U. S. FOREST SERVICE RESEARCH NOTE PSW- 90

PACIFIC SOUTHWEST FOREST & RANGE EXPERIMENT STATION

Berkeley, California 1965

Temperatures in a Large Natural-Fuel Fire

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ABSTRACT: Temperatures in a large natural fuel test fire were measured with bare, shielded aspirated, and shielded unaspirated chromel-alumel thermocouples. With the bare thermocouples, values of 2650°F. were recorded--much higher than most previously published data from field and laboratory wood fires. Soil temperatures were consistent with prior work.

The U. S. Forest Service, under contract with the Office of Civil Defense (Project 2536A), is investigating the characteristics of large mass fires (Countryman 1964). Knowledge of temperatures in these fires is of particular importance because it can help:

- Establish the relationship between laboratory and field fires.
- Test the validity of theoretical fire models.
- Construct thermodynamic models of field scale fires.
- Compute convection column velocities.
- Determine the effect of environment on fire and of fire on its environment.

For such purposes, we need to measure the temperatures at several locations within the fire area, the time-temperature relationships, the rate of temperature rise and fall, the effect of air entrainment on temperatures, and the rate of heat loss into the soil. Much of the work thus far has been concerned with devising dependable measurement systems for large-scale test fires. This note describes methods used and presents some preliminary results.

Past Work

Flame, gas, and soil temperatures reported for fires in natural fuel have come mainly from two sources: (a) studies of the effects of fire on the environment and (b) laboratory experiments concerned with describing the thermodynamic characteristics of fire. Few data seem to be available on gas temperatures from wood fires. In any case, it is difficult to compare the results of most of these experiments owing to differences in quantity and type of fuels, weather conditions, and location of sample points in and around the fire.

OCD REVIEW NOTICE

This report has been reviewed in the Office of Civil Defense and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Office of Civil Defense.

Broido and McMasters (1960), working with a fire that burned 900 tons of windrowed trees and brush, measured temperatures of gases drawn into a pipe through a shielded opening 3 feet above ground. Maximum temperatures recorded inside the pipe were 1720° F. at 1 foot above ground level and 1450° F. at 2 feet above ground. Gas at 1 and 2 feet above ground level inside a similar 3-foot pipe placed 5 feet out from the fuel reached only 560° F. and 590° F., respectively. However, for a fire in about 250 tons of lumber and railroad ties distributed over 4 acres they reported that gas temperatures inside the pipe reached about 2600° F. before thermocouple failure.

Temperatures of 1600° F. were recorded from unshielded thermocouples on 5 headfires and 5 backfires in 8-year-old gallberry-palmetto roughs on the Alapaha Experimental Range near Tifton, Georgia (Davis and Martin 1960). Nelson and Sims (1934) reported that headfires in the longleaf pine type had temperatures that reached 1500° F. They also judged that by the appearance of clay cones (seger cones), the maximum temperature generated 6 inches above ground in hardwood leaf litter was 1830° F. In the same study, melted or distorted alloy spirals indicated that temperatures at 5 feet above ground generally reached 390° F. In a study of bark temperatures during forest fires, Fahnestock and Hare (1961) recorded values from bare iron-constantan thermocouples up to 1555° F., 3 feet above the ground on the lee side of a tree.

Vehrencamp (1956) burned railroad ties and reported that temperatures of bare chromel-alumel thermocouples in the center of the convection column at 40 feet reached 1050° F. He also found that a test fire in sagebrush had column temperatures up to 800° F., 20 feet above the fuel bed. His data were collected with bare thermocouples, but Vehrencamp's first approximation of the maximum error due to radiation is 150° F.

Bruce, Pong, and Fons (1959) measured temperatures with bare thermocouples several heights above wood crib fires. At 34 inches above the fuel surface the temperature reached 1500° F.; at 107 inches it rose only to 330° F. The temperatures nearer the fuel were lower than at 34 inches.

Beadle (1940) measured soil temperature during forest fires just under the soil surface and 1-inch deep. Values of 390° F. and 140° F., respectively, were measured with organic compounds of known melting points. Bentley and Fenner (1958) reported that a fast-moving fire in light litter type fuel heated the soil "surface" to 200-250° F. and just under the surface to 150-200° F. as measured with temperature-sensitive paints.

Methods

The study area is at 7,100 feet elevation, near Basalt, Nevada. Several plots, ranging in size from 4-1/2 to 50 acres, have been constructed with individual piles of fuel arranged to simulate average American housing tracts (fig. 1). Each pile contains 20 tons (ovendry weight) of natural fuel. About 95 percent is pinyon pine (Pinus monophylla Torr.)

