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NATIONAL BUREAU OF STANDARDS REPORT

7306

IGNITION OF SOME WOODS EXPOSED
TO LOW LEVEL THERMAL RADIATION

By

A. J. Buschman

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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ABSTRACT

Critical intensities for the pilot ignition of some common materials have been determined. An effort is made to correlate data from a flame-spread test in which the specimen is subjected to a non-uniform radiant exposure with data from the pilot ignition of uniformly irradiated specimens in order to understand the effect of the presence of a flame.

Intensity of irradiation and time of ignition have been employed in computation of surface temperatures at the time of ignition. Equations are presented which show the dependence of ignition time and surface temperature upon the physical and thermal properties of density, conductivity, and specific heat.

1. INTRODUCTION

The radiant ignition of wood has received considerable attention during the past few years. This attention has been focused primarily upon short pulses of high intensity thermal radiation although some work has been done in the range where intensities are less than one calorie per square centimeter per second and the time of exposure relatively long. It is the purpose of the present report to present some work in this latter range.

The flame-spread test, described in detail in reference 1, had been developed to study the rate of travel of a flame along a surface which was receiving a non-uniform, low level, thermal radiant input. The introduction of the flame-spread test has increased interest in the behavior of materials exposed to thermal radiation at levels effective during fires since these tests showed that materials would burn at incident intensities which were below those considered as critical in reference 2. Critical intensity is defined as the level of irradiation below which ignition does not occur. While it is reasonable to expect some increased heat transfer due to the presence of the flame, this effect was not expected to be of the magnitude found in the flame-spread data when compared with the results of reference 2. It was therefore necessary to determine the critical intensities and the intensity-time relationships for typical materials and to make a direct comparison with the flame-spread test results on the same materials.

2. EXPERIMENTAL DETAILS

A twelve by eighteen inch vertical gas-fired refractory panel, described in detail in reference 1, was used as the source of the radiant energy. The panel was maintained at a radiant output corresponding to that of a blackbody at a temperature of 670°C for the flame-spread test and for this reason was operated at this level for both the uniform flux and delayed ignition tests.

All specimens were conditioned at 75°F and 50 per cent relative humidity for at least forty eight hours prior to any test. The density of all materials was determined by weighing and measuring the volume. The conductivity was obtained from equation 6-29 of reference 3 relating the thermal conductivity to the density of the material. The specific heat of all materials tested was taken to be .34 cal/g°C.

3. UNIFORM FLUX TESTS

This series of tests deals solely with pilot ignition, that is a small pilot flame was placed one-half inch above and one-half inch in front of the specimen in order to ignite the evolved gases. Direct contact between the pilot and the specimen was avoided in order to reduce to a minimum the heat added by the pilot. Reference 1 presents some work on the effect of pilot position upon ignition time.

Intensities were varied by positioning the specimen at various distances normal to the panel along its centerline. This yielded a range of intensities from .890 cal/cm^2 sec at a distance of 4.25 inches to .342 cal/cm^2 sec at a distance of twelve inches from the panel. Visual observations show that even at the closest position convection currents from the panel do not reach the specimen. Therefore, the predominant mode of heat transfer was by radiation with natural convection effects at the specimen surface due only to the temperature of the specimen.

The intensity was measured at selected distances normal to the radiant panel and along its centerline using a copper sheet calorimeter. The calorimeter consisted of a blackened 1/16-inch thick copper sheet which was two and a quarter inches square with a 24 gauge chromel-alumel thermocouple swaged into the rear surface. From the rate of temperature rise measured on a high speed recorder and the weight and heat capacity of the copper sheet, the intensity was calculated assuming blackbody absorption of radiation.

Specimens were two and one-quarter inches square and one-quarter inch thick. Surface area was made as small as possible in order to have a more uniform input yet large enough to avoid errors due to insufficient area. Reference 4 presents some work on the effect of specimen area upon ignition time. The specimen thickness of one-quarter of an inch was the same as that of the standard sample used in the flame-spread test reference 5. This thickness was sufficient so that no appreciable temperature rise occurred on the rear surface prior to ignition and the specimen could therefore be considered semi-infinite prior to this time.

The specimen was held in position in front of the panel by a holder fabricated of cement-asbestos board. The holder provides support as well as freedom from drafts therby minimizing forced and natural convective losses from the rear and along the edges. Aluminum foil was placed around the opening on the front of the holder and along the edges in order to reduce the heat input to the holder as much as possible. The holder was then placed on a pivoted arm so that it could be rapidly placed in position in front of the panel.

