NOTE

ASSESSMENT OF THE SELF-IGNITION CONDITIONS OF FOREST LITTER DEPOSIT LAYER

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INTRODUCTION

Forest fire may be caused by a variety of agents, e.g., man-made fire, lightning. One of these, as recently confirmed by Jones *et al.* (1990, 1991) quantitatively using the oxidation kinetics of forest litter or leaves, is self-ignition of the layers of litter or leaves deposited on the forest floor. Besides oxidation, the heat which promotes the self-ignition of biological matter can come from the metabolic processes of moulds and bacteria and the hydrolysis reactions (Walker 1967).

A slab model with unsymmetrical heating profile may be used to simulate the self-heating process of a layer of dry forest litter either covering a large area of ground under the trees of a forest, or on an originally bare piece of land covered as a result of natural wind movement (*see* Fig. 1). The model is demonstrated in Fig. 2 where l is the total thickness of the slab (m), x is the distance from the top surface (the top surface being x = 0), T_h is the top surface temperature (hot), and T_c is the bottom surface temperature (cold) (at x = l). On a sunny summer day in the North Island of New Zealand, the solar radiation flux received by the flat ground is approximately 600 W/m^2 (Lovell-Smith & Baldwin 1992) and the surface temperature of the ground can be quite high. As a result of the warm ambient temperature and radiative heat flux from the sun, T_h is considered to be higher than T_c. An infinite heat sink of constant temperature as low as a few degrees Celsius, T_s, is assumed below the bottom surface (the interface between the forest litter layer and the soil surface). The ambient temperature is generally higher than T_c and lower than T_h. During the long period of deposition, under warm conditions the forest litter will be oxidised and will release heat. If

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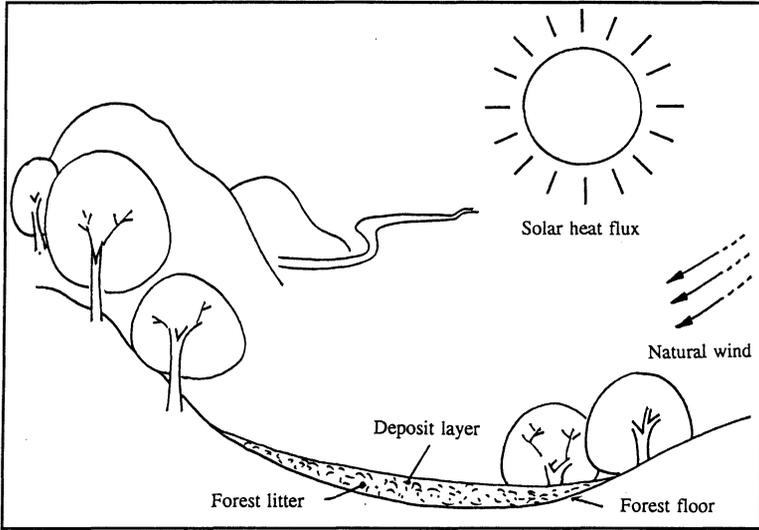* To whom correspondence should be addressed.

FIG. 1–Forest litter deposit layer and its natural environment

the heat loss to the ambient is limited, the heat generated by oxidation will accumulate and, at a certain point, the deposit will catch fire spontaneously. Under different environmental conditions, e.g., solar heat intensity, wind speed, the top and bottom surface temperatures may vary.

The fundamental equation that governs the steady-state energy balance of the reacting slab (Frank-Kamenetskii 1939) may be written as follows (Bowes 1984):

$$d^2\theta/dz^2 + \delta\,e^\theta = 0 \tag{1}$$

where   z is the dimensionless distance from the top surface of the slab and is equal to x/l
   θ is the dimensionless temperature excess and is defined as

$$\theta = E/RT_{ref}^2\,(T - T_{ref}) \tag{2}$$

and δ is the Frank-Kamenetskii (1939) parameter, which is related to the thickness of the slab and the top surface temperature, and is defined as

$$\delta = (E/RT_{ref}^2)\,(l^2\,Q\,\rho\,A/k)\,\exp(-\,E/RT_{ref}) \tag{3}$$

where   E is the activation energy and A is the frequency factor of the reaction
   R is the univeral gas constant
   Q is the heat of the reaction
   ρ is the packing density of the slab
and   k is the thermal conductivity of the slab.

