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PROJECT FIRE MODEL

SUMMARY PROGRESS REPORT

PERIOD NOVEMBER 1, 1958 TO APRIL 30, 1960

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PACIFIC SOUTHWEST FOREST AND RANGE EXPERIMENT STATION
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Summary Progress Report
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PROJECT FIRE MODEL

I. Introduction

This report summarizes progress from November 1, 1958, to April 30, 1960, in a study conducted by the Pacific Southwest Forest and Range Experiment Station of the Forest Service in cooperation with the Office of Civil and Defense Mobilization. Called PROJECT FIRE MODEL for convenience, the project sought to develop and study a laboratory-scale fire which would provide a diagnostic model of a steady-state, free-burning fire in solid fuel.

A satisfactory fire model has been developed, using a crib of wood sticks on a movable bed. An approximate heat balance, accounting for 91 percent of the heat energy, has been attained, and data have been collected on some fuel and environmental parameters that govern the combustion.

Authorization for the work is contained in Office of Civil Defense and Mobilization Contract No. DCM-SR-59-10, and U. S. Forest Service Contract No. 12-11-005-20170, dated October 27, 1959 and later amended for FY-1960.

A. Importance

Since the start of organized forest-fire control effort, the Forest Service has conducted research on free-burning forest fires under realistic natural conditions or as close to natural conditions as possible. These studies have solved immediate practical problems and advanced the technical arts of forest-fire fighting, but few of the studies were directed at increased basic knowledge of forest-fire behavior. Most basic research on fire has been conducted by scientists in other fields and has been devoted in large measure to controlled fire for heat and power production. Consequently, the work has contributed little to an understanding of the free-burning urban or forest fire. Basic research on free-burning fires, directed towards a fuller knowledge of fire behavior and the combustion process, now appears essential for further advances in fire fighting. In other fields as complex as that of free-burning fire the basic research approach has met great success. Consequently it appears safe to predict that basic fire research will accelerate the advance of technical arts and speed progress in control of both forest and urban fires.

This basic approach is in line with the recommendations made to the President in December 1958 by his committee of scientific advisors, who counselled more emphasis on broad research and less on gadget-making and <u>ad hoc</u> experiments. To use the committee's words, "too much attention to mechanical things and too little to basic research would lead to an impoverished science and a second-rate technology. The most impractical thing that can be done in designing and directing programs of scientific research is to worry overmuch about how practical they are. The strongest program is the program with the greatest breadth and scope."

The Committee on Fire Research and the Fire Research Conference of the National Academy of Sciences-National Research Council studied the present status of fire-fighting techniques and statistics, and concluded that the ability to cope with large fires, both forest fires and urban conflagrations can be realized only through a major expansion of fundamental research on fire. The Committee, therefore, drew up a recommended national program for fire research, stressing basic studies and outlining seven areas in which these studies would contribute most significantly to an understanding of fire behavior. From the seven areas we have selected the one which would lead to the determination of model laws for fire spread. This area is of particular interest to the Forest Service and to civil defense. A plan was drawn up to attack the problem in the way considered most promising for contributing to the understanding of fires.

This attack seeks a better understanding of the fundamental factors which govern uncontrolled fires. Such knowledge is especially important because of the hazards of fire that are almost certain to exist in urban, rural, and wildland areas stricken by nuclear weapon attack. As the most suitable approach for obtaining this understanding, the Committee on Fire Research of the National Academy of Sciences-National Research Council has recommended "model" studies, concentrating on the more significant variables and developing a suitable fire system in which the importance of the variables can be evaluated and their effects reproduced and studied. Suitable models will not only give a better understanding of the phenomena of uncontrolled fire but should also enable fire-research specialists to explore new and revolutionary techniques of controlling large-scale fires with minimum expenditure of time and resources.

B. Objectives

1. To develop one or more uncontrolled aerothermodynamic systems[1] burning solid fuels, in which the parameters that govern the combustion may be experimentally examined.

2. 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.

3. To obtain all necessary information on the following, as affected by the properties of the air, fuel, and base:

   a. Total rate of energy release.

   b. Distribution of the energy released.

   c. Temperature, pressure, convection, and radiation pattern in and around the fire.

   d. Composition of the volatile gases immediately before ignition, and also during and after combustion.

   e. Flame height and volume.

C. Scope

1. As a prelude to the study of solid-fuel fires, liquid fuels were burned to explore the experimental difficulties, develop a suitable model-scale technique, and relate the rate of burning with the area of the fuel surface.

2. In a "diagnostic" fire-model phase of the study, wood was used to diagnose the importance of the many parameters that affect solid-fuel fires and to provide the necessary knowledge for setting up "predictive" fire models in a later stage of the study. This immediate phase was restricted to laboratory fires in homogeneous fuel beds composed of wood sticks of known size and shape, burning under steady-state

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1/ An uncontrolled aerothermodynamic system is one in which the rate of fuel consumption is dependent on the rate of evolution of heat and on the rate of transport of oxygen to the combustion zone.

conditions. These laboratory fires represented on a reduced scale a section of the combustion zone of a moving fire front burning in homogeneous fuel beds without spotting. Propagation of fire by firebrands was excluded for the present.

II. Activities

A. Work Plan

A plan setting forth the proposed methods of study was prepared, and is given in the Appendix.

B. Liquid Fuel Fires

Two liquid hydrocarbons were burned under carefully controlled conditions in water-cooled pans ranging in diameter from 0.22 to 12 inches. The rates at which the liquids were consumed by burning were correlated with the diameter of the pan. For pan diameters from 0.22 to 6 inches the rate of burning decreased with increase in pan diameter. For pans larger than 6 inches the rate of burning increased with pan diameter. A formula involving dimensionless quantities and a modified Grashof Number was developed to describe the phenomenon. A report on these liquid-fuel fires was prepared under the title, "Rate of Combustion from Free Surfaces of Liquid Hydrocarbons," and presented to the Combustion Institute, Western States Section, April 26, 1960.

C. Equipment

The fire laboratory is a 40- by 40-foot frame building 28 feet high with heavy redwood tongue and groove siding as sheathing. The space between the 2 x 4 framing members was filled with 4-inch glass wool insulation. The interior was finished with 1/2-inch gypsum board, and the exterior with prepared asbestos roll sheeting. The roof is of heavy tongue and groove redwood planking, resting on 6- x 6-inch beams and covered with builtup felt and asphalt roofing. The building as a whole is well insulated; little heat flows to or from the outside through the walls and ceiling. In each of the four walls is a 10-square foot window, opened during test fires to provide unrestricted movement of air into the laboratory.

1. A chain belt mechanism by which the fuel is moved into a fire to hold the fire in a stationary position in space was designed, fabricated, and installed (fig. 1).

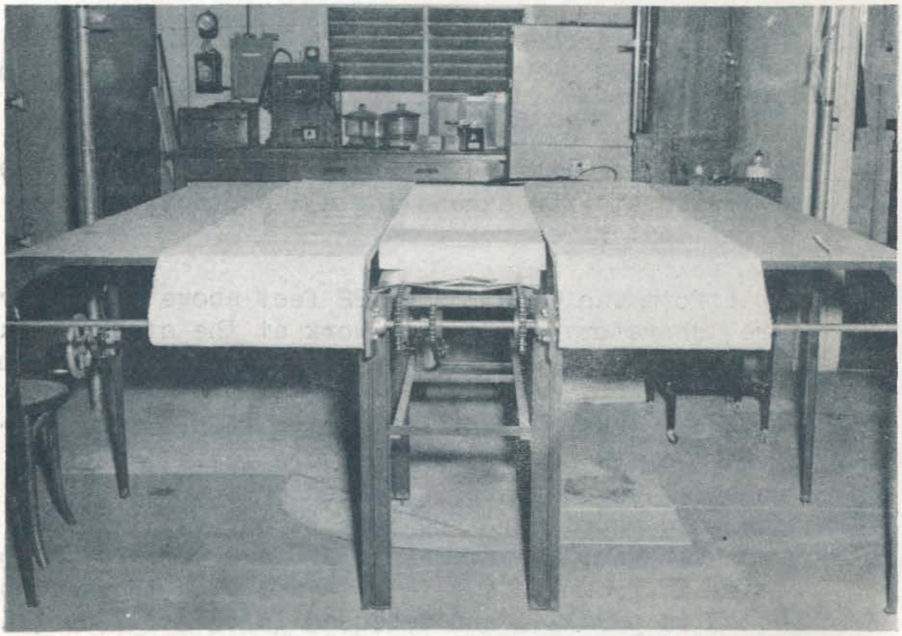


Figure 1.--Combustion table, showing the chain-belt drive mechanism with concrete slabs and traveling asbestos belts on either side.

2. A mechanism for drawing two heavy asbestos sheets, one on each side of the fire, in synchronism with the flame spread was designed and installed to simulate the relative movement of ground and fire front (fig. 1).

3. A stack, 22 inches in diameter, with a multiblade exhauster driven at 563 RPM by a 3-HP motor (fig. 2), was installed and tested for flow characteristics and effect on rate of spread. This exhaust system with a capacity of 5,400 CFM replaced one with a capacity of 1,780 CFM, which proved to be inadequate for exhausting all convective gases from the larger test fires.

4. A platform was constructed 22 feet above the floor of the fire laboratory for men to work at the stack in taking gas samples and measuring stack-gas velocities and temperatures.

5. To reduce gustiness of air coming in from the four windows, double layers of air filters were installed (fig. 3). Adjustable louvres were installed on the outside of the windows to assure equal air-flow rate through all windows as measured with vane anemometers. Average temperature of air coming in from windows is obtained with thermocouples connected in parallel and imbedded in the filters (fig. 3).

6. A network of 36 chromel-alumel thermocouples (fig. 4) was installed above the combustion table and connected to multiple-point recording potentiometers (fig. 5) to measure temperature of the flame and convection column.

7. A thermocouple was installed in the stack and connected in series with those at the windows to measure the differences in temperature between incoming air and stack gases during the test fires. The difference in temperature is recorded by a single-point potentiometer (fig. 3).

8. A Pitot tube was installed in the stack and connected to a micro-differential pressure transducer (fig. 6) to measure the velocity of the stack gases flowing from the room during the test fires.

9. A static-pressure probe was connected to a micro-differential pressure transducer (fig. 6) to measure static pressure within the flame and other parts of the convection column during the test fires.

10. A series of thermocouples was suspended from ceiling to floor and connected to a multiple-point recording potentiometer to give a continuous record of the lapse rate inside the room during each experimental fire.

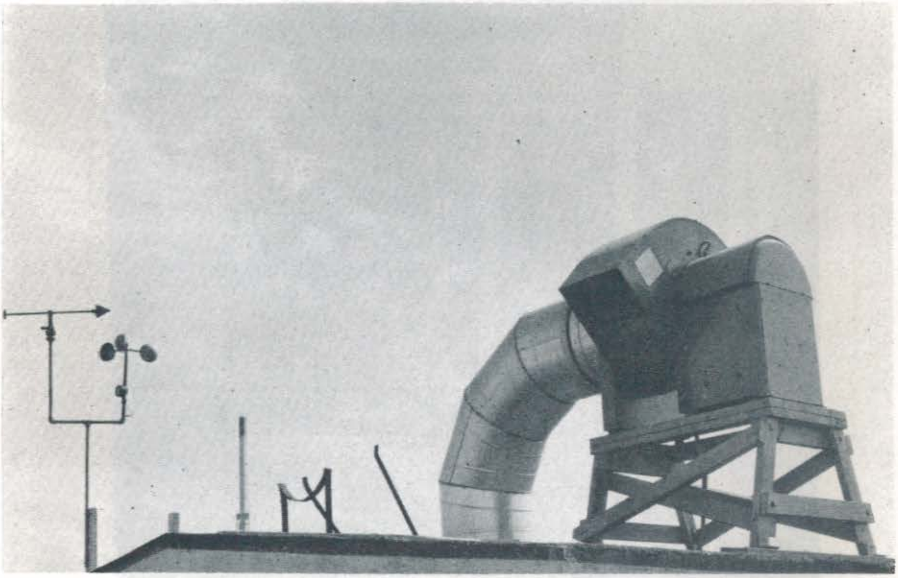


Figure 2.--Multiblade exhauster used to draw combustion gases up the stack to control flow of air into the combustion room.

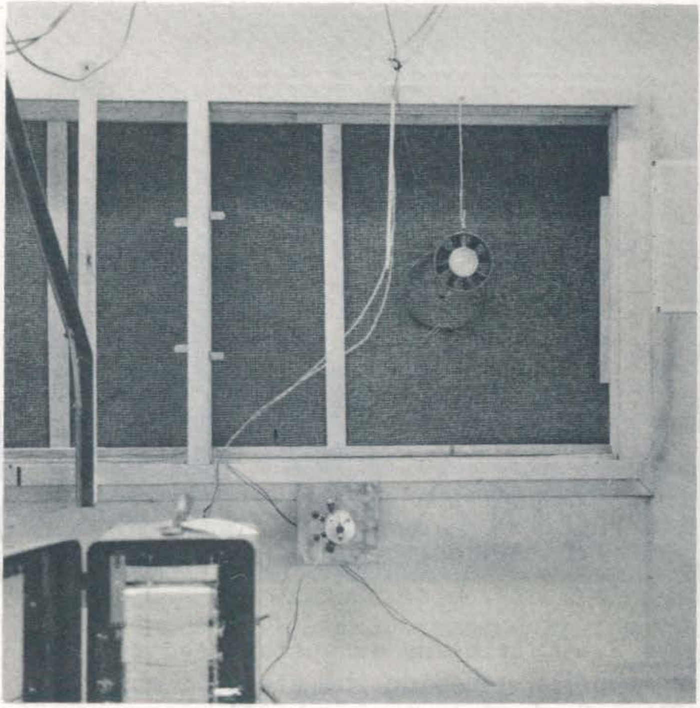


Figure 3.--Air-intake window with filters, thermocouple, and vane anemometer in place. At lower left, single-point recording potentiometer for recording temperature differences.

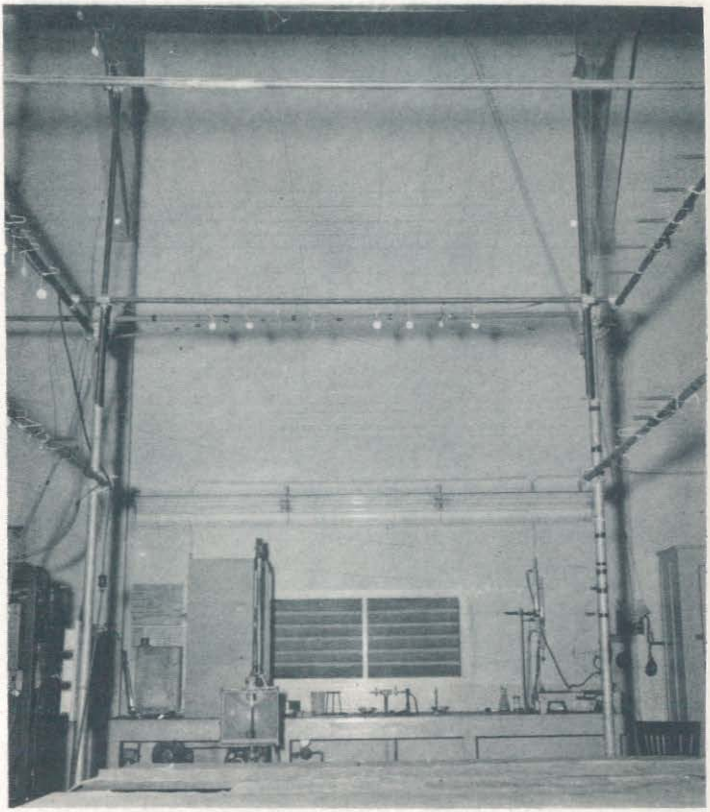


Figure 4.--Network of thermocouples for measuring temperature of flame and convection column.