In performing a test, the lighted pilot was placed in position and then the specimen was pivoted into position at time zero. The time for ignition to occur was recorded from visual observations. The observation of sustained flaming on the surface of the specimen was taken as evidence of ignition. Flashing in the hot gasses above the specimen was not considered as evidence of ignition. This flashing effect did not occur in the higher intensity exposures but was quite common in the range of the critical intensity of the material.

The materials tested in this manner were tempered hardboard, and maple, oak, poplar, spruce, and balsa woods. These materials were used to give a wide range in density and thermal conductivity.

During a test, the intensity of radiation reaching the specimen tends to increase due to reflective effects. Since the specimen is not a blackbody, it reflects some of the indicdent radiation and returns a portion of it back to the panel. The panel, also not a blackbody, absorbs some of this reflected radiation and reflects a portion of it back to the specimen. This process continues indefinitely until the equilibrium is maintained. This new equilibrium will result in a higher panel temperature (the panel being originally set for a blackbody temperature of 670°C) and therefore in a higher incident intensity at the surface of the specimen. The effective blackbody temperature of the panel after a ten minute exposure was found to increase from 670°C to 686°C and the intensity at the surface of the specimen was increased from .890 to .947 cal. /cm^2 sec at the 4.25 inch position.

In order to reduce this effect, a servo-control system was employed to maintain the panel temperature reasonably constant. The panel was originally set for a blackbody temperature of 670°C using the radiation pyrometer employed for this purpose in the flame-spread test. A second radiation pyrometer placed adjacent to the specimen and facing the panel was used to control the supply of gas to the panel. Its output in series with a pre-set potentiometer whose output in opposition cancelled out the pyrometer when the panel was at the proper temperature was fed to the servo-control amplifier which controlled the supply of gas to the panel. In this manner small changes in panel temperature were sensed and corrected by changes in the flow of gas to the panel. Since the refractory panel has a large thermal inertia it did not respond rapidly to the changes in flow rate. However, the output of the control pyrometer was kept within ± .02 millivolts corresponding to ± 2.3 degrees Centigrade of the desired temperature.

4. DELAYED IGNITION TESTS

This series of tests was designed to provide ignition data to supplement the uniform flux tests and the flame-spread tests. The specimen exposure was the same as in the flame-spread test except that the pilot was not applied at the start of the test but was delayed for selected time periods.

The test specimen was six by eighteen inches and was placed in position facing the panel at an angle of inclination of thirty degrees. The intensity along the specimen has been measured and is reported in reference 1. The ignition times measured for these tests corresponds to the delay period plus ten seconds. The additional ten seconds were allowed to permit the flame to become established thereby leaving a mark on the surface which clearly indicated the position of the flame front. After ten seconds of pilot ignition, the flames were immediately extinguished and the maximum distance reached by the flames was measured. The intensity at this position was determined from reference 1, figure 8.

5. RESULTS AND DISCUSSION

The data obtained from the present series of tests are presented in Table I. The times in the data for the delayed ignition tests include the ten seconds allowed for the flame to become established. The critical intensities are also presented in Table I.

The critical intensities were obtained from the uniform flux data by plotting the intensity against the reciprocal time of ignition and extrapolating to zero on the reciprocal time scale. This corresponds to the intensity required for ignition at infinite time. A typical plot of this type is shown in Figure 1. It was then possible to determine the relationship between excess intensity, (intensity above critical), and time. Figure 1 is a logarithmic plot of intensity above critical versus time for tempered hardboard. Similar plots for the other materials tested have been prepared and it has been found that the slope, which appears constant for each material, is not the same for all materials as had been suggested in reference 2.

It is possible to represent the data using an empirical formula of the type

$$(I-I_p)\ t^n = A$$

where I_p is the critical intensity for pilot ignition, n is a constant determined from the slope of the line as in Figure 2, and A is a constant.

Attempts have been made to express the values of the parameters I_p, n, and A in terms of the physical and thermal properties of the materials. The solution of the heat flow equation for a semi-infinite slab initially at zero temperature heated on the surface by radiation from a medium at a constant temperature, reference 6, page 72, equation 5, shows the surface temperature rise to be a function of the $K\rho C_p$ product, where K is the thermal conductivity ρ is the density, and C_p is the specific heat.

