78044 Speeches

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Forest Fire Modelling

Several types of early studies of free-burning fires in forest fuels which led to techniques now used in forest fire modelling are briefly discussed in this paper. A description is given of a steady-state propagating flame model which uses a crib made of wood sticks of known physical properties. The model described represents a section of the combustion zone of a moving fire front. This model is used to study forest fire behavior as a part of a continuing program started in 1959. Results of flame radiation measurements and mean effective emissivity are presented for thirty experimental fires.

INTRODUCTION

In the management of forest areas, there has been a trend over the years toward placing fire-control activities such as rating fire danger, determining size of suppression crews, and planning fire-suppression strategy and technique on a more scientific basis. This trend has resulted in greatly improving the techniques of planning and managing the fire-control organization. Moreover, the technological advancements in communication, transportation including aircraft, use of chemical retardants, and fireline building equipment have revealed a serious lack of basic information on forest fire behavior.

This paper presents some of the types of early studies in fire behavior which led to techniques now used in forest fire modelling. A description is given of a steady-state propagating flame model currently used to study the free-burning of wood fuel. Results of flame radiation measurements for model fires are also included. The experimental work was initiated early in 1959 and the study was designated as Project Fire Model.[1] The general objectives of the project are to evaluate the effects of the independent variables of fuel, fuel bed, and atmospheric conditions on the dependent variables such as rate of burning and fire spread, flame size, rate of energy released, and convection column temperature.

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[1] Project supported by Office of Civil Defense through contracts administered by the National Bureau of Standards.

 Presented at ASME-ASCE Meeting in Boston, Mass., August 1963.

EARLY STUDIES

Fire behavior is a general term covering all natural forest-fire phenomena of importance from the standpoint of fire control. Of prime importance to forest protection are fire ignition and rate of fire spread; ignition because it largely controls the occurrence of fires, and spread because it affects the size which fires may attain during any time interval.

Gisborne (1), Stickel (2), Wright (3), and others have studied forest-fire ignition hazard through the determination of changes in fuel moisture with different weather conditions, relating these moisture variations to ignitibility through tests with several ignition sources. Their experimental work established that with ordinary ignition sources—such as matches, smoking materials, and small campfires—ignition occurs only when the forest fuel moisture is less than 30 percent of the dry weight of fuel. These early studies also gave an understanding of the influence of meteorological factors on moisture variations in several forest fuel types. The results of these studies permit making fairly reliable estimates of the moisture content of litter fuels from changes in weight of standard fuel moisture sticks.

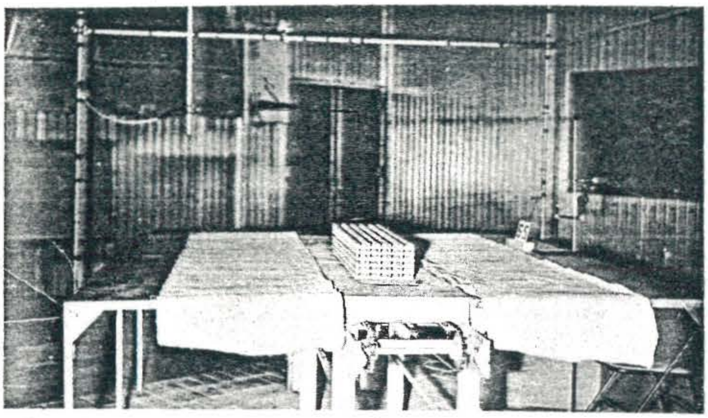
Early studies in California by Show (4) and Curry and Fons (5) consisted of observations on the fire-perimeter increase of small test fires burning under natural forest conditions of fuel, weather, and topography. Analyses of the field test fire data made it apparent that without a basic understanding of the many physical processes involved, the results of the experiments could not be applied beyond the limits of the conditions under which the observations were made. Furthermore, under field conditions none of the important factors, such as the attributes of the atmosphere, the arrangement of the fuel bed, and the physical properties of the fuel particles, remained sufficiently uniform throughout an experiment to allow accurate descriptions of the numerous variables influencing the rate of fire spread. In order to understand the influence of the many variables on the rate of fire spread it was decided to conduct laboratory experiments with fires in fuel beds of typical homogenous forest fuels. These experiments were first performed by Curry and Fons (6) and Fons (7) in still air for different conditions of fuel, fuel-moisture content, fuel-bed compactness, and later by Fons (8) in a wind tunnel in which the air velocity was controlled. These laboratory fires in beds of natural fuels were only a slight improvement over field test fires because it was still not possible to completely define the fuel bed variables.