T_{ref} is a reference temperature which should be chosen to be close to both the boundary temperatures and the maximum temperature in order to provide accurate results when using the Frank-Kamenetskii approach (Wake *et al.* 1992). T_{ref} was stipulated at 313 K in the current analysis.

It can be seen that this model (Equation 1) neglects the effect of the reactant consumption and the effect of moisture transfer. The former can be justified considering the high activation
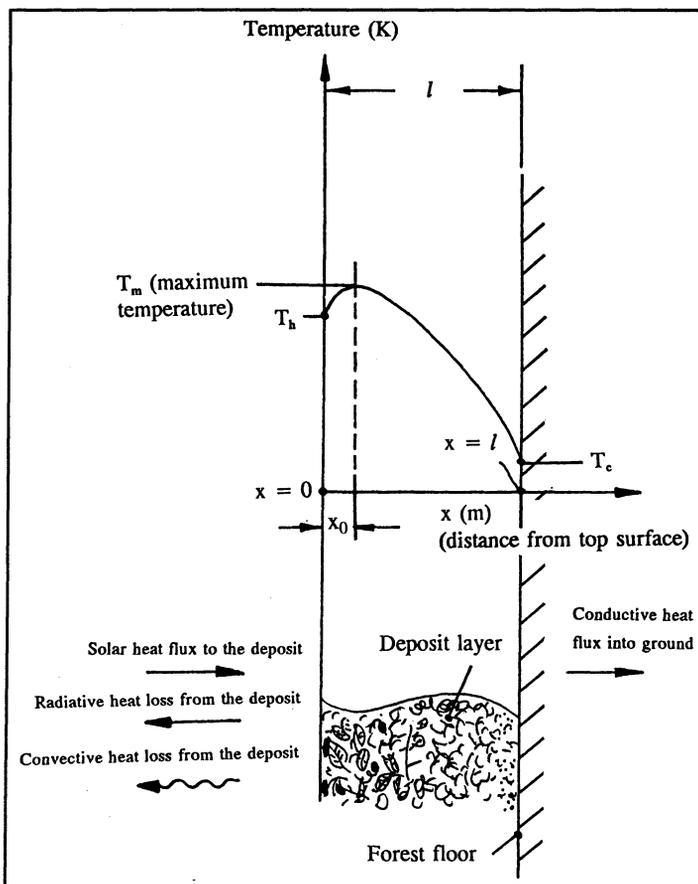
FIG.2–A slab model to simulate the forest deposit layer

energy and the large exothermicity of the reactions involved in the process of ignition of forest litter (Jones *et al.* 1991). The latter effect may be evaluated and lumped into the heat of reaction by a discounted value of the dry material (Jones *et al.* 1991). The chemical kinetics, e.g., the activation energy and the heat of reaction, are usually determined using the simple electric oven test where a certain quantity of a test sample is contained in a metal mesh cube which is placed at the centre of the oven and heated at different oven temperatures (Jones *et al.* 1990). The maximum test sample size is limited by the oven space, and lowest oven temperature for achieving ignition is usually 80°C higher than the ambient temperature in practice. The prediction of a low-temperature ignition using this model involves the extrapolation of the oxidation rate which has been shown to over-estimate the risk and therefore provides a safer measure. Nevertheless, the model presented here can serve only as a preliminary model, which has the advantage of requiring a minimum number of parameters to be determined experimentally before a prediction can be made. The model cannot be recognised as a mechanistic approach.

These kinetic parameters and the physical properties of the forest litter necessary for a prediction using Equation 1 are listed in Appendix 1.

The boundary conditions at $z = 0$ and $z = 1$, with the involvement of both radiative and convective heat transfer, may be considered to be

$$\text{at } z = 0, \ \theta = \theta_h \geq 0 \tag{4}$$

$$\text{at } z = 1, \ \theta = \theta_c < 0 \tag{5}$$

where the subscripts h and c denote the hot and cold surfaces, respectively. It can be seen that the top boundary condition is using always at a constant temperature as its complexity is not fully understood.

