

A Steady-State Technique For Studying The Properties of Free-Burning Wood Fires

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ABSTRACT

A laboratory study was set up by the U. S. Forest Service with the ultimate objective of determining model laws for properties of wood fires, including rate of spread. This is a report of the first phase of the work, the development of a suitable bed of solid fuel and the technique of study. The bed chosen for initial study is in the form of long cribs of wood sticks. The technique is to start the crib burning at one end and to move the crib so as to keep the flame in a fixed position in space. Thermocouples in the convection column, radiometers, Pitot tubes, gas sampling tubes, and other equipment are stationary. After an initial period of growth, the fire reaches a steady state. The effect of such variables as species of wood, density of wood, moisture content, size of fuel particle, spacing, dimensions of crib, wind, and slope, on the rate of the fire and the partition of energy can be measured.

Introduction

Much has been written concerning the process of combustion, mostly on controlled combustion. Relatively little has been written on uncontrolled fire. The reported work on models of uncontrolled fires¹⁻³ consists of studies of laboratory fires under transient conditions, which includes the build-up time in the determination of the rate of burning. Some workers have made contributions to convection column theory^{4, 5} and others have stressed the need to design an appropriate model representing an uncontrolled fire for development of model laws of fire behavior.^{6, 7}

To the authors' knowledge, a technique for studying uncontrolled fires under steady-state conditions for wood fuels has not been reported. Such a technique could make it possible to study all phases of solid fuel fires, both theoretically and experimentally, investigating individually all parameters that affect the fire, and inquiring into the effect of each independent variable on each aspect of the fire behavior.

The U. S. Forest Service has conducted research for many years on free-burning forest fires under realistic or simulated natural conditions. A recent study at the Pacific Southwest Forest and Range Experiment Station was made on free-surface burning of liquid hydrocarbon fuels. From data on 148 experimental fires, a dimensionless correlation based on heat transfer-mass transfer analogy was established for rate of combustion for liquid fuel fires of limited size. The free liquid surfaces differed radically from those of solid fuels, and the liquid-fuel fires never reached a steady state. There was a clear need to develop a steady-state technique in wood fuels for basic studies of fire.

Following the recommendations of the Committee on Fire Research of the National Academy of Sciences—National Research Council for an expanded research program on fire, the Office of Civil and Defense Mobilization made funds available to augment fire model research work of the Forest Service. The objective of the first phase of Project Fire Model has been to develop a steady-state aerothermodynamic system, burning solid fuels, in which the parameters that govern the combustion may be examined over an extended period of time.

It is planned to use this system in a program of "diagnostic modeling" of a free-burning fire with the following objectives:

- 1) To study this type of system with experimental fire models in which fuel, fuel bed, fire base, and atmospheric conditions are controlled; to evaluate quantitatively the effects of each variable on the fire; and to determine the model laws for fire properties including rate of fire spread;
- 2) To obtain information about the effects of the properties of the air, fuel, and fire base on the following:
 - a) Total rate of energy release
 - b) Distribution of the released energy

- c) Temperature, pressure, convection, and radiation pattern in and around the fire;
- 3) To achieve a heat balance on a free-burning wood fire.

Method

Essential elements for the fire model are a wood fuel bed, a combustion table equipped to transport the fuel bed at a controlled rate, a base of slabs on which the fuel rests, and instruments to measure specified variables.

The fuel bed is a crib of wood sticks of square cross section (Figure 1). The physical features of such a crib can be controlled—for example, the species of wood, the density of the wood, the dimensions of the sticks, the moisture content, the spacing, and the width and height of the crib.

The crib is formed by placing the sticks in tiers with a particular spacing between sticks. A small drop of thermo-setting resin glue is placed on each junction to bond the crib into a rigid assembly. Before testing, the cribs are conditioned to moisture equilibrium in an atmosphere of constant relative humidity and temperature. The moisture content of the conditioned wood is determined by xylene distillation.

The ignition device (Figure 2) is a shallow trough containing 10 to 20 cc of n-hexane and an asbestos wick. One end is set afire by lighting the asbestos wick. The fire gradually spreads to the other end of the crib, reducing the wood to a residue of charcoal.

A chain-belt mechanism in the combustion table is used to move the crib (Figure 3). The crib and its base rest on the chain belt which is moved manually by a worm-gear drive to hold the column of flame stationary (Figure 4). The mechanism also draws two heavy asbestos sheets (Figure 3), one on each side of the fire, in synchronism with the flame spread to simulate the relative movement of ground and fire front.

Several separate slabs make up the base for the test cribs. Any practical material may be used for the slabs, such as earth, concrete, or prepared flooring. Thus far, preformed concrete slabs with a density of about 90 pounds per cubic foot have been used.

