlcty Bi-directional velocity probe 0.25" H2O = delta 2.5 V  (m/s)
 60 2T1     Site 1:  Splash panel, lt                    |Thermocouple
 61 2T2     Site 2:  Splash panel, ctr                   |Thermocouple
 62 2T3     Site 3:  Base splash panel, rt               |Thermocouple
 63 2T4     Site 4:  Top splash panel, lt                |Thermocouple
 64 2T5     Site 5:  Top splash panel, ctr               |Thermocouple
 65 2T6     Site 6:  Top splash panel, rt                |Thermocouple
 66 2T7     Site 7:  Mid splash panel & hood, ctr        |Thermocouple
 67 2T8     Site 8:  Range hood, lt                      |Thermocouple
 68 2T9     Site 9:  Range hood, ctr                     |Thermocouple
 69 2T10    Site 10: Range hood, rt                      |Thermocouple
 70 2T11    Site 11: Ceiling above range hood, ctr       |Thermocouple
 71 2T13    Site 13: Ceiling, 30 cm from ctr lt wall     |Thermocouple
 72 2T14    Site 14: Ceiling, 30 cm from ctr front wall  |Thermocouple
 73 2T15    Site 15: Ceiling, 30 cm from rt, front walls |Thermocouple
 74 2T16    Site 16: Ceiling, 30 cm from ctr rt wall     |Thermocouple
 75 2T17    Site 17: Ceiling, 30 cm from rt, back walls  |Thermocouple
 76 2T18    Site 18: Range left edge, ctr front to back  |Thermocouple
 77 2T19    Site 19: Range ctr lt to rt and front to back |Thermocouple
 78 2T20    Site 20: Range right edge, ctr front to back |Thermocouple
 79 2T21    Site 21: Range lt front corner               |Thermocouple
 80 2T22    Site 22: Range front edge, ctr lt to rt      |Thermocouple
 81 2T23    Site 23: Range rt front corner               |Thermocouple
 82 2T24    Site 24: Range lt rear burner                |Thermocouple
 83 2T25    Site 25: Range rt rear burner                |Thermocouple
 84 2T26    Site 26: Range rt front burner               |Thermocouple
 85 2T27    Site 27: Range lt front burner               |Thermocouple
 86 2T28    Site 28: Focus burner edge of drip pan hole  |Thermocouple
 87 2T29    Site 29: Range beneath surface lt front burner|Thermocouple
 88 2T30    Site 30: Range beneath surface ctr both ways |Thermocouple
 89 2T31    Site 31: Oven, top ctr lt to rt, near front  |Thermocouple
 90 2T32    Site 32: Range hood inside front edge, left  |Thermocouple
 91 2T33    Site 33: Range hood inside front edge, right |Thermocouple
 92 2T34    Site 34: Range hood under filter, left       |Thermocouple
 93 2T35    Site 35: Range hood under filter, right      |Thermocouple
 94 2T36    Site 36: Mid-height splash panel, left       |Thermocouple
 95 2T37    Site 37: Mid-height splash panel, center     |Thermocouple
 96 2T38    Site 38: Mid-height splash panel, right      |Thermocouple
 97 2T39    Site 39: Submerged in food near pan ctr bottom|Thermocouple
 98 2T40    Site 40: At gas sampling probe tip           |Thermocouple
 99 2T41    Site 41: Gas sampling probe surface 1/3 way  |Thermocouple
100 2T42    Site 42: Gas sampling probe surface 2/3 way  |Thermocouple
101 2T43    Site 43: Near duct velocity probe            |Thermocouple
                                                                      999
  1.0
  1.0
                                                                      999
INPUT=DATA IMAGES, CHANNELS PER LINE=4
READING=(KC)3*(C)(K )(+ ++--)7*(R)(KE)3*(E)(K )(KX)
TIME=(KT)(KI)(KM)(KE)12*(A)2*(HK )(K:)2*(MK )(K:)2*(SK )(K )(KX)50*(A)
EOR=(K KE)(KEKO)(KOKR)(KRK )
EOF=(KE)(KO)(KF)
```

```
SKIP=(S1Z3R3)7
GAS%          Convert gas analyzers from voltage to volume percent
3
04  3  Z          R  0.3    X  CO Analyzer
05  3  Z          R  6.     X  CO2 Analyzer
28  3  Z          R  0.0093 X  Hydrocarbon Analyzer
TC
1
60 101                      X  Thermocouple calculation
VELOCITY
1
56  24.9  Z  3  1  101      X  Duct velocity
COMPUTE
1
56-0.0                      X  $1 Duct velocity voltage
COMPUTE
2
(01-.00148980)/2.846        X  $2 Laser scattering, 5 deg.
(03-.0206837)/2.612         X  $3 Laser scattering, 10 deg.