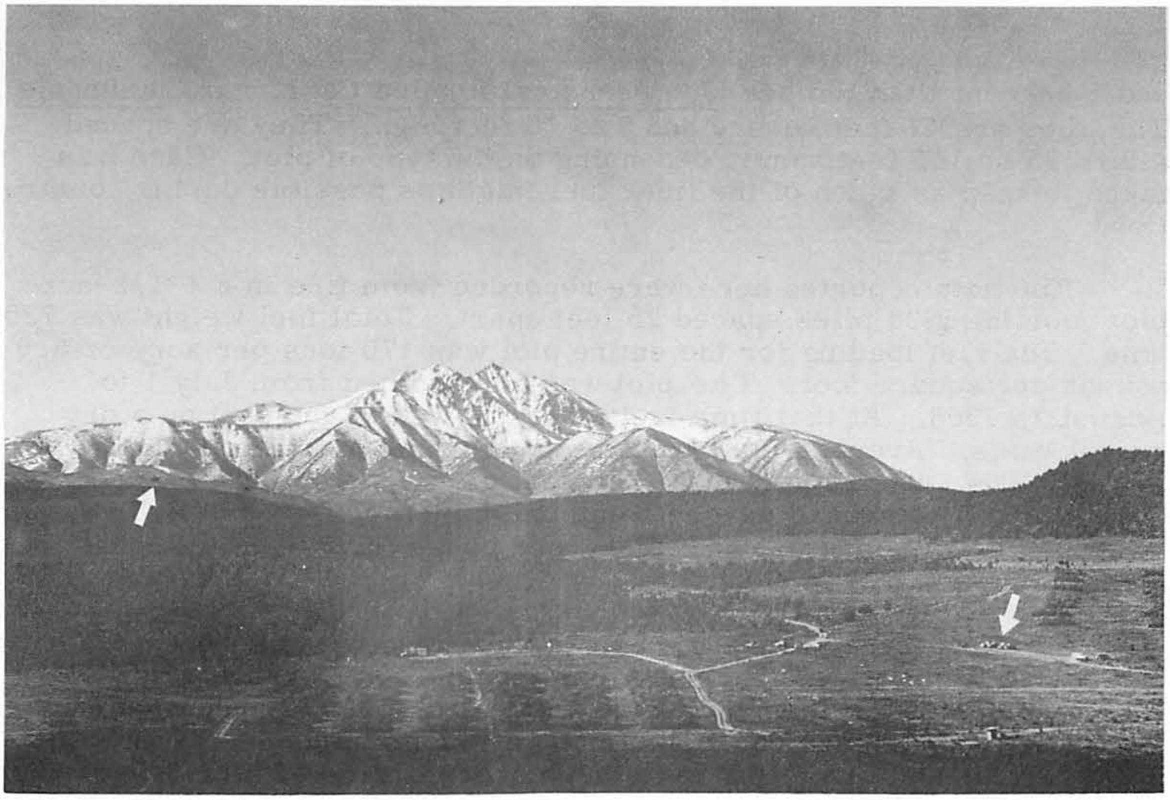

Figure 1.--Test fire plot before ignition. Note Helicopter (left) and four pickup trucks (right).

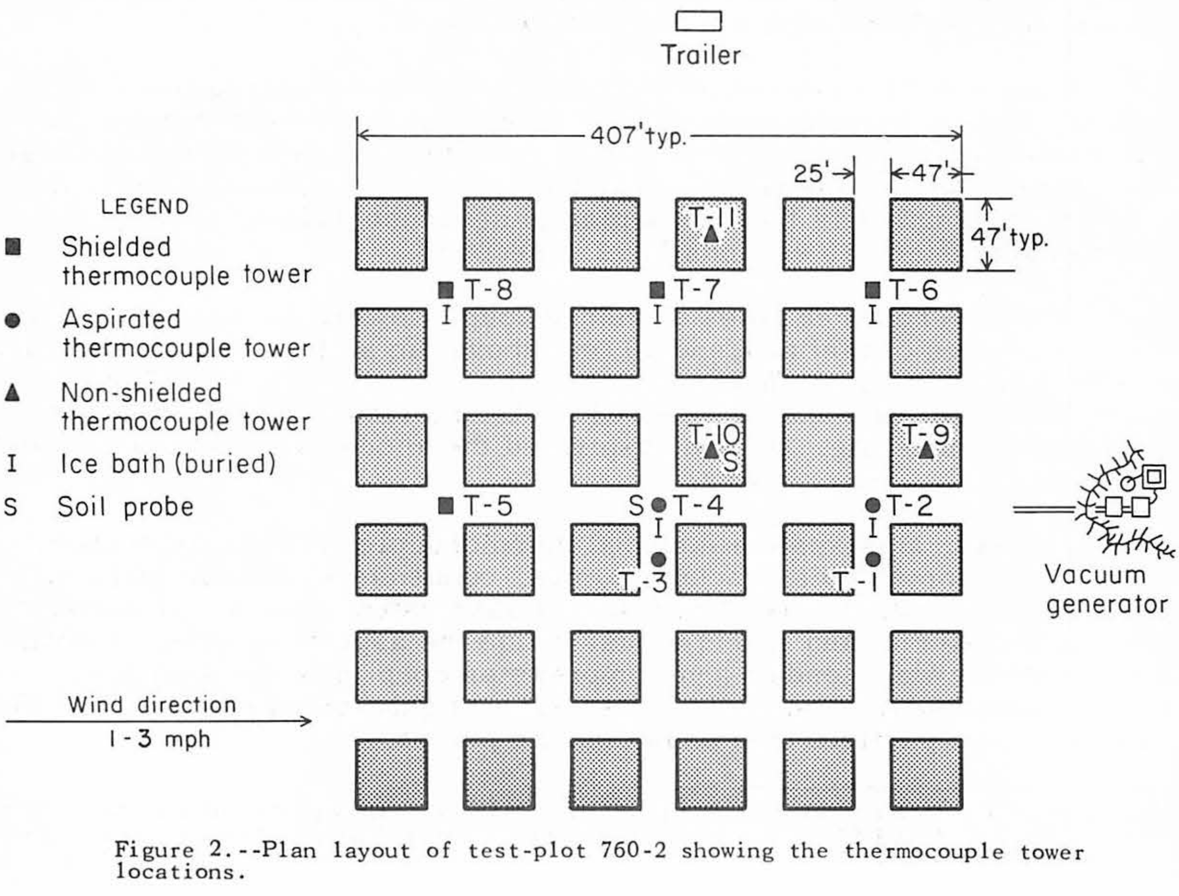

Figure 2.--Plan layout of test-plot 760-2 showing the thermocouple tower locations.

and 5 percent Utah juniper (Juniperus californica Carr. var. utahensis). The piles are 47 feet square and 7 to 10 feet high. They are spaced either 25 or 115 feet apart, depending on the type of plot. Care was taken to keep as much of the finer fuel intact as possible during construction.[1]

The data reported here were recorded from fire in a 4-1/2-acre plot containing 36 piles spaced 25 feet apart. Total fuel weight was 720 tons. The fuel loading for the entire plot was 170 tons per acre or 8.0 pounds per square foot. The plot was constructed from July 1 to August 2, 1963. At that time fuel moisture was 86 percent on a dry weight basis. Average fuel moisture at the time of ignition, 8:30 a.m. May 15, 1964, was 20 percent. The heat of combustion of this fuel, as determined by standard oxygen bomb calorimetry, is 9,500 B.T.U. per pound for needles and 8,500 B.T.U. per pound for twigs, branches, and stems.

Temperatures on this burn were measured with probes made from inconel-sheathed and magnesium-oxide insulated, 22 gauge (B.S.) chromel-alumel thermocouple wire, strapped to 1-1/2-inch steel pipe towers. These probes corrected many of the prior problems encountered in supporting and insulating bare thermocouple wire within and above a field test fire. Plastic coated chromel-alumel wire led from the probe underground to the respective cold junctions. The pile probes extended to the edge of the fuel. The cold junctions were immersed in buried vacuum bottles filled with ice and distilled water.