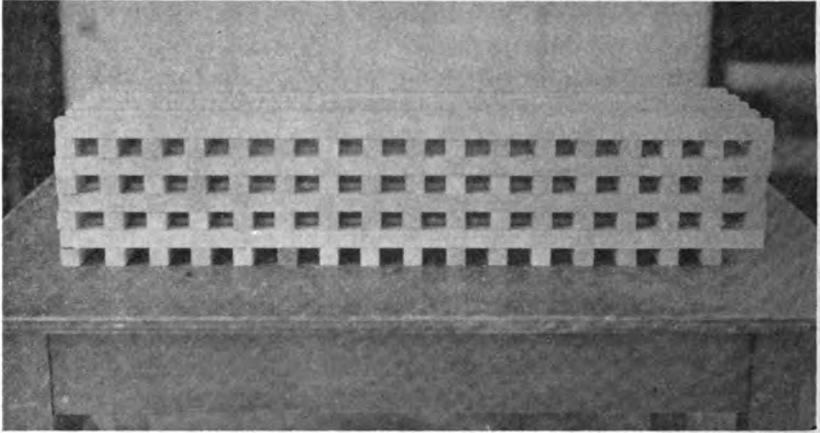


Figure 1. Wood crib assembled for a test fire. A trough of hexane will be ignited under the left-hand edge, and the flame will travel through the crib from left to right.

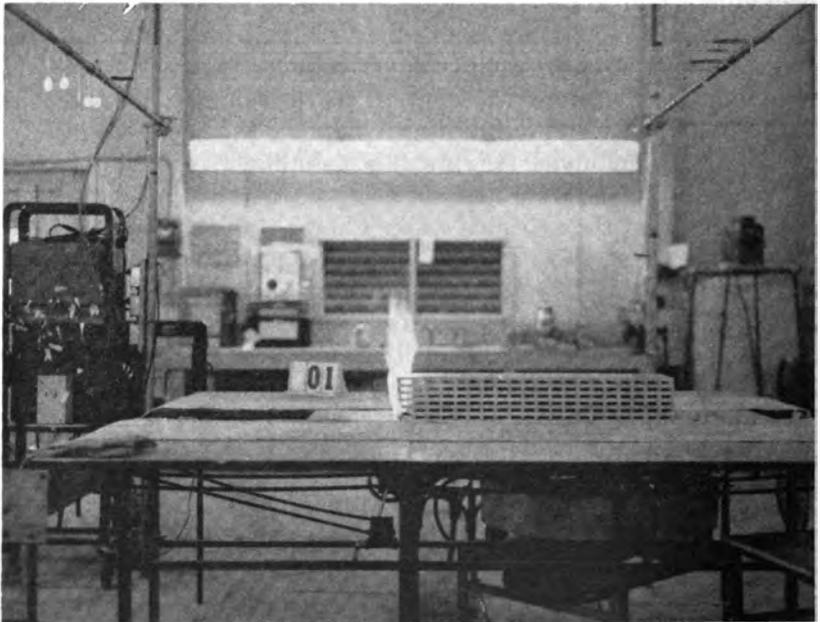


Figure 2. Ignition of a test crib. The flame is from burning hexane in a shallow trough beneath one end of the crib. The hexane soon burns away leaving the wood afire.

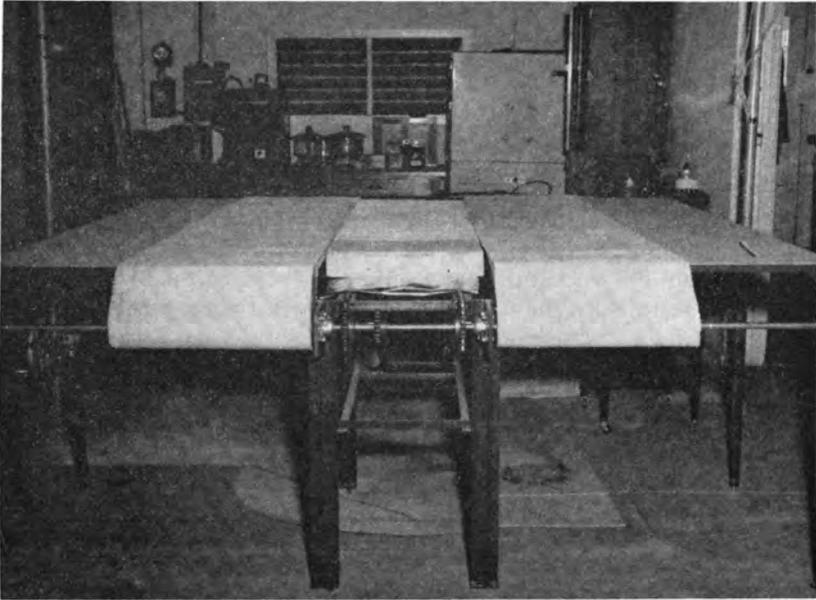


Figure 3. Combustion table with chain belt manually driven by the hand wheel seen under the table at the far left. On the chain belt are concrete slabs on which the test crib will be placed. At each side of the concrete slabs are asbestos belts which move with the slabs.

