AUGUST 1960
TECHNICAL PAPER 50

Effects of Mass Fires on Personnel in Shelters

A. BROIDO AND A.W. McMASTERS

PACIFIC SOUTHWEST
FOREST AND RANGE
EXPERIMENT STATION
BERKELEY - CALIFORNIA

FOREST SERVICE - U. S. DEPARTMENT OF AGRICULTURE

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of the following individuals and groups:

Mr. J. R. Murray, Forest Service instrument specialist, who developed or modified much of the instrumentation.

Dr. M. Feldstein, Laboratory Director of the San Francisco Bay Area Air Pollution Control District, who analyzed all of the bottled gas samples.

Mr. A. B. Everts, U. S. Forest Service (retired), and Mr. Carl C. Wilson, Chief, Forest Fire Research, Pacific Southwest Forest and Range Experiment Station, who expedited the administrative arrangements.

Personnel of the Los Angeles, Richmond, and El Cerrito Fire Departments who made the tests possible in their respective cities.

Personnel of the East Bay Municipal Utility District, especially Mr. William Hartman, Land Maintenance Superintendent, who cooperated in the Briones Burn.

The many personnel of the Pacific Southwest Forest and Range Experiment Station, the United States Naval Radiological Defense Laboratory, the Camp Parks Fire Department, and the Santa Rita Rehabilitation Center who assisted in the conduct of the Camp Parks Burn.

EFFECTS OF MASS FIRES ON PERSONNEL IN SHELTERS

By

A. Broido, Physical Chemist

and

A. W. McMasters, Engineer

Division of Forest Fire Research

The material used in this report was developed under a research contract (Contract No. DCM-SR-59-7) sponsored by the Office of Civil and Defense Mobilization.

Technical Paper No. 50 August 1960

U. S. DEPARTMENT OF AGRICULTURE, FOREST SERVICE

PACIFIC SOUTHWEST FOREST AND RANGE EXPERIMENT STATION

CONTENTS

EFFECTS OF MASS FIRES ON PERSONNEL IN SHELTERS

By
A. Broido, Physical Chemist
and
A. W. McMasters, Engineer
Division of Forest Fire Research

INTRODUCTION

IMPORTANCE OF THE STUDY

In the mass fires resulting from air attack during World War II, many people lost their lives in shelters in fire areas (2, 9). The greatest number of deaths occurred in basements or makeshift shelters. In many cases, positions of the corpses indicated that death came peacefully and unexpectedly. A frequent assumption is that death was due to carbon monoxide poisoning. However, cause of death has also been attributed to such effects as (a) asphyxiation resulting from the depletion of oxygen either through conversion to carbon dioxide or by suction created within the burning area, (b) the effects of inhaling hot blasts of air, and (c) roasting of the shelter occupants as a result of heat transfer into the shelter. The confusion which still exists concerning the sources of hazard is exemplified by the apparent inconsistency between reports of past experiences and present practice in Germany. Although most reports describing the great German fires of World War II list carbon monoxide as the principal cause of death, current shelter plans of the West German Government ignore carbon monoxide and call for sand filters to remove heat from the ventilation air (13).

In the event of a nuclear attack on the United States, current civil defense plans (24) call for the protection of large numbers of our population in shelters. These may range from thick reinforced-concrete blast shelters down to makeshift fallout shelters in individual residences. Since nuclear detonations are expected to produce large area fires (3), it is essential to consider the effects of such fires on people taking shelter within the fire zone. Those in heavy reinforced-concrete shelters located deep underground and with an independent air supply will obviously not be affected by a fire burning overhead. If a makeshift combustible shelter is located in a frame structure, the consequences of ignition of the structure, although unpleasant to contemplate, are equally obvious. However, many situations may be expected in which the shelter itself will survive the effects of the fire, while the shelter occupants will not survive unless proper precautions are taken. Even after such a fire has subsided, the hazard due to toxic gases in smouldering or slow-burning ruins around or over shelters within the burned area may continue for hours. Since the appropriate precautions depend directly upon the effects being protected against, it is important to determine just what type of countermeasures need to be taken and under what conditions.

PAST WORK

Human tolerances of the various effects reputed to have caused deaths in fireproof shelters have been determined in studies of fire fighting, submarine, and manned rocket operations. A summary of the generally accepted levels is presented in appendix A. Not so well established is the nature of the threat to be expected in the fire area. Although a number of designs and types of shelters have been tested for blast and radiological protection, the fuel-free terrain in which these tests have taken place offered no opportunity to study the effects of mass fires over and around the shelters.

Just as the evidence obtained in wartime fires has proved to be too conflicting for unequivocal interpretation, so have data from past experimental fires led to conflicting interpretations. Thus, evidence for carbon monoxide poisoning as a possible explanation comes from a series of "burn-out" tests conducted in an experimental dwelling-room (4). In these tests the production of toxic concentrations varied considerably depending on the supply of air to the fire and its path through the room. A maximum concentration of 13.8 percent carbon monoxide was reached between the sixth and eleventh minutes in one of the fires. On the other hand, attempts to measure carbon monoxide concentrations sufficiently high to produce death have not been successful on large-scale outdoor fires (26).

OBJECTIVE

Under the terms of the Memorandum of Understanding between the Office of Civil and Defense Mobilization and the Pacific Southwest Forest and Range Experiment Station (Contract No. DCM-SR-59-7); dated September 1, 1958, the objectives of this study were to:

1. Determine if critical concentrations of carbon monoxide or toxic gases are present in an area surrounded by fire and in a shelter within such an area.

2. Learn if there is an oxygen deficiency in an area surrounded by fire and in a shelter within such an area.

3. Determine temperatures to be expected within a shelter in a fire area, especially the transmission of heat through ventilation systems or other openings.

4. Determine size of a cleared area necessary to protect personnel (in shelters) when the area is completely surrounded by fire.

SCOPE

The scope of the study was dictated by limited manpower and a very limited budget. Funds allocated for the project did not permit construction of full-scale shelters or large scale fires exclusively for project use. Practically all field testing was accomplished with simulated shelter vents on fires planned for other purposes.

The fires included a series of tests in structures being demolished by fire in several California cities--tests which were undertaken primarily to check out and calibrate instrumentation improvised from a variety of surplus military parts, but which served also to provide much interesting data. Five such fires were instrumented: two in one classroom of the Robert Louis Stevenson Junior High School, being demolished in Los Angeles, 1/ two in buildings which had been turned over to the Richmond Fire Department for destruction in connection with a redevelopment project, and one in an El Cerrito municipal building which was being razed.

Then the East Bay Municipal Utility District made a large-scale burn possible by requesting aid from the Experiment Station in clearing about 100 acres of wooded land for a reservoir site near Orinda, California. To clear the site, trees and brush were bulldozed into windrows for subsequent drying and burning. The fire instrumented for these studies consisted of 11 windrows covering a total of about 9 acres.

Finally, a time extension of the original contract permitted one additional proof test of previous assumptions and conclusions in a large area burn involving a full-scale shelter at Camp Parks, Pleasanton, California. At this site the U. S. Naval Radiological Defense Laboratory had constructed a 100-man underground shelter. For the burn, about 300 tons of fuel were stacked in a 4-acre plot around this shelter, in an arrangement simulating fuel distribution in a densely populated area of single-story dwellings.

1/ This school was offered by the Los Angeles Board of Education to the Los Angeles Fire Department for the purpose of conducting fire tests to answer questions raised as a result of the tragic fire at the Our Lady of the Angels School, Chicago, Illinois on December 1, 1958, in which 95 pupils and teachers died. The official report of those tests, entitled "Operation School Burning," has been published by the National Fire Protection Association, Boston, Mass. (1959).

INSTRUMENTATION

METHODS OF DRAWING SAMPLES

Most of the measurements made during the course of this project can be lumped into two categories: temperature measurements and gas concentration measurements. Vacuum pumps (i.e. vacuum cleaners) were used to draw air first through vents instrumented for temperature measurements, then through a cooling bath to cool the gases before their entry into appropriate gas concentration measuring devices.

On the basis of discussions with Office of Civil and Defense Mobilization engineering personnel, simulated intake vents were made of 4-inch steel pipe 3 feet long, designed to extend 2 feet above grade, and equipped with a protective cap on the inlet end (fig. 1). For the preliminary calibration tests at the Stevenson Junior High School, the cap was removed and replaced by a 10-foot section of 4-inch inside-diameter galvanized sheet steel pipe (fig. 3). Individual tubes were run through the pipe to measurement locations at heights of 2, 6, and 10 feet above the floor. For all of the other experiments, air was drawn directly into the vent itself.

In addition to these stationary vents, a portable vent, or probe (fig. 4), was used in several experiments to check temperatures and gas concentrations which could be expected if a vent were buried under the rubble smoldering after the flames had died down.

TEMPERATURE MEASUREMENTS

Mass fire temperatures.--Although many conflagrations have occurred, the literature reports few actual temperature measurements (1). Measurements made by the National Bureau of Standards on fire tests of 2- and 5-story brick-joisted buildings showed that temperatures as high as 2000° F. were reached in 20 minutes, and 2200° to 2400° F. in 40 minutes. Debris covered by fallen brick walls remained at about 1000° F. for 2 or 3 days (16, p. 522). Besson (1) states that the temperatures reached in mass fires probably will not exceed 1535° C. (2795° F.).

For fire exposure tests of building materials, the National Fire Codes (17, pp. 252-253), recommend a standard temperature-time curve--reaching 1300° F. after 10 minutes and then climbing slowly to a temperature of 1700° F. after one hour. Heat transfer calculations given in appendix B show that such a fire over 3 feet of soil would result in a negligible increase in the temperature of a buried shelter. Although the properties of both soil and concrete vary greatly, in general concrete and wood are at least as good insulators as soil, so heat transfer through underground walls may be ignored as a mechanism for producing casualties to personnel in underground fallout shelters of accepted design. The conduction of heat into the shelter through the walls of the shelter vents is also considered in appendix B. These computations indicate that heat transfer down the vent walls is small in comparison with the heat generated by shelter occupants. Thus, the intake of hot gases through the shelter vents remains the only possible heat transfer mechanism of serious consequence.

Selection of instrumentation.-- To confirm the computations given in appendix B, temperatures of both the vent wall and the inflowing gases were measured. To measure pipe wall temperatures, chromel-alumel thermocouples were chosen because of their ability to record temperatures up to 2500°F. To keep the instrumentation simple, it was decided to mount identical thermocouples in the gas stream flowing through the vents and later to correct the thermocouple readings to true gas temperatures. The corrections can be made by considering the vent-thermocouple system as a large, shielded, aspirated thermocouple.

With the 12-foot stack, temperatures were measured at each of the intake vents. With the 3-foot simulated air intake vents, measurements were made just beneath the cap and at distances of 1, 2, and 3 feet below the cap. At each location, thermocouples were installed in the gas stream and in the pipe wall and led off inside protective piping (fig. 2) to an underground cold junction. Several vents had thermocouples installed at more than one point at the same height to investigate radial asymmetry of the temperature distribution. For example, figure 5 shows schematically the thermocouple locations in the three simulated intake vents used during the Briones Burn.

Gas temperature calculations.--Because of heat transfer among the gas stream, the thermocouple, and the shielding pipe, an aspirating thermocouple does not measure exactly the temperature of the inflowing gas. The thermocouple temperature is influenced by the temperature of the pipe walls, the gas flow rate past the couple, the absorption spectrum of the inflowing gas, and the emissivity of the thermocouple. With the system selected, differences between the thermocouple reading and true gas temperature could run as high as 500°F. for gas temperatures around 2000°F.

The true gas temperature was estimated by correcting the thermocouple reading according to the procedure suggested by Fishenden and Saunders (10). Assuming a perfectly transparent gas and negligible heat conduction away from the thermocouple junction, a steady state 2/ is achieved at the thermocouple junction whenever

$$Q_c = Q_r \qquad (1)$$

where Q_c is the convective heat transfer between the gas and the thermocouple and Q_r is the radiant heat transfer between the thermocouple and the pipe wall.

2/ Under conditions of operation, the time constant of the thermocouple system was appreciably less than 1 minute.

Substituting the expression for the convective and radiant heat transfer into equation 1 gives:

$$\alpha_c(t_g - t_c) = \alpha_r(t_c - t_w) \qquad (2)$$

where α_c and α_r are the heat transfer coefficients of convection and radiation respectively and t_g, t_c, and t_w are the temperatures of the gas, thermocouple, and pipe wall. The term $(t_g - t_c)$ is, of course, the correction factor which must be added to the recorded thermocouple temperature to obtain the true gas temperature. Therefore, the problem is to evaluate the expression $\alpha_r (t_c - t_w) / \alpha_c$.

If we assume the convection heat transfer is by forced convection, we can evaluate α_c from the Nusselt number equation for flow around a cylinder oriented perpendicular to a gas stream:

$$\alpha_c = \frac{k}{d} f(R) \qquad (3)$$

where d is the diameter of the thermocouple, k is the thermal conductivity of the gas, and f(R) is a complicated function of the Reynolds number for the gas flowing past the thermocouple. The radiant heat transfer coefficient for a thermocouple which is assumed to be of small size compared to the surrounding enclosure is:

$$\alpha_r = \frac{\sigma e(T_c - T^4_w)}{(T_c - T_w)} \qquad (4)$$

where e is the thermocouple emissivity, T_c and T_w are the absolute values of the thermocouple and wall temperatures, and σ is the Stephan Boltzmann constant.

Combining the last three equations, we obtain:

$$\frac{(t_g - t_c)}{(t_c - t_w)} = \frac{\sigma ed(T^4_c - T^4_w)}{k(T_c - T_w)f(R)} \qquad (5)$$

If T_c and T_w are not grossly different 3/, then

$$T^4_c - T^4_w = 4T^3_m (T_c - T_w) \qquad (6)$$

where T_m represents their mean value $\frac{T_c + T_w}{2}$. Then, introducing N as a complicated function of T_m, k, and R, equation 5 may be rewritten to give:

$$(t_g - t_c) = edN(t_c - t_w) \qquad (7)$$

3/ If T_c and T_w differ by a factor of two, this approximation introduces an error of only about 10% in the estimate of the value for α_r.

Curves of N for various values of t_m and the product Vd (where V is the gas velocity) are given by Fishenden and Saunders for the case of a wire (thermocouple) situated at right angles to the gas stream. In the present study, the gas velocity of the system was measured with an oil manometer connected into the stream. Since d is known, and t_c and t_w are both measured, the correction term may be computed directly from equation (7) if the emissivity is known. On the basis of values given by Fishenden and Saunders, a value of 0.5 was assumed for the emissivity of a chromel-alumel couple. This value may well be in error by as much as 20 percent. Thus, the temperature corrections may also be in error by 20 percent, introducing an error in the true gas temperature ranging up to about 5 percent at a gas temperature of 2000°F.

GAS CONCENTRATION MEASUREMENTS

Continuous recording instrumentation.--Because most fires were to be limited to wood fuels, it was decided to limit gas concentration measurements to oxygen, carbon dioxide, and carbon monoxide. Most of the commercial equipment which would measure a continuous sampling of one or more of the three gases was quite elaborate and rather expensive. Therefore inexpensive instruments were purchased and modified where necessary for connection to recording equipment.

Continuous oxygen measurement was made with a modified Thermco Instrument Corporation Model P-9 Oxygen Analyzer which utilizes the paramagnetic properties of oxygen for the analyses (fig. 6). A Thermco Model P-11, Carbon Dioxide Analyzer, which operates by measuring the thermal conductivity of the inflowing gas, was used in the first calibration test. However, this instrument gives erroneous results in the presence of the fairly large quantities of carbon monoxide found, so its use was discontinued.

Continuous carbon monoxide measurements were made with instruments developed from surplus detectors which had previously been used as warning devices in aircraft. These detectors split the flow of a gas sample through two cells connected by a thermopile. One cell contains activated hopcalite which catalyzes the oxidation of carbon monoxide. The resulting temperature difference between the two cells is a function of the carbon monoxide concentration in the air being sampled.

Each unit was calibrated against a series of carbon monoxide samples whose concentrations had been accurately determined by Dr. Milton Feldstein, Laboratory Director, San Francisco Bay Area Air Pollution Control District. A separate calibration curve was obtained for each unit, although the sensitivity of all units was roughly 100 millivolts for a carbon monoxide concentration of one percent (by volume).

A single carbon monoxide detector unit is shown in figure 7, while figure 8 illustrates the triple unit constructed to permit simultaneous sampling from three vents.

In the Los Angeles tests, gas was drawn into a separate intake located at the 2-foot level of the 12-foot stack and was conducted through a cooling bath to an instrument center located outside the building. In all subsequent burns, gases were drawn directly into the simulated shelter intake vent, through a buried cooling bath, and to a protected control center where the detectors were located.

During the second Los Angeles test, high concentrations of carbon monoxide caused the detector to burn out. Consequently the apparatus was modified to permit closure of the detector whenever carbon monoxide concentrations rose to destructive levels. A later calibration test indicated that the carbon monoxide detector can tolerate concentrations of the gas up to 2 to 3 percent before the soldered connections melt because of excessive heat generated in the cell.

Bottle gas samples.-- During the Los Angeles tests a few gas samples were collected in bottles for subsequent analysis, but the method of taking the samples was poor, and the results of these samples were questionable. To insure that good gas samples would be taken on subsequent tests, an automatic sampling device was constructed (fig. 9). The unit can handle six gas sampling bottles in sequence. Upon signal, the valves of one bottle open, a vacuum pump draws the gas sample into the bottle, the valves are automatically closed, and the unit positions itself to take the next sample.

The bottled samples were submitted to the Bay Area Air Pollution Control District and analyzed by Dr. Feldstein using a Beckman IR-4 Infrared Spectrophotometer with a 10-meter-path-length gas cell. All samples were analyzed for carbon monoxide and carbon dioxide and, in addition, select samples were analyzed for any other major constituents.

TEST FIRES

LOS ANGELES TESTS

The two calibration tests in Los Angeles were conducted on May 23 and 25, 1959, in Room 108 of the Robert Louis Stevenson Junior High School, 725 S. Indiana Street (fig. 10). Fuel for the first fire consisted of 2 x 4 mill ends scattered to a depth of about 2 feet throughout the room (fig. 11) and ignited in one corner. The fire was permitted to burn until, in the opinion of the Los Angeles Fire Department, it was endangering the floor above. It was extinguished after 17 minutes--long before the fuel at the base of the vent (located in the center of the room) could be burned.

For the second test, the room was loaded with lath and pallets in order to obtain a hotter fire (fig. 12). The fuel was ignited at a number of points around the outer edges of the room and allowed to burn for less than 12 minutes before extinguishment was necessary to prevent cave-in of the floor above (fig. 13).

RICHMOND TESTS

The first calibration test in Richmond was conducted on August 5, 1959 on a two-story four-apartment building, measuring 50 x 28 feet, with stucco covered exterior, sheetrock covered interior, oak floors, and scrap lumber to simulate furnishings (fig. 14). The intake vent was located in the center of a 16 x 11-foot living room on the first floor of the fourplex. The building was ignited and permitted to burn to the ground (figs. 15, 16, 17, 18).

The fuel for the second Richmond test conducted on September 29, 1959, consisted of two single-story wood houses, one measuring 50 x 22 feet and the other 24 x 18 feet, about 7 feet apart at their nearest corners (fig. 19). Two vents were used in this fire: one located in the living room of the larger house, the other placed between the two buildings at their point of nearest approach. During this fire the Richmond Fire Department found it necessary to spray considerable quantities of water in order to protect adjacent dwellings. This spraying not only modified the progress and characteristics of the fire but had some detrimental effects upon the instrumentation used and the results obtained.

BRIONES BURN

During the reservoir clearing operation in Briones Canyon, trees and brush on the slopes around the damsite were knocked down by tractors and pushed into windrows for subsequent drying and burning. The study area contained 11 windrows on a total of about 9 acres (figs. 20, 21 and 22). Clearing was started in April 1959, and fuel moisture samples of both heavy and light fuels were taken at intervals throughout the summer to check on completeness of drying.

By mid-September fuel moisture of the small twigs had dropped to 12 percent, that of 8-inch logs to 40 percent and that of 18-inch logs to 50 to 70 percent. On September 16, 1959, an isolated pile 150 x 25 feet, ranging in height from 4 to 12 feet was ignited to check completeness of burning. The lighter fuels burned out completely in less than an hour, leaving the smoldering remains of the heavier logs which, on being bulldozed into a concentrated pile, were slowly consumed to leave a minimum residue.

The main burn was ignited on November 2, 1959. The average moisture content of the heavy fuels at the time of the fire was about 40 percent; for the leaves and small twigs, about 10 percent. Total fuel on the 9-acre site was estimated at 900 tons oven-dry weight.

For this burn, three simulated shelter air intakes were instrumented and installed between the fourth and fifth windrows at the fire site (fig. 23). One vent, vent A, was placed 3 feet inside the upper edge of the fifth windrow; another, vent B, 5 feet outside the upper edge of the fifth windrow; and a third, vent C, midway between the fourth and fifth windrows (about 25 feet from each). The gases drawn into these vents were conducted to a buried instrument box located near the vents. This box contained the gas sampling mechanism and gas detectors for the vents. The instruments in the box were remotely controlled during the fire from a bunker located outside the immediate fire area. This control bunker contained recorders for obtaining temperature, oxygen, and carbon monoxide records.

The piles were ignited in sequence starting with the top windrow at 1:00 p.m. Temperature was 60°F. and relative humidity was 60 percent. The placement of the intake vents was designed to take advantage of uphill drafts anticipated as a result of the fire. Instead, westerly winds, with speeds ranging from 10 to 14 miles per hour and gusts up to 20 miles per hour, blew the flames downslope (fig. 24).

EL CERRITO RUBBLE PROBE TEST

An opportunity to investigate the lingering effects of fire in rubble presented itself when it was learned that the El Cerrito, California, Fire Department planned to use the razing of an old municipal building as a fire training exercise. The building (fig. 25) had been the old firehouse, jail, and police station. The jail section had thick concrete walls and the remainder of the building had stucco- and brick-covered walls. The building was ignited at 9:20 a.m. on March 8, 1960, and permitted to burn freely. (The nearby buildings and telephone and power lines were protected by a water curtain during the peak of the fire.) The second floor walls collapsed about 1 hour after start of the fire, and the brick-covered first floor walls began to collapse shortly thereafter.

After all unstable wall remnants had collapsed and the general area cooled down sufficiently, probing of the rubble piles was begun. Measurements were made of temperatures, carbon monoxide concentrations, and oxygen concentrations at various locations within the rubble (fig. 26) at intervals starting about 4 hours after ignition and ending about 22 hours after ignition (7:00 a.m. on the 9th), when earth-moving equipment was brought in to complete the demolition.

To permit experimental verification of the conclusions of a shelter design study, the U. S. Naval Radiological Defense Laboratory (NRDL) constructed a 100-man prototype underground shelter at Camp Parks, Pleasanton, California (21). Since the shelter design included a "fire storm" protection capability, a cooperative program was undertaken.

The very limited budgets of the two participating groups precluded the installation of extensive instrumentation. However, the availability of a considerable quantity of scrap lumber, some manpower to relocate the fuel and assist in the installation of instrumentation, and a competent fire department to provide necessary protection permitted the conduct of a minimum experiment. Additional support was offered by the Defense Atomic Support Agency (DASA), which authorized the release of certain instrumentation available at NRDL, and by the U. S. Army Electronic Proving Ground, Fort Huachuca, Arizona, which made available a 3-man team to assist in the meteorological measurements for a 4-day period at the time of the burn.

The original fire plans called for the burning of about 500 tons of assorted scrap lumber and poles distributed over a 4-acre area around the shelter. For a variety of reasons, the final fuel loading was only about half that planned--the biggest deficit occurring in the heavy, long burning fuels (poles and railroad ties). The wood was distributed to simulate fuel distribution in a densely populated area (about 30 percent density) of single-story dwellings. The fuel was placed in piles measuring 20 x 15 feet, 7 feet high, and spaced 12 feet apart along 3 concentric rectangles with 50-foot spacing between rectangles (figs. 27, 28). The three piles nearest the shelter entrance were increased to a height of 9 feet by including randomly throughout each pile an additional 2 feet of non-combustible rubble--pieces of concrete, brick, and gypsum board.

Limited instrumentation was installed in the entranceway (fig. 29) and main room of the shelter. However, the principal measurements were made from three simulated air intake vents located near the shelter entrance--vent A in a rubble-free wood pile, vent C in a pile containing rubble, and vent B midway between the other two (fig. 30). As with the Briones Burn, gases were led to a buried instrument box and controls to a shielded control bunker outside the fire area.

The piles were ignited by a series of six ignition circuits--two in each of the concentric rectangles. In order to insure nearly simultaneous burning of all three "rings" even if both ignition circuits in any one ring failed, about 2000 gallons of used crankcase oil were sprayed on the fuel piles. Experienced forest fire fighting personnel stood by with lighted drip torches to assist in the ignition if needed.

The innermost ignition circuit was closed at 6:41 a.m. on April 15, 1960. The successive circuits were closed at 30-second intervals, and all functioned perfectly. The weather at the time of the fire, together with the radiation and pressure measurements made during the fire, are presented in appendix C.

The fire grew rapidly after ignition of the outermost "ring." By 6:45 strong indrafts from all sides were blowing the flames toward the center of the fire, with flames 50 feet high visible through the dense black smoke. By 6:47 the smoke began to clear, and within another minute or two there was a noticeable reduction in fire intensity. By 6:51, 10 minutes after the first ignition, the merging flames had separated into a group of individually burning fires. Within another 10 minutes some of the piles had been reduced to a bed of glowing coals and stopped flaming. An hour after the start, one could enter the fire area if he avoided still-burning or smoldering fuels. The progress of the fire is depicted in figures 31-37.

RESULTS

LOS ANGELES TESTS

Data from the successful measurements of gas concentration and temperature for the two tests in the Stevenson Junior High classroom are presented in figure 38. As stated previously, the Thermco Carbon Dioxide Analyzer gave erroneous results because of the high carbon monoxide concentrations, and the bottled gas samples gave questionable results because of the poor sampling method and long storage before analysis.

For each test, the upper part of figure 38 presents the measurements obtained from the oxygen and carbon monoxide analyzers, corrected for the time constants of the instruments (about 1 minute). In the lower part of figure 38, two sets of temperature curves are presented for each of the three elevations--one representing the gas temperature as measured by a thermocouple shielded from a direct view of the flames by the ceramic elbow (thermocouples 1 and 2, fig. 3), the other representing the erroneous value obtained by a thermocouple (TC-3, fig. 3), which is heated by direct radiation from the flame.

It may be seen from figure 38 that the slower burning fire obtained in test no. 1 gave conditions much less severe than those in test no. 2. During the first test, the oxygen concentration never fell to a dangerous level and the carbon monoxide concentration reached only 0.35 percent (a dangerous level but much below that found in test no. 2). Since the fire was extinguished before the fuel at the base of the vent could be burned, temperatures were much higher at the ceiling than they were at the lower air intakes.

During the second test, the carbon monoxide concentration reached lethal levels within 5 minutes, and reached levels sufficiently high to burn out the carbon monoxide detector within 9 minutes (it is estimated that concentrations exceeded 3 percent). By the time the fire was extinguished, the oxygen concentration had dropped to critical levels for human survival. Again in this test the temperatures reached their highest levels at the 10-foot intake. On the basis of the National Fire Codes standard temperature-time curve, the recorders were set for a full scale reading of 1800°F. This temperature was exceeded within 8 minutes of start of ignition. 4/

RICHMOND TESTS

The recorded data obtained during Richmond test no. 1 are presented in figure 39 (temperatures) and figure 40 (carbon monoxide concentration). The most important temperature observations are the following: (1) the hottest measured temperatures occurred after the second story collapsed around the vent (at about 40 minutes), (2) gas temperatures exceeding 2500°F. were found for short periods, and (3) under some circumstances, relatively cool air entering the vent was heated to high temperatures as a result of heating of the vent walls by radiation from the fire. (Heat transfer from the vent walls to the air stream is by convection to the air and by radiation to the entrained smoke particles.)

