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Pyrolysis of Vegetation by Brief Intense Irradiation

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When nonreflected intense visible radiation, of about 4 x 10^6 J/(m^2-s), is incident on a dense vegetative layer (~3-kg/m^2 loading, 0.3-m height) for even a second or two, the absorbing leafy matter can be desiccated and gasified. Simple unsteady one-dimensional models are formulated and solved to characterize the rate of propagation earthward of the pyrolysis front, at which the vegetative population under consideration totally disappears. Distinct treatments are undertaken for 1) temperate-cereal-like layers which contain only "foliage" (hay, wheat, grass); and 2) brush-like layers, in which not only effectively pyrolyzable leafy matter, but also partially pyrolyzable woody-stem matter exist. Qualitative remarks consider soot formation in the pyrolyzate and/or combustion of the hydrocarbon-vapor pyrolyzate with interstitial air.

Nomenclature

$\bar{a}$ = assigned positive constant, Eq. (33)
b = assigned positive constant, Eq. (31)
c_a = specific heat capacity at constant pressure of ambient air
c_s = specific heat capacity at constant pressure of steam
c_v = specific heat capacity of organic matter prior to pyrolysis
c_w = heat capacity of the water content of the vegetation
$d(y, t)$ = effective diameter of the foliage
$d^{(0)}(y)$ = initial effective diameter of the foliage
$E(y, t)$ = energy flux (energy/area/time)
$E^{(0)}(t)$ = energy flux at the top of the vegetation
h = enthalpy per volume of space
i = discrete index for the spatial coordinate y
j = discrete index for time t
L = depth of the vegetative layer ($L > 0$)
L_e = latent heat of vaporization of water (at the boiling temperature)
M = assigned positive integer, Eq. (25a)
m = integer in a sequence
$n(y)$ = number of biological entities per unit cross-sectional area at position y
$Q(y)$ = heat required to pyrolyze the vegetation initially contained in a unit volume at position y
$Q_c(y)$ = enthalpy per unit volume required for desiccation and pyrolysis of foliage
$Q_v(y)$ = enthalpy per unit volume required for desiccation and pyrolysis of pyrolyzable woody matter
$S(y, t)$ = extinction coefficient, Eq. (16a)
T_a = ambient temperature
T_e = normal boiling temperature of water
T_p = temperature at which pyrolysis of vegetation is complete
$T(y, t)$ = temperature
t = time since onset of irradiation
t_f = temporal interval of irradiation
$t^*(y)$ = inverse function of $y^*(t)$
t_0 = $t^*(0)$
t_1 = time at which all the foliage at $y = 0$ is pyrolyzed
t_2 = time at which all the pyrolyzable woody-stem matter at $y = 0$ is pyrolyzed
$V(y, t)$ = fraction of volume occupied by leafy vegetation
$V^{(0)}(y)$ = initial fraction of volume occupied by leafy vegetation
$W(y, t)$ = fraction of volume occupied by the pyrolyzable portion of the woody-stem matter
$W^{(0)}(y)$ = initial fraction of volume occupied by the pyrolyzable portion of the woody-stem matter
$\bar{W}^{(0)}(y)$ = fraction of the volume occupied by the nonpyrolyzable portion of the woody-stem matter
$x(y)$ = ratio of the water content to the oven dry weight for the organic matter
y = vertical coordinate ($y = 0$ is the top of the vegetative layer)
$y^*(t)$ = depth to which pyrolysis of the vegetation is complete
$y_1(t)$ = locus delimiting the time-space domain for which $V(y, t) > 0$
$y_2(t)$ = locus delimiting the time-space domain for which $W(y, t) > 0$
α = parameter describing the obliquity of the biological entities to the incident radiation
$\bar{\alpha}(y)$ = extinction coefficient for radiation owing to foliage in a mixed vegetative layer
β = extinction coefficient for radiation in a uniform leafy layer
$\bar{\beta}(y)$ = extinction coefficient for radiation owing to woody-stem matter in a mixed vegetative layer
Γ = assigned positive integer, see Eq. (28)
γ = parameter describing obliquity of biological entities to the vertical
ρ_a = density of ambient air
ρ_v = initial mass of organic matter per volume occupied by organic matter
$\Sigma(y)$ = thermal inertia of nonpyrolyzable woody matter

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I. Introduction

IN the aftermath of a thermonuclear explosion in the lower atmosphere, thermal radiation precurses blast arrival. Under some conditions the radiation creates a near-ground "thermal layer," in which the sound speed is augmented above that of the ambient atmosphere.[1] Such a stratification has practically significant consequences for the structure of the later-arriving blast wave. In turn, the modified structure results in appreciable alteration in the extent of scouring of dust and in the magnitude of forces on objects (e.g., vehicles). For vegetation-free ground, primarily the phase change of soil moisture is responsible for the depth and properties of the thermal layer.[2] The thermal-layer effect typically is augmented by the presence of vegetation because much of the heat that reaches unvegetated soil remains in the soil, and only a fraction produces rising steam; with vegetation, more of the heat is absorbed by the above-ground vegetation and never reaches the soil. Here we examine the above-ground temperature increase, and hence, augmented thermal-layer effect, owing to vegetation and its pyrolytic response to the incident radiation.

Some models (e.g., Bush and Small[3]) of the response of a vegetative layer to brief intense irradiation by visible light (such as that associated with a nuclear weapon) do not account for the possible onset of a pyrolysis front that then propagates with time through the vegetative layer toward the soil beneath. This pyrolysis may substantially alter the response, because the pyrolyzate generally is hydrocarbon-like vapor that absorbs mainly in the infrared,[4] whereas, leafy matter absorbs mainly in the visible.[5] We here consider three simple models of the phenomenon; each model is of unsteady one-dimensional character, and such models imply a horizontally uniform stand.