Figure 3, therefore, shows the dependence of I_p, n, and A upon the product $K\rho C_p$. Both I_p and n can be represented by linear functions of $K\rho C_p$ while A can be expressed as a simple quadratic in $(K\rho C_p)^{\frac{1}{2}}$. The relations are as follows:

$$I_p = 4.24 \times 10^{-1} - 8.75 \times 10^{-4} (K\rho C_p \times 10^6)$$

$$n = 9.75 \times 10^{-1} - 1.20 \times 10^{-3} (K\rho C_p \times 10^6)$$

$$A = K\rho C_p \; [\; 6.90 \times 10^2 - 3.15 \times 10^4 (K\rho C_p)^{\frac{1}{2}} \;]^2$$

Intensities at the time of ignition when calculated using the above equations to determine the constants are within six percent of the intensities obtained when using the experimentally determined values.

Figure 4 compares all the data for tempered hard board for the three conditions of testing. The solid line represents the empirical equation with the parameters evaluated experimentally. The dashed line represents the flame-spread data while the delayed ignition and uniform flux data are points as indicated on the figure.

The delayed ignition data and the uniform flux data agree very well over the entire range shown in Figure 4. At high intensities and short times, it appears as if the flame-spread data would closely agree with the uniform flux data as represented in this range by the solid line. At the lower intensities and longer times, the flame-spread data falls far below the critical intensity. This is undoubtedly due to the presence of the flame since the delayed ignition data are only slightly below the solid line and agree very well with the uniform flux data. The predominant mode of heat transfer producing the increased heat flow is not known. Certainly some increased radiant energy results from the presence of the flame both directly to the specimen as well as by reflections from the panel and the surroundings.

Figure 5 presents a sketch of the basic geometry of the flame-spread test showing the position of the flame as it travels down the specimen. It is to be noted that the flame does not extend out from the surface appreciably at its leading edge. It is therefore assumed that the flame contributes a negligible quantity of direct radiant energy to the specimen in front of the flame front.

The radiant energy from the flame is directed towards the panel as well as towards the specimen behind the flame front. That portion which reaches the panel is partially absorbed thereby increasing the panel temperature. The increased panel temperature along with the partially reflected energy from the flame cause increased radiation to reach the specimen in front of the flame front. The section of the specimen behind the flame front also receives additional heat from the flame due to convection currents. The flame temperature is considerably higher than the specimen temperature and could add large amounts of heat to the system.

Surface temperatures in front of the flame front can be calculated, as will be shown later, but temperatures behind the flame front have not been determined. However, it is expected that large gradients exist in the neighborhood of the flame front causing a higher flow of heat down the specimen than that obtained in the absence of a flame. All of the above mentioned modes of heat transfer contribute towards producing ignition below the critical intensity of incident radiation.

Another possible source of energy is self-heating. At the ignition temperature considerable heat is generated per unit volume for materials such as wood fiberboard. Surface temperatures at the time of ignition can be estimated. However, these temperatures exist only in a region close to the surface and it is difficult to estimate the contributions of self heating.

The results are similar for maple, poplar, spruce, and balsa woods as shown in Figures 6, 7, 8, 9, and 10 respectively. It can be seen that the deviation between the uniform flux data and the flame-spread data varies from species to species. This deviation is a measure of the heat added to the system by the flaming specimen and by associated heat transfer processes and should therefore be related to the physical and thermal properties of the materials. A correlation in terms of the thermal properties is currently being sought utilizing the data reported herein and additional flame-spread data on other wood species.

6. SURFACE TEMPERATURES

The data from the uniform flux tests has been used to calculate the surface temperatures at the time of ignition. These temperatures were obtained through the use of an equation presented by Lawson, Fox, and Webster, reference 7, by modification of previously referenced work, reference 6:

$$\theta_{(o,t)} = \theta_{max} \left[1 - \exp \beta^2 \operatorname{erfc} \beta \right]$$

where $\theta_{(O,t)}$ is the surface temperature rise at time t, T is the temperature on the Kelvin scale, T_o is the initial temperature on the Kelvin scale, θ_{max} is the maximum temperature rise on the surface, β is a non dimensional parameter, $\psi\left[\frac{t}{K\rho C_p}\right]^{\frac{1}{2}}$, ψ is a heat transfer factor which permits radiative and convective heat transfer to be lumped and considered as a linear function of temperature difference, t is time in seconds, K is the thermal conductivity, ρ is the density and C_p is the specific heat.

The surface temperature at the time of ignition can be obtained from the above equation if the value of T_{max} can de determined. Knowing T_{max}, ψ can be obtained from the following:

$$\theta_{max} = I/\psi$$

so that $\psi = \dfrac{I}{T_{max} - T_o}$.

