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SPONTANEOUS COMBUSTION OF FOREST FUELS: A REVIEW

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ABSTRACT

Spontaneous combustion is thought to be a cause of many of the fires which occur in areas such as peat bogs or dry snags. The theories of spontaneous heating are presented, along with a discussion of possible ignition mechanisms in both wood-chip and hay fires. The physical conditions which would most likely support spontaneous combustion are also discussed. A bibliography of available literature is given.

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INTRODUCTION

Spontaneous combustion has always been suspected as being the cause of many fires in various cellulosic materials, mainly wood, hay, and wool. Pulp and paper companies report significant quantities of wood chips spoiled by spontaneous heating within the chip piles^{1,2,3,4}. Some of these piles have been known to ignite when the centres become exposed to the air⁵. Such experiences have now resulted in better storage and handling methods, so that losses are being minimized. Similar effects and results have been observed in hay and wool piles. The economic losses suffered by industry in these areas have been sufficient to prompt research into the causes of spontaneous heating and combustion, and the best means of preventing it.

It has been suspected but never actually proven that many forest fires which have lightning listed as the official cause might have been started by spontaneous combustion. These fires occur in such places as bogs and areas of the forest floor with thick layers of litter that could support the spontaneous combustion process. Kourtz (1967)⁶ found that almost one-third of fires whose causes are attributed to lightning occur in dry snags, a material which could be susceptible to processes of spontaneous heating. Strengthening the belief in spontaneous combustion as a legitimate cause of forest fires is the eye-witness account of fires in the marshes of southern Louisiana by Viosca⁷ in 1924. Since early detection is often crucial in controlling forest fires, a knowledge of the conditions which are favorable for spontaneous combustion would be extremely useful in the scheduling of reconnaissance flights over areas with a high probability of fire occurrence.

This paper will examine and summarize work already done in the field of spontaneous combustion. It will present the various theories of preheating which provides the energy necessary to start the exothermic combustion reactions. The actual spontaneous combustion reactions will be analyzed, with the mathematical equations and results being presented. Finally, the physical conditions which would probably be most favorable for spontaneous fires will be discussed, although the actual conditions will have to be proven by future experimentation and studies. A bibliography of available literature is also included.

ANALYSIS OF SPONTANEOUS COMBUSTION REACTIONS

Spontaneous combustion, like all other combustion processes, is an exothermic oxidation reaction. Frank-Kamenetskii⁸ proposed a mechanism of thermal explosion which postulates an increasing rate of reactant consumption to explain how materials could ignite spontaneously. This is further developed by Walker (1967)⁹. The ignition mechanism, which may be of a chemical, biochemical or physiochemical nature, raises the temperature of the material to a level at which it will support a state of combustion. At the ignition point, a thermal balance exists between heat generated and heat being dissipated. Since the generation of heat is proportional to the cube of the dimension (half-thickness or radius) and since dissipation is proportional only to the dimension or the dimension squared, this can lead to an increasing reaction rate nonlinear with time, a thermal explosion mechanism, possibly resulting in ignition.

Included in Frank-Kamenetskii's thermal explosion theory was the concept of a critical value of δ (δ_c), shown in equation (1) and above which value no stationary centre-temperature θ_0 exists, resulting in self-ignition:

$$\delta = \left(\frac{A}{k}\right) r^2 \left(\frac{E}{RT_a^2}\right) e^{-E/RT_a} \quad (1)$$

where A = rate of heat production per unit volume when T_a is infinitely large
k = thermal conductivity
r = radius
E = activation energy
R = gas constant
 T_a = ambient temperature

Critical values for δ have been calculated for various shapes and are shown in Table 1.

Table 1. CRITICAL VALUES OF δ .

(Lee: Storage and Transportation of Hazardous Materials;
J. Applied Chem., Vol. 19, December 1969)

Shape	δ
Infinite slab	0.88
Infinite cylinder radius r	2.00
Infinite rod, square cross-section	1.69
circle, radius r	1.89
Sphere, radius r	3.32
Cube, half-width r	2.47

Kinbara and Akita¹⁰ have presented the fundamental equation for self-ignition:

$$C_p \rho \frac{\partial T}{\partial t} = k \nabla^2 T + A e^{-E/RT} \quad (2)$$

where C_p = specific heat

ρ = density

T = absolute temperature

A = rate of heat production/unit volume when T is infinitely large

E = activation energy

$A e^{-E/RT}$ = Arrhenius heat generation term

Because of the symmetrical distribution of temperature in a slab, cylinder, or sphere of uniform material, the above equation can be written in the dimensionless form:

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial \xi^2} + \frac{m}{\xi} \frac{\partial \theta}{\partial \xi} + \delta e^{\theta} \quad (3)$$

where δe^θ corresponds to the Arrhenius heat generation term simplified by Frank-Kamenetskii.