Equation 1 with the boundary conditions 4 and 5 can be solved analytically. The solution is given by Wake *et al.* (1992) as follows:

$$\theta(z) = \theta_m - 2 \ln \cosh \left[(\delta \, e^{\theta_m}/2)^{1/2} \, (z - z_0) \right] \tag{6}$$

The constant z_0 is determined by the boundary conditions (Equations 4 and 5). We also note that $\theta(z = z_0) = \theta_m =$ the maximum value of θ (if $0 \leq z_0 \leq 1$), where $z_0 = x_0/l$.

We can then obtain δ as a function of θ_m, θ_h, and θ_l according to Wake *et al.* (1993):

$$\delta = 2 \, e^{-\theta_m} \{ \cosh^{-1} [\, e^{(\theta_m - \theta_h)/2} \,] + \cosh^{-1} [\, e^{(\theta_m - \theta_c)/2} \,] \} \tag{7}$$

Obviously, the critical value of δ (δ_{cri}) and the critical maximum value of θ (θ_m), beyond which the temperature distribution inside the slab is no longer stable (ignition will occur), are reached when

$$d\delta/d\theta_m = 0 \tag{8}$$

By applying the appropriate physical and chemical parameters to the above equations and the different boundary temperatures, the critical thickness of the deposit layer for a fire to occur spontaneously can be calculated from Equation 3.

BASIC CALCULATIONS AND DISCUSSION

The computer software package MATLAB was used to calculate the critical value of δ using Equations 7 and 8, given the appropriate boundary dimensionless temperatures, θ_h and θ_c. These dimensionless values were then converted to the dimensional values, which are more meaningful in practice. Different combinations of the top surface temperature, T_h, and the bottom surface temperature, T_c, were used and the critical thickness of the deposit layer of the forest litter was calculated under these boundary conditions (Table 1).

TABLE 1–Maximum thickness (m) of a forest litter deposit layer under different boundary conditions

Temperature at lower (cold) surface T_c –273 (°C)	Temperature at upper (hot) surface, T_h –273 (°C)				
	20	30	40	50	60
5	8.2	4.9	2.9	1.7	1.4
10	6.6	4.0	2.4	1.4	1.1
20	4.2	2.6	1.6	1.0	0.6

As presented here, it can be seen that there is potential for the spontaneous ignition of a forest litter deposit layer if the layer thickness is greater than 0.6 m. For different types of forest litter, e.g., those that have different oil contents, the chemical and physical parameters would cause variations in the predicted critical thickness.

As indicated earlier in this Note, the model is intended to quantify the actual process using a limited number of parameters and it does not describe in any great detail the mechanism of the self-ignition of natural biological matters. This Note serves only as a preliminary attempt to demonstrate the magnitude of the problem. Understanding of the detail of the chemistry and the physics involved in the process is essential for interpreting precisely the predicted results and also for improving the mathematical model to be able to describe both the composition effect and the effect of moisture transfer. To this end, studies could be carried out in a manner similar to those on self-ignition of coal by Chen (1991, 1992), Stott & Chen (1991), and Chen & Stott (1992, 1993).

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APPENDIX 1

CHEMICAL AND PHYSICAL PROPERTIES USED IN THIS STUDY

In this study, the forest litter was assumed to have a certain oil content. The activation energy, E, was taken as 70 kJ/mol dry solid, which is broadly consistent with the values in the literature for the oxidative degradation of biopolymers (Bolland 1949; Howard & Malook 1987; Jones *et al.* 1991). The heat of reaction, Q, was assumed to be 11×10^3 kJ/kg dry solid and the reaction frequency factor, A, was taken as 69.6 s^{-1} according to Jones *et al.* (1991). The packing density of the deposit layer, ρ, was assumed to be 120 kg/m³. The thermal conductivity, k, was taken as 0.072 $W/m^2.K$ and was obtained from heat transfer measurements on live vegetation (Jones 1990; Jones *et al.* 1991).