

Smoldering Initiation in Cellulosics under Prolonged Low-Level Heating

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Scant field information and the difficulty of conducting long-term research experiments on the low-level heating of cellulosics until ignition occurs have led to the advancement of an incipient smoldering ignition predictive model.

FOR A LONG time, evidence has shown that, even when heated at low levels, wood products will eventually combust. This, of course, impacts on the safe use of cellulosic materials and is of concern to code authorities and certification laboratories. Levels somewhat above 100° C are suspected of leading to combustion initiation. Such levels are apparently encountered for wood in continuous contact with steam pipes, for example. Prolonged exposure to 100° C temperatures has been cited as safer. (McGuire 1969 and Matson et al. 1959 provide extensive discussions of available information relating to this phenomenon.) Under controlled conditions, no ignition of wood has been observed for periods of heating up to 3 years below 150° C (Voight 1933) or of fiberboard and wood heated to 120° C for periods of 4 years (McGuire 1969).

Such information has led to regulations on a maximum temperature of about 100° C as allowable for wood under prolonged exposure to heat and currently affects wood use in solar collectors, installation of cellulosic insulation, and clearances for wood near heating units.

T H E P R O B L E M

Can one predict when smoldering combustion is imminent based upon the available thermal degradation and combustion properties of wood prod-

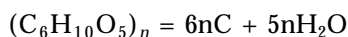
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ucts? What conditions must be met for the model to be applicable to actual cases encountered in the use of cellulosics?

BACKGROUND INFORMATION

Browne (1958) has conducted a comprehensive survey of the combustion of wood and its control. He reported that the results of slow and fast pyrolysis of wood are markedly different. He further observed the following. Under slow pyrolysis, as characterized by a temperature range between 100° and about 280° C, the wood loses weight slowly and eventually becomes charred. Little change has been observed below 100° C. The amount of char produced (about 40 percent by weight) is about double that produced under fast pyrolysis (about 20 percent by weight). The amount of tar produced is proportionately reduced to small amounts and the volatiles liberated are largely nonflammable.

Tsuchiya and Sumi (1977) and Kanury (1972) found that energy is slowly released, which, if not lost to the surroundings, increases the temperature of the wood faster than it can be dispersed. Smith (1959) has observed that the temperature at which self-heating becomes evident in many wood fiber species is about 160° C. This can move the reactions into a fast pyrolysis state and glowing or flaming combustion. If the energy is dispersed, cellulosics can be reduced to charcoal without flaming occurring. Fons (1950) found that ponderosa pine heated in air between 232° and 443° C could be reduced to char without flaming, after which the charcoal began to smolder or glow. Theoretically, cellulosics can be totally converted to carbon and water if pyrolysis can be controlled to only dehydrate the wood:



It would appear that temperatures must be maintained below 220° C for dehydration to occur (Tang 1967). Rapid or fast pyrolysis above 280° C tends to produce the opposite effect on woods - little charcoal, much tar, and highly flammable gases. The carbonization of sawdust results in about 20 percent charcoal; this result was confirmed in thermal degradation experiments (Tang 1967). The mixture of gases released in rapid pyrolysis becomes combustible as a result of secondary pyrolysis, and can be ignited (Martin 1956). The means for such gases to ignite without a flame being present can occur as charcoal spontaneously combusts and ignites them. Charcoal spontaneous ignition has been recorded at as low as 150° C (Browne 1958).

Thus, production of charcoal in the thermal degradation of cellulosics can play a key role in initiation of smoldering combustion or flaming.

The rate of charcoal production can be predicted using kinetic data available in the literature. Stamm (1956) and MacLean (1945-1954) report degrade parameters for many heated wood products. The kinetic factors are derived from fitting a first-order reaction model for weight, w , loss with

time, t , to various heating conditions, T This model is:

$$d(w/w_0) dt = -K_1(w/w_0) \quad (1)$$

where

$$w_0 = \text{initial sample weight}$$

$$K_1 = A \exp [-\Delta E/RT].$$

Here A is the frequency factor, K_1 the reaction rate, and ΔE the pseudo-activation energy. Kinetic factors for various woods and wood forms under oven and steam heating, and heating within molten metal are given in Table 1 (Stamm 1956).

The form of the above Equation 1, though employed by Stamm to characterize thermal degrade, does not accurately describe the phenomenon over the whole range of degradation. It predicts, for example, that eventually the material is consumed, when in reality it is converted to a stable charcoal at low temperatures. Tang (1967) has employed the preferred form:

$$dw/dt = -K_2(w - w_r) \quad (2)$$

where w_r is the residual weight of charred wood at the end of the thermal reaction, to sufficiently account for this.

Figure 1 illustrates variation of reaction rates, K , with temperature for oven heating of wood and heating below molten metal as derived from Equation 1 (Stamm 1956) and that as calculated using MacLean's (1951) data in Equation 2 with a residual char weight, w_r , of 40 percent that of initial wood weight.