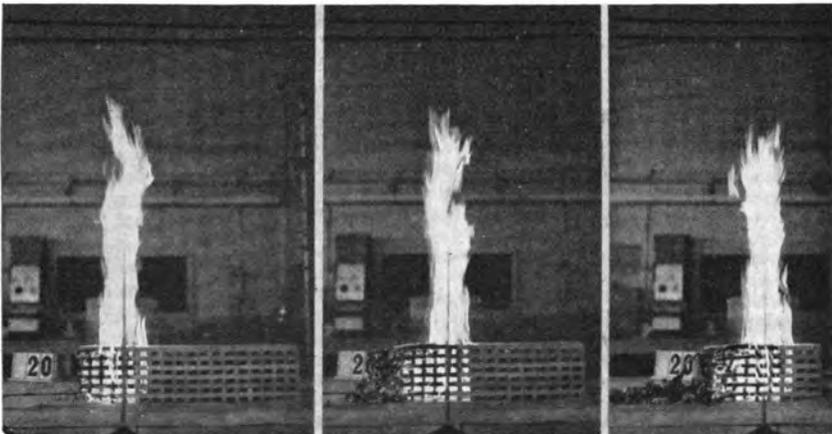


Figure 4. Flame from a test fire at three different times, illustrating the fixed position of the flame as the crib moves.

To measure temperatures of the convection column, a grid of 36 chromel-alumel thermocouples is placed above the combustion table, crosswise and lengthwise of the crib, from 1 inch above the top of the crib to 10 feet above the level of the table (Figure 5). The thermocouples are connected to multipoint recording potentiometers.

The smoke from the fire flows up into an 11-foot square hood and is vented through a stack 13 inches in diameter. Near the top of the stack is a motor-driven blower to force the exhaust. A thermocouple in the stack measures the temperature of the combustion gas. A Pitot tube connected to an ionization-type pressure transducer measures the velocity of the stack gas.

Radiation from the crib fires is measured by a thermopile radiometer (Figure 6) mounted so that it can be pointed toward the fire at various angular elevations from the horizontal, the radiometer being always at a radial distance of 14 feet from a selected point in the fire. The stand is movable so that the radiometer can be pointed at the fire from front, back, or either side.

To measure the heat transmitted from the fire to the base, the center slab of the base is removed soon after each fire and immersed in water in a sealed and insulated calorimeter box (Figure 7). The temperatures of slab and water gradually come to equilibrium, and the heat content of the hot slab is calculated from the rise in temperature of the water.

The burning wood leaves a residue of charcoal consisting of ash, carbon, and partially carbonized wood. The residue from each fire is collected, weighed, and pulverized. Samples of the charcoal powder are burned to ash in a muffle furnace to determine their carbon content, and other samples are tested for their heat value in a bomb calorimeter.

A technique of collecting samples of combustion gas in glass sampling bottles has been developed for analysis either in Orsat apparatus or by gas chromatography.

A series of thermocouples, suspended from ceiling to floor in the laboratory and connected to a multiple-point recording potentiometer, gives a continuous record of the lapse rate inside the room during each experimental fire. Also, thermopile heat-flow meter plates, fastened to the walls and ceiling of the room,

