

Forest Fuel Ignitibility

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What is flammability? The author suggests that it consists of ignitibility, sustainability, and combustibility. He defines ignitibility in terms of fuel properties and heat source intensity. Similar methods for determining sustainability and combustibility have not yet been formulated.

OVER the years, a number of researchers have undertaken to develop a measure of the ignitibility of various types of combustible material, including forest fuels. Usually, they have considered ignition to be that point in the time-temperature history of the test specimen when either a flame or a glowing ember appears. In recent years, the time from initial exposure to flame or glowing ember (ignition delay time) has been associated with a particular surface temperature. The reported values of ignition temperature range widely,^{1,2} varying from 190° C to more than 600° C. Over 30 years ago, an American Society for Testing and Materials (ASTM) subcommittee³ was assigned the job of establishing methods to determine ignition characteristics and to develop a standard test. I. K. Walker⁴ noted that, in 1950, the subcommittee was discharged until “. . . there may be developed a more consistent understanding of the meaning of the term ignitibility.”

Since that time, numerous researchers, including Fons,⁵ Thomas,⁶ Simms,⁷⁻⁹ Martin,¹⁰ Akita,¹¹ and Sauer,¹² have investigated ignition phenomena. Martin¹⁰ thoroughly reviewed past research and graphically described the ignition behavior of cellulose (Figure 1).

The region in the upper right-hand section of Figure 1 represents the type of ignition associated with forest fires and other free-burning fires. This region can be described as having a critical irradiance of near 0.5 calorie per square centimeter per second ($\text{cal cm}^{-2} \text{sec}^{-1}$), slow heating rates, and ignition temperatures of about 300° C.

The normalized radiant exposure in Figure 1 is composed of Q , the radiant exposure; ρ , the sample density; c , the sample specific heat; and

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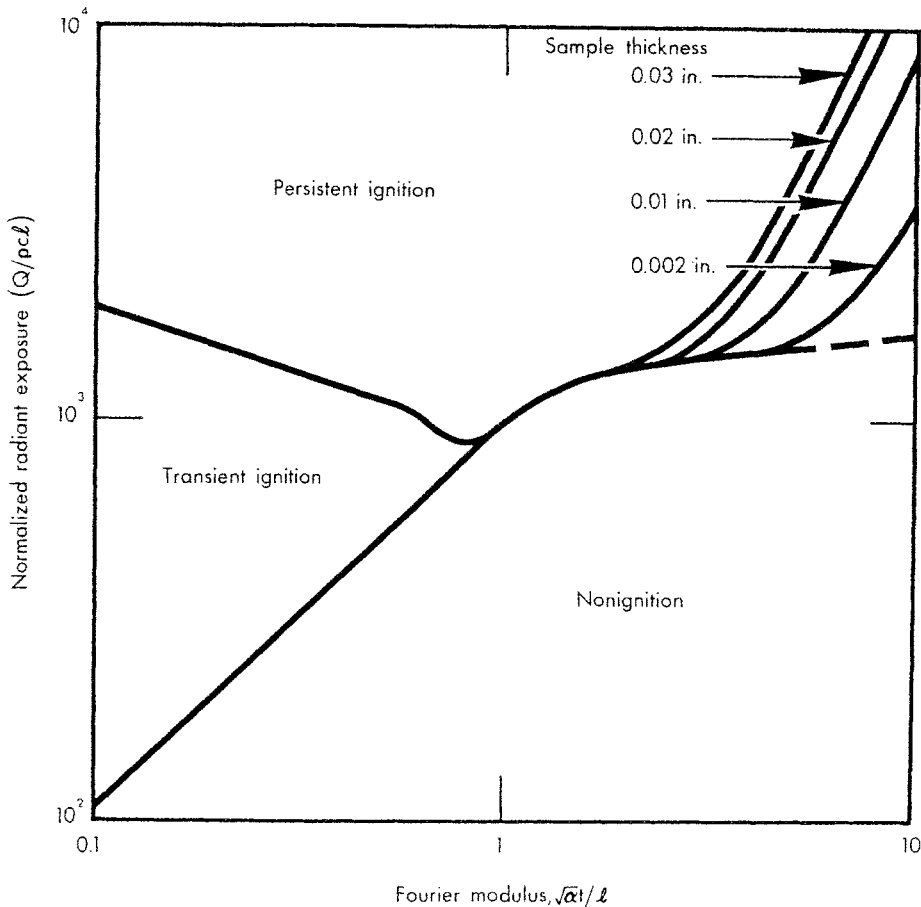