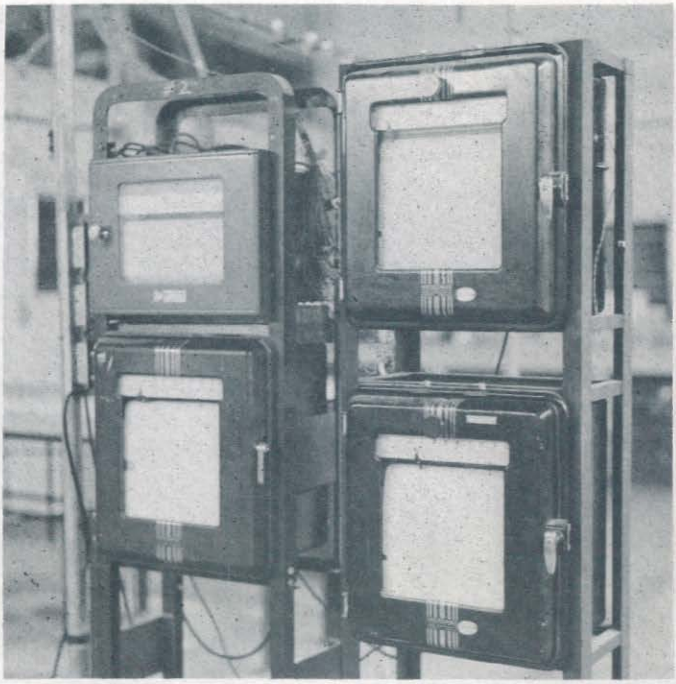


Figure 5.--Multiple-point potentiometers for recording flame and convection column temperatures.

Figure 6.--Pressure transducers and strip-chart recorder used to measure stack velocity and pressures in the convection column.

11. Three heat-flow transducers were installed on the walls and ceiling of the fire laboratory to measure the flow of heat in and out of the building during the experimental fires.

12. Three directional radiometers were installed on curved supports at a radial distance of 14 feet from a point selected as the "center" of the test fire to measure the radiation at the front, back, and side of the fire at various elevations from 15° below to 50° above the horizontal (fig. 7).

13. A form was built for the fabrication of pre-cast concrete slabs to serve as the base of the crib fires, and experiments were carried out to learn the proportions of cement, sand, and Perlite aggregate for light-weight concrete of various densities. A set of seven precast concrete slabs of about 90 pounds per cubic foot density was made to serve as the base for the experimental fires (fig. 8).

14. A calorimeter was built to measure the heat absorbed from the fire by the base slabs (fig. 9).

15. A glass apparatus train was set up for taking samples of combustion gas from the flame and convection column for analysis by gas chromatography.

16. A gas-chromatograph is used in analyzing the composition of the combustion gases generated by the test fires (fig. 10).

17. A bomb calorimeter was installed for measuring the heat value of the test wood and charcoal (fig. 11).

18. An insulated cabinet was provided with a fan and a bath of saturated solution of sodium bromide salt to maintain a relative humidity of 58 percent at a temperature of 70°F., for conditioning the wood cribs to an equilibrium moisture content of approximately 10 percent (fig. 12).

19. Glass distillation apparatus was set up to measure moisture content of wood samples by xylene distillation (fig. 13).

20. A carbon arc was set up to cast a shadowgraph of the flame and convection column onto a screen, and provisions were made for photographing the image (fig. 14).

21. Two motion picture cameras were adapted to take time-lapse movies of the fires from the side and rear (fig. 15).

D. <u>Heat Value of Wood Fuel</u>

To determine the heat value of the white fir wood used as the fuel, about 60 half-inch sticks were selected at random and

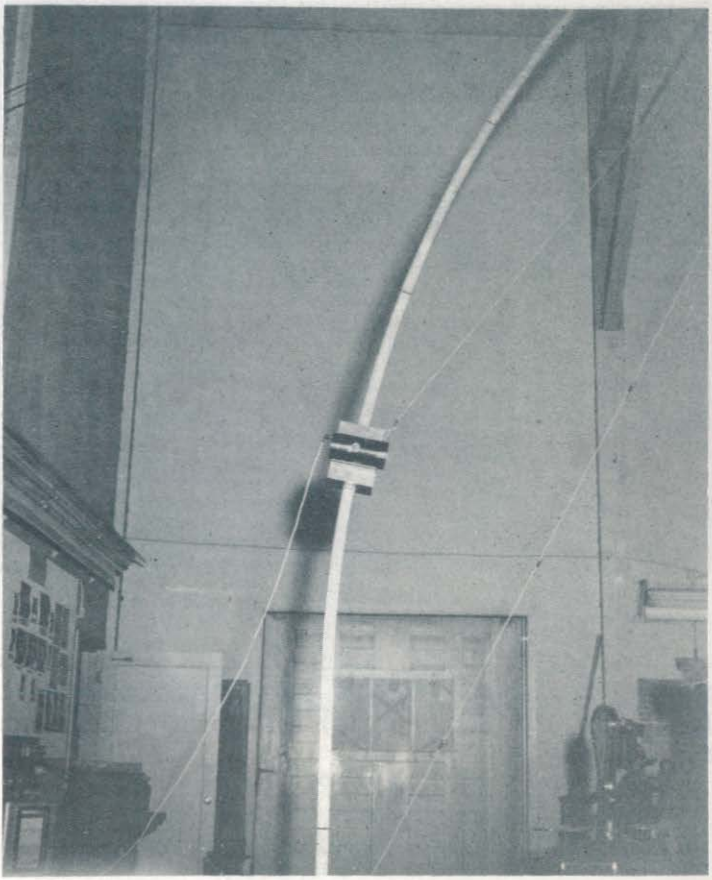


Figure 7.--Directional radiometer mounted on a standard for measuring radiation from the fire along 14-foot radii.

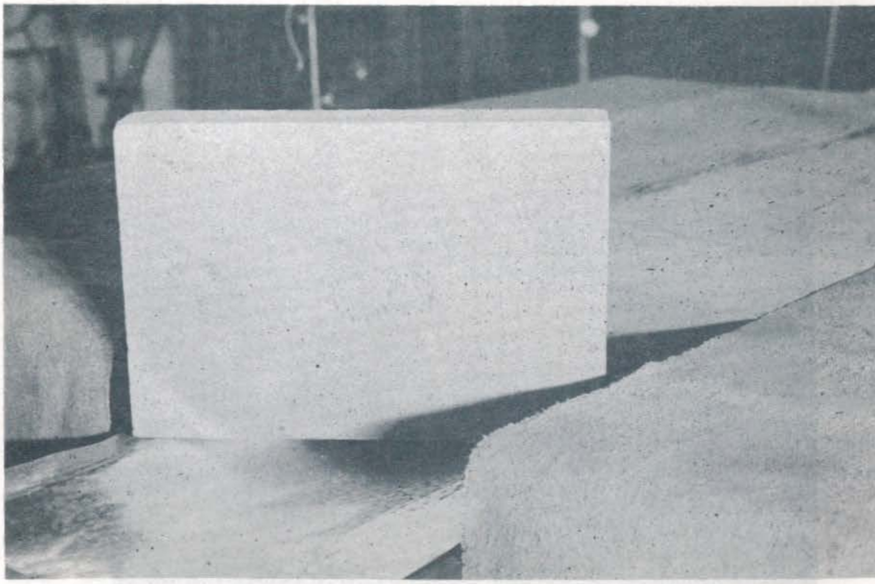


Figure 8.--Light-weight concrete slab (90 pounds per cubic foot; 3 inches thick, 12 inches long, and 18 inches wide) on which cribs are burned.

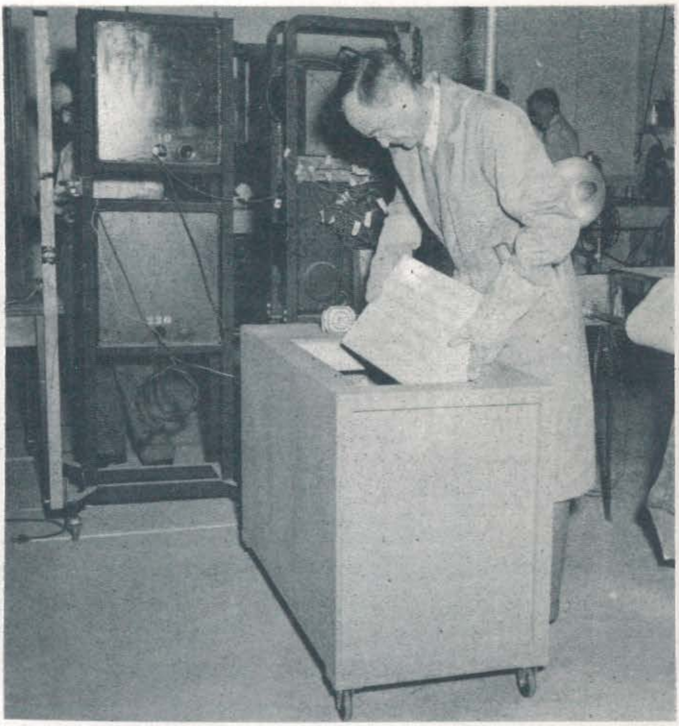


Figure 9.--Specially built calorimeter for measuring heat absorbed by base slabs.

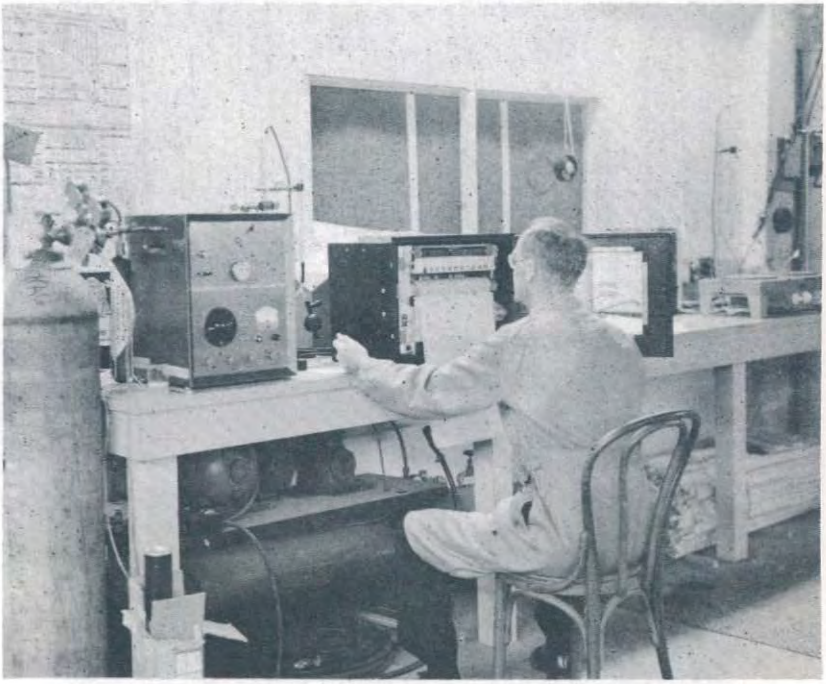


Figure 10.--Gas-chromatograph apparatus for combustion-gas analysis.

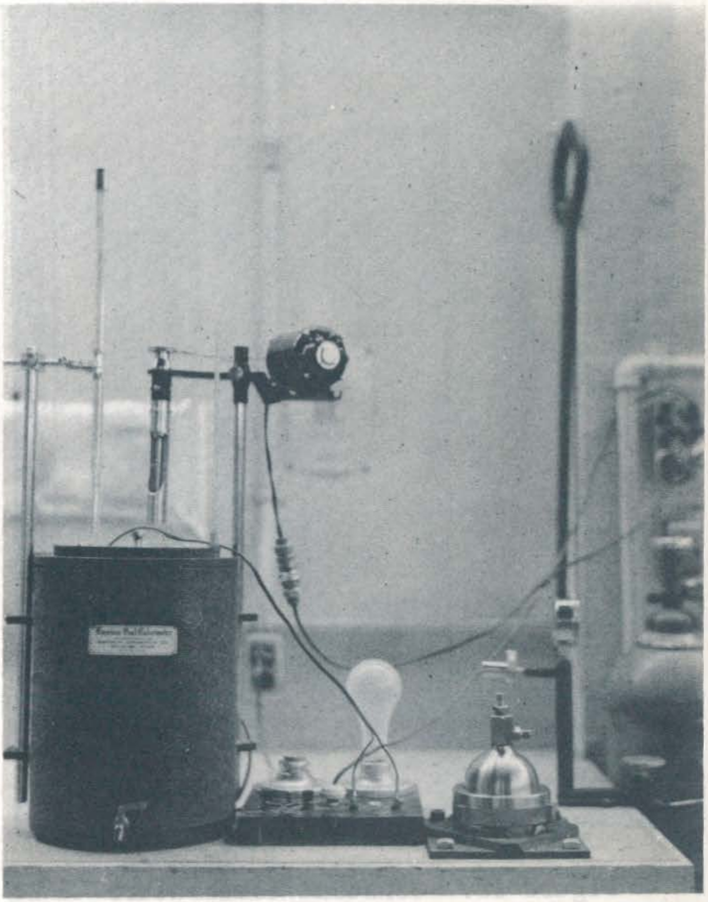


Figure 11.--Bomb calorimeter used for heat value measurements.

Figure 12.--Constant temperature-humidity cabinet in which test cribs are conditioned to moisture equilibrium.

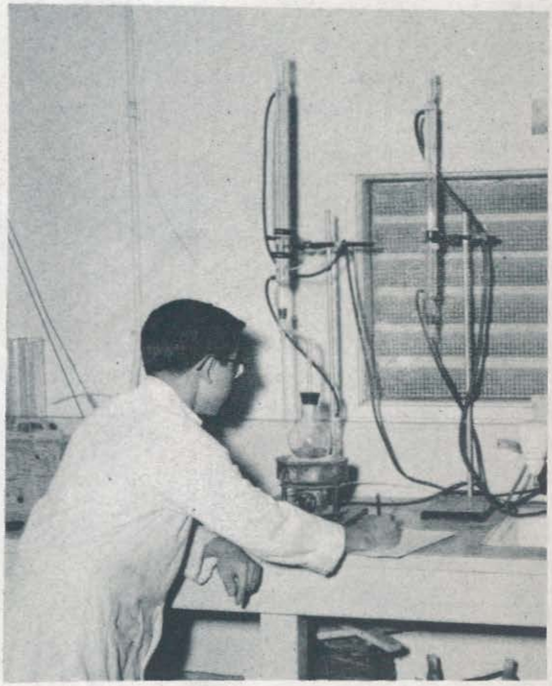


Figure 13.--Xylene distillation apparatus for determining moisture content.

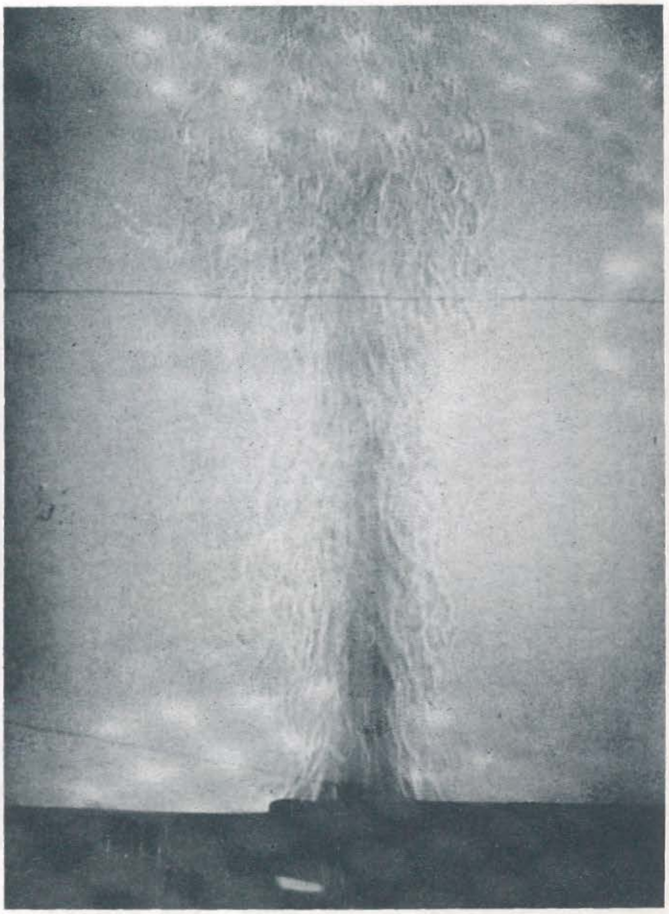


Figure 14.--Typical shadowgraph of flame and convection column of a test fire.