The first two models, one more rudimentary than the other, attempt to describe the phenomena in a temperate cereal-like field (e.g., hay, grass, or wheat), in which no residual stem structure remains after the leafy matter is pyrolyzed. The third model undertakes to describe the response of brush, in which possibly charred stem matter persists (at least for a while) after the leafy matter is gasified.

We do not include the processes either of the possible burning of the pyrolyzate with air or of the possible formation of soot (carbonaceous particulate) in any of the cases. In a concluding section we briefly comment on how such processes might modify results obtained from the models. Also, we do not consider the interaction of the nonreflected incident radiation with the soil supporting the vegetation, an important consideration in the case of sparse or nonexistent vegetation.[2]

Finally, Ross[5] develops models in terms of the foliage area density (area of foliage per volume of stand), and of the cumulative leaf area index, a particular integral of the foliage area density over height in the stand. We prefer to develop models in terms of the volumetric fraction of the vegetative layer occupied by vegetation, and of particular integrals over height of the volumetric fraction. The models introduced here are highly simplified with respect to both the geometric details of the vegetative structure and the interaction of radiation with that structure. The lack of sophistication has the advantage that the analysis is appreciably shortened. Also, results are not tied to details of the vegetation which are normally unavailable, because knowledge of such details requires meticulous inventorying. We envision a broad-area, rather uniform stand of vegetation of modest height. For such a disclike geometry, radiation scattered from an incident "pencil" of radiation into a neighboring pencil is likely to be compensated for by radiation scattered from the neighboring pencil into the pencil under examination. Therefore, we concentrate on radiative absorption.

A radiative flux of 4×10^6 J/(m^2-s) is a factor of about 5×10^3 times the direct solar flux on a surface normal to the Sun's rays at the Earth's surface on a cloudless winter day, for 45-deg solar altitude.[6] The radiation pressure associated with the solar flux is about 4×10^{-6} Pa; thus, the radiation pressure associated with the flux of interest here is about 2×10^{-2} Pa, whereas normal atmospheric pressure is about 10^5 Pa.

The authors have found no data in the unclassified literature with which to compare the models to be presented, and perhaps these notes can helpfully guide an experimental simulation, e.g., with a solar furnace.[6]

II. First Model for Temperate Cereal-Type Vegetation

When vegetation is irradiated by the radiative-energy precursor from a nuclear weapon, the energy received per unit horizontal area per unit time can be calculated from known weapon characteristics and from postulated height of burst, as a function of distance from ground zero by taking account of the obliquity of the rays at each such distance.[1] We shall denote by $E^{(0)}(t)$ the pertinent fraction of the energy flux (energy/area/time) at the top of the vegetation. Depending again on the obliquity, the attenuation at a given time of that flux with distance below the vegetation top can be characterized (approximated) by

$$E_y(y, t) = [V(y, t)/V^{(0)}]\beta E(y, t) \tag{1}$$

where, clearly, β is the reciprocal e-folding distance into the vegetation that is associated with the absorption of radiation of the appropriate spectral content in vegetation having a fractional volume occupancy $V^{(0)}$. $V(y, t)$ is the "solidity" (i.e., the fraction of the volume) at level y and at time t consisting of vegetation, which may undergo pyrolysis. Initially $y = 0$ is the top of the vegetative layer, and $y = -L$, $L > 0$, the bottom. $t = 0$ is the onset of irradiation.

The rate of increase of the enthalpy per unit volume of space $h(t)$ owing to absorption by the vegetation, is consequently, because of Eq. (1)

$$h_t(y, t) = [V(y, t)/V^{(0)}]\beta E(y, t) \tag{2}$$

provided that we ignore the small fraction of the radiation backscattered into the atmosphere.

We shall adopt as a suitable model of the evolving geometry of the vegetation, one that postulates no change in the radiative absorption of a piece of vegetation until all of the pyrolysis of that piece has been completed, at which time that portion of the plant ceases to absorb any radiation. We let

$$y = y^*(t) \tag{3}$$

denote the depth into the vegetation to which the pyrolysis-completion interface has penetrated at t. With that notation, for a vertically uniform stand

$$V = \begin{cases} V^{(0)} & \text{in} \quad y < y^*(t) \\ 0 & \text{in} \quad y > y^*(t) \end{cases} \tag{4}$$

We also introduce the notation wherein the time at which the pyrolysis interface is at y is denoted by

$$t = t^*(y) \tag{5}$$

and wherein the enthalpy per unit volume of space that is required to pyrolyze all of the vegetation in that unit volume is denoted by

$$h_{\text{pyrolyzation}} = Q \tag{6}$$

The (given) enthalpy for pyrolysis of the vegetation initially contained in a unit volume Q includes both preheating to the pyrolysis temperature and drying (the latent heat for fuel pyrolysis ordinarily being negligible). Using Eqs. (3), (4), and (6), we integrate Eq. (2) to obtain, if the enthalpy under ambient conditions is taken to be zero

$$h(y, t) = \int_0^t \beta E(y, t_1)\, \mathrm{d}t_1 \quad \text{in} \quad t < t^*(y) \tag{7}$$

In particular

$$Q = \int_0^{t^*(y)} \beta E(y, t_1)\, \mathrm{d}t_1 \tag{8}$$

We can now interpret Eq. (1) to obtain

$$E(y, t) = \begin{cases} E^{(0)}(t) & \text{in} \quad y \geq y^*(t) \\ E^{(0)}(t)\exp\{\beta[y - y^*(t)]\} & \text{in} \quad y \leq y^*(t) \end{cases} \tag{9a}$$

