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USDA Forest Service
Research Paper INT-140
August 1973

**EFFECTIVE HEATING OF FUEL
AHEAD OF
SPREADING FIRE**

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The author thanks Mr. Merlin Brown, Electronics Technician at the Northern Forest Fire Laboratory, for his extreme care in fabricating and implanting the fine-wire thermocouples used in this study.

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Abstract

A method is presented for the evaluation of the heating efficiency required for ignition as a spreading fire closes with fuel.

An array of thermocouples was implanted in the fuel ahead of the fire to obtain the heat absorbed by the fuel prior to ignition. The fraction absorbed compared to the total that would be absorbed if uniformly heated is the effective heating number. The effective heating number is represented in its final form as decreasing exponentially with the reciprocal of the surface area-to-volume ratio.

The spreading fire is carried in a regular fuel crib array. Two fuel sizes are used in cross-sectional dimension: 0.6 cm. and 1.3 cm. Isotherms are generated from the temperature field at ignition and presented for both fuel sizes to determine heat absorbed.

Introduction

A spreading fire is a series of particle-to-particle ignitions where the energy necessary for propagation has its source within the combustion zone where particles are undergoing a measurable weight loss through pyrolysis (Fons 1946). These consecutive ignitions do not depend on uniformly heated fuel. Frandsen (1971) accounted for nonuniform heating ahead of the fire by defining the effective heating number.

Fuel particles ahead of a spreading fire (fig. 1) receive heat from the combustion zone, which increases their internal energy. The distribution of heat within similarly shaped fuel particles at ignition is dependent on the following factors: location of the heat source and heat flow through the surface; surface area-to-volume ratio and thermal diffusivity of the fuel. A moisture gradient can also play a major role. Assuming that the net heat flux and diffusivity are fairly constant and that the moisture gradient is zero, then the surface area-to-volume ratio becomes the significant independent variable. Only in fine fuels (diameter <1 mm.) is heating uniform. Larger fuels do not achieve uniform internal temperatures because heat impinging on the particle cannot diffuse from the surface at a rate comparable to the influx of heat. The result is a thermal gradient within the particle that may leave the temperature of the central portion, or of one side, relatively unchanged, depending on whether the flow of heat is uniform over the surface or unidirectional.

Although fire spread is attributed to particle-to-particle ignition, the interval between ignitions must be averaged over a long time to obtain a rate of spread representative of the bulk array. The average rate of spread can then be related to the average fuel bed properties. If a constant rate of spread is achieved, the quasi-steady state exists. The fuel bed can then be represented by a minimum unit fuel cell that has all the characteristics of the fuel array and retains its usefulness as an elemental unit volume in applying the conservation of energy (Frandsen 1971).