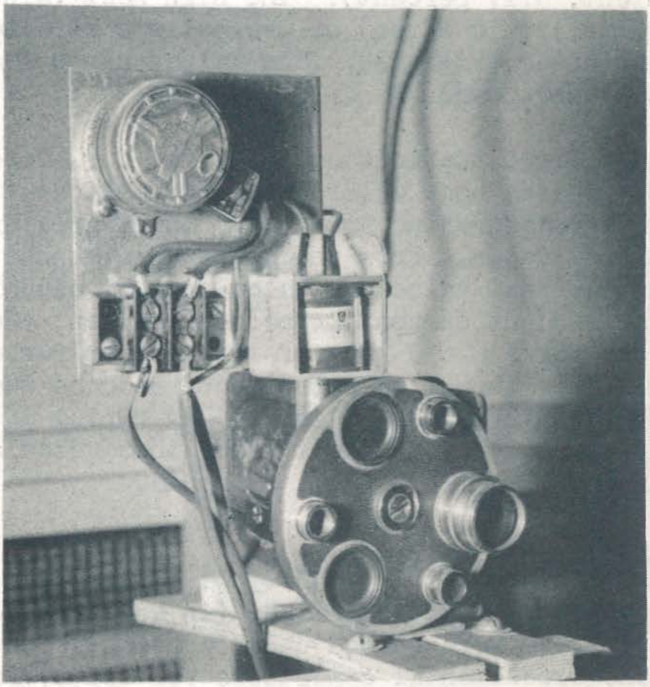


Figure 15.--Camera adapted to take time-lapse movies of test fires.

reduced to sawdust. The sawdust was thoroughly mixed, and samples were pressed into pellets of about 1/4-inch diameter. The pellets were dried in a dessicator over calcium chloride then tested for moisture content by xylene distillation (average moisture content, 3.17 percent). The high heat values (with moisture condensed to liquid water) of the pellets were determined by a bomb calorimeter (fig. 11). The values of 10 tests averaged 8659 B.t.u. per pound.

In the test fires the moisture from the fuel does not condense as it does in the bomb calorimeter. Therefore, the low heat value (with moisture in vapor form) is of greater interest than the high heat value. From the measured high heat value of the wood, the low heat value was calculated by assuming that the wood is 50 percent carbon, 44 percent oxygen, and 6 percent hydrogen, and forms 0.539 lbs. of water vapor for each pound of dry wood. This amount of water vapor reduces the high heat value by 0.539 x 972 or 524 B.t.u./lb. by virtue of its latent heat of vaporization. The low heat value thus calculated for the white fir wood is 8135 B.t.u. per pound.

E. Test Fires

Twenty-seven wood-fuel test fires (in addition to many exploratory test fires) were burned under carefully controlled conditions. The experimental conditions for all 27 fires are given in table 1. Principal purposes of the test fires were as follows:

1. To verify that the fires reach a steady state of burning.

2. To learn the effect of density of the wood on the rate of spread of fire through the fuel beds.

3. To learn the effect of height and width of fuel bed on the rate of spread of fire.

4. To learn the effect of stick size on the rate of spread of fire through wood fuel.

5. To obtain data as to temperatures in the flame and upper convection column of the fires.

6. To measure the heat energy radiated by the fires for correlation with the rate of combustion.

7. To measure the heat energy that passes from the fire to the concrete base on which the fuel bed rests and its variation with density of wood.

Table 1.--Summary of experimental conditions for crib fires made from white fir[1] sticks at 1-1/4-inch spacing

Fire No.	Room[2] temperature: Before fire	Room[2] temperature: After fire	Relative humidity: Before fire	Relative humidity: After fire	Nominal stick size[3]	Crib weight: Air dry	Crib weight: Bone dry	Moisture content	Specific gravity[4]	Crib size: Height	Crib size: Width	Crib size: Length	Total No. of tiers[5]	Loading
	°F.	°F.	%	%	in.	lbs.	lbs.	%		in.	in.	in.		lbs/sq.ft.
1	65.0	69.5	50.0	49.5	1/2	8.27	7.54	9.81	0.434	5.50	9.25	35.5	12	3.31
2	68.0	72.0	48.0	42.0	1/2	6.90	6.32	9.01	.361	5.50	9.25	35.5	12	2.77
3	68.0	73.0	54.0	53.0	1/2	9.67	8.76	10.27	.511	5.50	9.25	35.5	12	3.84
4	70.0	73.0	55.0	53.0	1/2	5.87	5.32	10.31	.303	5.50	9.25	35.5	12	2.33
5	72.5	80.5	59.0	50.5	1/2	7.52	6.81	10.42	.393	5.50	9.25	35.5	12	2.99
6	70.0	75.5	53.0	49.5	1/2	7.66	6.90	11.06	.396	5.50	9.25	35.5	12	3.03
7	69.5	73.5	57.0	51.5	1/2	2.40	2.15	11.46	.386	2.75	5.75	35.5	6	1.52
8	71.8	80.0	54.8	48.5	1/2	11.25	10.17	10.59	.387	13.00	5.75	35.5	28	7.17
9	69.0	74.0	61.4	56.0	1/2	6.36	5.74	10.84	.387	2.75	16.25	35.5	6	1.43
10	68.2	81.0	62.4	49.0	1/2	29.84	26.91	10.87	.386	13.00	16.25	35.5	28	6.72
11	67.0	75.3	64.4	57.1	1/2	12.86	11.67	10.22	.391	5.50	16.25	35.5	12	2.91
12	68.5	81.0	64.6	50.0	1/2	23.75	21.55	10.22	.393	10.25	16.25	35.5	22	5.38
13	70.1	80.2	64.8	53.2	1/2	17.54	15.93	10.10	.389	13.00	9.25	35.5	28	6.99
14	70.5	84.1	67.6	51.8	1/2	24.00	21.79	10.16	.394	13.00	12.75	35.5	28	6.93
15	70.3	76.0	61.0	55.4	1/2	11.93	10.81	10.37	.465	5.50	9.25	47.75	12	3.52
16	69.9	78.0	68.5	57.7	1	20.44	18.54	10.24	.385	8.00	10.00	37.00	8	7.21
17	71.9	81.0	66.4	55.0	1/2	23.63	21.37	10.56	.387	10.25	16.25	35.50	22	5.33

Table 1 (Continued)

Fire No.	Room temperature[2/] Before fire	Room temperature[2/] After fire	Relative humidity Before fire	Relative humidity After fire	Nominal stick size[3/]	Crib weight Air dry	Crib weight Bone dry	Moisture content	Specific gravity[4/]	Crib size Height	Crib size Width	Crib size Length	Total No. of tiers[5/]	Loading
	°F.	°F.	%	%	in.	lbs.	lbs.	%		in.	in.	in.		lbs/sq.ft.
18	70.9	76.7	64.5	58.1	1/2	12.95	11.74	10.32	.391	5.50	16.25	35.50	12	2.93
19	71.5	77.3	67.0	57.5	9/32	8.42	7.60	10.79	.399	8.13	9.50	35.63	28	3.23
20	73.5	80.9	52.1	40.5	3/4	13.86	12.52	10.74	.384	8.25	8.44	35.44	12	6.02
21	73.9	86.0	50.5	36.0	1-1/4	31.69	28.71	10.36	.384	7.50	8.75	61.25	6	7.72
22	74.5	80.4	61.5	50.5	1/2	10.17	9.17	10.89	.389	5.50	9.25	47.75	12	2.99
23	61.5	62.0	58.5	56.5	1/2	11.38	10.29	10.66	.390	8.37	9.25	35.50	18	4.51
24	62.5	64.0	54.5	51.0	1	20.50	18.53	10.66	.385	8.00	10.00	37.00	8	7.21
25	63.5	68.5	55.5	50.5	1-1/4	31.87	28.82	10.61	.386	7.50	8.75	61.25	6	7.74
26	58.2	61.0	56.5	54.0	3/4	18.46	16.70	10.53	.388	8.25	8.44	47.00	12	6.06
27	57.5	61.5	63.5	61.0	1/2	10.19	9.22	10.52	.389	5.50	9.25	47.75	12	3.01

1/ White fir (Abies concolor).

2/ Temperature taken 4 feet above floor level.

3/ Actual dimensions in inches: Fire No. 19--.286 x .287; Fires Nos. 1 to 14--.447 x .460; Fire No. 15--.448 x .458; Fires No. 17, 18, 22, 23, and 27--.451 x .458; Fires No. 20 and 26--.677 x 683; Fires No. 16 and 24--.982 x .995; Fires No. 21 and 25--1.242 x 1.246.

4/ Based on bone-dry weight and bone-dry volume.

5/ Lateral and longitudinal tiers in equal number.

8. To obtain data on the amount of charcoal left by wood fires, its variation with the density of the wood and the fuel loading, and its heat content.

9. To obtain data on flame height and flame width.

10. To obtain data on the composition of the stack gas above a wood-fuel fire.

11. To obtain information on the time for a wood-fuel fire to build up to a steady state from the instant of ignition, and data on the effects of stick size and height and width of fuel bed on the build-up time.

12. To determine the heat balance for a wood-fuel fire.

F. Documentary Film

Movie sequences in a 16-mm color film were shot of the fire laboratory, crib preparation, test fires, equipment, experimental arrangement, and technical procedures of the project for documentary purposes.

G. Paper for International Symposium on Fire Research

A paper, entitled "A Steady-State Technique for Studying the Properties of Free-Burning Wood Fires," was presented on November 10, 1959, to the First International Symposium on Fire Research held at the National Academy of Sciences, Washington, D. C.[2/]

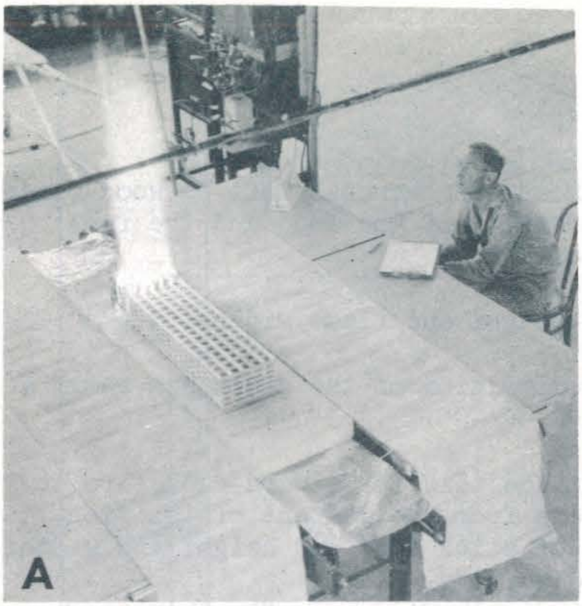
III. Results

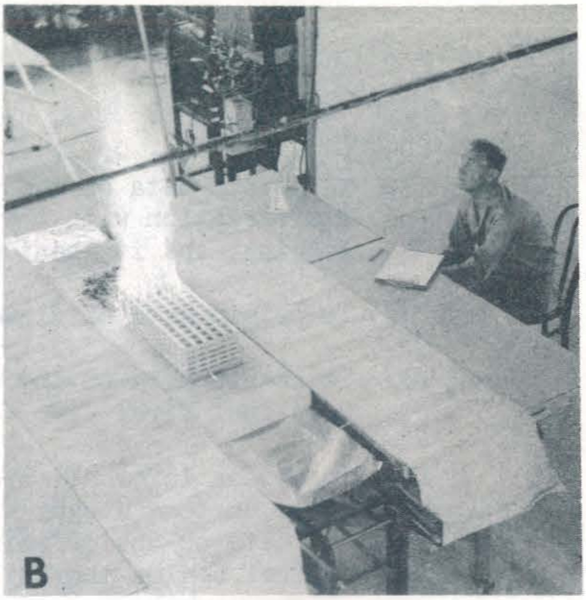
A. Rate of Spread

The rate of spread of the fire through the wood cribs was determined by measuring the rate at which the fuel had to be moved into the fire to hold the flame at a fixed position in space. This technique is illustrated in figure 16A to 16D.

The rates of spread of the test fires are given in table 2. Typical curves for the spread of fire through cribs of white fir wood are shown in figure 17. The spread of fire is linear after an initial period of build-up. How well a steady state of burning was achieved by the technique employed is indicated by the linearity in figure 17 and is illustrated by the three photographs in figure 18.

2/ Fire Research Abstracts and Reviews, Vol. 2, No. 1, January 1960.





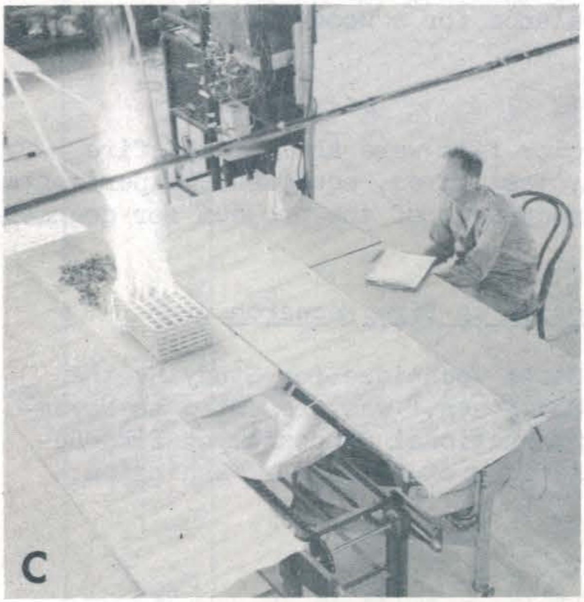


Figure 16.--Crib fire No. 6.

A, Five minutes after ignition. The operator at the right is slowly moving the crib to maintain the flame at a constant position in space.

B, Eleven minutes after ignition.

C, Fifteen minutes after ignition.

D, Twenty minutes after ignition. Note that the crib and concrete base, also the asbestos sheets, have moved from their positions in fig. 16A.