Lethal concentration of carbon monoxide were reached as the building began to collapse, the highest concentrations occurring as the roaring fire began to die down and the building was reduced to a pile of rubble. To protect the instrumentation, the carbon monoxide instruments were switched out of the gas stream when the concentrations exceeded 1.2 percent. The oxygen analyzer was found to be extremely sensitive to fluctuations in line voltage from the power generator, and the resulting oxygen record was uninterpretable.

Results of the spectral analysis of the six gas bottle samples taken during this test are presented in table 1. Of these samples, the first five were taken from the simulated shelter vent, the sixth was taken during probing of the residual rubble. Probing observations were undertaken from 3 to 5 hours after start of the fire. Rubble temperatures were so high (in the presence of a reducing (carbon monoxide) atmosphere) that the probe thermocouples failed almost immediately. Carbon monoxide measurements indicated carbon monoxide concentrations as high as 0.2 to 0.4 percent during this period.

4/ In a series of comparable experiments conducted in Canada (18), G. W. Shorter et al., too, found room temperatures could rapidly exceed those given by the standard time-temperature curve.

Table 1.--Analysis of bottled gas samples taken during Richmond test no. 1

Sample number	Time after start	Carbon monoxide	Carbon dioxide	Methane
	Minutes	Percent	Percent	Percent
1	13	0.048	0.1	10^{-4}
2	19	0.042	0.1	10^{-4}
3	34	1.16	4.0	0.07
4	44	3.2	8.0	0.15
5	113	0.03	0.1	$<10^{-4}$
6	197	0.03	0.1	$<10^{-4}$

The recorded data obtained during Richmond test no. 2 are presented in figure 41 (temperatures) and figure 42 (oxygen and carbon monoxide concentrations). Unfortunately, the temperature recording circuit for the vent between the houses failed shortly after the start of the fire and remained inoperable for about 50 minutes. By the time this circuit was reestablished all of the thermocouples in the vent inside the large house had failed. The outside vent circuit failed again at 64 minutes and remained out for a 70-minute period except for a 15-minute interval at some unknown time within that period. A linear interpolation between the beginning and end portions of the curves indicate that the circuit began to function approximately 111 minutes after the fire started, and the appropriate curves in figure 41 have been drawn accordingly.

The oxygen analyzers functioned properly throughout the entire test. As may be seen from figure 42, the oxygen concentration in the outside vent never reached dangerous levels, but that in the inside vent dropped to extremely low values about 20 minutes after the start of the fire. At about the same time, the inside carbon monoxide detector failed--apparently due to clogging by plaster dust. Subsequent carbon monoxide measurements were obtained by switching the outside detector alternately between the two vents. No satisfactory bottled gas samples were obtained during this test because the vacuum pump failed.

BRIONES BURN

The temperature data for the Briones Burn are given in figure 43 (vent A), figure 44 (vent B), and figure 45 (vent C).

As might be expected, the highest temperatures were obtained at vent A, much cooler temperatures at vent B, and coolest temperatures at vent C. However, the wall temperatures at 1 foot below ground level were approximately the same for all three vents.

The results of the continuous gas concentration measurements are given in figure 46. The curves have been corrected for the slow response time of the instruments. At vent A, the carbon monoxide reading rapidly went off scale, and the detector burned out before precautionary measures could be taken. The oxygen concentration dropped to practically zero(<2 percent) at about 8 minutes. At vent B, carbon monoxide concentrations gave off-scale readings within 5 minutes of ignition time although oxygen (and temperature) conditions were much less severe. The gas concentrations at vent C never reached toxic levels, but carbon monoxide concentrations sufficient to cause mild headaches lingered for several hours.

Results of the spectral analyses of the gas bottle samples taken during this burn are presented in table 2. Unfortunately no samples were taken during the first 10 minutes, when gas concentrations were most severe. However, the samples do show that even in a fast-burning, rubble-free fire such as this, serious carbon dioxide and severe carbon monoxide effects can be found as late as an hour and a half after ignition.

Table 2.--Analysis of bottled gas samples taken during the Briones burn

Time after start, minutes	Vent	Carbon monoxide	Carbon dioxide	Methane
		Percent	Percent	Percent
12	C	0.02	0.40	--
13	A	.08	5.40	.0004
17	B	.03	2.25	.0002
21	C	.016	0.80	--
30	A	.04	5.60	--
31	B	.06	0.40	--
33	C	--	.21	--
34	A	.04	5.60	--
46	A	.13	3.50	.0002
85	C	.02	0.40	--
87	A	.16	5.80	.0008
88	B	.02	0.80	.0001
97	C	.008	.40	--
156	C	.016	.40	--
158	A	.04	.35	.0004

EL CERRITO RUBBLE PROBE TEST

Although probings into the rubble of the El Cerrito test fire were made at a large number of points, three typical locations were used for repeated probings over long time intervals. These three locations are circled in figure 26, and the data obtained are shown in table 3. During several probings, gas samples were collected for subsequent spectrometric analysis and these results are given in table 4. It may be seen from these tables that almost 24 hours after the start of the fire, temperatures of almost 1900 °F. and carbon monoxide concentrations greater than 1 percent could still be found within the rubble piles.

Table 3.--Representative gas concentrations and temperatures in the El Cerrito Rubble Probe Test

Time after start, hours	Probing number	Carbon monoxide	Oxygen	Temperature
		Percent	Percent	°F.
Location 1: Probe pushed about 4 inches into loose rubble next to brick wall at right of entrance				
4.0	4	.33	--	910
4.3	9	.60	17.9	900
6.0	14	.09	20.3	580
6.7	17	.06	20.0	360
9.7	21	.02	20.8	225
13.2	29	.03	20.8	280
21.3	34	.03	20.7	80
Location 2: Probe pushed about 6 inches into loose rubble under pocket of plasterboard				
4.5	11	.42	16.9	1290
5.9	12	.06	19.8	550
6.7	16	.08	20.0	480
9.7	20	.06	20.8	270
13.2	28	.04	20.8	250
21.3	35	.02	20.8	80
Location 3: Probe pushed about 4 inches into bed of glowing coals in rubble piled about 3' high				
9.9	24	.95	18.3	890
21.6	37	.70	14.9	1890

Table 4.--Analysis of bottled gas samples taken during the El Cerrito rubble probe test

Time after start, hours	Sample number	Carbon monoxide (detector)	Carbon monoxide (bottle)	Carbon dioxide	Remarks
		Percent	Percent	Percent	
1.7	1-1	--	0.40	0.7	Sample taken through window in S.E. corner of building. No flame in room; roof burned through in adjacent garage.
4.3	1-2	.35	0.38	2.8	Underneath hood-like covering of plaster.
9.8	1-3	.25	0.25	3.0	On top of coals under a canopy of plaster-board.
21.2	1-4	1.17	1.2	8.0	Probe pushed in about 4" about 2 ft. up in a 3 ft. pile of rubble.
21.6	1-5	.70	0.73	8.4	Probe pushed about 4" into bed of hot coals.

CAMP PARKS BURN

Temperature measurements.-- Results of the temperature measurements for the Camp Parks Burn are given in figures 47 and 48 (vent A), figure 49 (vent C), figure 50 (vent B) and figure 51 (shelter entrance). The fire in the rubble-free pile built up quite rapidly, and all of the above-grade thermocouples in vent A burned out within the first 10 minutes. In the pile containing rubble, temperatures in vent C rose quite rapidly, but not nearly as high as in vent A, then levelled off at moderately high values until, about 4 hours after ignition, the rubble pile began to collapse about the vent entrance. At this time temperatures again rose rapidly and remained high and irregular for about 2 more hours until the rubble settled to its final depth--below the vent entrance (fig. 37). The rubble remained hot for a long time after measurements were terminated. In fact, 5 days later, when the area was being cleared, freshly exposed fuel in the bulldozed rubble piles again burst into flames.

Some vent wall temperature data were lost from vent C because of failure of the recorder to print out some results on several circuits. At the 2-foot level, the wall temperature was recorded for the first 1-3/4 hours, but after that only two values were printed out--at 280 minutes and at 337 minutes. At grade level the wall circuit did not print for the first hour, but printed almost continuously thereafter. The wall circuit 1 foot below grade apparently opened before the start of the fire and gave no readings whatever. Wherever wall temperatures were not recorded, it was necessary to estimate them in order to apply corrections to the gas temperatures. The estimation was made by a number of different extrapolations, and since the corrections were not very sensitive to the wall temperature used, the additional error from this source in the gas temperature values given is not more than 10 to 20°F.

The relatively low temperatures obtained by thermocouples not actually in one of the fuel piles may be seen in the data for vent B and for the shelter entrance. As may be noted in figure 29, TC-12 was suspended in front of the entrance. TC-1 through TC-4, mounted on the inside of the uninsulated portion of the entrance, reached values of 200° to 300°F. for a short while. The exhaust vent (TC-24) reached a peak temperature of 150°F. No other thermocouple recorded a temperature higher than 100°F., and most of the thermocouples in the entranceway and at other locations throughout the shelter, failed to show any significant increase in temperature as a result of the fire.

Gas concentration measurements.-- Gas concentration measurements at Camp Parks included the following: (1) continuous oxygen measurements at each of the three simulated vents; (2) continuous carbon monoxide measurements at each of the three simulated vents and inside the shelter entrance; and (3) gas bottle sampling from each of the three simulated vents and in the main room of the shelter.

Oxygen results: Oxygen concentrations for vents B and C are shown in figure 52. As may be seen, the oxygen concentration at vent B did not drop significantly at any time. At vent C, the oxygen concentration began to decrease almost immediately (approximately 1 minute after ignition of the inner ring) and dropped almost to zero (less than 2 percent). The oxygen concentration remained at a very low level until the vent began to emerge from the rubble pile as the pile collapsed around it some 3 to 4 hours after the start of the fire.

The oxygen analyzer connected to vent A began to give erratic results before the start of the fire, and the subsequent record is completely uninterpretable.

Continuous carbon monoxide recordings: The unit connected to vent A indicated an off-scale reading (greater than 2 percent carbon monoxide) about 1-1/2 minutes after ignition of the inner "ring," and this unit burned out shortly thereafter. The highest value of carbon monoxide observed in vent B was 0.08 percent about 6 minutes after ignition of the first "ring." Other representative values for this vent are given in the last column of table 5. The carbon monoxide analyzer attached to vent C indicated no reading until about 4 minutes after ignition of the first "ring;" then it rapidly shot off scale. Although the unit was disconnected from the flow system in time to prevent burning out, repeated attempts to obtain an on-scale reading soon filled the instrument with a large volume of liquid, wood-distillation products and no further meaningful data could be obtained with this unit. The carbon monoxide analyzer in the shelter entrance showed no detectable concentration of carbon monoxide entering the shelter (less than 0.02 percent). The unit was subsequently connected to a known source of carbon monoxide to confirm the fact that it was operating properly.

Bottled gas samples: The results of the spectrometric analysis of the bottled gas samples are given in tables 5 and 6. As may be seen in table 6, the carbon monoxide concentration in vent A remained high for only a relatively few minutes-dropping rapidly as the wood pile was consumed. On the other hand, the carbon monoxide concentration entering vent C remained extremely high for 3 or 4 hours--dropping to safe levels only after the rubble pile settled below the level of the vent entrance. The carbon monoxide concentrations observed were 4 or 5 times the concentration sufficient to cause death in 2 or 3 minutes. A representative gas sample from this vent was also subjected to gas chromatographic analysis, with the results given in the footnote to table 6.

Analysis of the gases in the main shelter room showed the highest carbon monoxide concentration observed to be only 0.001 percent before opening the shelter door. After the shelter was opened and several groups of observers had passed through, the concentration rose to 0.02 percent.

In table 5, considerable discrepancy may be noted between the values obtained for vent B by analysis of the gas bottle samples (column 3) and those obtained with the carbon monoxide detector unit (column 5). Subsequent measurements taken inside the buried instrument box showed a very high accumulation of carbon monoxide in this box (no attempt had been made to vent the instrument exhausts outside the box). A linear accumulation with time would give the interpolated values in column 4 for carbon monoxide concentration in the box. It is almost certain that one of the hoses connected to the gas sampler for vent B opened and that the samples were actually drawn from inside the instrument box.

CONCLUSIONS

Within the limitations of this project's rather restricted scope, the results recorded contribute significantly towards the attainment of its listed objectives. The conclusions reached, however,

Table 5.--Carbon monoxide measurements during the Camp Parks Burn

Time after start, minutes	In shelter	Vent B (bottle)	Interpolation for instrument box	Vent B (detector)
	Percent carbon monoxide			
6	--	--	--	.08
8	--	.03	.04	.06
12	< .001	--	--	.04
16	--	.16	.15	.07
19	< .001	--	--	.08
30	--	.44	.35	.05
34	.001	--	--	.04
69	--	.72	.85	.02
122	.02	--	--	.02

Table 6.--Analysis of bottled gas samples taken during the Camp Parks Burn

Time after start, minutes	Vent A		Vent C	
	Carbon monoxide	Carbon dioxide	Carbon monoxide	Carbon dioxide
	Percent			
6	1.5	7.7	--	--
14	--	--	5.8	7.8
18	.11	0.7	--	--
27	--	--	1/ 5.2	1.5
33	.16	.06	--	--
37	.16	.04	--	--
65	.16	.3	--	--
81	--	--	5.0	6.2
90	--	--	7.0	7.7
170	--	--	6.5	8.0
326	--	--	.04	1.5

1/ Other gases identified (by gas chromatography)

Ethane --------------- 1280 ppm
Ethylene ------------- 2280 ppm
Acetylene ------------ 456 ppm
Propane -------------- 254 ppm
Propylene ------------ 920 ppm
C_4 compounds ---------- 528 ppm
C_5 compounds ---------- present but not identified
C_6 compounds ---------- present but not identified

should be tempered by the limitations imposed. Thus, although the experiments conducted during the course of this study were designed to shed some light on what might be expected under conditions of mass fire, it is important to remember that the largest burn conducted in this series was much smaller than the minimum necessary to fall within the definition of a mass fire. The two large burns described in this report covered areas of 9 and 4 acres, respectively, while mass fires require the involvement of at least 640 acres (1 square mile) (23). Also, since a large-scale fire is a highly variable and complex phenomenon, it is difficult to decide how "typical" these fires might be, that is, how often events observed during these fires would be found in other "similar" fires. As a matter of fact, it is necessary to use considerable caution in extrapolating the measurements made during these fires to other locations within the same fires.

However, the same inability to predict with certainty the conditions that will prevail at any time at any point in a future fire necessitates the establishment of "worst-case" conditions, and the development of precautions and countermeasures for such conditions. If a dangerous situation was encountered even once during these experiments, it is safe to assume that it will be encountered again in some future fire and that a feasible attempt to mitigate the consequences should be encouraged.

With the above precautions in mind, the major conclusions which appear from examination of the data obtained during this project may be listed as follows:

1. Extreme carbon monoxide concentrations are to be expected in large-scale fires burning out of doors.

2. Although oxygen depletion and high carbon dioxide concentrations may also occur, their effects will be of consequence only if some steps are taken to eliminate the carbon monoxide hazard.

3. Air temperatures in the fire may be expected to exceed 2000°F, and conventional ventilation systems, if operated during the fire, may be expected to carry into the shelter much more heat than is generated by the shelter occupants.

4. If ventilation systems are to be operated during a fire, shielding of the intake vents from radiant heat should be considered since, under certain circumstances, cool intake gases may actually be heated in passing through the vents.

5. Smoldering rubble will maintain higher temperatures and toxic gas concentrations for longer periods than the more impressive flaming phase of a large fire. In fact, it appears that if shelter vents are located so that they will not be covered by rubble, closure for more than an

hour or two will seldom, if ever, be necessary. Conversely, if the vents are covered by rubble, closure for a period of days may be required.

6. Placing a home shelter vent just outside of a residence may be of little value since high concentrations of toxic gases will sometimes be found in these locations.

7. Although fatal concentrations of carbon monoxide were found 5 feet from the fire--and concentrations sufficiently high to cause headaches were found 25 feet from the nearest fuel--during the Briones Burn, no significant concentrations were found outside of the burning piles during the Camp Parks Burn. What would occur in a much larger fire is impossible to predict, but a good rule to follow would seem to be: where possible, locate a shelter in a cleared area sufficiently large that the shelter will not be covered with rubble, and within that area locate the vent as far as possible from combustible materials.

APPENDIX A

HUMAN TOLERANCE OF VARIOUS FIRE EFFECTS

If the area above an underground shelter is subjected to the fire effects of a nuclear detonation, the intake air entering the shelter vents may be hazardous to the shelter occupants. The major hazards to the shelter occupants include:

(1) oxygen depletion
(2) carbon dioxide
(3) carbon monoxide
(4) heat

While a hazard may exist from certain other toxic gases, e.g. hydrogen sulfide, nitrogen oxides, hydrocyanic acid, and certain hydrocarbon vapors, (8) these gases are found only in special cases and do not have the universal applicability of the hazards listed above.

Factors such as the concentration of the gases and the duration of exposure have a general influence in establishing the consequences of exposure of shelter occupants to these hazards. However, these consequences are also affected by such factors as the individual susceptibility and the degree of physical activity. It is obvious, therefore, that the various sources of data, obtained under different circumstances and for different types of individuals, present conflicting information. Nevertheless, the following sections provide a reasonable indication of the possible consequences of exposure of shelter occupants to the four major hazards.

Oxygen deficiency.--Anoxia (oxygen deficiency) is defined as a lack of sufficient oxygen for the metabolic needs of the body tissues. It can result from a decrease in the oxygen content of inhaled air or from interference with any phase of the uptake, transport, and utilization of oxygen.

Table 7 summarizes information compiled by Sollman (20 p. 700) and indicates the effects of decreased oxygen concentration in the inhaled air.

Carbon dioxide.-- High carbon dioxide concentrations in the intake air are of concern for three reasons: (1) there are direct toxic effects of carbon dioxide itself. (2) Since carbon dioxide acts to stimulate the respiratory center of the brain, its presence in high concentrations may cause an abnormally high intake of other toxic gases. (3) High carbon dioxide concentrations usually occur as a result of combustion and thus frequently are accompanied by a lowered oxygen concentration. The effects of carbon dioxide when no oxygen deficiency occurs in the inhaled air are listed in table 8, which was also prepared from information compiled by Sollman (20, p. 695).

Table 7.--Effects of oxygen deficiency

Oxygen content of inhaled air, percent	Effects
20.9	No effects; normal air.
15	No immediate effect.
10	Dizziness; shortness of breath; deeper and more rapid respiration; quickened pulse, especially on exertion.
7	Stupor sets in.
5	Minimal concentration compatible with life.
2-3	Death within one minute.

Table 8.--Effects of carbon dioxide (oxygen content normal)

Carbon dioxide content of inhaled air, percent	Effects
.04	No effects; normal air.
2.0	Breathing deeper; tidal volume increased 30%.
4.0	Breathing much deeper; rate slightly quickened; considerable discomfort.
4.5 - 5	Breathing extremely labored, almost unbearable for many individuals. Nausea may occur.
7 - 9	Limit of tolerance.
10 -11	Inability to coordinate; unconsciousness in about 10 minutes.
15 -20	Symptoms increase, but probably not fatal in 1 hour.
25 -30	Diminished respiration; fall of blood pressure coma; loss of reflexes; anesthesia. Gradual death after some hours.

Carbon monoxide.--Carbon monoxide combines with hemoglobin in the victim's blood, thus preventing the hemoglobin from transporting oxygen to the body tissues. The affinity of hemoglobin for carbon monoxide is 210 times greater than that for oxygen (22). Thus, the ultimate effect of an excess of carbon monoxide is the same as occurs with an oxygen deficiency.

Claudy (7) presents a table (reproduced here as table 9) describing the physical effects observed in clinical tests when a victim has been exposed to an atmosphere containing carbon monoxide. Presumably the effects described in this table apply to young, healthy fire fighters, who are most quickly affected due to their active metabolism for they absorb the gas faster than do older persons with a lower metabolic activity (8).

Table 9.--Effects of carbon monoxide

Carbon monoxide content of inhaled air, percent	Effects
0.02	Possible mild frontal headache after 2 to 3 hours.
0.04	Frontal headache and nausea after 1 to 2 hours. Occipital (rear of head) headache after 2-1/2 to 3-1/2 hours.
0.08	Headache, dizziness and nausea in 3/4 hour. Collapse and possible unconsciousness in 2 hours.
0.16	Headache, dizziness and nausea in 20 minutes. Collapse, unconsciousness and possible death in 2 hours.
0.32	Headache and dizziness in 5 to 10 minutes, unconsciousness and danger of death in 30 minutes.
0.64	Headache and dizziness in 1 to 2 minutes, unconsciousness and danger of death in 10 to 15 minutes.
1.28	Immediate effect. Unconsciousness and danger of death in 1 to 3 minutes.

Heat.--Buettner (5) in a study of human reactions to heat above the "comfortable range" compiled data from a large number of tests and reports and presented them in an illustration reproduced in figure 53. The figure presents safe exposure times based on the assumptions that wall and air temperature are equal, free convection occurs between the air and the skin, and water condensation on the skin can be neglected.

One other heat effect which has been suggested as contributing to the death of shelter occupants has been the searing of lungs due to inhalation of hot gases. With respect to this possibility, Buettner (6) states that air which is hot enough to cause internal burns due to inhalation would probably have caused lethal external burns much more rapidly. Moritz et al. (15) in studies conducted to determine the effects of inhaled heat observed, ". . . . the quantity of heat that can be stored in the volume of gas that constitutes a breath is remarkably small. At any given air temperature the number of calories that can be transferred to the respiratory tract incident to the inhalation of a breath of hot air is limited by the volume of that breath, whereas in the case of the surface of the body where convection currents are capable of bringing a practically unlimited volume of hot air in contact with the skin, an infinitely greater caloric transfer can occur for each unit of surface area exposed." In one of their tests, (that were conducted on dogs) a source temperature of 932°F. dropped to 122°F. within the trachea of a dog during a period of active and deep breathing.

APPENDIX B

HEAT TRANSFER COMPUTATIONS

Heat flow into a shelter through shelter walls.--Since a principal requirement of shelters in time of nuclear attack is protection against the radiological hazards of fallout, all useful shelters will have considerable mass interposed between the inside and outside of the shelter. For example, for underground shelters, 3 feet of earth cover is required to give essentially complete radiation protection. Such a shield should also provide a more than sufficient barrier to heat flow into the shelter from a fire burning overhead. However, a simple computation was made to confirm this assumption.

For this computation, it was assumed that an underground shelter can be considered a small cavity in a semi-infinite solid. An alternate assumption would be that the shelter served as a complete insulating medium under an infinite slab of thickness corresponding to the burial depth. Actual heat conduction into a shelter would be expected to be intermediate between that computed under these two assumptions, but, under the assumed conditions, the two values do not differ greatly, and it is felt that the semi-infinite solid will more nearly represent the true conditions.

Computations were made for 4 materials: wood (white pine--perpendicular to the grain), concrete (ranging from cinder to 3,000 psi stone concrete), soil (ranging from loose packed clay and silt of normal moisture content, 21 percent, to wet compacted sand, 4 percent moisture content,) and steel (1 percent carbon). The temperature on the outside of the solid, which was originally at 60°F., was assumed to rapidly reach, and be maintained at, 2000°F. For various thicknesses of the 4 materials, computations were made of the time necessary for the temperature of the inside surface to increase 30° to 90°F. The results of these computations, based upon the equation on p. 39 of reference 14 and data from references 21, 27, and 12, are presented in figure 54.

As may be seen, a fire maintaining a temperature of 2000° F. for 2 hours or so would not produce a significant temperature change inside a shelter which affords any reasonable fallout protection. In fact, unless essentially the entire surface of the shelter is covered with hot rubble for periods considerably longer than 24 hours, transfer by conduction through the walls into a shelter covered by 3 feet of earth (or equivalent) may be ignored.

Heat flow through the ventilation system.--The recommended minimum ventilation rate into shelters is 5 cubic feet per minute per person (25). According to Strope, *et al*. (12), the total heat output per shelter occupant is about 400 BTU per hour. For the simulated shelter intake vents used in these experiments the air intake rate was maintained at about 25 cubic feet per minute corresponding to a shelter occupancy of 5 persons. The heat output of the occupants of such a shelter, then, would be 2,000 BTU per hour, and it is of interest to see how heat flow into the shelter through such a system would compare with this internally generated value (Strope already has considered the problem of heat loss to the ground in such a system).

The first question of interest concerns the heat flow down the pipe walls assuming the ventilation system were turned off. As an extreme case, it can be assumed that the above-grade portion of the pipe is maintained at a temperature of 2000°F. and that heat flow is unidimensional down the 3-foot below-grade length of the pipe to a heat sink maintained at 70°F. Using equations and parameter values given by Giedt (11), it may readily be computed that heat flow into the shelter under such circumstances is 285 BTU/hr.--quite small compared with that generated by the shelter occupants. (The same size pipe could, of course, be used with more or fewer occupants.)

The next question concerns the heat carried into the shelter by hot gases if the ventilation system is operating. Again using data from Giedt, it may readily be computed that air entering at 2000°F. would carry into the shelter a net heat of 56,000 BTU/hr.--much more than the heat generated by the shelter occupants.

To shelter occupants, of course, it is immaterial whether the entering air reached its maximum temperature before entering the ventilation system or while moving through the above-grade portion of the vent. Heat losses below grade, or to a filtering system, would have to reduce this heat flow by a factor of 100 or more to keep this method of shelter heating from being limiting.

APPENDIX C

ANCILLARY MEASUREMENTS AT CAMP PARKS

METEOROLOGICAL MEASUREMENTS[5/]

General weather.--During the week of April 11, 1960 a succession of fronts moved across northern and central California. The strongest of these passed through central California the forenoon of April 11. It was associated with a rather strong trough aloft and produced varying amounts of light rain in the area. The last frontal passage before the Camp Parks burn occurred early on April 14. It produced no rain in the Camp Parks area. Behind the front surface, high pressure extended into the Pacific Northwest and set up a pattern favorable for northwesterly winds in the Camp Parks area. A slight trough aloft was associated with this front, and, as it moved to the east, the Camp Parks area was in a region of northwesterly winds aloft also. Wind speeds aloft were quite strong because of the nearness of the jet stream which extended through southwestern Oregon and northeastern California.

Weather forecast.--Weather forecasts for the Camp Parks area were obtained from the Weather Bureau Forecast Center in San Francisco daily for several days before the burn. On April 13 the outlook received indicated fair weather for April 15. The forecast received the forenoon of April 14 again indicated fair weather, with a morning low temperature of 40°F. The forecast received the afternoon of April 14 was similar, and predicted westerly winds of 8 to 15 knots. It appeared then that there would be no stratus in the morning and that the ridge aloft would remain off the coast so that northwesterly winds aloft could be expected.

Weather observations.--Surface observations of wind were recorded at Camp Parks for 10 days before the burn, and temperature and humidity were recorded for 3 days before, in an attempt to detect local weather patterns that would be of help in selecting a suitable ignition time. The wind observations showed mostly light and variable winds during the night hours with some north and northeast winds, apparently due to drainage off the slopes of Mt. Diablo. Shortly after sunrise, the direction would become westerly and would continue through the day. Speeds would increase around mid-afternoon and would remain moderately strong through the afternoon.