Figure 1. Generalized ignition behavior of cellulose. (Modification of graph presented by Martin ¹⁰.)

l , the sample thickness. The Fourier modulus contains α , the sample thermal diffusivity; t , the exposure time; and l , the sample thickness.^a

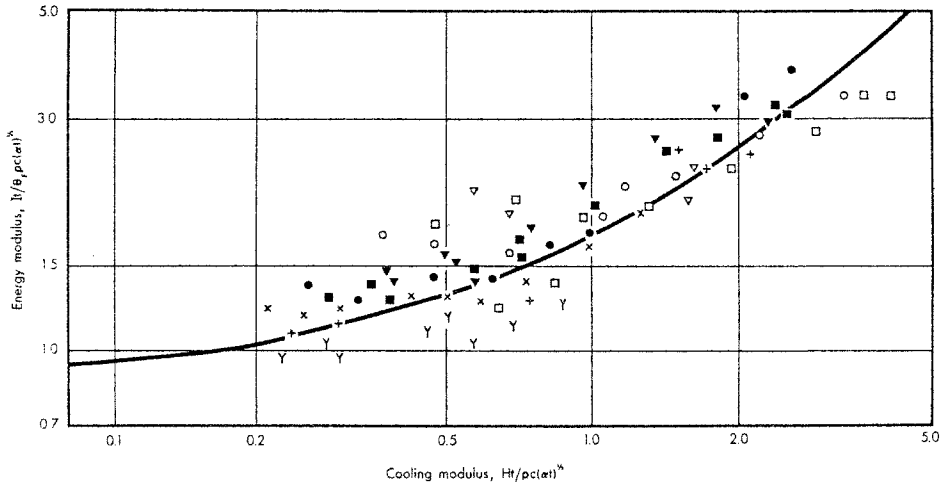
Ignition behavior in this region has been studied by several investigators, including Simms⁷⁻⁹ in England. Simms' extensive studies explored ignition of cellulosic material and showed that spontaneous and pilot ignition can be described by using a fixed ignition temperature and then correlating two moduli. The moduli for pilot ignition,⁹ [an energy modulus, $I t / \rho c (\alpha t)^{1/2} \theta_F$, and a cooling modulus, $H t / \rho c (\alpha t)^{1/2}$] were correlated as shown in Figure 2. The energy modulus contains I , the radiant intensity; and θ_F , the front surface temperature of the sample, besides previously defined terms. The cooling modulus contains H , the Newtonian cooling coefficient. Ignition temperature ranged between 300° C and 410° C, depending on the

^aTo provide continuity throughout this paper symbolism has been standardized and defined when first introduced.

distance, d , separating the sample from the pilot flame.

More recently, Koohyar *et al.*¹³ suggested another approach. Koohyar described ignition at low heating rates from flame irradiance, which he said provided better correlation than previous methods. Results of the Koohyar study are shown in Figure 3. The two moduli developed are an irradiance modulus, $H/\Delta\theta_F k$, and the square root of the Fourier modulus $(\alpha t/l^2)^{1/2}$, where $\Delta\theta_F$ is the surface temperature rise and k is the sample thermal conductivity. The irradiance modulus is a form of the Biot number (hl/k) , which is an index of the relative resistance to heat flow in a solid and a fluid, and includes h , the heat transfer coefficient. The Fourier modulus is a measure of the degree to which heating or cooling has penetrated a sample.

These theoretical interpretations of experimental results have led to dimensionless groups that allow the researcher to correlate data, but do not show the interested practitioner how to estimate the ignitibility of a fuel. This paper presents an approach that shows the relative effects of fuel size, density, specific heat, and ignition source intensity upon delay time to ignition. In addition, I discuss the general concept of flammability and show ignitibility to be only a portion of the flammability picture.