δ = Frank-Kamenetskii's criticality factor

θ = reduced temperature $(E/RT_a^2) (T-T_a)$

ξ = reduced distance x/r

τ = reduced time $(k/C_p \delta r^2) t$

m = a constant depending on the shape of the body

= 0 for a slab

= 1 for a cylinder

= 2 for a sphere

r = radius or half-thickness

x = distance from the centre measured perpendicularly to the surface.

This equation has been solved analytically for $m = 0$ and 1 , and temperature distributions have been shown for $m = 2$.

Walker⁹ has investigated the effects of water on spontaneous combustion. He suggests that diffusion of heat will cause a difference in water vapour concentration within the material. This results in mass transfer to the surface by gaseous diffusion, thereby removing the latent heat of vaporization. Between 60°-100°C, this mechanism becomes predominant, and leads to a very large temperature coefficient of effective thermal conductivity for wet porous solids. The thermal conductivity can also increase as a result of the effect on density by bound moisture contained in hygroscopic material.

He also found that when the relative humidity (RH) is less than 100 percent, mass transfer of water vapour will lower the RH of the hot zone and raise the RH of the cold zone. This eventually becomes a path of almost constant water vapour concentration between the two zones. A balance develops between gaseous and thermal diffusivity, causing a drop in the thermal conductivity at temperatures above 60°C.

As a result of his work he was able to conclude that:

- (1) water will affect the thermal diffusivity, altering the specific heat of the material,
- (2) departing moist air can remove the latent heat of vaporization, and,

- (3) wetting may be a 'trigger' mechanism in spontaneous combustion by changing the heat of sorption.

Similar effects have been observed in the spontaneous heating of air-dry materials. If the material is hygroscopic, a rise in temperature will increase the concentration of water vapour in the interstitial atmosphere, causing an outward diffusion of water vapour and an inward diffusion of air. This will give the surface a higher partial pressure of oxygen while drying out the material. A higher concentration of reactant at the centre than at the perimeter is the result, enhancing the possibility of a thermal explosion.

Various methods of lowering the ignition temperature of cellulose have been examined. Walker et al.,¹¹ looked at the effect of long continued heating in dry air. They found that at temperatures between 148°C and 173°C, an early central temperature maxima was reached within two or three hours, and then increased slowly with time. This suggests that the cellulose slowly degrades to yield pyrolysis products which react exothermally with gaseous oxygen. For ambient temperatures above 182°C, the cellulose was thermally unstable and reached the ignition point.

It has been found that solid cellulose will react with oxygen at 80°C. Walker suggests that some mechanism of chain cleavage occurs, producing pyrolyzed glucose units (perhaps laevoglucosan) which reacts more quickly with gaseous oxygen.

Weatherford and Sheppard¹² have examined the temperature history curves for one-sided heating, and discovered a critical slab thickness above which the surface temperature never exceeded that corresponding to an infinitely thick slab. This suggests that for sustained ignition, the surface temperature must increase more rapidly than for an infinitely thick slab. They postulate a thermal feedback mechanism from within the slab which would alter the temperature history. A plane slab undergoing symmetrical heating will experience a heat flux on the surface of symmetry. At the same time the initial thermal energy will move back to the heated slab by means of a random self-diffusion process. Their correlated results showed that for a constant source temperature, a constant fuel-escape rate led to an approximately constant surface temperature.

Kinbara and Kawasaki¹³, in an experiment to spontaneously ignite a sphere of sawdust of 50 cm. diameter, found a critical ambient temperature of 130°C. The time for ignition was 240 hours, with the centre of the sphere remaining constant at 65°C for most of this period. They believe that this was caused by either the effects of water vapour or the absorption of heat by the decomposition of the wood.

IGNITION MECHANISMS

As stated in the previous section, the process of preheating may be either chemical, biochemical or physiochemical, or perhaps some combination of them, including the possibility of solar heating. The literature concerning these mechanisms considers preheating in wood-chip piles and hay fires, as a result of work done by both pulp and paper companies and agricultural researchers. For the purpose of a review of possible ignition mechanisms, both materials will be discussed.

(a) Wood Chips

The method of preheating in chip piles is not well defined, with various explanations being suggested, although it is most likely that a combination of processes occur. Springer and Hajny¹ have observed that chip piles usually have a centre temperature of about 140°F about two weeks after construction. This may be followed by a gradual increase over a period of several months and then a rapid temperature increase resulting in ignition. Their experimentation involving fresh-cut aspen and Douglas fir chips revealed that respiration of the living sapwood cells (mainly ray parenchyma) is the primary cause of oxygen consumption the first two days after chipping. This accounts for the initial temperature rise, with bacteria and fungi being responsible for the slow gradual increase. Blackerby (1963)¹⁴ cites studies by D.L. Brown of Portland General Electric Co. which provided evidence that tramp metals in sawdust piles may act as a catalyst for temperature increases. Deacetylation of wood has been suggested by Schmidt (1969)¹⁵ as a preheating mechanism, having observed clouds of acetic acid coming off broken-up chip piles. These piles had interior temperatures of about 165°F, which could have led to ignition of the piles had they been left alone. An analysis of a spontaneous combustion fire in a 235,000 ton chip pile at the Weyerhaeuser Company plant in Springfield, Oregon in 1966 suggested that water diffusion from wet chips to dry veneer fines caused heating, with iron salts present to catalyze the resulting exothermic oxidation⁵.