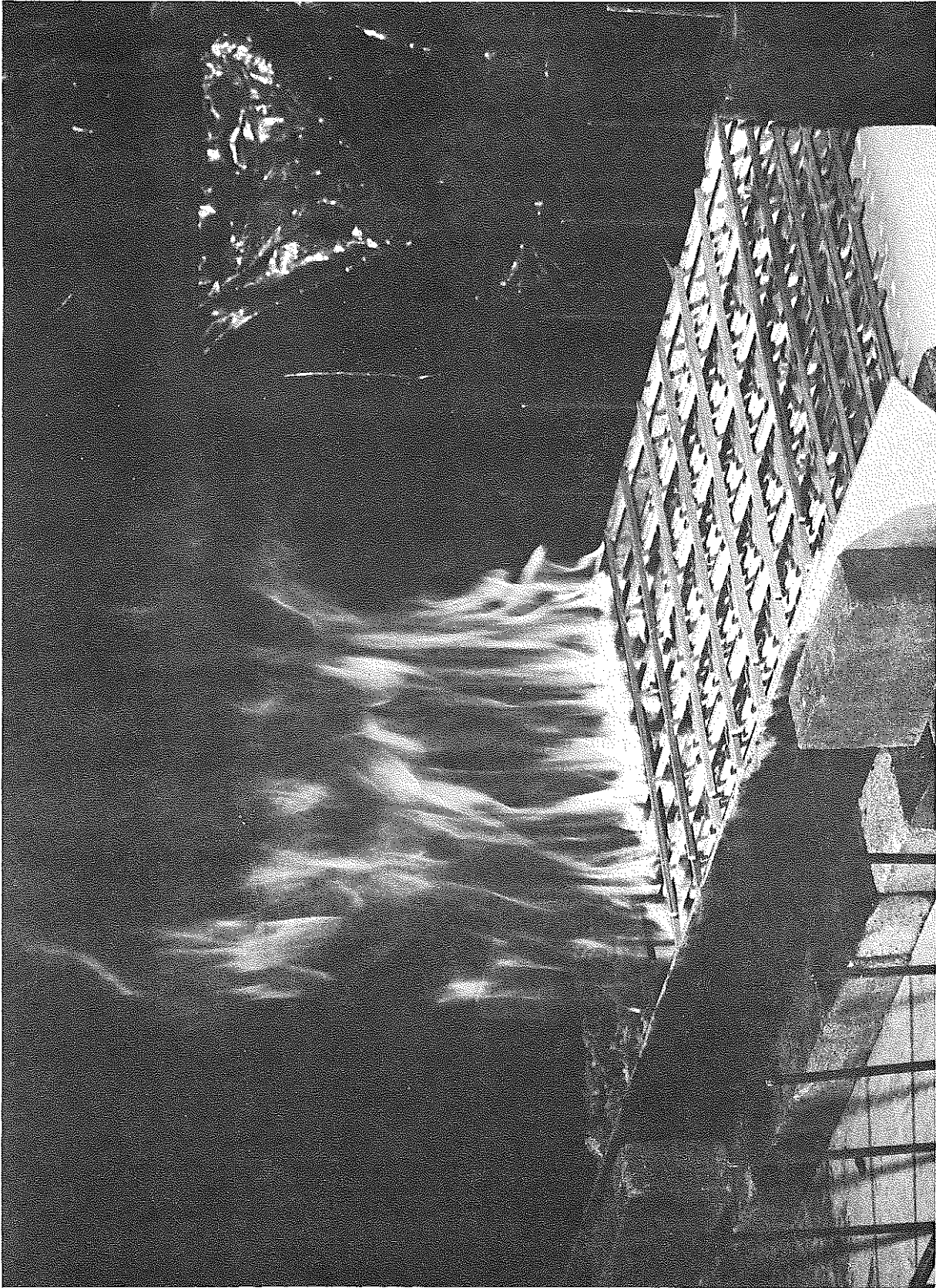


Figure 1.--Fire spreading through a fuel crib.

To employ the concept of the unit fuel cell, the individual particle view must be extended to the array within the unit cell. The unit cell then replaces the particle as the heat absorber. Consequently, attention is focused on the heat absorbed per unit volume, $\rho_b Q_{ig}$, rather than on the heat absorbed per unit mass by the individual particle where ρ_b is the bulk density and Q_{ig} is the heat of preignition.

In the unit volume concept the distribution of heat within the particle is less important; so the assumption that all heat is uniformly absorbed to a given depth in the fuel particle (Thomas 1967) is an equally useful concept. Frandsen (1971) extended the individual particle concept to the fuel array by introducing effective bulk density. The problem is now resolved to the efficiency of heating the unit fuel cell to ignition. The heat per unit volume, $\rho_b Q_{ig}$, is necessary to bring the unit cell uniformly to ignition. Therefore, the heat per unit volume for ignition at non-uniform heating is $\epsilon \rho_b Q_{ig}$, where ϵ , the effective heating number, is the efficiency. The unit fuel cell is not restricted to regular arrays. In field conditions where irregular arrays exist, the unit fuel cell must be described by statistical methods.

The following brief exposition serves to show how ϵ is related to the fire spread model developed by Rothermel (1972).

The rate of fire spread through a fuel array depends on the static fuel parameters, β , ρ_p , and Q_{ig} , and the dynamic source function, I_R , (Rothermel 1972). The static parameters are related to the absorption of energy in the preignition phase, whereas the dynamic source function is related to the combustion zone. Their ratio leads to the rate of fire spread through the array:

$$R = \frac{\xi I_R}{\epsilon \rho_b Q_{ig}} = \frac{I_p}{\epsilon \beta \rho_p Q_{ig}} \quad (1)$$

where ξ is the efficiency of converting total reaction intensity, I_R , to propagating intensity, I_p -- the portion of intensity driving the fire (Rothermel 1972).

ϵ = Effective heating number

β = ρ_b / ρ_p = packing ratio = volume occupied/total bulk volume

ρ_b = Owendry bulk density

ρ_p = Owendry particle density

Q_{ig} = Heat of preignition, the heat per unit owendry mass necessary to ignite the fuel.

In this study, the effective heating number was related to the size (surface area-to-volume ratio) of the particles making up a regular fuel array of similarly shaped particles. All other variables were held constant. For convenience, the subscript p has been dropped from ρ for the remainder of the paper. Henceforth, the particle density will be denoted simply as ρ .

Method of Analysis

Fuel cribs were used in this investigation because of the relative ease of construction and instrumentation, and their symmetry relative to the fire front. The thermal gradient within the particle members of the cell must be obtained to determine the heat absorbed up to ignition by the unit cell.

The unit cell reproduces the crib by consecutively repeating the cell in all three cartesian coordinates. Each horizontal layer of cells was alternately shifted with respect to adjacent layers to obtain a more uniform array (fig. 2).

Ignition takes place when a significant portion of the cell undergoes visual flame attachment. At ignition, isotherms are constructed from the observed gradient. Through symmetry, these isotherms are assumed to form curvilinear surfaces that are parallel to the front of the spreading fire.

The heat absorbed between adjacent isotherms is calculated and summed over the area of the isothermal profile to determine the total heat absorbed. The total heat absorbed by the unit cell up to ignition is $\mathcal{Q}V_u$, where \mathcal{Q} is the nonuniform heat absorbed per unit volume and V_u is the total volume of the unit cell including the unoccupied space. The equivalence of this product to the heat absorbed by the members of the unit cell is:

$$\mathcal{Q}V_u = \ell A \rho Q_A + t B \rho Q_B. \quad (2)$$

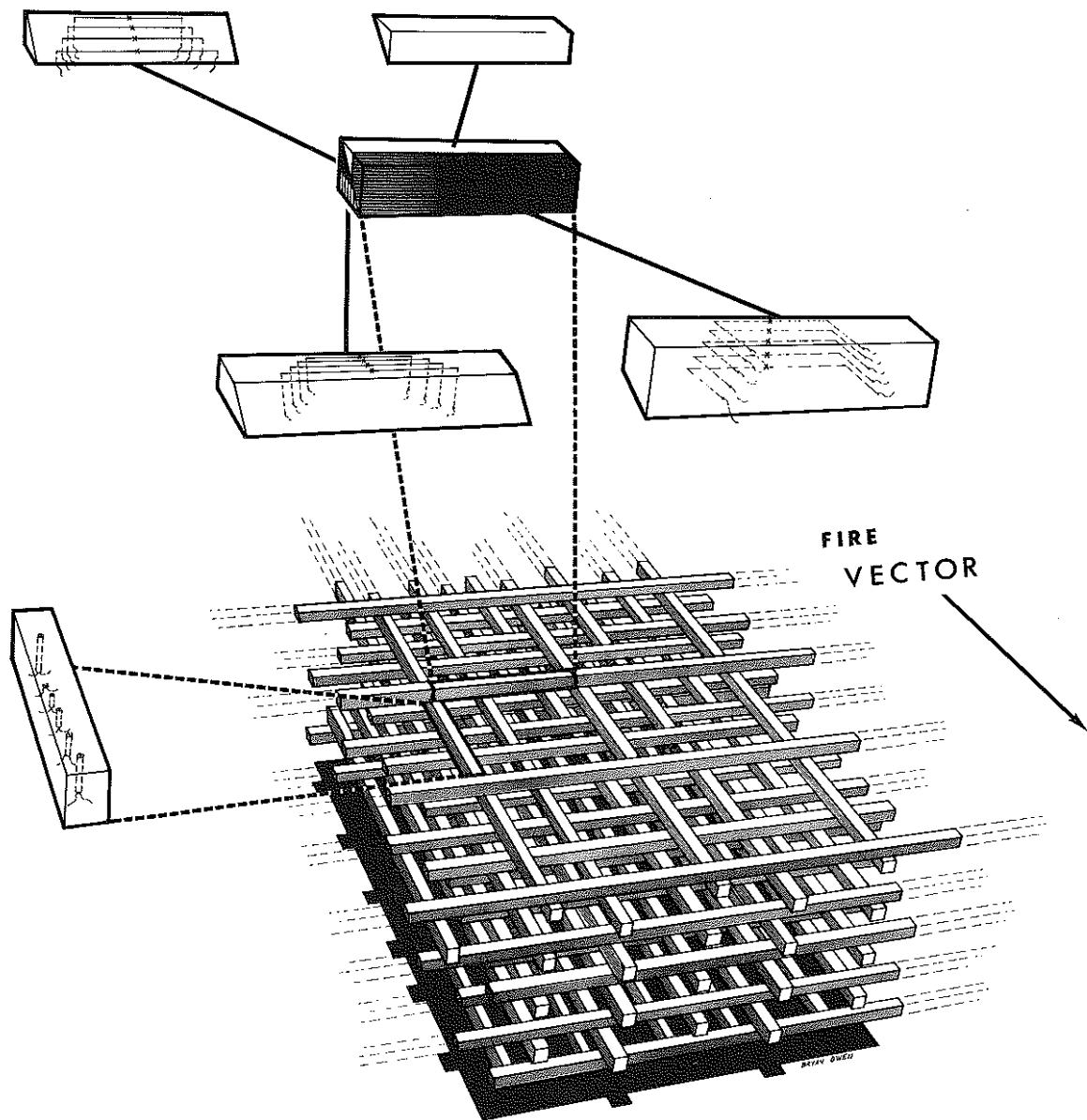


Figure 2.--A fuel crib showing the basic unit cell. At left is the thermocouple arrangement in the longitudinal member and above is the arrangement in the transverse member. The cross-sectional area of a member is $A = t^2$ and the side area is $B = t\ell$, where t is the member thickness and ℓ is the spacing on centers between fuel members.

Two identical members of length, ℓ , make up the unit cell. They overlap and join at right angles (fig. 2). Q is the nonuniform heat absorbed per unit oven-dry mass. The A and B subscripts refer to the transverse and longitudinal members, respectively. A comparison standard for determining the effective heating number was established by assuming uniform heating throughout the two members of the unit cell.

Thomas and Simms (1963) used the moist fuel specific heat and the temperature rise to ignition to determine the heat necessary to bring the fuel uniformly to ignition. I have employed a method similar to that used by Byram and coworkers (1952), with two

simplifications: the heat of desorption is ignored¹ and the water in the fuel is assumed to be completely vaporized at 100° C. A temperature-dependent dry fuel specific heat (Dunlap 1912),

$$C_d = C_0 + C_1 T, \quad (3)$$

is used in place of the constant value used by Byram and coworkers (1952), where:

$$C_0 = 0.266$$

$$C_1 = 0.00116.$$

Both members of the cell would absorb the same heat per unit mass if the unit cell were uniformly heated. For example, the heat absorbed within the transverse member would be:

$$H_A = V_A \rho \{ f C_w (100 - T_a) + f Q_w + [C_0 + C_1 (T_{ig} + T_a)/2] (T_{ig} - T_a) \}, \quad (4)$$

where:

V_A = Volume of transverse member of unit cell

f = Fractional fuel moisture content relative to its oven-dry mass

C_w = Specific heat of water

C_d = Specific heat of oven-dry fuel

T_{ig} = Ignition temperature

T_a = Ambient temperature

Q_w = Heat of vaporization of water.