A heat balance at the surface of the specimen can be arranged to provide the radiant interchange configuration factor in terms of the temperatures of the source, the specimen, and the room as follows:

$$\varphi = \frac{\sigma(T_2^4 - T_3^4) + H(T_2 - T_3)^{1.25}}{\sigma(T_1^4 - T_3^4)}$$

where φ is the radiant interchange configuration factor from the specimen to the panel, σ, is the Stefan-Boltzmann constant, 1.37 x 10^{-12} cal/cm^2 sec $(^oK)^4$, T is the absolute temperature, H is the free convection heat transfer coefficient for a vertical plane. The subscripts 1, 2, and 3, refer to the source, the specimen, and room respectively. Since both the source and room temperatures can be measured, the configuration factor can be plotted as a function of T_2 max. The configuration factor can also be obtained from the following:

$$\varphi = \frac{I}{\sigma T_1^4}$$

thereby making it possible to obtain T_{max} from the plot of φ versus T_2 max.

Surface temperatures at the time of ignition, calculated from the above equations, are shown in Table 2 and presented graphically in Figure 11. The data can be well represented by the linear expression

$$T_{ign} = 667-.527\ (K\rho C_p \times 10^6).$$

7. SUMMARY

Critical intensities have been determined for the following materials: tempered hardboard, maple, oak, poplar, spruce and balsa woods. Intensity above critical has been related to the time of ignition in the following manner:

$$(I - I_p)\, t^n = A.$$

A general equation expressing the constants in terms of the physical and thermal properties has been obtained. They are:

$$I_p = 4.24 \times 10^{-1} - 8.75 \times 10^{-4} (K\rho C_p \times 10^6)$$

$$n = 9.75 \times 10^{-1} - 1.20 \times 10^{-3} (K\rho C_p \times 10^6)$$

$$A = K\rho C_p \quad [6.90 \times 10^2 - 3.15 \times 10^4 (K\rho C_p)^{\frac{1}{2}}]^2.$$

Surface temperatures at the time of ignition have been calculated from a solution, reference 6, for a semi-infinite slab initially at temperature zero and heated on the surface by radiation from a medium at a constant temperature. The radiation and free convection boundary conditions have been lumped and are represented by a heat transfer factor which is linearly dependent upon temperature difference. The surface temperatures calculated in this manner are reasonably constant over a wide range of incident radiation. The calculated surface temperatures at the time of ignition can be well represented by the linear relationship

$$T_{ign} = 667 - .527 (K\rho C_p \times 10^6)$$

The deviation at the lesser intensities between the uniform flux and the flame-spread data is a measure of the heat added to the system by the flame. This too should show a dependence upon the physical and thermal properties of the material. A correlation in terms of the thermal properties is currently being sought.

8. SYMBOLS

A	Constant depending upon species.
C_p	Specific heat, cal/g°C.
H	Convective heat transfer coefficient, cal/cm^2 sec °C.
I	Intensity of irradiance, cal/cm^2 sec.
I_p	Critical intensity of irradiance, cal/cm^2 sec.
K	Thermal conductivity, cal/cm^2 sec (°C/cm).
n	Constant exponent depending upon species.
t	Time, seconds.
T	Temperature, degress K.
T_o	Initial temperature, degrees K.
T_{max}	Maximum temperature, degrees K.
β	Non-dimensional parameter, $\psi \left(\frac{t}{K\rho C_p}\right)^{\frac{1}{2}}$
θ_{max}	Maximum temperature rise above T_o degrees K.
ρ	Density, g/cm^3
σ	Stefan-Boltzmann constant, 1.37×10^{-12} cal/cm^2 sec(°K)^4
φ	Radiant interchange configuration factor from the specimen to the panel.
ψ	Heat transfer factor which permits radiative and convective heat transfer to be lumped and considered as a linear function of temperature difference, cal/cm^2 sec (°C)

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/_2_7 Lawson, D. I. and Simms, D. L. : The Ignition of Wood by Radiation. British Journal of Applied Physics, Vol. 3, pp. 288-292, September, 1952.

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Table 1. - Results of Uniform Flux and Delayed Ignition Tests

UNIFORM FLUX DATA

I \ t	Tempered Hardboard	Maple	Red Oak	Poplar	Spruce	Balsa
.890	52.8	39.9	42.5	32.4	22.9	7.5
.780	66.9		45.0	36.3		
.695	88.2		66.8		45.3	12.8
.445	281	327	347	280	392	155
.392	422	641		575		
.342	600					
I_p	.265	.355	.363	.385	.395	.417

DELAYED IGNITION DATA

t \ I	Tempered Hardboard	Maple	Red Oak	Poplar	Spruce	Balsa
20						.425
40				.729		.301
70	.739		.734	.569	.490	.230
100	.688					
130	.650	.586	.609	.468	.385	.200
145	.588					
190	.545	.430	.531	.435	.375	
310	.473	.375	.413	.239	.270	
490	.378					
730		.289				

Intensities are given in cal/cm^2 sec.
Times are given in seconds.

