man and DeVries (*2*) at atmospheric pressure increased from $C_p = 0.346$ calorie per gram per ° C. at 99.5° C. to $C_p = 0.370$ at 149.2° C. Although the enthalpy data measured in the present work cannot be used to obtain accurate values of the specific heat, this quantity can be estimated from Table II. At the lowest pressure, 60 pounds per square inch gage, the average value between 82.2° and 148.9° C. (180° to 300° F.) is 0.38 calorie per gram per ° C. Since a significant increase in specific heat from 14.7 to 60 pounds per square inch absolute pressure would be expected for acetaldehyde, these two results are in reasonable agreement.

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Heating and Ignition of Small Wood Cylinders

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The literature provides limited information on the time of ignition of wood under conditions of rapid heating such as occur in forest and structure fires. An investigation was made of ease of ignition as affected by such physical properties of wood as initial temperature, size, and moisture content and by temperature of ambient gas or rate of heating. Temperature-time history curves are shown for two radii of wood specimens. With the temperature-time data and an equation for unsteady-state heat conduction, the surface temperature of wood when flame appears is calculated. With the method used, the surface ignition temperature of wood under conditions of rapid heating was found to be nearer 650° than the 550° F. temperature often quoted in the literature.

EXPERIMENTAL determination of the ignition temperature and ignition period of solids is usually done at a low rate of heating. This paper presents a method and the results of an investigation using wood cylinders under rapid heating, like the conditions that occur in forest and structure fires. Only one species of wood was used, but the results establish some fundamental relations believed to be applicable in principle to all types and kinds of fuels.

This information is useful in several fields. In studies of the ways in which forest fires start and spread (*4, 5, 7*), there is frequent need for accurate information on ignition temperature of forest fuels under conditions of rapid heating. Fire prevention and control work require knowledge of how ease of ignition is affected by physical properties of the fuel, such as initial temperature, size, and moisture content and by temperature of the ambient gas or flame. In studies of the use of water and chemicals for fire suppression, knowledge of temperatures associated with the appearance of flame and with glowing fuels is needed to determine the cooling necessary to prevent rekindling, particularly for forest-type fuels.

Brown's summary (*2*) of studies by many investigators reveals that there is no general agreement as to the ignition temperature of any solid fuel. The principal sources of disagreement are (1) the definition of ignition temperature, which may refer to the surface or mean temperature of the specimen or to the external temperature of a bar, an ambient gas, or an oven and (2) the criteria used to indicate the ignition point, such as appearance of glow or flame or some critical point on the time-temperature curve.

Landt and Hausmann (*9*) give ignition periods for several sizes of specially processed materials and for a few species of woods, presumably of one size, with several values of moisture content.

METHOD

The method employed in this study was to measure the time required for self ignition and the internal temperatures during the ignition period of wood cylinders inserted in an electric furnace. Air was admitted to the furnace through an opening in the door. The initial temperature of each specimen was known, and the furnace was maintained at a constant, known temperature considerably higher than the ignition temperature of the wood. The time interval between insertion of the specimen and first appearance of flame was recorded. The length of this interval was defined for the purposes of this experiment as ignition time. The temperature at some point within each specimen was recorded throughout the heating interval. A series of these records for a number of specimens together with the measurement of ignition time provided the experimental data from which surface temperature of the specimens at ignition were calculated.

APPARATUS

The apparatus used to measure ignition time and temperature (Figure 1) consisted of an electric furnace with No. 20 gage Chromel-Alumel thermocouples in porcelain insulating tubes, a precision potentiometer, a photoelectric cell and amplifier, a strip chart recorder with two magnetic marker pens, a photoelectric recording potentiometer equipped with one magnetic marker pen, and a device for inserting the wood specimens.