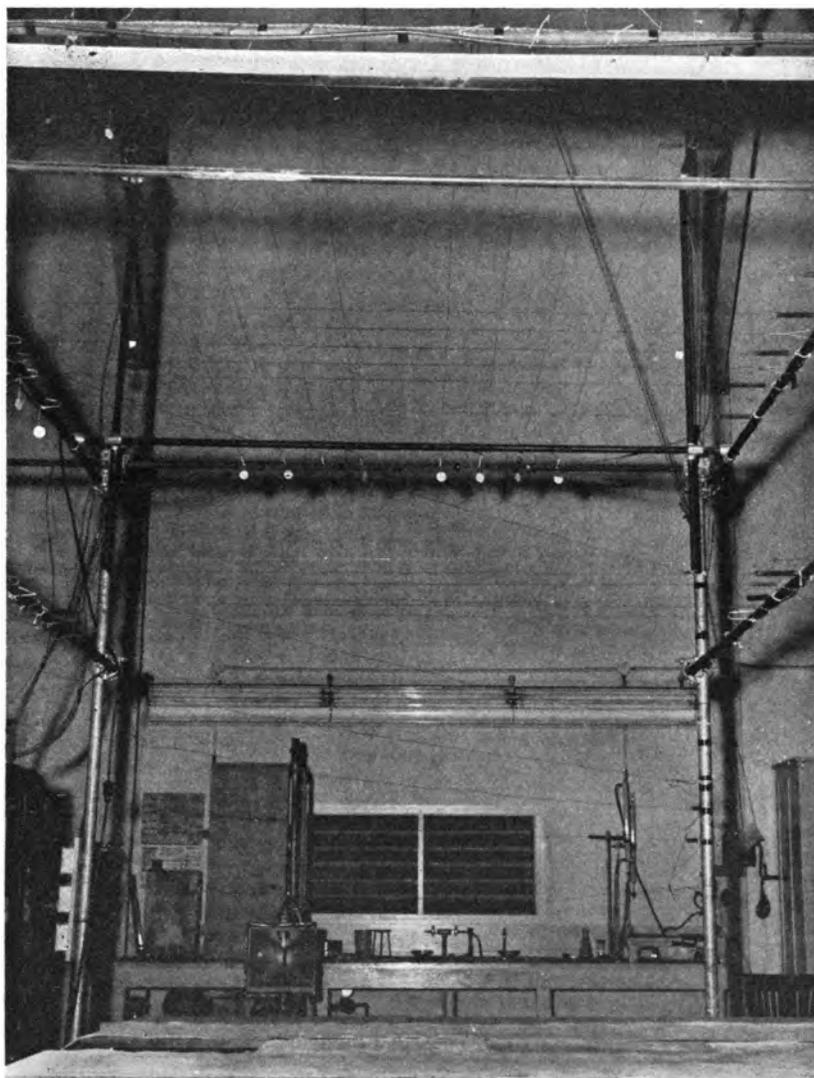


Figure 5. Grid of thermocouple wires above the combustion table

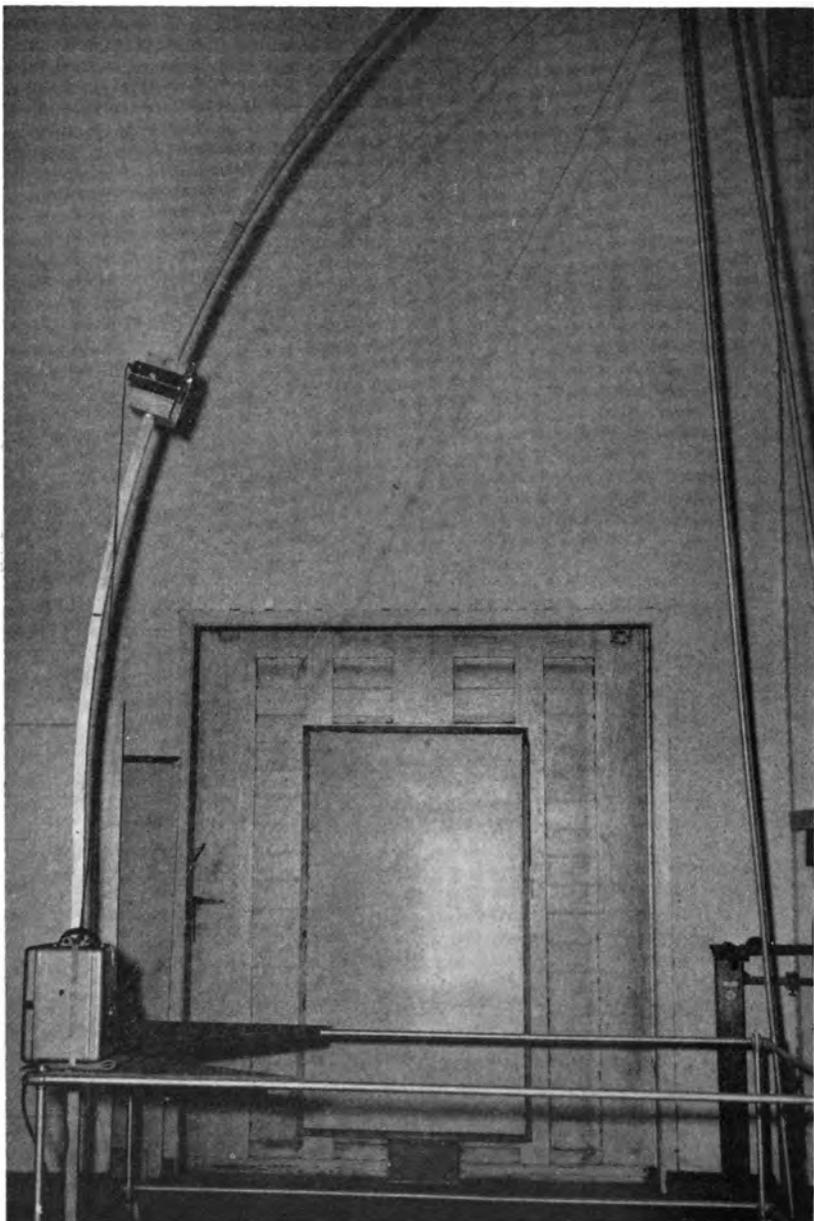


Figure 6. Thermopile radiometer mounted on a long circular-arc arm on which the radiometer can be slid up or down to various altitudes, always pointing at a selected point in the fire.