Copper wire was used as lead for the several hundred feet from each ice bath to instrument trailers. These lead-ins went through one of 3 sequence programers to balancing potentiometer recorders. These were Varian Model No. G-11A, and had a 1-second time constant. Each programer sampled 14 thermocouples in sequence and any given junction was sampled every 35 seconds for 2.5 seconds.

There were three types of thermocouple towers on this test burn. Within the piles of fuel at 7 and 20 feet above the soil were bare chromel-alumel thermocouples. In the aisles at the same heights were both shielded unaspirated and shielded aspirated thermocouples to measure gas temperatures (fig. 2). One aspirated thermocouple was also located at 50 feet on the center tower.

The aspirated system included thermocouple probes, aspiration tubes, radiation shields, vacuum pumps, condensers, butane tanks and generators (figs 3, 4). The probes were fabricated from the previously described material and inserted just inside the aspiration tube. Galvanized steel thin wall conduit and compression couplings made up the vacuum manifolds. The radiation shield was galvanized sheet steel. A condenser and particle trap protected the pumps.

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[1] Details of plot construction are given in study plan No. 2521E, on file at Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Riverside, Calif.

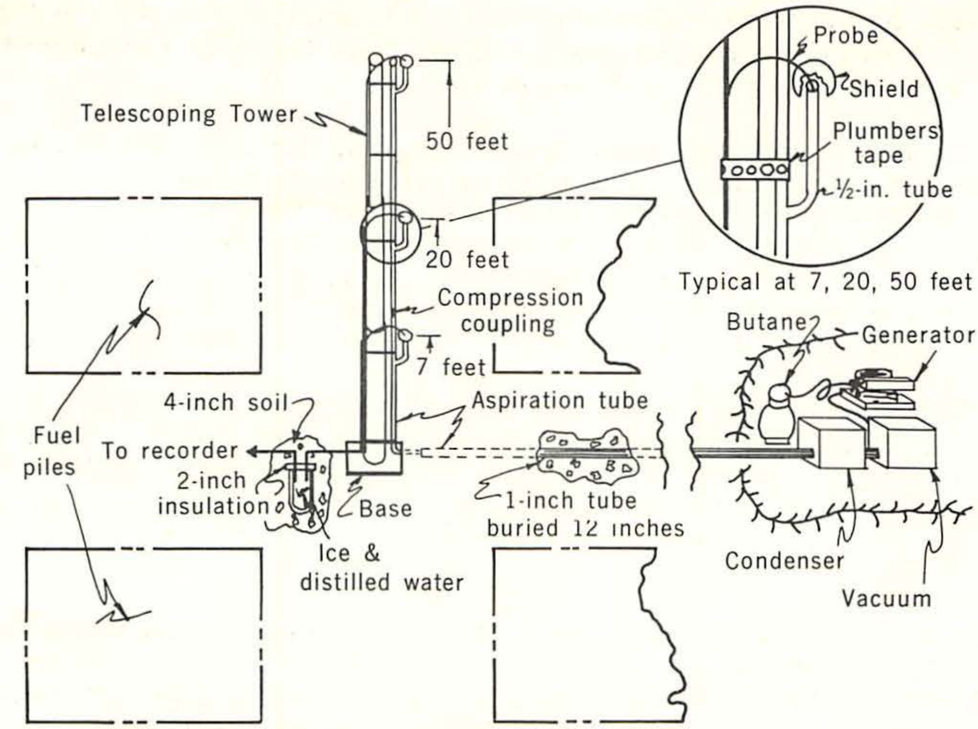

Figure 3.--Aspirated thermocouple system showing the 50 foot tower.

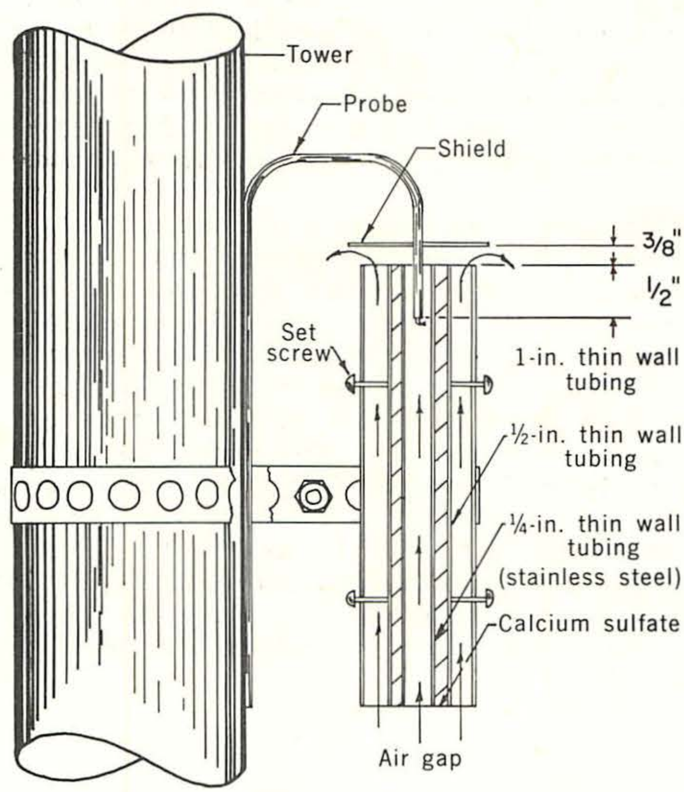

Figure 4.--Thermocouple shield used on this test fire.

Soil temperatures were obtained from probes at depths of 3 and 6 inches, between piles and under a pile. The junction was coated with plastic cement to insulate it from ground.

The shielded unaspirated thermocouples were protected from radiation by a multi-layer shield which consisted of three sections of tubing, each 4 inches long, secured one inside the other (figs. 3, 4). The outer tubes were 1- and 1/2-inch galvanized steel. The smaller inner tube was 1/4-inch stainless steel. A layer of calcium sulfate was placed between the 1/2-inch and 1/4-inch tube. A horizontal shield of galvanized sheet steel was placed 3/8 inch above the upper opening.