The temperature and humidity traces showed nothing but the normal diurnal changes.

Pilot balloon observations were taken hourly on April 13 and 14 from 0600 to 1200 P.s.t. On April 15 runs were made hourly

---

5/ Information furnished by M. J. Schroeder, research meteorologist, U. S. Weather Bureau, on assignment to the Pacific Southwest Forest and Range Experiment Station.

0600 to 0900 P.s.t., and additional runs were made at short intervals during the first part of the fire.

On April 13, because of the presence of a layer of stratus clouds, the first pilot balloon observations were short runs. During the latter portion of the forenoon, after the clouds dissipated, winds were generally westerly to 10,000 feet and speeds were of the order of 6 to 10 m.p.h. up to 6,000 feet and 10 to 15 m.p.h. up to 10,000 feet.

On April 14 winds were generally northwesterly up to 10,000 feet. Speeds were of the order of 10 to 15 m.p.h. in the first 5,000 feet then increased to 20 to 35 m.p.h. in the 5,000 to 10,000-foot layer.

Weather during the morning of April 15.--The radiosonde observation from the Weather Bureau Airport Station at Oakland taken at 0400 P.s.t. (fig. 55) showed that the marine layer was fairly deep. The base of the marine inversion was at 5,000 feet. Although the inversion was not strong, the air masses both below and above the inversion were comparatively stable. Considerable heating would have been required to produce an unstable layer to even 7,000 to 10,000 feet.

The surface winds, temperature, and humidity for the period 0300 to 0900 are shown in figure 56. Surface winds, which became southwesterly shortly after sunrise, were in the process of veering to northwesterly and increasing in speed during the first part of the fire. The temperature had reached a minimum of nearly 40°F. just before 0600 and was climbing rapidly at the time the fire was ignited. The humidity, after reaching a maximum of about 100 percent was falling rapidly at that time.

Winds aloft the morning of April 15 (fig. 57) were northwesterly and much stronger than they had been the previous days. A significant factor which undoubtedly affected fire behavior was the strong increase in the wind speed from the surface through the first 600 feet. This was evident on all pilot balloon runs. Those runs that reached higher elevations also showed a distinct minimum speed in the region of 3,000 to 5,000 feet above sea level. Most runs indicated another maximum in speed of 45 to 55 m.p.h. between 7,000 and 10,000 feet.

Conclusions.--With the limited meteorological program used during this burn, it was not possible to detect any significant effects of the fire on the local weather pattern. In fact it appeared that the weather had almost complete control of the fire. Although the fire produced indrafts near the surface on all sides, any convection column that tried to form, quickly entered the region of strong winds just above the surface and was carried off to the southeast. These strong winds aloft, combined with the stable structure of the lower atmosphere, effectively prevented the formation of a vertical convection column.

RADIATION MEASUREMENTS

Radiation measurements of the Camp Parks Burn were obtained as an aid in describing the progress of the fire. These measurements were limited to available instrumentation, namely, one directional thermopile radiometer and one spherical copper radiometer.

The directional radiometer, described elsewhere (19), was placed about 40 feet above ground in the fire tower adjacent to the Camp Parks fire station. The tower was located 890 feet north of the center of the shelter (700 feet from the nearest side of the outer fuel ring). The radiometer's field of view included all of the fuel piles but two: one at each of the closest two corners of the outer fuel ring. A continuous record was obtained of the radiant energy received from the fire by the radiometer and is presented in figure 58.

Simple integration of the radiation values received by the directional radiometer over a hemisphere of a radius of 890 feet covering the fire area would result in a total considerably lower than the actual radiant energy released by the fire. Since the directional radiometer was set up in a location perpendicular to the wind, the record obtained may represent the average radiation emitted in a horizontal plane around the fire. However, locations above the fire on such a hemisphere would see much more of the radiating area.

The spherical copper radiometer consisted of a 3-inch diameter thin walled copper sphere, coated with lamp black, with a chromel-alumel thermocouple located in the center of the air space inside the ball. The ball was mounted eleven feet above the top of the shelter berm on the top of the antenna mast connected to the exhaust vent of the shelter. A continuous record of the temperature of the air space inside the blackened ball was obtained during the fire and is presented in figure 59.

A comparison of figures 58 and 59 indicates that the average time of maximum radiant energy emitted by the fire was about 7 minutes after the ignition of the inner ring of fuel. The temperature of the spherical copper radiometer reached a peak value 6 minutes after ignition of the inner ring. Since this instrument was located in such a position that it would receive more energy from the inner ring than from either of the other two rings, this time to peak probably corresponds to the "peak" time of the inner ring. The directional radiometer record peaked at 8 minutes after ignition of the inner ring, or 6 minutes after the ignition of the outer ring. This result may be expected since this radiometer was positioned so as to receive more radiation from the outer ring than from either of the other rings. The dense smoke caused by the burning of the oil sprayed on the fuel piles also prevented this radiometer from seeing the inner two rings until some 9 minutes after the initial ignition.

It may be concluded that the radiant energy emitted by each fuel ring rapidly increased after ignition to a "peak" at 6 minutes after the ring was ignited and then dropped off slowly. The average peak radiation of the fire probably occurred at 7 minutes after initial ignition.

PRESSURE MEASUREMENTS

In attempting to answer questions concerning the fire behavior, the pressure fluctuations within a fire area are of interest. Also, questions have been raised concerning possible oxygen depletion in an underground shelter caused by a severe drop in the atmospheric pressure within a fire area.

Only one pressure measurement was made during the Camp Parks Burn. A Friez microbarograph was placed in the main room of the shelter and a continuous record of the atmospheric pressure was obtained. A copy of this record, magnified 40 fold on the pressure scale, is presented in figure 60.

Although the trace was difficult to read with any great degree of accuracy, figure 60 does indicate that a slight but definite pressure decrease, sharper than the routine fluctuations in the trace, occurred about 8 minutes after ignition of the inner ring of fuel. Comparison with the other curves obtained from this fire leads to the conclusion that a decrease in atmospheric pressure occurred at the time of the "peak" of the fire.

LITERATURE CITED

1. Besson, J., and Fackler, J. P.
   1951. Fire-belt spaces in metropolitan areas. Tech. Ref. Anal. Br., Engin. Res. Dev. Labs. Rpt. USA ERD CE 8-76-04-214. 28 pp., illus.

2. Bond, Horatio
   1946. Fire and the air war. Nat'l Fire Protect. Assoc. Boston. 262 pp., illus.

3. Broido, A., and Trilling, C.
   1955. Thermal vulnerability of military installations. U.S. Nav. Rad. Defense Lab. Rpt. USNRDL-TR-101. 91 pp., illus.

4. Bruce, H. D.
   1953. Experimental dwelling-room fires. U. S. Forest Serv. Forest Prod. Lab. Rpt. No. D1941. 22 pp., illus.

5. Buettner, K.
   1957. Heat transfer and safe exposure time for man in extreme thermal environment. ASME Paper No. 57-SA-20. (Abstract in symposium, Man and His Thermal Environment.) Mech. Engin. 79(11): 1029-1035.

6. Buettner, K.
   1959. Personal communication.

7. Claudy, W. D.
   1954. Carbon monoxide in fire fighting. Nat'l. Fire Protect. Assoc. Rpt. No. F21-1. 11 pp.

8. Committee on Fire Gas Research.
   1952. Fire gas research report. Nat'l. Fire Protect. Assoc. Quart. 45(3): 280-306, illus.

9. Earp, Kathleen F.
   1953. Deaths from fire in large scale air attack-with special reference to the Hamburg fire storm. Home Office Rpt. CD/SA-28. Scientific Advisory Branch, Whitehall, S.W.1. 30 pp.

10. Fishenden, M., and Saunders, O. A.
    1939. The errors in gas temperature measurement and their calculations. J. Inst. Fuel. (London). 12(6): S 5 - S 15, illus.

11. Giedt, W. H.
    1957. Principles of engineering heat transfer. D. Van Nostrand Co. Inc. New Jersey. 372 pp., illus.

12. Ingersoll, L. R., Zobel, O. J., and Ingersoll, A. C.
1948. Heat conduction. Mcgraw-Hill Book Co. New York. 278 pp., illus.

13. Leutz, Herrmann
1960. Results of tests on continuously occupied shelters. Presented at the National Academy of Sciences-National Research Council meeting on Environmental Engineering in Protective Shelters (February 8-10, 1960)

14. McAdams, W. H.
1954. Heat transmission. McGraw-Hill Book Co., New York. 532 pp., illus.

15. Moritz, A. R., Henriques, F. C., and McLean R.
1945. The effects of inhaled heat on the air passages and lungs. Amer. Jour. Path. 21: 311-356, illus.

16. Moulton, R. S.
1954. Crosby-Fiske-Forster handbook of fire protection. 11th ed. Nat'l. Fire Protect. Assoc. Boston. 1560 pp., illus.

17. National Fire Protection Assoc.
National Fire Codes. Boston. Vol. 3, 769 pp., illus.

18. Shorter, G. W., McGuire, J. H., Hutcheon, N. B., and Legget, R. F.
1960. The St. Lawrence burns. Nat'l. Fire Protect. Assoc. Quart. 53(4): 300-316, illus.

19. Snyder, N. W., Gier, J. R., and Dunkle, R. V.
1955. Total normal emissivity measurements on aircraft materials between 100 and 800°F. Trans. Amer. Soc. Mech. Engin. 77: 1011-1019.

20. Sollman, T.
1948. Systematic action of gases. A manual of pharmacology. 7th ed. W. B. Saunders Co. Philadelphia. pp. 693-711.

21. Strope, W. E., Porteous, L. G., and Greig, A. L.
1959. Specifications and costs of a standardized series of fallout shelters. U.S. Nav. Rad. Def. Lab. Rpt. USNRDL-TR-366. 129 pp., illus.

22. U. S. Department of the Navy
1956. Submarine medicine practice. Bur. Med. and Surg. NAVMED-P5054. 357 pp., illus.

23. U. S. Federal Civil Defense Administration
1953. Civil defense urban analysis. Fed. Civ. Def. Admin. Tech. Manual TM-8-1. 85 pp., illus.

24. U. S. Office of Civil and Defense Mobilization.
1958. The national plan for civil defense and defense mobilization. Annex 10. National shelter plan. 7 pp.

25. U. S. Office of Civil and Defense Mobilization.
1958. Family shelters for protection against radioactive fallout. Off. Civ. Def. Mobil. Tech. Bul. TB-5-3. 8 pp., illus.

26. Vehrencamp, John E.
1955. An investigation of fire behavior in a natural environment. Univ. of Calif. (Los Angeles) Dept. of Engin. Rpt. No. 55-50. (Oper. Firestop Tech. Rpt. No. 1) 85 pp., illus.

27. Washburn, E. W.
1927. International critical tables. V. 2. McGraw-Hill Book Co., New York. 616 pp., illus.

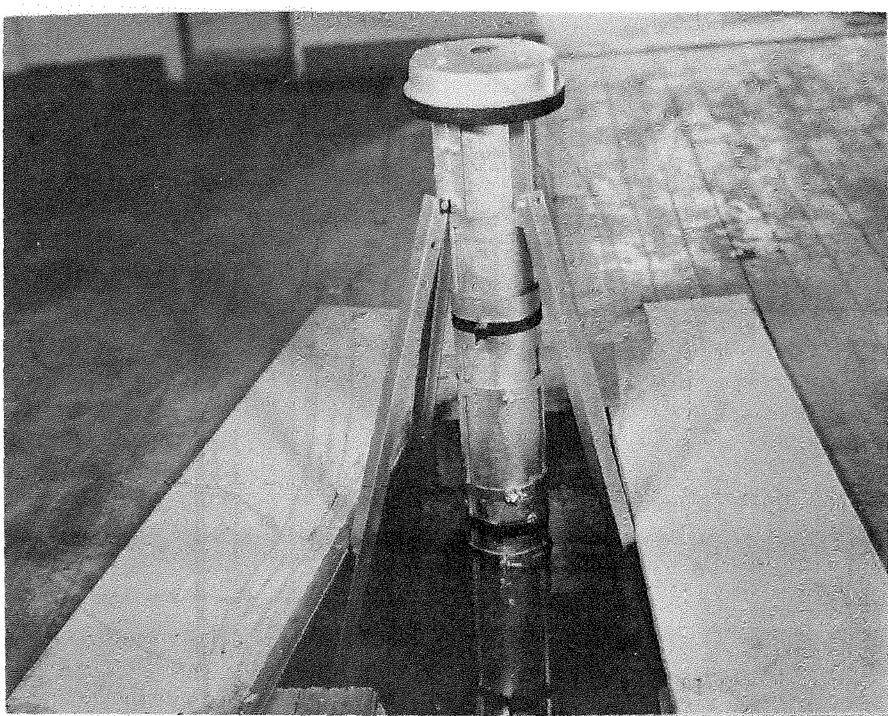


Figure 1.--Simulated air intake vent made of 4-inch steel pipe.

Figure 2.--Simulated air intake vent installation showing protective piping for leading off thermocouple wires.

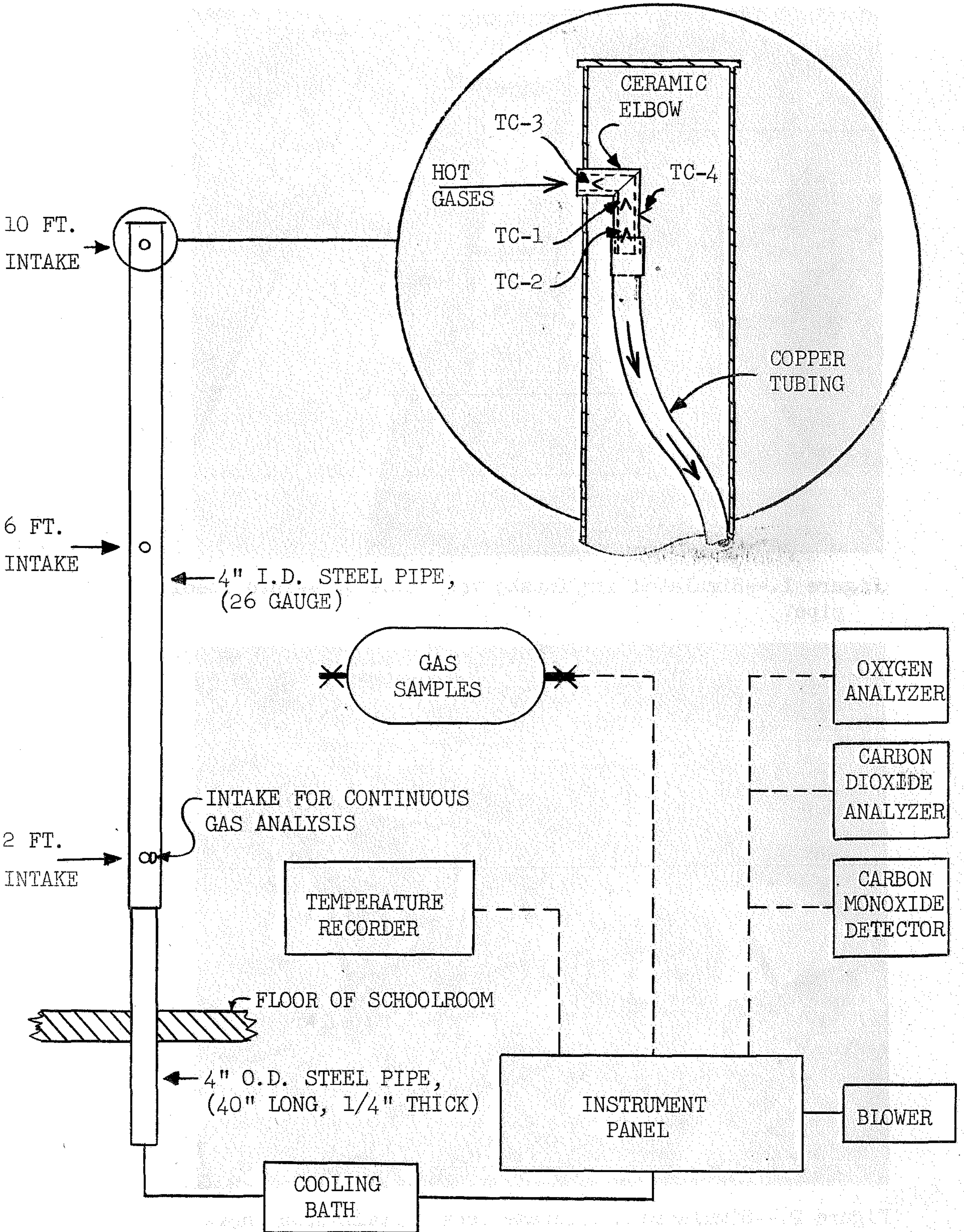


Figure 3.--Diagram of vent system for Los Angeles calibration tests.

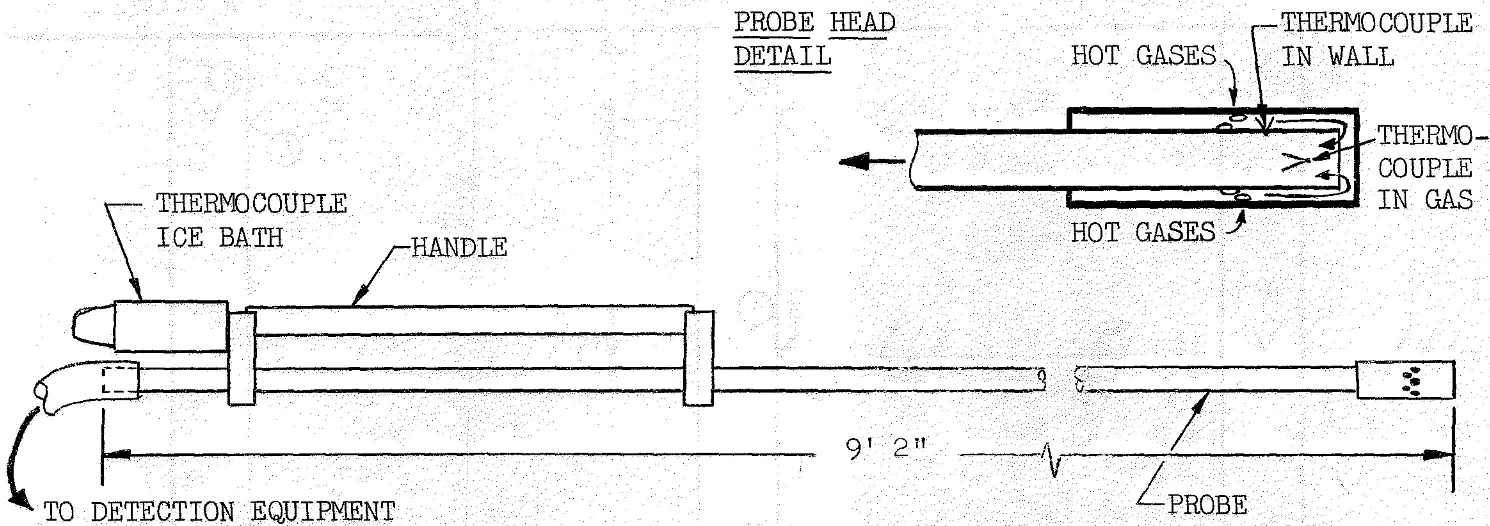


Figure 4.--Sketch of portable vent used for probing rubble.

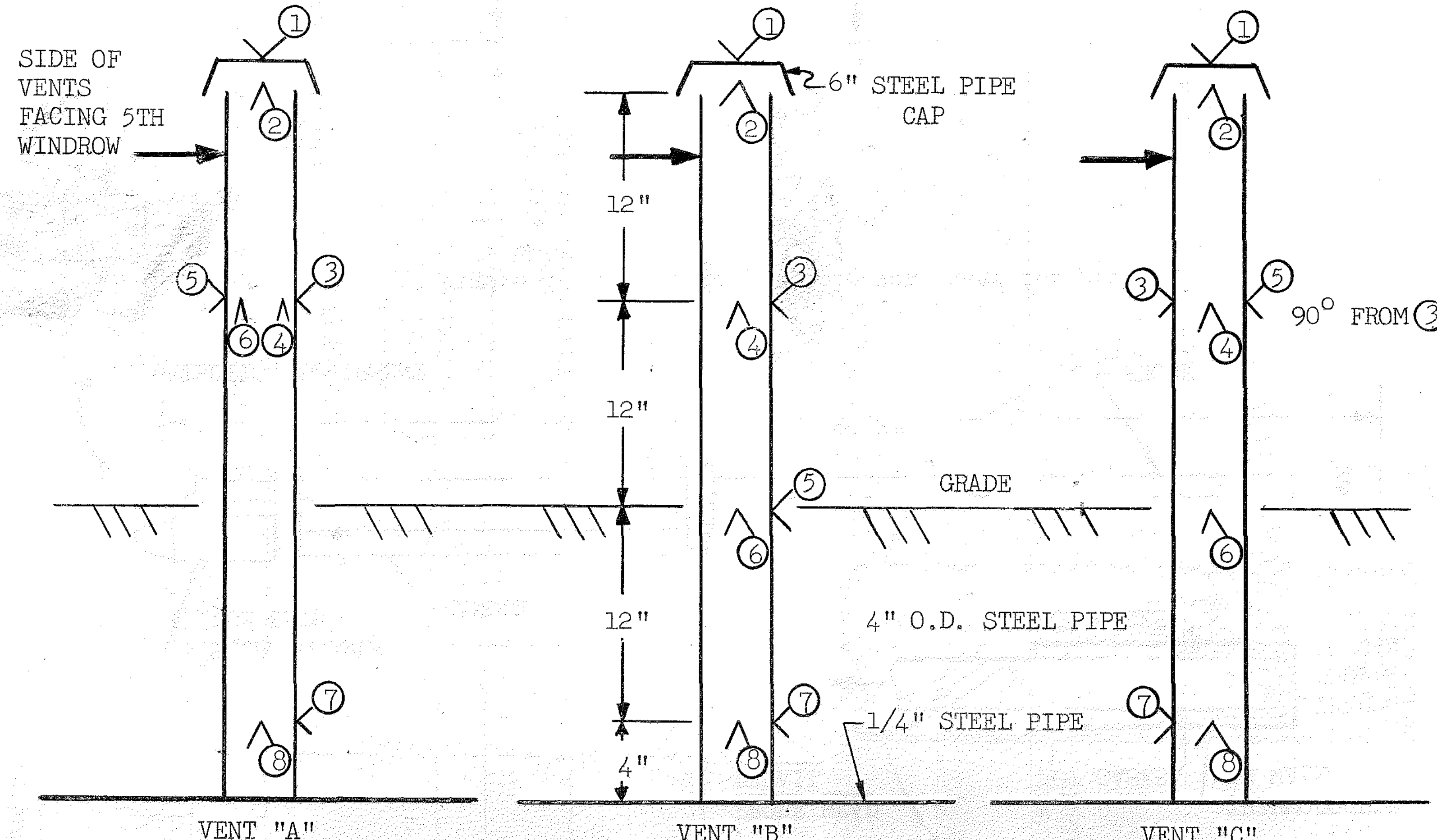


Figure 5.--Thermocouple locations in simulated intake vents for the Briones Burn.

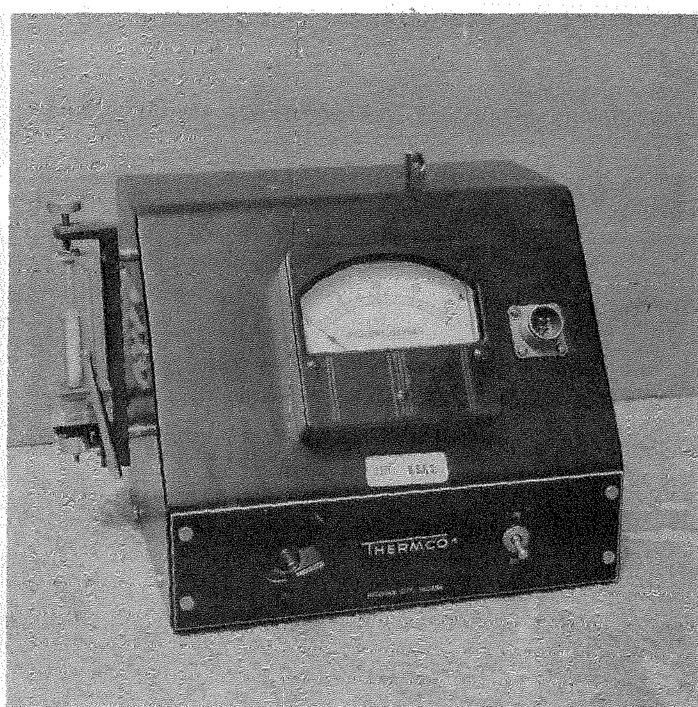


Figure 6.--Oxygen Analyzer Thermco Instrument Corporation Model P-9.

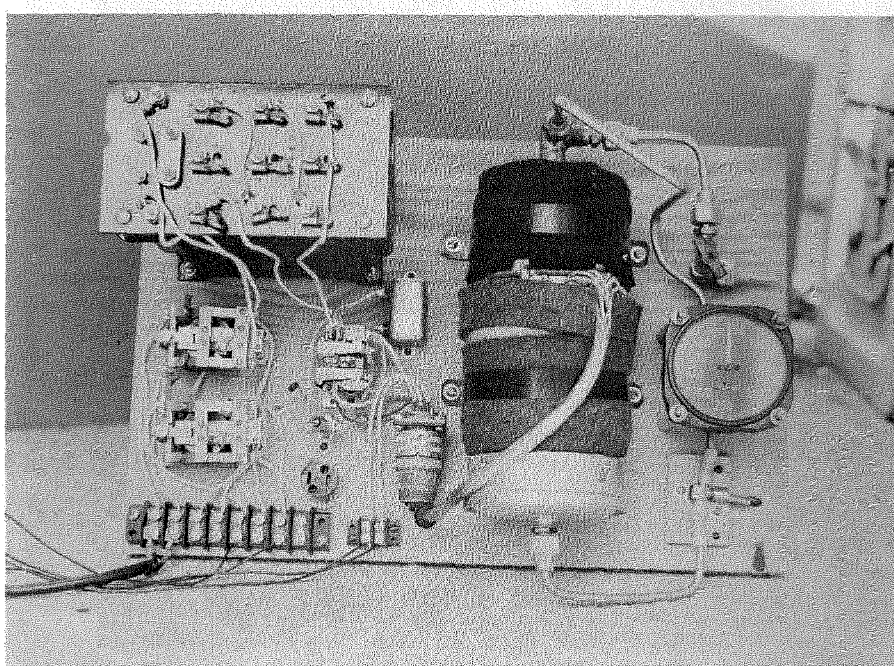


Figure 7.--Carbon Monoxide Detector -- single unit.