Note that the irradiation of the ground[3] is given by

$$E(-L, t) = \begin{cases} E^{(0)}(t) & \text{in} \quad t \geq t^*(-L) \\ E^{(0)}(t)\exp\{-\beta[L + y^*(t)]\} & \text{in} \quad t < t^*(-L) \end{cases} \tag{9b}$$

From Eqs. (8) and (9a)

$$Q = \beta \exp(\beta y) \int_0^{t^*(y)} E^{(0)}(t_1)\exp[-\beta y^*(t_1)]\, dt_1 \tag{10}$$

We now differentiate Eq. (10) with respect to y and obtain

$$0 = \beta^2 \exp(\beta y) \int_0^{t^*(y)} E^{(0)}(t_1)\exp[-\beta y^*(t_1)]\, dt_1$$

$$+ \beta \exp(\beta y) \frac{dt^*(y)}{dy} E^{(0)}[t^*(y)]\exp\{-\beta y^*[t^*(y)]\} \tag{11}$$

Hence

$$0 = Q + E^{(0)}[t^*(y)] \frac{dt^*(y)}{dy}$$

Since

$$\frac{dt^*(y)}{dy} = \frac{1}{dy^*(t)/dt}, \qquad \frac{dy^*(t)}{dt} = -\frac{E^{(0)}(t)}{Q} \tag{12}$$

We find an initial condition for Eq. (11) by noting that there is an earliest time $t^*(0)$ for which, at $y = 0$, according to Eq. (8)

$$Q = \int_0^{t^*(0)} \beta E(0, t_1)\, dt_1 \tag{13}$$

Prior to that time, y^* is zero and the right side of Eq. (8) is meaningless. Accordingly, Eq. (13) defines the time $t^*(0) = t_0$ such that

$$y^*(t) = \begin{cases} 0 & \text{in} \quad t \leq t_0 \\ -\displaystyle\int_{t_0}^{t} \frac{E^{(0)}(t_1)}{Q}\, dt_1 & \text{in} \quad t \geq t_0 \end{cases} \tag{14}$$

Note that the pyrolysis-front position $y^*(t)$ is independent of the absorptive parameter β, except for the definition of time t_0. The absorption by the remaining vegetation is not germane to the progression of the front except for identifying the value of t_0. Note also that the trajectory of the pyrolysis interface in the y-t plane depends on the orientation of the light rays only through the fact that $E^{(0)}(t)$ depends on that orientation.

The idealizations in the formulation have permitted a closed-form solution (reduction to quadratures). With a facile, preliminary characterization of the cereal-layer response so provided, a slightly more detailed model requiring numerical treatment is developed in the next section.

III. Alternate Model for Temperate Cereal-Type Vegetation

We now consider a model that accounts for the possible variation in properties of the vegetative layer with depth, and that accounts for a fractional decrease of the extinction coefficient at a site with the decrease of the characteristic diameter of the vegetation at that site.

We characterize the vegetation in a little more detail by introducing $n(y)$, the (average) number of entities (such as twigs, leaves, etc.), per unit area, that penetrate the plane at coordinate y, and by retaining $V(y, t)$, the time-varying fraction of the volume at y in a slice of thickness δy that is occupied by vegetation. We also need two orientation parameters in this characterization. One, γ, describes the obliquity of the biological entities relative to the vertical; explicitly, $\gamma = \sec \theta$, where θ is the polar angle, with vertically upwards being the initial ray, and attention is limited to small values of θ. The other orientation parameter, α, describes the obliquity of those leaves to the rays of the incoming radiation, and therefore, depends on the height of burst $\bar{b}$ and the range from the hypocenter r; explicitly, $\alpha = r/(\bar{b}^2 + r^2)^{1/2}$.

We define an effective (time-varying) diameter $d(y, t)$ for the foliage at y by

$$V(y, t) = \gamma \pi n(y) d^2(y, t)/4 \tag{15}$$

and it follows that the fraction of the radiation that is intercepted at y in a slice δy is

$$\frac{\delta E(y, t)}{E(y, t)} = S(y, t)\delta y, \quad S(y, t) = \alpha n(y) d(y, t) \tag{16a}$$

so the rate at which energy is removed from the radiative flux per unit volume is

$$E_y(y, t) = S(y, t)E(y, t) \tag{16b}$$

The wavelengths of the radiation are taken to be so much smaller than the dimension of the foliage over the preponderance of the irradiation that this geometric-optics model suffices.

Furthermore, the volume fraction $V(y, t)$ decreases with time according to the energy balance

$$V_t(y, t) = -S(y, t)E(y, t)/Q(y) \tag{17}$$

where $Q(y)$ is the heat required to "process" the vegetation initially contained in a unit volume at level y. Substitution of Eqs. (15) and (16a) in Eq. (17) gives

$$d_t(y, t) = -[2\alpha/(\pi\gamma)][1/Q(y)]E(y, t) \tag{18}$$

Thus, for given $Q(y)$, $n(y)$, α, and γ, Eqs. (16b) and (18) are two equations for the two dependent variables $E(y, t)$, $d(y, t)$ over the domain $-L \leq y \leq 0$, $t \geq 0$. The boundary condition and the initial condition are (Fig. 1)

$$d(y, 0) = d^{(0)}(y), \quad \text{given} \tag{19}$$

$$E(0, t) = E^{(0)}(t), \quad \text{given} \tag{20}$$

From Eqs. (18) and (20)

$$d(y, t) = d^{(0)}(y) - \frac{2\alpha}{\pi\gamma} \frac{1}{Q(y)} \int_0^t E(y, t_1)\, dt_1 \tag{21}$$