To ignite the fuel, ten 1-pound igniters of jellied diesel oil encased in plastic film were used in each pile. All igniters were fired simultaneously by means of electrical squibs and fuses. Ignition time (time zero) is the time when the fuel actually begins to burn (fig. 5).

Results

In all three of the instrumented piles, temperatures were recorded above 2650° F. However, chromel-alumel thermocouples are not very reliable above 2300° and the materials melt at about 2600°F. Thus, recorded temperatures higher than 2600° , are of questionable accuracy. Temperature recorded at tower T-9 (see fig. 2) rose to 1140° F. at 20 feet and to 2204° F. at 7 feet in the first 6 minutes after ignition (fig. 6); the recorded temperature at 20 feet reached 2650° F. at 7-1/2 minutes. This tower began to fail at 13-3/4 minutes, and the heights of the thermocouples after this are not known. Recorded temperatures at T-10 and T-11 reached 2650° F. within 2-1/4 minutes after ignition (figs. 7, 8). No valid data were recorded after this time from these two pile towers.

Gas temperatures recorded with the aspirated system showed a similar quick jump from ambient to the initial maximum, but there was a lag behind the values of the bare thermocouples. This lag can only be determined approximately because of the 35-second interval between readings, but appears to be 1 minute. The temperature at 20 feet was higher than that at 7 or 50 feet on tower T-4. The first peaks in gas temperatures (uncorrected) at 7, 20, and 50 feet were 1250° F., 2000° F., and 540° F., respectively (fig. 9). The initial peaks for tower T-3 at 7 and 20 feet were 1400° F. and 1100° F., respectively (fig. 10). The gas temperatures at T-3 and T-4 were quite similar at the second peak: about 1500° F. at 20 feet and 1300° F. at 7 feet. These two peaks are apparent in both gas and bare thermocouple data. Radiation measurements taken on the perimeter of the fire show also these two peaks at corresponding times. No data were recorded from T-1 and T-2 because of circuit failure.

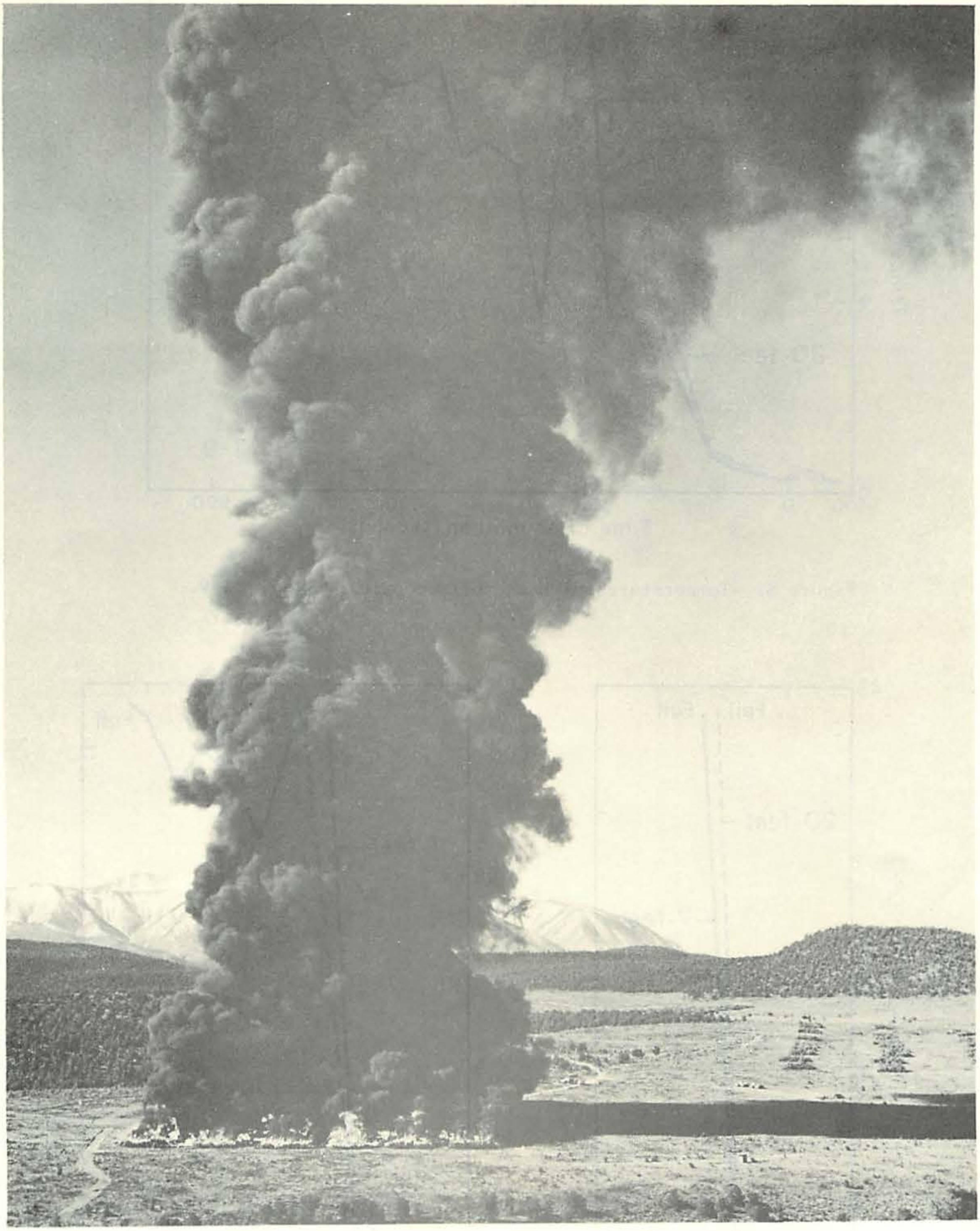

Figure 5.--Test fire 3 minutes after firing igniters.