On both the strip chart recorder and recording potentiometer one pen was operated by a solenoid connected to two parallel electric circuits in such a way that the insertion device opened the solenoid at the instant the specimen entered the furnace. The amplified impulse from the photoelectric cell closed it again at the instant the specimen was ignited. The second pen on the strip chart was operated by a solenoid that was in series with a timer driven by a synchronous motor; this pen checked the speed of the chart by recording marks on the strip chart at 0.5-second intervals. The speed was approximately 18 inches per minute.

The specimen insertion mechanism consisted of a holder, with an adapter for different size specimens, mounted on a V-shaped runner. This slid along a horizontal runway, about 21 inches in length, to an opening in the furnace through which the specimen passed. The runner was drawn by a weight and was released by a hand-operated trigger. When the specimen was half way in the furnace, the runner opened the circuit switch and recorded the insertion time. The movement of the runner was sufficiently rapid

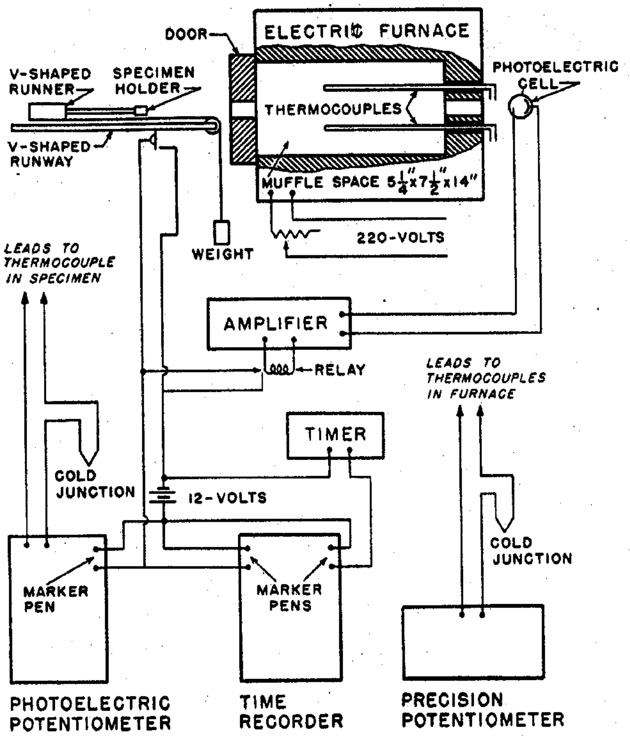

Figure 1. Apparatus for Determination of Ignition Time and Temperature of Wood Specimens

that the time spent by the specimen in transit between room temperature and furnace temperature was only a small fraction of a second.

PROCEDURE

Specimens of ponderosa pine wood $^3/_{32}$, $^1/_8$, $^5/_{32}$, $^3/_{16}$, $^1/_4$, and $^3/_8$ inch in diameter were employed in the experiment. Specimens were selected from prepared stock for uniformity in structure and density, and sizes exceeding ±0.003 inch of their nominal diameter were rejected. Each was cut to $5^1/_8$ inches in length and sandpapered to remove rough spots. One end of the specimen was tipped with casein glue to prevent ignition of the exposed end during the test period.

In the determination of ignition time, 30 to 40 specimens of one size constituted a run.

The desired range of moisture content for the different runs was obtained by exposing specimens to air of necessary temperature and humidity for a sufficient time to bring their moisture contents to the desired levels. For example, moisture content of 1.5% was obtained by placing the specimens over a tray of calcium chloride in an electric drying oven at 150° F. for 48 hours and then removing them to a desiccator and allowing them to cool to the desired temperature before starting a run.

Moisture-content determinations were made with samples prepared from the same stock of each diameter size and exposed to the same conditions as were the specimens for the runs. Immediately after a run was completed, the amount of water in the sample was determined by xylene reflux distillation (*3*). The weight of the water was subtracted from the original weight of the sample to give the dry weight, for calculation of the percentage of moisture.

Initial temperatures of specimens at less than 100° F. were obtained by making runs when the room was at the desired temperature. Initial temperatures of 100° F. and above were obtained by preheating the specimens in an electrically heated thermostatically controlled box, fitted on the runway of the inserting mechanism in such a way that a specimen could be inserted into the furnace without being exposed to outside air.