θ_F	Distance	Fiber insulating board	Columbian pine	Oak
$^{\circ}\text{C}$	cm.			
300	0.62	○	■	x
380	1.25	□	●	+
410	1.90	▽	▼	Y

Figure 2. Correlation of results for different positions of pilot flame. Data points represent different test conditions given in the tabulation. (Modification of graph presented by Simms⁹.)

DEVELOPMENT

In order to develop a definition for ignitibility, a review was made of the research done on the ignition of cellulosic materials.^{b, c} The ignition process is complex and exceptions to any method of appraisal are expected. One of the most common conditions for ignition is achievement of a given surface temperature. Various researchers have used a number of temperatures ranging from the temperature where exothermic reaction begins¹ to more than 600° C,² depending upon the test conditions imposed. In the case of free-burning fires and other common ignition sources, we are considering low heat rates (less than 3 to 4 cal cm⁻² sec⁻¹) and long ignition delay times (greater than 1 sec). Ignition temperature then should be close to the temperature of exothermic reaction as advocated by some researchers.^{1, 14} Exothermic reaction is evidenced when the temperature of a fuel sample exceeds the temperature of the environment. Ignition temperature should normally be somewhat higher, coinciding with the generation of combustible gases by the pyrolysis associated with the exothermic reaction.

If we assume that pyrolysis has just begun when ignition occurs, we can hold constant the physical properties of the fuel sample and base our prediction of ignition on the time-temperature history associated with heat transfer processes. At such times, a degree of uncertainty must be accepted because of chemical and physical properties not considered. These include extraneous volatile content, reaction activation energy and order, and thermal absorptivity. The intent of this paper is to provide a general description of the ignition process, which may be useful to the person with a broad interest in fuels and fire.

If we assume (a) that the fuel undergoes no chemical change up to exothermic reaction and ignition temperature and (b) that ignition temperature and heat source intensity are constant, then the time-temperature history of the fuel is predictable. Langhaar¹⁵ presents a dimensional analysis that yields an equation relating the temperature rise to two dimensionless groups — the Fourier and Biot moduli:

$$\frac{\theta_F - \theta_0}{\theta - \theta_0} = 1 - \text{Exp} - \frac{Akt}{\rho cl^2} \quad (1)$$

where θ = furnace temperature, θ_0 = ambient temperature, and A = function of Biot modulus. This equation, which was developed by Gurney

^b Stockstad, D. S., Ignition properties of fine forest fuels. USDA Forest Serv., Intermountain Forest & Range Experiment Station, Ogden, Utah. 1967. (Unpublished problem analysis on file at the Northern Forest Fire Laboratory, Missoula, Montana.)

^c Stockstad, D. S., Ignition temperatures of selected fine forest fuels. USDA Forest Serv., Intermountain Forest & Range Experiment Station, Ogden, Utah. 1967. (Unpublished Study Plan 2104-03 on file at the Northern Forest Fire Laboratory, Missoula, Montana.)