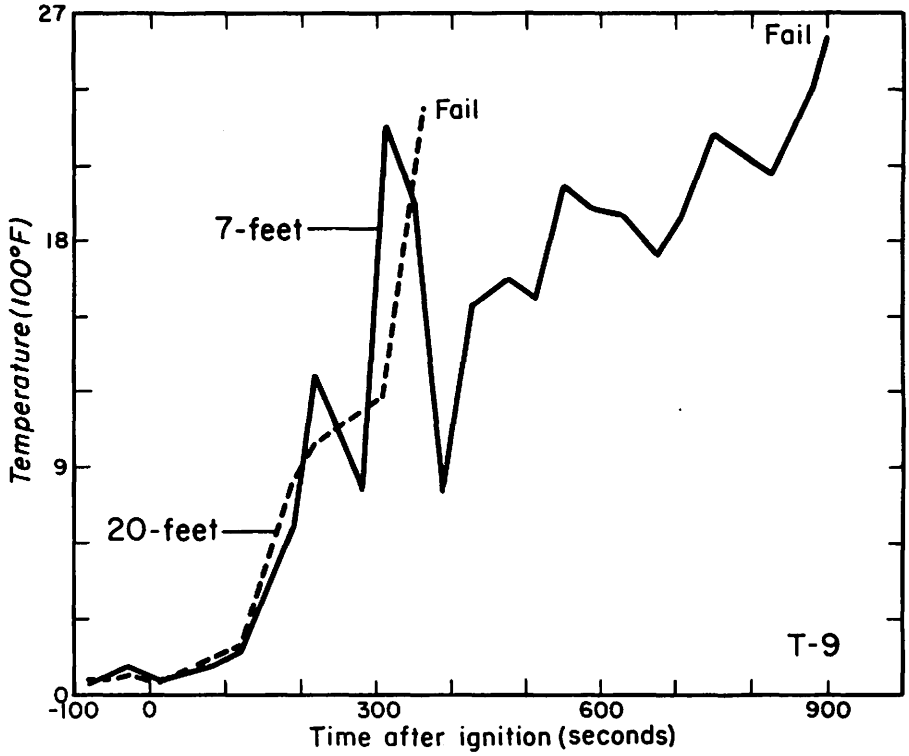

Figure 6.--Temperatures of bare thermocouple probes at T-9.

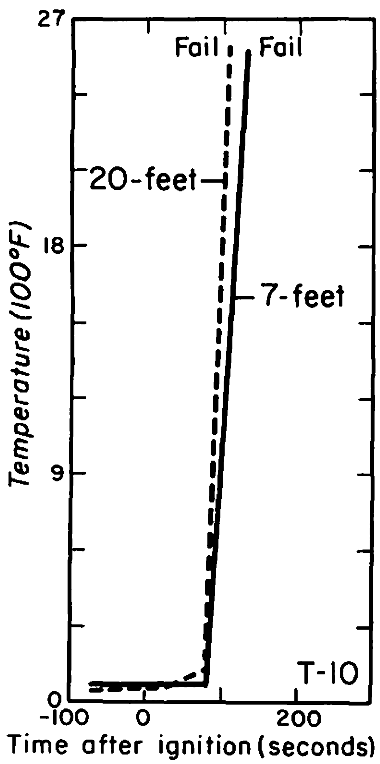

Figure 7.--Temperatures of the bare thermocouple probes on T-10 at 7 and 20 feet.

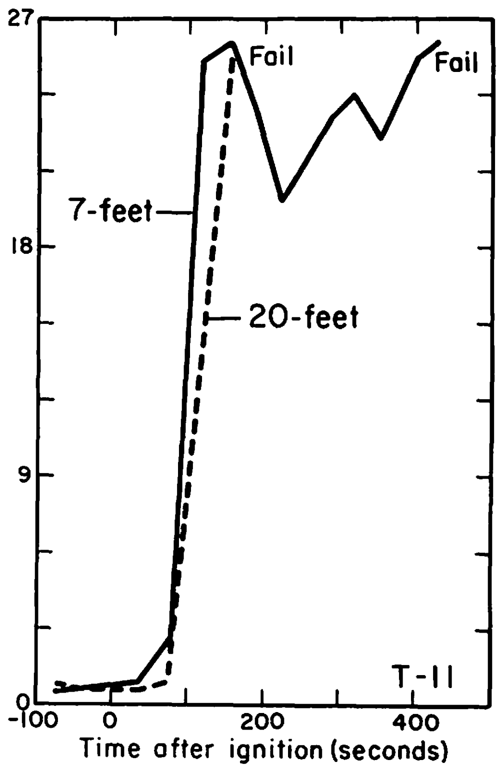

Figure 8.--Temperatures of the bare thermocouple probes on T-11 at 7 and 20 feet.