In 1958 the Committee on Fire Research and Fire Research Conference of the National Academy of Sciences—National Research Council studied the status of firefighting techniques and statistics, and concluded that the ability to cope with large fires, both forest fires and urban conflagrations, can be realized only through more intensive fundamental research. The Fire Research Committee (9) 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.

Following the recommendations of the Fire Research Committee (9), a steady-state propagating flame model for burning wood fuels was developed. With this model the parameters which govern combustion can be examined and measured over an extended period of time. The model represents on a reduced scale a section of the combustion zone of a moving firefront burning in a homogeneous fuel bed.

STEADY-STATE FIRE MODEL

The essential elements of the fire model are: a wood fuel bed built in the form of a crib (Fig. 1), a combustion table equipped to transport the fuel bed at a controlled rate,



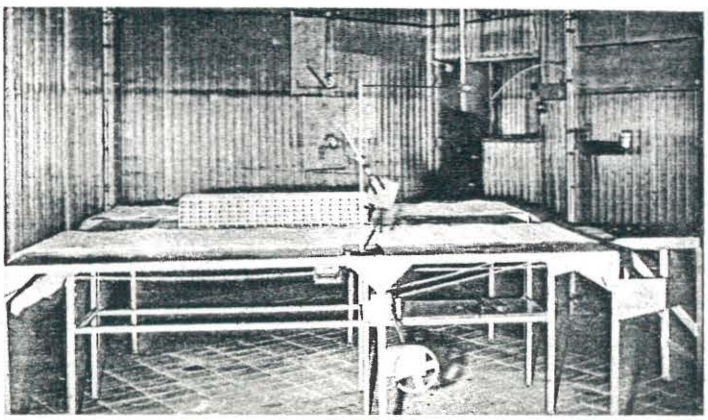


FIG. 1. End and side views of combustion table showing the chain-belt drive mechanism with concrete base slabs, asbestos sheets on either side, operator's hand wheel, and a wood crib in place for a test fire.

an ignition device, a base of inert material of known density, and sensing and recording instruments to measure specific variables (Fons et al. (10)).

The fuel bed is a crib of wood sticks of square cross section. The physical features of such a fuel bed can be controlled. The species, density, moisture content, size and spacing of the wood sticks, and the width and height of the fuel bed are all selected before the crib is built. The crib is formed by placing the sticks in tiers with the selected spacing between sticks. A drop of resorcinal-formaldehyde resin glue is placed on each junction to bond the crib into a rigid assembly. For several weeks before burning, the crib is conditioned to an equilibrium moisture content in an atmosphere of constant temperature and relative humidity.

The ignition device is a narrow, shallow trough containing an asbestos wick saturated with a liquid hydrocarbon. This device is placed at one end of the crib. The liquid hydrocarbon is ignited to initiate combustion in the fuel bed. The fire gradually spreads to the other end of the crib, reducing the wood to a residue of ash and charcoal.

The combustion table is equipped with a chain-belt mechanism which moves the crib and two heavy asbestos sheets, one on each side of the fire, in synchronism with the flame spread to simulate movement of the fire front relative to the ground. The crib and its inert base rest on the chain-belt, which is moved manually by a gear (Fig. 1) to hold the flaming zone of the burning crib in a fixed position (Fig. 2).

The combustion gases diluted by the entrained air are expelled from the room through a 2-foot-diameter exhaust stack. The incoming conditioned air is supplied to the room at a rate of about 5,000 cubic feet per minute through several louvered outlets in a continuous duct located near the ceiling around the room. The entrance to the stack is a hood 12 feet in diameter and located 12 feet above the combustion table.