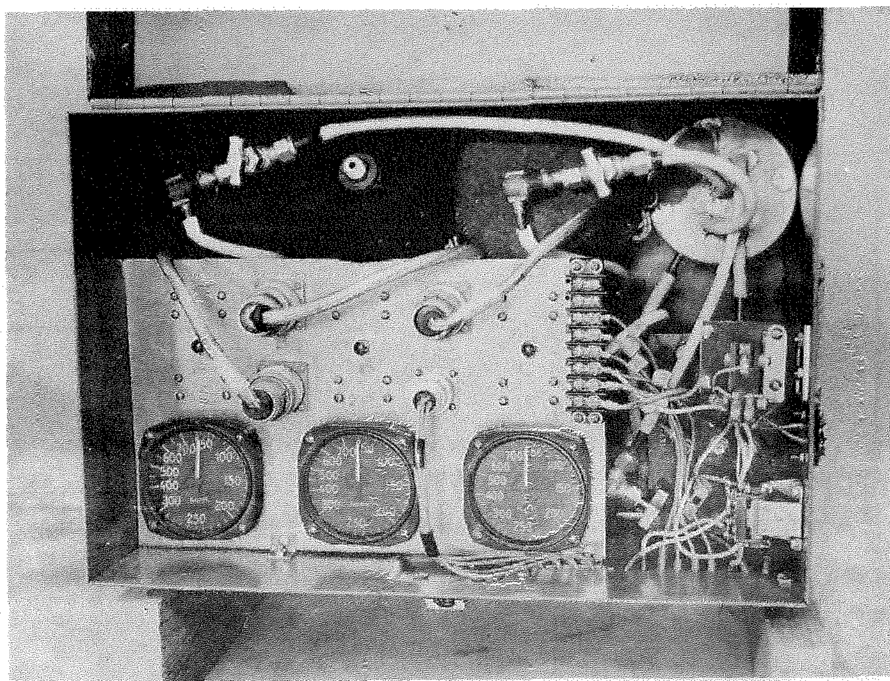


Figure 8.--Carbon Monoxide Detector -- triple unit.

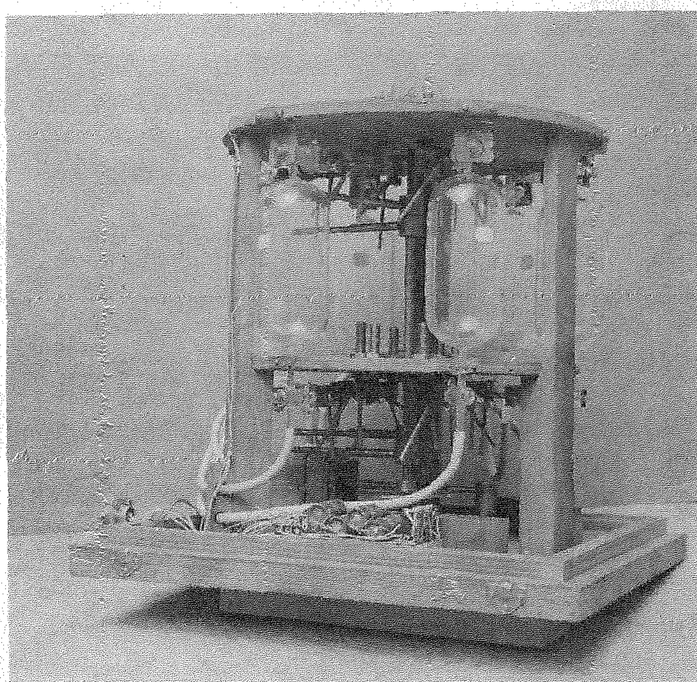


Figure 9.--Automatic gas sampling device with six sample bottles installed.

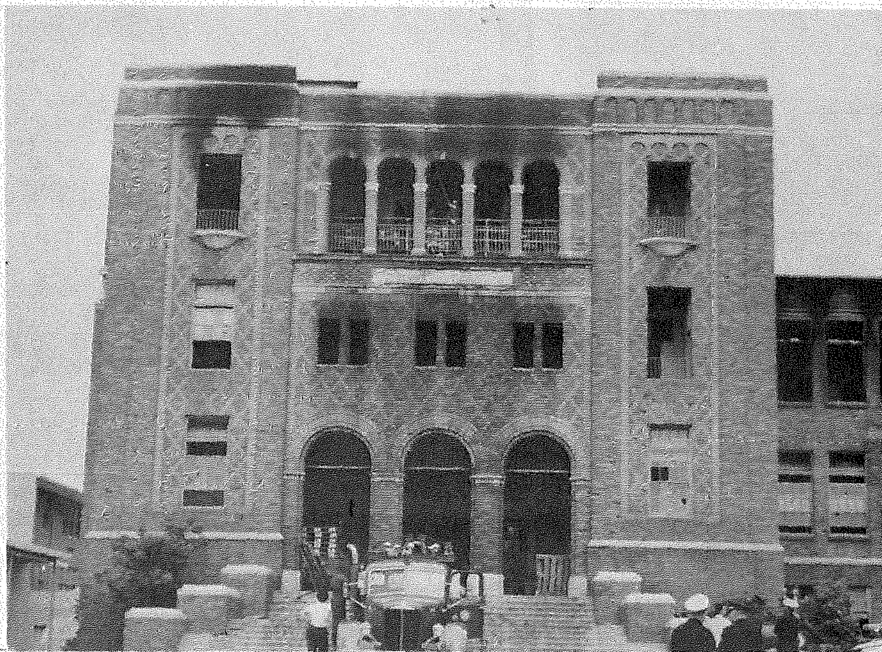


Figure 10.--Robert Louis Stevenson Junior High School, Los Angeles. Room 108, to far right of entrance, was used in these tests.

Figure 11.--Fuel distribution in classroom before Los Angeles Test No. 1.

Figure 12.--Fuel distribution in classroom before Los Angeles Test No. 2.

Figure 13.--Outside view of classroom during Los Angeles Test No. 2.

Figure 14.--Scrap lumber surrounding vent in first floor living room for Richmond Test No. 1.

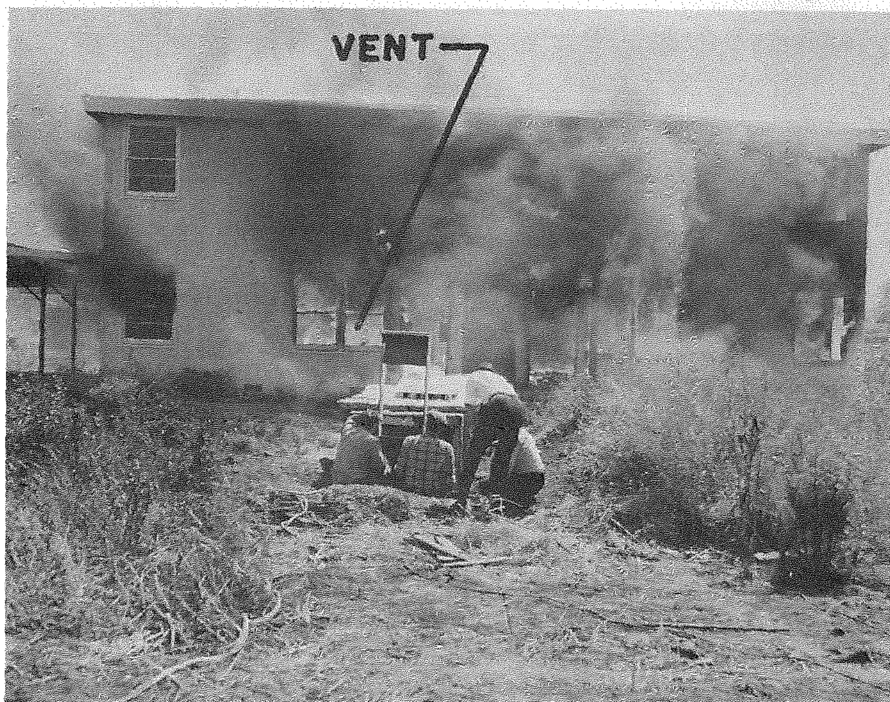


Figure 15.--Outside view of fourplex just after ignition of Richmond Test No. 1.

Figure 16.--Richmond Test No. 1 -- 33 minutes after ignition.

Figure 17.--Richmond Test No. 1-- 45 minutes after ignition.

Figure 18.--Rubble remaining after Richmond Test No. 1.

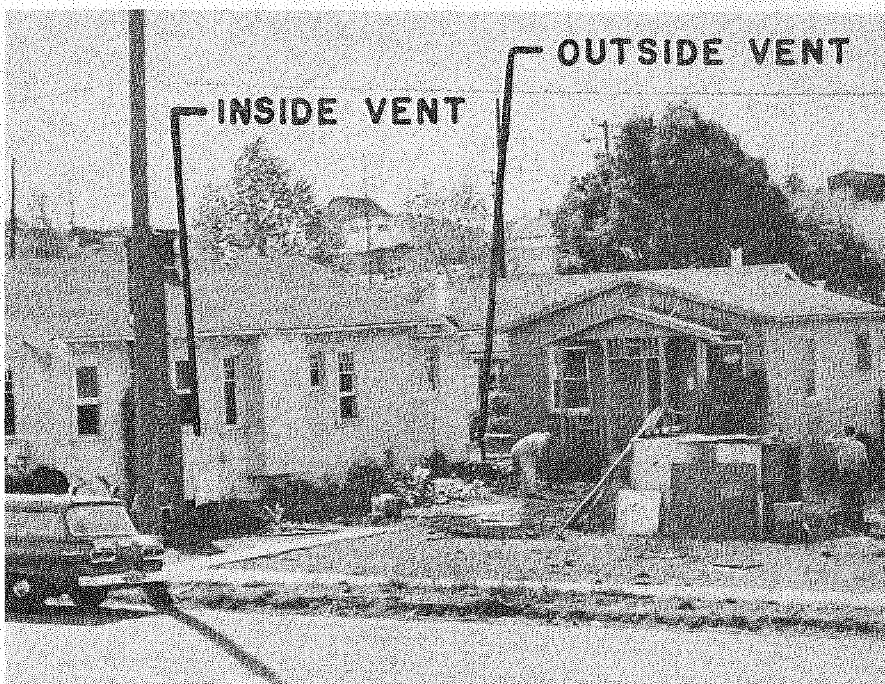


Figure 19.--Two wood houses observed in Richmond Test No. 2. One vent was located in living room of left house, the other outdoors between the two houses.

Figure 20.--Aerial view of the Briones Burn area.

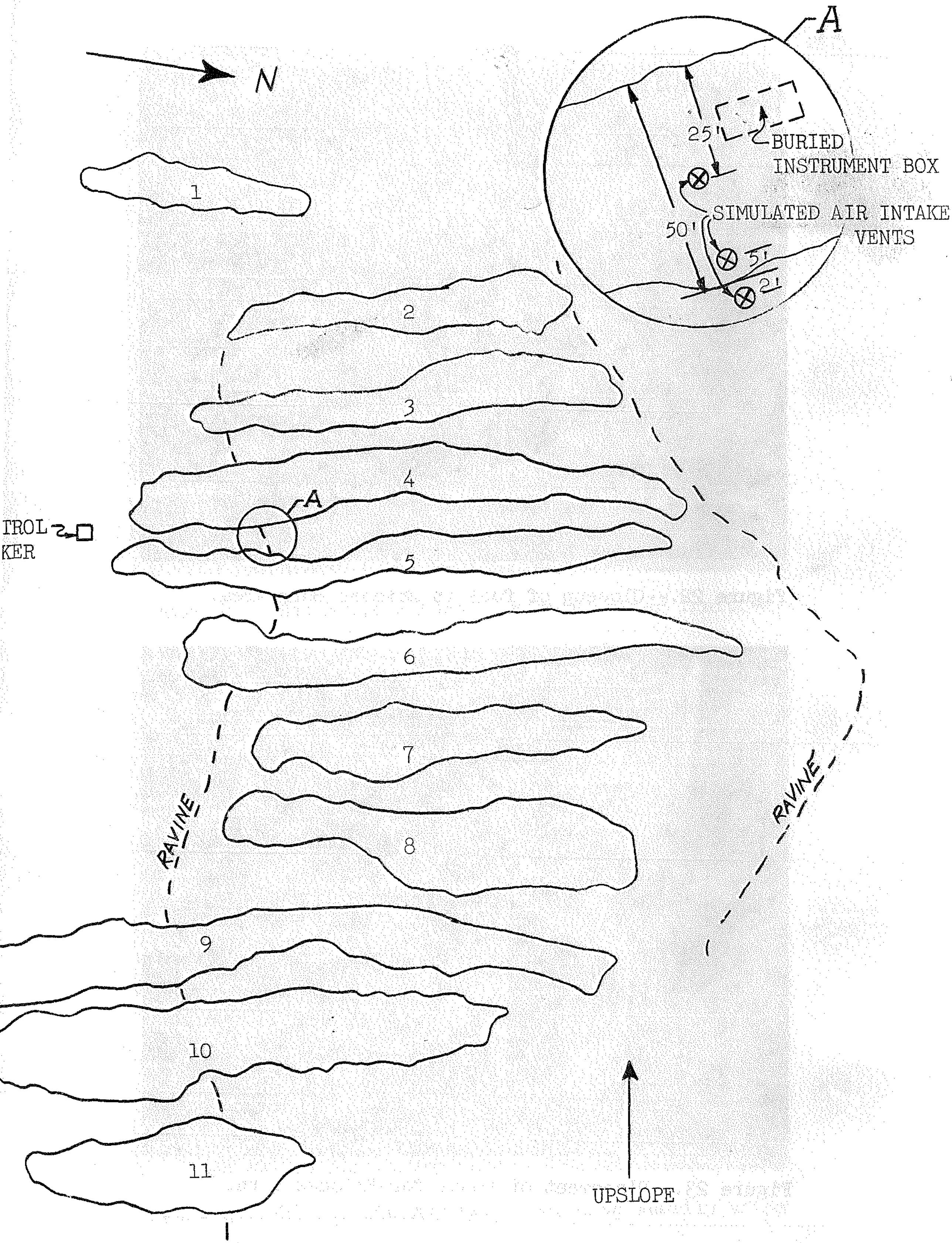


Figure 21.--Sketch of Briones Burn area showing instrument location.

Figure 22.--Closeup of fuel in Briones Burn area.

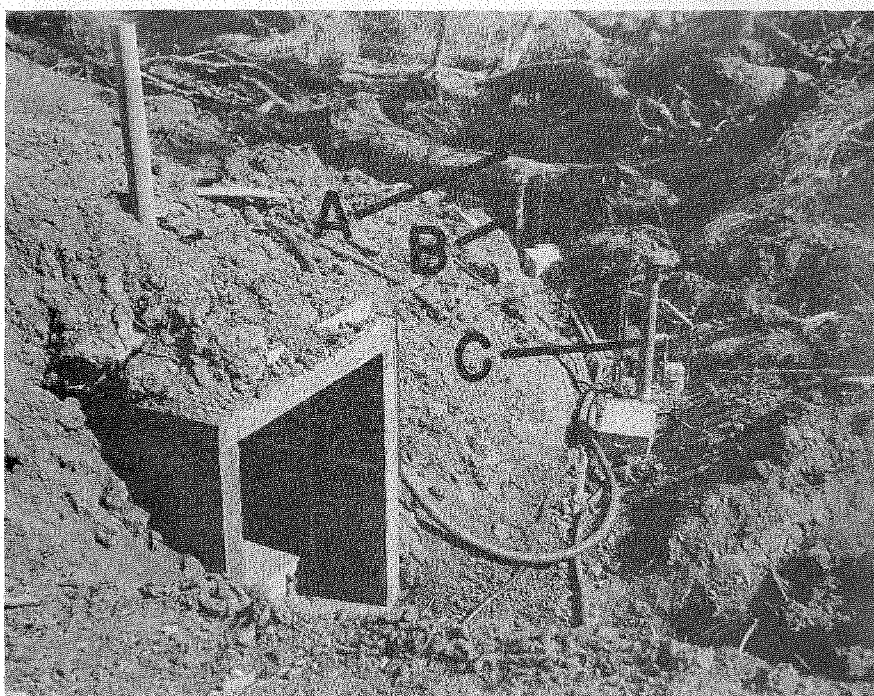


Figure 23.--Placement of vents for Briones Burn.

Figure 24.--The Briones Burn 10 minutes after ignition.

Figure 25.--El Cerrito municipal building shortly after ignition.

Figure 26.--Rubble left after El Cerrito Test showing typical probe locations.

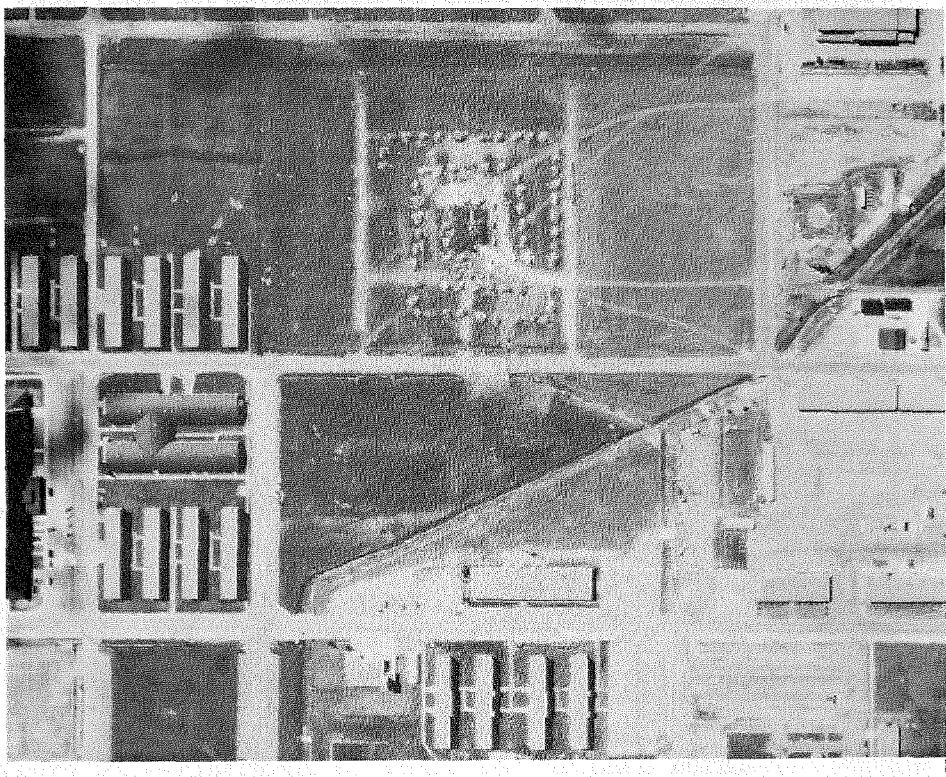


Figure 27.--Aerial view of Camp Parks Burn area.

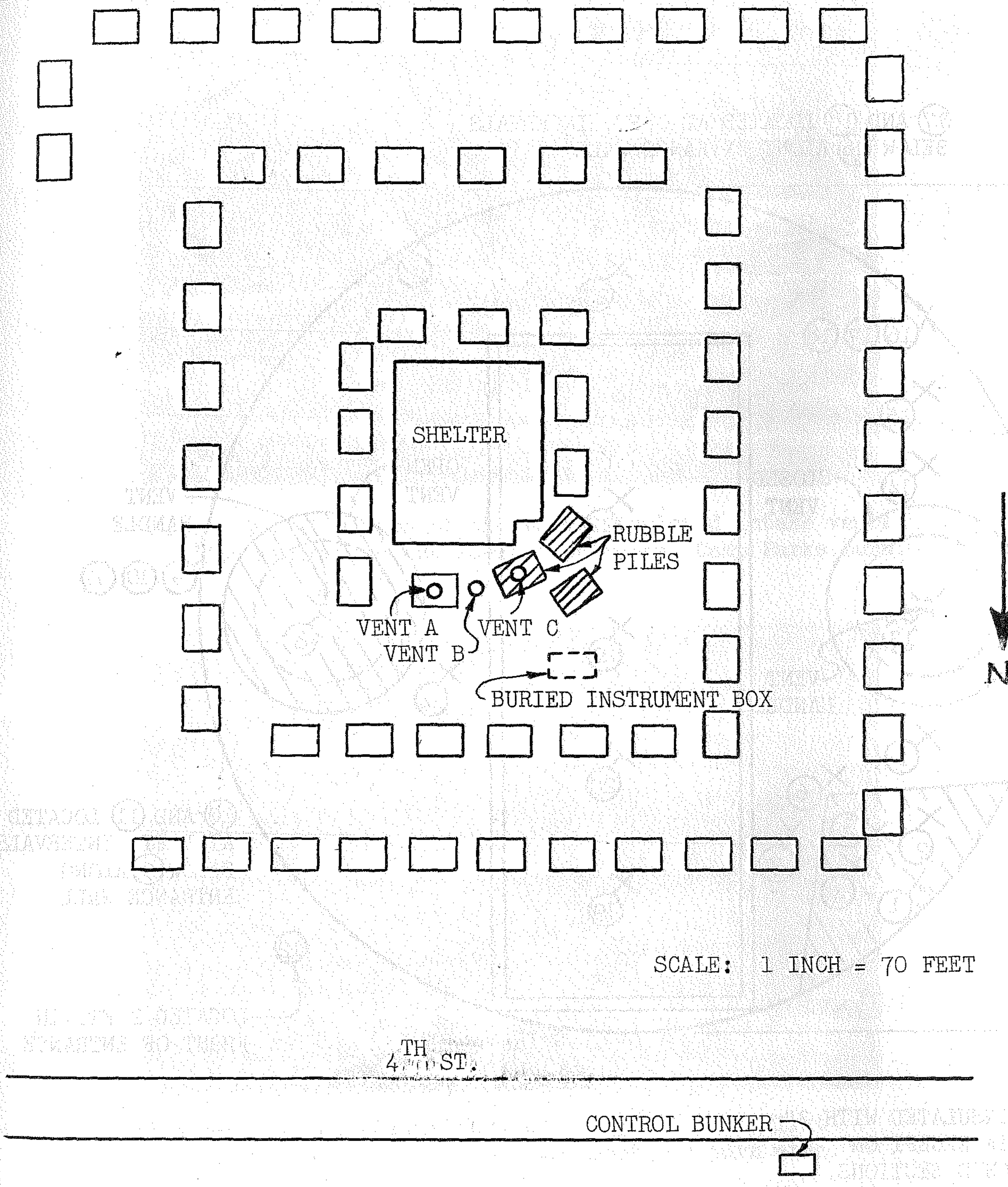


Figure 28.--Schematic of fuel distribution about 100-man shelter at Camp Parks.

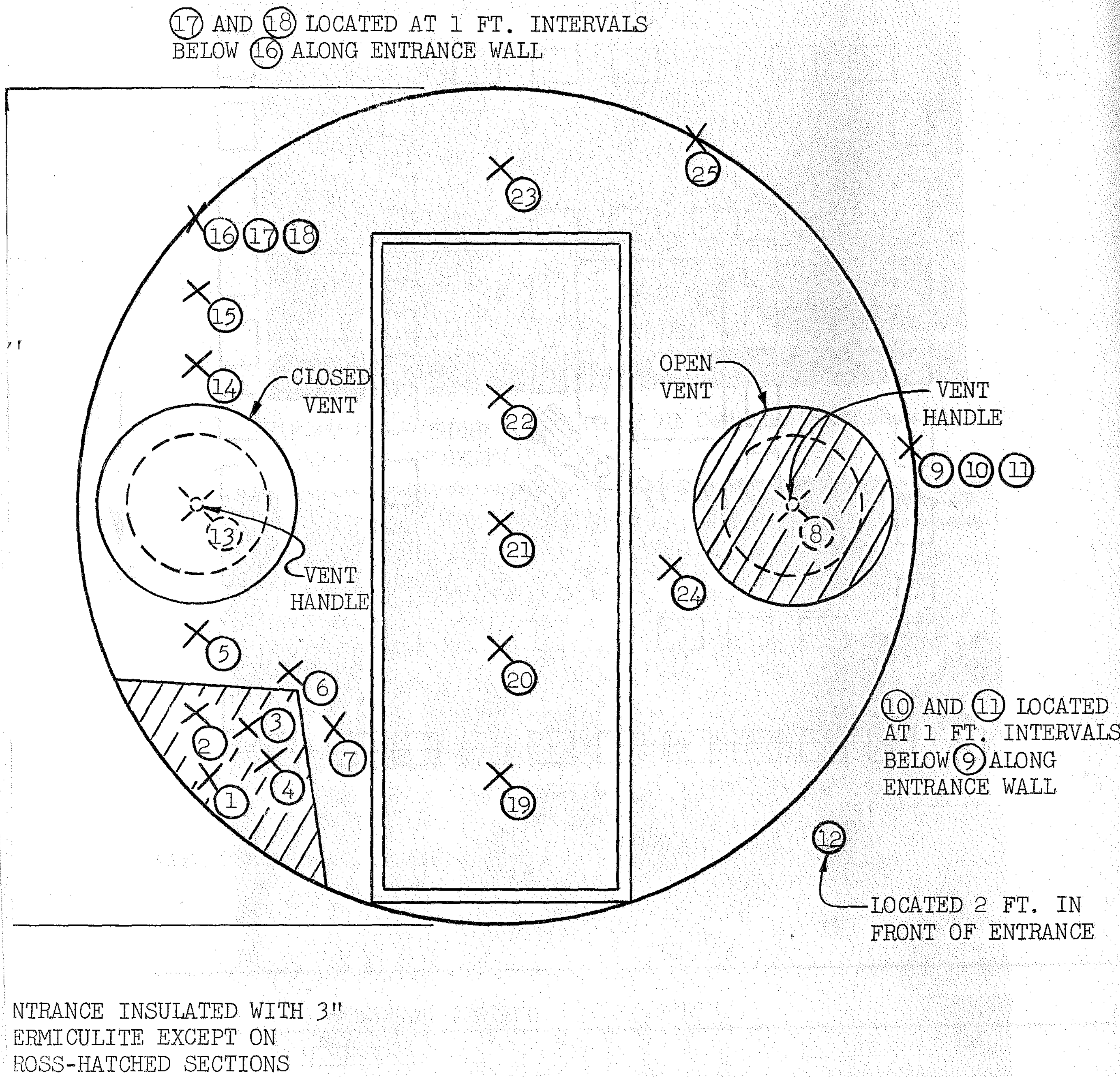


Figure 29.--Location of thermocouples in shelter entrance, Camp Parks Burn.

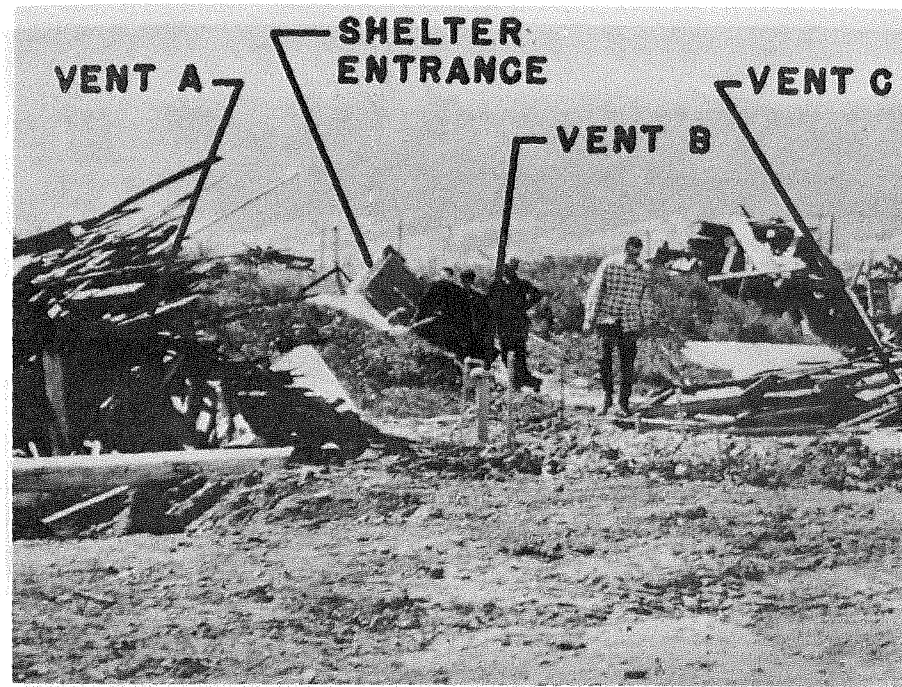


Figure 30.--Location of the three simulated intake vents with respect to the shelter entrance, Camp Parks Burn.