Shafizadeh and Bradbury (1979) examined the fundamentals and parameters surrounding the smoldering of cellulosic materials. They con-

TABLE 1. Activation energies of wood and cellulose calculated from thermal degradation data (Stamm 1956)

Material	Heating condition *	Property Loss measured	Time range	Temperature range °C	Activation energy Cal/Mole °K	Log K_{at} 150°C Hr ⁻¹
Coniferous wood:						
Southern and white pine, Sitka spruce and Douglas-fir sticks and Sitka spruce veneer	Oven	Weight	1hr-2.4 yr	93.5-250	29,500	-3.9
Douglas-fir sawdust	Under molten metal	Weight	1 min-6 days	167 -300	29,800	-4.4
	Oven	Weight	16 hr-64 days	110 -220	25,000	-4.0
Cellulose from Douglas-fir	Oven	Weight	16 hr-64 days	110 -220	26,000	-4.1
Hemicellulose from Douglas-fir	Oven	Weight	2 hr-64 days	110 -220	26,700	-3.4
Lignin from Douglas-fir	Oven	Weight	16 hr-64 days	110 -220	23,000	-4.3
Coniferous wood:						
Southern and white pine, Sitka spruce, and Douglas-fir sticks	Steam	Weight	1-200 hr	121 -177	15,800	-2.7

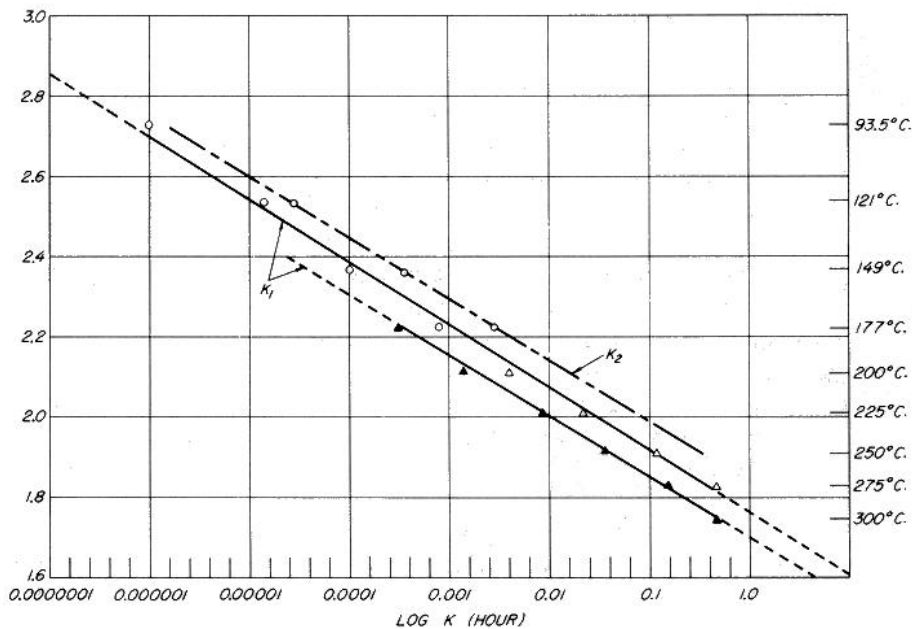


Figure 1. Reciprocal of absolute temperature versus logarithm of K , where K , the reaction constant, is determined from weight loss/time experiments for heated wood samples. Open symbols for specimens heated in oven. Shaded symbols for specimens heated beneath the surface of a molten metal.

clude that "oxidation of char is the sine qua non requirement for smoldering combustion." In addition, their studies supportively show that chars produced by low-temperature pyrolysis of cellulosic materials are highly reactive as compared to graphite and other forms of pure carbon. The oxidation of such char produces smoldering and/or glowing combustion.

SMOLDERING INITIATION

Reaching the charcoal state is essential to initiation of spontaneous smoldering combustion. With adequate dispersal of volatiles produced during low-temperature heating (to prevent flaming ignition), incipient smoldering combustion can be predicated on formation of charcoal.

This conclusion may be considered pessimistic, but without evidence regarding time to ignite the formed charcoal, results of analysis will likely be conservative. That is, predicted times to incipient smoldering ignition will be shorter than would in reality occur.

In the heating temperature range between 100° and 220° C, it can be inferred that charcoal yield is about 40 percent as compared to 20 percent obtained under rapid pyrolysis conditions. It is this approaching of a 40 percent char level that can be conservatively employed to estimate the time to initiation of the smoldering state for cellulosics heated where volatile dispersion exists. Oven heating, where total sample volume is small with respect to oven air circulation and ventilation, is one experimental case.

Cellulosic insulation (untreated) is another, for dispersion of volatiles is easily accommodated in the loose structure. A third would be well-ventilated heated wood sections.