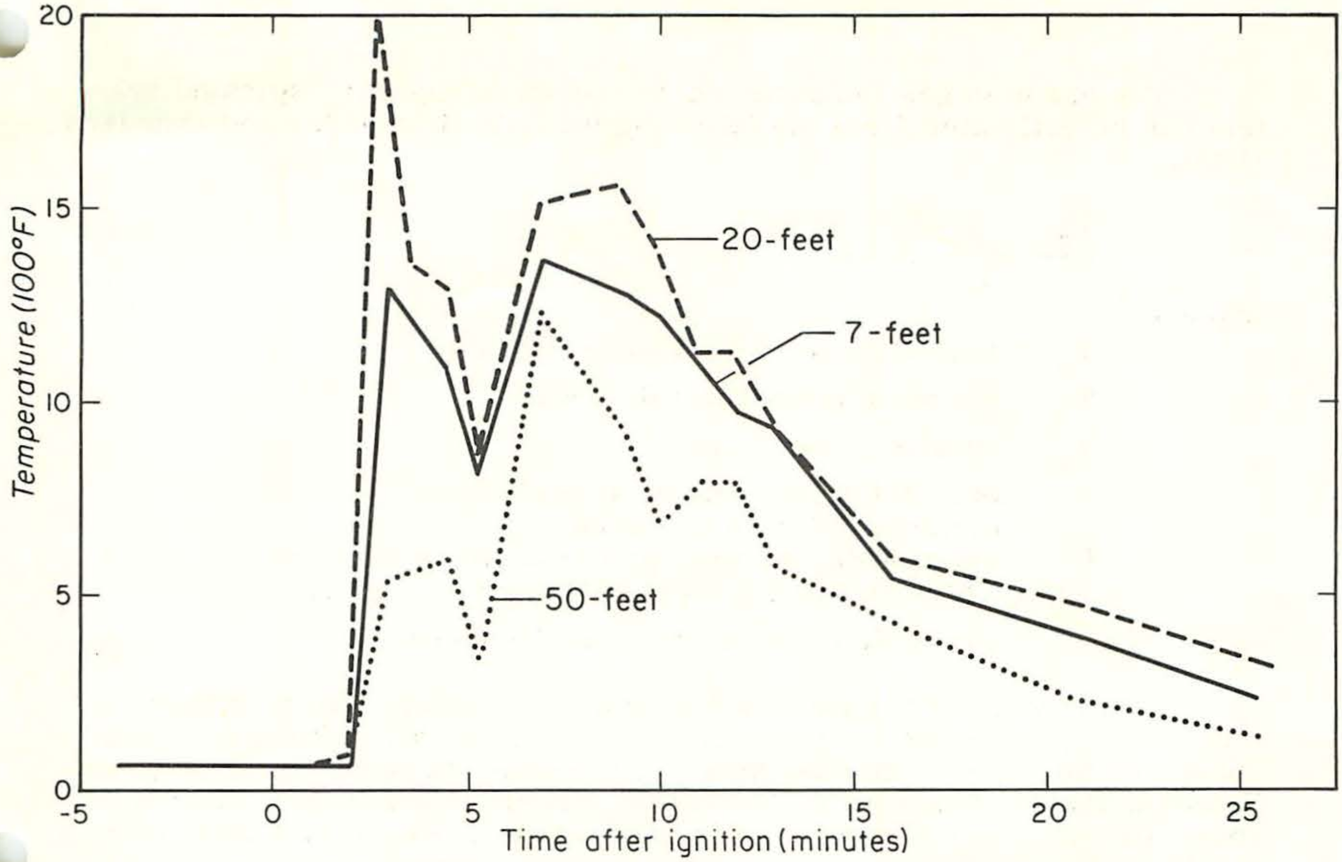

Figure 9.--Gas temperature at T-4, 7, 20, and 50 feet.

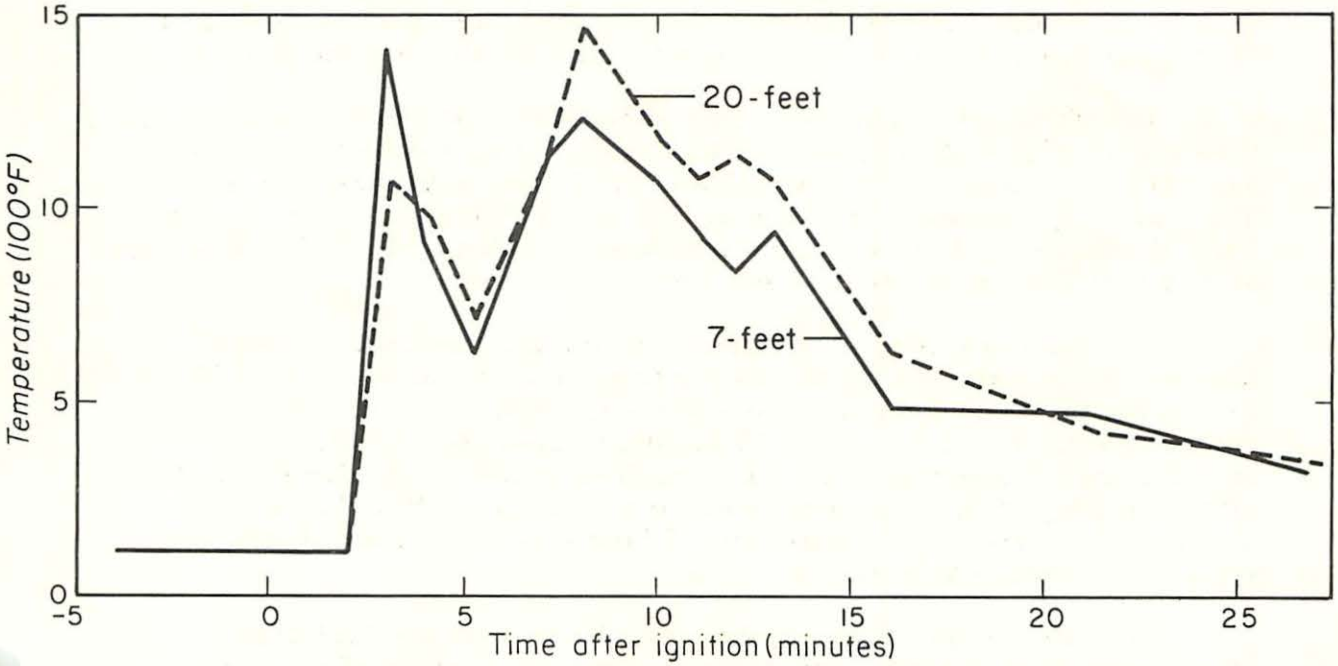

Figure 10.--Gas temperature on tower T-3 at 7 and 20 feet.

The error in gas temperature measurement by this aspirated system can be estimated from the following formula (Fishenden and Saunders 1939):

$$\frac{T_g - T_c}{T_c - T_w} = N\,d\,e.$$

Where:

T_c = temperature of the thermocouple
T_w = temperature of the shield wall
T_g = temperature of gas
e = emissivity of chromel-alumel
d = diameter of wire in inches
N = relationship between gas velocity, diameter of wire and the mean of T_c and T_w, given in table by Fishenden and Saunders.

The average of the gas velocity over the five aspirated couples was 56 feet per second as determined from a multivaned flowmeter and corrected for pipe friction as shown in Machinery's Handbook (Oberg and Franklin 1930). Assumed emissivity of chromel-alumel is 0.5 based upon Fishenden and Saunders. The diameter of the wire is 0.0201 inch and N is 35. The temperature of wall was not measured so an assumption must be made. At this gas velocity, 200° F. difference between the wall and the junction seems reasonable. If this assumption is used as a maximum the expected error is around ± 4 percent. This means that the gas temperatures in Figures 8 and 9 are probably within ± 4 percent of actual values. The position of the thermocouple and the high gas velocity greatly limit the effect of wall temperature on the junction.