The onset of pyrolysis occurs at time t_0, where t_0 is the minimum value of t compatible with

$$d(0, t_0) = 0 \tag{22a}$$

Hence, t_0 is given implicitly by

$$\frac{\pi\gamma}{2\alpha} Q(0)d^{(0)}(0) = \int_0^{t_0} E^{(0)}(t_1)\, dt_1 \tag{22b}$$

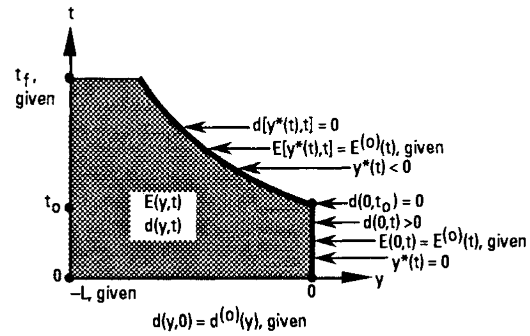

Fig. 1 Over the shaded domain, solution is sought for the radiative flux $E(y, t)$ and the typical "leaf" dimension $d(y, t)$, for an intensely irradiated temperate cereal-type vegetative layer. The time of onset of pyrolysis t_0, and the subsequent position of the pyrolysis front $y^*(t)$, are to be found as part of the solution.

The pyrolysis-front locus $t^*(y)$ is given by

$$0 = d^{(0)}(y) \frac{2}{\pi} \frac{\alpha}{\gamma} \frac{1}{Q(y)} \int_0^{t^*(y)} E(y, t_1)\, \mathrm{d}t_1 \tag{23}$$

for $t > t_0$, where, of course, $y^*(t_0) = 0$. The diameter $d(y, t) = 0$ for $y^*(t) \le y \le 0$ for $t \ge t_0$, and is given by Eq. (21) for $-L \le y < y^*(t)$ for $t \ge t_0$. Thus, one has a fixed domain, in which Eq. (21) gives $d(y, t)$, for $-L \le y \le 0$ for $0 < t \le t_0$, but one has a moving-boundary problem for $t > t_0$ over the domain $-L \le y \le y^*(t)$. From Eqs. (16a) and (16b)

$$E(y, t) = \begin{cases} E^{(0)}(t) & \text{in } \; y^*(t) \le y \le 0 \\ E^{(0)}(t)\exp\left[\alpha \int_{y^*(t)}^{y} n(y_1) d(y_1, t)\, \mathrm{d}y_1\right] & \text{in } \; -L \le y \le y^*(t) \end{cases} \tag{24}$$

where, again, $y^*(t) = 0$ for $0 \le t \le t_0$, and, again, the flux reaching the soil, $E(-L, t)$, is of particular interest.[2]

The numerical treatment of Eqs. (21–24) is straightforward, and a few remarks suffice to delineate the particular procedures adopted here. A rectangular grid is adopted in (y, t) space; i.e., $E(y, t) \equiv E(y_i, t_j) = E_{i,j}$ and $d(y, t) \equiv d(y_i, t_j) = d_{i,j}$, where, for (specified) positive integer M

$$y_i = -(i - 1)(\Delta y), \quad i = 1, 2, \ldots, M + 1; \quad \Delta y = (L/M) \tag{25a}$$

$$t_{j+1} > t_j, \quad t_1 = 0 \tag{25b}$$

One first solves Eq. (22b), with the aid of Eqs. (19) and (20), to obtain t_0, as defined in Eq. (22a). From Eqs. (19) and (24), one obtains $E_{i,1}$ for all i. For each successive $j(>1)$, one may obtain solution over all i by iteration of the following difference equations based on the trapezoidal rule:

$$E_{i,j}^{(m)} = E_{i-1,j} \exp\{\alpha[(y_i - y_{i-1})/2][n_i d_{i,j}^{(m-1)} + n_{i-1} d_{i-1,j}]\} \tag{26}$$

$$d_{i,j}^{(m)} = d_{i,j-1} - [2\alpha/(\pi\gamma Q_i)][(t_j - t_{j-1})/2][E_{i,j}^{(m)} + E_{i,j-1}] \tag{27}$$

where $Q(y) \equiv Q(y_i) = Q_i$ and $n(y) \equiv n(y_i) = n_i$. We let $E_{i,j}^{(1)} = E_{i,j-1}$ so $d_{i,j}^{(1)}$ immediately available, and iteration proceeds ($m = 2, 3, 4, \ldots$) until some criterion for the effective invariance of successive iterates is satisfied, and convergence is taken to have been achieved. The increment $(t_j - t_{j-1})$ for $j = 2, 3, \ldots, \Gamma + 1$, depends on the desired temporal resolution (in the interval $0 \le t \le t_0$) of the solution, as reflected in the choice of Γ, where $d_{1,\Gamma+1} = 0$, i.e., $t_0 \equiv t_{\Gamma+1}$. For $j = \Gamma + 2, \Gamma + 3, \ldots, \Gamma + M + 1$, i.e., for $t > t_0$

$$d_{i,j} = 0, \quad E_{i,j} = [E^{(0)}]_j, \quad i = 1, 2, 3, \ldots, (j - \Gamma) \tag{28}$$

From Eq. (23), or, more directly, from its differenced form [essentially Eq. (27)]

$$d_{j-\Gamma,j} = d_{j-\Gamma,j-1} - [\alpha/(\pi\gamma Q_{j-\Gamma})](t_j - t_{j-1})(E_{j-\Gamma,j} + E_{j-\Gamma,j-1}) \tag{29a}$$

or

$$0 = d_{j-\Gamma,j-1} - [\alpha/(\pi\gamma Q_{j-\Gamma})](t_j - t_{j-1})\{[E^{(0)}]_j + E_{j-\Gamma,j-1}\} \tag{29b}$$

one may solve for $(t_j - t_{j-1})$, since all the other quantities are available either as input or from previous calculation at time t_{j-1} with Eqs. (26) and (27). Higher resolution of the free-boundary (pyrolysis-front) progression in time for $t > t_0$ is accessible by assignment of a larger value for the parameter M.