Since $H_A = \rho V_A Q_A$ and $Q_A = Q_B = Q_{ig}$ for uniform heating, the heat of preignition per unit oven-dry mass of moist fuel rising from ambient to ignition temperature is:

$$Q_{ig} = f C_w (100 - T_a) + f Q_w + [C_0 + C_1 (T_{ig} + T_a)/2] (T_{ig} - T_a). \quad (5)$$

Q_{ig} is made up of three products: the heat necessary to bring fuel moisture to boiling temperature, the heat of vaporization of fuel moisture, and the heat necessary to ignite oven-dry fuel.

The amount of heat nonuniformly absorbed by the unit cell is calculated stepwise throughout the fuel member by using isotherms developed from the thermal gradient. There are two equations for the heat absorbed by each member within the volume bounded by consecutive isotherms: one for $T_0 \leq 100^\circ \text{C}$. and one for $T_0 > 100^\circ \text{C}$., where T_0 is the minimum isotherm. Each equation consists of two parts:

1. Heat absorbed by all area elements up to T_0 ;

¹Heat of desorption should be included; however, the added refinement is not justified when compared to the overall accuracy of these measurements.

2. The summation of heat absorbed by each elemental area (A_j or B_j bounded by T_{j-1} and T_j up to $T_j = T_{ig}$).

For example, the heat of preignition for the transverse member is:

$$T_o \leq 100^\circ \text{ C.}$$

$$Q_A = Q_1 + \frac{1}{A} \sum_{j=1}^{j=m} A_j [fC_w + C_0 + C_1 (\bar{T}_j + T_o)/2] (\bar{T}_j - T_o) + \frac{1}{A} \sum_{j=m+1}^{j=n} A_j (fC_w (100 - T_o) + fQ_w + [C_0 + C_1 (\bar{T}_j + T_o)/2] [\bar{T}_j - T_o]), \quad (6a)$$

where:

$$Q_1 = [fC_w + C_0 + C_1 (T_o + T_a)/2] (T_o - T_a).$$

$$T_o > 100^\circ \text{ C.}$$

$$Q_A = Q_2 + \frac{1}{A} \sum_{j=1}^{j=n} A_j [C_0 + C_1 (\bar{T}_j + T_o)/2] (\bar{T}_j - T_o), \quad (6b)$$

where:

$$Q_2 = f[C_w (100 - T_a) + Q_w] + [C_0 + C_1 (T_o + T_a)/2] (T_o - T_a)$$

and,

$$\bar{T}_j = (T_{j-1} + T_j)/2$$

$$\bar{T}_j < 100^\circ \text{ C. for } j < m$$

$$\bar{T}_j = 100^\circ \text{ C. for } j = m$$

$$\bar{T}_j > 100^\circ \text{ C. for } j > m$$

$$\bar{T}_j = \text{maximum average temperature of } A_n \text{ for } j = n.$$

The value for Q_B is obtained by applying equations (6a) and (6b) to the longitudinal member after replacing the summing area A with B . Both results are readily evaluated by using a simple iterative computer program to sum the heat absorbed by each elemental area.

Finally, the effective heating number, ϵ , is evaluated by comparing the ratio of the total heat absorbed within the unit volume, $\rho \lambda t^2 (Q_A + Q_B)$, to the total heat that would have been absorbed had the unit volume been heated uniformly to ignition, $2\rho \lambda t^2 Q_{ig}$. Thus,

$$\epsilon = (Q_A + Q_B)/2Q_{ig}. \quad (7)$$

Technique

A unit cell from the upper layer was instrumented to obtain the temperature profile within the cell members. Two fuel sizes were used (0.6 cm. (1/4 inch) and 1.3 cm. (1/2 inch)) in square cross section. Both fuel arrays had a packing ratio of 0.08. The packing ratio, β , is the ratio of the occupied volume to the total volume of the unit cell. From the geometry of the bed,

$$\beta = t/\ell. \quad (8)$$

The horizontal layers lie one upon the other and are alternately shifted, so that identical horizontal members are spaced $4t$ on centers below each other. The greatest separation between fuel crib members is in the horizontal direction, the direction of fire spread. From equation (8) the spacing, ℓ dimension, is 8 cm. for $t = 0.6$ cm. and 16 cm. for $t = 1.3$ cm.

Equation (8) is developed from the unit cell shown in figure 2 and applies exclusively to that arrangement. Intuitively, the rate of spread is dependent on both t and ℓ , but a simple dependency cannot be derived by substituting $\beta\rho$ or $(t/\ell)\rho$ into equation (1) for ρ_b , since I_p is also dependent on β in a less direct manner.

The instrumented cribs were burned under controlled (no-wind) conditions at the Northern Forest Fire Laboratory (Rothermel and Anderson 1966). A uniform fire front across the full width of the bed was obtained by igniting alcohol-soaked excelsior in the crib spaces at one end.

