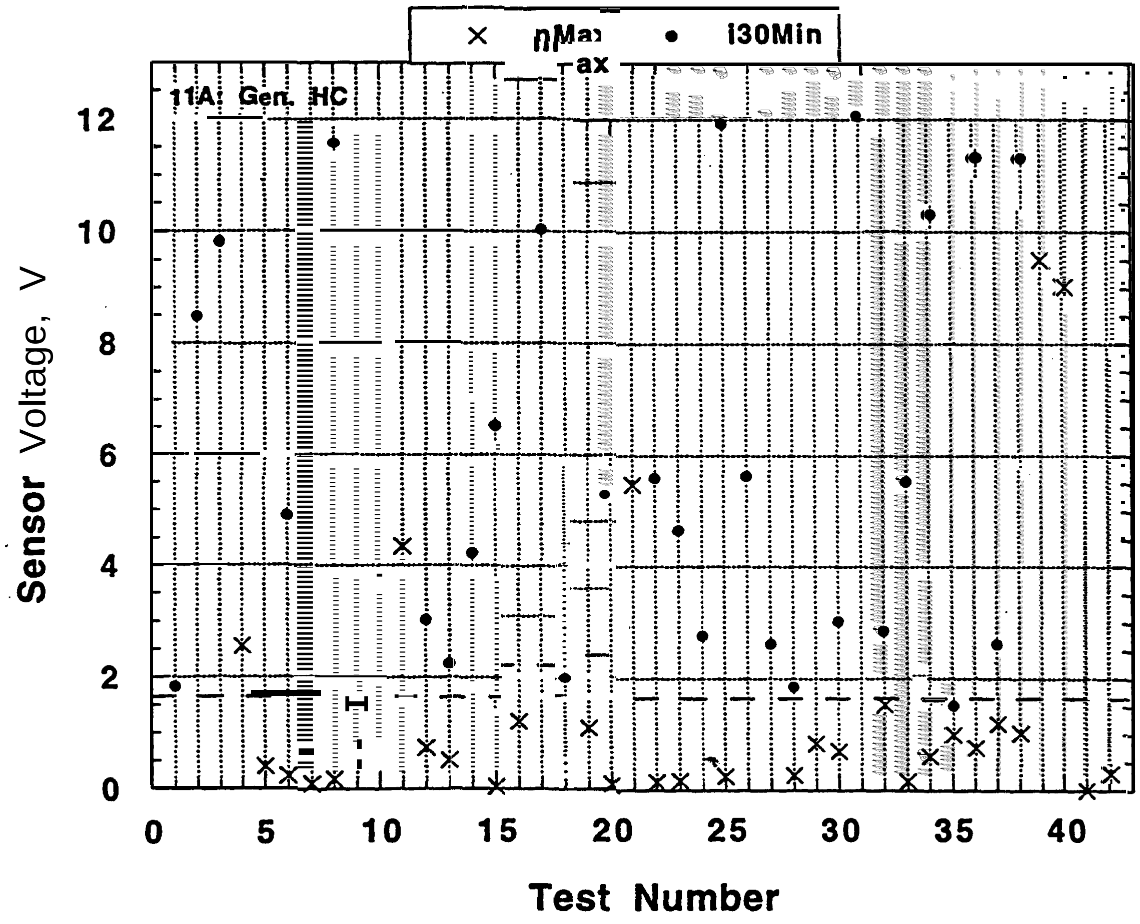

Figure 36. Site 11 general-hydrocarbon sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

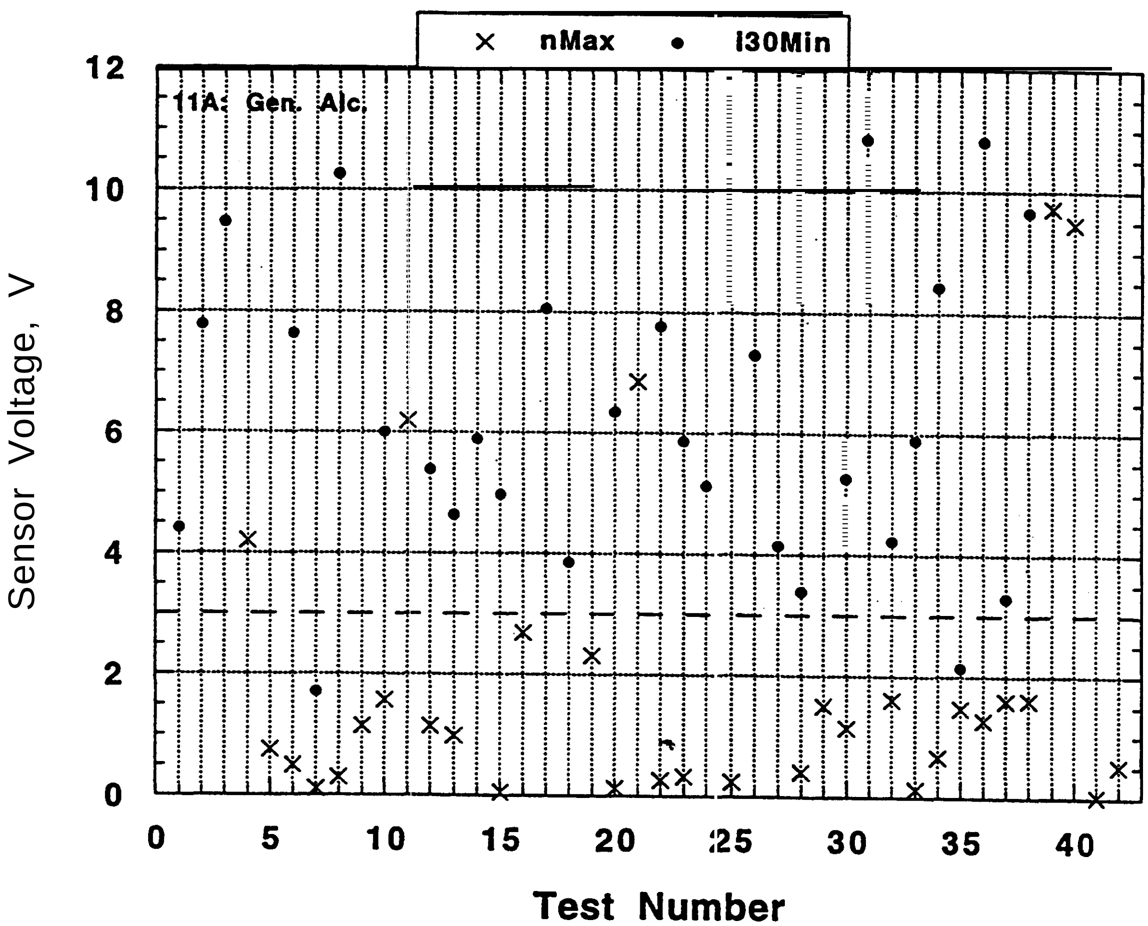

Figure 37. Site 11 general-alcohol sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

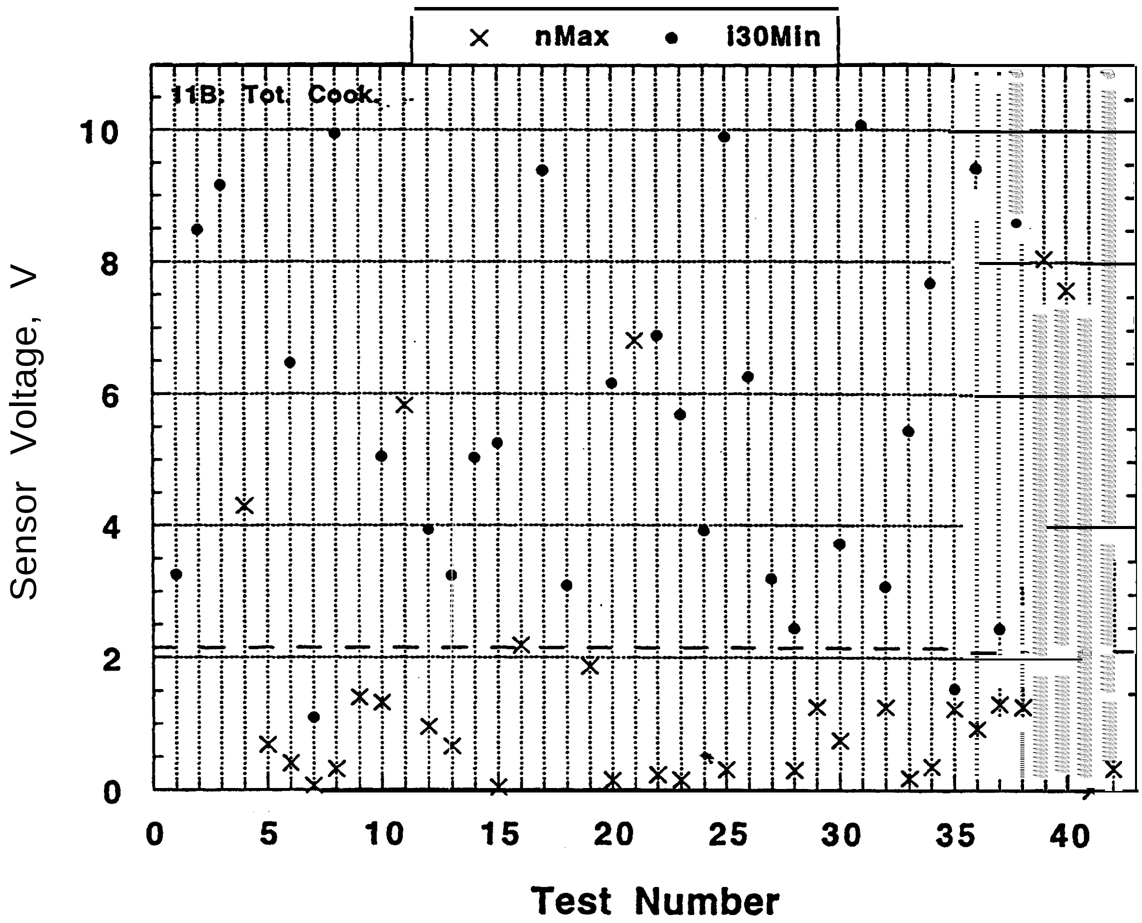

Figure 38. Site 11 total-cooking-gas sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

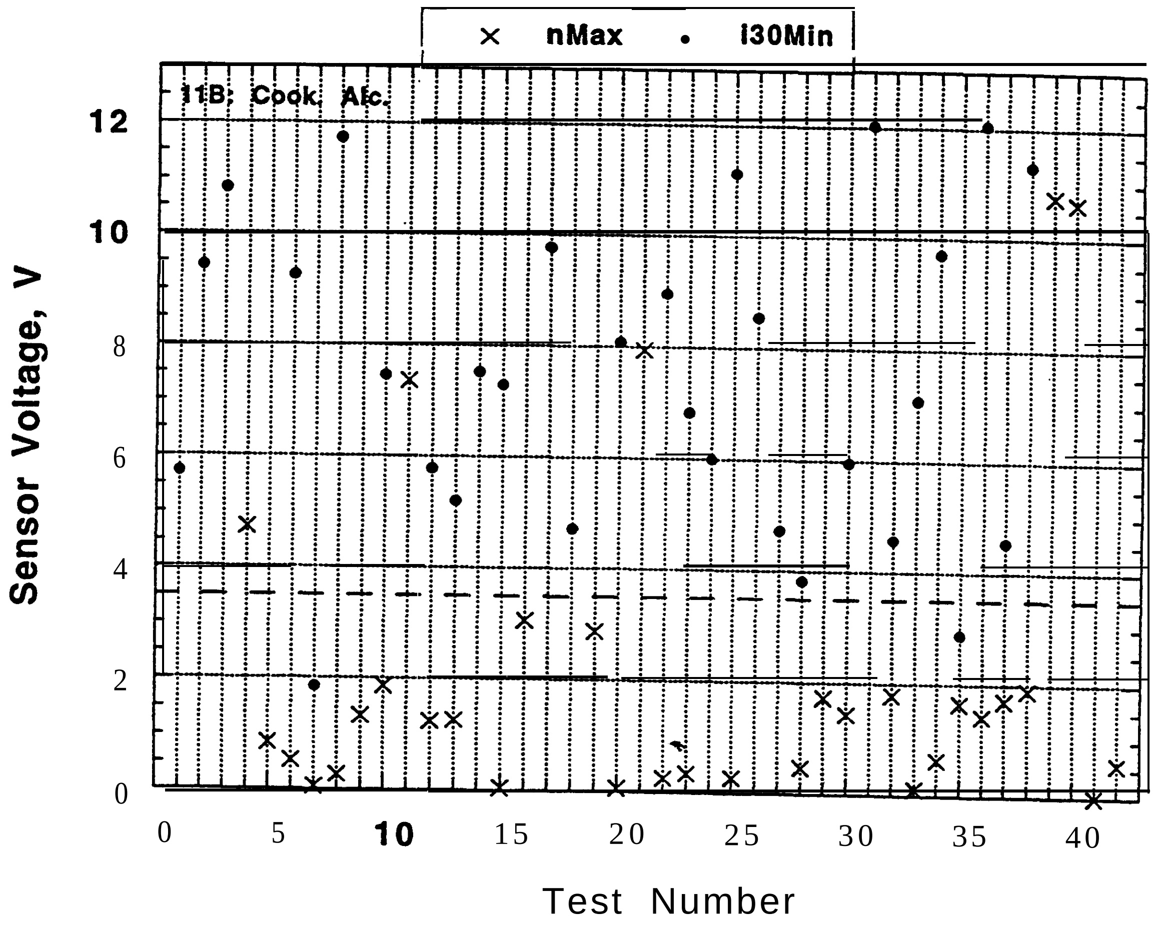

Figure 39. Site 11 cooking-alcohol sensor maximum normal and minimum ignition output 30 s before ignition versus test number.