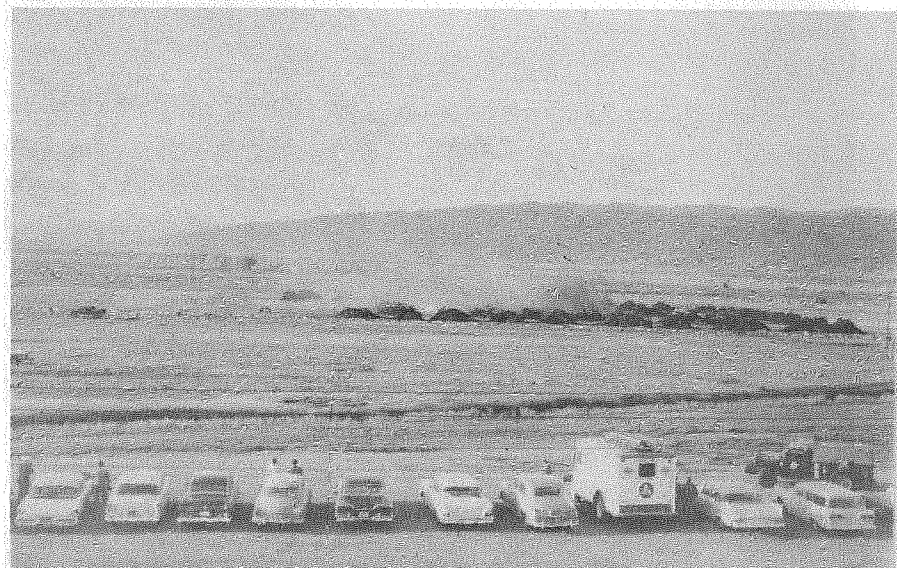


Figure 31.--Camp Parks Burn after ignition of first "ring." View from fire tower north of burn area.

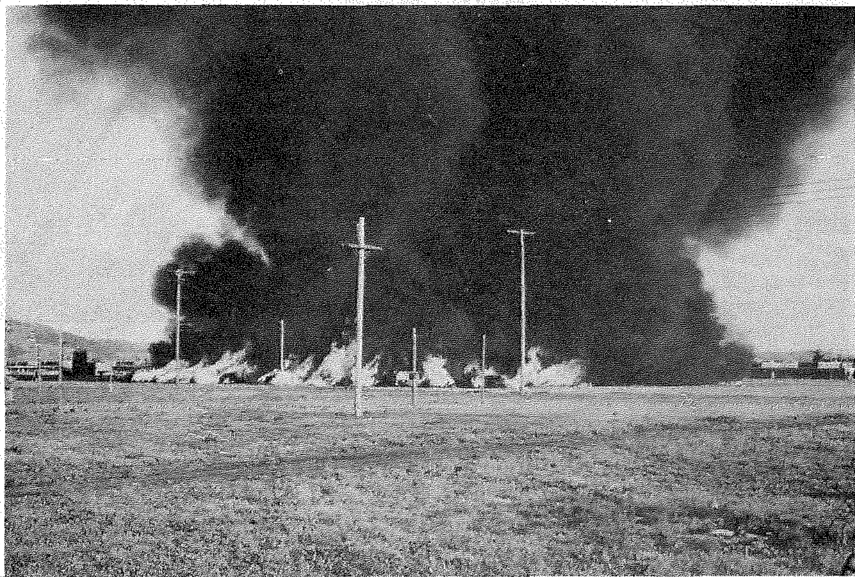


Figure 32.--Camp Parks Burn from southwest 2 minutes after ignition of outer ring. Note surface indrafts from all directions.

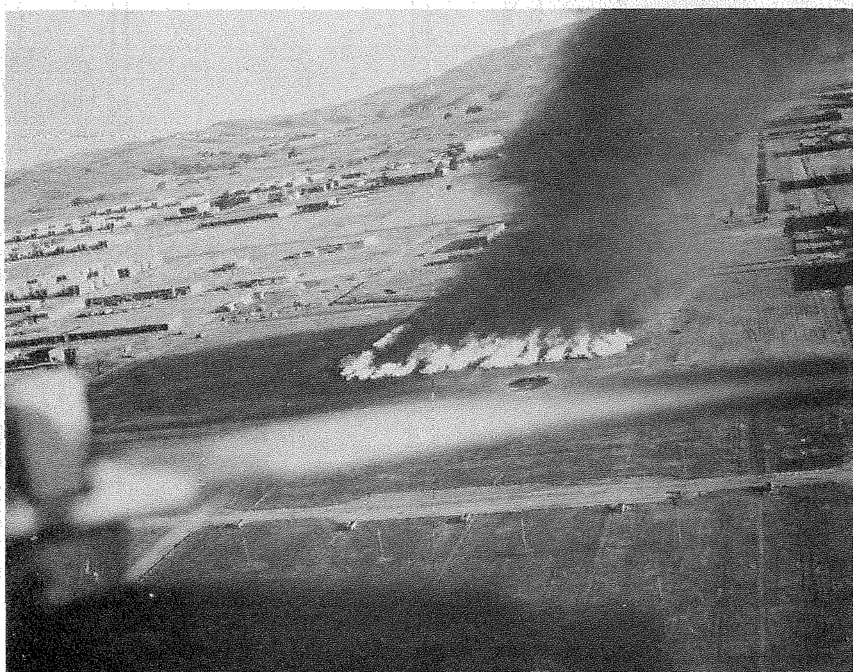


Figure 33.--Camp Parks Burn from helicopter. View from south 7 minutes after start. Note all flames still bent toward center of fire.

Figure 34.--Camp Parks Burn from helicopter. View from southeast 15 minutes after start. Individual piles burning independently.

Figure 35. Camp Parks Burn 1 hour after start. Area hot but accessible.

Figure 36.--Vents A and B after the Camp Parks Burn.

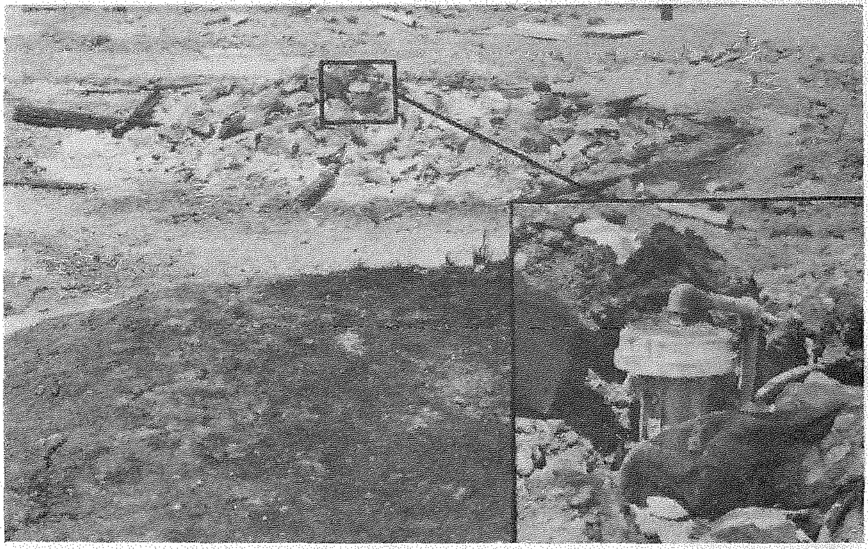


Figure 37.--Vent C protruding from rubble after the Camp Parks Burn.

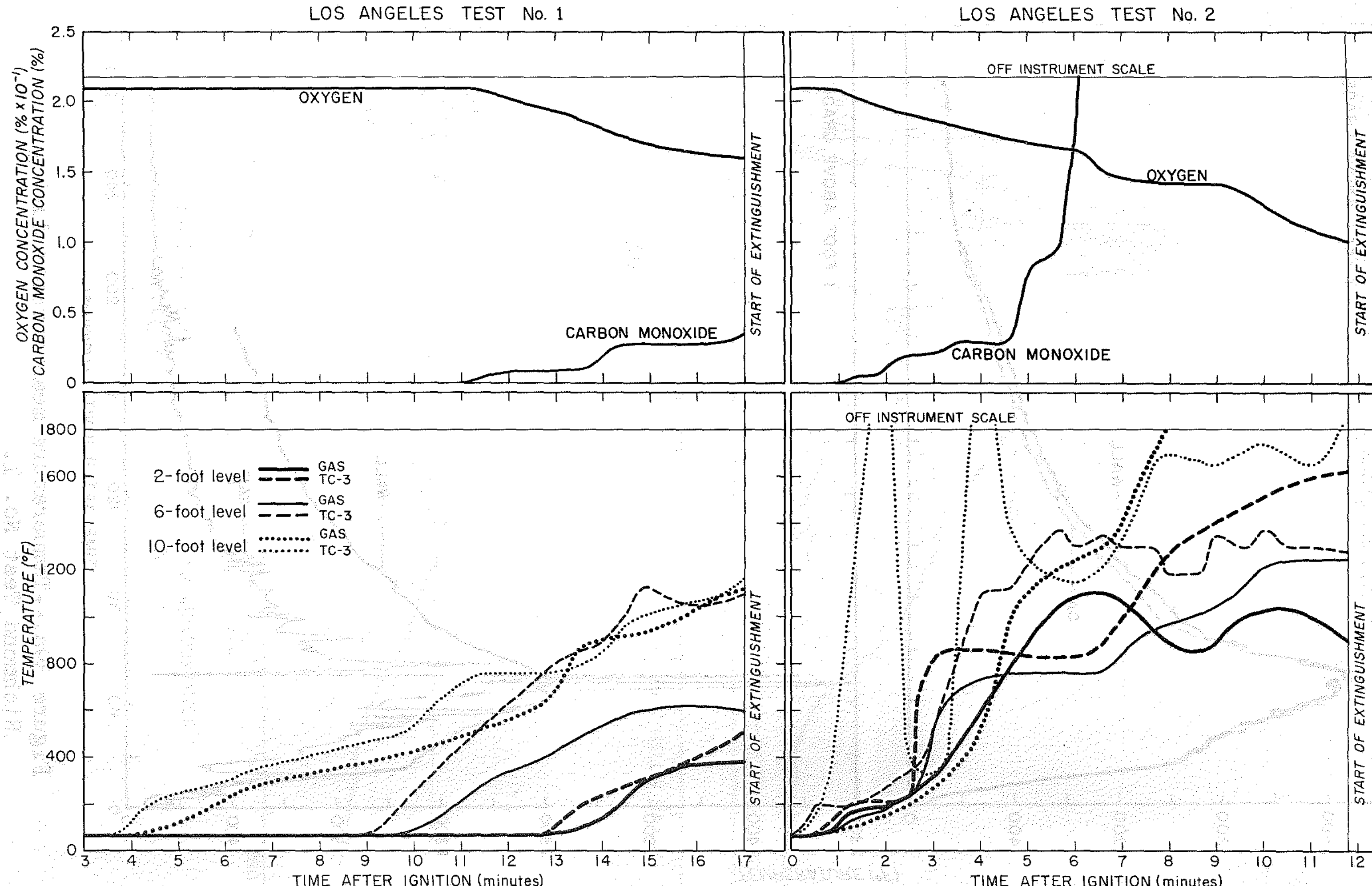


Figure 38.--Gas concentrations and temperatures during Los Angeles Tests.

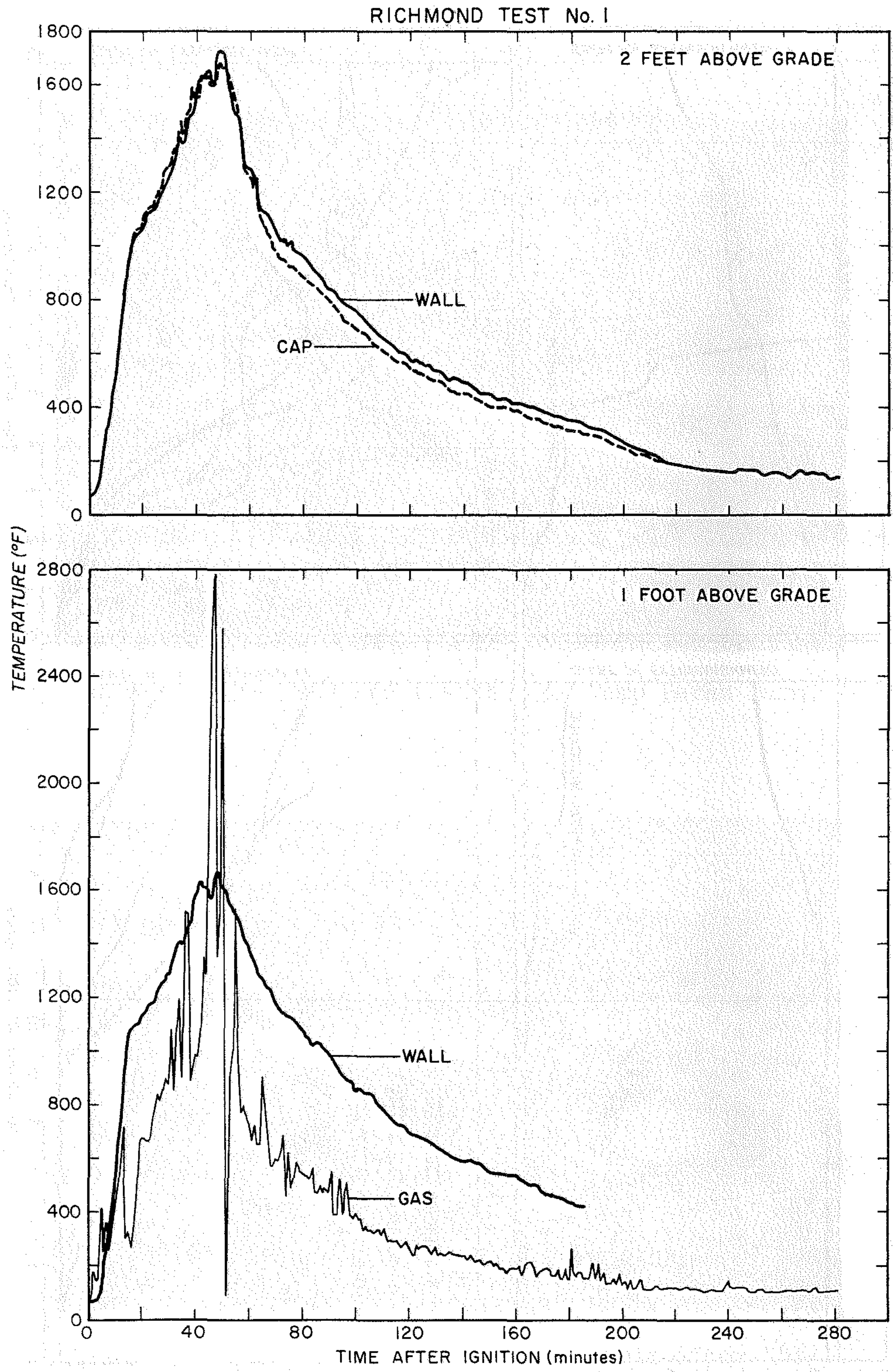


Figure 39a.--Temperature measurements during Richmond Test No. 1.

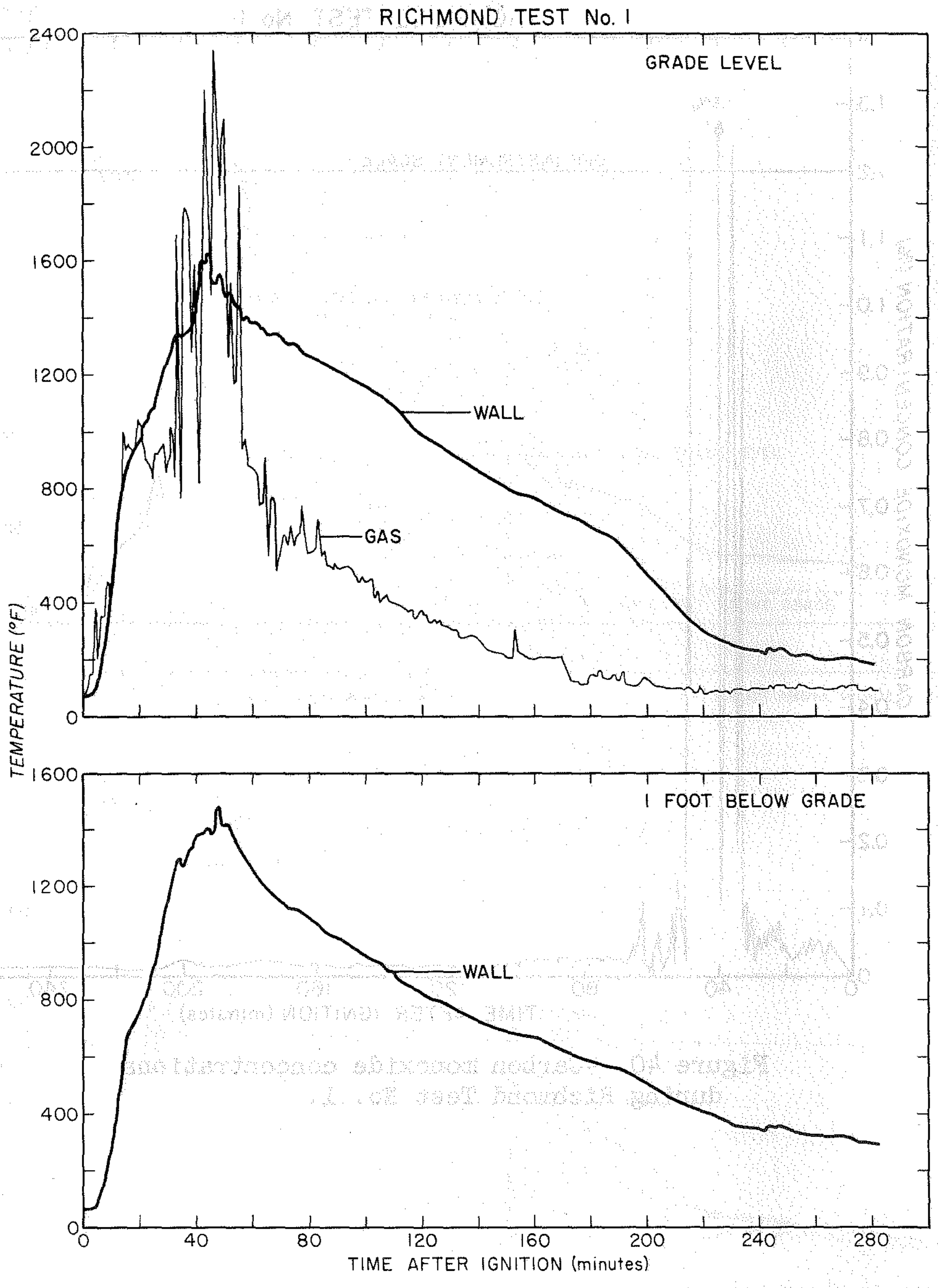


Figure 39b.--Temperature measurements during Richmond Test No. 1.

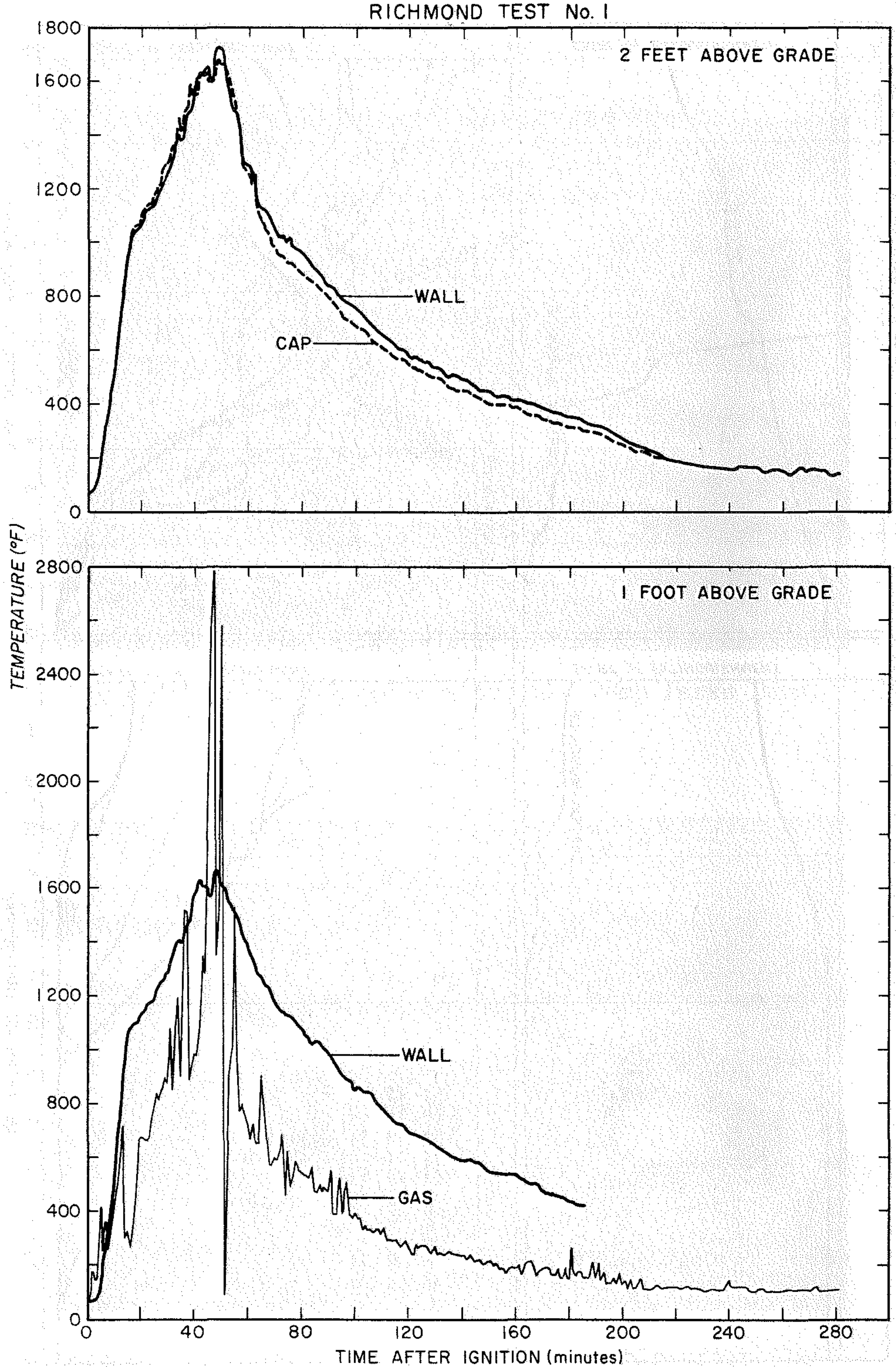


Figure 39a.--Temperature measurements during Richmond Test No. 1.

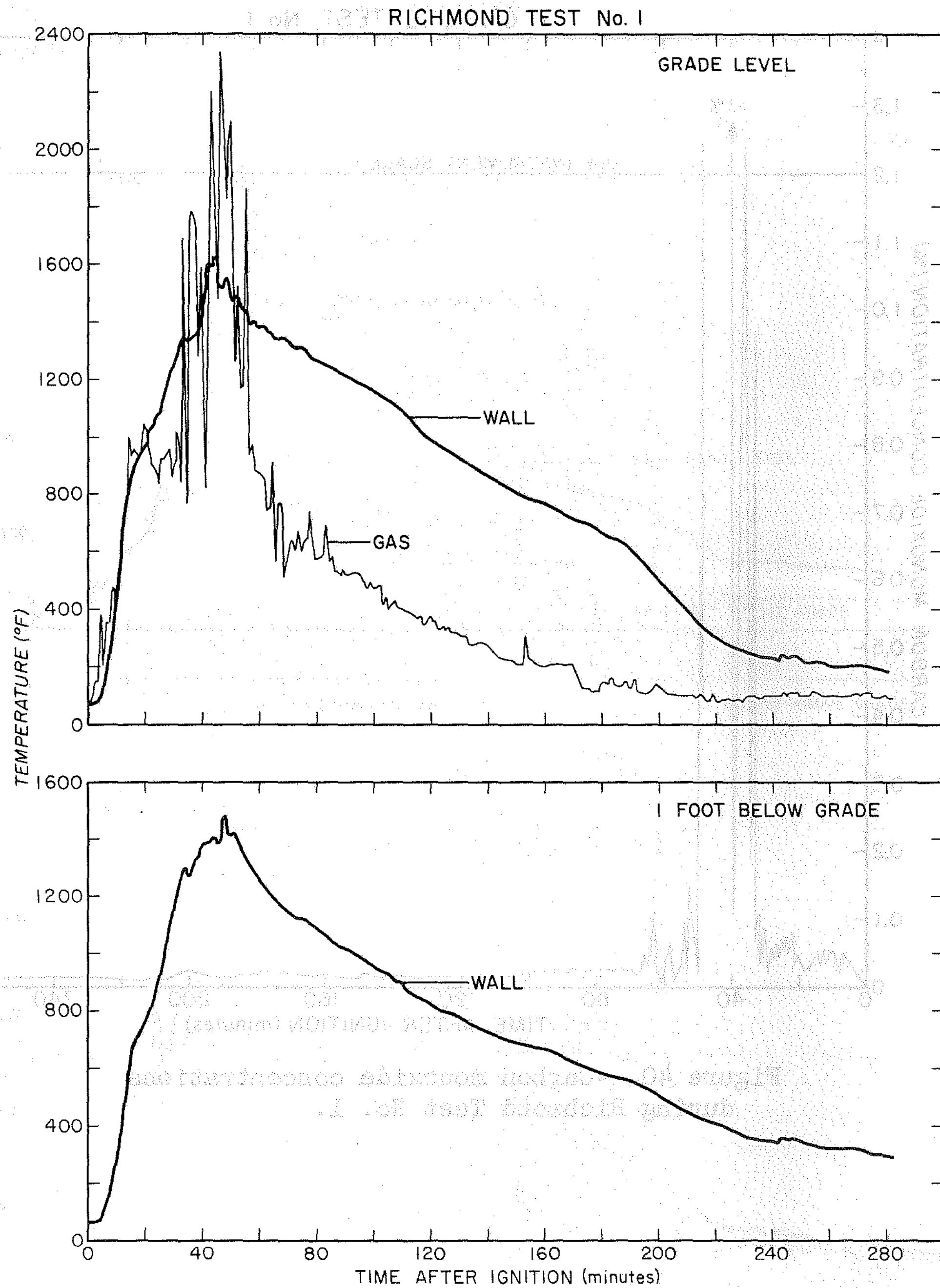


Figure 39b.--Temperature measurements during Richmond Test No. 1.