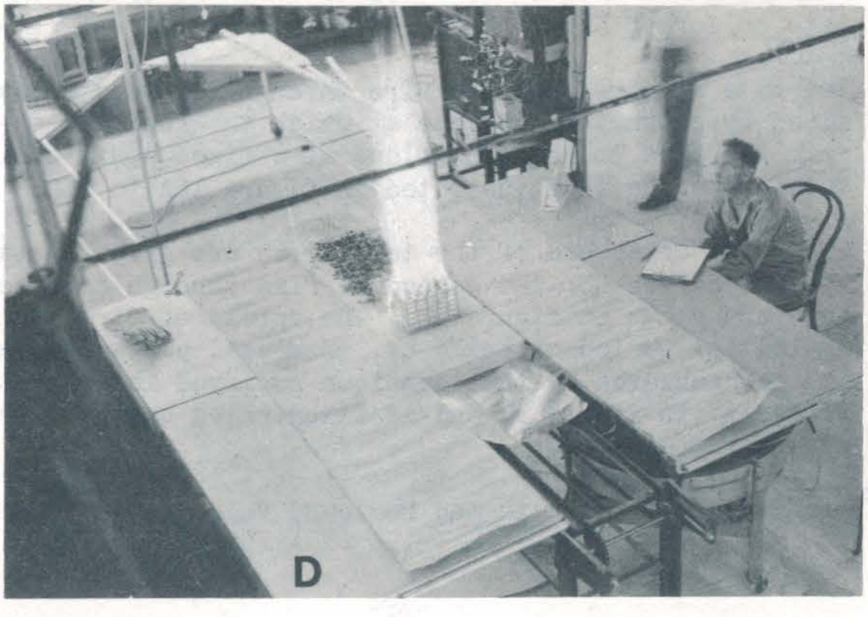


Table 2.--Rate of spread and charcoal residue[1] data

Fire No.	Rate of spread	Heat of combustion of fuel[2]	Weight of charcoal	Charcoal yield	Ash in charcoal[3]	Heat value of charcoal	Heat of combustion of charcoal	Heat of fuel in residual charcoal
	in./min.	B.t.u.	lbs.	%	%	B.t.u./lb.	B.t.u.	%
1	1.51	61,337	0.106	1.41	35.8	7,238	767	1.25
2	1.91	51,413	.086	1.36	32.6	8,541	735	1.43
3	1.23	71,262	.116	1.32	32.8	8,085	938	1.32
4	2.38	43,278	.069	1.30	42.0	5,974	412	0.95
5	1.74	55,399	.098	1.44	34.7	7,058	692	1.25
6	1.79	56,131	.085	1.23	34.1	7,318	622	1.11
7	1.41	17,490	.037	1.72	32.4	6,033	223	1.28
8	1.68	82,733	.137	1.35	30.7	8,323	1,140	1.37
9	1.38	46,695	.080	1.39	28.8	8,821	706	1.51
10	1.92	218,913	.303	1.13	40.3	7,103	2,152	0.98
11	1.87	94,935	.135	1.16	37.8	6,929	935	0.98
12	1.75	175,308	.250	1.16	34.0	8,479	2,120	1.21
13	1.87	129,590	.203	1.27	30.5	8,874	1,801	1.39
14	1.86	177,261	.285	1.31	30.5	8,898	2,536	1.43
15	1.37	87,939	--	--	--	--	--	--
16	1.15	150,822	.293	1.58	25.3	8,437	2,472	1.64
17	1.78	173,829	.243	1.14	39.1	5,436	1,321	0.76
18	1.61	95,488	.139	1.18	35.3	6,097	847	0.89
19	2.13	61,825	.079	1.04	41.8	4,837	382	0.62
20	1.24	101,850	.193	1.54	29.0	7,653	1,477	1.45
21	1.25	233,555	.489	1.70	23.5	8,828	4,317	1.85
22	1.78	74,598	.112	1.23	42.9	4,484	504	0.68
23	1.81	83,709	.131	1.27	36.0	6,554	859	1.03
24	1.30	150,742	.312	1.68	32.6	7,703	2,403	1.59
25	1.10	234,451	.419	1.45	35.2	8,310	3,482	1.48
26	1.38	135,855	.250	1.50	37.1	6,116	1,529	1.13
27	1.74	75,005	.111	1.20	42.2	6,418	712	0.95

1/ Bone-dry basis.
2/ Based on the low heat value, 8135 B.t.u./lb.
3/ Non-volatile residue at red heat.

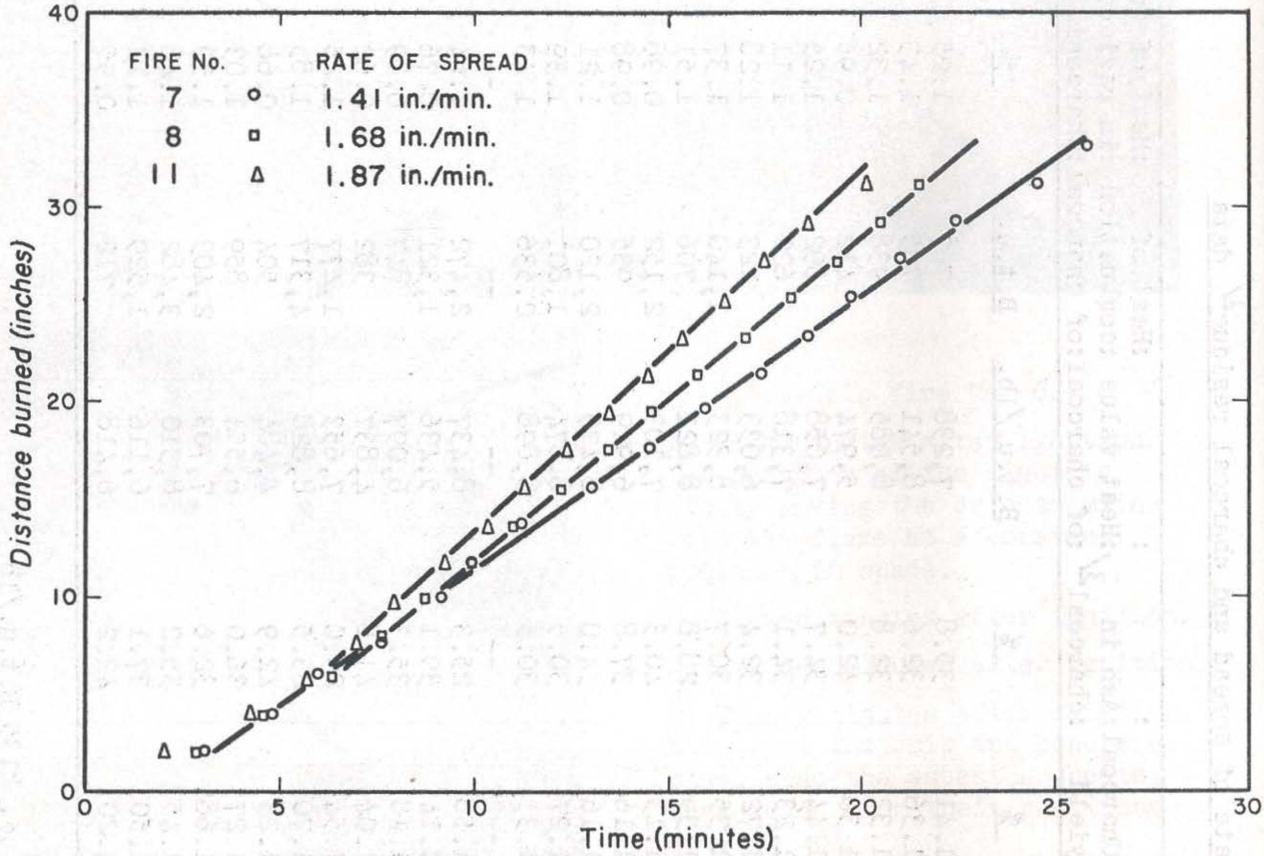


Figure 17.--Spread of fire through cribs of white fir wood.

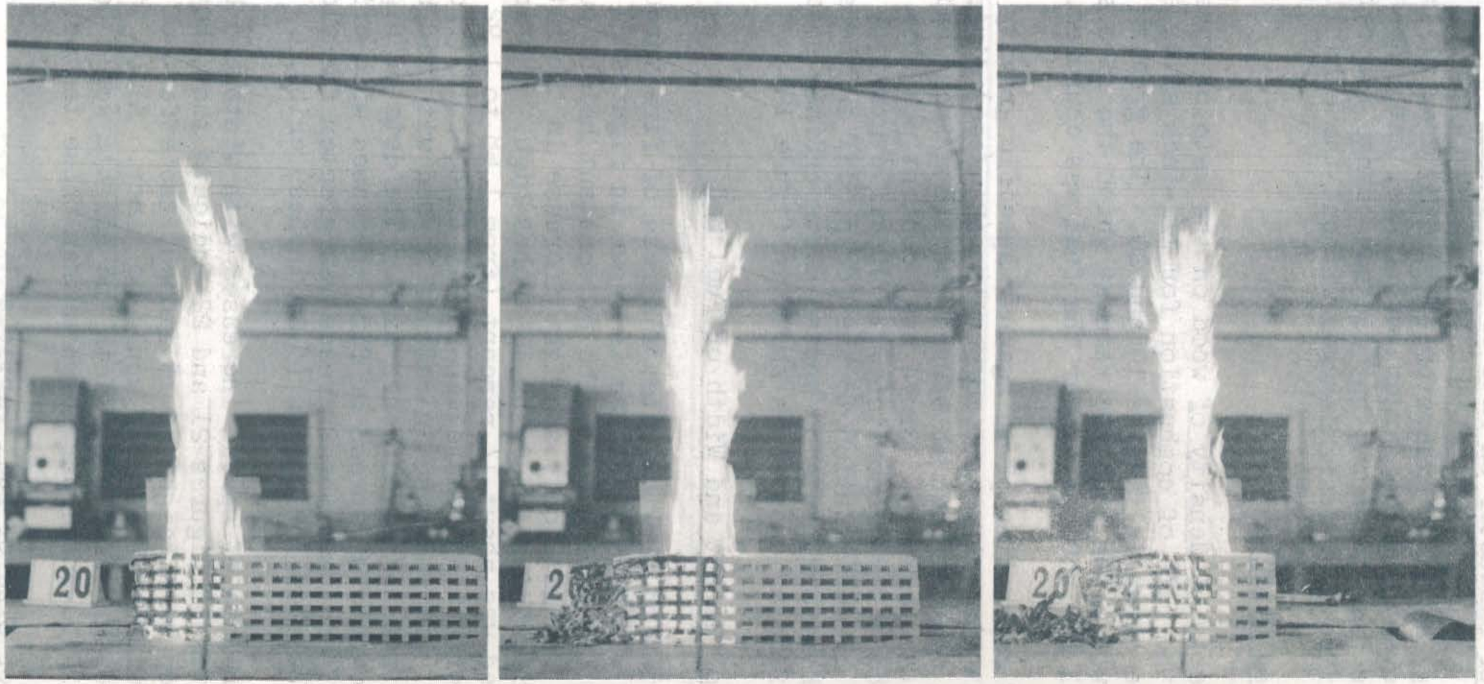


Figure 18.--Flame from a test fire at three different times, illustrating the fixed position of the flame as the crib moves.

B. Effect of Exhauster on Rate of Fire Spread

The large capacity exhauster (5400 CFM) drew all combustion gases, even from the larger test fires, into the stack without spillage from the hood, but did not change the rate of spread of the fire from that measured without the exhauster.

C. Effect of Density

The effects of density of wood on the rate of spread of fire and on the rate of combustion for 1/2-inch stick size (white fir) are shown in figures 19 and 20. The greater the density of the wood, the less the rate at which the fire spread through the fuel bed and the slower the fuel was consumed.

Rate of combustion plots against specific gravity of wood as a straight line. Rate of combustion (Btu/sec) divided by heat content per unit length of fuel bed (Btu/inch) becomes rate of spread (inches/sec). Since heat content per unit length of fuel bed is directly proportional to specific gravity, rate of spread bears a linear relation to the reciprocal of the specific gravity. Therefore, rate of spread plots against specific gravity in the form of a curve as shown in figure 19.

D. Effect of Height and Width of Fuel Bed

The variation for the rate of spread of fire through cribs of several widths and heights is shown in figures 21 and 22. The data of figure 21 (for cribs of constant height but of various widths) indicate only a slight increase in the rate of spread with crib widths for cribs 13 inches high. The increase in rate of spread was about 14 percent (from 1.68 to 1.92 inches/minute) as the crib width increased nearly three-fold (from 5.75 to 16.25 inches). An increase in rate of spread with width was not observed in cribs 2.75 inches high. The data of figure 22 indicate that the rate of spread of fire increased with crib height or loading, and that the increase was greater for wide (16.25 inches) cribs than for narrow (5.25 inches) cribs.

Although rate of spread increased with width and height of crib, the curves of figures 21 and 22 indicate that, beyond a width of 16 inches or a height of 13 inches, the effect of small additional widths or heights would be minor. Also, it is probable that greater effects of width and heights would be found at narrower widths and lower heights than those tested.

E. Effect of Size of Fuel Particle

To learn the effect of stick size on the rate of spread of fire through wood fuel, cribs of approximately the same size were

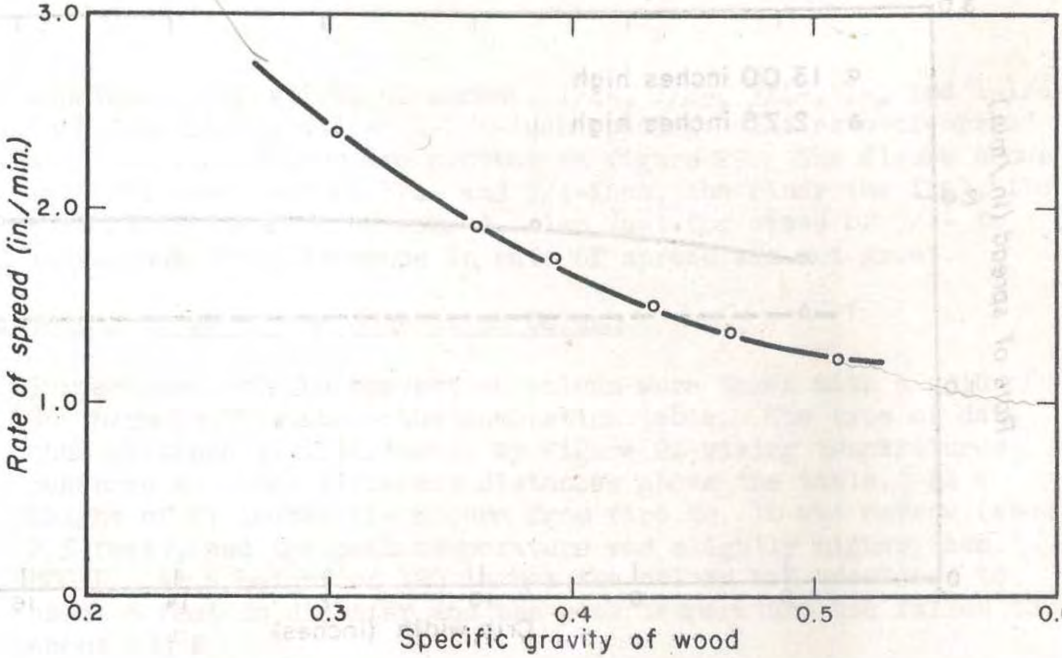


Figure 19.--Rate of fire spread through cribs of white fir of different specific gravity; crib and stick size constant (height 5.5 in.; width 9.25 in.; stick size 1/2 in.)

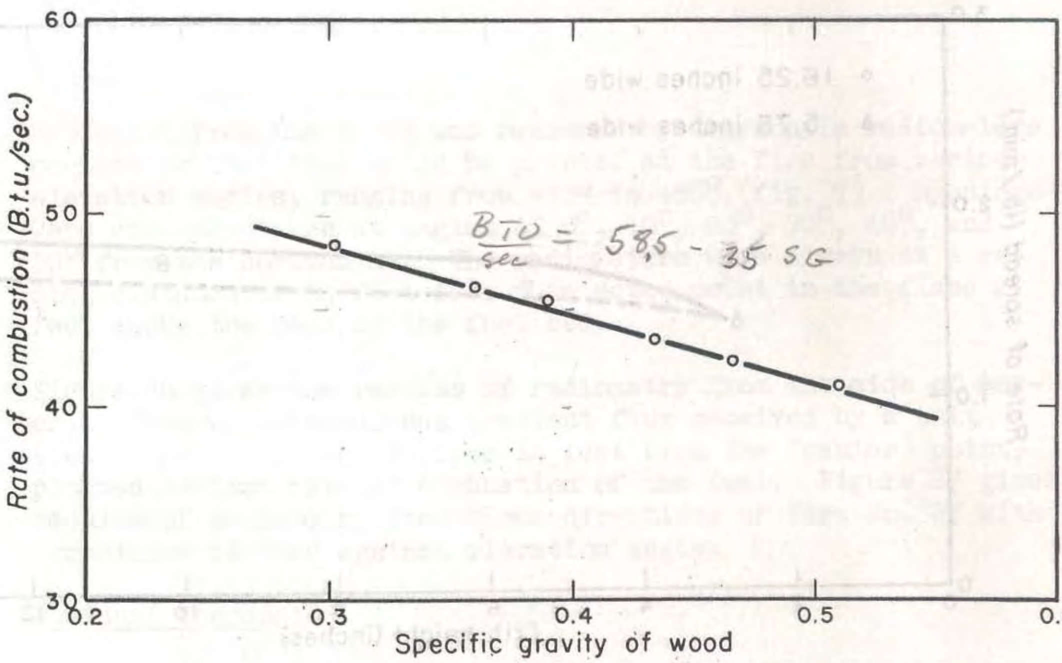


Figure 20.--Rate of combustion of cribs of white fir of different specific gravity; crib and stick size constant (height 5.5 in.; width 9.25 in.; stick size 1/2 in.)