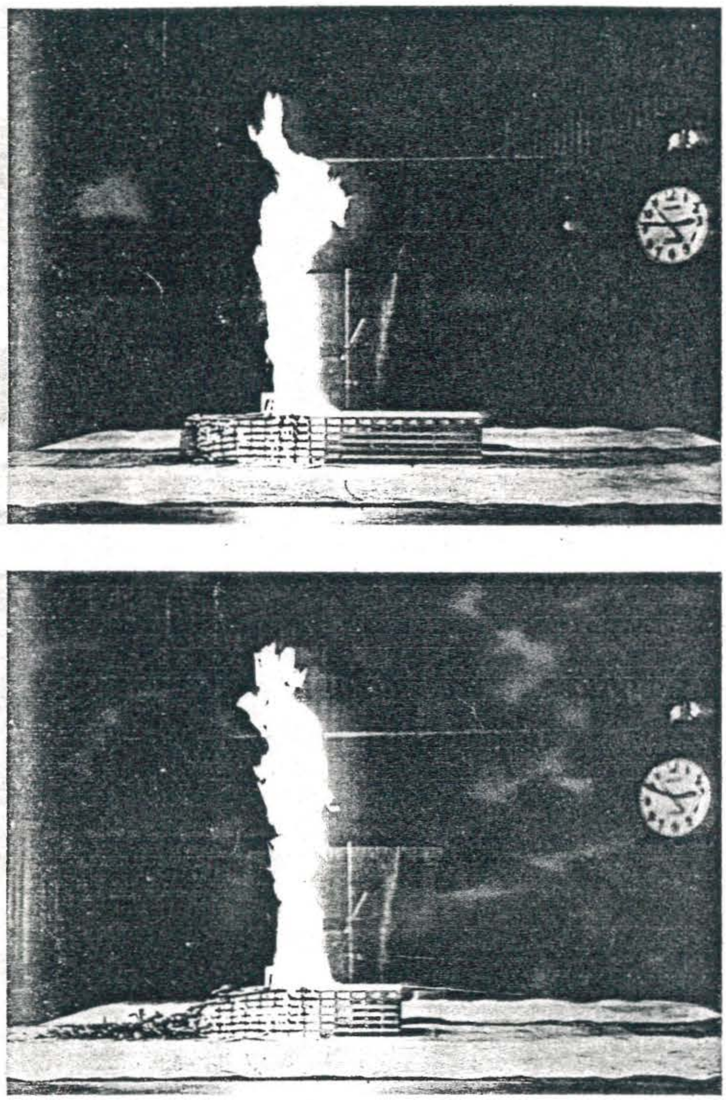


FIG. 2. A test fire at two different times, illustrating the fixed position of the flame as the crib moves.

Time-lapse cameras mounted on the wall photograph the test fires for subsequent measurements of flame depth and length. Three grids of thermocouples suspended at different levels above the combustion table measure temperatures of the convection column. A thermocouple and a Pitot tube mounted in the exhaust stack measure the temperature and velocity of combustion gases. Thermopile radiometers located at the front, rear, and side of the test fire measure radiation. The sensing elements are connected to recording instruments in a control room adjacent to the combustion room.

Two important features of the model are: (1) the crib is made relatively long and a zone of fire travels the length of the crib. After an initial buildup, the rate of burning or spread reaches a constant value, which holds until near the end, and thus the difficulty of investigating a fire burning under transient conditions is avoided. (2) The position of the flaming zone is held fixed in space by moving the fuel into the fire. This method permits the grids of thermocouples in the flame and convection column, radiometers surrounding the fire, and other sensing devices to be stationary. The rate of fire spread is equal to the rate the crib is moved to maintain the flame in a fixed position (Fig. 2). Fig. 3

presents curves showing the steady-state periods for the spread of fire through cribs of wood with different specific gravities.

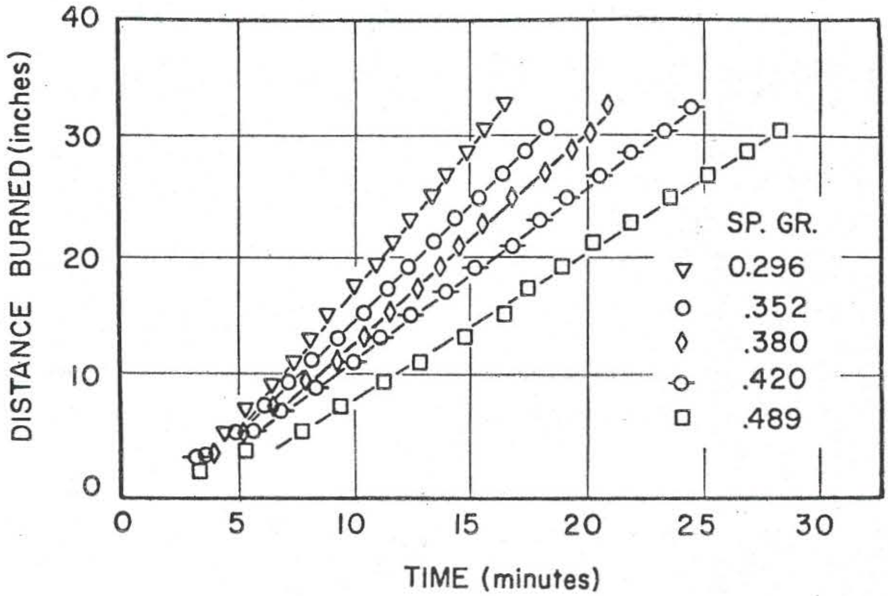


FIG. 3. Steady-state burning through cribs of white fir wood with different specific gravities.