Temperature fields within the members of the unit cell were obtained from 5 mil. chromel-alumel thermocouples within the longitudinal and transverse fuel members (figs. 3 and 4). (The view shown above the fuel array in figure 2 illustrates how the transverse member was sectioned to implant the array of thermocouples. Resorcinol glue was used to hold the parts together.) The leads immediately adjacent to the junction of the thermocouple are parallel to the axis of the transverse member for at

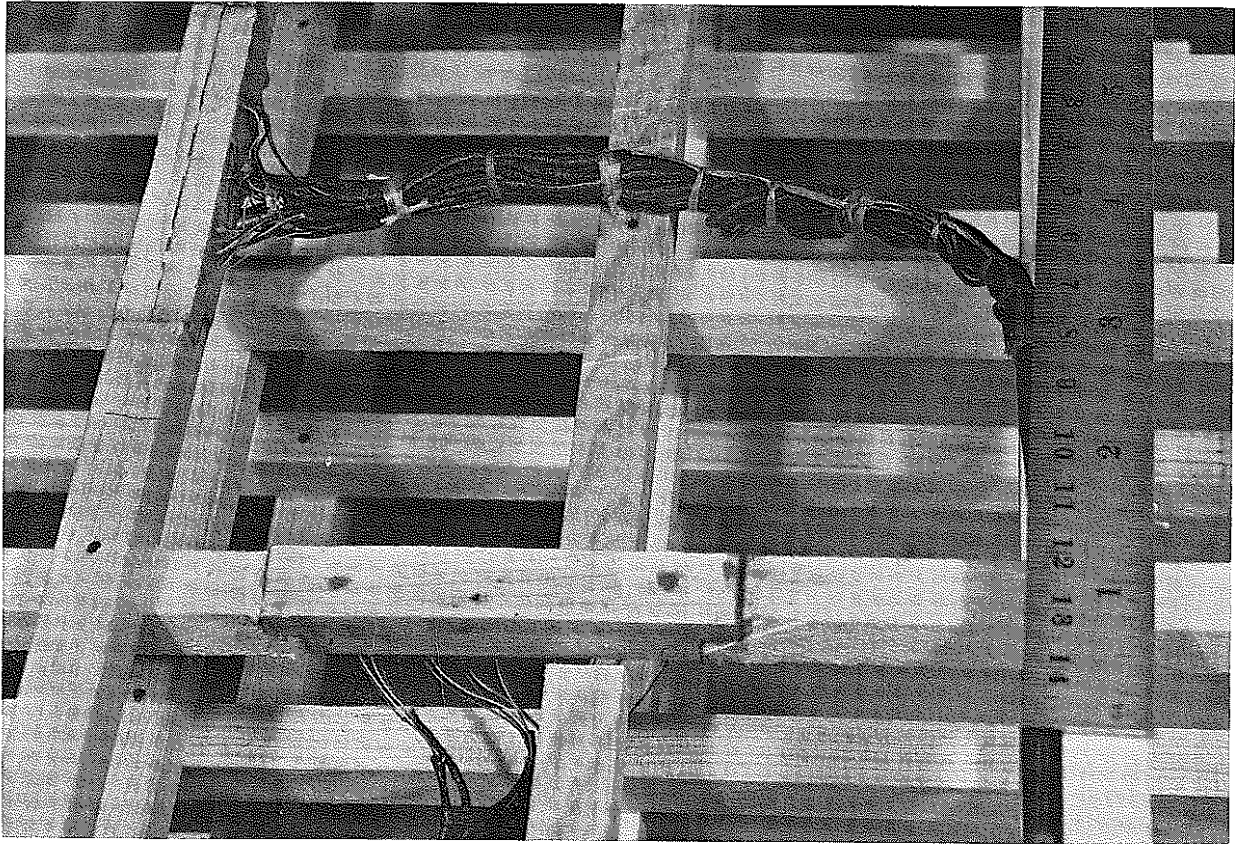


Figure 3.--Instrumented transverse and longitudinal fuel members as they appear in the fuel crib array. Fire spread is from the left.

least 0.6 cm. before coming through the back or bottom of the fuel member. Thus, the junction and the immediately adjacent leads lie in an isothermal surface minimizing heat transfer to or from the junction along the leads. The temperature field is captured by simultaneous measurements at the moment of ignition. (The scan time is extremely short compared to the time of the event.) Since only a limited number of thermocouples could be placed in the transverse fuel member, the highest density was concentrated in the region of the steepest temperature gradient, the upper corner nearest the advancing fire (fig. 4). Therefore, isotherms generated from the temperature field outside the upper corner are less reliable.

Applying the same instrumentation procedure to the longitudinal fuel member would require an extensive array of thermocouples parallel to those located in the transverse members. The alternate method adopted was based on the average rate of spread of the thermal wave that travels along the longitudinal member. From the average rate of spread it is possible to convert temperature variations with time to temperature variations with distance. Thus, it is only necessary to determine the temperature variation with time at various prescribed vertical depths in the fuel member. The temperature distributions at each depth can be interrelated through the ignition time. Small holes were drilled to varying depths from the bottom (fig. 2). Chromel-alumel thermocouples were inserted the full depth of each hole and plugged with wooden dowels. There is no appreciable temperature gradient normal to the vertical plane determined by the thermocouples. The velocity of the thermal wave was obtained by superimposing the temperature histories of the two top thermocouples and noting their shift in time and separation.