Table 2. - Surface Temperatures at the time of Ignition from the Uniform Flux Data.

Material	Intensity (Cal/cm^2 sec) .890	.780	.695	.445	.392	.342	Ave T
	Temperature °K						
Tempered Hardboard	591	577	577	567	559	556	571
Maple	620			612	616		616
Red Oak	638	613	615	618			621
Poplar	678	657		647	666		662
Spruce	652		645				649
Balsa	664		663				664

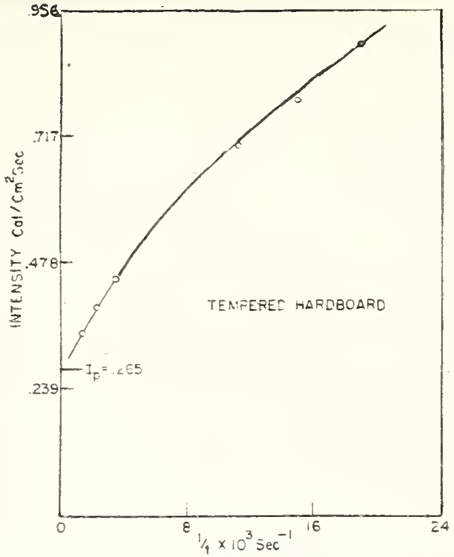

FIG.1 – METHOD OF OBTAINING CRITICAL INTENSITY (I_p)