Figure 7. Hot concrete block being put into a water calorimeter to measure its heat content.

provide data on the rate of transfer of heat out from or into the room through the ceiling and walls during the tests.

Two motion-picture cameras take time-lapse movies of the fires from the side and rear. From these photographs the width and height of the flame can be measured and any unusual behavior can be detected. A carbon arc casts shadowgraphs of the flame and convection column onto a screen, and the images are photographed.

Two important features of the procedure are: (1) The crib is made relatively long, and a zone or band of fire travels the length of the crib. After an initial period of buildup, the crib fires reach a steady state which they hold until near the end. Thus is overcome the difficulty of investigating a fire that starts small, grows to a maximum, then declines. It is the behavior of the fire in the steady state that is currently being investigated. (2) The position of the flame is held fixed in space by moving

the fuel into the fire. This technique permits thermocouples, radiometers, and other instruments to be stationary. The rate of fire spread is the rate the fuel has to be moved to maintain the flame in fixed position.

Results

Project Fire Model during its first year has developed an aerothermodynamic system burning solid fuels under steady-state conditions. Some of the data obtained are presented here to illustrate its diagnostic usefulness.

In the experimental fires to date steady-state conditions have been maintained for 15 to 30 minutes, but the duration of the steady state is limited only by such practical considerations as the length of the crib. During the steady-state burning, rate of spread of fire through the crib was linear (Figure 8). The linearity of the rate of spread after the critical build-up indicates how well a steady state has been achieved.

The effect of density of the wood on the rate of spread of the fire was investigated early because the information was essential to the selection of wood for the cribs. An increase in specific gravity decreased the rate of spread of the fire through the crib (Figure 9). The rate of combustion expressed in Btu. per second plotted against specific gravity of the wood in the crib was linear (Figure 10).

The horizontal distribution of temperature in a convection column at several heights is shown in Figure 11, and the change in temperature up the central axis of a convection column in Figure 12. Thermocouples in the flame just above the crib registered a lower temperature than those a short distance higher in the flame, where maximum temperatures were recorded up to 1650°F.

The part of the heat of combustion that went into the concrete slabs on which the cribs rested, varied from 2.3 per cent for the largest crib tested to 7.1 per cent for the smallest. In Figure 13 the rate of penetration into the concrete is plotted against the fire intensity, both expressed in terms of Btu. per second per foot of fire front. The points plotted in Figure 13 are rather scattered inasmuch as the rate of penetration depends also on the width and height of the crib and the density of the

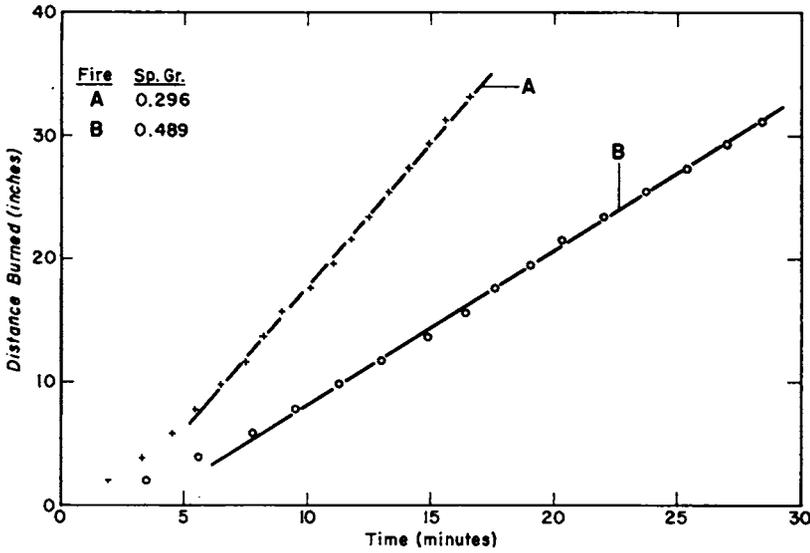


Figure 8. Spread of fire through cribs of white fir wood of two different specific gravities.