IV. Illustrative Calculations for the Alternative Model

For ease of reference, except as explicitly noted, all quantities take on their nominal assignment in the calculations to be reported. These nominal assignments, typical of a wheat or hay field, are as follows (where the time domain of interest is $0 \le t \le t_f$):

$$\alpha = 1, \quad \gamma = 1, \quad L = 0.333 \text{ m} \tag{30}$$

$$n(y) = b[1 + 0.75(y/L)], \; 1/\text{m}^2 \tag{31}$$

$$d^{(0)}(y) = [1 - 4(y/L)]/10^3, \text{ m} \tag{32}$$

$$E^{(0)}(t) = \begin{cases} 6\bar{a}(t/t_f)[1 - (t/t_f)], & \text{J/(m}^2\text{-s), parabolic flux} \\ \bar{a}, & \text{J/(m}^2\text{-s), const flux} \end{cases} \tag{33}$$

A series of values will be assigned to the parameters b and $\bar{a}$, but, as a general guide, the following may be useful: $b = 10^4/\text{m}^2$ characterizes a relatively heavy loading, and $b = 10^3/\text{m}^2$, a relatively lightloading; $\bar{a} = 4 \times 10^6$ J/(m^2-s). This value for $\bar{a}$ is typical of the radiation incident on the earth a few kilometers from the hypocenter of a low-altitude burst of a large nuclear weapon ($\sim 4 \times 10^{15}$ J, or the equivalent energy yielded by explosion of a megaton of TNT). Also, we take $t_f = 2$ s. Further

$$Q(y) = \rho_a c_a (T_p - T_a)[1 - V^{(0)}(y)] + \rho_v\{[c_w(T_e - T_a) + L_e]x(y) + c_v(T_p - T_a)\}V^{(0)}(y) \tag{34}$$

where the initial solidity $V^{(0)}(y)$, the complement of the porosity, is given by Eq. (15) with $d(y, 0)$ given by Eqs. (19) and (32), and the other parameters are as follows: $\rho_a = 1.18$ kg/m^3, $c_a = 1.01 \times 10^3$ J/(kg-K), $T_p = 700$ K, the ambient temperature of the vegetative layer $T_a = 300$ K, $c_w = 4.18 \times 10^3$ J/(kg-s), $T_e = 373$ K, $L_e = 2.26 \times 10^6$ J/kg, $c_v = 2.01 \times 10^3$ J/(kg-K), the (true) density of the vegetative-layer organic matter (prior to pyrolysis) $\rho_v = 0.92 \times 10^3$ kg/m^3, and $x(y)$ is typically a small fraction for dead vegetation and often roughly near unity for live vegetation. Any water content boils off and presumably rises from the vegetative layer before the onset of pyrolysis; this ascending steam may condense upon mixture with ambient air, but, in any event, no steam is expected to linger in the layer, and so there is no term $c_s(T_p - T_e)$ to be added to the factor multiplying $x(y)$ in Eq. (34), where c_s is the specific heat capacity of steam at constant pressure.

For purposes of characterizing the above-listed parametric assignments, it may be noted that, for the heavy loading ($b = 10^4/\mathrm{m}^2$), the effective extinction coefficient holding initially at the surface of the vegetative layer $S(0, 0) = 10/\mathrm{m}$, a value roughly 1% of the corresponding extinction coefficient for visible light in many soils. If this value for $S(0, 0)$ held over the entire nominal depth ($L = 0.33$ m), then the magnitude of the flux at the bottom of the vegetative layer $E(-L, 0)$ would be reduced by a factor of about $1/e^3$ from the value holding at the top of the layer. Since $\rho_v = 10^3$ kg/m^3, $V = 0.01$, and $L = 0.33$ m, the product of these three factors gives the fuel loading to be roughly 3 kg/m^2, a heavy loading of thin "fuel," comparable to that in coniferous stands in rural Ontario, Canada. Alternatively, if $b = 10^3/\mathrm{m}^2$, both the characteristic extinction coefficient and the loading would be reduced by an order of magnitude, i.e., would be reduced to values more typical of Montana cropland. The heat of pyrolysis of heavy dry ($b = 10^4/\mathrm{m}^2$, $x = 0$) vegetation $Q = 8 \times 10^6$ J/m^3, or crudely 2.7×10^6 J/m^2 over the depth ($L = 0.33$ m) of the layer; the radiative flux $\bar{a} = 4 \times 10^6$ J/(m^2-s) exceeds this requirement.