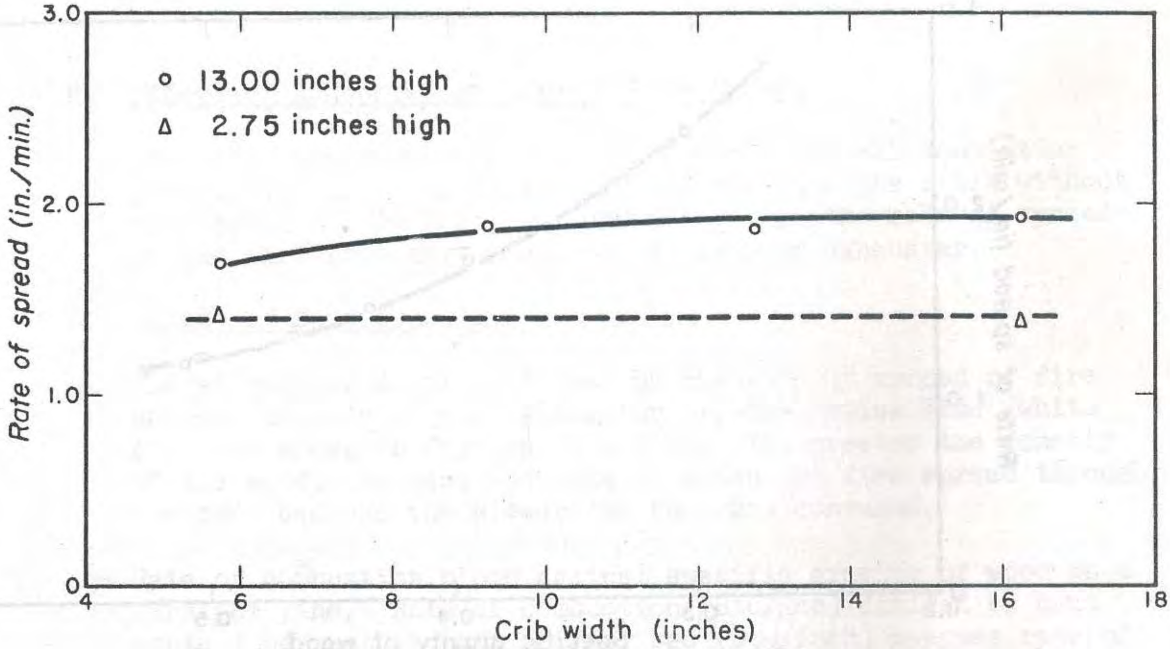


Figure 21.--Rate of fire spread through cribs of white fir with different crib widths.

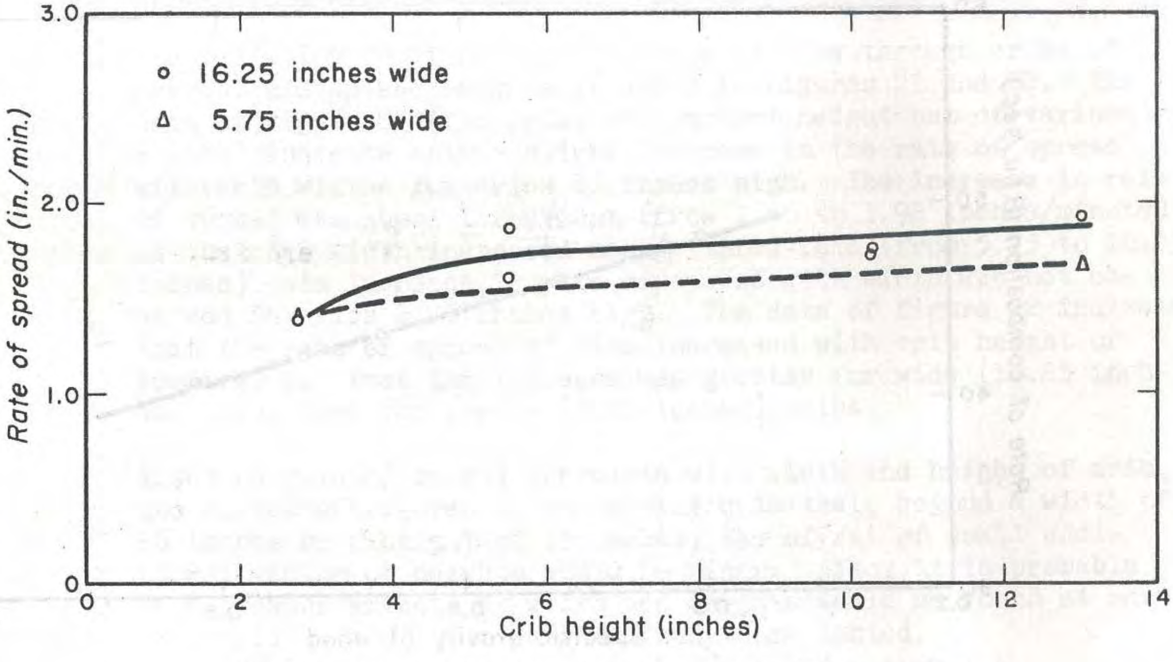


Figure 22.--Rate of fire spread through cribs of white fir with different crib heights.

constructed of sticks of nominal 1/4-, 1/2-, 3/4-, 1-, and 1-1/4-inch dimensions, all at 1-1/4-inch spacing. The rate-of-spread data for these fires are plotted in figure 23. The figure shows that between sizes of 1/4- and 3/4-inch, the finer the fuel, the more rapid the rate of spread, also that for sizes of 3/4- to 1-1/4-inch the difference in rate of spread was not great.

F. Temperatures of the Convection Column

Temperatures of the convection column were taken with a grid of 36 thermocouples above the combustion table. The type of data thus obtained is illustrated by figure 24 giving temperatures measured at three different distances above the table. At a height of 47 inches the column from fire No. 16 was narrow (about 2.5 feet), and the peak temperature was slightly higher than $800^{\circ}F$. At a height of 120 inches the column had broadened to about 6 feet in diameter and the peak temperature had fallen to about $200^{\circ}F$.

Figure 25 shows the vertical distribution of temperature up the central axis for fire No. 16. The temperature 1-inch above the crib, in a region of sooty, incomplete combustion, was less than temperatures in the cleaner flame a short distance higher. Maximum temperatures measured in the flame were slightly above $1600^{\circ}F$.

G. Radiation

Radiation from the fires was measured by thermopile radiometers mounted so that they could be pointed at the fire from various elevation angles, ranging from -15° to $+50^{\circ}$ (fig. 7). Readings were commonly taken at angles of 0°, 10°, 20°, 30°, 40°, and 50° from the horizontal. The radiometers were always at a radial distance of 14 feet from a selected point in the flame 2 feet above the base of the fuel bed.

Figure 26 gives the results of radiometry from the side of several fires with irradiance (radiant flux received by a unit area of perpendicular surface 14 feet from the "center" point) plotted against rate of combustion of the fuel. Figure 27 gives results of radiometry from three directions of Fire No. 27 with irradiance plotted against elevation angle.

H. Residual Charcoal

All available data to date on the charcoal left by the burning cribs are given in table 2. The weight of the charcoal is plotted against fuel loading in figure 28. The heat remaining in the charcoal as unburned compounds averaged 1.21 percent of the total heat (low heat value) of the fuel.

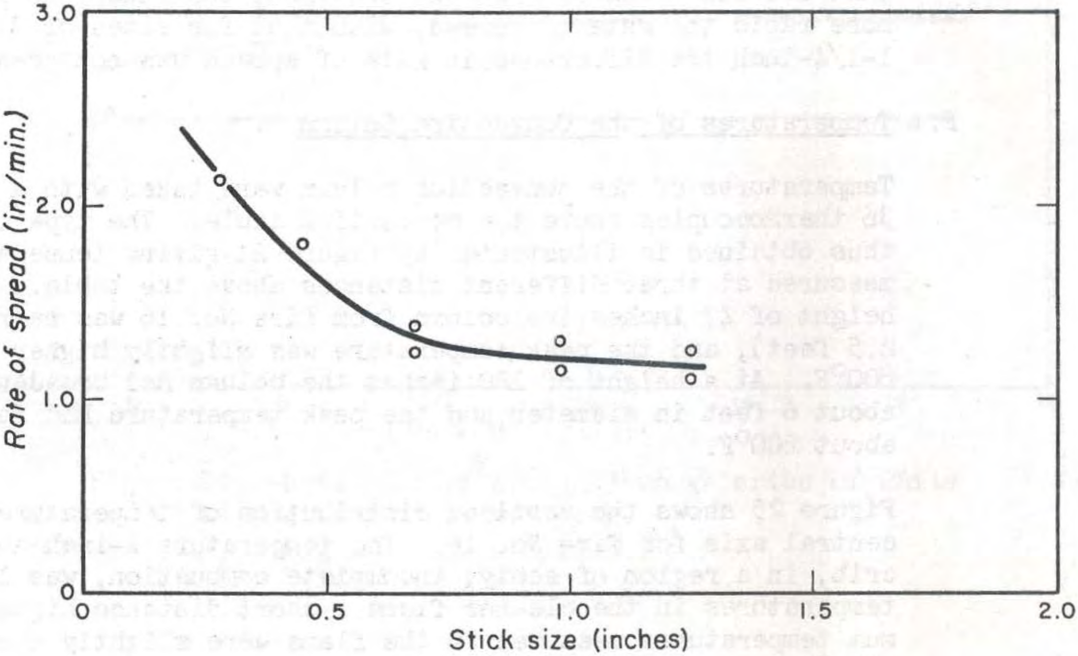


Figure 23.--Rate of fire spread through cribs of white fir of different stick size.

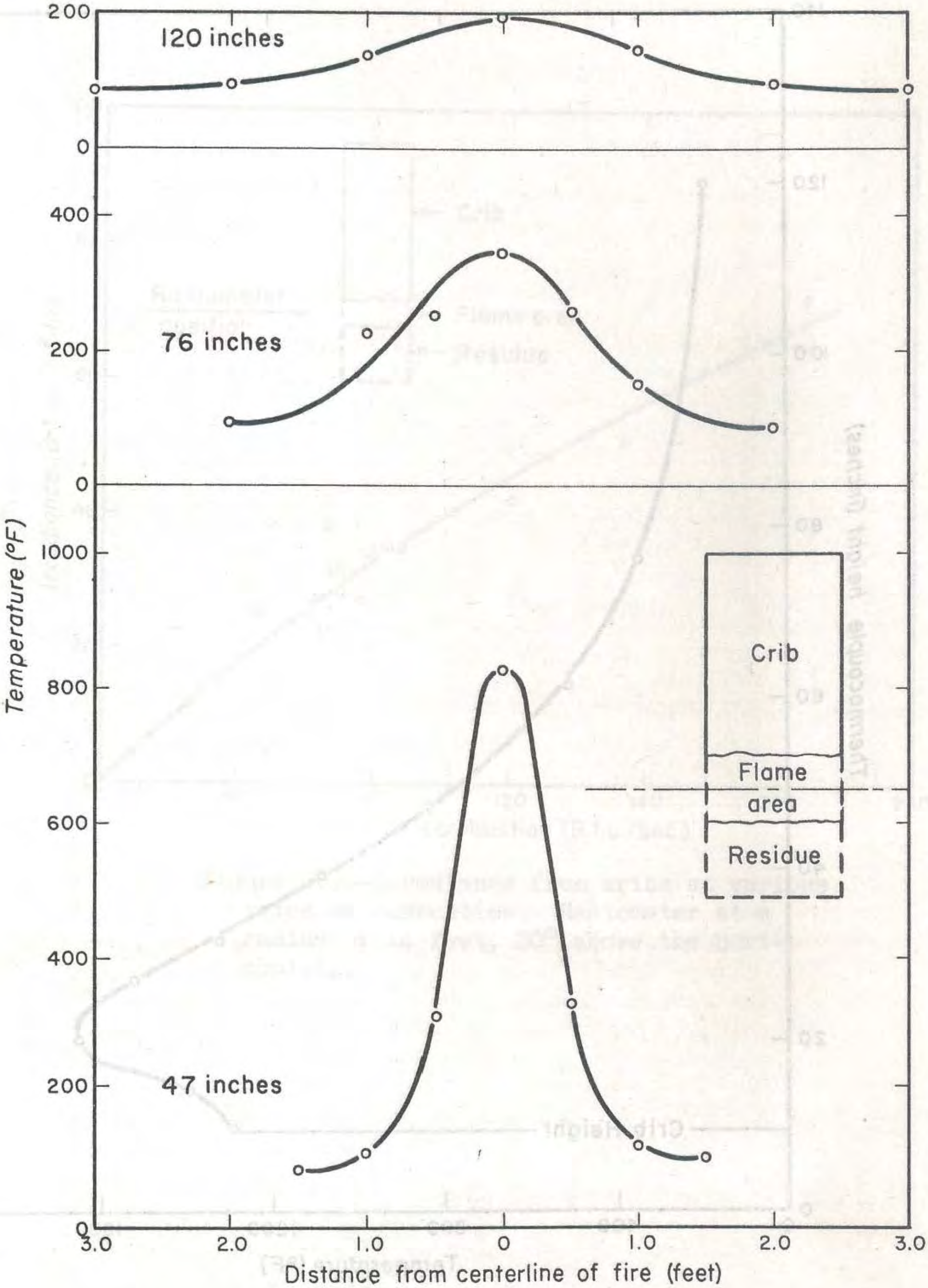


Figure 24.--Horizontal distribution of temperatures at three heights above table top, measured by thermocouples during Fire No. 16.

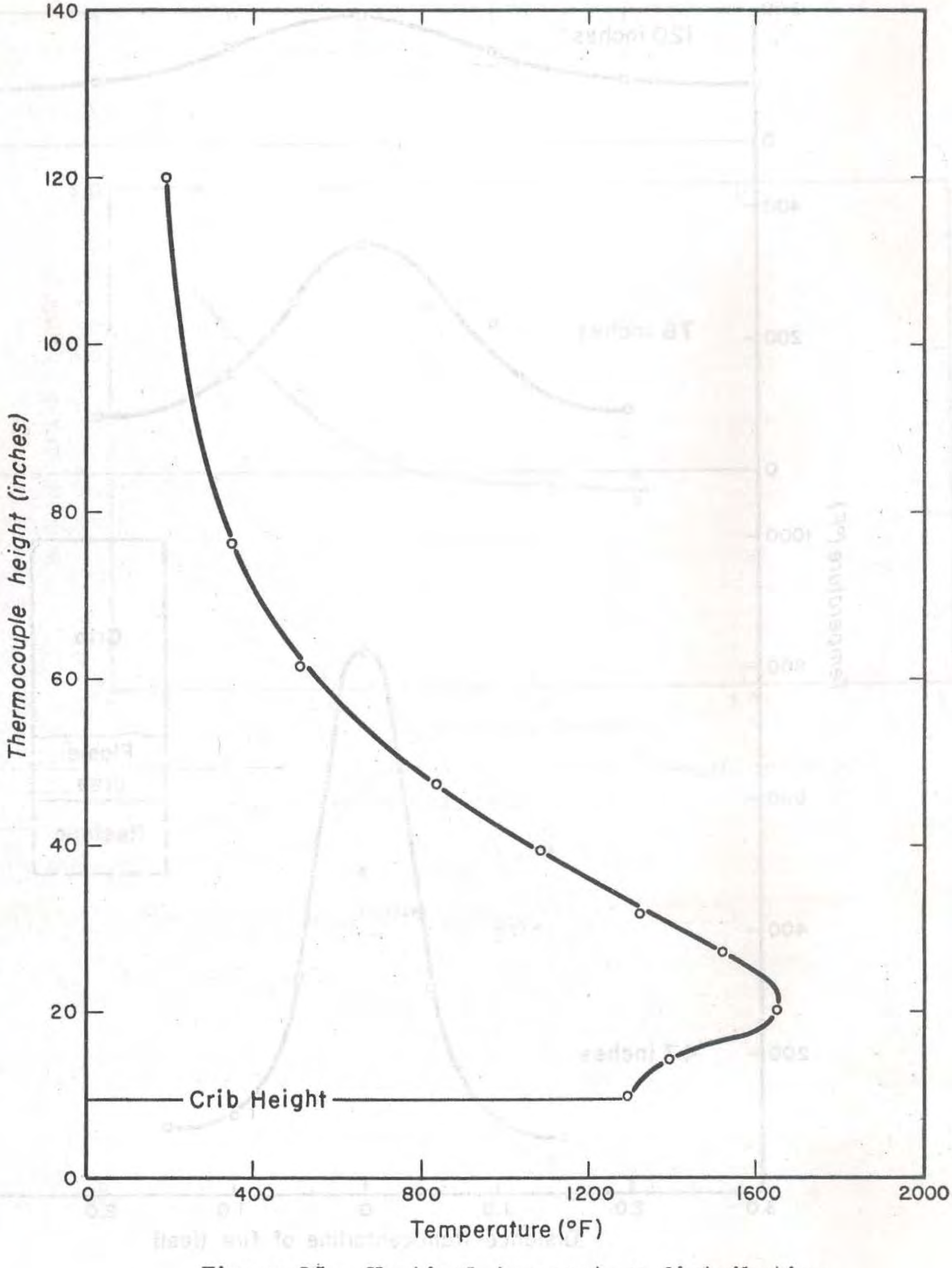


Figure 25.--Vertical temperature distribution along central axis of flame and convection column during Fire No. 16.