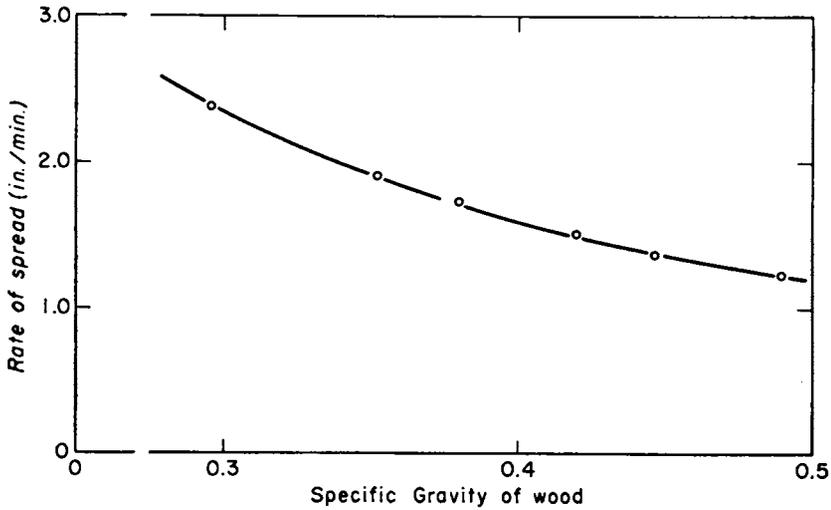


Figure 9. Rate of fire spread through cribs of white fir of different specific gravity.

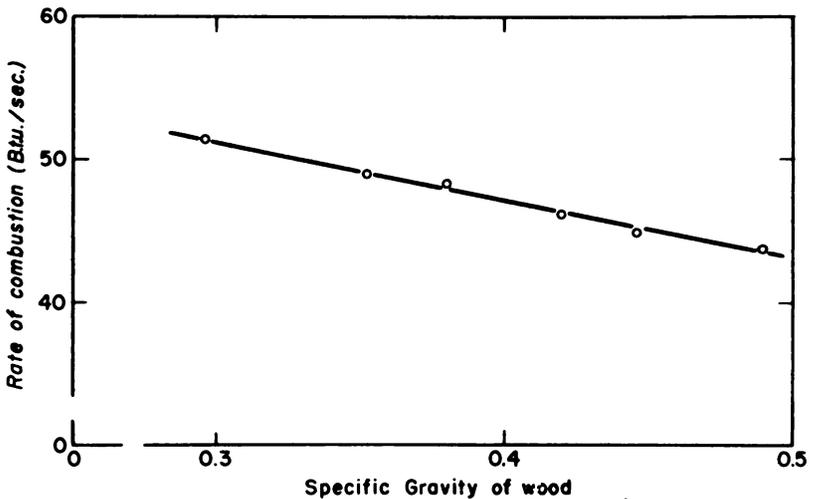


Figure 10. Rate of combustion through cribs of white fir of different specific gravity.

wood, and the data are insufficient to allow segregation of these four parameters.

Some of the heat value of the fuel is always left in the form of unburned charcoal. Figure 14 shows the amount of charcoal left as a residue from cribs of different weights. The heat remaining in the charcoal averaged 1.21 per cent of the total heat of the fuel.

Figure 15 plots irradiance to the side of the fire at an angle of 20° from the horizontal against rate of combustion. With irradiation measured from the sides, front, and rear of the burning crib at several angular altitudes, it should be possible to get a close estimate of the radiation energy from these model fires.