The shielded unaspirated thermocouples, all of which were toward the outside edges of the plot, showed much lower temperatures than the aspirated thermocouples. An initial rapid rise is apparent at location T-5 and T-7, but does not show at T-6 and T-8 (figs. 11, 12, 13, and 14). Readings at T-7 reached a maximum of about 1400° F. Readings at T-6 and T-8 never went above 500° F.

Soil temperatures in the center of the plot (midway between the four center piles) rose quite rapidly from near freezing to 120° F. at 3-inch depth. The temperature at 6-inch depth at this same location, rose from 32° F. to 60° F. in 45 minutes, then rose gradually to 75° F. at 180 minutes after ignition. It remained quite steady for some time after this (fig. 15). The temperature at 3-inch depth between piles decreased slowly after 30 minutes; 5 hours after ignition it was about equal to the value at 6 inches.

The soil temperatures under the pile of burning fuel began to rise 30 minutes after ignition and were still rising slightly after 5 hours and 40 minutes of recording. The temperature at 3 inches reached 175° F.; at 5 inches, 105° F. The 30 minute lag behind temperatures between the

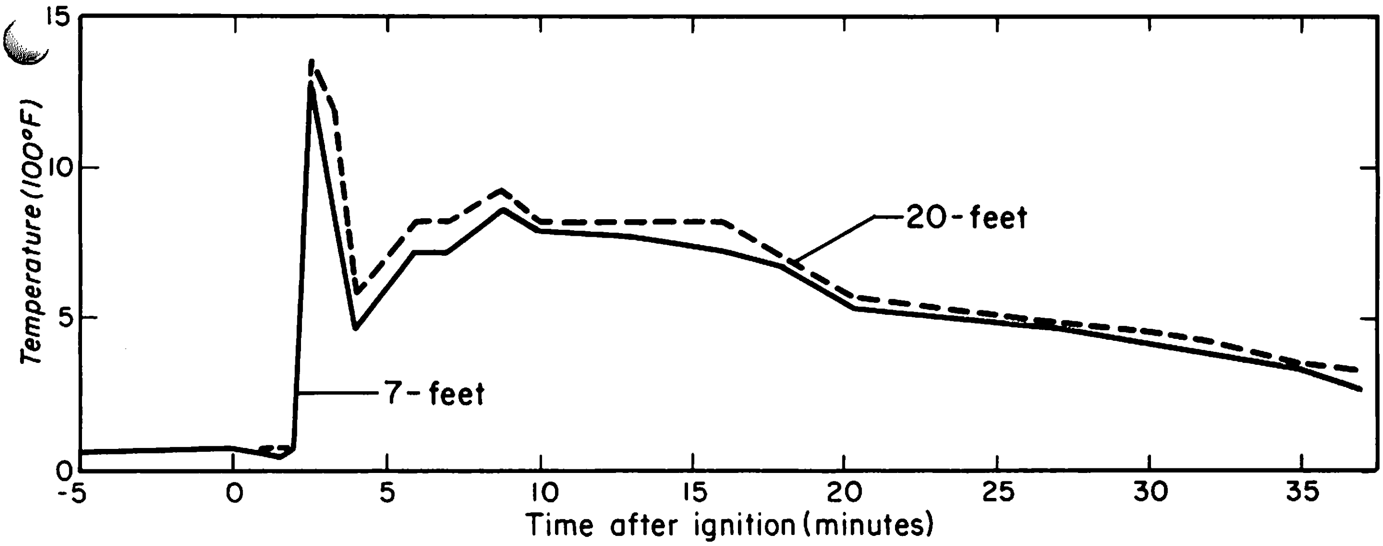

Figure 11.--Results from the shielded thermocouple probes on T-7.

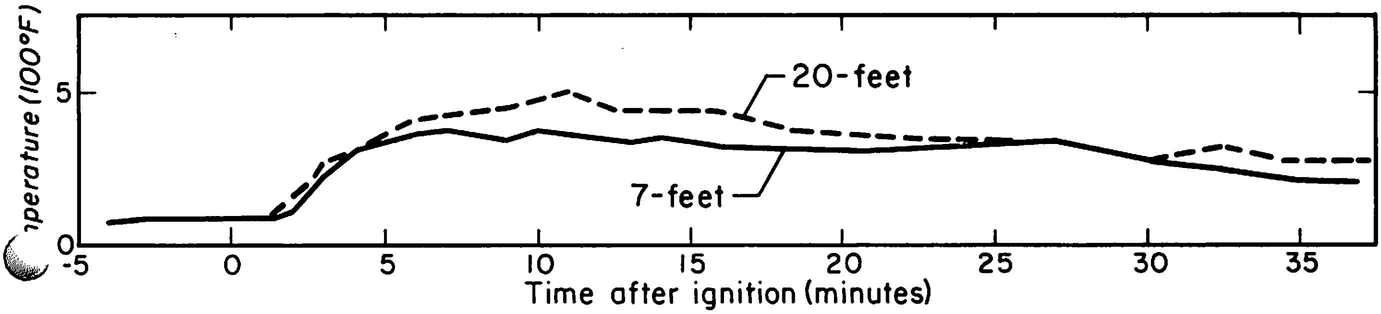

Figure 12.--Results from the shielded thermocouple probes on tower T-8.

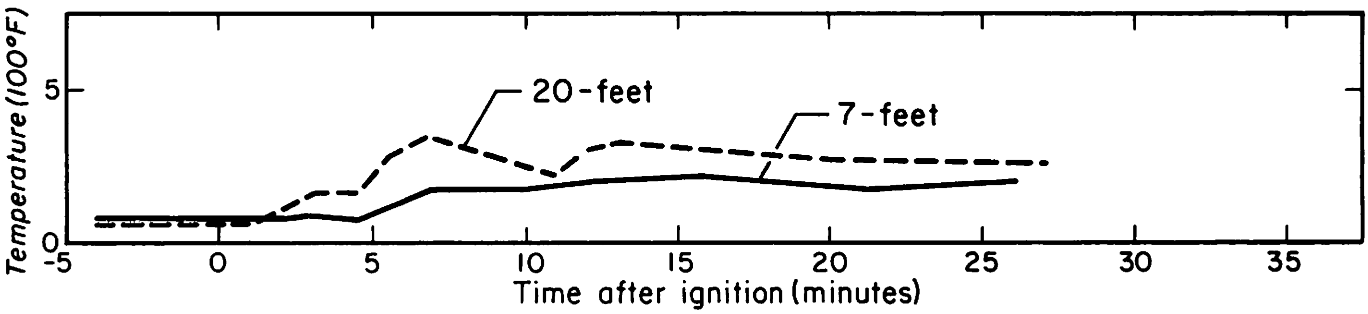

Figure 13.--Results from the shielded thermocouple probes on tower T-6.