Results presented in Figs. 2 and 3 suggest that, for given fluence over the interval $0 < t < t_f$, the sensitivity of vegetative-layer response to moderate variations in the flux history is not great. In Fig. 2, the termination of the curves prior to $t_f = 2s$ is owing to the propagation of the pyrolysis front $y^*(t)$ to the position $-L$, i.e., to the soil. For later time, $E(-L, t) = E^{(0)}(t)$, and is not plotted. The layer depth L is recalled to be 0.333 m (see Fig. 3). The results in Figs. 4 and 5 indicate greater sensitivity to moisture content of the vegetation, especially at higher vegetative loadings. While the optical-extinction coefficient S is linearly proportional to the areal number density n and to the typical element thickness d, the solidity V is quadratically proportional to d and only linearly proportional to n; however, Figs. 6 and 7 suggest that the distinction in pyrolysis-enthalpy requirement owing to moderate differences in even $d^{(0)}(y)$ accounts for little change in the pyrolysis-front propagation. Thus, it is not surprising to learn that holding the parameters for the nominal case fixed, but varying the pyrolysis temperature T_p from 525 to 875 K, and/or varying the vegetative-layer depth from 0.25 to 0.41 m, also results in a small variation in the temporal interval required for pyrolysis-front propagation through the

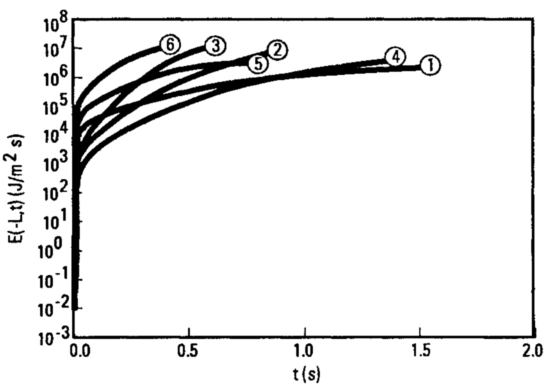

Fig. 2 For the nominal case [$t_f = 2$ s, $b = 10^4/\mathrm{m}^2$, $x(y) = 1$], the radiative flux at the soil surface $E(-L, t)$ is presented for the following six cases: cases 1, 2, and 3 entail the parabolic incident-radiative-flux profile of Eq. (33) with $\bar{a} = 2 \times 10^6$, 4×10^6, and 8×10^6 J/(m^2-s), respectively; cases 4, 5, and 6 entail the constant profile of Eq. (33) with the same sequential assignments for the parameter $\bar{a}$.

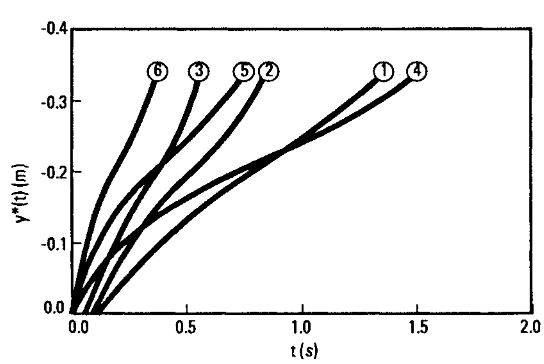

Fig. 3 Companion presentation for Fig. 2, the pyrolysis-front position $y^*(t)$ is presented. For case 1, $t^*(0) = 0.116$ s, whereas, for case 6, $t^*(0) = 0.00487$ s, where $t^*(0)$ is the time of onset of pyrolysis at the top of the ambient vegetative layer $y = 0$.

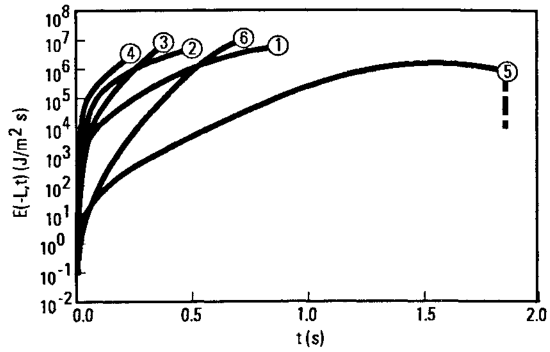

Fig. 4 For the parabolic-flux profile with $t_f = 2$ s and $\bar{a} = 4 \times 10^6$ J/(m^2-s), the soil-surface radiative flux $E(-L, t)$ is presented for the following six cases: cases 1, 3, and 5 all entail water-content ratio $x(y) = 1$, but ambient, topmost, leafy-areal-number-density value $b = 10^4/\mathrm{m}^2$, $5 \times 10^3/\mathrm{m}^2$, and $2 \times 10^4/\mathrm{m}^2$, respectively; cases 2, 4, and 6 all entail water-content ratio $x(y) = 0$, with b taking on the same succession of values as in cases 1, 3, and 5.

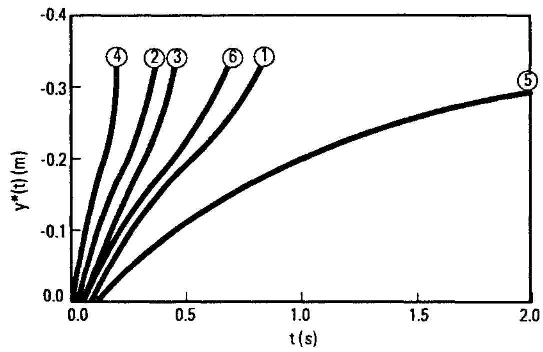

Fig. 5 Companion presentation of pyrolysis-front position $y^*(t)$ for the cases examined in Fig. 4. Case 5 entails sufficiently dense and wet vegetation that the pyrolysis front does not propagate to the soil surface within the interval of irradiation ($t_f = 2$ s).