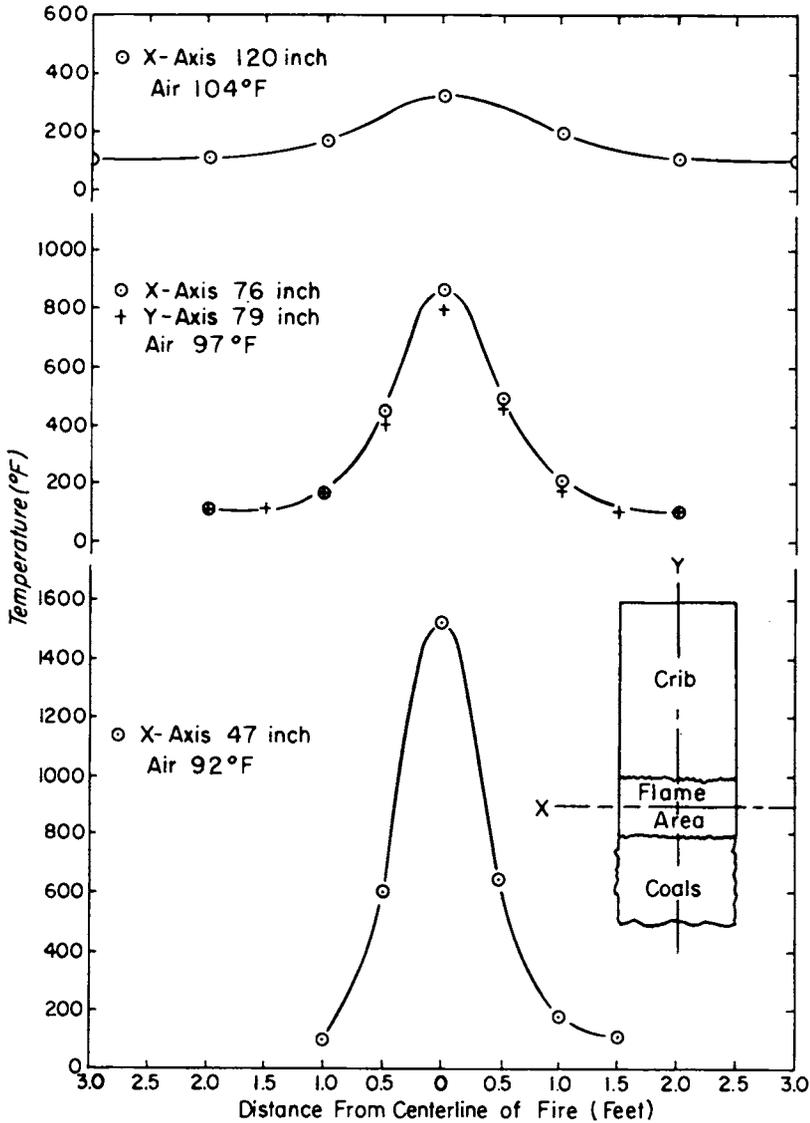


Figure 11. Horizontal distribution of temperatures at four heights above table top measured by thermocouples along X and Y axes.

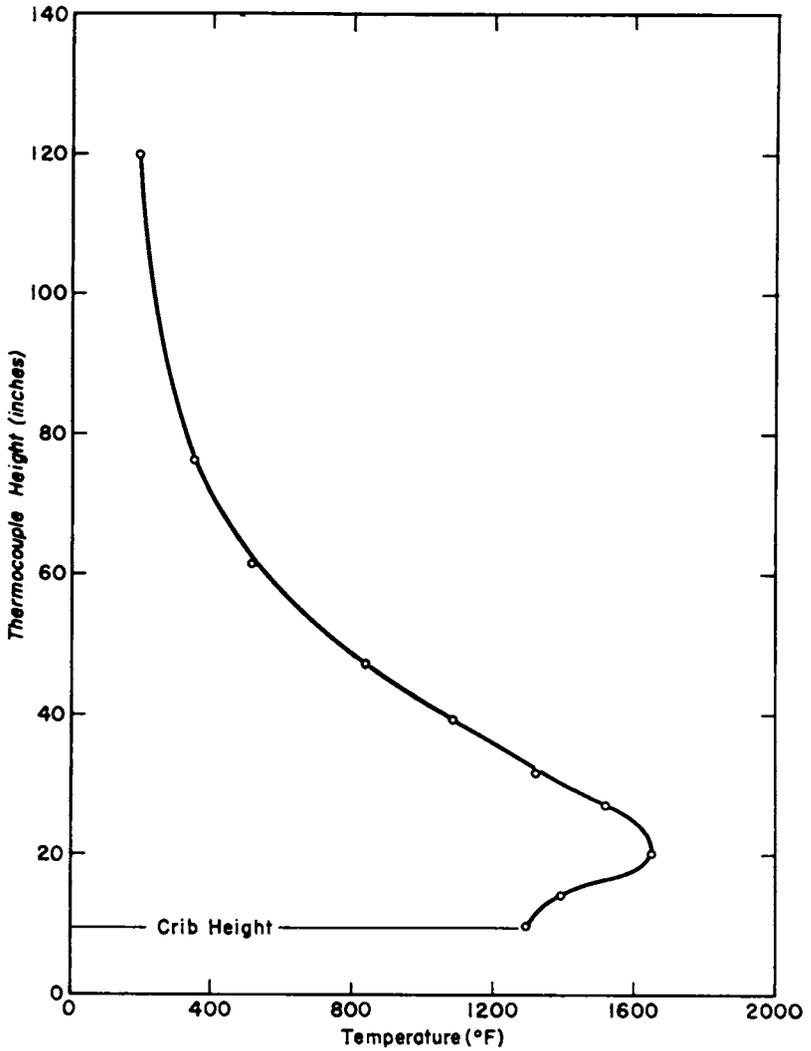


Figure 12. Vertical temperature distribution along central axis of flame and convection column.