During each run the electric furnace was maintained at a nearly constant temperature. By frequent slight adjustment of the furnace rheostat control it was possible to maintain the furnace temperature within 3° F. of that desired for the run.

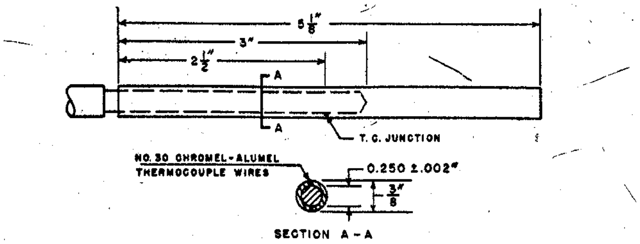

Figure 2. Detail Showing Position of Thermocouple in Specimen

The calculation of surface ignition temperature required data on temperatures at specified radii within the specimen. To measure these temperatures, it was first necessary to devise a method for placing a thermocouple at a specified radius. This was accomplished by drilling a longitudinal hole in the specimen to a distance approximately $^3/_5$ of its length. Another specimen of a size that fitted snugly into the drilled hole, was used for a plug. Before the plug was driven into the specimen, a calibrated thermocouple, butt-welded junction, made from No. 30 Chromel-Alumel wire was looped over the end of the plug so the junction was approximately 0.5 inch from the end (Figure 2). With this arrangement, the thermocouple wires on either side of the junction were on the same radius as the junction, thus eliminating any error in temperature measurement that would be caused by heat conduction along the wire to and from the junction.

IGNITION TIME

Three series of runs were made to determine the respective effects of moisture content, initial temperature, and specimen size on ignition time with furnace temperature constant at 1150° F. (Table I). The coefficient of variation (*12*) for these runs varies between 6 and 9%, being nearer the lower limit for the smaller size and nearer the upper limit for the larger size.

To show how furnace temperature or rate of heating affects ignition time, additional runs were made of several specimen sizes at 1.5% moisture content (Figure 3). The furnace temperature was varied from 1300° F., where all sizes ignited at approximately the same time, to 830° F., where most specimens of the $^3/_8$-inch size were reduced to charcoal without flame. The

TABLE I. IGNITION TIME OF WOOD CYLINDERS, WITH FURNACE TEMPERATURE CONSTANT AT 1150° F.

Series	Run No.	No. Specimens	Specimen Diameter, Inch	Moisture Content, %	Initial Specimen Temp., ° F.	Average Ignition Time, Sec.
I	1	35	$^1/_4$	2.2	88	6.83
	1	32	$^1/_4$	3.6	82	7.21
	1	34	$^1/_4$	7.8	81	8.90
	1	33	$^1/_4$	11.3	80	10.51
	1	32	$^1/_4$	19.3	78	15.47
II	1	33	$^1/_4$	1.5[a]	50	6.87
	1	36	$^1/_4$	1.5	100	6.63
	1	35	$^1/_4$	1.5	150	6.70
III	3	96	$^3/_{32}$	1.5[a]	90	4.38
	3	102	$^1/_8$	1.5	90	5.08
	3	94	$^5/_{32}$	1.5	90	5.60
	3	97	$^3/_{16}$	1.5	90	6.00
	3	104	$^1/_4$	1.5	90	6.73
	3	98	$^3/_8$	1.5	90	7.50

[a] Specimens oven-dried at 150° F. for 48 hours.