COMPUTE
25
06-.42924                   X  $4 Total cooking, Site 1
07-1.0173                   X  $5 Total cooking, Site 2
08-.58112                   X  $6 Total cooking, Site 3
09-.49598                   X  $7 Total cooking, Site 4
10-.54161                   X  $8 Total cooking, Site 5
13-.92102                   X  $9 Total cooking, Site 6
14-.49003                   X  $10 Gen. hydrocarbons, Site 7
15-2.0943                   X  $11 Gen. alcohols, Site 7
16-.52189                   X  $12 Total cooking, Site 7
17-1.6631                   X  $13 Cooking alcohols, Site 7
18-2.7460                   X  $14 Cooking water, Site 7
19-.67362                   X  $15 Total cooking, Site 8
20-.28267                   X  $16 Gen. hydrocarbons, Site 9
21-.95643                   X  $17 Gen. alcohols, Site 9
22-.67188                   X  $18 Total cooking, Site 9
23-2.7097                   X  $19 Cooking alcohols, Site 9
24-.48877                   X  $20 Cooking water, Site 9
25-1.3222                   X  $21 Carbon monoxide, Site 9
29-.64290                   X  $22 Total cooking, Site 10
30-.41498                   X  $23 Gen. hydrocarbons, Site 11
31-1.4557                   X  $24 Gen. alcohols, Site 11
32-.71764                   X  $25 Total cooking, Site 11
33-1.5247                   X  $26 Cooking alcohols, Site 11
34-.46844                   X  $27 Cooking water, Site 11
35-1.3123                   X  $28 Carbon monoxide, Site 11
COMPUTE
1
(9.4679-2)/9.4679           X  $29 Laser attenuation
SMOOTH
1
$29  00  3                  X  $30 Laser attenuation, smoothed
RENAME
   $1   VelV  Bi-directional probe raw voltage                    (V)
   $2   Scat5 Laser scatter signal, 5 deg.                        (V)
   $3   Scat10Laser scatter signal, 10 deg.                       (V)
```

```
$4   Ctot1 Total cooking, Site 1
$5   Ctot2 Total cooking, Site 2
$6   Ctot3 Total cooking, Site 3
$7   Ctot4 Total cooking, Site 4
$8   Ctot5 Total cooking, Site 5
$9   Ctot6 Total cooking, Site 6
$10  Hgen7 Gen. hydrocarbons, Site 7
$11  Agen7 Gen. alcohols, Site 7
$12  Ctot7 Total cooking, Site 7
$13  Calc7 Cooking alcohols, Site 7
$14  Cwat7 Cooking water, Site 7
$15  Ctot8 Total cooking, Site 8
$16  Hgen9 Gen. hydrocarbons, Site 9
$17  Agen9 Gen. alcohols, Site 9
$18  Ctot9 Total cooking, Site 9
$19  Calc9 Cooking alcohols, Site 9
$20  Cwat9 Cooking water, Site 9
$21  CO9   Carbon monoxide, Site 9
$22  Ctot10Total cooking, Site 10
$23  Hgen11Gen. hydrocarbons, Site 11
$24  Agen11Gen. alcohols, Site 11
$25  Ctot11Total cooking, Site 11
$26  Calc11Cooking alcohols, Site 11
$27  Cwat11Cooking water, Site 11
$28  CO11  Carbon monoxide, Site 11
$29  Atten Laser attenuation                          (V/V)
$30  AttenSLaser attenuation smoothed (3 pt)          (V/V)
                                                            999
END
```

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SUPPLEMENTARY NOTES

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A significant portion of residential fires stem from kitchen cooking fires. Existing fire data indicate that these cooking fires primarily are unattended and most often involve oil or grease. Previous study has determined that strong indicators of impending ignition for several foods cooked on range surfaces are temperatures, smoke particulates, and hydrocarbon gases. The purpose of this experimental investigation was to determine the feasibility of utilizing one or more of these common characteristics of the pre-ignition environment as input to one or more sensor(s) in a pre-fire detection device.

A total of 16 cooking procedures was examined. Simulations of unattended cooking leading to ignition as well as normal, or standard, cooking procedures that have the potential to mimic pre-ignition characteristics were included in the study. Each case was tested on a typical electric range with an inactive range hood. To determine the effects of range type and hood status on sensor performance, two cases were repeated with the range hood active and three cases were repeated on a gas range. The total number of variations was 21, and each test was repeated once for a total of 42 tests.

Many variables were measured. A sample probe carried gases to carbon monoxide, carbon dioxide, and hydrocarbon analyzers. Thermocouples provided temperature measurements near the food and around the range. Hydrocarbon-gas sensors were placed on and around the range. Photoelectric and ionization smoke detectors were placed around the room. Each sensor was evaluated for its ability to alarm before ignition and not generate false alarms.

The experimental conclusions are based on measurements of combinations of specific ranges, pans, foods, and ventilation. The major conclusions of this research are: (1) Several sensors offered high levels of differentiation when used alone. A majority of cooking cases would appropriately cause alarm or not alarm, yet some would either falsely alarm or fail to alarm depending on the setting of the threshold. (2) A limited effort at algebraically combining sets of two sensor signals generated even more robust differentiation. (3) Based on the findings of this investigation, pre-fire detection systems for range-top cooking are physically feasible and merit further consideration of economic viability and practicality.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

appliances; fire detection; fire prevention; ignition prevention; kitchen fires; residential buildings; sensors; smoke detectors; smoke measurement

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