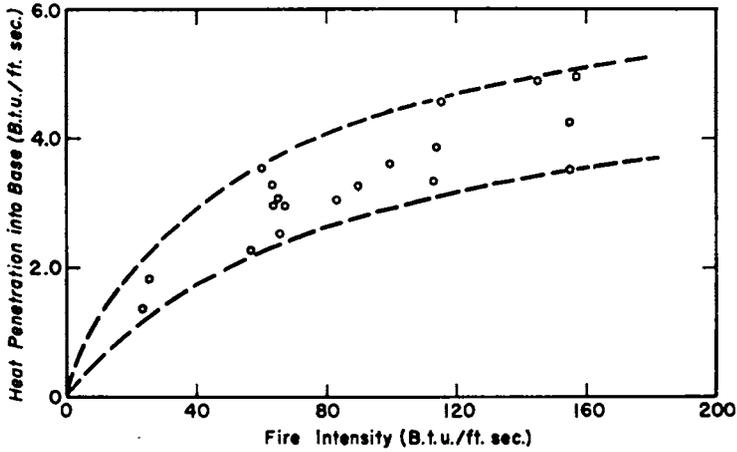


Figure 13. Relation between fire intensity and penetration of heat into the concrete base.

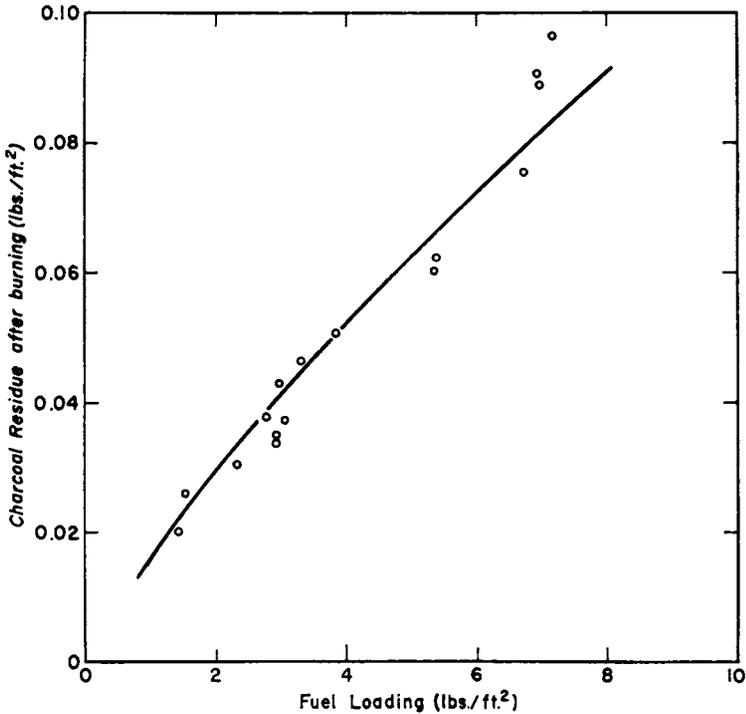


Figure 14. Charcoal from cribs of different fuel loading ($\frac{1}{2}$ -inch white fir sticks).

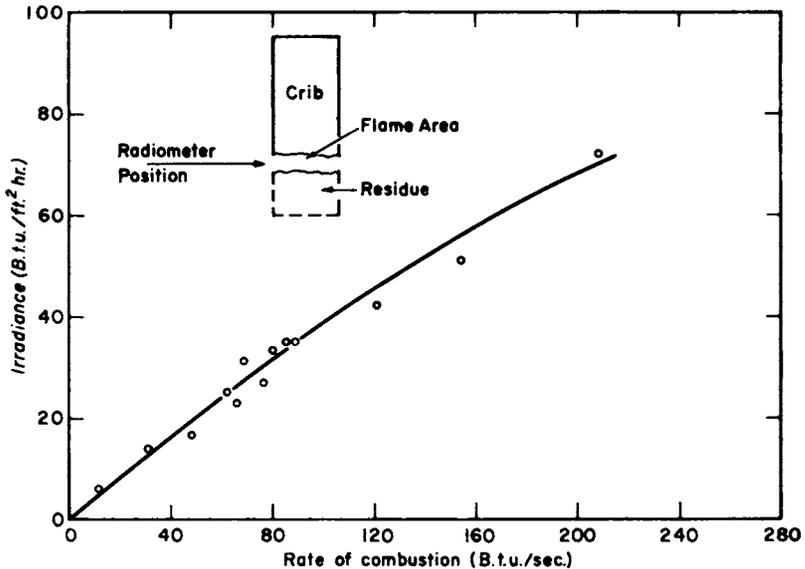


Figure 15. Irradiance from wood cribs at various rates of combustion. Radiometer at a radius of 14 feet, 20° above the horizontal.

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