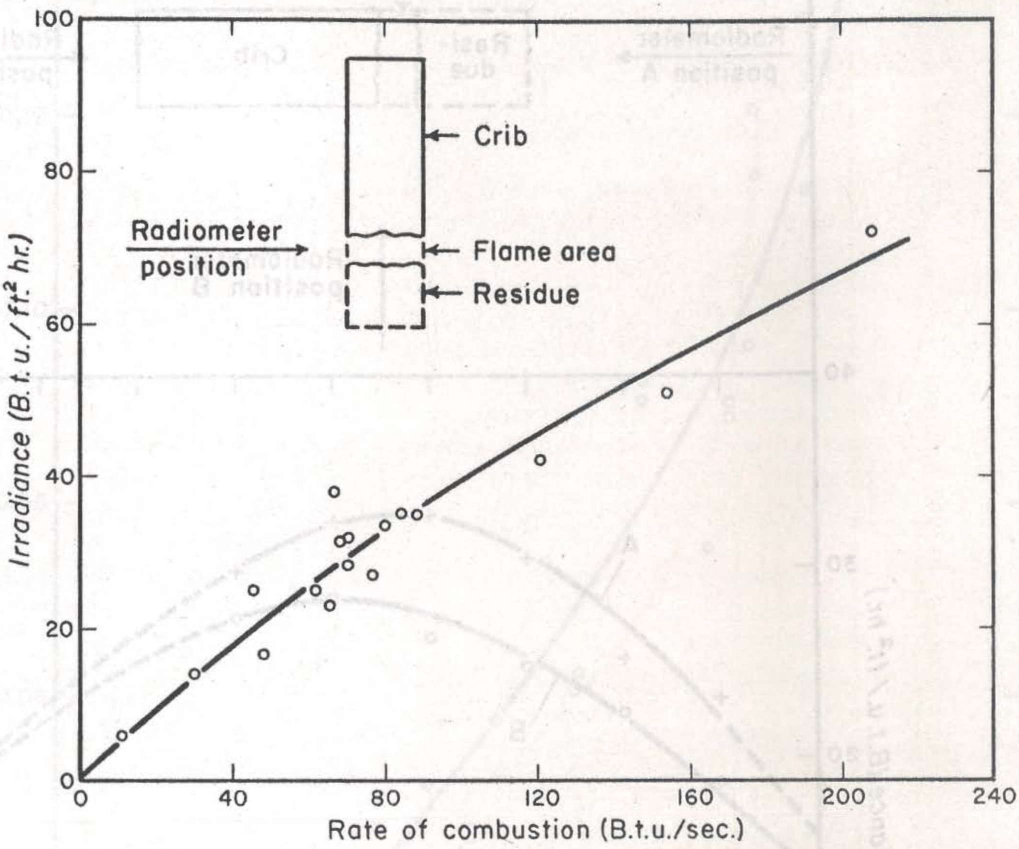


Figure 26.--Irradiance from cribs at various rates of combustion. Radiometer at a radius of 14 feet, 20° above the horizontal.

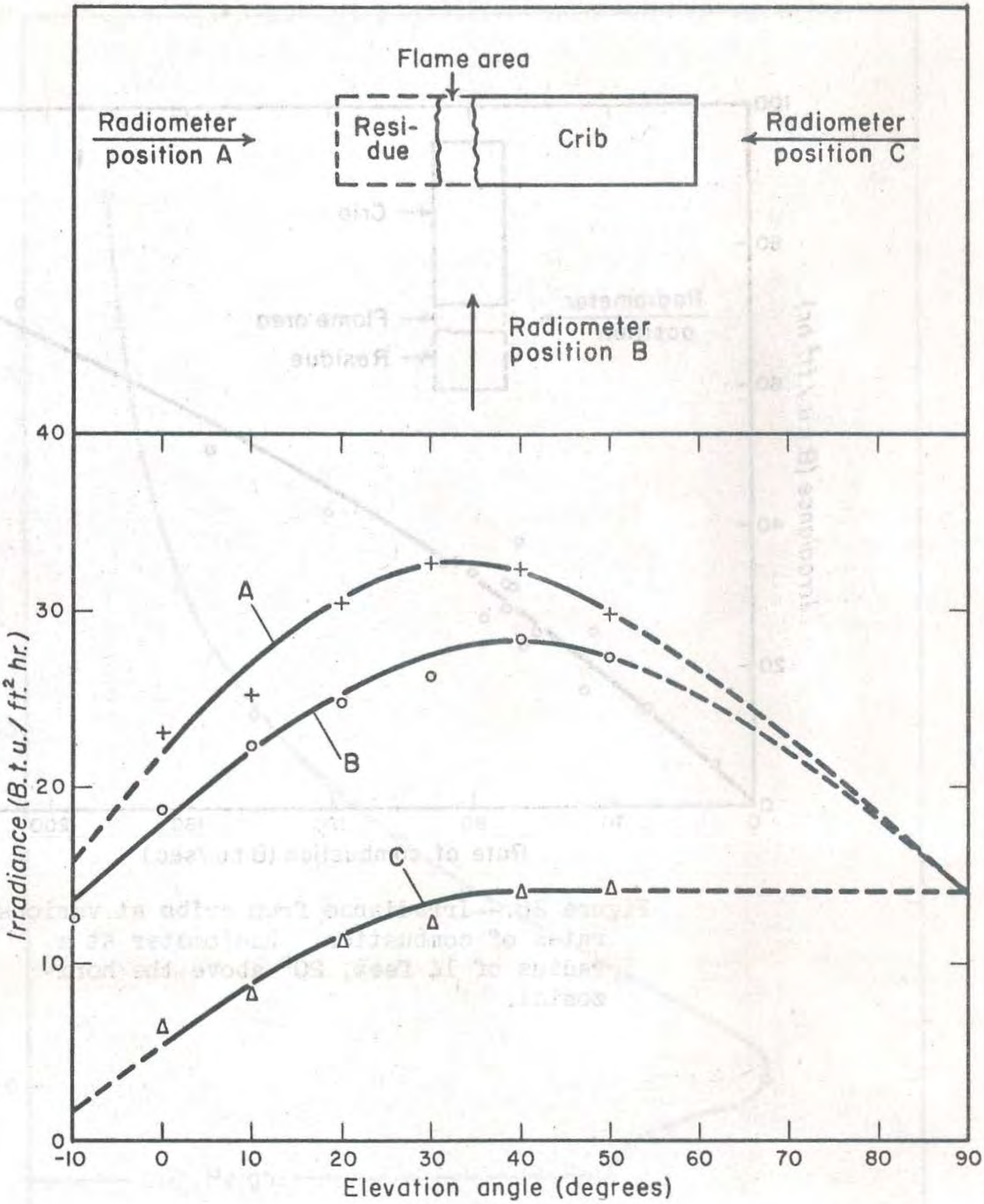


Figure 27.--Distribution of irradiation at different elevations during Fire 27, measured at a distance of 14 feet from a reference point within the fire 2 feet above the base of the fuel bed.

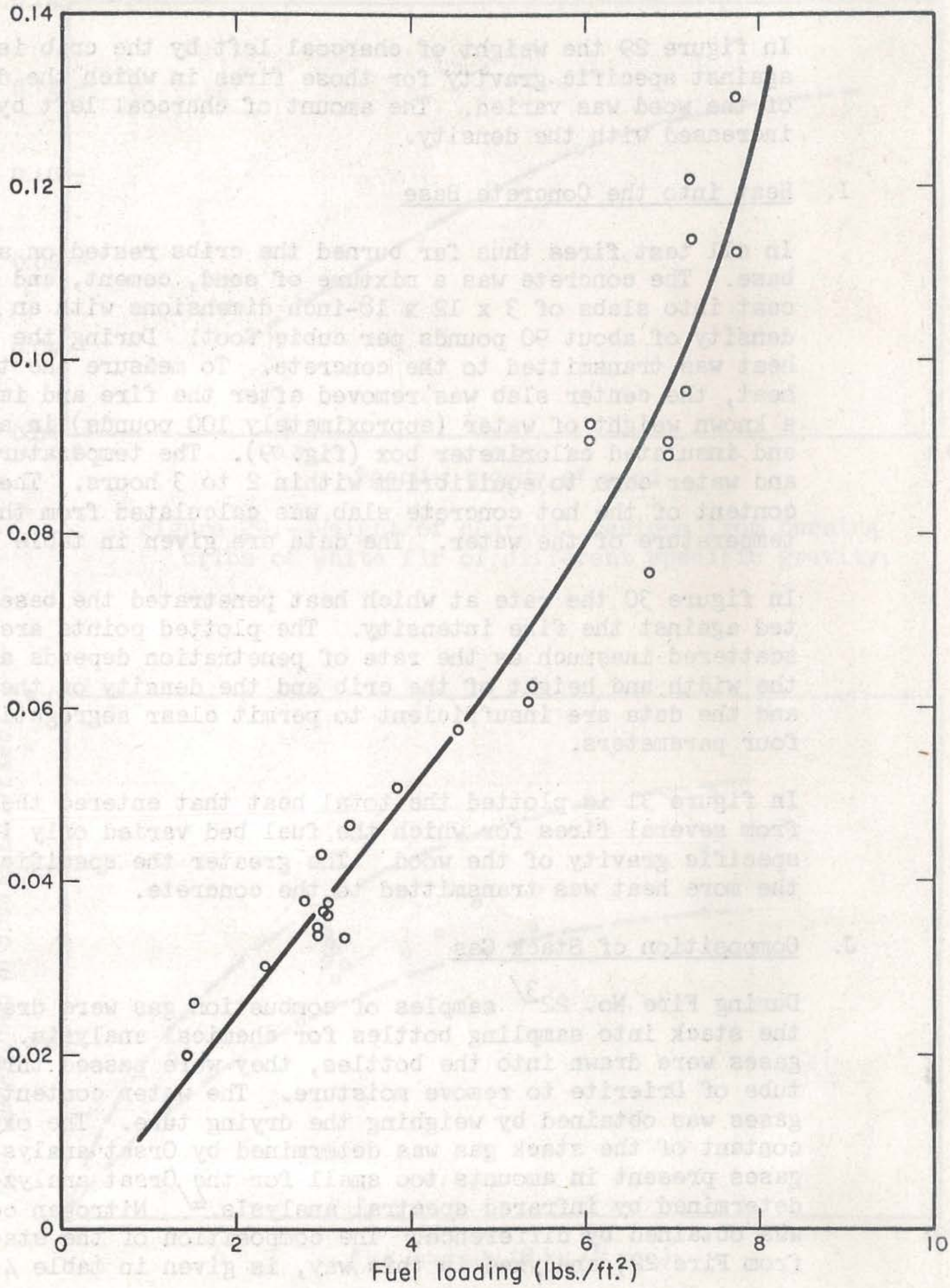


Figure 28.--Charcoal from cribs of different fuel loading.

In figure 29 the weight of charcoal left by the crib is plotted against specific gravity for those fires in which the density of the wood was varied. The amount of charcoal left by the fire increased with the density.

I. Heat into the Concrete Base

In all test fires thus far burned the cribs rested on a concrete base. The concrete was a mixture of sand, cement, and Perlite, cast into slabs of 3 x 12 x 18-inch dimensions with an air-dry density of about 90 pounds per cubic foot. During the fire, heat was transmitted to the concrete. To measure the transmitted heat, the center slab was removed after the fire and immersed in a known weight of water (approximately 100 pounds) in a sealed and insulated calorimeter box (fig. 9). The temperature of slab and water came to equilibrium within 2 to 3 hours. The heat content of the hot concrete slab was calculated from the rise in temperature of the water. The data are given in table 3.

In figure 30 the rate at which heat penetrated the base is plotted against the fire intensity. The plotted points are rather scattered inasmuch as the rate of penetration depends also on the width and height of the crib and the density of the wood, and the data are insufficient to permit clear segregation of all four parameters.

In figure 31 is plotted the total heat that entered the concrete from several fires for which the fuel bed varied only in the specific gravity of the wood. The greater the specific gravity, the more heat was transmitted to the concrete.

J. Composition of Stack Gas

During Fire No. 22[3/] samples of combustion gas were drawn from the stack into sampling bottles for chemical analysis. As the gases were drawn into the bottles, they were passed through a tube of Drierite to remove moisture. The water content of the gases was obtained by weighing the drying tube. The oxygen content of the stack gas was determined by Orsat analysis. The gases present in amounts too small for the Orsat analyzer were determined by infrared spectral analysis.[4/] Nitrogen content was obtained by difference. The composition of the stack gas from Fire 22, analyzed in this way, is given in table 4.

3/ Fire No. 22 was burned with the smaller exhauster (see II, C-3, page 6), drawing 29.7 cubic feet per second up the stack.

4/ By courtesy of the Bay Area Air Pollution Control District, San Francisco, California.

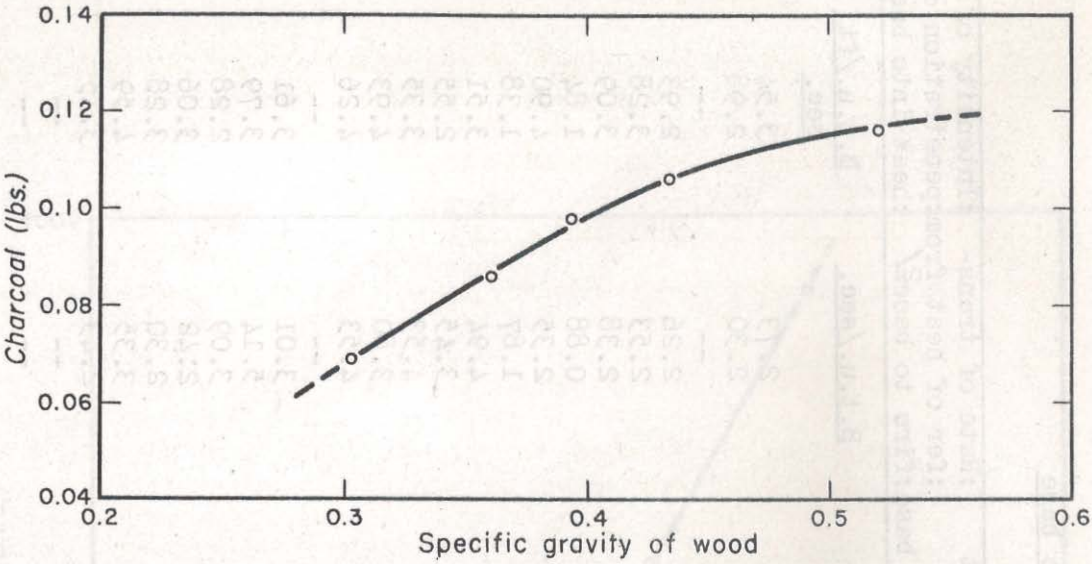


Figure 29.--Weight of charcoal residue from burning cribs of white fir of different specific gravity.