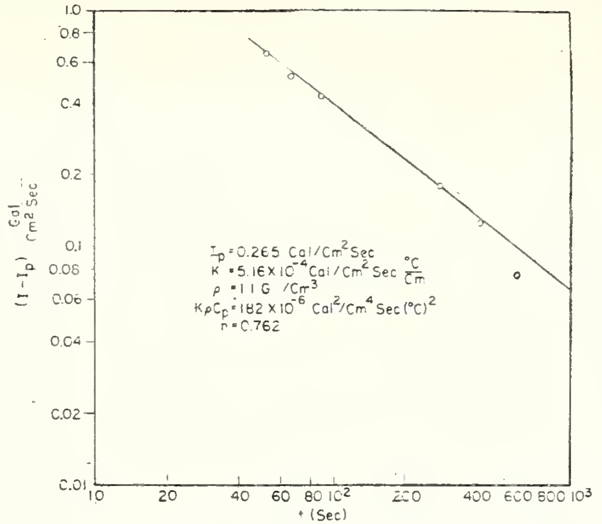

FIG.2 – IGNITION TIME FOR TEMPERED HARDBOARD AT SEVERAL INTENSITIES ABOVE CRITICAL

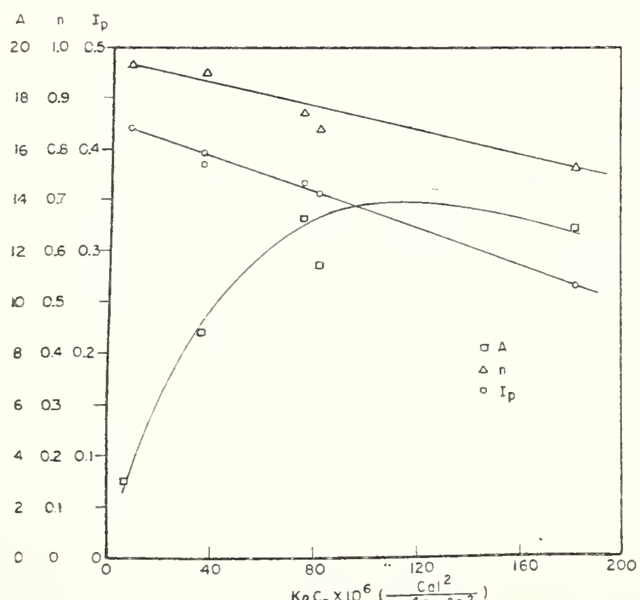

FIG.3 – RELATIONSHIP BETWEEN CONSTANTS AND $K\rho C_p$

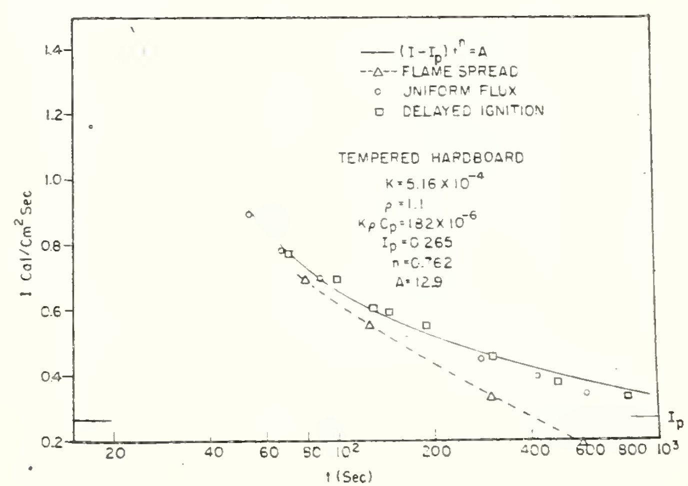

FIG.4 – RESULTS OF UNIFORM FLUX, DELAYED IGNITION AND FLAME SPREAD TESTS FOR TEMPERED HARDBOARD

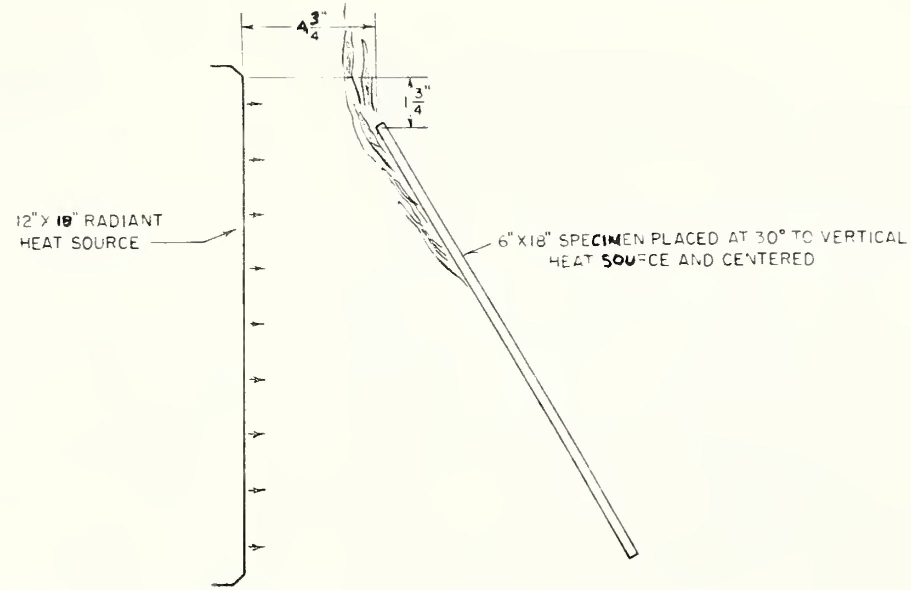

FIG.5-SKETCH OF SPECIMEN DURING FLAME SPREAD TEST

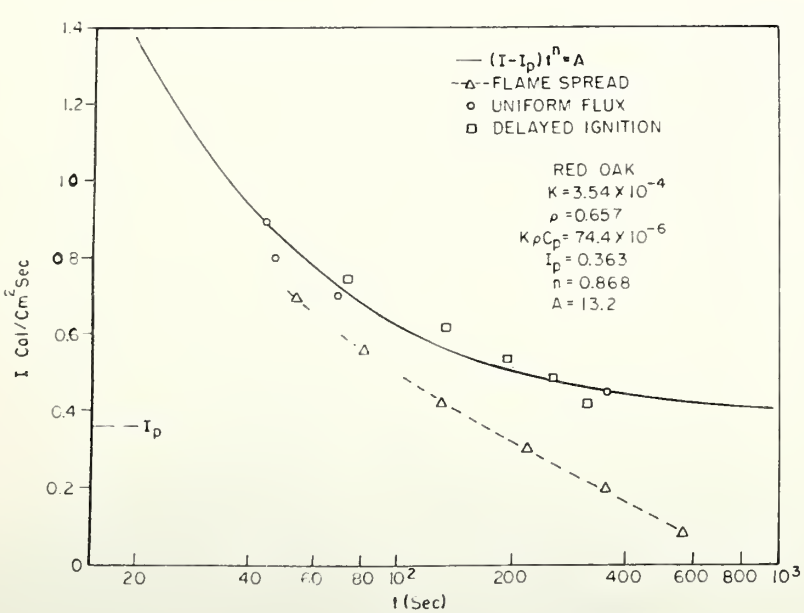

FIG.6 - RESULTS OF UNIFORM FLUX, DELAYED IGNITION AND FLAME SPREAD TESTS FOR RED OAK