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 3 1% 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, I 1 and 2 1, 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

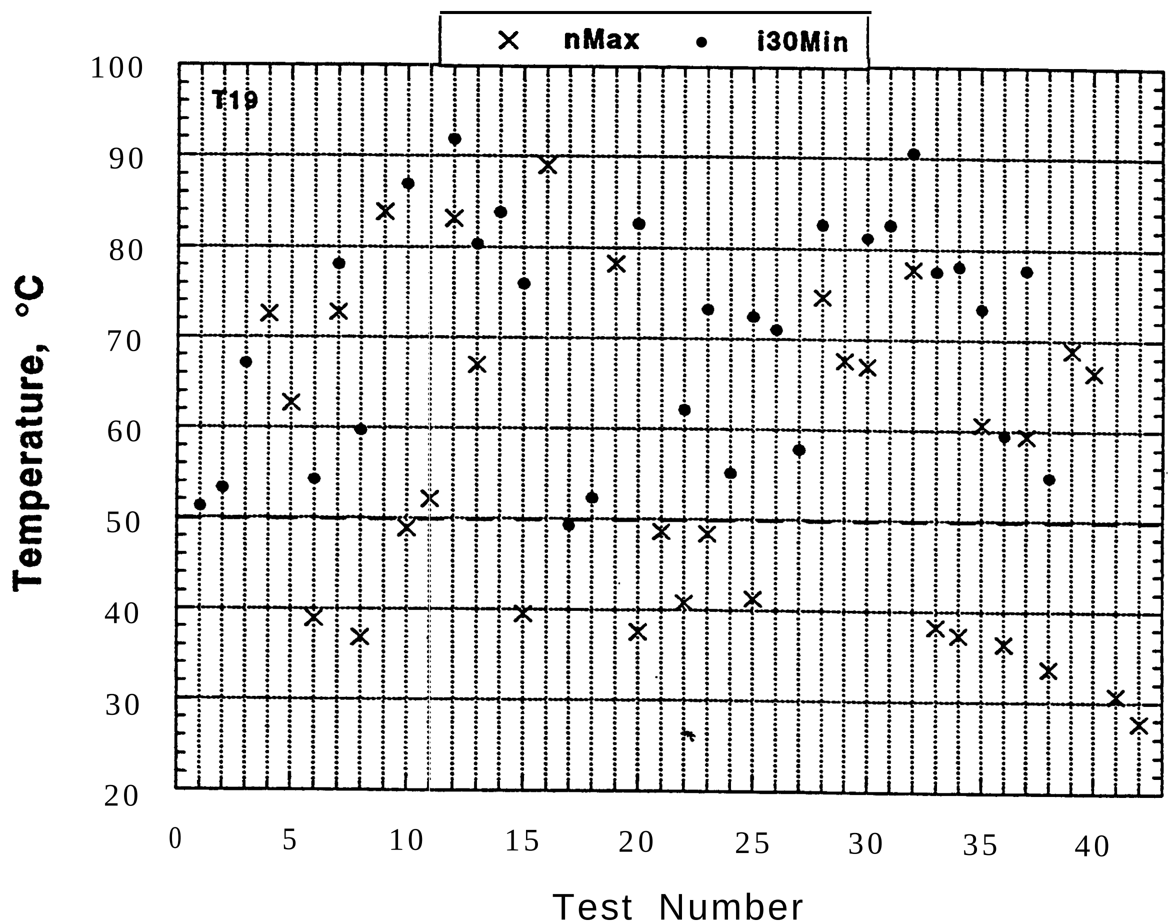

Figure 40. Site 19 thermocouple temperature maximum normal and minimum ignition output 30 s before ignition versus test number.

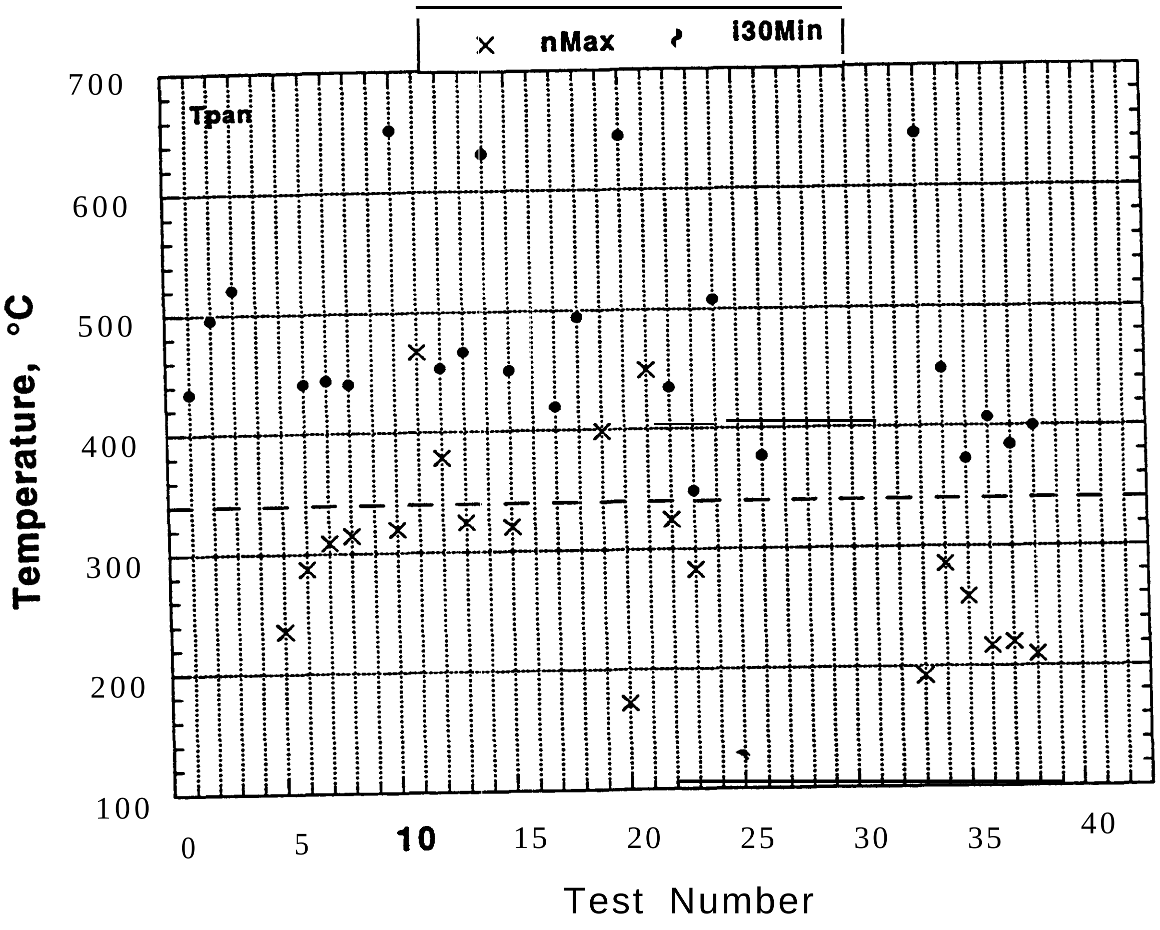

Figure 41. Focus-burner pan-bottom temperature maximum normal and minimum ignition output 30 s before ignition versus test number.

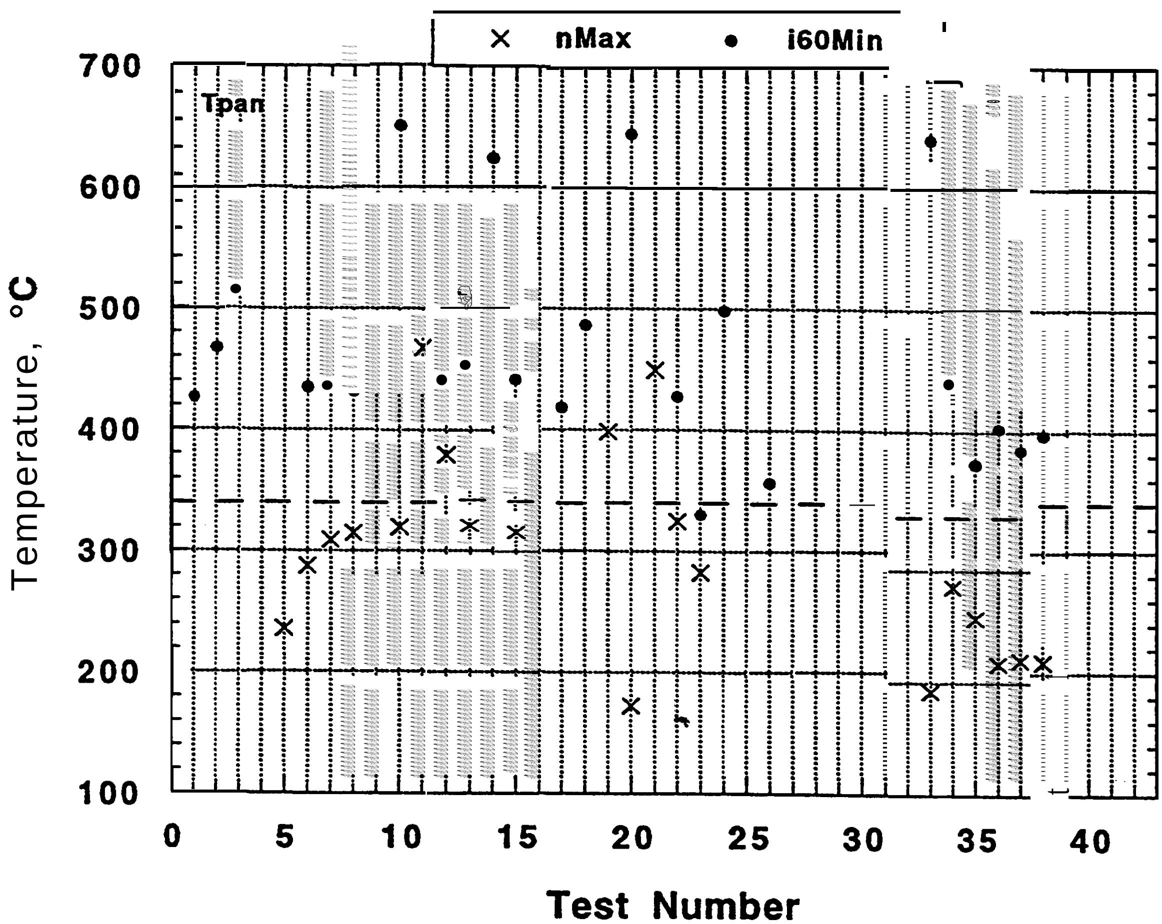

Figure 42. Focus-burner pan-bottom temperature maximum normal and minimum ignition output 60 s before ignition versus test number.

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

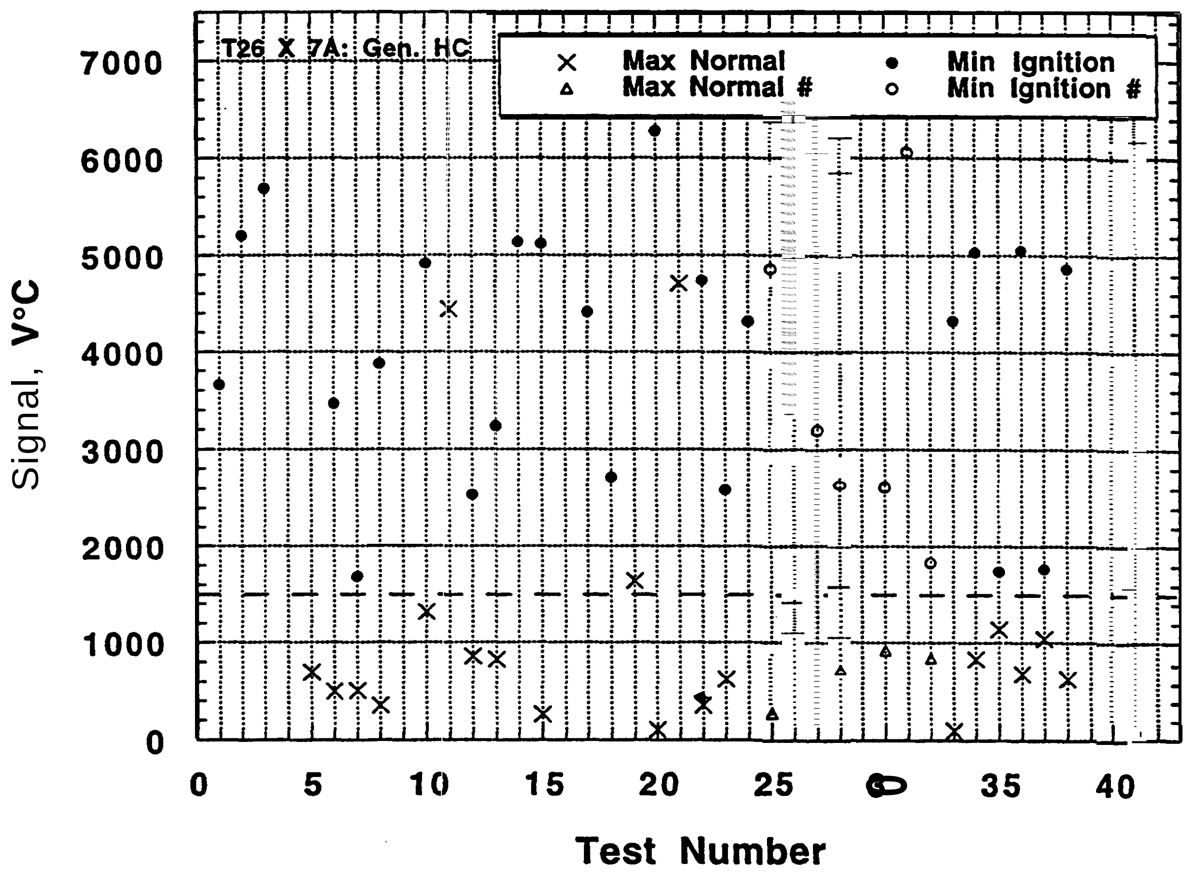

Figure 43. Focus-burner pan-bottom temperature multiplied by site 7 general-alcohol sensor voltage maximum normal and minimum ignition output 30 s before ignition versus test number. # signifies the results from substitute thermocouple data.