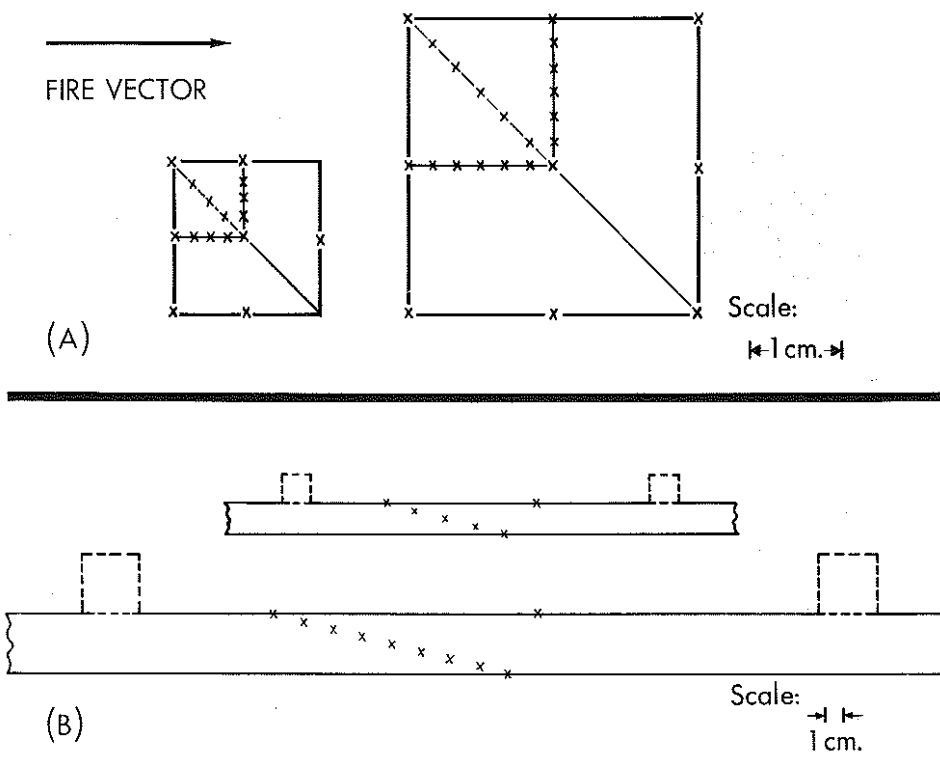


Figure 4.--Cross-sectional views of the location of thermocouples within the transverse and longitudinal members of the unit cell. A is transverse and B is longitudinal. Thermocouple positions are indicated by the crosses.

The velocity of an advancing thermal wave in the longitudinal member, along with the rate of spread of the fire, is tabulated below. The packing ratio was held constant at 0.08.

Size (Cm.)	Velocity (Cm./sec.)	
	Fire spread	Thermal wave
0.6	0.33	20.53*
.6	.33	.53*
1.3	.33	1.40
1.3	.33	.95

The discrepancy between the rate of spread of the fire and the rate of spread of the thermal wave within the unit cell is a result of the quasi-steady character of the fire. Viewed at close range, the fire appears to stop at each transverse member and then quickly travel down the longitudinal member to the next transverse member where it waits again. Viewed from a distance, the average rate of spread draws our attention away from the unsteady motion of the fire on the microscale. The thermal wave is probably more representative of the longitudinal fuel member than of the fuel array.

*Values obtained from adjacent longitudinal members in the same fire.

Results

Isotherms obtained from longitudinal and transverse members of a unit cell within the fuel array are shown in figures 5 and 6, respectively. Two fuel sizes are represented: 0.6 cm. and 1.3 cm. The transverse and longitudinal members are analyzed separately; no attempt is made to merge isotherms because no temperature data are taken in the region of the connection. Isotherms in this region are extrapolations. Consequently, the isotherms in the longitudinal members do not show masking by the transverse member near their intersection.

Areal temperature distributions from figures 5 and 6 were used in equations (6a) and (6b) to obtain the nonuniform heat absorbed by the individual unit cell members up to ignition (table 1). No longitudinal member was instrumented during the first test at the 0.6-cm. sample size; however, two adjacent longitudinal members were instrumented in the second test at the 0.6-cm. sample size.

Because final results are limited in figure 7, more than one function will fit the data. However, the exponential form,

$$\epsilon = \exp(-4.53/\sigma),$$

is favored because:

1. The data lie close to the exponential curve;
2. the curve point ($\epsilon=1$, $1/\sigma = 0$) acts as a constraint on the possible curves that can pass through the data points; and
3. the region of the curve covering small particle sizes (near $\epsilon=1$) exhibits a linear relationship with $1/\sigma$, as suggested earlier by Thomas (1967) with $\Delta \propto 1/\sigma$.

Although data are confined to fuels small in cross section, extrapolation to 0.6 cm. is dependable. This judgment is based on reasonable results obtained by using the above exponential relationship in Rothermel's (1972) fire spread model.