RESULTS

To date about 100 experimental fires have been burned using this steady-state model. Measurements of the dependent and independent variables have been analyzed to establish quantitative relationships between certain fire properties and the fuel and fuel bed parameters. Some of the results, such as a dimensionless relationship of flame dimension and modified Froude number, a dimensionless relationship of the fuel and fuel bed variables and burning time, and temperature distribution of the convection column have been reported elsewhere (10), (11), (12). Estimates of radiation and flame emissivity of these fires are included here. Physical characteristics of the wood, the crib arrangement, the environment during the burning period, and experimental data such as rate of flame propagation, and flame dimensions for all these fires are presented in a summary report (13).

Radiation.

a. Irradiance.—The irradiance of the crib fires was measured by directional thermopile radiometers at three different positions (Fig. 4). Detailed description of the directional radiometer is given in reference Gier and Boelter (14). Briefly, the radiometer consists of a 150-junction, silver-constantan thermopile mounted in the rear of a cylindrical metal housing. A rear plate with a narrow slot allows radiation entering the front opening of the radiometer to impinge on the hot-junction receiver strip, while shielding the cold-junction strip. The output of the thermopile is linear. A calibration factor, K, in Btu/ft^{2}hr per millivolt output is furnished for each instrument by the manufacturer.

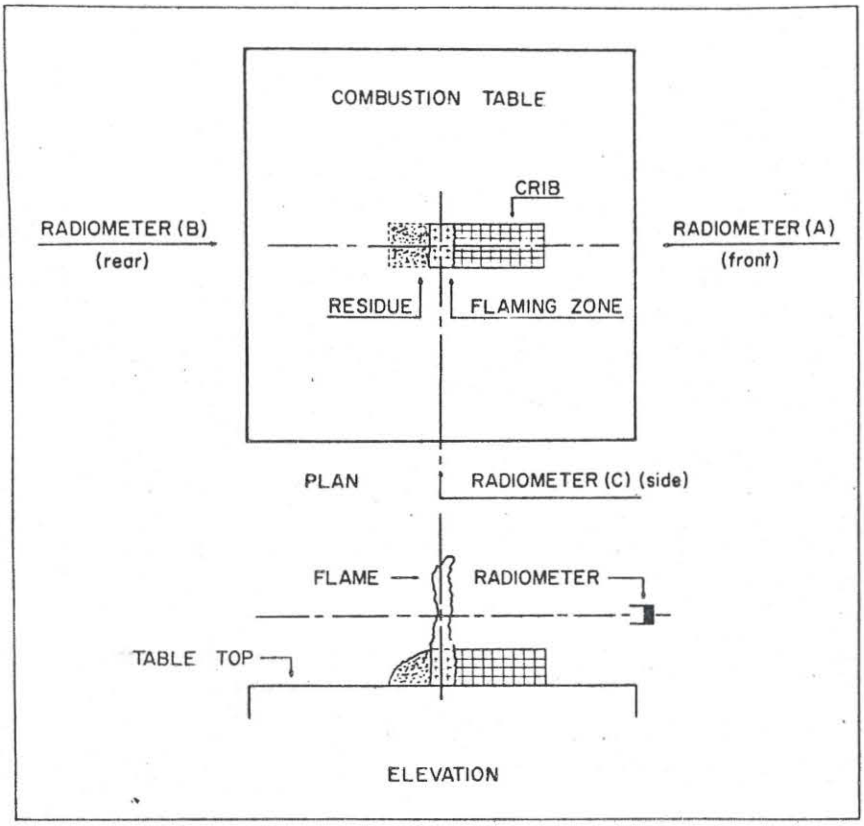


FIG. 4. Schematic diagram, illustrating positions of radiometers relative to crib and flaming zone.