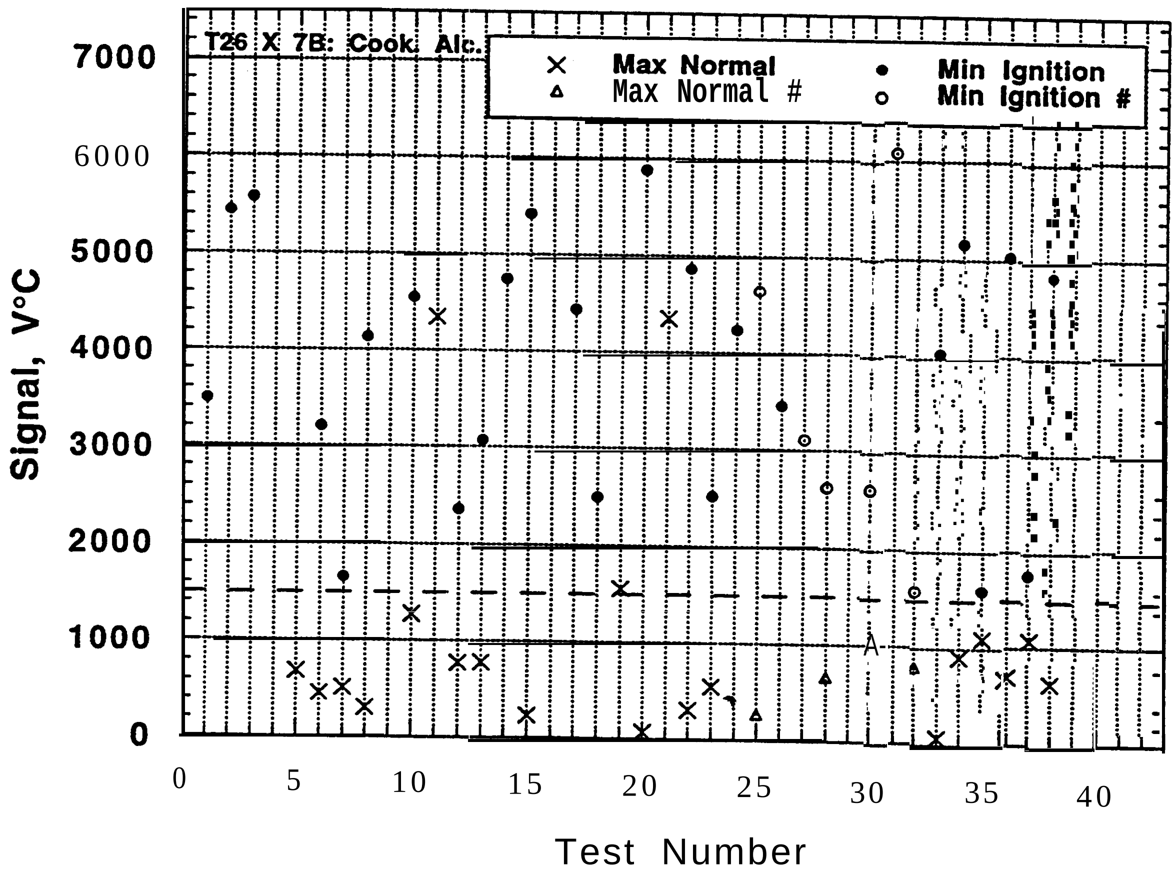

Figure 44. Focus-burner pan-bottom temperature multiplied by site 7 cooking-alcohol sensor voltage maximum normal and minimum ignition output 30 s before ignition versus test number. # signifies the results from substitute thermocouple data.

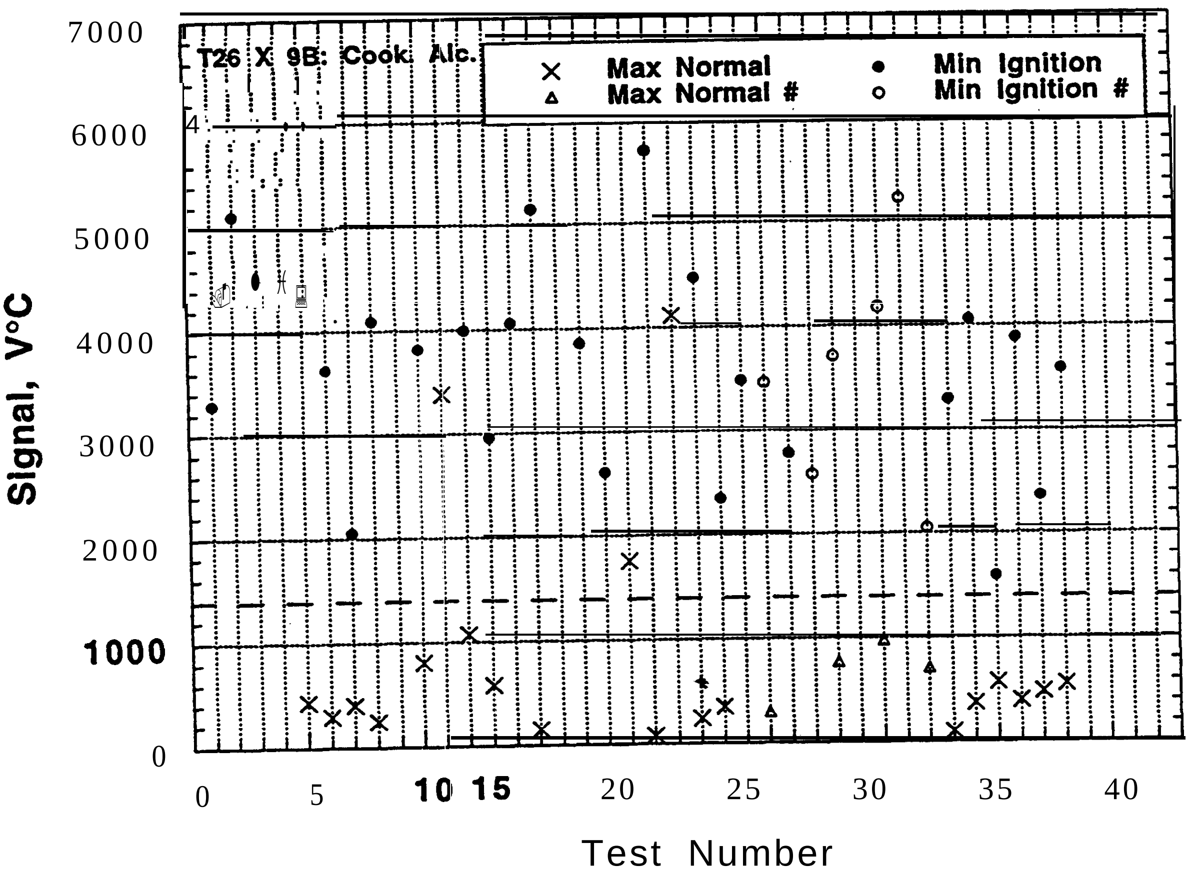

Figure 45. Focus-burner pan-bottom temperature multiplied by site 9 cooking-alcohol sensor voltage maximum normal and minimum ignition output 30 s before ignition versus test number. # signifies the results from substitute thermocouple data.

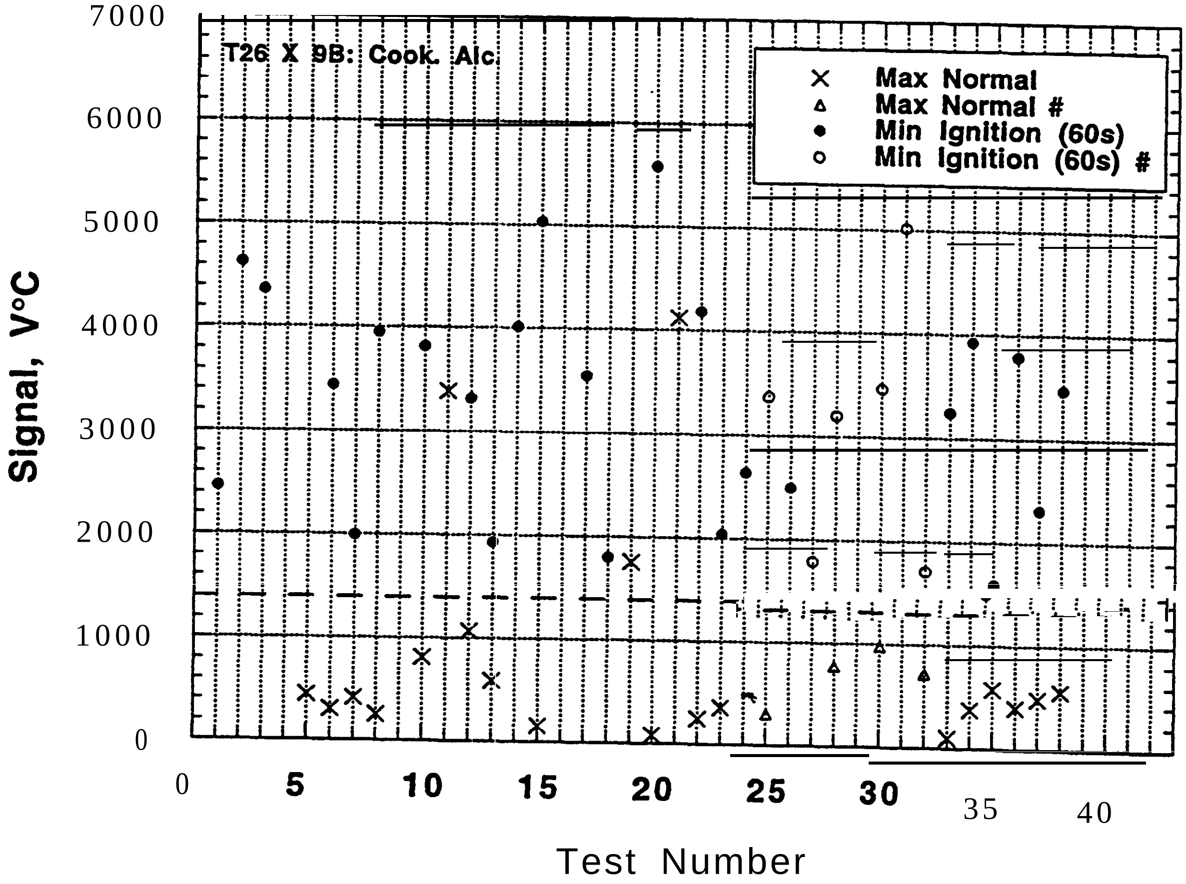

Figure 46. Focus-burner pan-bottom temperature multiplied by site 9 cooking-alcohol sensor voltage maximum normal and minimum ignition output 60 s before ignition versus test number. # signifies the results from substitute thermocouple data.

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 tlhe 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

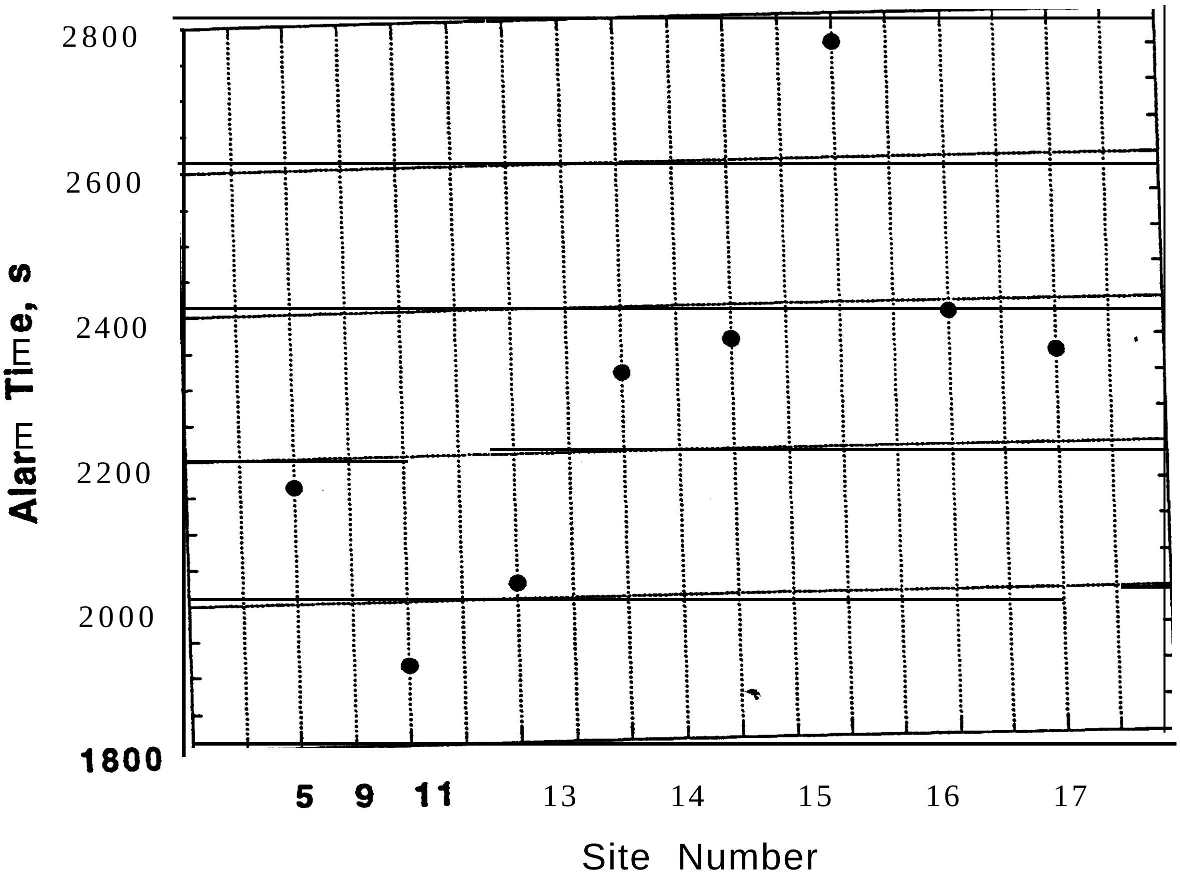

Figure 47. Average photoelectric, smoke-detector alarm time for all tests versus site number.

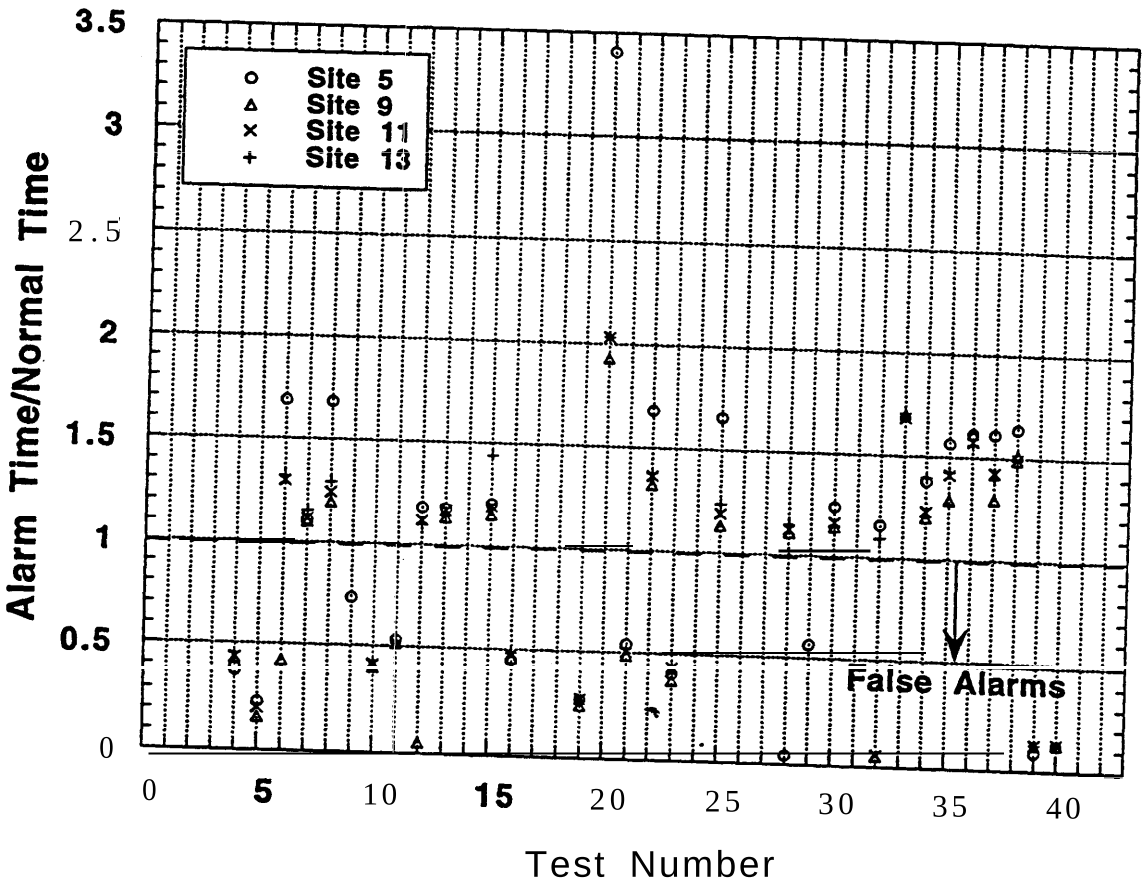

Figure 48. Sites 5-1 3 photoelectric smoke detectors ratio of alarm times to normal times for all tests versus test number.