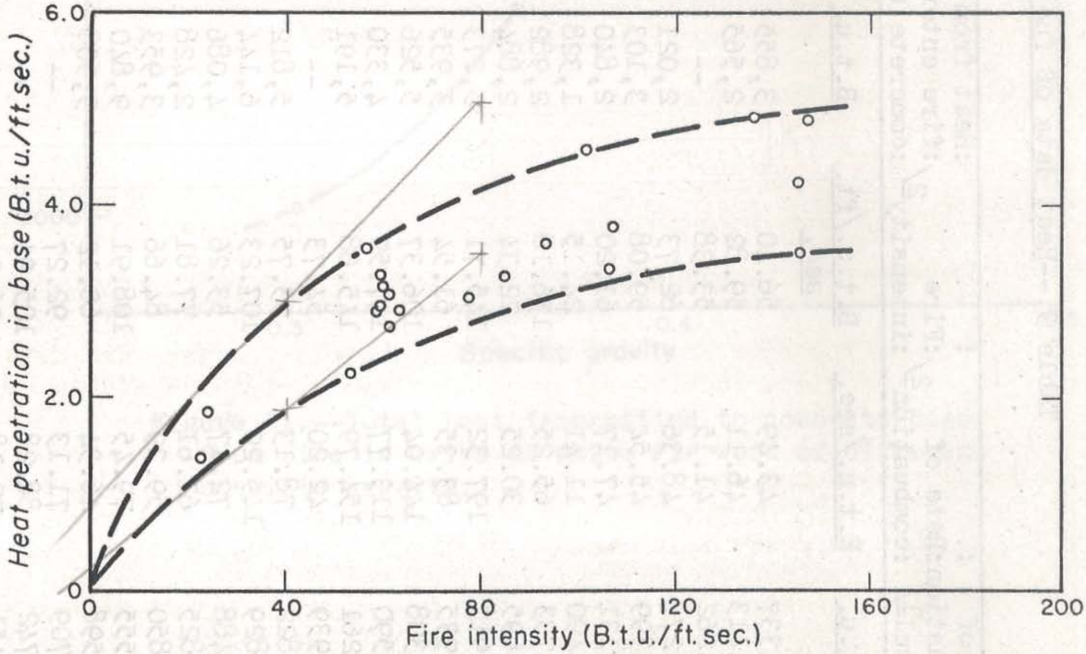


Figure 30.--Relation between fire intensity and penetration of heat into the concrete base.

Table 3.--Heat data of fuel and concrete base

Fire No.	Heat of combustion of fuel 1/	Rate of combustion 2/	Fire intensity 2/	Heat from fire entering concrete base	Fuel heat entering concrete base	Rate of transfer of heat from fire to base 2/	Intensity of penetration of heat into base 2/
	B.t.u.	B.t.u./sec.	B.t.u./ft. sec.	B.t.u.	%	B.t.u./sec.	B.t.u./ft. sec.
1	61,337	43.49	56.40	3,855	6.3	2.73	3.54
2	51,413	46.11	59.82	2,565	5.0	2.30	2.98
3	71,262	41.15	53.38	--	--	--	--
4	43,278	48.36	62.73	2,021	4.7	2.26	2.93
5	55,399	45.54	59.08	3,103	5.6	2.53	3.28
6	56,131	47.17	61.20	2,840	5.1	2.38	3.09
7	17,490	11.41	24.15	1,328	7.6	0.88	1.84
8	82,733	65.25	136.18	2,982	3.6	2.35	4.90
9	46,695	30.25	22.34	2,884	6.2	1.87	1.38
10	218,913	197.32	145.71	5,273	2.4	4.94	3.51
11	94,935	83.35	61.54	3,935	4.1	3.45	2.55
12	175,308	144.04	106.37	5,526	3.2	4.53	3.35
13	129,590	113.77	147.59	4,330	3.3	3.80	4.93
14	177,261	154.79	145.68	5,191	2.9	4.53	4.26
15	87,939	42.20	54.73	--	--	--	--
16	150,822	78.13	93.75	5,812	3.9	3.01	3.61
17	173,829	145.29	107.23	6,144	3.5	5.14	3.79
18	95,488	72.17	53.26	4,086	4.3	3.09	2.28
19	61,825	61.61	77.81	2,428	3.9	2.42	3.06
20	101,850	59.39	84.66	3,953	3.9	2.30	3.28
21	233,555	79.45	108.91	9,840	4.2	3.35	4.59
22	74,598	46.34	60.12	3,908	5.2	2.43	3.15
23	83,709	71.13	92.27	--	--	--	--
24	150,742	88.28	105.94	--	--	--	--
25	234,451	70.18	96.24	--	--	--	--
26	135,855	66.48	94.52	--	--	--	--
27	75,005	45.55	59.10	3,693	4.9	2.24	2.91

1/ Based on the low heat value of the fuel, 8135 B.t.u./lb.

2/ The time of these quantities is the time for the flame to travel the length of the crib at its uniform rate beyond the range of end effects. The true time of combustion and time of transfer of heat to the base is longer, inasmuch as combustion and transfer action continues in the glowing charcoal after the flame has passed.

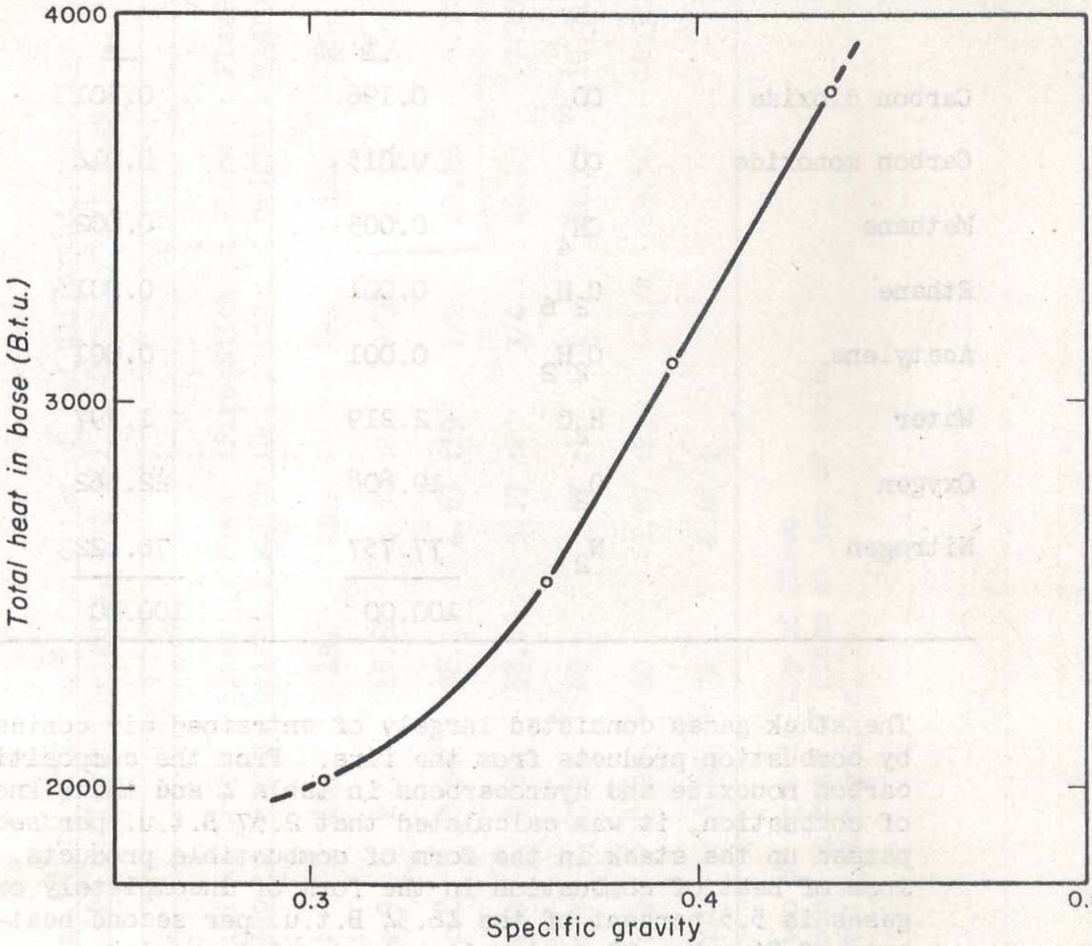


Figure 31.--Total heat transmitted to concrete base from fire in cribs of white fir wood of different specific gravity.

Table 4.--Composition of stack gas above Fire 22

Compound	Formula	Composition by volume	Composition by weight
		%	%
Carbon dioxide	CO_2	0.196	0.301
Carbon monoxide	CO	0.015	0.014
Methane	CH_4	0.003	0.002
Ethane	C_2H_6	0.001	0.001
Acetylene	C_2H_2	0.001	0.001
Water	H_2O	2.219	1.397
Oxygen	O_2	19.808	22.162
Nitrogen	N_2	77.757	76.122
		100.00	100.00

The stack gases consisted largely of entrained air contaminated by combustion products from the fire. From the composition of carbon monoxide and hydrocarbons in table 4 and their known heats of combustion, it was calculated that 2.57 B.t.u. per second passed up the stack in the form of combustible products. This loss of heat of combustion in the form of incompletely oxidized gases is 5.5 percent of the 46.34 B.t.u. per second heat-energy rate of Fire No. 22 during its steady-state regime.

K. Height and Width of Flame

Measurements were made of height and width of flame from the time-lapse movies taken from the side of the fire during the steady-state period. The height and width of flame for those fires in which specific gravity of wood, stick size, and height of crib were varied are presented in table 5. Figure 32 shows typical flames from burning cribs of several stick sizes.

L. Time to Develop Steady State

Although the main purpose of this project was to study the behavior of a wood fire in a steady-state condition, some supplementary data on the time taken by the fires to build up to a

Table 5.--Height and width of flame[1] for cribs of (A) different specific gravity, (B) different heights, and (C) different stick size

(A)				(B)				(C)			
Fire No.	Specific gravity bone-dry	Flame height	Flame width	Fire No.	Crib height	Flame height	Flame width	Fire No.	Stick size	Flame height	Flame width
		in.	in.		in.	in.	in.		in.	in.	in.
4	0.303	36.93	4.70	9	2.75	18.82	4.50	23	9/32	45.23	3.68
2	.361	35.28	4.57	18	5.50	38.15	4.63	19	1/2	42.26	5.15
5	.393	35.44	4.27	11	5.50	38.55	5.17	20	3/4	40.03	7.10
1	.434	32.97	4.32	17	10.25	[2] 60	5.57	16	1	38.75	10.71
15	.465	33.99	4.02	12	10.25	[2] 60	5.67	21	1-1/4	29.50	16.31
3	.511	33.63	3.95	10	13.00	[2] 72	6.62				

1/ Height: Length from top of crib to tip of flame.
Width: Length from front to rear of flame at top of crib.
2/ Approximations from still photographs.

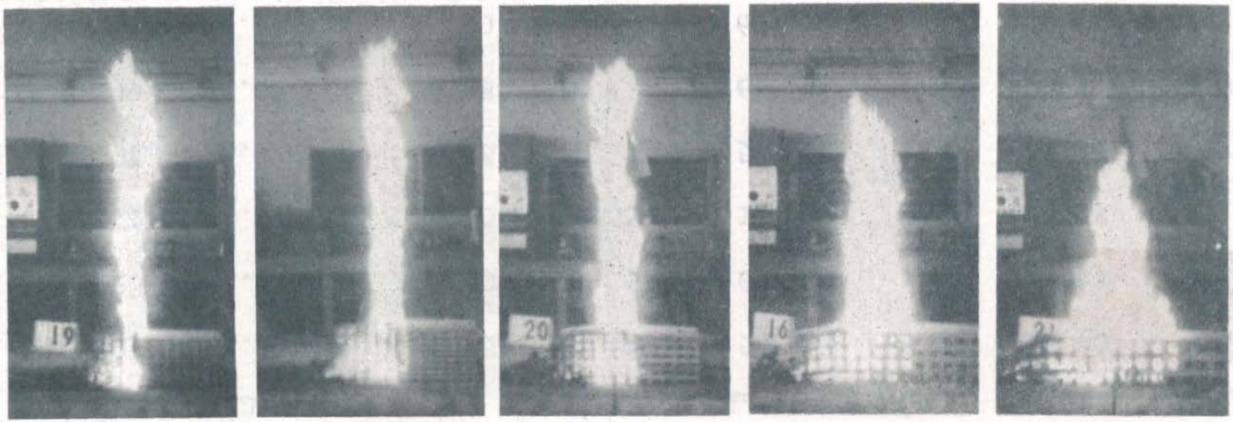


Figure 32.--Flames from burning cribs made of wood sticks of several sizes.

steady state have become available. These data are plotted against crib width, crib height, and stick size in figures 33 and 34. The larger the crib and the bigger the stick size, the longer was the time after ignition for the fire to reach a steady state. In the range tested an increase in the width of crib increased the build-up time only slightly. On the other hand, an increase in stick size had a pronounced effect on build-up time; there was an increase of over 250 percent for the 1-1/4-inch sticks compared with the 1/4-inch sticks.

M. Heat Balance

With the large stack and exhauster, it is possible to measure the convective heat from the test fires. A complete heat balance was attempted on Fire No. 27 with the following results:

	Steady-state rate	
	Btu/sec	Percent
Convective heat	28.10	61.7
Radiation	8.26	18.1
Heat into concrete base	2.24	4.9
Heat value of charcoal	0.43	1.0
Heat value of unburned combustion gases	1/ 2.50	1/ 5.5
Heat accounted for	41.53	91.2
Heat unaccounted for	4.02	8.8
Heat value of the fuel	45.55	100.00

1/ The analysis of the combustion gases of Fire No. 27 was inconclusive; the value of 5.5% was adopted from the data of Fire No. 22.

IV. Conclusions

The following conclusions are drawn from data on the crib fires tested to date on Project Fire Model:

A. Wood fuel can be burned at a steady rate by the technique developed.

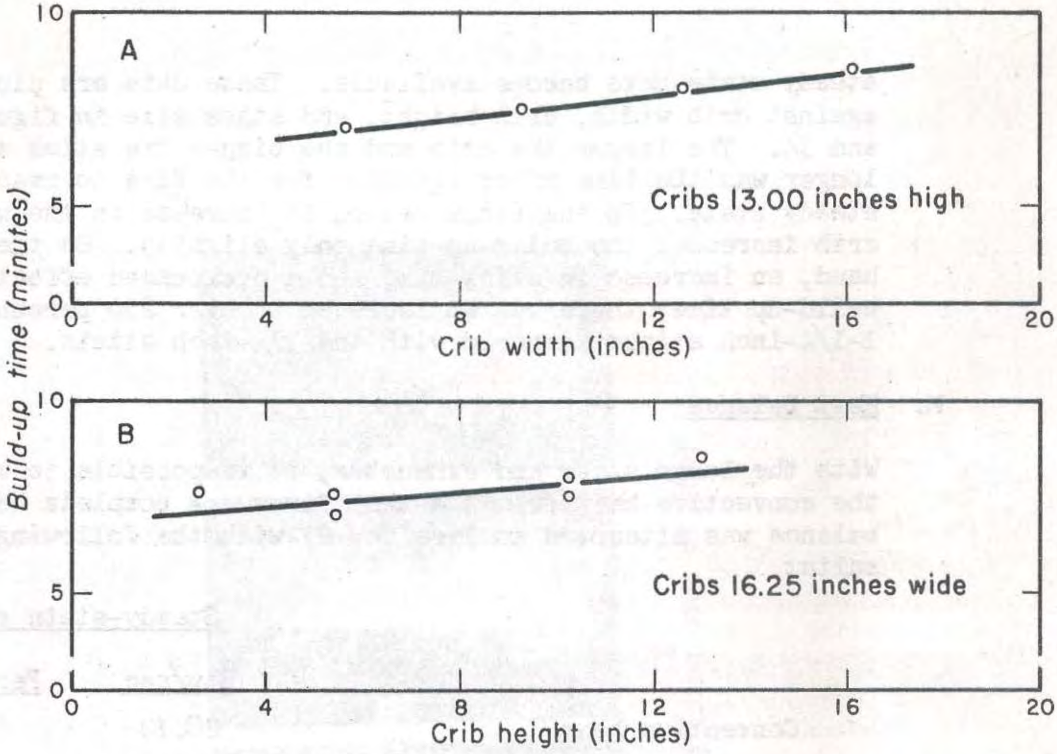


Figure 33.--Fire build-up time in cribs of (A) various widths and (B) various heights.