Fig. 5 shows irradiance, I, as a function of rate of combustion, Q, is determined by the following equation:

$$Q = HRw_bW \qquad (1)$$

where Q = rate of combustion
R = rate of fire spread
w_b = width of fuel bed
W = bone-dry weight of fuel burned per unit area
H = low heat value of fuel.

The results shown in Fig. 5 indicate that the irradiance values at the side and rear of the crib fires are approximately equal. The results also show that the irradiance at the front of the fire is about 60 percent of the irradiance measured at the side or rear. The decrease in irradiance at the front of the fire may be accounted for by the fact that the burning zone within the crib is shielded from the radiometer by the unburned portion of the crib (see Fig. 4, radiometer position (A)). This suggests that the burning zone within the crib contributes about 40 percent of the irradiance toward the unburned fuel.

b. Radiative Heat. —Measurements of the irradiance were made at several points for determining the radiative heat, Q_r. These measurements were made for fires in cribs of different species of wood. For these fires the three radiometers at positions (A), (B), and (C) in Fig. 4 were mounted on carriages which could be moved along a curved standard to various elevation angles, ranging from -15° to + 50°, Fons et al. (10). The radius of curvature for the standard was 14 feet with the origin at a point in the flame 2 feet above the base of the fuel bed. The horizontal or zero position of the radiometer angle, therefore, corresponds to the base of a hemisphere with a radius of 14 feet. Readings for each radiometer were taken at angles of 0°, 10°, 20°, 30°, 40°, and 50°

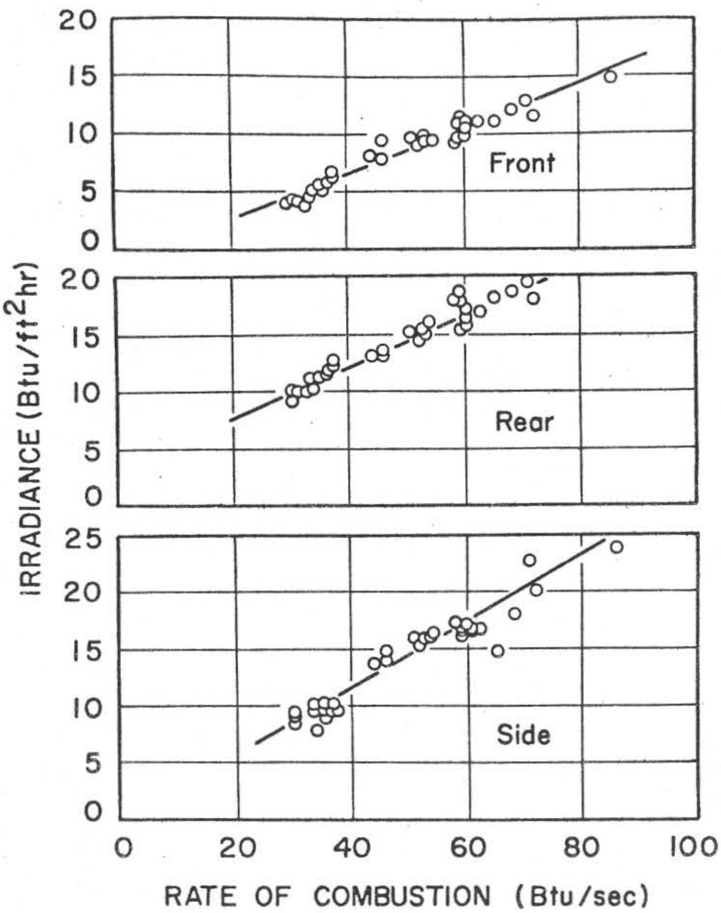


FIG. 5. Irradiance, I, of crib fires measured at three positions, as a function of rate of combustion, Q. Radiometers at 18.6 feet from center-line of flame.

during the steady-state burning period of a fire. Irradiance data for each of the three positions were plotted against elevation angles for 0° to 50°. The curves drawn through the points were extended to -10° and 90° to approximate the irradiance below 0° and above 50°. This method of approximating the irradiance above 50° should not seriously affect the final result because the surface area of the hemisphere from 50° to the zenith or 90° is only 15 percent of the surface area used in calculating the total radiant energy. The cutoff angle imposed by the combustion table on the radiometers was about 8° below the horizontal, so radiant energy from -8° to -90° was not included in the integration procedure. It is assumed that the radiant energy intercepted by the top of the combustion table is transferred to the entrained air as convective heat.