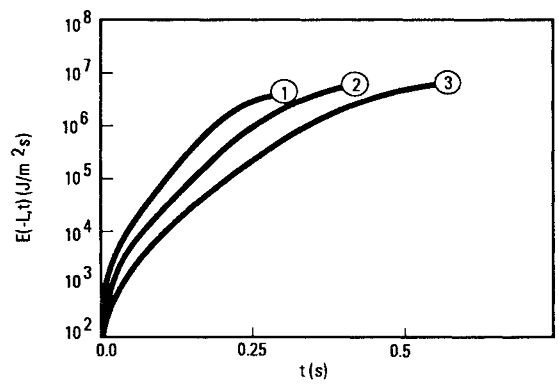

Fig. 6 For the parabolic-flux profile with $t_f = 2$ s, $\bar{a} = 4 \times 10^6$ J/(m^2-s), $b = 10^4/\mathrm{m}^2$, and $x(y) = 0$, the soil-surface radiative flux $E(-L, t)$ is presented for the following three cases: $d^{(0)}(y) = [1 - n(y/L)]/10^3$ in meters, where $n = 3$, 4, and 5 in cases 1, 2, and 3, respectively.

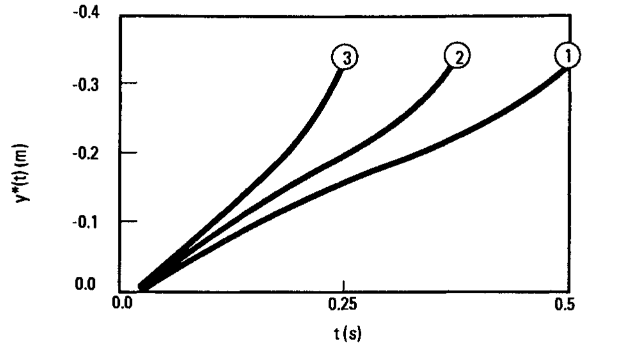

Fig. 7 Companion presentation of the pyrolysis-front position $y^*(t)$ for the cases examined in Fig. 6.

layer. The flux, loading, and moisture content are the major factors in cereal-type vegetative-layer response to irradiation.

V. Model for Brush-Type Vegetation

We outline a three-population-type model involving a volume fraction $V(y, t)$ for the leafy matter, a volume fraction $W(y, t)$ for the pyrolyzable portion of the woody-stem matter, and a volume fraction $\bar{W}^{(0)}(y)$ for the nonpyrolyzable portion of the woody-stem matter, in a vegetative layer initially lying in the region $-L \le y \le 0$, where again $y = 0$ is the top of the layer. Of interest is the radiative flux $E(y, t)$ during the temporal interval $0 \le t \le t_f$, where $t = 0$ is defined to be the onset of irradiation [such that, if $E(0, t) \equiv E^{(0)}(t)$, with $E^{(0)}(t)$ given, then $E^{(0)}(0+)$ and/or $E_t^{(0)}(0+)$ is finite]. Of course, the ambient profiles $V(y, 0) = V^{(0)}(y)$, $W(y, 0) = W^{(0)}(y)$, and $\bar{W}^{(0)}(y)$ also are given (see Fig. 8).

The model of pyrolysis both of the leafy matter and of the pyrolyzable woody matter is similar to that formulated in Sec. III, although we do not here introduce the constituent factors whose product is the volume fraction. The model of radiative absorption by vegetation recalls the formulation of Sec. II: no change in the radiative absorption by a vegetative population at a site occurs until the time at which all of the possible pyrolysis of that population has been completed at the site. At that time, that population ceases to absorb any radiation. However, the nonpyrolyzable portion of the woody-stem matter is taken to become char (as opposed to pyrolyzate) upon being heated (simultaneously with the colocated pyrolyzable woody-stem matter) to the pyrolysis temperature. Under local circumstances in which the fuel vapor from the leafy matter and from the pyrolyzable woody-stem matter are no longer present to absorb the radiation, the nonpyrolyzable woody-stem matter (char) can continue to absorb; this local absorption is reflected, then, not in phase transition (by definition), but in local temperature rise.

If one considers the degenerate case of an absence of woody-stem matter, whether pyrolyzable or not, then this brush-type-vegetation model recovers the properties of the model introduced in Sec. II, although the model here permits variation of vegetative-layer properties with depth, whereas the model in Sec. II pertains only to those vegetative layers with properties that are invariant with depth. Since it is straightforward to consider cases in which any subset of the three populations (foliage, pyrolyzable stems, and nonpyrolyzable stems) is present, discussion from here on is limited to the case in which all three populations initially are present.

The problem may be posed as follows (see Fig. 8):

$$E_y(y, t) = \begin{cases} [\bar{\alpha}(y) + \bar{\beta}(y)]E(y, t) & \text{where } V(y, t),\ W(y, t) > 0 \\ [\bar{\beta}(y)]E(y, t) & \text{where } V = 0,\ W \text{ and/or } \bar{W}^{(0)} > 0 \end{cases} \tag{35}$$

$$V_t(y, t) = -[\bar{\alpha}(y)/Q_v(y)]E(y, t) \quad \text{where } V(y, t) > 0 \tag{36}$$

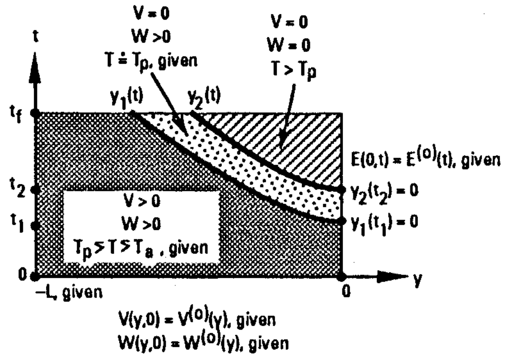

Fig. 8 For a brush-type vegetative layer, the volume fraction of foliage is $V(y, t)$, the volume fraction of pyrolyzable matter from twigs is $W(y, t)$, and the temperature is $T(y, t)$.

