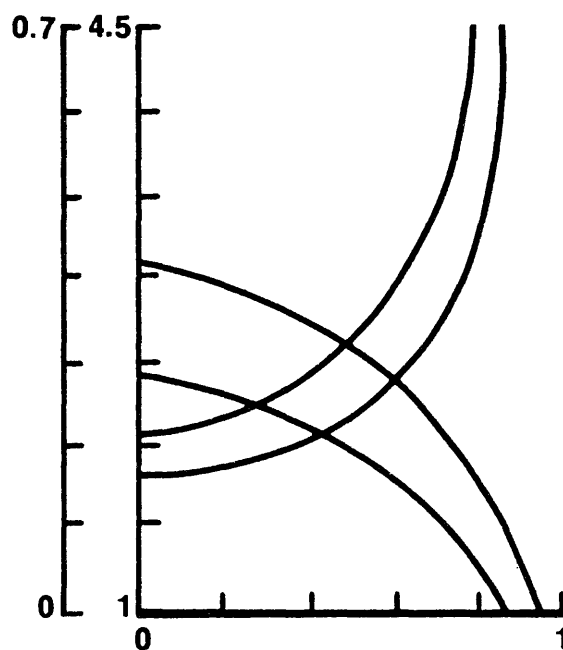


THERMOCHEMICAL PROPERTIES OF FLAME GASES FROM FINE WILDLAND FUELS

Frank A. Albini



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RESEARCH SUMMARY

This paper presents a theoretical model for the process by which is generated the gaseous fuel that burns in the free flame at the edge of a spreading wildland fire in fine fuels. The model is based upon a heat and mass balance for a hypothetical unit mass of solid fuel. As the fuel is heated, it is first desiccated, then pyrolyzed to release a fraction of its weight as combustible (and noncombustible) volatiles, with the remainder converted to char. The heat required to effect this process is supplied by partial combustion of either (1) the volatiles released or (2) equal fractions of volatile fuel and char, leading to two sets of equations. The equations predict the heat of combustion, the stoichiometric air/fuel mass ratio, the mass-averaged temperature, and the mass fraction of unburned fuel in the gas mixture, assuming that the partial combustion occurs at the rich limit (final temperature = 1100°C). Also given are equations for the fuel gas mass produced per unit mass lost by the fuelbed within the gas-generating zone.

Energy loss from the system is calculated as a fractional loss of radiant energy from the fuelbed. The radiant energy is assumed to be emitted from a tilted plane that represents the surface of contact between burning and unignited fuel. The fractional energy loss depends upon a single parameter of the fuelbed that is proportional to the fuel weight loading multiplied by the surface/volume ratio of the fuel particles. This functional dependence offers the possibility that a limiting value of fuel moisture content can be related to the geometrical properties of the fuelbed.

Several empirical relationships and approximations are introduced to simplify the equations and to reduce data requirements in using the model. It is argued that the speculative and approximate nature of the conceptual model do not warrant greater precision, so the simplifications, in themselves, do not weaken the theory.

Dependence of the fuel gas properties upon the fraction of fuel converted to char offers the possibility of calculating the synergistic interaction of fuel moisture content and the fire retardant effect of increasing the char fraction formed.

The interplay of intrinsic fuel properties, loading, particle size, and moisture content may permit testing of the theory by comparison with results from laboratory burns near the extinction limit of moisture content.

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INTRODUCTION

Fires spreading through wildland fuels can vary greatly in behavior, from smoldering in compact surface fuels to racing through shrub or tree crowns. The size and shape of the flames from such fires can be useful in describing the character of the fire. Flames are often photographed for research purposes, both in open burning (Adkins and Clements 1976; Anderson and others 1966; Brown 1972) and in laboratory fires (Rothermel and Anderson 1966; Thomas 1963). Relating flame structure to fuel properties and burning conditions has been the object of many research undertakings (Byram 1959; Thomas 1963; Steward 1964; Morton 1965; Nielsen and Tao 1965; Wohl and others 1949; Putnam and Speich 1963; Putnam 1965; Rothermel and Anderson 1966), because flame size is important in predicting or describing fire behavior and effects (Van Wagner 1967; Anderson 1969; Albini 1976).