Irradiance measurements from the front and rear radiometers (positions A and B, Fig. 4) were used to calculate the radiative heat for 1/2 of the surface area or 1/4 each of the partial sphere -8° to +90° in the integrating procedure. The measurements from the side radiometer (position C, Fig. 4) were used in computing the radiative heat for the remaining half of the surface area. Estimates of radiative heat, Q_r, obtained by the integration method are presented in Table 1. The average radiative heat, Q_r, for the 15 fires is approximately 17 percent of the average rate of combustion, Q.

Flame Emissivity. The emissive power, E_b, from a black body or an ideal radiator at temperature, T, may be expressed by the Stefan-Boltzmann equation as

$$E_b = \sigma T^4 \tag{2}$$

Thus, if E_b is the emissive power from a black body, the emissivity of a non-black body, with an emissive power, E, may be defined as

$$\epsilon = \frac{E}{E_b} \tag{3}$$

For a diffuse surface, Equation (3) may be considered to define the total or mean effective emissivity with respect to radiation from a surface at any angle. Combining equations (2) and (3) gives

$$\epsilon = \frac{E}{\sigma T^4} \tag{4}$$

TABLE 1. Radiative heat, Q_r, and rate of combustion, Q, from crib fires

Fire No.	Q_r	Q	Fire No.	Q_r	Q
	Btu/sec	Btu/sec		Btu/sec	Btu/sec
1M	7.66	44.3	3S	5.55	34.7
3M	8.12	44.9	4S	5.27	39.5
4M	7.58	41.0	1Y	6.28	37.2
5M	8.28	46.0	2Y	6.08	35.5
2B	8.88	51.3	3Y	6.14	36.4
3B	8.45	52.0	4Y	5.52	33.6
4B	8.24	50.0	5Y	5.41	33.4
5B	9.22	52.1			

The equation for calculating the emissivity of a flame from radiometer measurements must consider the radiant energy exchange between the flame and the radiometer receiver strip. For this purpose the equation must include the geometrical view factor between the receiver strip and the flame surface. The shape of the flaming zone of a crib fire is nearly rectangular when viewed from the side, front, or rear (Fig. 2). Table of view factors for rectangular sources , to a point in a plane parallel to the source, is presented in Appendix.

The radiometer, at the position of zero degrees, sees a circular area within which is a nearly rectangular flaming surface in a plane parallel to the radiometer receiver strip. The measured irradiation, K(mv), of the radiometer receiver strip, considered as an incremental area, ΔA_1, is composed of several parts:

1. Energy emitted by flame surface of area, A_2, at temperature, T_2, is $\sigma\epsilon_2 F_{21} A_2 T_2^4$.
2. Energy emitted by an area, A_3, at temperature, T_3, within the circular area viewed by the radiometer with A_2 excluded is $\sigma\epsilon_3 F_{31} A_3 T_3^4$.
3. Energy emitted by the surroundings at temperature, T_4, and reflected from A_2 is $\sigma(1-\epsilon_2)\epsilon_4 F_{21} A_2 T_4^4$.
4. Energy emitted by the surroundings at temperature, T_4, and reflected from A_3 is $\sigma(1-\epsilon_3)\epsilon_4 F_{31} A_3 T_4^4$.
5. Energy emitted by the receiver strip to area, A_2, is $-\sigma\epsilon_1 F_{12}\Delta A_1 T_1^4$.
6. Energy emitted by the receiver strip to area, A_3, is $-\sigma\epsilon_1 F_{13}\Delta A_1 T_1^4$.

It is assumed that $T_1 = T_3 = T_4$, $\epsilon_1 = \epsilon_3 = \epsilon_4 = 1$, and that by the reciprocity theorem $F_{12}\Delta A_1 = F_{21}A_2$ and $F_{13}\Delta A_1 = F_{31}A_3$. Adding the energies emitted by the several parts gives an expression for irradiation

$$K(mv) = \sigma\epsilon_2 F_{12} (T_2^4 - T_1^4) \tag{5}$$

where (mv) is the millivolt output of the radiometer and K is its calibration factor in Btu/ft^{2}hr per millivolt.

Solving Equation (5) for ϵ_2 the emissivity of the flame is

$$\epsilon_2 = \frac{K(mv)}{F_{12}\,\sigma(T_2^4 - T_1^4)} \tag{6}$$

The product, K(mv), in Equation (6) is equivalent to the emissive power, E, of a surface given by Equation (4).