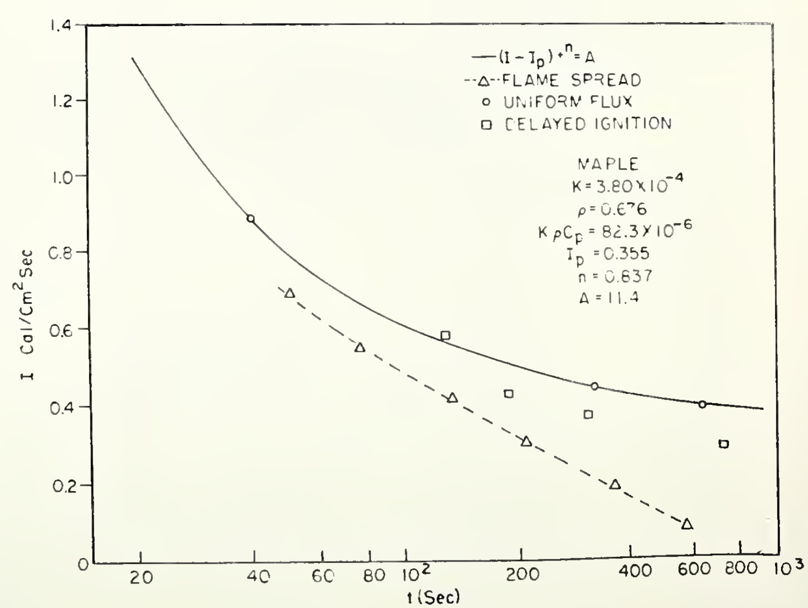

FIG.7 - RESULTS OF UNIFORM FLUX, DELAYED IGNITION AND FLAME SPREAD TESTS FOR MAPLE

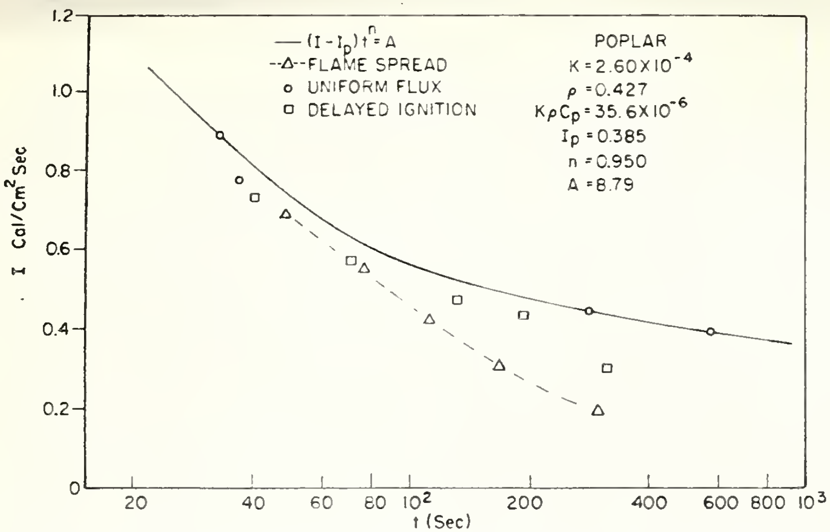

FIG. 8 – RESULTS OF UNIFORM FLUX, DELAYED IGNITION AND FLAME SPREAD TESTS FOR POPLAR

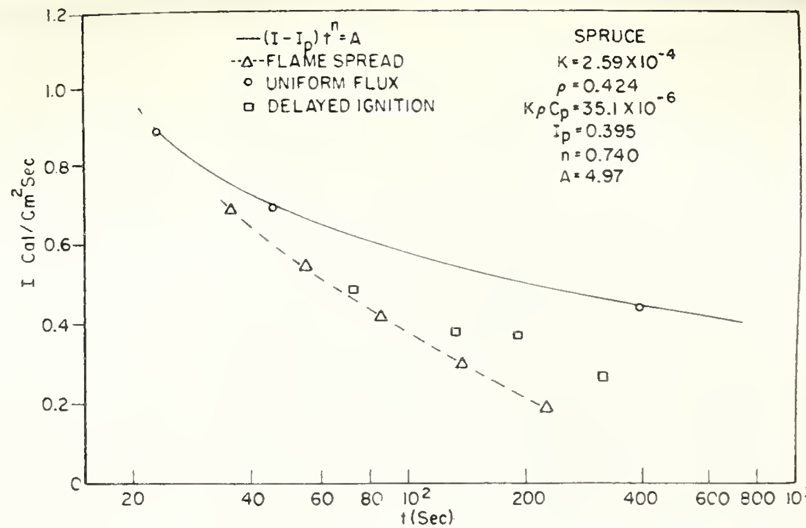

FIG. 9 – RESULTS OF UNIFORM FLUX, DELAYED IGNITION AND FLAME SPREAD TESTS FOR SPRUCE

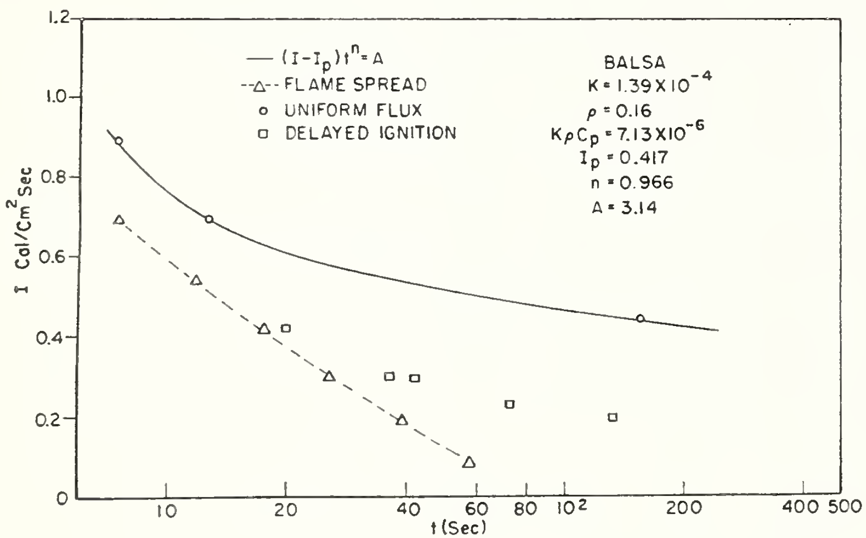

FIG. 10 – RESULTS OF UNIFORM FLUX, DELAYED IGNITION AND FLAME SPREAD TESTS FOR BALSA