The observation of these and other observers seems to point to a combination of mechanisms, with biological reactions providing an initial temperature increase great enough to start a physiochemical process which will raise the temperature to the ignition point.

(b) Hay

The processes by which hay is preheated to a temperature capable of sustaining an oxidation reaction are basically the same as those involved in chip fires, but the contribution of each may be changed. Some researchers (Norman et al. (1941)¹⁶, Rothbaum (1963)¹⁷) believe that the temperature rise in hay is largely microbiological in origin, while others such as Milner and Geddes (1946)¹⁸ in studies of spontaneous heating in soybeans believe that an initial temperature rise of 50-55°C is caused by the actions of moulds but a secondary heating phase is caused by a non-biological oxidation, with no set temperature limit. They found that this secondary phase was paralleled by carbon dioxide evolution. Firth and Stuckey (1946)¹⁹ have observed acetic and formic acids in volatile acidity.

Walker and Harrison (1960)²⁰ have shown that, in oxidations of solid material by oxygen, the reaction rate is affected by the partial pressure of the oxygen. Wedberg and Rettger (1941)²¹, experimenting with cracked corn, found that the maximum temperature increase in a sample of about 400 gms is associated with an oxygen gas flow of between 175 mls and 225 mls per hour.

Rothbaum¹⁷ found that since moist hay cannot exceed the temperature at which its water-vapour pressure is equal to atmospheric pressure, its moisture content must be reduced to obtain temperature increases of more than 100°C. Maximum heating rates occurred at 97.5% R.H., with ignition temperatures capable of being reached. He concluded that water vapour plays an important part in all stages of spontaneous combustion mechanisms, and that microbiological mechanisms occur only within a narrow range of R.H., and lead to chemical reactions.

PHYSICAL CONDITIONS FAVORABLE FOR SPONTANEOUS HEATING

Fuels most likely to support spontaneous combustion are probably peat and dead and rotting wood or grass. In order for any heat that is generated to remain within the fuel system, there must be a sufficient depth of fuel to provide adequate insulation, the actual depth depending on the thermal conductivity of the substance being considered.

For the first heating phase, that caused by thermophilic bacteria, weather and soil conditions must be optimal for the maximum survival time of the bacteria. These initial conditions of heat and high moisture content will most likely occur in the

spring and early summer of the year. The high starting level of the water table will cause an initial high moisture content in the fuel. As the water level drops and the daily temperature increases, the fuel moisture will be reduced until the optimum level for the survival of the bacteria is reached. As long as these conditions remain favorable, the bacteria will continue to generate heat, stopping only when the temperature of their surroundings becomes too great for their survival.

It is at this point that the spontaneous heating process either continues or is ended. Normally, bacteria cannot survive at the temperatures required to initiate the pyrolysis reactions. However, if the proper physical conditions are present, then it is possible for the temperature rise to continue. This requires that the quantity of heat generated by the bacterial phase be large enough to reduce the moisture content of the material to a level which will allow the generation of heat to continue by chemical oxidation reactions. If there is sufficient oxygen available, the heat generated by these reactions will continue to dry the fuel and raise the internal temperature until the ignition point is reached.

Since it is not known at what point the conditions must change to facilitate the oxidation reactions, the necessary information must be determined experimentally. A program currently being implemented by the Forest Fire Research Institute involves the monitoring of the physical conditions at a field site considered susceptible to spontaneous heating, as well as laboratory experimentation into what conditions are most favorable for spontaneous heating.

CONCLUSIONS

This paper is intended only as a combined summary and literature review of past work which has been concerned with spontaneous heating in combustible fuels. It is the result of studies preliminary to a program of research on spontaneous combustion now underway at the Forest Fire Research Institute to investigate and reinforce the theories presented here. The theoretical reactions have been discussed, as have possible ignition mechanisms and physical conditions which are most likely to support spontaneous heating.

The thermal explosion theory of ignition, developed by Frank-Kamenetskii, is the most popular explanation of spontaneous heating, with possible preheating mechanisms being of a biochemical or chemical nature. To obtain maximum temperature in the preheating stages, and to start the oxidation reactions, proper weather and

fuel conditions are required. These requirements are probably the limiting factors for fires caused by spontaneous combustion, since they will only occur a small percentage of the time.

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