Figure 2, as derived from Equation 1 of Stamm's (1956) results, may be employed to estimate time to smoldering ignition of wood samples that are essentially exposed to an "oven-heated" condition. The 40 percent residual weight line indicates that at least a month would be required for small sections to reach the smoldering combustion state at 175° C, and about 1 year of heating at 145° C to 150° C is required. A similar analysis employing Equation 2 was undertaken for the time to achieve a 45 percent weight level, with the final residual char state assumed to be 40 percent of the initial weight. The time to achieve this level as a function of heating temperature resulted in a line having times only slightly longer than that shown in Figure 2. It was, therefore, concluded that the results derived from Equation 1 could be a conservative predictor of heating time to reach an incipient smoldering state.

Figure 2 is in relatively close agreement with observations recorded by the Forest Products Laboratory (1958). Oven-heated wood specimens (0.32 by 0.64 by 7.6 cm) lost 65 percent of initial weight (including 6 to 8 percent moisture content) after being heated at 140° C for 320 days. An equivalent weight loss was recorded after 165 days of heating at 150° C. Ignition did not occur in either case.

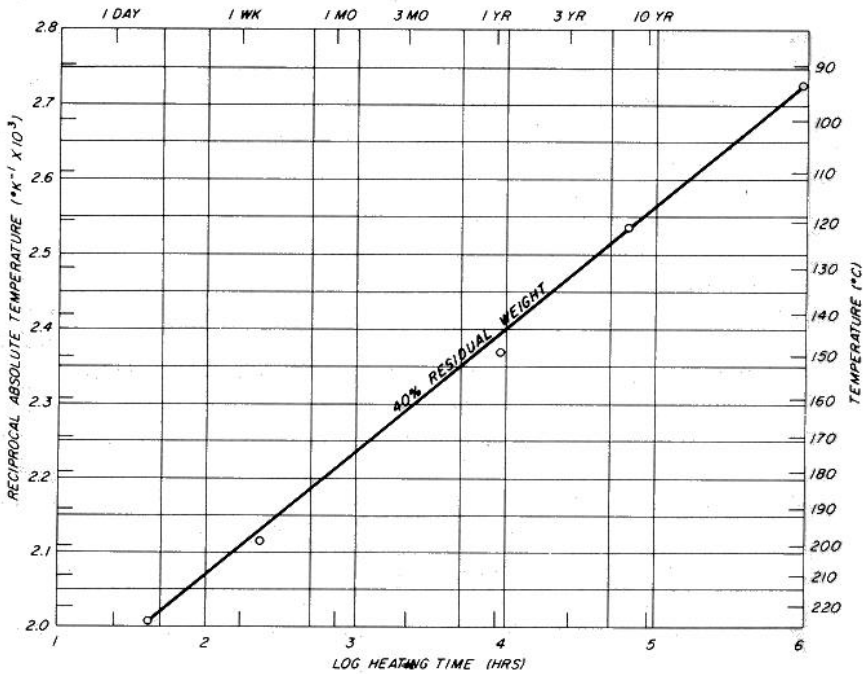


Figure 2. The time required to achieve a 40-percent residual weight level for oven-heated woods as a function of heating temperature.

A second can be examined that of untreated cellulosic fiber or sawdust heated in ovenlike conditions. (Cellulosic insulation is produced from recycled newsprint, which is produced from mechanically ground wood. Hence, recycled newsprint should have the same kinetic factors as sawdust.) Employing Stamm's (1956) kinetic data in the range of 110° to 220° C results in a 40 percent residual weight curve close to that shown in Figure 2. This indicates 1 year of heating at 150° C would be required to induce smoldering combustion and over 10 years at 120° C. If extrapolated to a 250° C heating period, it predicts that about 36 hours of heating is required to initiate combustion. Recent research (Ohlemiller 1979) has indicated that exposures of cellulosic insulation below 250° C for up to 81 hours do not result in smoldering ignition.

Because cellulosics degrade thermally with time, the ability to predict conversion to charcoal under intermittent or cyclic low temperature heating is also possible. Of course, intermittent heating results in a much longer total time requirement before full conversion to char and potential for ignition is achieved. If, for example, cellulosics are exposed to 150° C for 8 hours per day and to 25° C for the remainder of the day, three times the amount of elapsed time in Figure 2 is required before conversion to charcoal is attained.

CONCLUSIONS

Scant field information and the difficulty of conducting long-term research experiments on the low-level heating of cellulosics until ignition occurs have led to the advancement of an incipient smoldering ignition predictive model. It is based upon the elemental assumption that cellulosics must be converted to char before smoldering ignition can occur. It does not confront the question of whether smoldering ignition will eventually occur or not upon reaching this state. Results are given of the analysis for wood, or cellulosic fiber derived from wood, in which the heating environment is below 220° C, and the wood or fiber is unconfined so that volatiles liberated can be dispersed. This is a necessary requirement to inhibit flaming ignition of these volatiles. It is believed that these results can be employed to determine what periods of time cellulosics may be safely heated without having smoldering ignition spontaneously occur. Such wood products can be evidently heated at temperatures to 150° C for a year or more without reaching a state suitable for ignition. As useful as this result is, the need for quantification by experimental means is evident. Though such experiments are difficult to construct and control, such efforts should be undertaken.

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