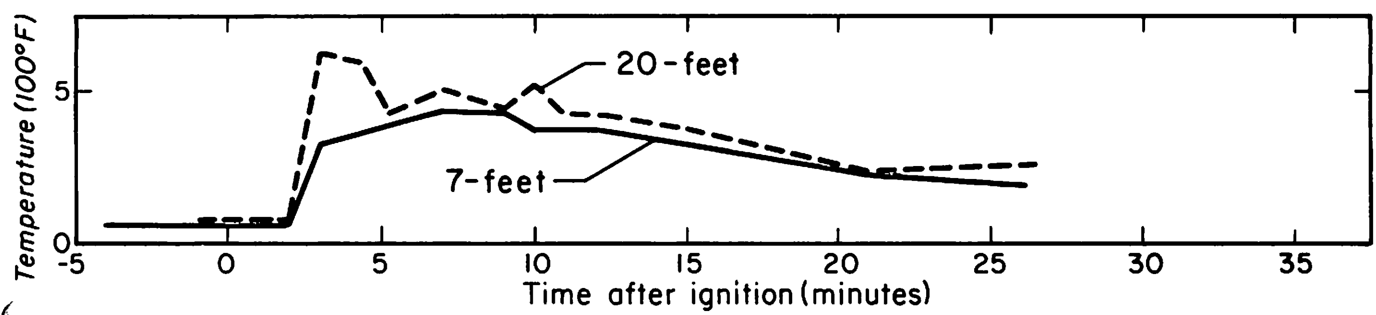

Figure 14.--Results from the shielded thermocouple probes on tower T-5.

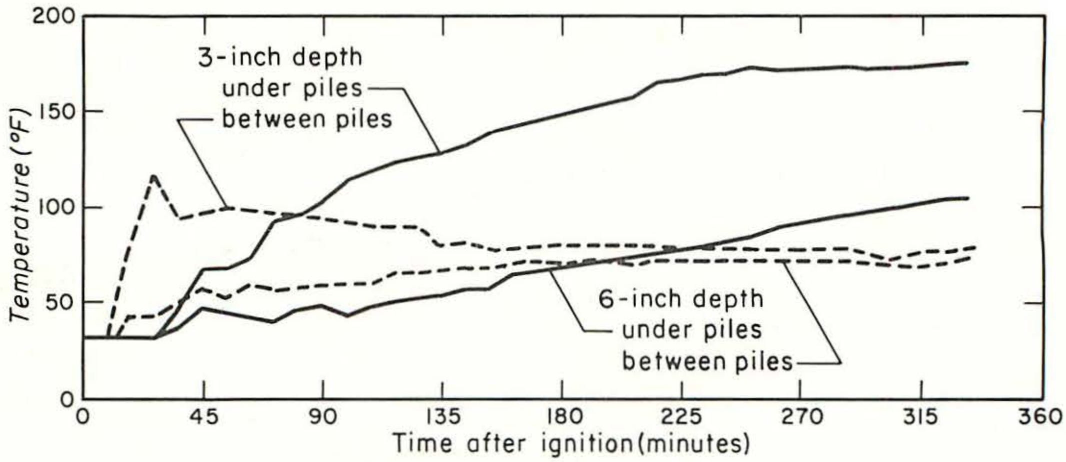

Figure 15.--Soil temperatures at two depths, under and between piles.

piles is probably due to insulation of the soil surface from radiation and conduction by non-burning fuel such as large logs.

Summary and Conclusions

Temperatures of 2650° F. were recorded by bare thermocouples in and above the flame zone on a large field test fire. Even higher temperatures are probable, judging from such evidence as the melting of steel and chromel wire and the light yellow-orange areas of flame appearing in certain areas of the fire. This means that the 1500° F. measured by Bruce, Pong, and Fons (1959), the 1800° F. predicted by Byram (Davis 1959), the 1500° F. reported by Lindenmuth and Byram (1948), and 2000° F. predicted by Vehrencamp (1956) are low for mass fire situations. These values relate to much lighter fuel loadings than in the present study. Our readings are more in agreement with the 2600° F. recorded by Broido and McMasters (1960). Therefore, it may be necessary to use values of 2600° F. or higher when trying to describe the thermodynamics of large fires.

Soil temperatures are in general agreement with past work although comparison is difficult because of differing test conditions.

Two temperature peaks were recorded by bare and aspirated thermocouples in this fire. Two peaks have shown up on most previous test fires in this study and are also apparent from the radiation data. The cause is apparently an initial fast rate of combustion of fine fuels followed by a period of less intense burning until intensity of fire in the medium and coarser fuels reaches a maximum.

Chromel-alumel thermocouples are suitable for most temperature measurements on large fires. But to record temperatures above 2650° F., some other material such as platinum-platinum rhodium junctions, must be used. An aspirated thermocouple system proved practical on this large field-test fire, but measurement of tube wall temperatures would aid correction of gas temperatures for the effects of the environment surrounding it.

The unaspirated shielded thermocouples, produced much too great a lag time to be of value for gas temperature measurement, as Vehrencamp (1956) found in earlier work. Earlier Forest Service tests had shown that temperature records from bare thermocouples fluctuated so rapidly that comparison of heat output at different points in the fire was difficult (Countryman 1964). Budget limitations prevented the installation of heating-rate transducers, so the shielded couples were used for a rough measurement of heating at different locations. Apparently the difference in heating between the towers at T-5 and T-7 and those at T-8 and T-6 is due to inflow of ambient air. The two locations exhibiting higher heating were exposed to inflow from only one direction. Points T-8 and T-6 were exposed to inflow from two directions.

In future tests the number of sample points will be increased to permit determination of horizontal and vertical temperature patterns. Heat flux will be measured with thin foil heating-rate transducers. A self contained aspirated thermocouple is also being developed to simplify instrumentation of large test fires.

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