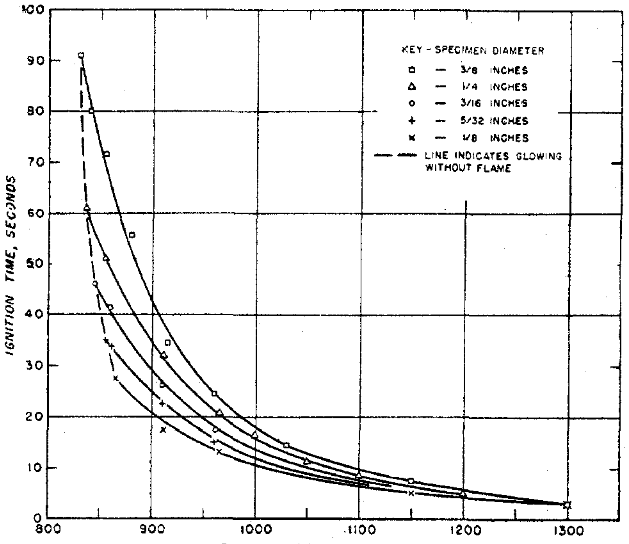

Figure 3. Effect of Furnace Temperature on Ignition Time

furnace temperature that reduced specimens to charcoal increased slightly with decrease in size. Once the specimen was reduced to charcoal, however, glowing was noted with temperatures as low as 450° F.

SURFACE TEMPERATURE AT IGNITION

Two runs were made in which the temperature-time history at two points within the specimen were recorded during the ignition period (Table II and Figure 4).

TABLE II. TEMPERATURE AT FIXED POINTS WITHIN WOOD CYLINDERS AT IGNITION TIME

(Furnace temperature constant at 1150° F.)

Run No.	No. Specimens	Specimen Diameter, Inch	Moisture Content, %	Initial Specimen Temp., ° F.	Average Temp. at Fixed Point, ° F.
1	17	3/8	1.5	90	129[a]
2	17	3/8	1.5	90	210[b]

[a] Temperature 3/32 inch from center of specimen: $r/r_0 = 0.500$; coefficient of variation 11.6%.

[b] Temperature 1/8 inch from center of specimen: $r/r_0 = 0.667$; coefficient of variation 9.6%.

From these data (Table II) the surface temperature of the fuel at ignition was calculated, starting with the simplified conduction equation:

$$\frac{\partial t}{\partial \theta} = a\left[\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r}\right] \tag{1}$$

This equation represents the heating of solid cylinders under *transient conditions, where:*

1. Thermal properties of the material are independent of temperature and time—that is, thermal diffusivity a is constant.
2. No heat sources are involved.
3. Temperature distribution is symmetrical about the axis—that is, temperature is constant at points of equal radius.
4. Heat flow axially is neglected—that is, cylinder is considered infinitely long.
5. Structure of the solid is homogeneous and isotropic.

If a cylinder is initially at uniform temperature t_0 and suddenly immersed in an atmosphere of constant temperature, t_f, and if the heat exchanged at the outer surface is considered proportional to the difference in temperature of the atmosphere and the outer surface (Newton's law of cooling), the boundary conditions are:

$$\begin{aligned} &\theta = 0:\ t = t_0, && 0 \leq r \leq r_0\,(\text{a}) \\ &\theta = \infty:\ t = t_f, && 0 \leq r \leq r_0\,(\text{b}) \\ &\theta > 0:\ \frac{\partial t}{\partial r} + \frac{f}{k}(t - t_f) = 0, && r = r_0\,(\text{c}) \end{aligned} \tag{2}$$

where f is the unit surface conductance, k is the thermal conductivity of the solid, and r_0 is the radius of the cylinder.

The analytical solution of the problem defined by Equations 1, 2a, 2b, and 2c has been given (*1*) as:

$$t = t_f - (t_f - t_0)\sum_{n=1}^{n=\infty} \frac{2}{\nu_n} e^{-\frac{a\theta}{r_0^2}\nu_n^2} \frac{J_1(\nu_n)\, J_0\left(\nu_n \frac{r}{r_0}\right)}{J_0^2(\nu_n) + J_1^2(\nu_n)} \tag{3}$$

Values of ν_n are determined from the following transcendental equation:

$$\nu_n = \frac{f}{k} r_0 \frac{J_0(\nu_n)}{J_1(\nu_n)} \tag{4}$$

$J_0(\nu_n)$ and $J_1(\nu_n)$ are Bessel's functions of the zero and first order, respectively, and $\nu_n = \alpha_n r_0$. α_n is a root of $J_0(\alpha_n r_0) = 0$ and through the film transfer factor is a function of surface temperature.