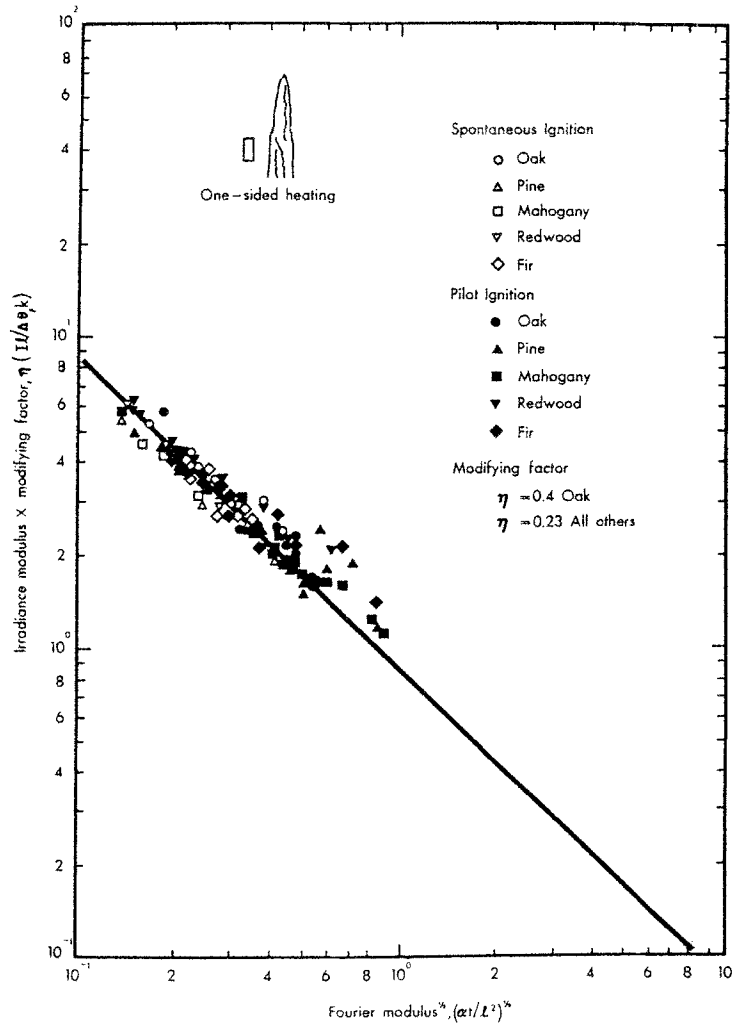


Figure 3. Correlation for ignition data for one-sided heating, including spontaneous and pilot ignition. (Modification of graph presented by Kooyhar et al.¹³)

and Lurie¹⁶ in 1923, has been expanded and refined to provide graphs and charts^{17, 18} that describe the time-temperature history of a test specimen.

Giedt¹⁷ has shown that when the Fourier number is greater than 0.2 and the reciprocal of the Biot modulus is greater than 100, the temperature history equation (1) reduces to:

$$\frac{\theta_F - \theta_0}{\theta - \theta_0} = 1 - \text{Exp} - \frac{ht}{\rho cl} \quad (2)$$

With the left-hand side of the equation and h held constant, the time to ignition temperature becomes a function of ρcl . If we know the ignition

temperature and the intensity of the ignition source, a measure of ignitibility in terms of delay time can be estimated from the physical properties of the fuel.

A P P R A I S A L

Ignitibility then is defined as the ignition delay time. Therefore, at any specific source intensity, the most ignitable fuel is the one that ignites in the shortest exposure time. We tested the applicability of this approach using data published by Fons⁵ and Akita¹¹ and results provided by C. George^d from other research investigations.

The ignition delay times were used to calculate fuel surface temperatures at ignition. The heat source intensities ranged from 0.20 to 3.0 cal cm⁻²-sec⁻¹, corresponding to a perfectly radiating source (blackbody) at from 350° C to 950° C. The average surface temperature at ignition was 346° C ± 40° C over the above range of intensities. These intensities represent the limits cited in the literature for the ignition of cellulosic material caused by some radiation source, e.g., a furnace or a free-burning slash fire^{8,9,19}. Ignition temperatures varied with heat source intensity, but not enough to invalidate the approach to ignitibility.

The next step was to determine the relation of ignition delay time to a fuel's physical properties, ρcl . The dimension l was determined by the way in which a sample was exposed to the heat. If the sample was totally immersed in a furnace, l equaled the half thickness; but if only one surface was exposed, l equaled the full thickness. We selected a single intensity and plotted the change in ignition delay time against the ρcl for each fuel. We repeated the process for each level of intensity. The family of curves that resulted is shown in Figure 4. These curves provide the base for establishing the measure of forest fuel ignitibility. The curve for the lowest limit of ignition examined (a heat source at 350° C) shows the position of fuels according to size. Density and specific heat were held constant on an oven-dry basis. Ignition delay time changes as alterations in density, specific heat, or size cause the ρcl to shift along the x-axis. As heat intensity increases, ignition delay time decreases and the relation between delay time and ρcl becomes more complex. This is a result of the functional relationship between the fuel's surface ability to absorb energy and the fuel's internal ability to conduct heat inward.