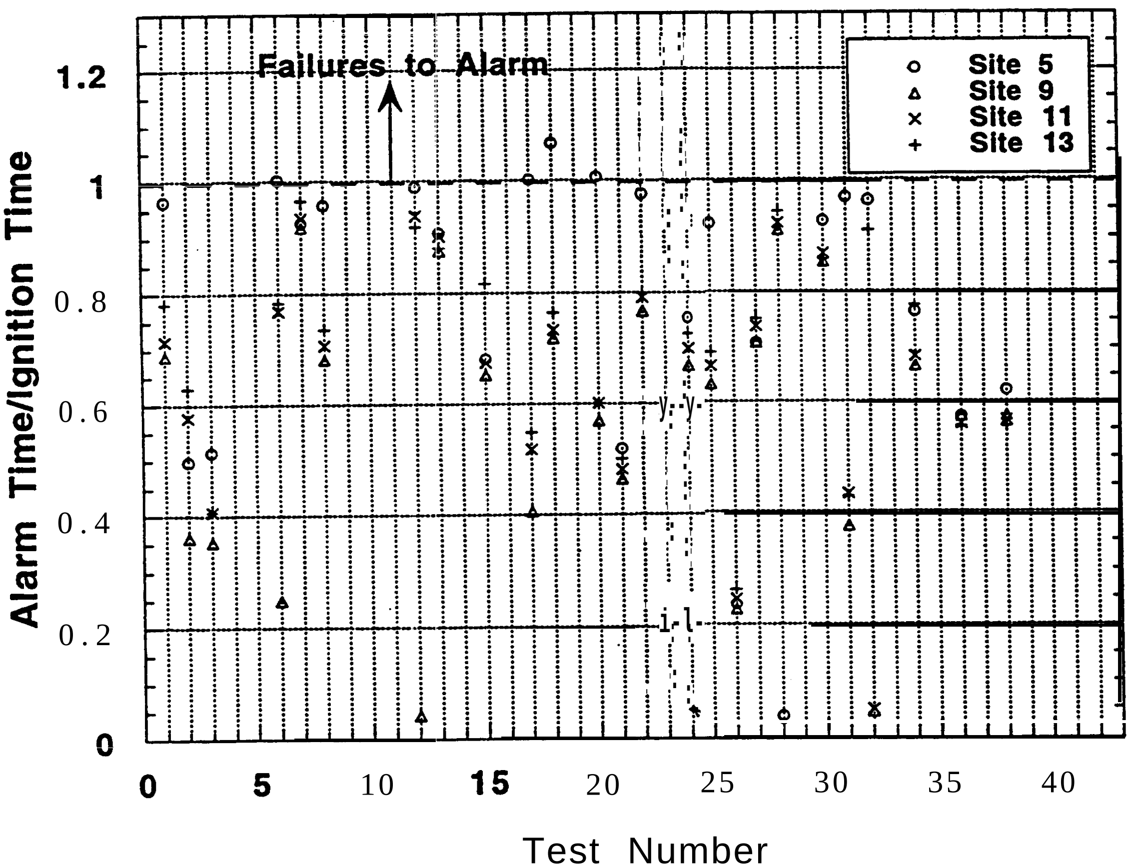

Figure 49. Sites 5-13 photoelectric smoke detectors ratio of alarm times to ignition times for all tests versus test number.

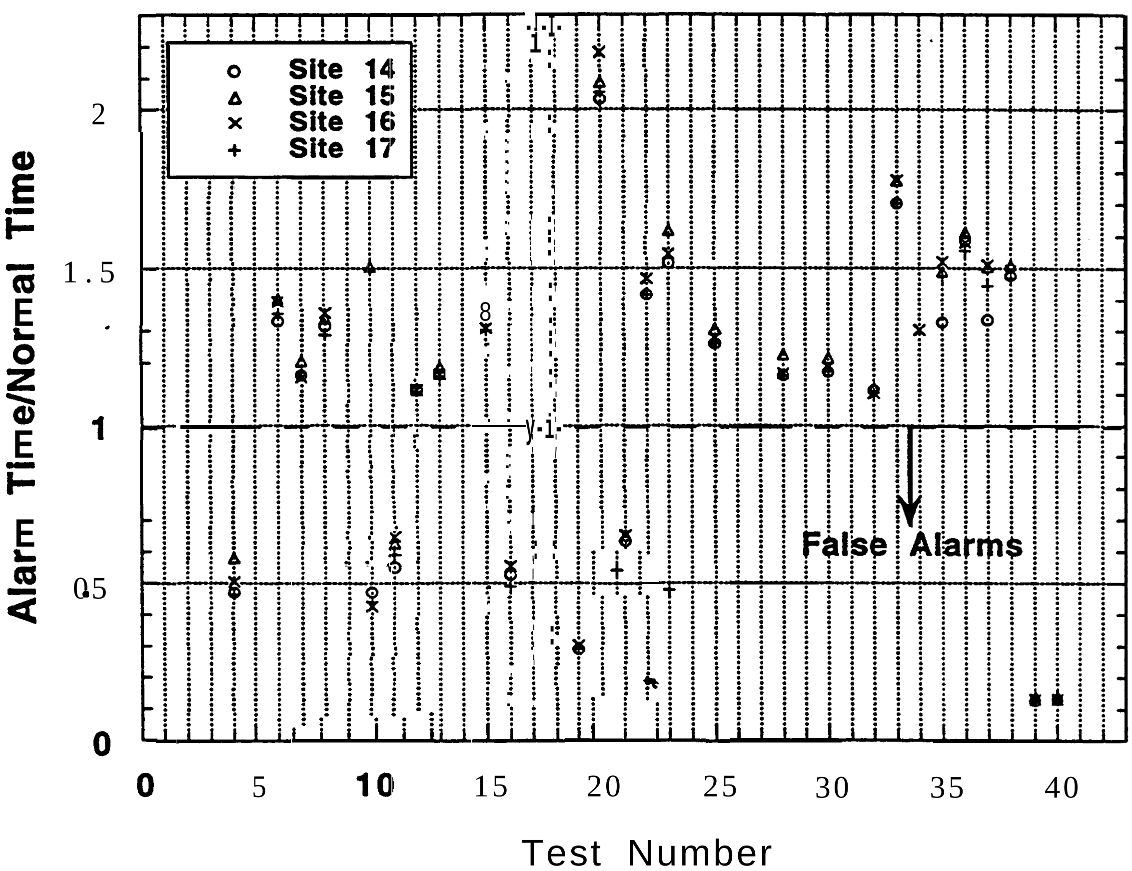

Figure 50. Sites 14-17 photoelectric smoke detectors ratio of alarm times to normal times for all tests versus test number.

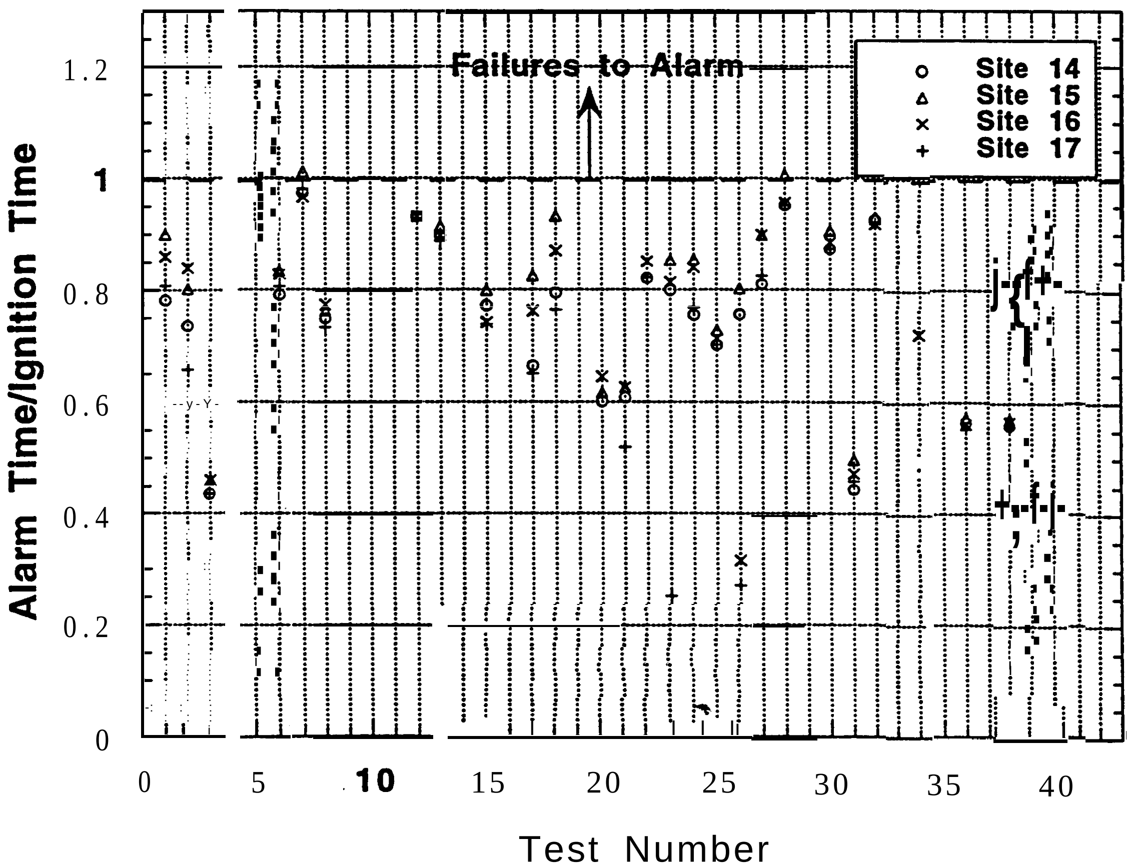

Figure 51. Sites 14- 17 photoelectric smoke detectors ratio of alarm times to ignition times for all tests versus test number.

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

Condition	Unattended1 (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-l 7, 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

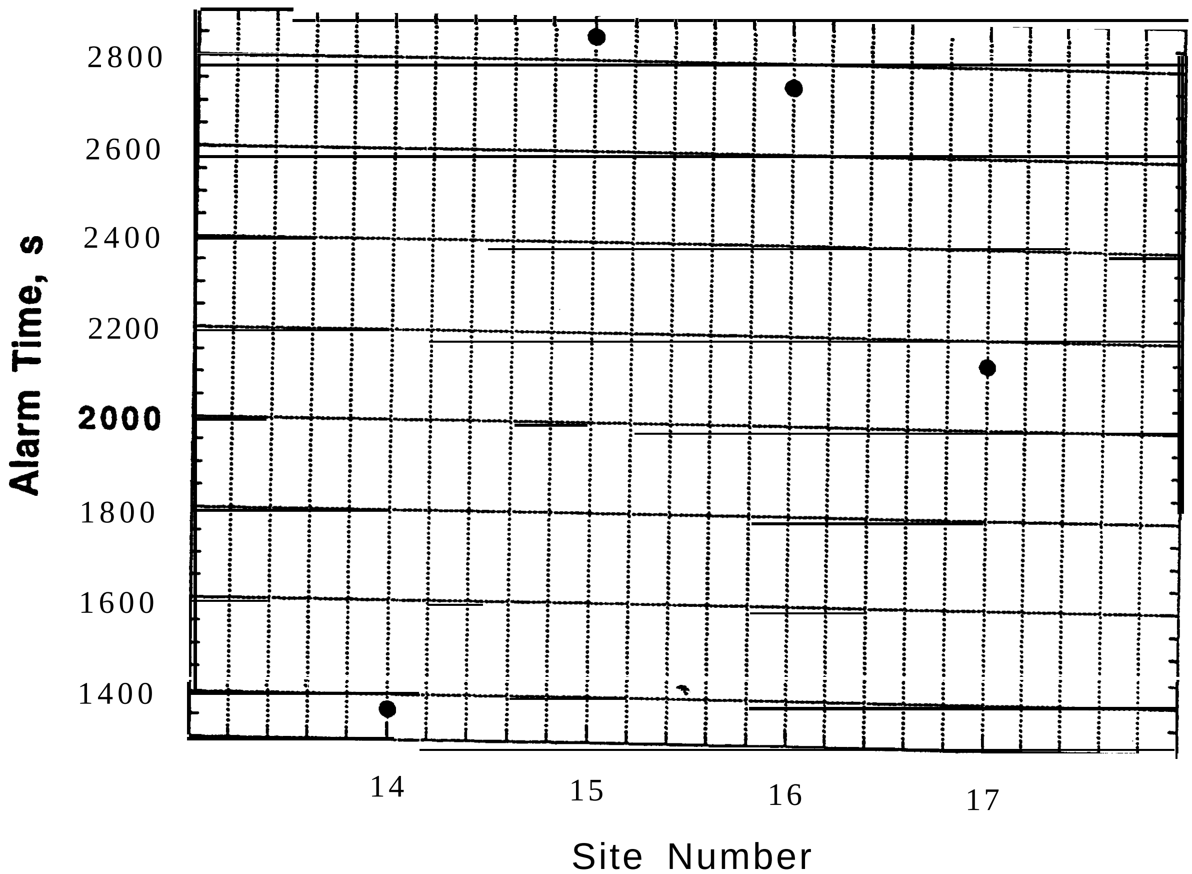

Figure 52. Average ionization smoke-detector alarm time for all tests versus site number.