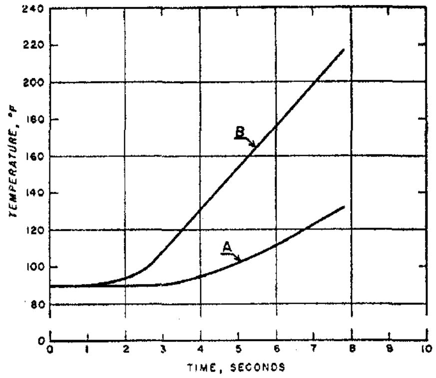

Figure 4. Temperature-Time History for 3/8-inch Diameter Specimen

Furnace temperature, 1150° F.; curve A = r/r_0 = 0.500; curve B = r/r_0 = 0.667

Equation 3 has been expressed by McAdams (*10*) and others (*1*) in terms of four dimensionless groups or moduli as:

A temperature difference ratio:

$$Y = \frac{t_f - t}{t_f - t_0} \tag{5}$$

A relative time ratio:

$$X = \frac{a\theta}{r_0^2} \tag{6}$$

A thermal-resistance ratio:

$$m = \frac{k}{fr_0} \tag{7}$$

A position ratio:

$$n = \frac{r}{r_0} \tag{8}$$

The functional relation expressing these quantities is:

$$Y = \phi[X, m, n] \tag{9}$$

Equations 3 and 4 were used to calculate temperature-time history tables of Y values for X from 0.025 to 0.6, for m from 0 to 100, and for several n values ranging from 0 to 1.00. These tables have been mimeographed and may be obtained by writing to the author.

Equation 3 permits evaluation of surface temperature of a specimen at ignition time, θ_i, providing the specified conditions are satisfied. For oven-dried wood it may be postulated that the thermal properties will remain relatively constant during the heating period. Wood, however, is far from being isotropic. Conductivity along the grain (*11*) is from two to three times as large as it is in the radial and tangential directions, but since the length of the specimens used in the tests was large in comparison to their diameter, the heat flow from the ends along the grain did not extend far enough during the ignition period to be of importance.

The condition that no heat source is involved during the heating period of wood may not be entirely satisfied because of exothermic decomposition at the surface a short interval before the appearance of flame. Since the temperature-time curves shown in Figure 4 do not reveal any change in slope before and immediately after ignition, apparently the time interval between exothermic decomposition and the appearance of flame is of small magnitude. It may be assumed, therefore, that no heat source or exothermic reaction was involved in bringing the specimen to the temperatures that were measured at the two radii at the instant of ignition.

From Table II with $t_f = 1150^\circ$ F., $t_0 = 90^\circ$ F., and the average temperatures of 129° and 210° F. measured at $n = 0.500$ and $n = 0.667$, respectively, the temperature-difference ratio Y value was calculated by Equation 5 for the two radius ratios. This resulted in values of $Y = 0.963$ for $n = 0.500$, and $Y = 0.887$ for $n = 0.667$. From the temperature-time history tables with Y values of 0.963 and 0.887 as parameters, sufficient values of X and corresponding values of m were determined for the two positions to allow the plotting of two curves of X as a function of m. The intersection of these two curves gave values $X = 0.0395$ and $m = 0.265$, to use for determining the temperature at any point within the specimen at ignition time.

With values of $m = 0.265$ and $X = 0.0395$, a value of $Y = 0.471$ was determined from the temperature-time history tables for the surface, where $n = 1.0$. Substituting $Y = 0.471$, $t_f = 1150^\circ$ F., and $t_0 = 90^\circ$ F. in Equation 5 results in a value of $t = 650^\circ$ F. for the surface temperature of the specimen when flame appears.