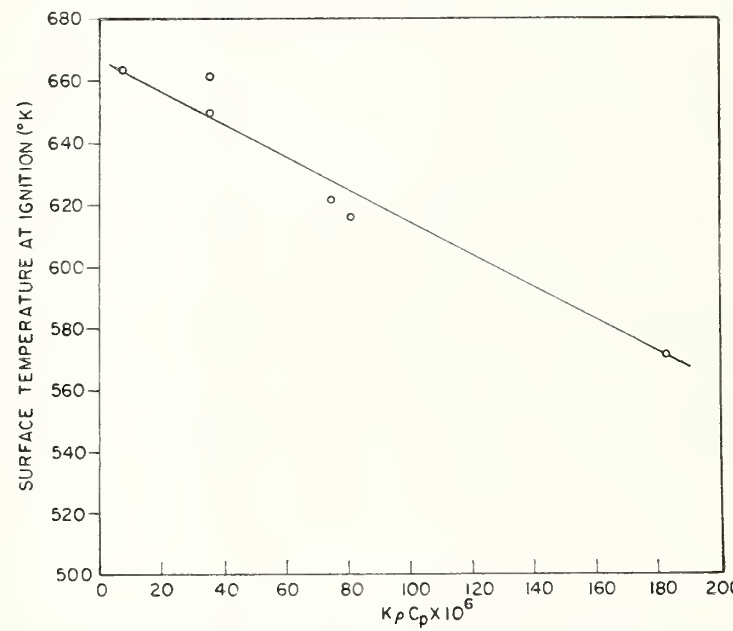

FIG. 11 – SURFACE TEMPERATURES AT TIME OF IGNITION FOR UNIFORM FLUX TESTS

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BOULDER, COLO.

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time Interval Standards. Electronic Calibration Center. Millimeter-Wave Research. Microwave Circuit Standards.

Radio Systems. High Frequency and Very High Frequency Research. Modulation Research. Antenna Research. Navigation Systems.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

NBS