With ignitibility defined in measurable terms as the delay time until ignition occurs, we have the first component essential for describing the flammability of a fuel. Ignition is assumed to occur when the fuel begins to generate heat or when flaming or glowing combustion is evident. In the latter case, greater variability can be expected. The time to ignition, the dependent measure, is a function of the stated properties of the fuel and

^d Unpublished experimental data on file at Northern Forest Fire Laboratory, Missoula, Montana.

the intensity of the heat source. With a heat source at 950° C, all fuels inspected ignited in about 1 sec or less.

DISCUSSION

With this approach, a foundation is established for a measure of forest fuel ignitibility. This is not the complete picture, however. Ignitibility is an important part of the fuel appraisal and fire-danger rating systems, but generally the term most often discussed (with no limits on meaning) is flammability. To me, flammability implies more than just time to ignition. I have considered flammability to have three components: ignitibility, sustainability, and combustibility.

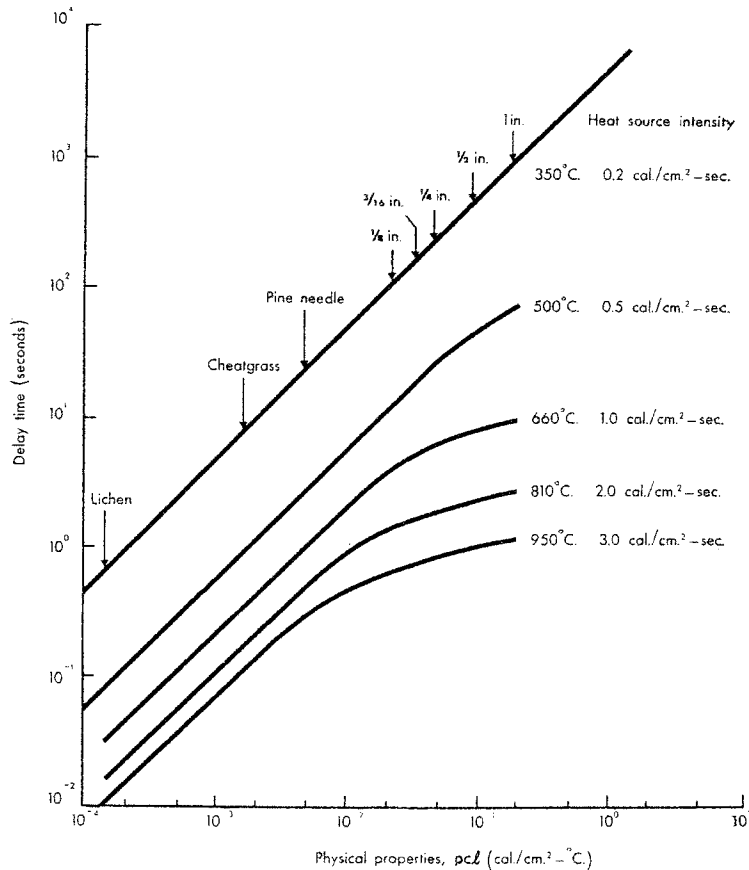


Figure 4. Relation of ignition delay time to the physical properties (sample density, specific heat, and thickness $[\rho cl]$).

Ignitibility, the first consideration, has been described. Sustainability is the measure of how well a fire will continue to burn with or without the heat source. The method for describing sustainability in terms of fuel properties has not yet been formulated. Conceptually, the measure could

be related to how stable the burning rate remains. Combustibility is the reflection of the rapidity with which a fire burns. Again, the parameters to be used have not been determined, but they will be correlated to the specific burning time of a fuel. Specific burning time is defined as the weight of the test sample divided by the maximum burning rate. Conceivably, for some fuels, sustainability and combustibility could be the same.

The concept developed in this paper is directed toward individual fuel elements, although field problems are more concerned with the fuel continuum. To amplify, ignitibility of a fuel continuum would still be governed by the ignition of fuel elements; sustainability would be more closely associated with the rate of spread; and combustibility would be the intensity of the fire or its rate of burning.

These three features of flammability can be combined to give an overall appraisal of fuels. With proper interpretation of fuel properties, thermodynamics, and thermochemical processes, we can develop a comprehensive, but flexible, reference for appraising the fire potential of forest fuels.

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