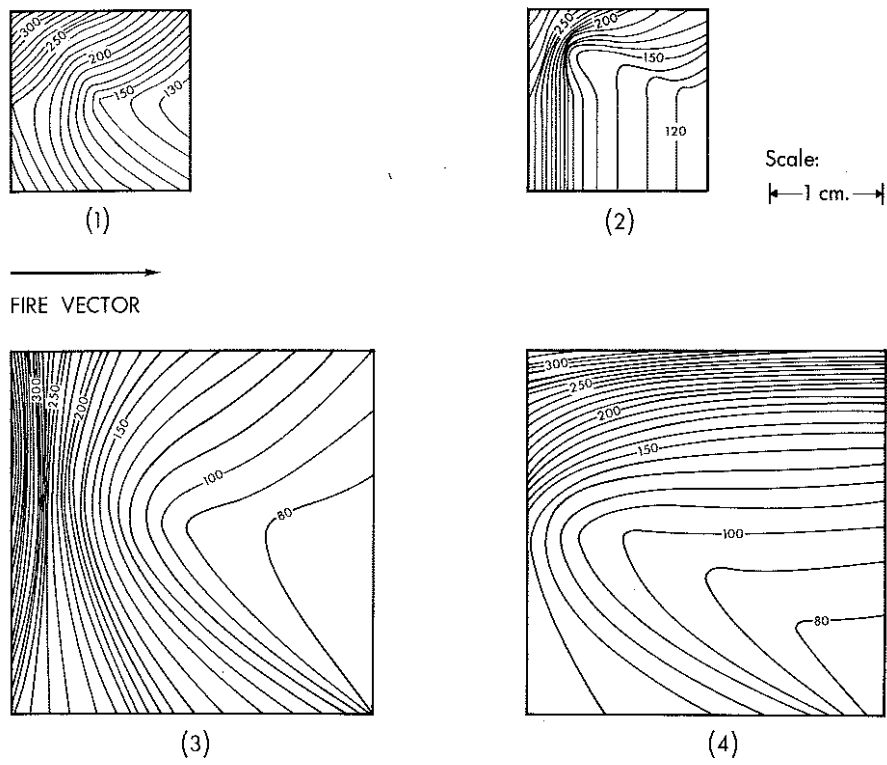


Figure 5.--A cross-sectional view of isothermal surfaces within the transverse member of the unit cell at ignition. Surfaces are parallel to the average combustion zone front. Each member is identified by test number for reference to table 1. $\beta = 0.08$.

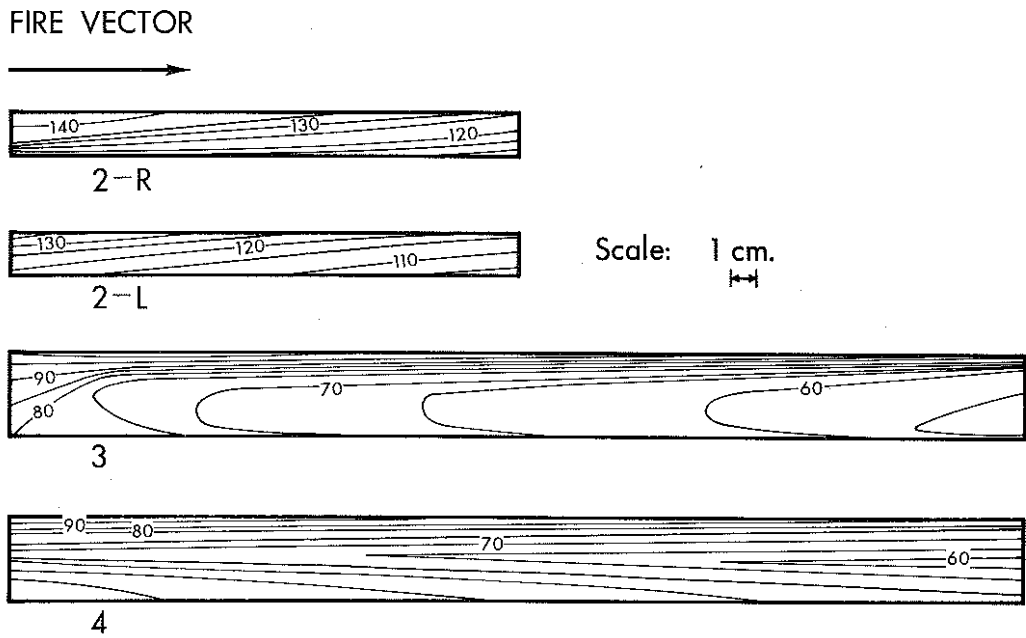


Figure 6.--An averaged cross-sectional view of isothermal surfaces within the longitudinal member of the unit cell at ignition. Surfaces are parallel to the average combustion zone front. Each member is identified by test number for reference to table 1. $\beta = 0.08$.

Table 1.--Effective heating number.

Test identification	Particle thickness	Q_A	Q_B	Q_A+Q_B	T_{ig}	Q_{ig}	ϵ
		---Cal./g.---			°C.	cal./g.	
1	0.6	108	¹ 84*	193	340	189	0.51
2-R	.6	94	75	169	300	164	.52
2-L	.6	94	71	165	300	164	.50
3	1.3	75	19	94	380	216	.22
4	1.3	72	20	93	330	183	.25

¹ * Value is obtained by assuming that the ratio between the two values of Q_A for the 0.6-cm. specimens is equivalent to the ratio of the values of Q_B where the known Q_B is an average of the R and L (right and left of transverse member) values.