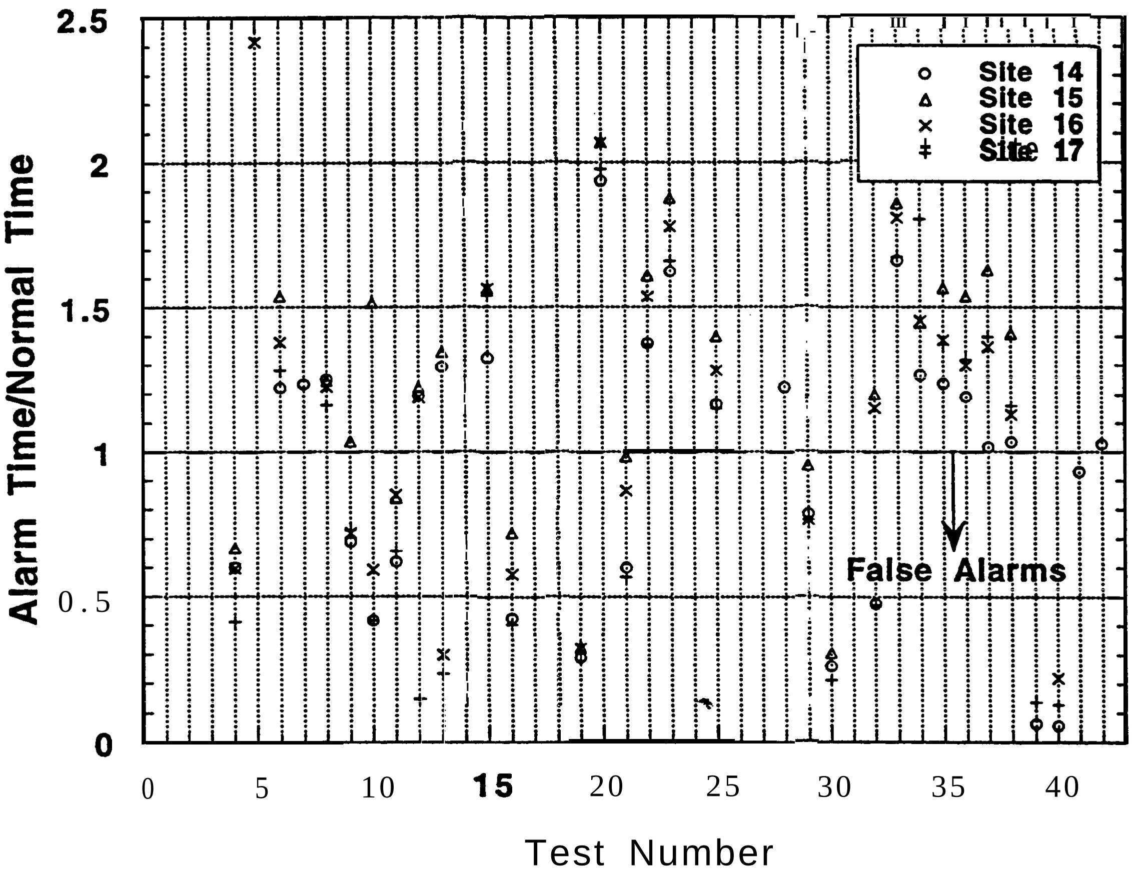

Figure 53. Sites 14-17 ionization smoke detectors ratio of alarm times to normal times for all tests versus test number.

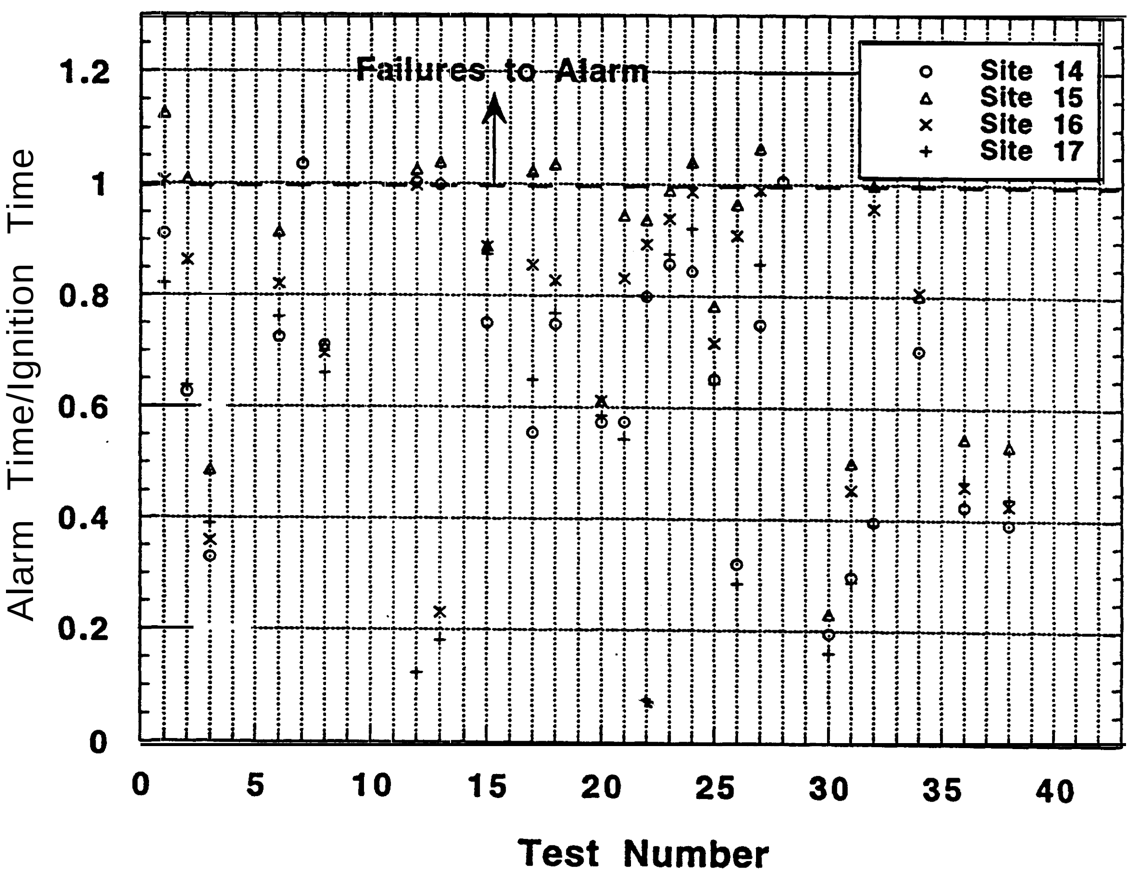

Figure 54. Sites 14-17 ionization smoke detectors ratio of alarm times to ignition times for all tests versus test number.

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

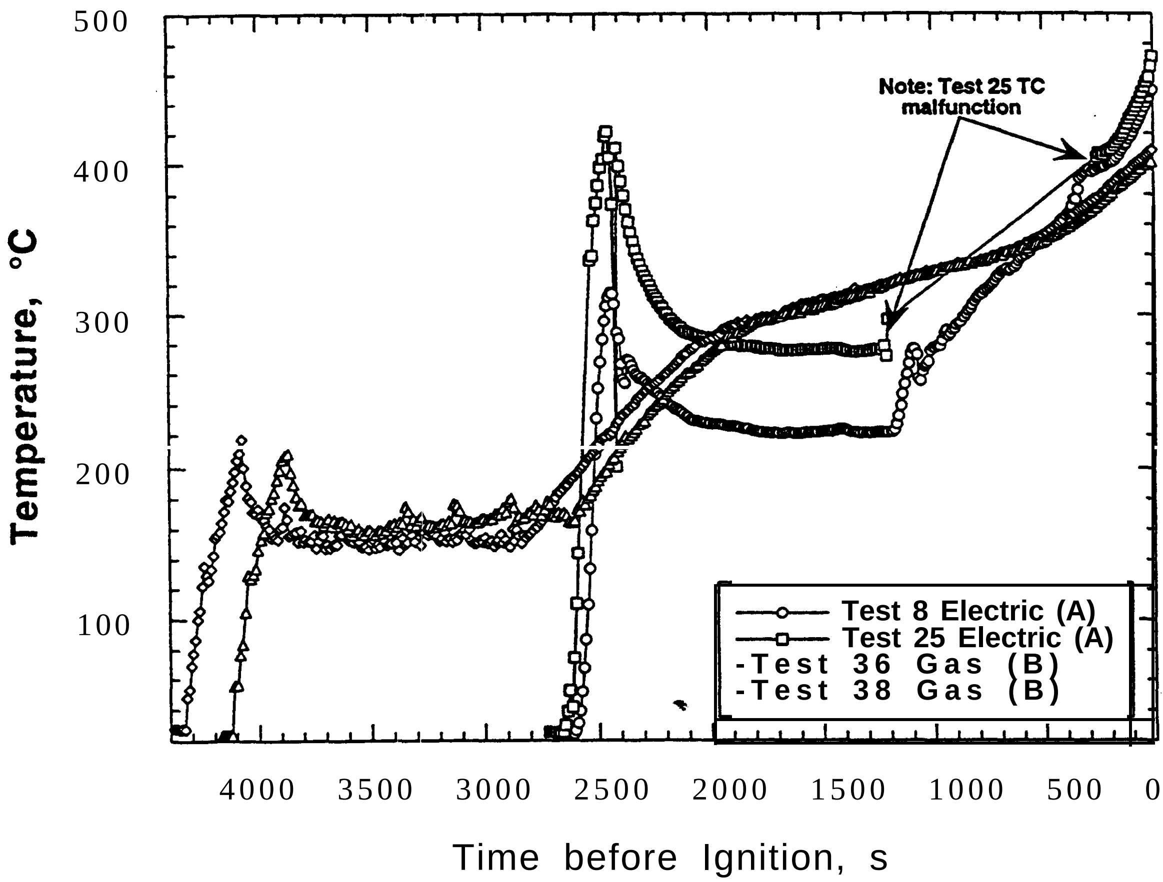

Figure 55. Pan-bottom temperature versus time before ignition for chicken in oil **(normal→unattended)** for the electric (A) and gas **(B)** ranges.

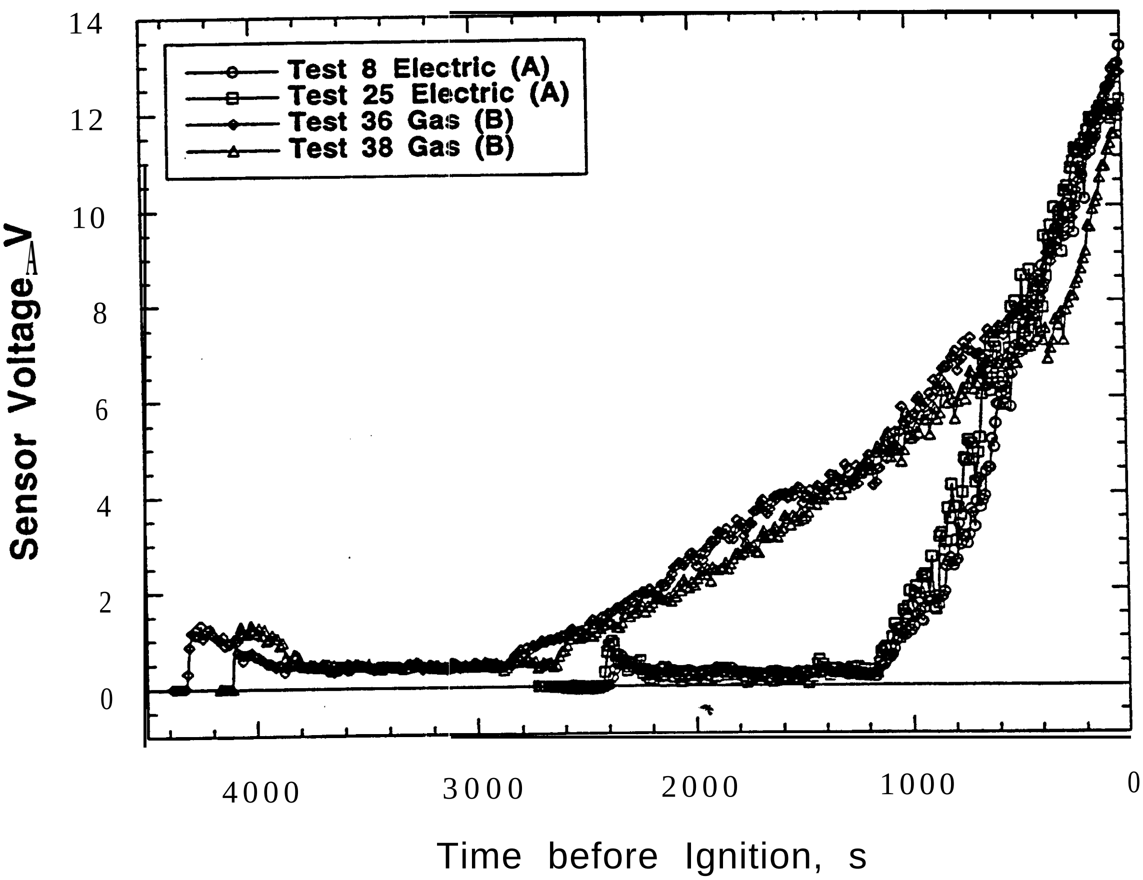

Figure 56. Site 9 general-alcohol sensor response versus time before ignition for chicken in oil (normal→unattended) for the electric (A) and gas (B) ranges.