The severity of a surface fire in terms of its resistance to control can be keyed to flame length (National Interagency Fire Training Center 1978), and flame height can be related to the height of lethal scorching of tree foliage (Van Wagner 1973). Flame height has also been related to the likelihood of crowning (Van Wagner 1977), and flame height, along with flame gas density and velocity, are needed to estimate the firebrand lofting capability of flames (Clements 1977; Tarifa and others 1965; Albini 1979). So the structure of the flame from a surface fire in wildland fuel provides much information about the fire in terms of its behavior and its possible effects. Thus a flame structure model may be used to predict behavior or effects of wildland fires, to interpret photographic data on wildland fires, and to analyze laboratory data.

Objectives

The flame from a spreading fire in wildland fuels can be classified technically as a free, turbulent, diffusion flame. The structure of such flames depends upon the properties of the gaseous fuel being burned, the size and shape of the gas-emitting area, the rate of flow of the gaseous fuel, and the flow field of the air into which the gaseous fuel is introduced. Most studies of the structure of flames begin with a series of assumptions, constraints, or measurements designed to specify the needed information in these four areas (Thomas and others 1961; Thomas 1963; Anderson and Rothermel 1965; Rothermel and Anderson 1966; Steward 1964; Fons and others 1960, 1962; Putnam 1965; Albini 1979; Becker and Liang 1978).

The principal use seen for the model presented here will be in analyzing and interpreting laboratory data. Direct measurements on flames, other than visual or photographic, are very difficult to obtain and often are subject to significant error or variation. Highly sophisticated diagnostic techniques now exist (Chigier and Strokin 1974; Lederman 1977) but are usually not applicable to spreading fires, especially if they are wind driven. More often, the experimenter is forced to record fuel weight as a function of time and rely on photography to capture flame structure information (Thomas 1963; Rothermel and Anderson 1966; Harmathy 1978A). When gaseous fuel is metered to a burner, there is no difficulty in describing thermochemical properties of the fuel since they are under the control of the experimenter. But in a spreading fire, processes at work within the flame-producing region at the edge of the fire determine the thermochemical properties of the gases

that feed the free flame. In order to interpret or analyze experimental data, then, it is necessary to infer these properties from prefire measurements of solid fuel parameters and the weight loss history recorded during the fire.

For example, consider a line fire propagating in surface fuels. The sketch shown in figure 1 illustrates how one might idealize the flow of gaseous fuel as issuing from a slot of width equal to the depth of the burning zone. The weighing platform indicated in the figure could provide a measurement of the rate of weight loss of the solid fuel. If one could calculate from the weight data the rate of emission and the properties of the gaseous fuel as it passed through the conceptual orifice, one would have available all the elements necessary to satisfy the data needs of a model for flame structure (assuming the wind field to be known).