This value of 650° F. as determined by the above method is considered as the surface ignition temperature, when flame appears, of the wood specimens used in the experiment.

DISCUSSION AND CONCLUSIONS

Although this study was confined to only one species of wood, the results have established the effects that initial temperature, moisture content, and size of the wood have on time of ignition as signified by the appearance of flame. It shows that initial temperature in the range 50° to 150° F. has but a negligible effect on ignition time. Moisture content, on the other hand, increased the ignition time considerably. The increase is more than can be accounted for by the increase in specific heat due to moisture. A plausible explanation seems to be that the presence of water-vapor at the surface extends the time required for the gaseous concentration of the flammable to build up for combustion. The way in which size affects ignition time depends on the rate of heating. Figure 3 shows that with furnace temperature less than 1300° F. ignition time increases as size increases. Data in Table I, series III, indicate that with furnace temperature at 1150° F. the ignition time increases with size but at a decreasing rate, so it would reach a maximum value at some size slightly greater than $^3/_8$-inch diameter. This is also true for other furnace temperatures less than 1300° F.

The results from changing the furnace temperature show that rate of heating affects ignition time considerably. Since a fire spreads fastest in the direction where ignition time is least, the results provide fundamental information useful in predicting critical sectors of rapid spread on a fire perimeter. A forest fire normally spreads rapidly through the finer, more readily ignited fuels, and only singes the larger fuel. The spread in this case is partially governed by the fineness of the fuel (*5*, *7*). Under such conditions the rate of heating at the fire front is in a range equivalent to that obtained in the furnace at temperature less than 1300° F., for which size affected the ignition time. It has been observed, however, that under favorable burning conditions, associated with high winds, steep slopes, and loosely arranged fuel, the fire intensity builds up to a point where size of material appears not to be significant in governing rate of spread. Under these conditions the rate of heating of the adjoining fuel at the fire front is at a value equivalent to or above that obtained in the furnace at 1300° F., where all sizes tested ignited at the same interval. These results indicate that in studies of spread of fires particular attention must be given to the character of the flame front.

Two findings provide knowledge useful in studies of the use of water and chemicals for fire suppression. These are the minimum furnace temperature at which ignition occurs with a flame and the minimum temperature at which charcoal glows. The results show that flame may appear in a mass of material if parts of it are at a temperature of 800° F. or higher. If part of the material has been reduced to charcoal, surrounding material at temperatures as low as 450° F. will cause the charcoal to glow. To prevent rekindling, therefore, all material must be cooled to 450° F. or less.

The surface ignition temperature when flame appears for the species of wood tested was found to be 650° F., which is somewhat higher than reported for wood by other investigators (*2*, *6*, *8*). Their values of approximately 560° F. are, however, for finely divided materials tested under conditions of low rate of heating.

NOMENCLATURE

a = thermal diffusivity of solids, sq. ft./hr.
e = 2.718 . . ., base of natural logarithms, dimensionless
f = unit surface conductance at outer surface, B.t.u./sq. ft. hr. ° F.
k = thermal conductivity of solid, B.t.u./sq. ft. hr. (° F./ft.)
$m = \dfrac{k}{fr_0}$, thermal resistance ratio, dimensionless
n = position ratio, r/r_0, also positive integer, dimensionless
r = radius at any point within solid cylinder, ft.
r_0 = outer radius of finite solid cylinder, ft.
t = temperature within solid cylinder, a function of time and position, ° F.
t_f = uniform temperature of atmosphere surrounding solid cylinder or furnace temperature, ° F.
t_0 = initial uniform temperature of solid cylinder, ° F.
$X = \dfrac{a\theta}{r_0^2}$, relative time ratio, dimensionless
$Y = \dfrac{t_f - t}{t_f - t_0}$, temperature difference ratio, dimensionless
θ = time, hours
θ_i = ignition time, hours

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