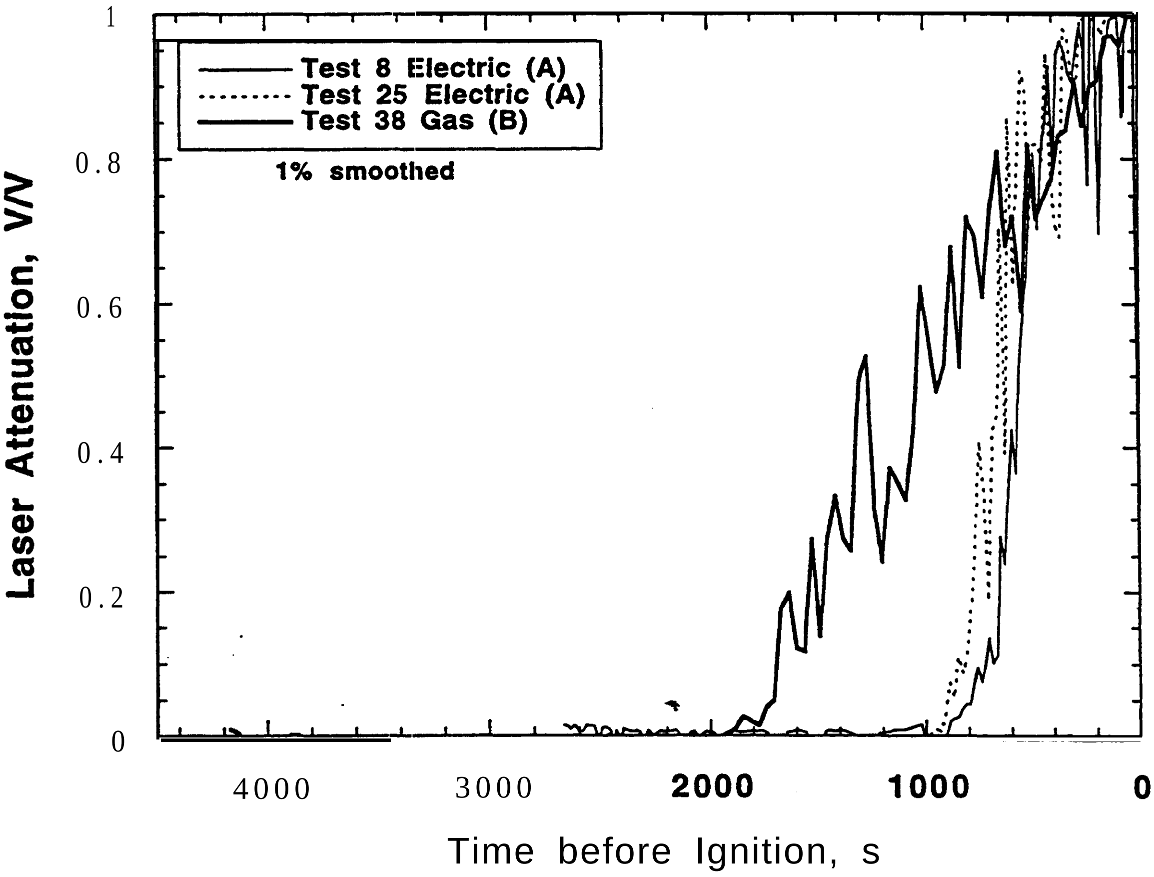

Figure 57. Laser attenuation versus time before ignition for chicken in oil **(normal→unattended)** for the electric (A) and gas **(B)** ranges.

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

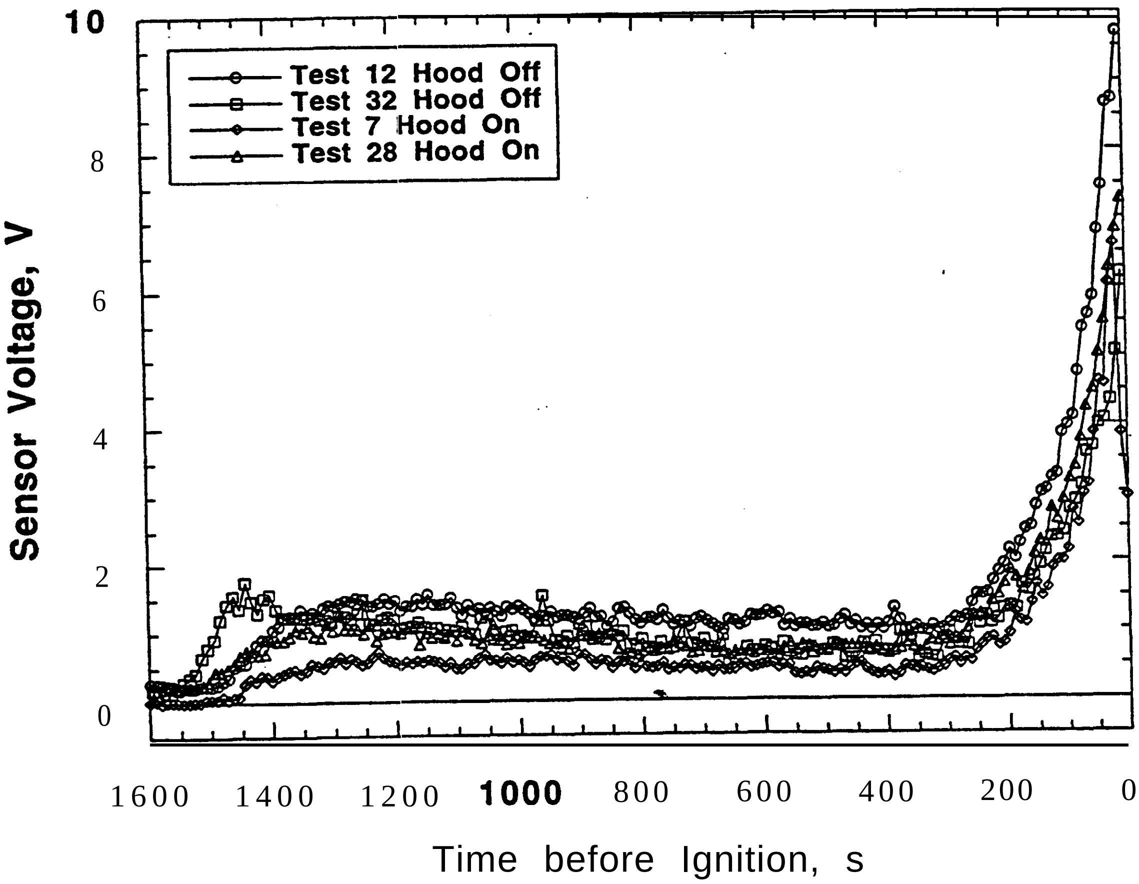

Figure 58. Site 9 general-alcohol sensor response versus time before ignition for water and oil (normal→unattended) for the electric (A) range with the hood on and off.

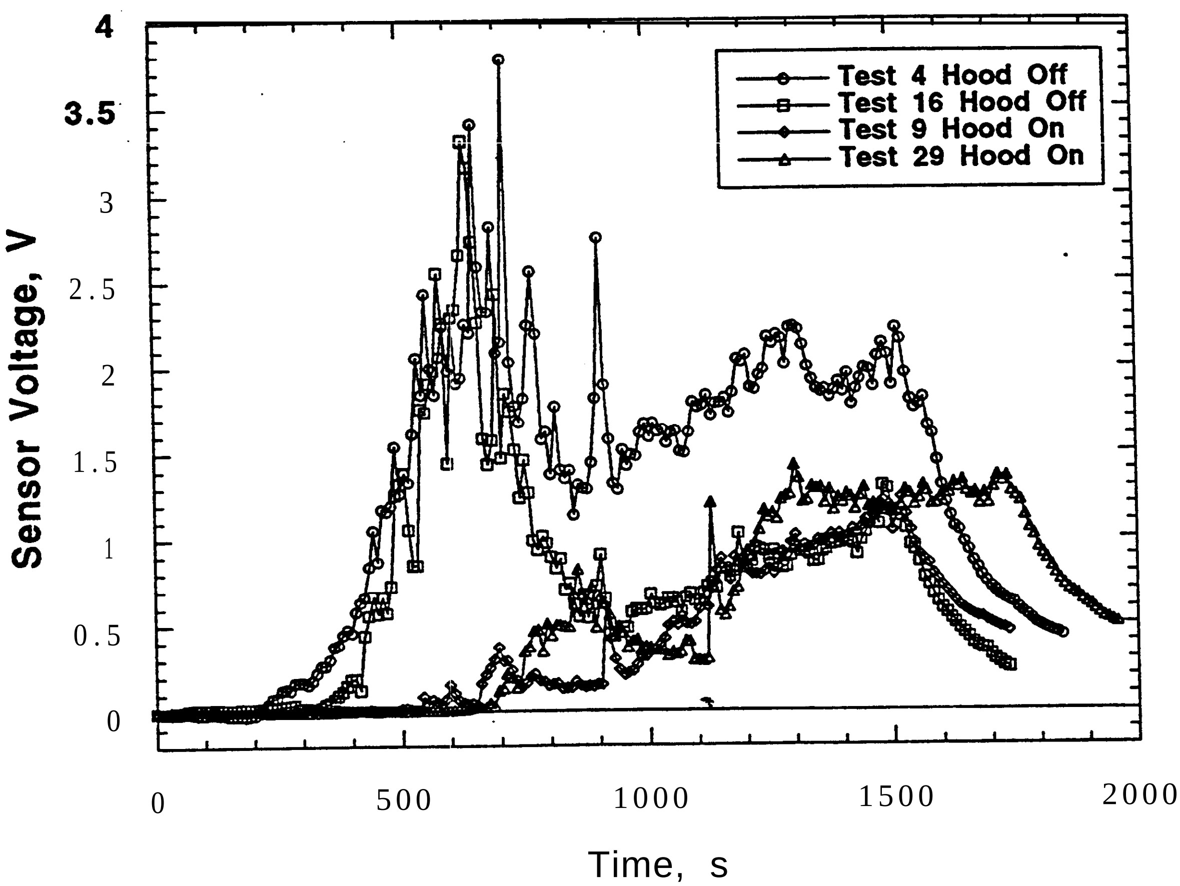

Figure 59. Site 9 general-alcohol sensor response **versus** time for broiled steak (normal) for the electric (A) range with the hood on and off.

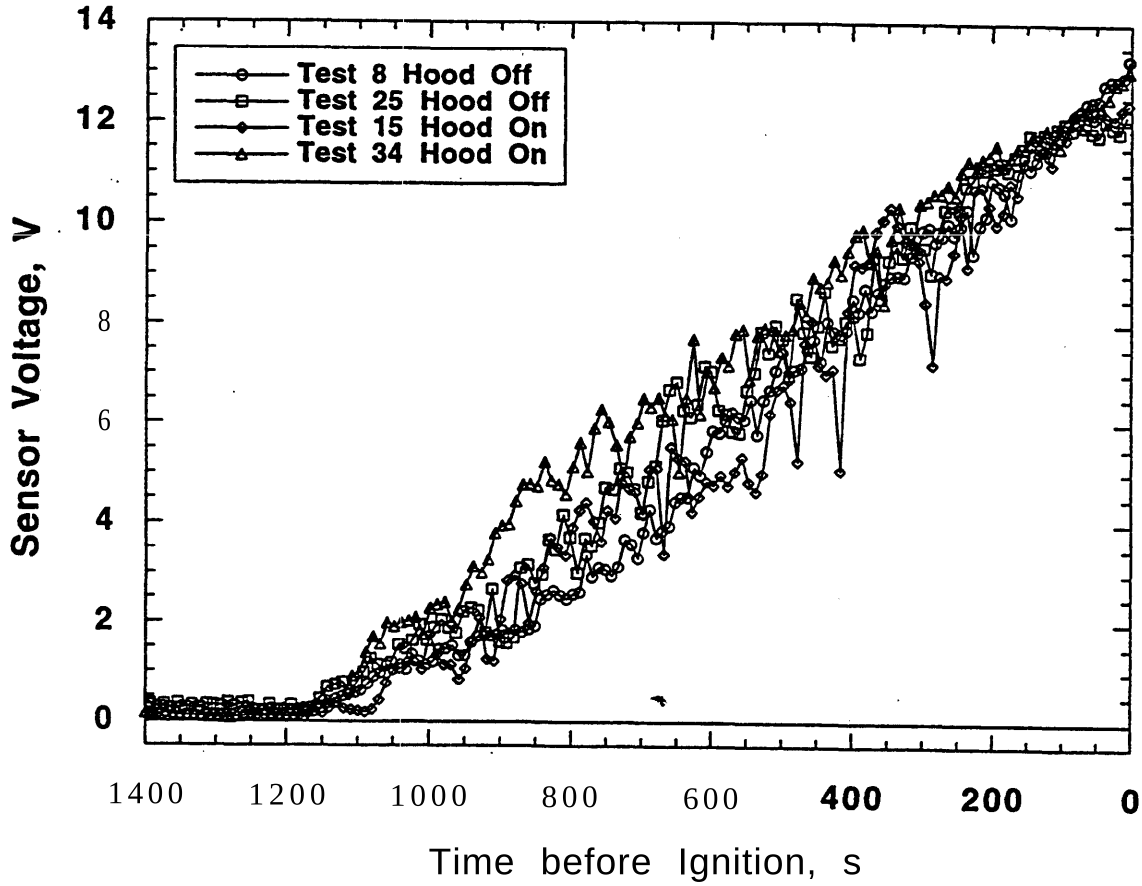

Figure 60. Site 9 general-alcohol sensor response versus time before ignition for chicken **(normal→unattended)** for the electric (A) range with the hood on and off.