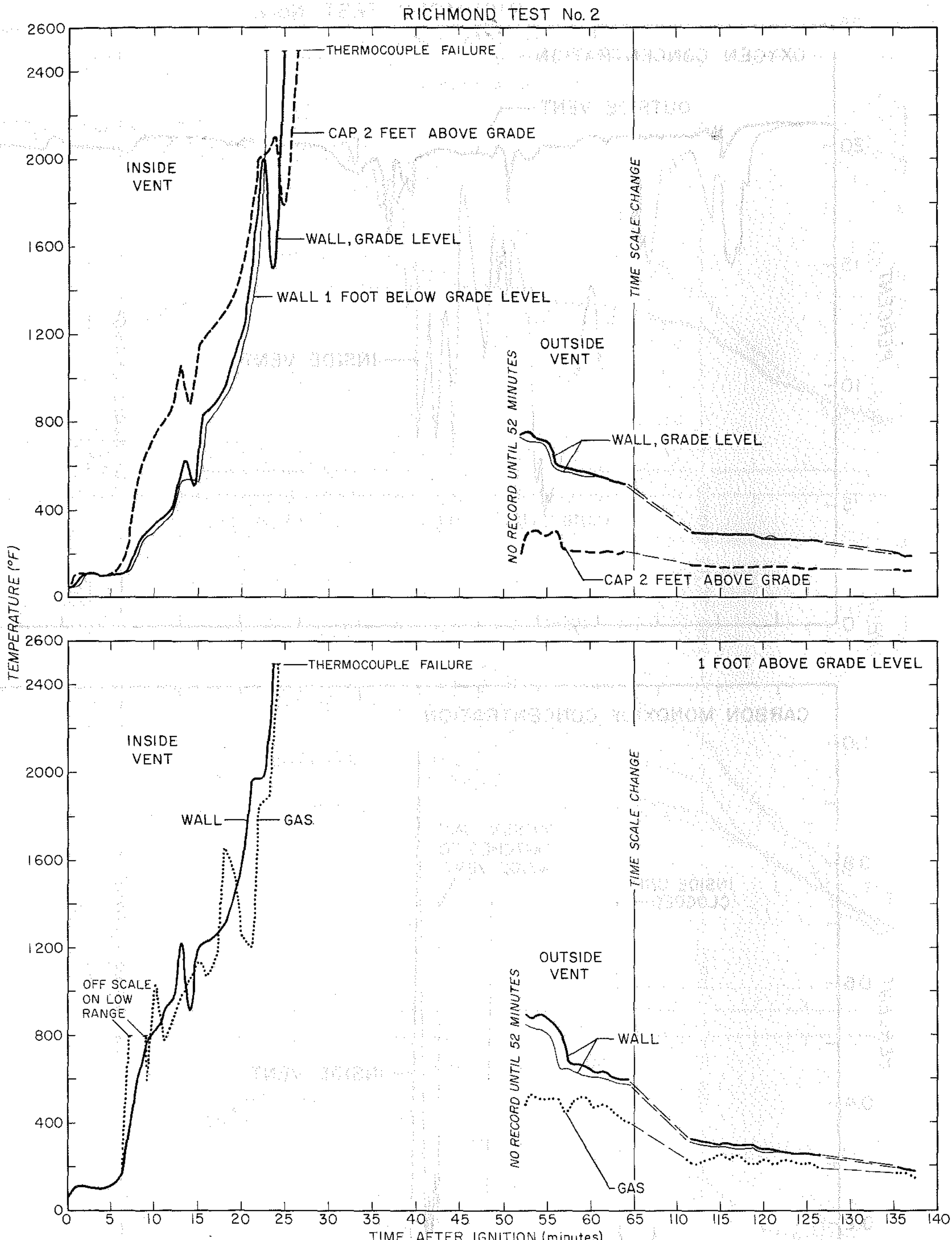


Figure 41.--Temperature measurements during Richmond Test No. 2.

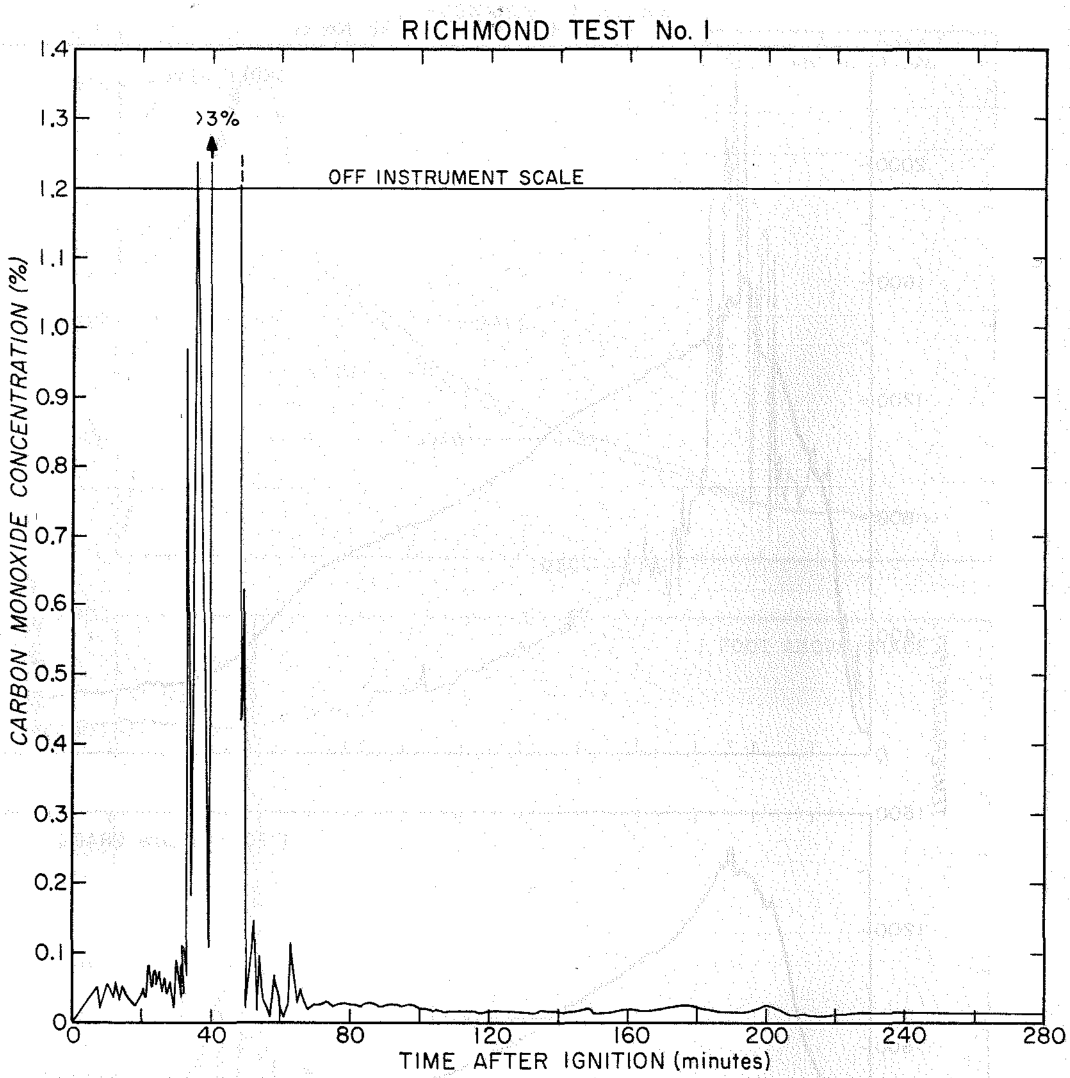


Figure 40.--Carbon monoxide concentrations during Richmond Test No. 1.

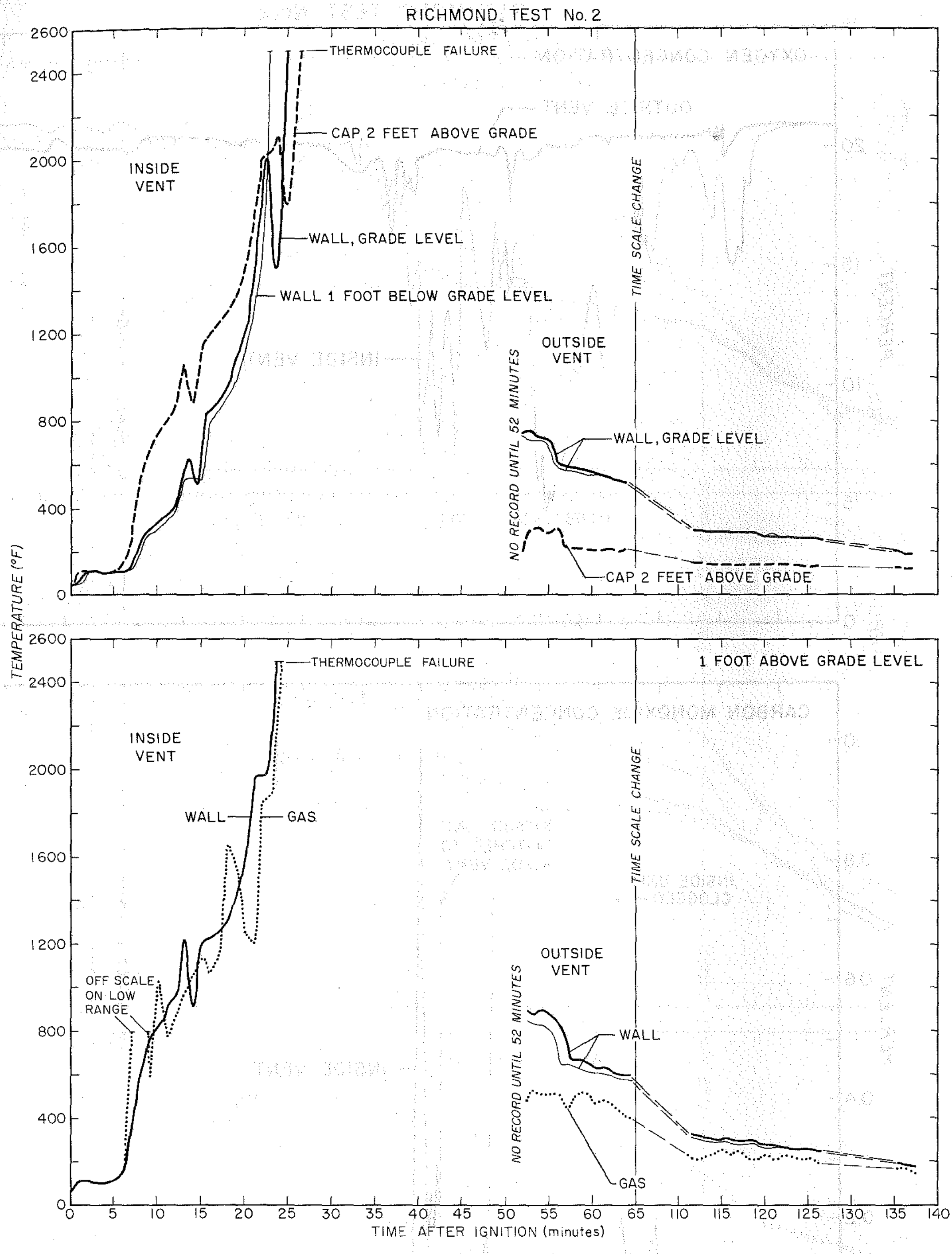


Figure 41.--Temperature measurements during Richmond Test No. 2.

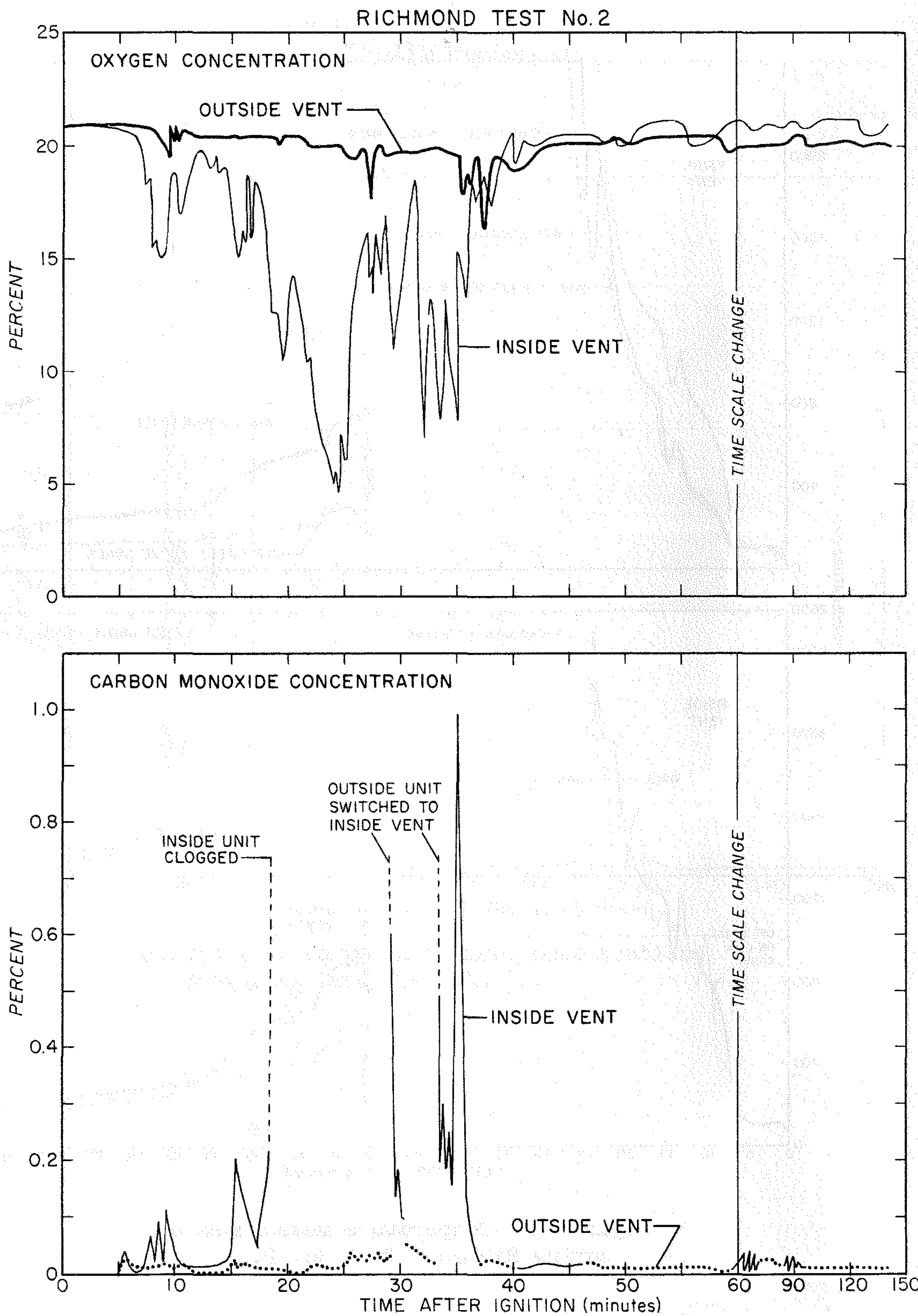


Figure 42.--Oxygen and carbon monoxide concentrations during Richmond Test No. 2.

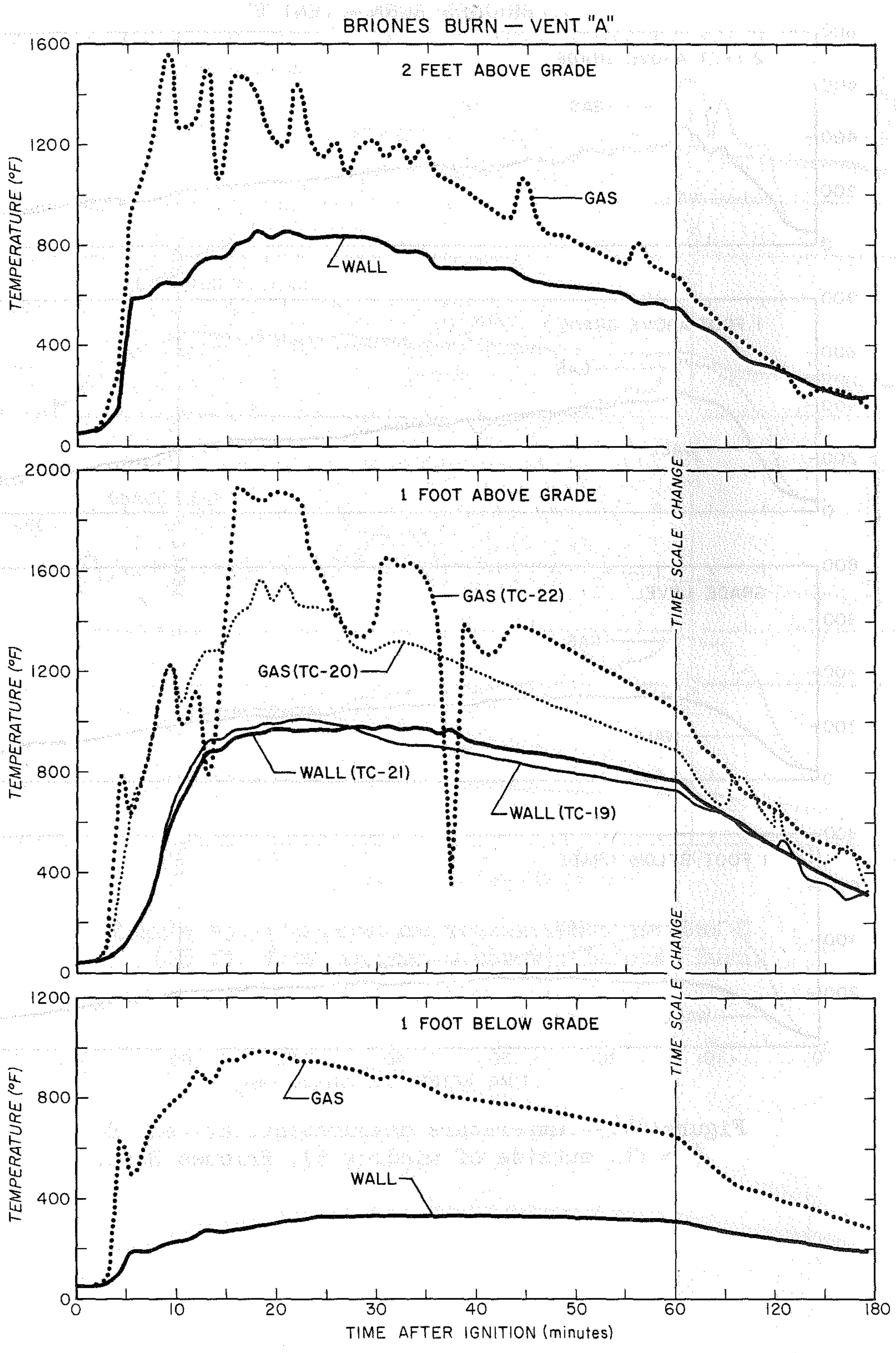


Figure 43.--Temperature measurements at vent A (in windrow 5), Briones Burn.

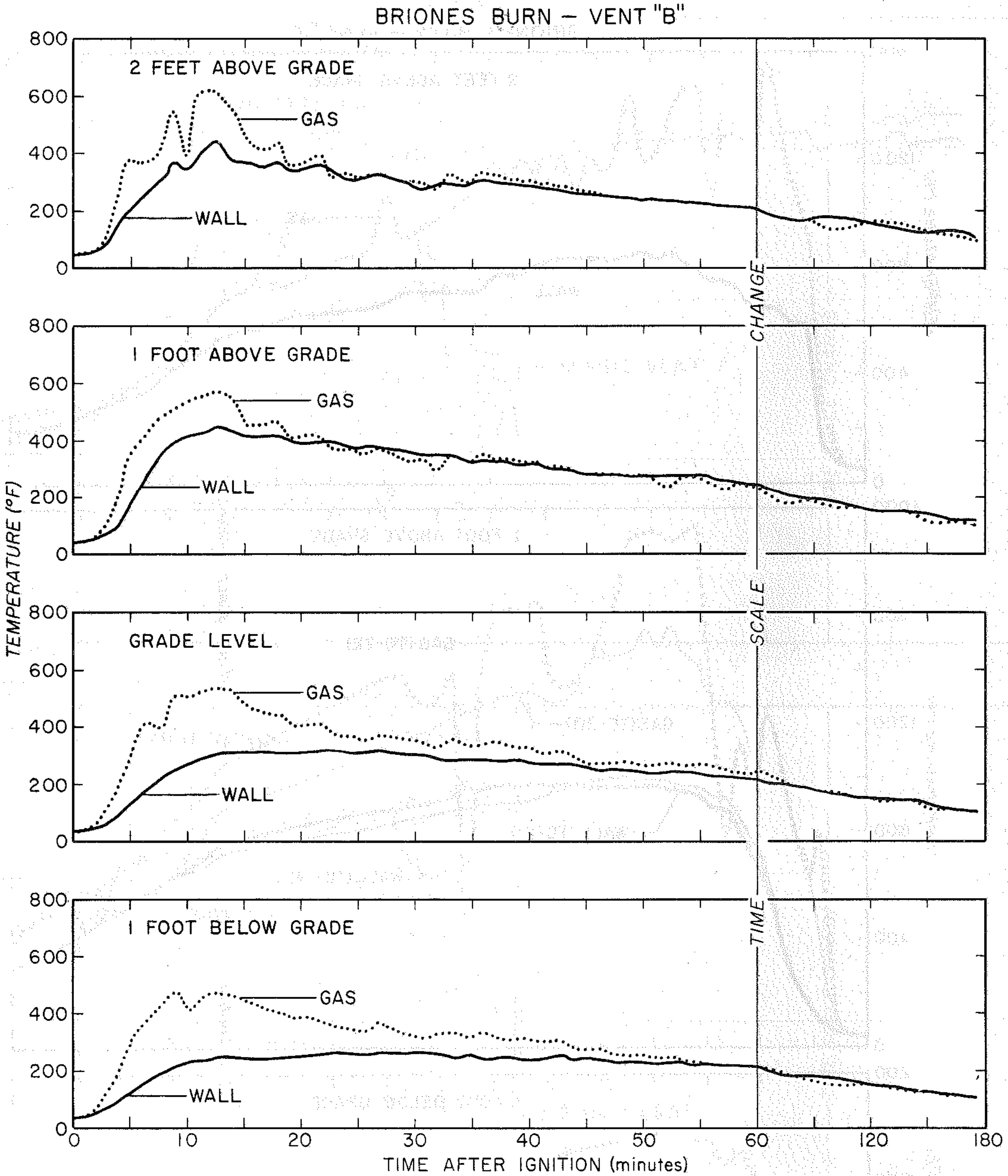


Figure 44.--Temperature measurements at vent B (5 ft. outside of windrow 5), Briones Burn.

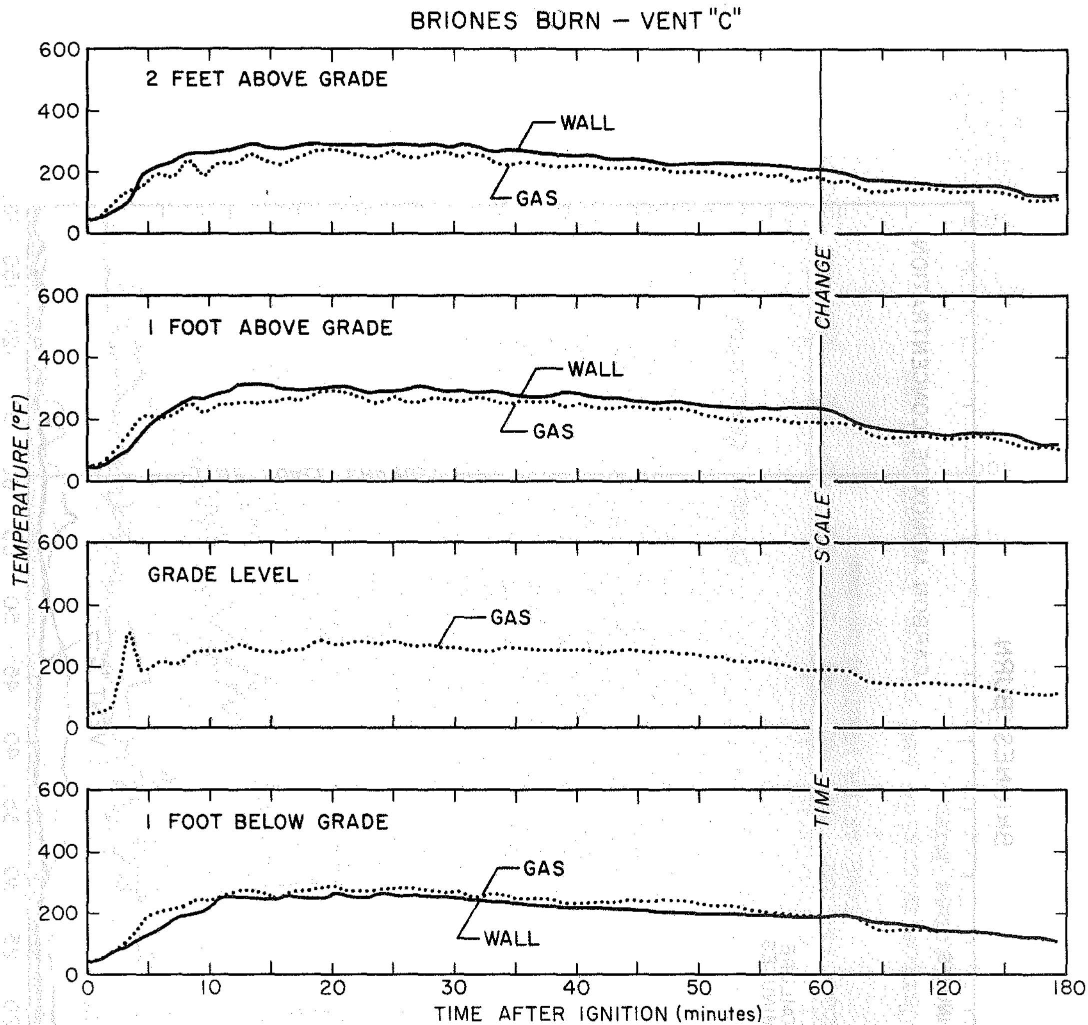
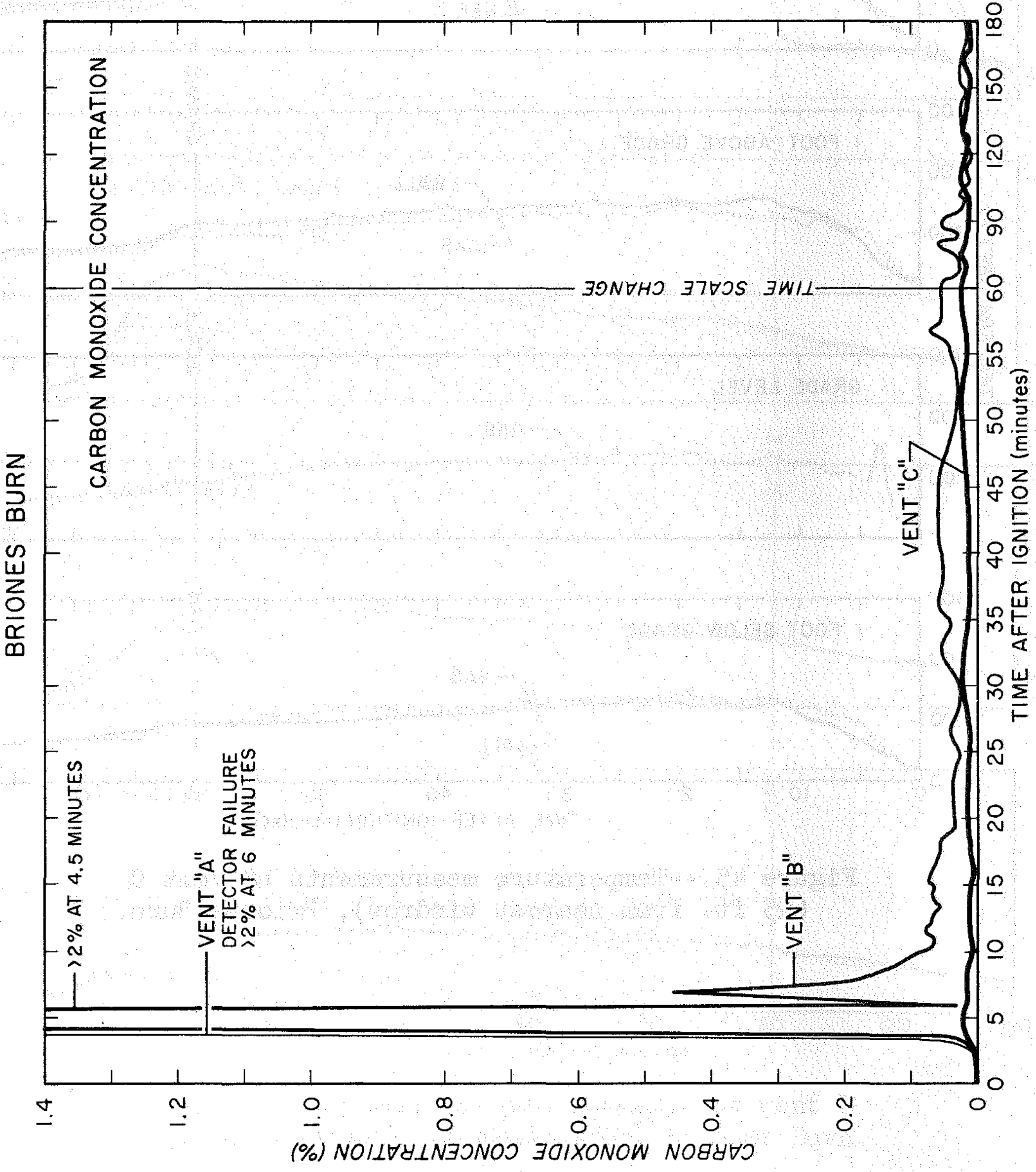


Figure 45.--Temperature measurements at vent C (25 ft. from nearest windrow), Briones Burn.