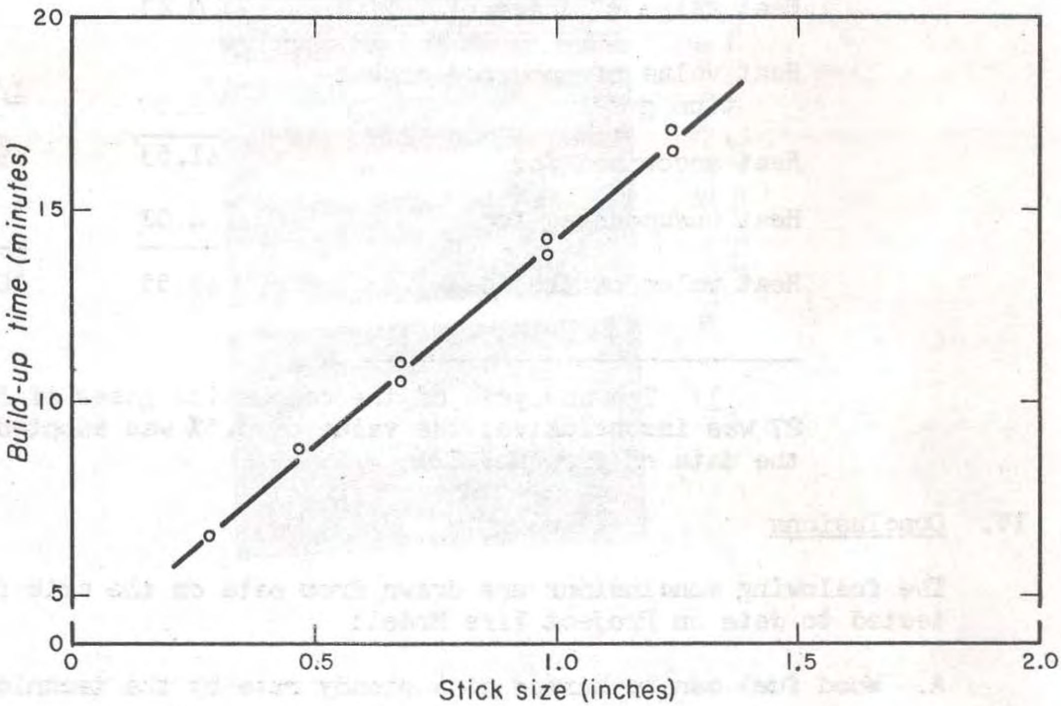


Figure 34.--Fire build-up time in cribs made of sticks of various sizes.

B. Crib fires can be closely duplicated by controlling the more important conditions.

C. The properties and behavior of wood-fuel can be determined during the steady-state burning.

D. By moving the fuel into the fire, the flame can be held in a fixed position in space, allowing stationary positions for measuring instruments.

E. The rate of spread of fire through a bed of wood fuel can be determined by measuring the rate of movement of the fuel bed into the fire to maintain the flame in fixed position in space.

F. The shape and temperature of the convection column from a fire can be learned by measurements with thermocouples.

G. The maximum temperature of the flame from the crib fires is about 1600°F. a few inches above the top of the fuel bed. Closer to the fuel in the region of very incomplete combustion and higher in the convection column cooled by entrained air, the temperatures are lower.

H. The convective heat from the crib fires can with proper equipment be determined by measuring the velocity of the combustion gas up a stack and the rise of the stack-gas temperature above that of the incoming air.

I. The radiation from a crib can be estimated with thermopile radiometers, directed towards the fire from three directions (front, back, and side) at several altitudes, by integrating the radiometer measurements over the hemisphere surrounding the fire.

J. The time for a wood-crib to build up to a steady state is longer the higher the crib and the larger the size of the sticks.

K. The rate of spread of fire through a crib-bed of wood fuel and the rate of combustion of the fuel decrease as the density of the wood increases.

L. The rate of spread of fire through a bed of wood fuel decreases as the size of the fuel particles (wood sticks) increases.

M. In a large room with ample intake area, forced flow of as much as 5400 CFM of air up the stack from a hood 12 feet above a crib does not change the rate of spread of the fire through the crib.

N. The height and width of the fuel bed of 1/2-in. square sticks of white fir has little effect on the rate of spread of fire through a wood crib beyond a crib height of 13 inches or a crib width of 16 inches.

O. The height and width of the flame from a wood fire increases with the crib height or loading.

P. The height and width of the flame of a wood crib fire decrease with increased density of the wood.

Q. The height of the flame of a wood crib fire decreases with increasing stick size, but flame width increases with increasing stick size.

R. A 3-inch concrete slab (90 lbs/cu. ft. density) is thick enough to prevent appreciable loss of heat out of the bottom during a crib fire, and the heat transferred to the slab from the fire may be estimated by a water calorimeter.

S. The heat value of the charcoal left as a residue from the crib fires in wood sticks of 9/32 to 1-1/4-inch size averages about 1.2 percent of the heat value of the wood fuel.

T. There is as yet no satisfactory method for analyzing very dilute combustion gases quantitatively, and a method should be developed in which all combustion products, including CH_4 and CO, are concentrated for analysis by gas-chromatography, infra-red spectroscopy, or mass spectography.

U. An approximate heat balance has been arrived at for a wood crib fire, with about 91 percent of the heat energy accounted for.

V. Plans for Continuation

A. A proposal for the continuation of Project Fire Model was prepared as of December 16, 1959 and submitted to the National Bureau of Standards for consideration. The proposal was approved for the period March 1, 1960 to June 30, 1961.

B. A brief description of the jobs proposed to be undertaken during the 15-month period are as follows:

1. <u>To learn the effect of density of wood of various species, both resinous and non-resinous, upon fire characteristics.</u>

   The effect of density on the rate of fire spread through wood cribs has been obtained for white fir wood (figure 19), but it is not known whether the same relation applies to other species. It is proposed to conduct tests with cribs of basswood, southern magnolia, sugar maple, and long leaf southern yellow pine, selected to be of high, medium, and low density within the natural range of each species.

The basswood, magnolia, and maple are non-resinous, diffuse-porous species of low, medium, and high densities, respectively. The long leaf southern yellow pine is a resinous wood of high density.

2. <u>To learn the effect of moisture content on fire characteristics</u>.

   Thus far the wood of all test cribs has been conditioned to about the same moisture content, averaging 10.4 percent. No experiments have been made on wood over a wide range of moisture content. It is proposed to test cribs of white fir wood conditioned to at least five different moisture contents between 4 and 24 percent, and to analyze the results for the effect of moisture content on the behavior of the fires.

3. <u>To formulate theories relating the properties of free-burning fire in wood-crib fuel beds to the independent variables affecting the fire</u>.

   The purpose will be to arrive at a systematic description of a wood fire in terms of its more important parameters and to explain such behavior aspects as rate of spread, convection column characteristics, and partition of energy. The test data obtained by experimentation will be analyzed to substantiate existing theoretical analyses concerned with fire behavior or to serve as a basis for improved or new theoretical formulas.

APPENDIX

Work Plan - January 12, 1959 (amended).

A. Requirements for each fire.

1. Wood fuel particles constant as to size, shape, and moisture content, and selected as to density.

2. Homogeneous fuel bed of known and describable structure.

3. Ambient conditions of temperature and relative humidity.

4. Constant ignition to achieve the steady state as early as practicable.

5. Steady state combustion, with size of fire, rate of spread, emission of radiation, convection column, and rate of deposition of residual fuel all constant.

B. Burner type.

1. A stoker-type burner is proposed, feeding a prepared fuel bed on a continuous conveyor belt into the fire at a controlled rate to keep the fire always at one position in space. Measuring instruments will have fixed locations with respect to the fire.

C. Independent variables.

1. Fuel material. It is expected that the character of the fuel will influence the fire through its heat content, density, specific heat, thermal conductivity, optical absorptivity, and rate of liberation of volatiles by destructive distillation. Only wood will be tested, and white fir (Abies concolor) will be the species studied first because of its uniformity, freedom from resin, and availability. Later, other species will be tested to learn the magnitude of the effects of physical and chemical properties on the fire. Heat value of each fuel will be measured in a bomb calorimeter.

2. Fuel particles, size, and shape. The first work will be with sticks of square cross-section of approximately 1/4, 1/2, 3/4, 1 and 1-1/4 inches.

3. Moisture content of fuel. Four moisture contents from 0 to 20 percent based on dry weight of the fuel will be used. Moisture content will be determined by xylene distillation.

4. Fuel temperature. Experimental fires will be carried out with four fuel temperatures, from 40°F. to 140°F.

5. Particle spacing in fuel bed (distance between fuel particles). Four or five variations will be used between the closest and farthest spacings at which the fires will burn as determined by preliminary experiments.

6. Fuel particle arrangement (geometry of spacing). Crib fuel beds will be built with square and diamond orientation, and regular and staggered location. Fuel beds of other forms and arrangements, such as of vertical sticks, and horizontal sticks, may also be used if such arrangements lend themselves to easier theoretical analysis.

7. Height of fuel bed. Heights of about 3 and 12-inches are planned with two other heights to be chosen later.

8. Width of fuel bed. Widths of about 6 and 16 inches are planned with possibly two other widths to be chosen later.

9. Air temperature. Tests will be made with room temperatures over as wide a range as available between 40°F. to 140°F. It may be that some experiments may have to be done in other laboratories where control facilities are available for higher and lower temperatures than can be had with uncontrolled ambient air.

10. Relative humidity. Tests will be made with ambient humidities over as wide a range as available between 10 and 80 percent. It may be that some experiments will have to be done in other laboratories where facilities are available for higher and lower humidities than can be had with uncontrolled ambient air.

11. Barometric pressure. The air pressures will be those of ambient conditions over as high a range as possible.

12. Lapse rate. The vertical variation of temperature in the laboratory room at the beginning of each experiment and during the experiment will be measured. Unless a pronounced lapse rate is found, no attempt will be made to vary the lapse rate to ascertain its effect.

13. Wind velocity. In the first experiments, the velocity of the indraft to the fire under free convection will be measured. In later experiments fires under forced draft in a wind tunnel will be studied in the range of 0 to 10 m.p.h. Consideration will be given to experiments with external radiation applied to the fuel in front of the fire to see if the principal effect of wind is to increase the radiant heating of the fuel bed by the flame.

14. Slope of the fuel bed. Experiments will be made on slopes between -50 and +50 percent (-30° to $+30^{\circ}$ from horizontal). Consideration will be given to experiments with radiation on the fuel in front of the fire to see if the principal effect of slope is to increase or decrease the radiant heating of the fuel bed.

15. Material of the base. The absorption of heat by the base slab on which the fire burns will depend on the thermal diffusivity and on the optical absorptivity of the slab surface. Some bases on which fires often occur are concrete, soil, and wood flooring. These vary in their absorptivity and diffusivity. For the fire model experiments it is proposed to study fire on three mixed types of base materials made of Portland cement, sand, and light aggregate mixed in various proportions to vary the diffusivity to match closely the values of concrete, soil, and wood flooring.

D. Effects on the fire (dependent variables).

As the independent variables listed in C above are varied, some or all of the properties of the fire may be affected. The following properties will be measured as dependent variables.

1. Rate of flame spread. In the experimental setup the fire will have a constant position, but the velocity with which the conveyor belt will carry fuel into the fire to maintain the fire at constant position will be measured. Operation of the belt will be manual at first, but possibly by automatic motor-drive later.

2. Size of flame. In preliminary experiments movies will be taken at 16 frames per second of typical fires to note the shape of the fires and any pulsation of the flame. The height and width of the zone of flame will be measured by means of black and white time-lapse photography, taking about 1 frame every 5 seconds (or other rate depending on the period of pulsation, if any) from front and side

directions taken syncronously. These will show when the flame has become stabilized in size after the ignition.

3. Radiant energy from the fire. A technique of measuring radiation from the fire will be devised through preliminary experiments with radiometers at several positions.

4. Convective heat. The rate at which thermal energy from the fire passes up the convection column will be determined from measurements of temperature and velocity of the stack gases. The best methods for measuring the temperatures and velocities will be ascertained in preliminary experiments.

5. Heat conducted into the base slab. After fuel has passed the zone of flame far enough that it is no longer giving off much convective heat or transmitting appreciable heat to the base, it will be removed and the base slab immersed in an insulated water calorimeter. It has been calculated that a slab of high density concrete will have to be 6 inches thick to preclude the loss of appreciable heat through the slab. Slabs of other materials of lower density need not be so thick.

6. Composition of flue gases. The flue gases from the wood fires will include principally C, CO, CO_2, O_2, N_2, H_2O, and hydrocarbon compounds. The relative proportions of these compounds may vary with the fuels and burning conditions. The stack gases will be collected in gas-sampling bottles and analyzed by gas-chromatography. The amounts of carbon, carbon monoxide, and hydrocarbons evolved by the fire are particularly important because their heat of combustion must be known and accounted for in establishing the heat balance for a fire.

7. Flame and convection column temperatures. The temperatures of the flame from free convection wood fires is a fundamental element of theoretical calculations, but it is not well known. Temperatures of the flame and of the convection column will be measured with banks of thermocouples transecting the flame and upper convection column.

8. Temperature within the burning fuel. In forming a theoretical analysis of the rate of combustion of a bed of wood fuel, the temperatures inside the mass of actively burning fuel are of particular importance. These temperatures may or may not vary with burning conditions, but, because of their importance, should be better known. Therefore, temperatures at various locations in the burning fuel bed will be measured by thermocouples.

9. Temperature of base slab. The temperature reached inside the base slab may vary with the characteristics of the fire, as well as with the physical properties of the slab material. To obtain these temperatures, thermocouples will be embedded in the slabs during the casting.

10. Various optical and mechanical methods have been proposed for measuring the velocity of the gases in the flame and upper convection column, also of the air being drawn into the column by entrainment. The best method or methods for the purpose will be ascertained by preliminary experimentation.

11. Pressure in the flame and convection column. Pressure may be either slightly positive or slightly negative, and may be of importance in explaining combustion phenomena and aiding theoretical analysis of air entrainment. A special commercial pressure gage will be considered for this purpose.

12. Composition and heat content of the residual fuel. A mixture of ash, carbon, and unburned or partially burned wood is usually left by the fire. A knowledge of the composition and heat content of this residual charcoal is needed for a complete heat balance. The heat contents of the charcoal will be measured in a bomb calorimeter.

13. Volatiles in and near the zone of flame. To understand the combustion process and what is happening at the forward front of the flame well enough to set up predictive models, it seems necessary to learn more about the composition of the gases in front of the flame where the fuel is being preheated just before ignition, below the flame just above the fuel bed, and up the column of flame into the upper convection column above the luminous flame. It is planned to sample the gases at these locations and to analyze the samples with a gas-chromatograph.