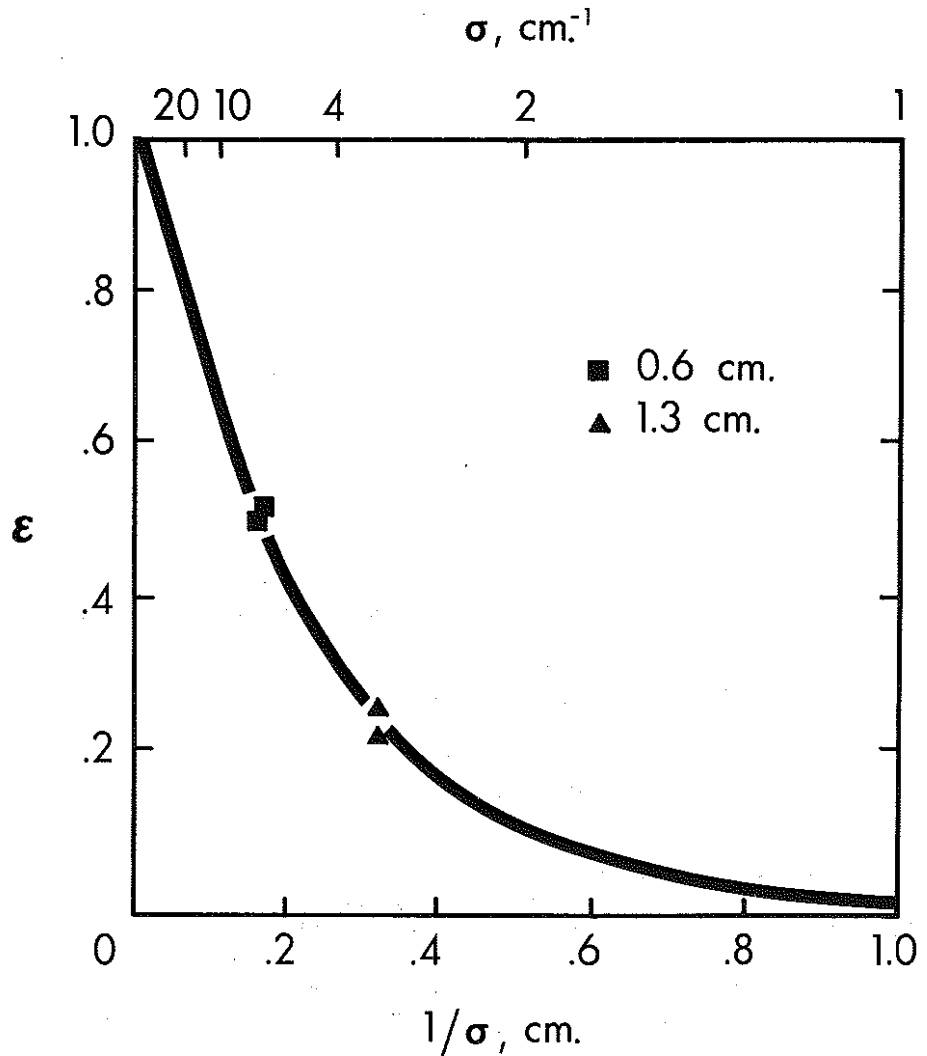


Figure 7.--A curve of ϵ , the effective heating number, versus the reciprocal of σ , the surface area-to-volume ratio. Since $\sigma = 4/t$, the abscissa may be viewed as one-fourth the thickness of the particle.

Conclusions

Nonuniform ignition over the unit cell weakens the analysis. This effect was minimized by choosing a small unit cell ($\beta=0.08$). The packing ratio here is representative of the upper range of packing ratios occurring in natural fuels.

The heating efficiency required to bring fuel ahead of a fire to ignition as it closes with the fire front has been investigated. Results show the dependence of ϵ , the fractional amount of the bulk density effectively brought to ignition, on the surface area-to-volume ratio of the fuel in the bed. At present, these data provide the only means for evaluating ϵ .

Structure and geometry have limited the number of sensing devices that can be installed in fuel members without greatly altering the measurement. Therefore, more thermocouples were placed in areas of greater sensitivity to the incoming flux. Combined results from the temperature profiles of the longitudinal and transverse fuel members provide a measure of the fractional amount of the bulk density that is involved in the ignition process. These results are reasonably sensitive to the surface area-to-volume ratio of the fuel member.

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Nomenclature

<i>Symbol</i>	<i>Definition</i>	<i>Units</i>
R	= Fire spread rate	cm./sec.
I_R	= Reaction intensity--the total intensity available from the combustion zone of a spreading fire	cal./cm. ² -sec.
I_P	= Propagating intensity--that portion of the reaction intensity that drives the fire	cal./cm. ² -sec.
ξ	= I_P/I_R	
ϵ	= Effective heating number--the fraction of the bulk density that is effectively brought to ignition	
ρ_b	= Owendry bulk density	g./cm. ³
ρ	= Owendry particle density	g./cm. ³
Q_{ig}	= Heat of preignition--the heat necessary to bring a unit owendry mass uniformly to ignition	cal./g.
\mathcal{Q}	= Nonuniform heat absorbed per unit volume up to ignition	cal./cm. ³
Q_A	= Nonuniform heat absorbed per unit owendry mass for the transverse member	cal./g.
Q_B	= Nonuniform heat absorbed per unit owendry mass for the longitudinal member	cal./g.
V_u	= Unit cell volume	cm. ³
V_A	= $t^2\ell$ --volume of transverse member of unit cell	cm. ³
t	= Square cross-sectional thickness of unit cell member	cm.
ℓ	= Length of unit fuel cell member	cm.
A	= t^2	cm. ²
B	= $t\ell$	cm. ²
β	= Packing ratio--the ratio of occupied volume to the total bulk volume	cm. ³ /cm. ³
C_w	= 1--specific heat of water	cal./g.-°C.
C_d	= $C_0 + C_1T$ --specific heat of dry fuel	cal./g.-°C.
C_0	= 0.266	cal./g.-°C.
C_1	= 0.00116	(cal./g.-°C.)/°C.
T	= Temperature	°C.
T_a	= Ambient temperature	°C.
T_{ig}	= Ignition temperature	°C.
f	= Fractional fuel moisture content relative to its owendry mass	g./g.
H_A	= Heat per unit dry mass absorbed by the transverse member of the unit fuel cell uniformly heated to ignition	cal.
Q_w	= 540--heat of vaporization of water	cal./g.