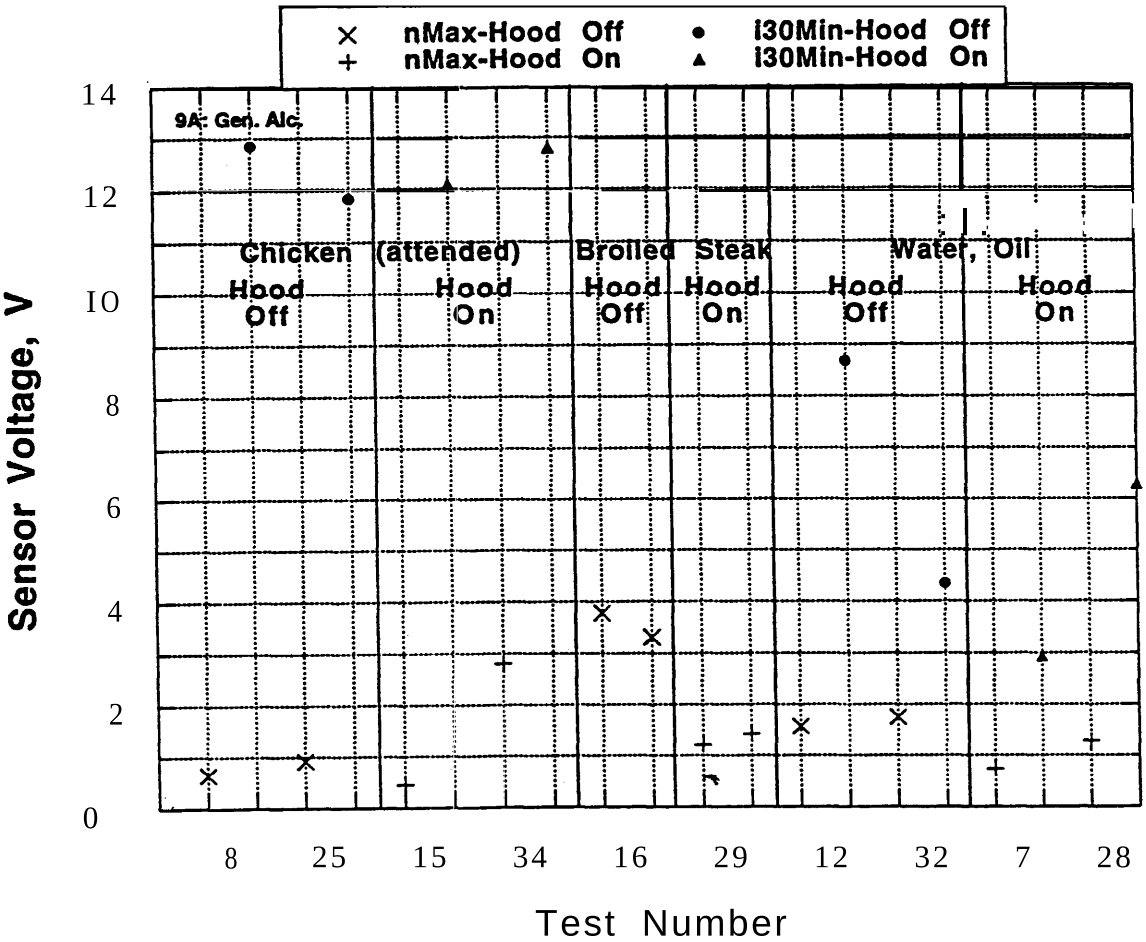

Figure 61. Site 9 general-alcohol sensor responses versus test number for water and oil, broiled steak, and chicken in oil (normal) for the electric (A) range with the hood on and **off**.

because it tended to increase the difference between normal and pre-ignition conditions. These effects were only determined for the typical electric range. The downdraft 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 downdraft 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 thii 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 prelimiiary 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

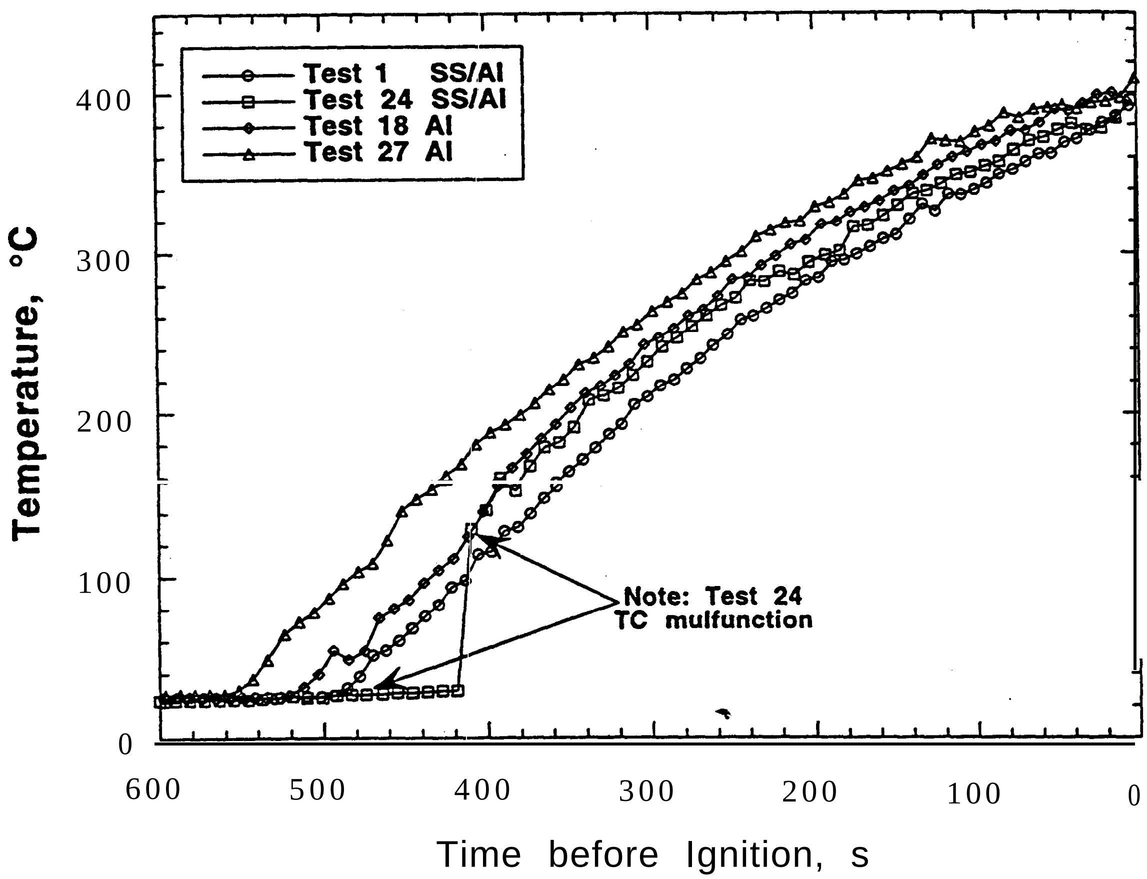

Figure 62. Food temperature versus time before ignition for soybean oil (unattended) on the electric (A) ranges in aluminum and stainless-steel pans.

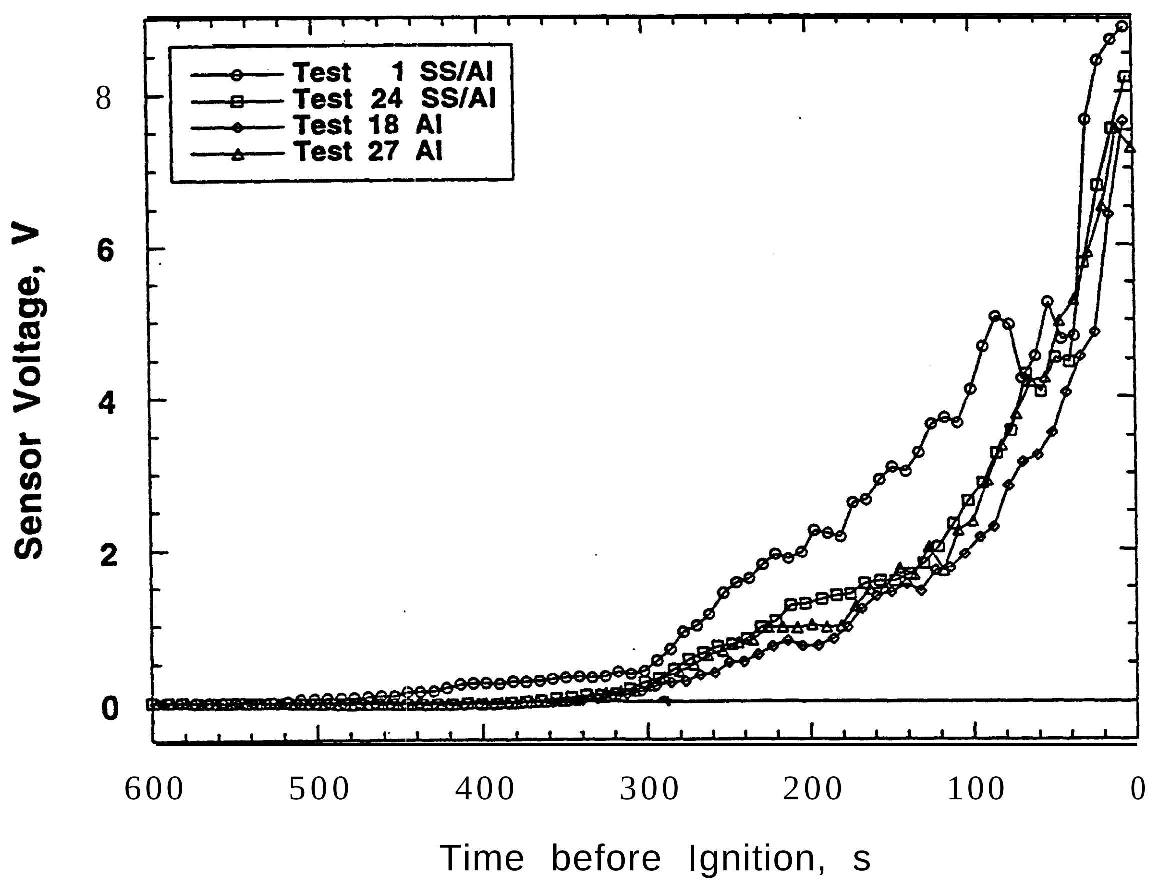

Figure 63. Site 9 general-alcohol sensor response versus time before ignition for soybean oil (unattended) on the electric (A) ranges in aluminum and stainless-steel pans.

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-fue 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 preignition 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

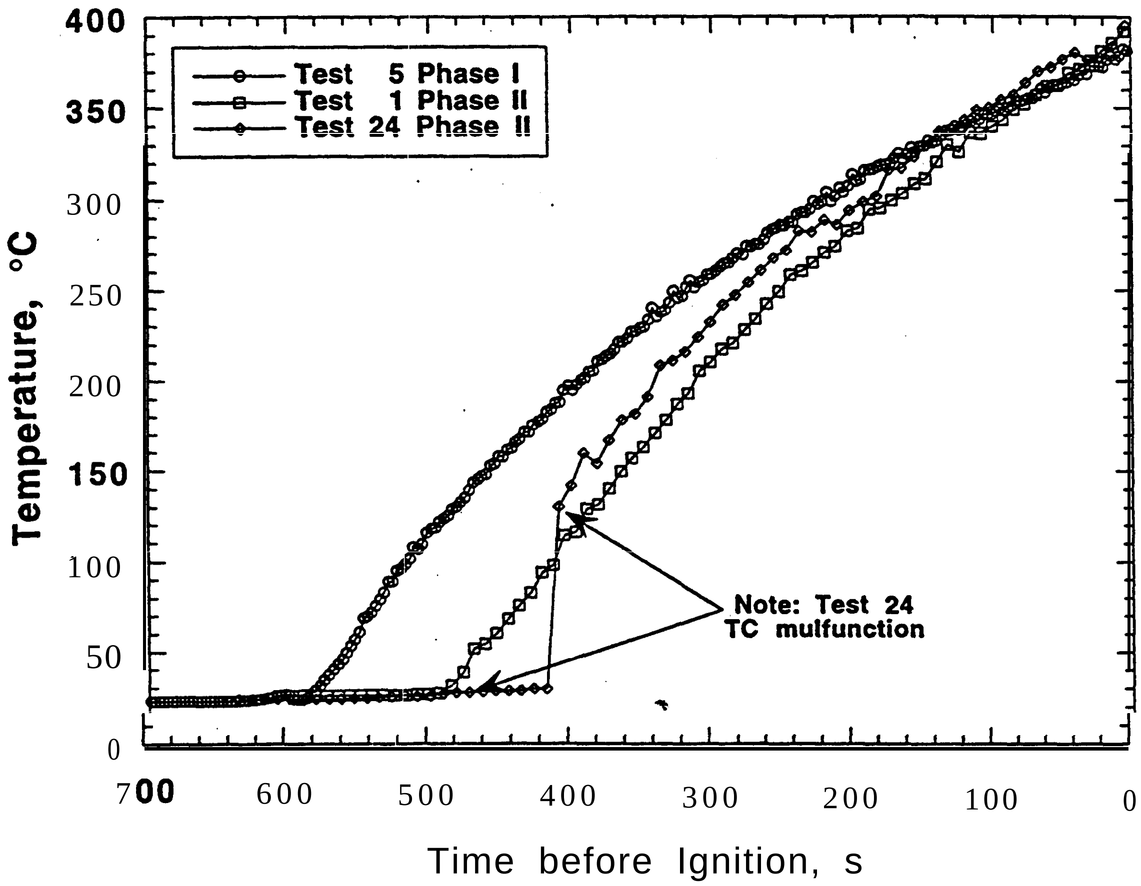

Figure 64. Food temperature versus time before ignition for soybean oil (unattended) on the electric (A) range: for Phase I and Phase II.

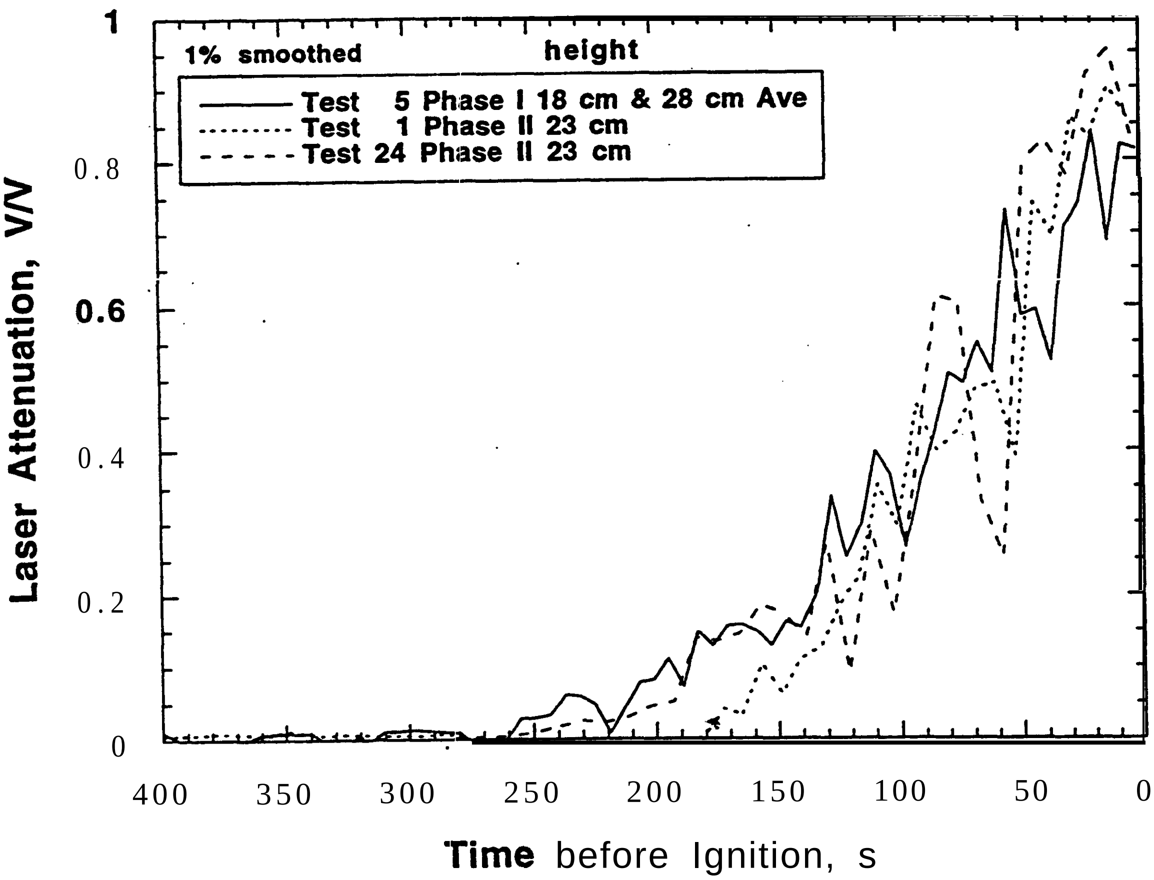

Figure 65. Laser attenuation versus time before ignition for soybean oil (unattended) on the electric (A) range for Phase I and Phase II.