Values of K(mv) were calculated from radiometer millivolt output, (mv), for rear and side positions of 30 crib fires. The corresponding view factors, F_{12}, were determined by Table 3 in Appendix from the measured flame dimensions of each fire. Flame temperature of each fire was assumed constant at 1600° F. for the entire flame zone, (10).

Table 2 presents the emissivities calculated by Equation (6), ϵ_r (rear view) and ϵ_s (side view), of 30 fires; also included in Table 2 are ratios of flaming zone depths, w_b/D, and ratios of emissivities, ϵ_r/ϵ_s.

TABLE 2. Emissivities for flames of crib fires

Fire No.	Rear view 1/			Side view 1/			w_b/D 2/	ϵ_s/ϵ_r
	K(mv)	$F_{12} \times 10^4$	ϵ_r	K(mv)	$F_{12} \times 10^4$	ϵ_s		
	$\frac{Btu}{ft^2hr}$	--	--	$\frac{Btu}{ft^2hr}$	--	--	--	--
31	15.0	22.8	0.213	14.8	11.8	0.407	1.85	1.91
32	13.8	25.2	.177	15.4	14.4	.347	1.71	1.96
33	13.0	26.4	.160	14.0	15.0	.304	1.74	1.90
34	13.2	27.2	.157	14.2	14.2	.324	1.81	2.06
35	17.4	29.6	.191	20.1	33.8	.193	0.86	1.01
37	13.2	22.0	.194	13.4	11.6	.376	1.93	1.94
38	14.4	24.4	.191	14.4	17.4	.270	1.38	1.41
39	13.0	23.6	.179	13.6	12.2	.362	1.81	2.02
40	13.6	23.6	.187	14.0	12.2	.373	1.85	1.99
41	11.6	21.8	.173	12.0	10.4	.374	2.01	2.16
42	12.8	23.4	.177	13.8	12.2	.366	1.89	2.07
44	11.2	22.2	.164	12.6	10.6	.385	2.06	2.35
45	12.2	23.4	.170	13.0	13.2	.320	1.78	1.88
46	9.5	18.8	.164	8.2	9.0	.297	2.10	1.81
47	8.5	18.0	.153	7.8	8.6	.295	2.06	1.93
48	8.5	17.6	.157	8.0	8.4	.309	1.97	1.97
50	8.5	17.6	.157	8.4	8.4	.325	2.15	2.07
51	8.0	18.2	.143	7.2	7.8	.301	2.31	2.10
52	10.1	19.4	.169	8.2	9.4	.285	2.01	1.69
53	10.4	19.8	.171	8.6	9.4	.297	2.06	1.74
54	10.6	18.8	.184	8.4	9.2	.297	2.06	1.61
55	9.7	18.6	.169	8.2	9.0	.297	2.01	1.76
56	8.8	17.6	.162	6.6	7.6	.283	2.26	1.75
57	9.7	19.4	.162	7.6	8.4	.296	2.26	1.83
59	15.8	20.4	.252	13.6	12.0	.368	1.71	1.46
60	15.1	23.0	.214	12.4	15.2	.265	1.44	1.24
62	14.7	29.0	.165	14.0	15.2	.300	1.81	1.82
63	15.5	26.4	.190	14.4	13.8	.338	1.89	1.78
64	15.9	28.4	.182	15.4	20.2	.247	1.34	1.36
65	16.7	25.0	.216	19.2	17.8	.350	1.36	1.62

1/ Radiometer position, see figure 4.
2/ w_b, depth of flame side view; D, depth of flame rear view.

TABLE 3. View factors, $F_z \times 10^4$, with reference to a parallel plane (calculated by Equation (7))

z/x	y/x								
	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.05	1.54	3.10	4.70	6.20	7.72	9.38	10.9	12.5	14.0
.06	1.84	3.72	5.64	7.44	9.26	11.3	13.1	15.0	16.9
.07	2.15	4.34	6.58	8.68	10.8	13.1	15.3	17.5	19.7
.08	2.46	4.96	7.52	9.92	12.3	15.0	17.4	20.0	22.5
.09	2.76	5.58	8.46	11.2	13.9	16.9	19.6	22.5	25.3
.10	3.07	6.20	9.40	12.4	15.4	18.8	21.8	25.0	28.1
.11	3.38	6.82	10.3	13.6	17.0	20.6	24.0	27.5	30.9
.12	3.68	7.44	11.3	14.9	18.5	22.5	26.2	30.0	33.7
.13	3.99	8.06	12.2	16.1	20.1	24.4	28.3	32.5	36.5
.14	4.30	8.68	13.2	17.4	21.6	26.3	30.5	35.0	39.3
.15	4.60	9.30	14.1	18.6	23.1	28.2	32.7	37.5	42.2
.16	4.91	9.92	15.0	19.8	24.7	30.0	34.9	40.0	45.0
.17	5.22	10.5	16.0	21.1	26.2	31.9	37.1	42.5	47.8
.18	5.53	11.2	16.9	22.3	27.8	33.8	39.2	45.0	50.6
.19	5.83	11.8	17.9	23.6	29.3	35.7	41.4	47.5	53.4
.20	6.14	12.4	18.8	24.8	30.9	37.5	43.6	50.0	56.2