BRIONES BURN
CARBON MONOXIDE CONCENTRATION
>2% AT 4.5 MINUTES
VENT "A"
DETECTOR FAILURE
>2% AT 6 MINUTES
VENT "B"
VENT "C"
TIME SCALE CHANGE
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
CARBON MONOXIDE CONCENTRATION (%)
0
5
10
15
20
25
30
35
40
45
50
55
60
90
120
150
180
TIME AFTER IGNITION (minutes)

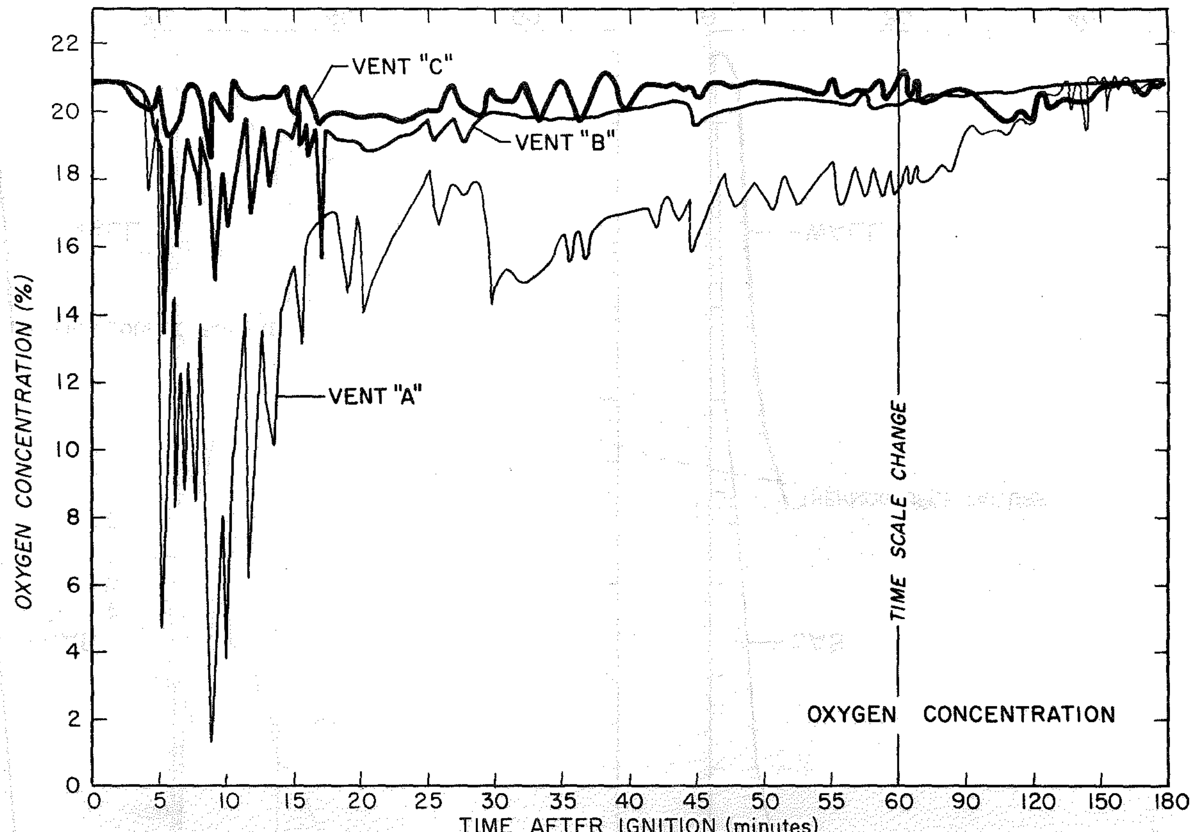


Figure 46.--Carbon monoxide and oxygen concentrations during the Briones Burn.

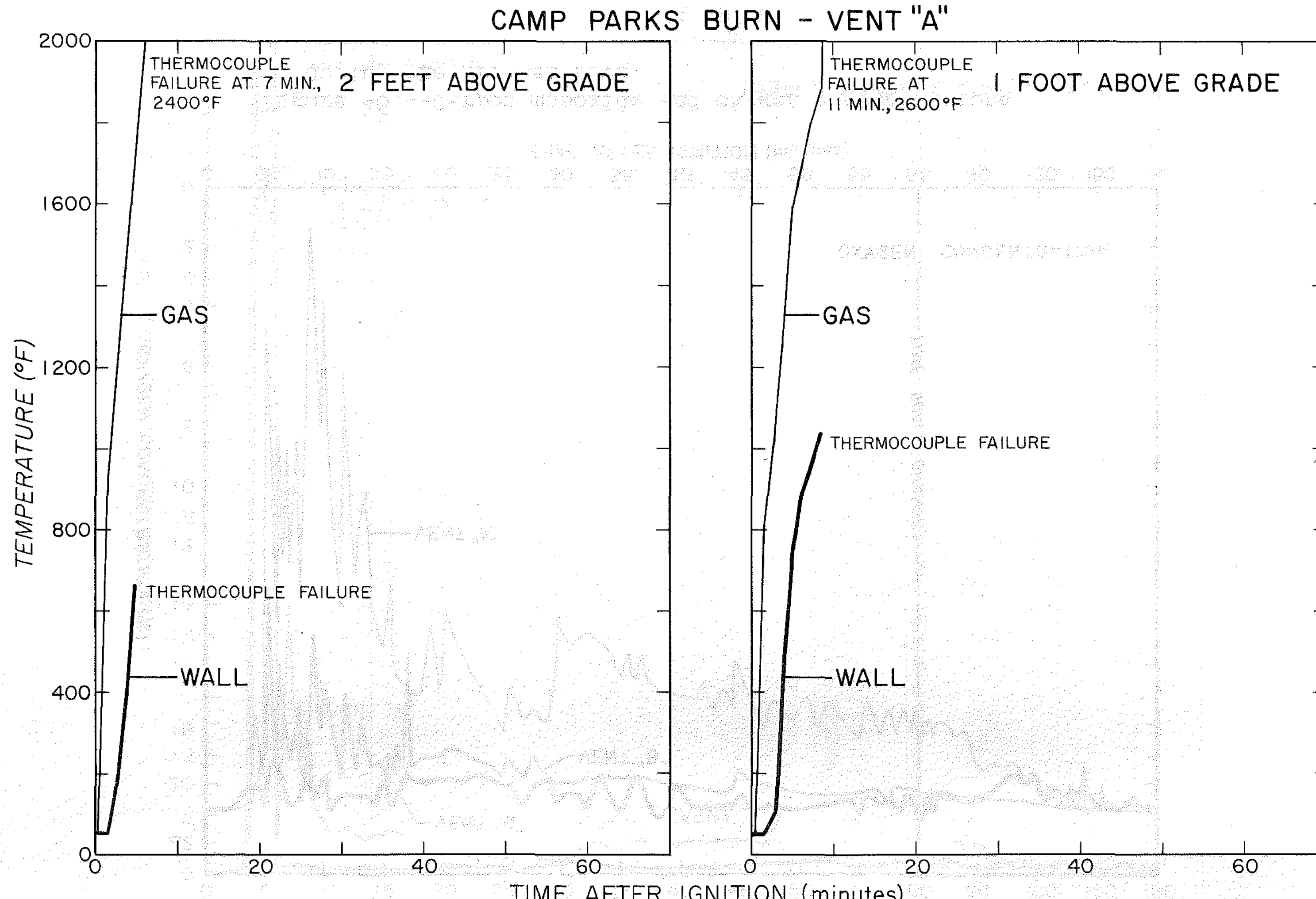


Figure 47.--Above-grade temperature measurements at vent A (in a rubble-free pile), Camp Parks Burn.

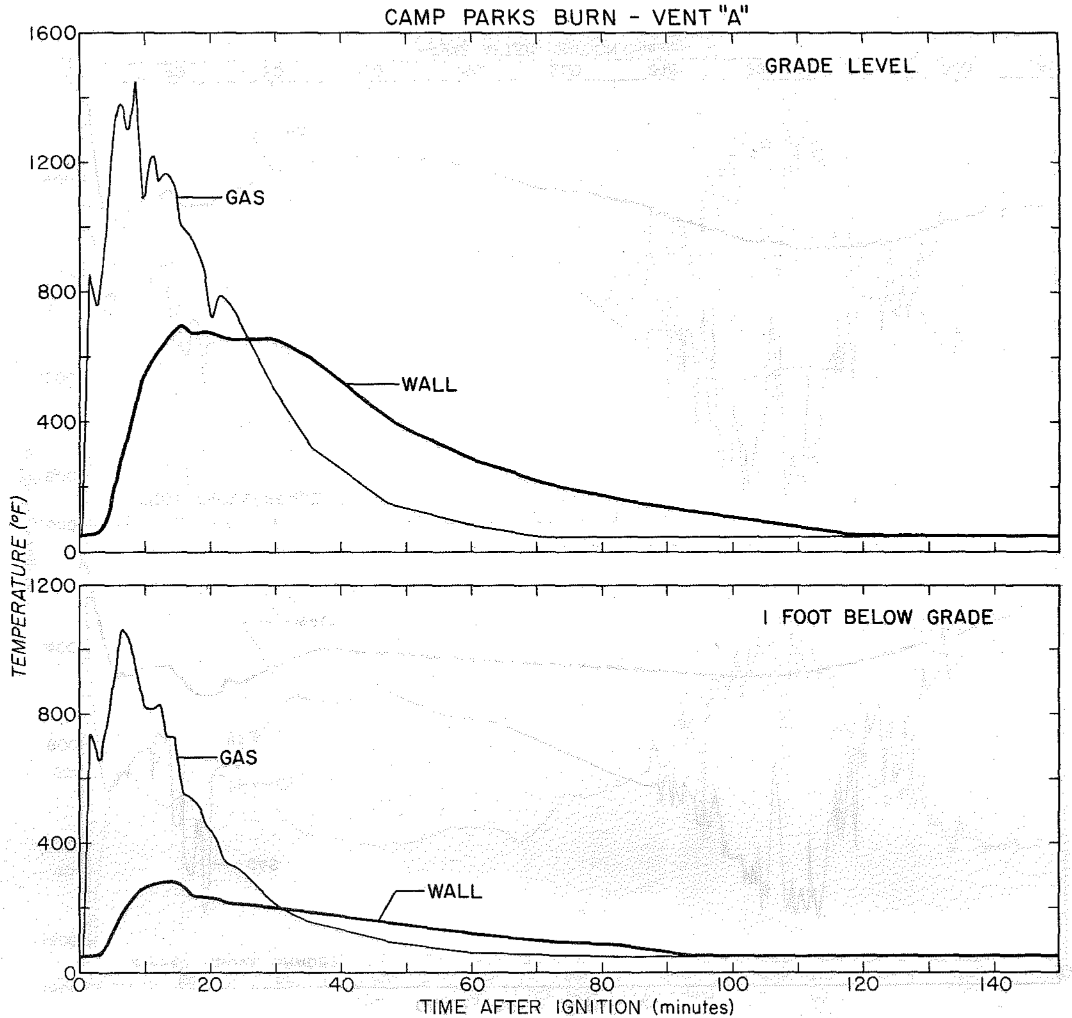
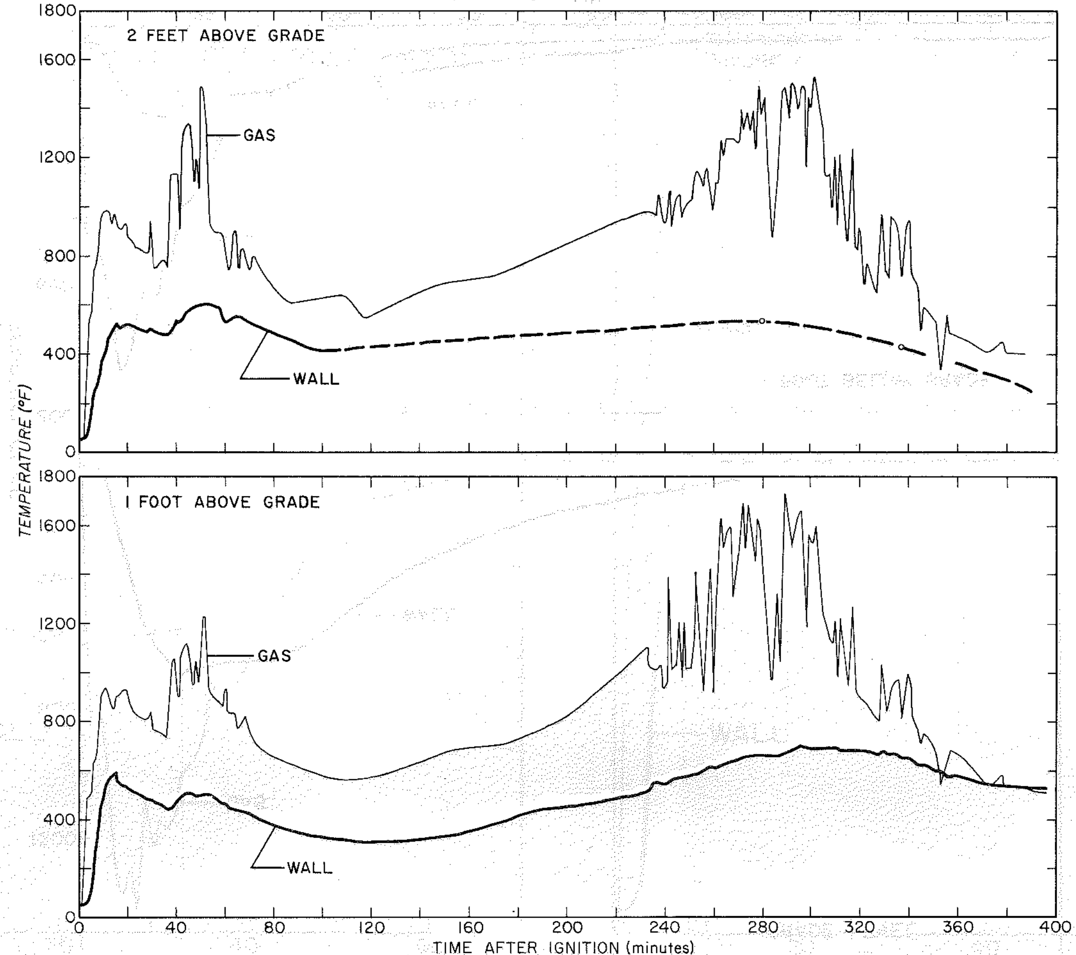


Figure 48.--Below-grade temperature measurements at vent A, Camp Parks Burn.

CAMP PARKS BURN – VENT "C"



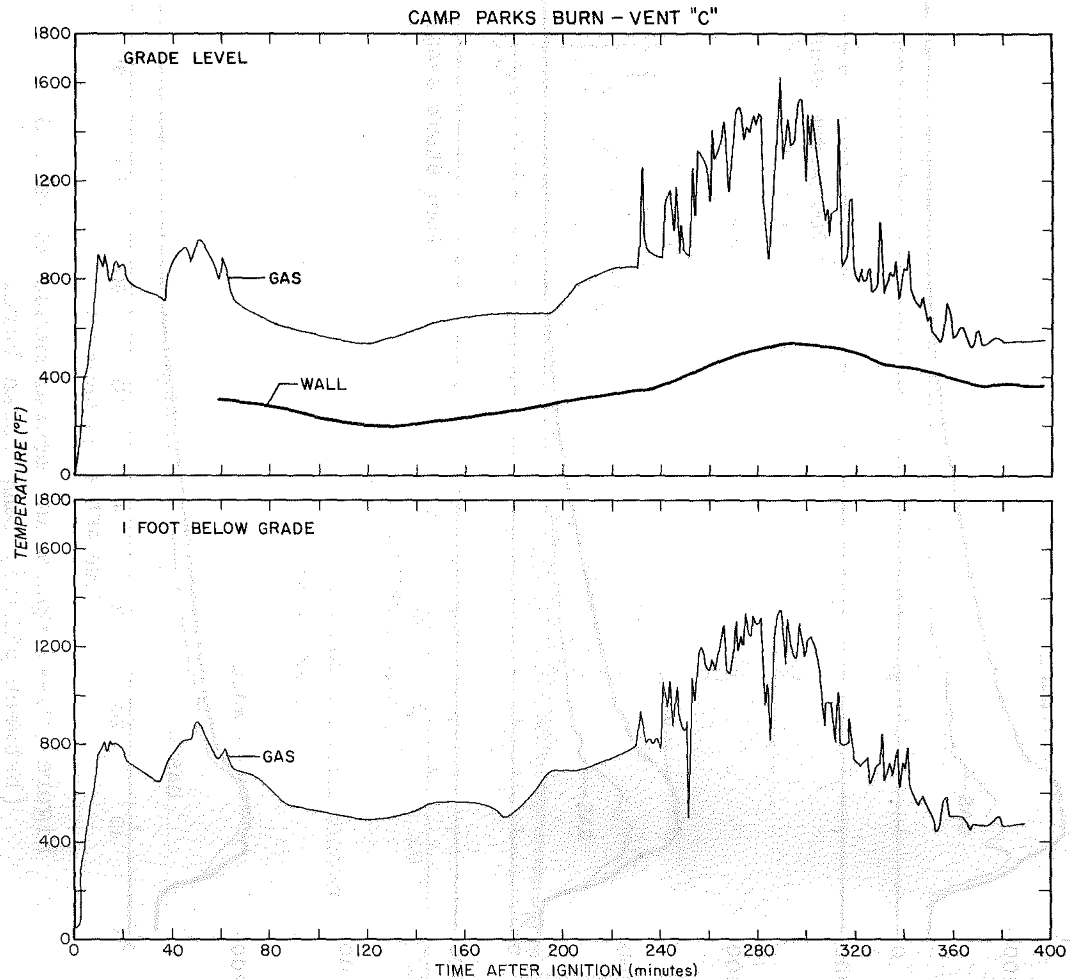


Figure 49.--Temperature measurements at vent C (in rubble pile), Camp Parks Burn.

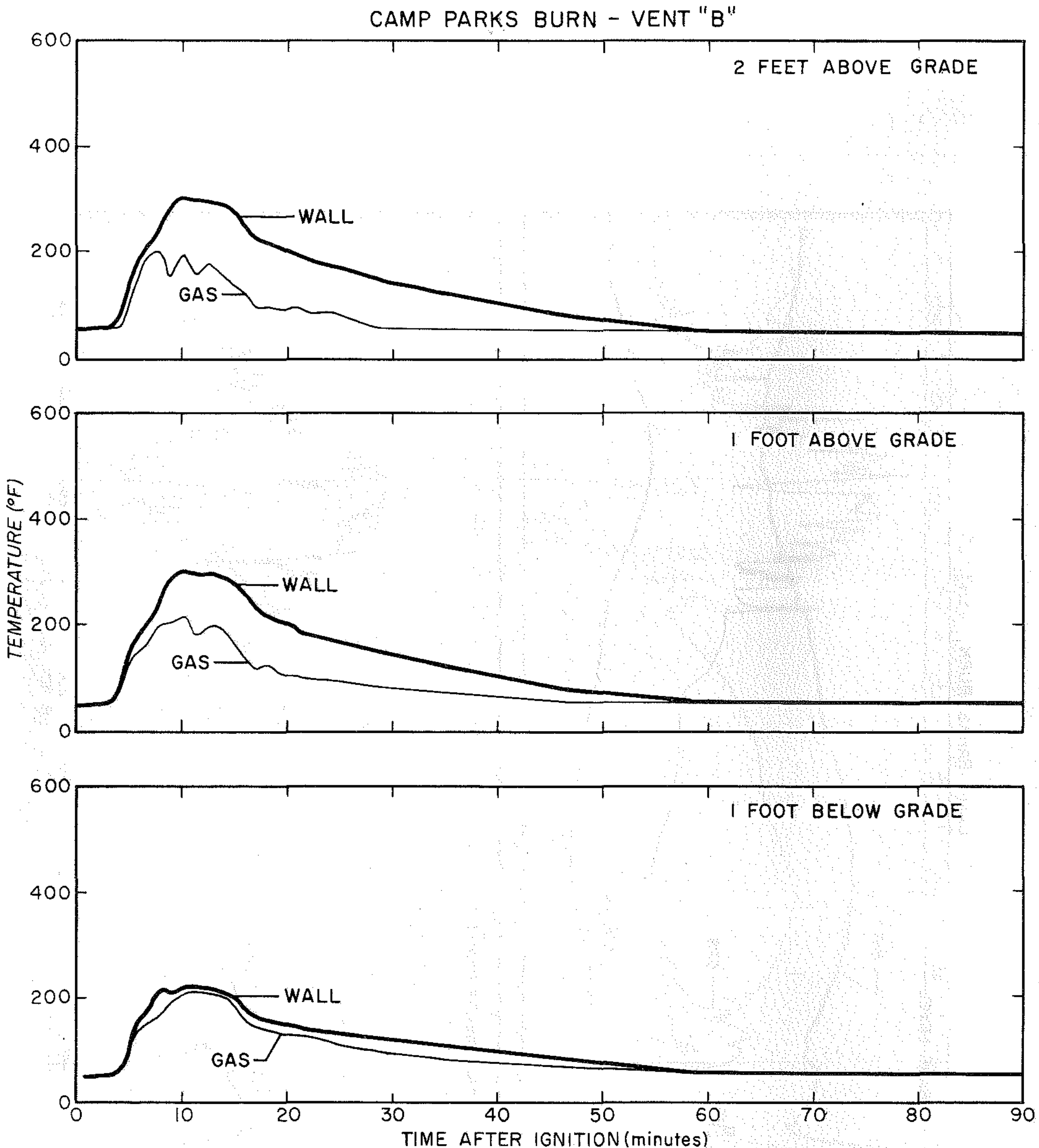


Figure 50.--Temperature measurements at vent B (between piles), Camp Parks Burn.

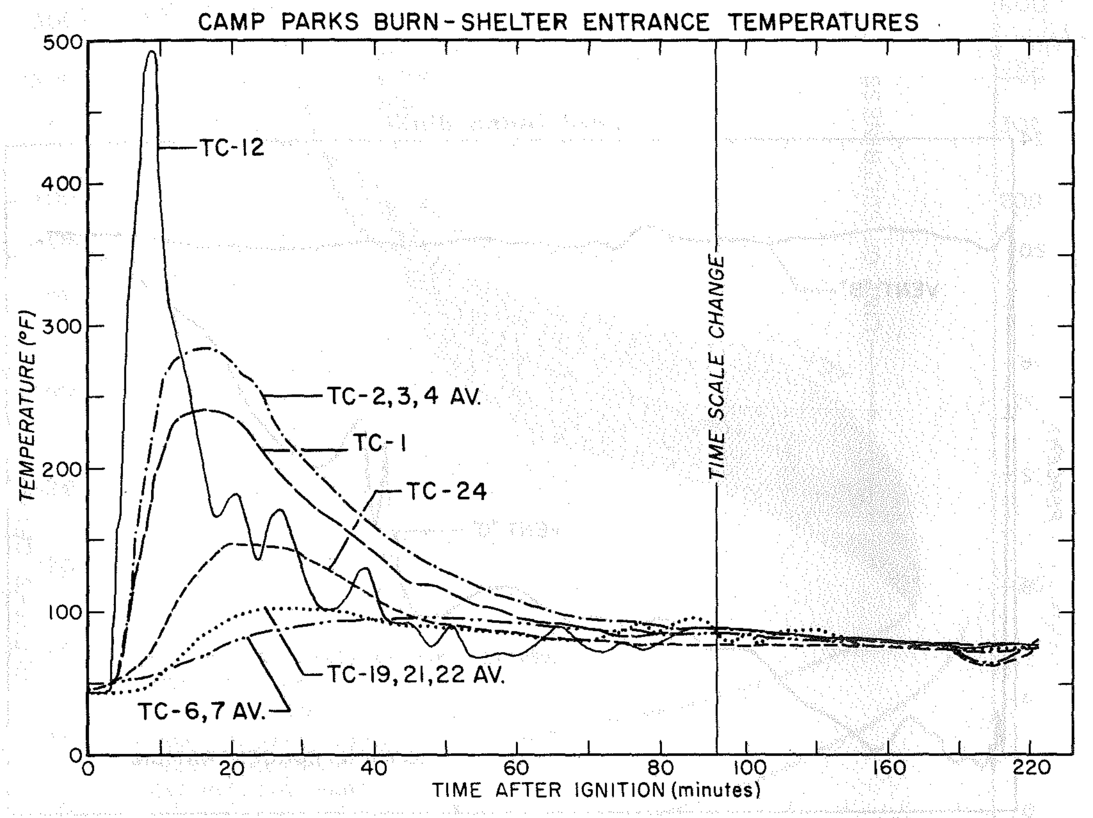


Figure 51.--Temperature measurements in entranceway of 100-man shelter, Camp Parks Burn.