$$W_t(y, t) = -[\bar{\beta}(y)/Q_c(y)]E(y, t) \quad \text{where } W(y, t) > 0 \tag{37}$$

$$T_t(y, t) = -[\bar{\beta}(y)/\Sigma(y)]E(y, t) \quad \text{where } V,\ W = 0,\ \bar{W}^{(0)}(y) > 0 \tag{38}$$

Here, $\bar{\alpha}(y)$ is the (given) extinction coefficient owing to the presence of foliage, and $\bar{\beta}(y)$ is the (given) extinction coefficient owing to the presence of woody-stem matter, pyrolyzable or not; $Q_v(y)$ is the (given) enthalpy requirement per unit volume for desiccation and pyrolysis of the foliage, and $Q_c(y)$ is the (given) analogous quantity for pyrolyzable woody matter; $T(y, t)$ is the temperature, examined only in the domain in which nonpyrolyzable woody matter exists but foliage and pyrolyzable woody matter does not, and $\Sigma(y)$ is the (given) thermal inertia of the matter in that domain. The locus $y_1(t)$, to be found, delimits the domain in which $V(y, t) > 0$, where $y_1(t_1) = 0$; the locus $y_2(t)$, to be found, delimits the domain in which $W(y, t) > 0$, where $y_2(t_2) = 0$; both t_1 and t_2 are to be found in the course of investigation. It may be remarked that for intense irradiation (a case of primary interest), $T(y, t) = T_p$, the (given) temperature of pyrolysis, throughout most of the domain in which V, W are finite. Also, the volume fraction of nonpyrolyzable woody matter $\bar{W}^{(0)}(y)$ is given; it enters in the specification of the thermal inertia $\Sigma(y)$.

The boundary and initial conditions may be specified as follows:

$$V(y, 0) = V^{(0)}(y); \quad W(y, 0) = W^{(0)}(y)$$

$$T[y_2(t), t] = T_p; \quad E(0, t) = E^{(0)}(t) \tag{39}$$

Not only the radiative flux reaching the topmost soil supporting the vegetation $E(-L, t)$, but also the peak temperature achieved, are of interest.

Adopted differencing procedures would follow directly from those outlined near the end of Sec. III. We regard our conceptual purposes as served by having sketched this generalized formulation for brush-type vegetation, and do not pursue the topic further.

VI. Other Phenomena

In this concluding section we very briefly allude to a variety of related phenomena previously omitted from discussion.

First, the major omission is anticipated to be the possible onset of sooting; because of the large absorptivity of light in the visible by typical, submicron-sized soot particles, the onset of sooting leads to further absorption of subsequent incident radiation. In this bootstrapping process, an opaque layer could form rapidly, such that virtually no radiation might reach the soil near the end of a, e.g., 2-s interval, even if most of the radiation reached the soil at the outset of the interval owing to a light vegetative loading [e.g., 0.005 g/cm^2 of hay, about 25 cm in height and oriented to the light so that the surface area (of each "plant") which is exposed to radiation is roughly 5 cm^2]. A soot yield of $(1/10^4)$ g/cm^2 (i.e., a 1% conversion to soot for a vegetative loading of 0.01 g/cm^2) would imply an approximate *e*-folding decrement in the transmission of light. However, before copious soot can form, some soot must form, and whether the soot-onset temperature for hydrocarbon vapors (crudely, 1300 K) is achieved is not entirely evident. Pyrolysis temperatures are characterized by 450–700 K for natural polymers, but combustion would be a means to achieve local "hot spots."

Second, for the parametric ranges of interest here, combustion is of practical interest only as a means of achieving a local hot spot for the onset of sooting. Only interstitial air (i.e., ambient air present within the vegetative layer) is plausibly available for mixing with pyrolyzed vapor and burning on a 2-s interval. Since the stoichiometric ratio by mass for air-to-fuel is typically 15/1, for 25-cm-high vegetation the colocated air, about 0.025 g/cm^2, implies that only 0.002 g/cm^2 of fuel can be burned; the associated heat of combustion, about 40 J/cm^2, is far exceeded by the incident flux of interest, 400 $J/(cm^2\text{-}s)$. Incidentally, burning may be inhibited for live vegetation because desiccation prior to pyrolysis may result in rising steam transiently separating the fuel-vapor/ambient-air reactants.

Third, the hot gas of the irradiated thermal layer expands vertically, under isobaric conditions to excellent approximation. Even with this expansion, one may have less dense fluid situated under more dense ambient air, and, in the presence of the earth's gravitational field, convective updraft ensues. The extent of the convective motion, which entrains the cooler ambient air to mix with the hotter vegetative-layer gas, may be estimated with the aid of empirical observations for bubble rise in liquid or of particle-free-volume ascent in bubbling-type solid/gas fluidized beds.[7] The vegetative-layer pyrolyzate may be displaced even further vertically, owing to the expansion of initially interstitial fluid (air, or water-heated to steam) of the supporting soil; in fact, it is this mechanism for possible further displacement that is one motivation for the interest in the radiative flux that reaches the topmost soil.

Finally, the extinction coefficient for an ice or snow cover is small, such that extinction of nonreflected radiation is distributed over too great a thickness to result in significant temperature rise. In any case, 2900 J/g is required to melt, heat, and evaporate snow at sea level, so a fluence of 400 J/cm^2 absorbed over a depth that encompassed $(\frac{1}{7})$ g/cm^2 of snow would produce no steam; probably one would observe the melting of a little snow to form a modest amount of slush.[2] If a thin glaze of ice covered the soil, the reflectivity of the surface would increase, and even if the interstitial fluids of the soil, upon heating, were to burst the glaze, tiny bits of lofted ice might cool the rising fluids.

Acknowledgment

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