CONCLUSION

The use of fire models in forest fire behavior research was the result of the need to develop an experimental system that would overcome the complexities encountered in the variations of fuel and weather variables involved in field test fires. The steady-state model described eliminates the difficulties encountered in field studies and allows accurate observations to be made of the fuel and fuel bed variables. The effect of these variables on flame dimensions, rate of burning, and rate of spread can be accurately measured and calculated. This type of model can also be readily adapted to studying effects of forced convection.

The author expresses his thanks to the Office of Civil Defense for the financial assistance through contracts administered by the National Bureau of Standards and to the Forest Research Council of the State of Georgia for making research facilities available in the current fire model work. He wishes to express his thanks to Mr. H. B. Clements and Mr. P. M. George of the Southern Forest Fire Laboratory for ably and faithfully assisting in the current model work. Thanks are also due to Messrs. H. D. Bruce, W. Y. Pong, and S. S. Richards of the Pacific Southwest Forest and Range Experiment Station at Berkeley, California, for their contributions in the development of the steady-state model.

APPENDIX

The radiant energy exchange between surfaces depends on the emissive, absorptive, and reflective properties of the surface and also on their geometrical shapes and arrangement. The ratio of the irradiance at a point and the unit energy emitted from a surface is defined as the geometrical view factor between the surface and the point. The shape of the flaming zone of a crib fire is approximately rectangular when viewed from the side, front, or rear. The positions at which radiometers were placed to measure irradiance for the flaming zone of a crib fire are shown in Fig. 4. The radiometers are aimed at a point 2-1/2 feet above the base of the crib and on the vertical axis of the flaming zone. In determining the view factor between a rectangular source and a given point, it is convenient to divide the surface of the source into several smaller rectangular areas (Moon (15)). The view factor for the total surface is then equal to the sum of the view factors for the smaller areas. Thus the surface of the flaming zone for a crib fire may be divided into four rectangular areas, each having one corner at the aiming point of the radiometer viewing that surface.

Consider a point, P, that lies on a perpendicular erected at one corner of a rectangular source with constant emissive power (Fig. 6). If the point lies in a plane parallel to the source, the equation for the view factor of the rectangular source (Moon (15)) is

$$F_z = \frac{1}{2\pi}\left[\frac{z}{\sqrt{x^2+z^2}}\sin^{-1}\frac{y}{r} + \frac{y}{\sqrt{x^2+y^2}}\sin^{-1}\frac{z}{r}\right] \tag{7}$$

where $r = (x^2 + y^2 + z^2)^{1/2}$.

View factors, F_z calculated by Equation (7) for a range of values z/x and y/x, are presented in Table 3. This table covers the range of view factors applicable to most laboratory crib fires when narrow view angle radiometers are used. Tables of view factors for larger rectangular sources, with y and z extending to infinity, are given by Moon (15).

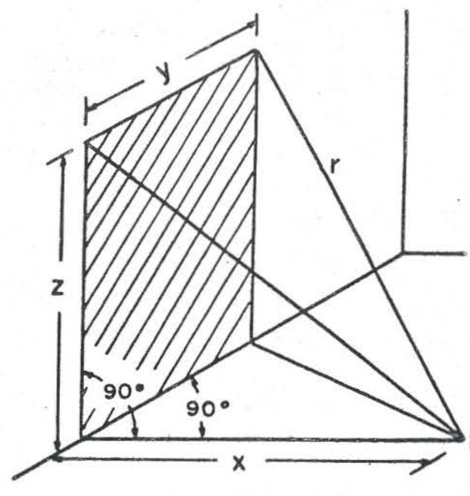


FIG. 6. Projected view of a rectangular source, with reference to a point, P.

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