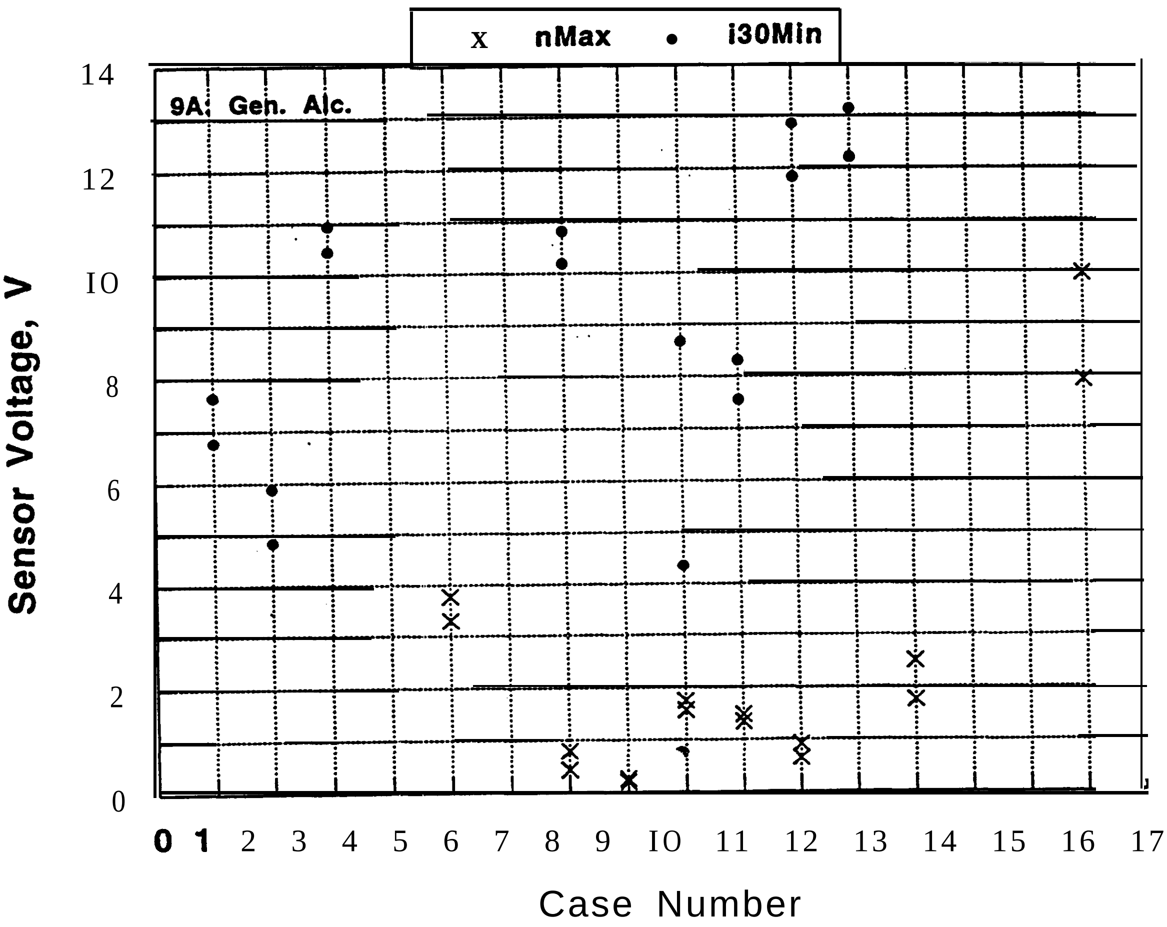

Figure 66. Site 9 general-alcohol sensor maximum normal and minimum ignition output 30 s before ignition versus cooking case number for tests using the electric (A) range and inactive hood.

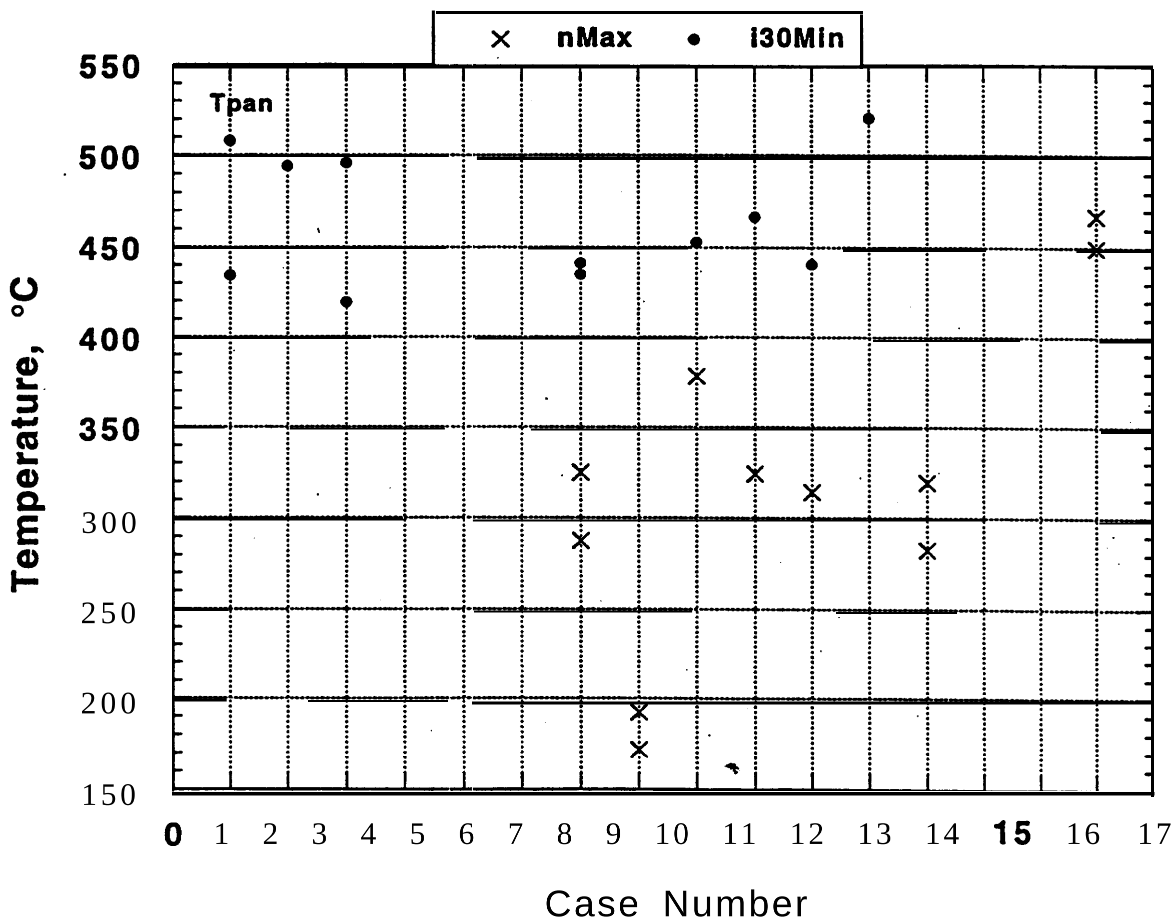

Figure 67. Pan-bottom temperature maximum normal and minimum ignition output 30 s before ignition versus; cooking case number for tests using the electric (A) range and inactive hood.

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

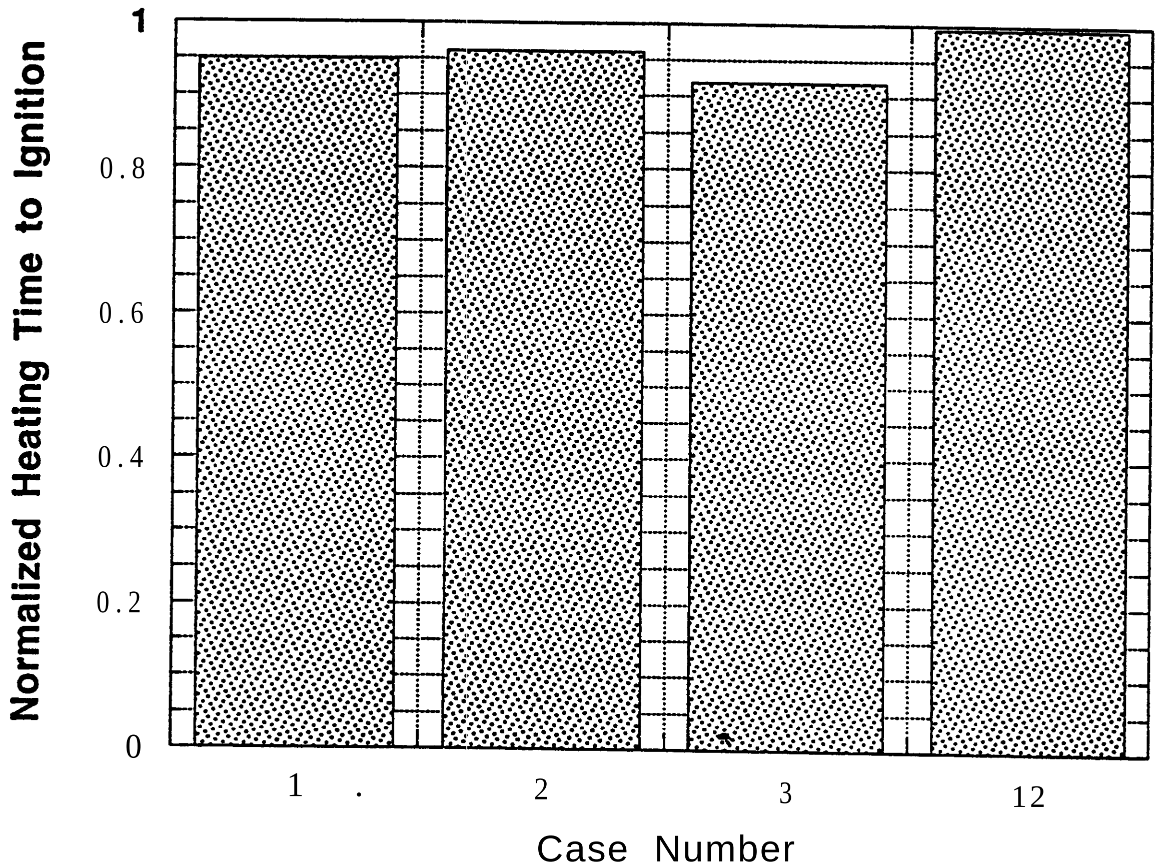

Figure 68. Heating time to ignition versus cooking case number for tests using electric (A) range and inactive hood.

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.

6.0 References

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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. Bidirectional 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		Food Summary	
Size	______ cm (in)	Substance	______
Type/Number	______	Scenario Number	______
Material	______ - -	Initial Volume	______ ml
Mass Measurements:		Remaining Volume	______ ml
Pan	______ kg	Initial Mass	______ kg
Lid	- - k g	Remaining Mass	______ kg
Pan+Lid	- -kg		
Pan+Lid+Food (before)	- -kg		
Pan+Lid+Food (after)	- -kg		
Other masses ______	- -kg		

Experiment Operators — Instrument(s)

- Marco Fernandez ☐ ______
- Rik Johnsson ☐ ______
- Michelle King ☐ ______
- Randy Shields c l ______

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

Clock Time @ 0 Time(min)	Comments/ Observations	Voltage/Gas Flow Readinas	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: CPSC960112JUN96 Scenario 1: Soybean Oil, SS Frying Pan, Hood Off

00	1Time	Elapsed time		(s)
01	2LScat1HeNe	laser 8 photodiode, scattering 5 deg. from forward		(V)
02	2LTran HeNe	laser & photodiode, transmission		(V)
03	2LScat2HeNe	laser & photodiode, scattering 10 deg. fran 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 pad, 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: fop 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	29Ahalc	Site 9:	¦Gen. alcohols	
22	29Btot	Site 9:	¦Total cooking	
23	296alc	Site 9:	¦Cooking alcohols	
24	29Bwat	Site 9:	¦Cooking water	
25	290	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	211Aalc	Site 11:	¦Gen. alcohols	
32	211Btot	Site 11:	¦Total cooking	
33	211Balc	Site 11:	¦Cooking alcohols	
34	211Bwat	Site 11:	¦Cooking water	
35	211D	Site 11:	¦Carbon monoxide	
36	211Xsig	Site 11:	(Photoelectric	
37	211Xalm	Site 11:	¦Photo. alarm	
38	213Xsig	Site 13: Ceiling, 30 cm from ctr lt wall	¦Photoelectric	
39	213Xalm	Site 13:	¦Photo. alarm	
40	214Xsig	Site 14: Ceiling, 30 cm from ctr front wall	¦Photoelectric	
41	214Xalm	Site 14:	¦Photo. alarm	
42	214Zsig	Site 14:	¦Ionization	
43	214Zalm	Site 14:	¦Ion. alarm	
44	215Xsig	Site 15: Ceiling, 30 an from rt, front walls	¦Photoelectric	
45	215Xalm	Site 15:	¦Photo. alarm	
46	215Zsig	Site 15:	¦ Ionization	
47	215Zalm	Site 15:	¦Ion. alarm	
48	216Xsig	Site 16: Ceiling, 30 cm from ctr rt wall	¦Photoelectric	
49	216Xalm	Site 16:	¦Photo. alarm	
50	216Zsig	Site 16:	¦Ionization	
51	216Zalm	Site 16:	¦Ion. alarm	

```
52 217XsigSite 17: Ceiling, 30 an 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, 1 t                    | 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 8 hood, ctr             |Thermocouple
67 2T8    Site 8:  Rangehood,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 an f rom ctr front wall      |Thermocouple
73 2T15   Site 15: Ceiling, 30 cm from rt, front walls      |Thermocouple
74 2T16   Site 16: Ceiling, 30 an from ctr rt wall          |Thermocouple
75 2T17   Site 17: Ceiling, 30 an 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
822124    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 bumer 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: Hid-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 Cocking 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)
```