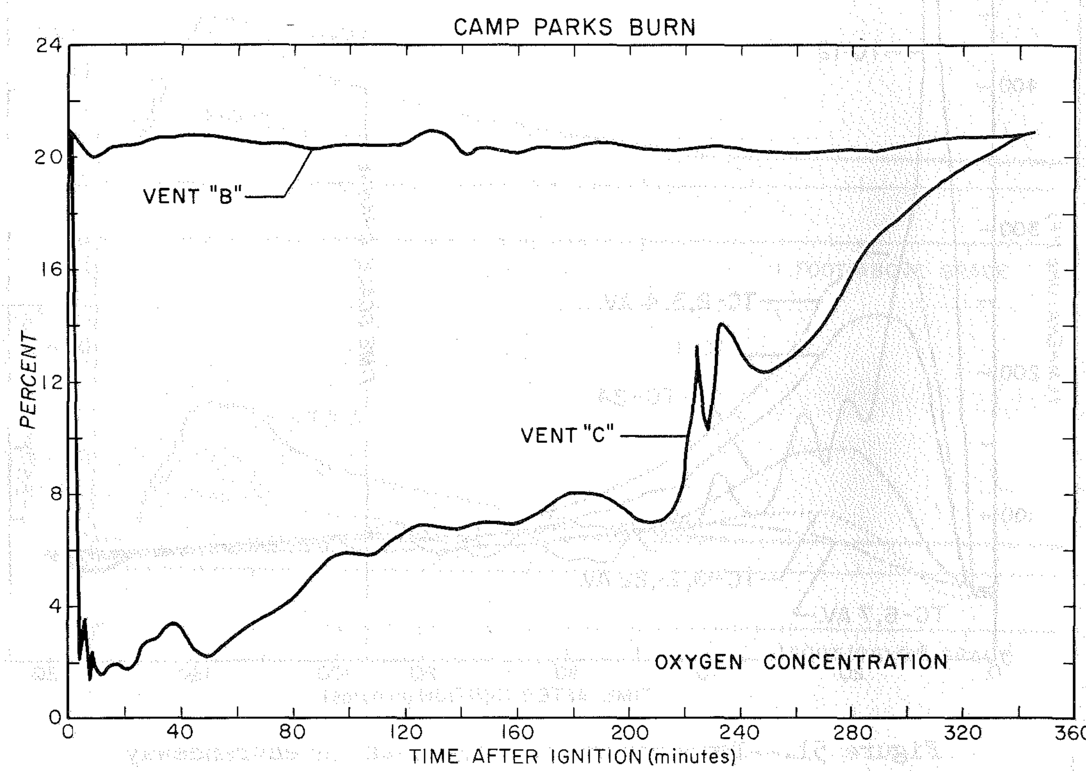


Figure 52.--Oxygen concentrations during the Camp Parks Burn.

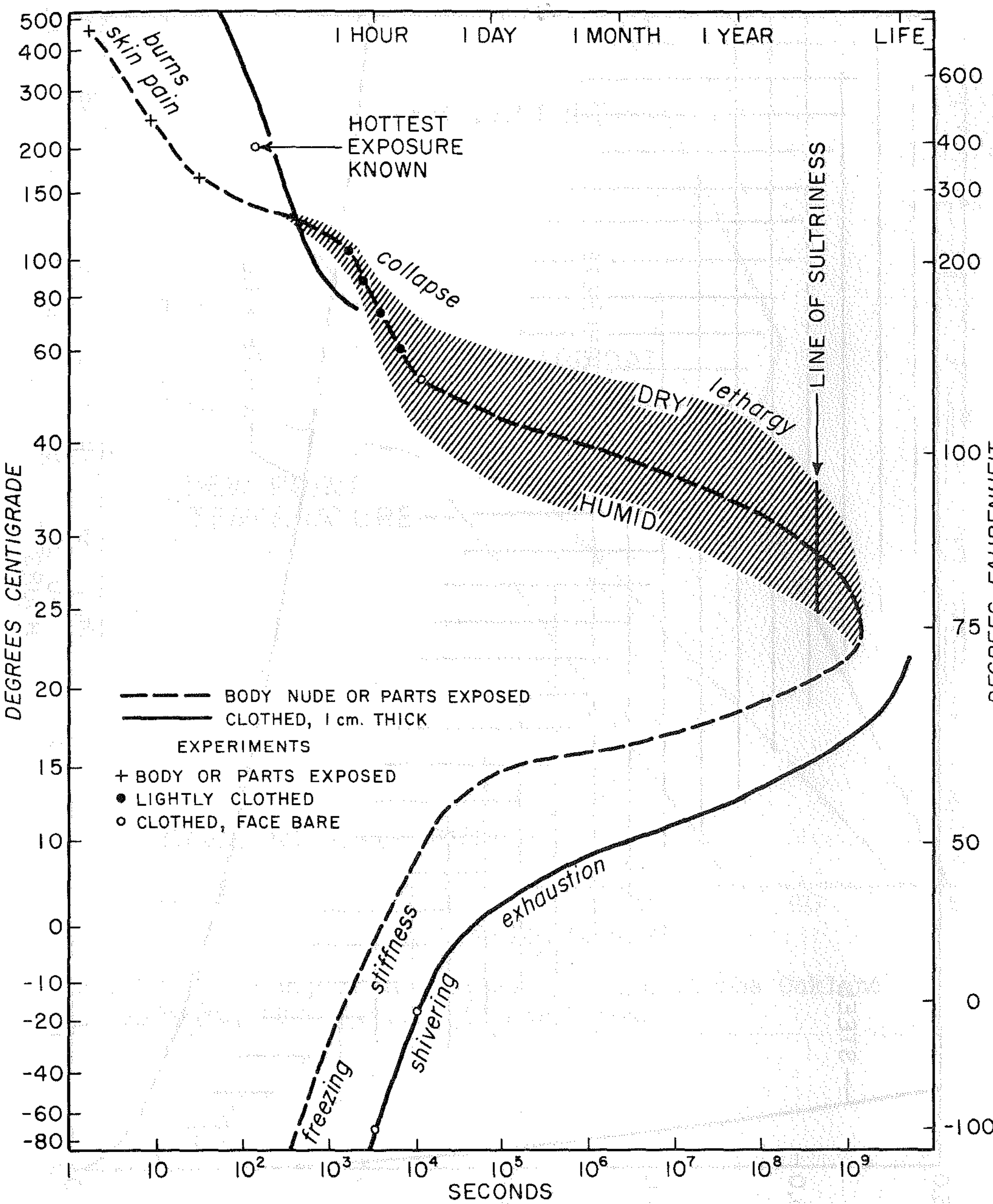


Figure 53.--Safe exposure time for man in extreme thermal environment.

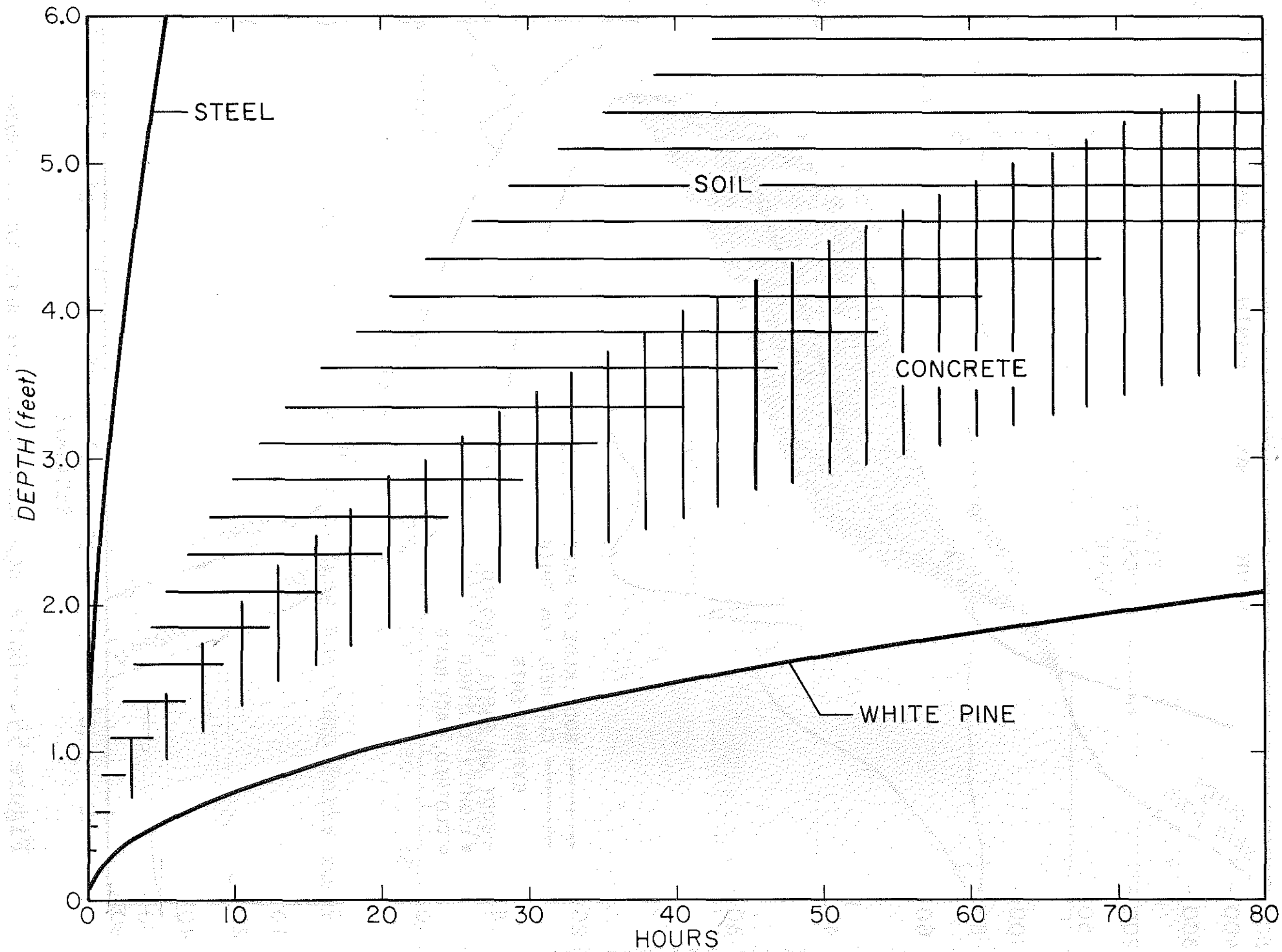


Figure 54.--Time for the temperature at a given depth within a semi-infinite solid, originally at 60°F., to reach 90°F. if the temperature on the surface is maintained at 2000°F.

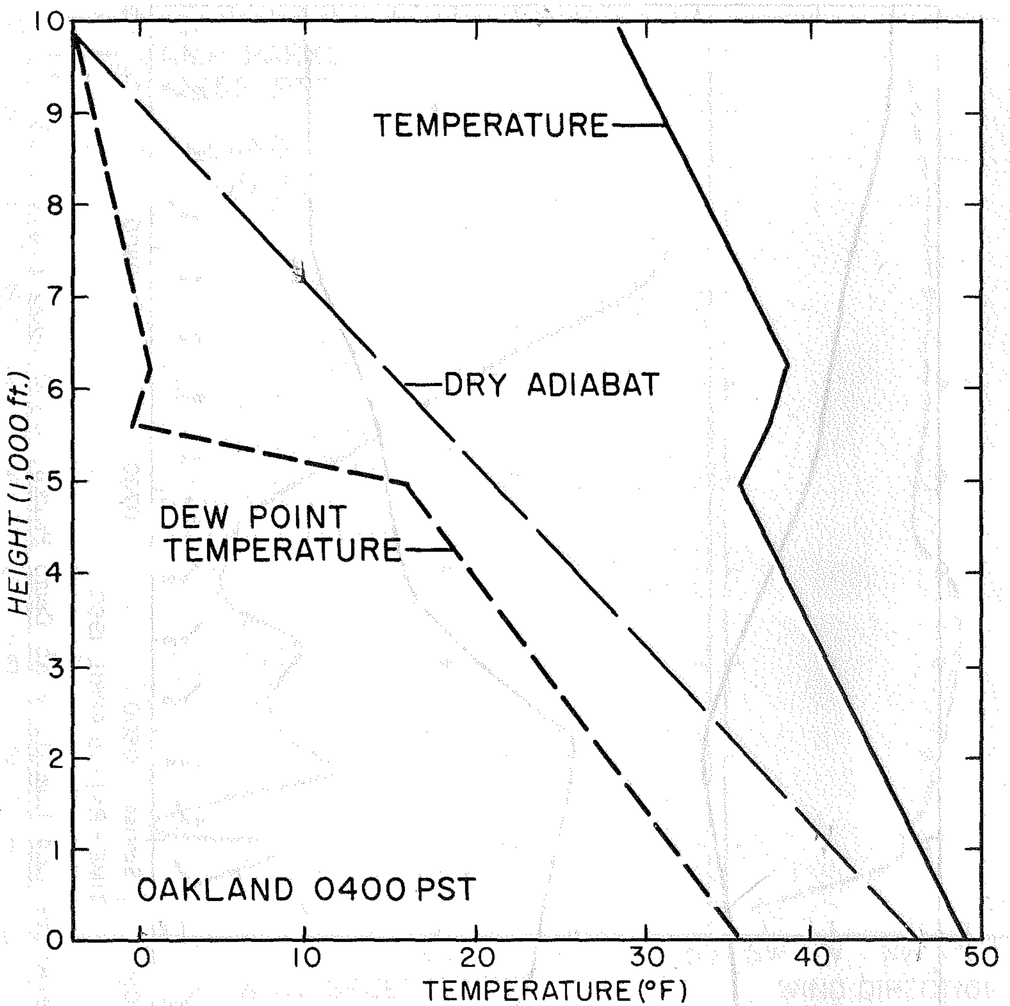


Figure 55.--Temperature-height profile at the Oakland Airport, 0400 P.s.t., 15 April 1960.

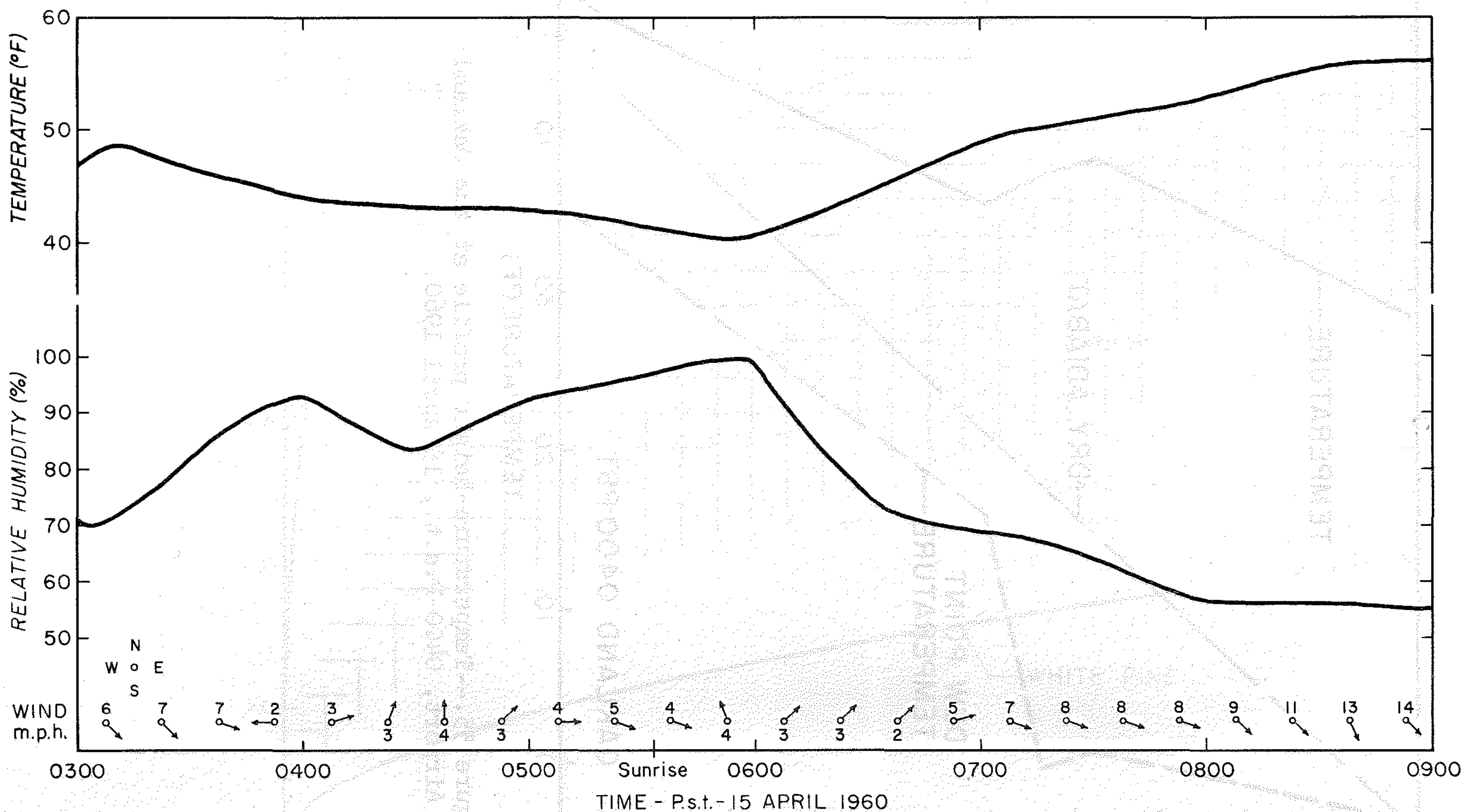


Figure 56.--Surface winds, temperature and humidity at Camp Parks, 0300-0900 P.s.t., 15 April 1960.

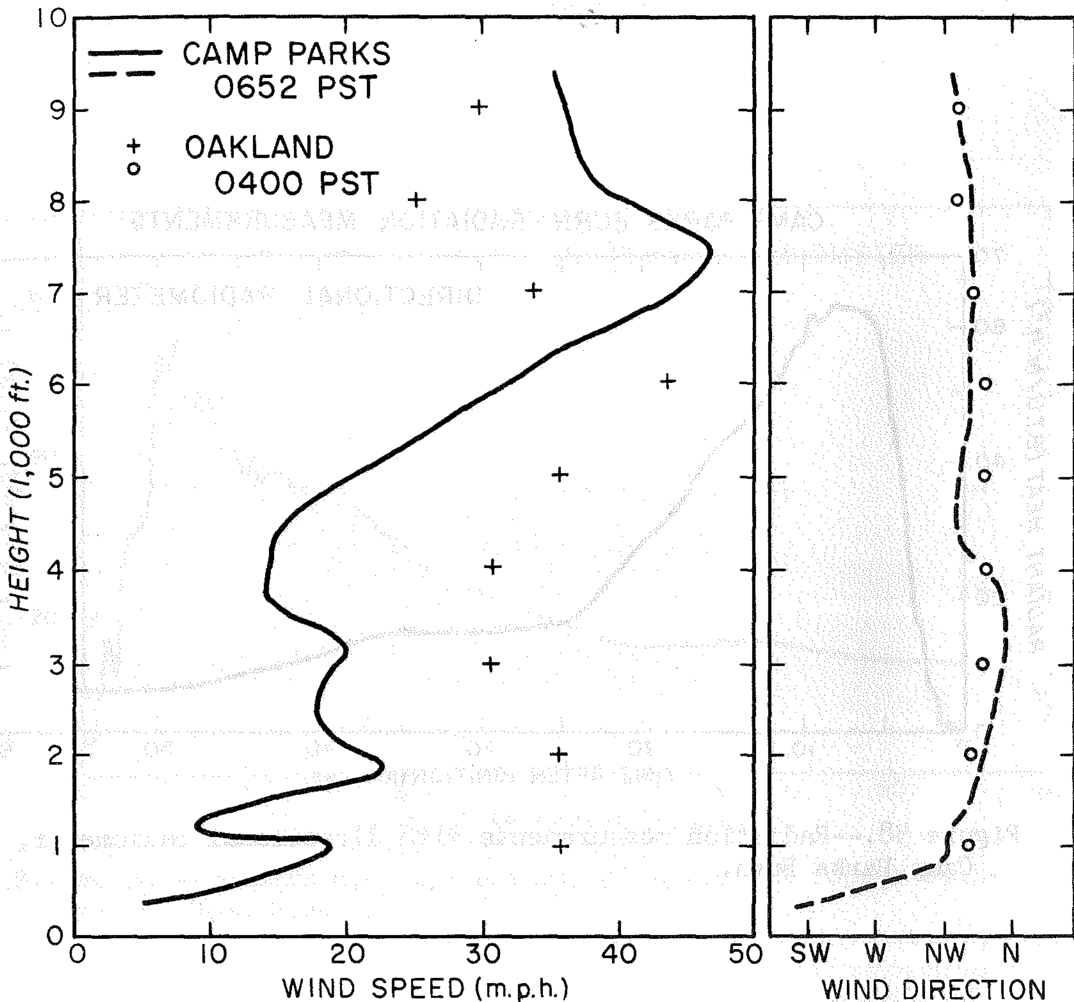


Figure 57.--Winds aloft at Camp Parks and the Oakland Airport; the morning of 15 April 1960.

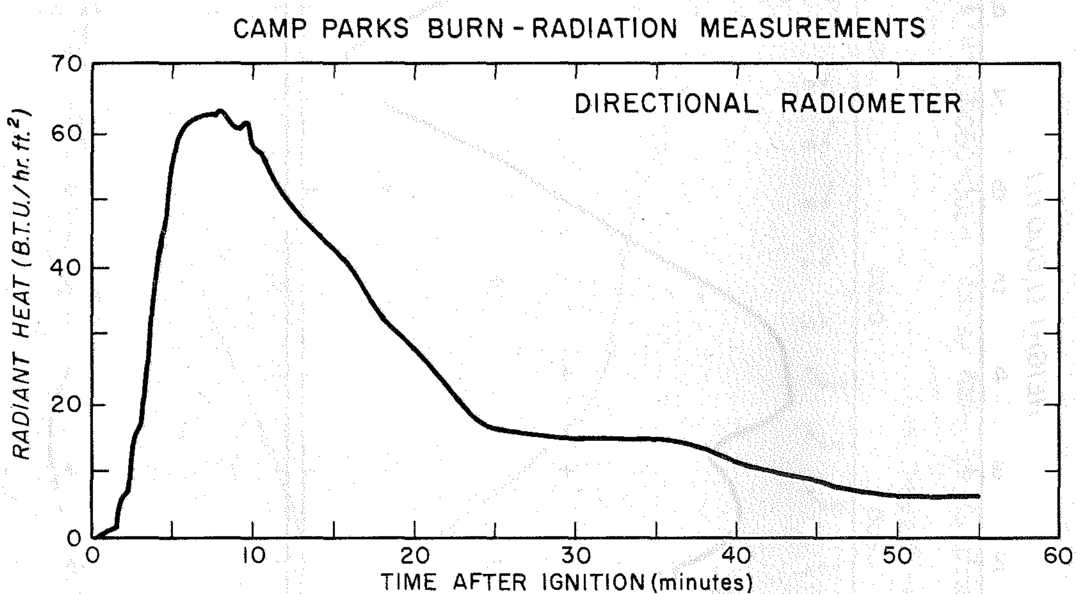


Figure 58.--Radiation measurements with directional radiometer, Camp Parks Burn.

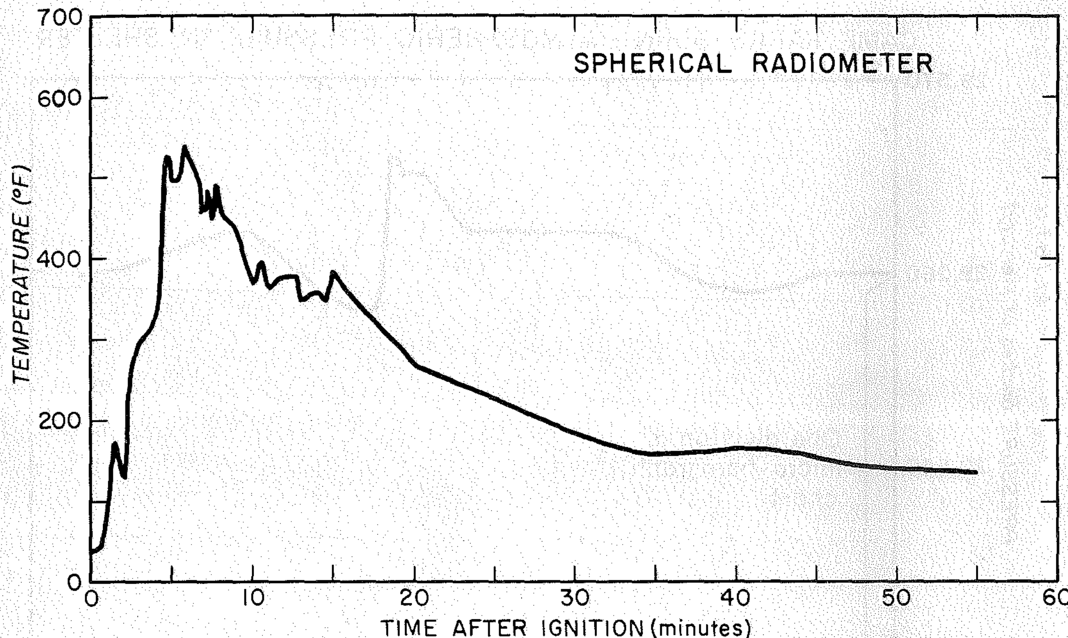


Figure 59.--Temperature-time history of spherical copper radiometer, Camp Parks Burn.

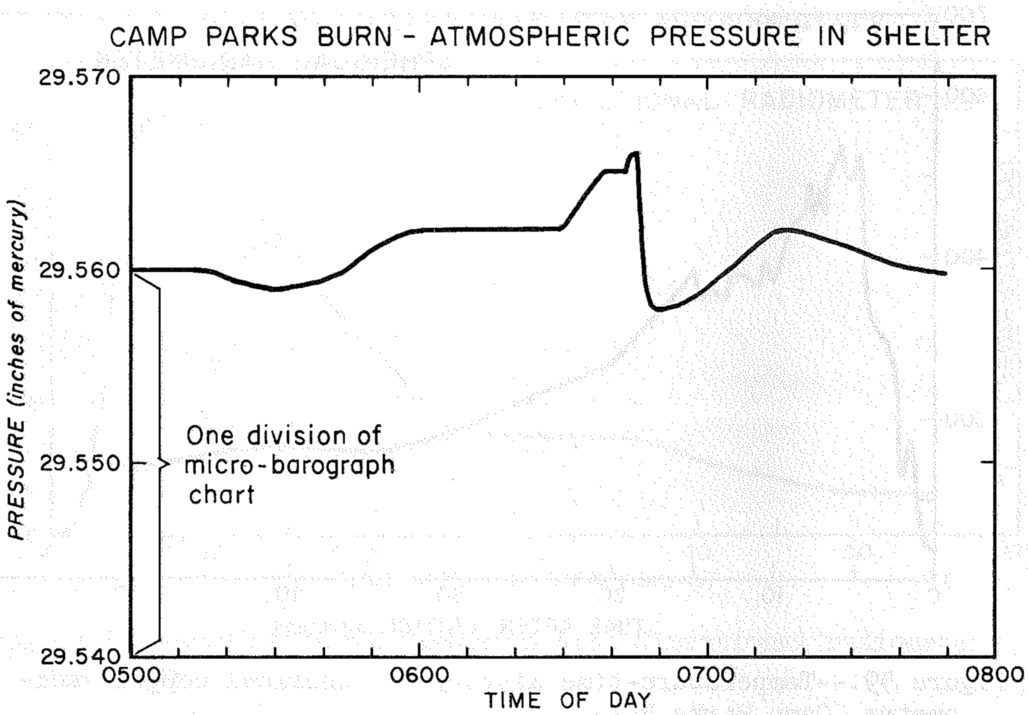


Figure 60.--Atmospheric pressure in shelter, Camp Parks Burn.