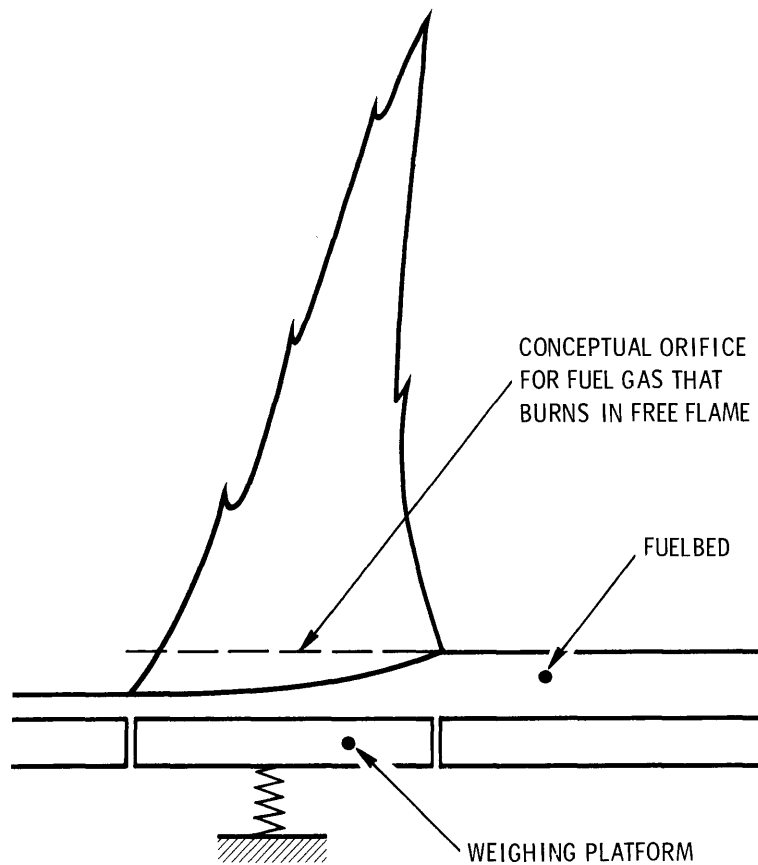


Figure 1.--Schematic diagram of a spreading fire, showing a fuelbed weight loss measuring scheme and the conceptual orifice for the flow of gaseous fuel that burns to form the free flame.

Scope

The purpose of this paper is to present a means of calculating the thermochemical properties of the fuel gases generated in the burning of fine forest fuels, using fundamental data that can be derived by laboratory procedures. These fundamental data are characteristics of the fuel material and can be catalogued for reference.

Attention is restricted here to fine fuels arranged in a uniform, homogeneous layer. The effect of fuel moisture content is included explicitly; the influences of fuelbed depth, compactness, and fuel particle size are explored parametrically. An effect of flame retardant salt additive is illustrated through the artifice of changing the fraction of the whole dry fuel converted to char during pyrolysis.

The model developed here is based on a highly simplified idealization of the processes taking place in the vicinity of the leading edge of a spreading fire. The idealized process is described verbally in the following section, with the detailed mathematical formulations spelled out in the appendixes. Empirical relationships and simplifying assumptions are discussed in the third section, and results are given in the fourth. The final section summarizes observations on the sensitivities of the model and proposes applications.

THE PROCESS OF COMBUSTIBLE-GAS GENERATION

The process by which combustible gas is generated near the front of a spreading fire can be described in terms of the history of a fuel particle as it passes through the zone under consideration. It is not possible to delimit this zone in specific geometrical terms, since the process described is only an abstraction and not an exact picture of all that transpires in a real fire. But by tracing the "experience" of a hypothetical particle of fuel we can reconstruct a physical process that approximates a real fire and so develop a model for it.

As the flame front approaches the fuel particle, the particle is heated and its temperature begins to rise. The heat is transported predominantly in the form of radiation (Thomas 1967; Anderson 1969; Telisin 1974; Fons 1946; Emmons 1963; Hotte1 and others 1965; Thomas and Law 1965; Williams 1977). The temperature of the fuel particle rises slowly at first, but increases very rapidly as the leading edge of the fire approaches to within 10 cm or less (Rothermel and Anderson 1966; Frandsen 1973). For sufficiently fine particles, the temperature on the inside of the particle will be very nearly equal to the temperature on its outer surface and the particle can be called "thermally thin" (Gebhart 1961; Frandsen 1973). In this paper attention will be restricted to fuelbeds composed only of such thermally thin particles. Typical wildland fuels that satisfy this condition are grass and the foliage of shrubs and trees. In wildland vegetation associations that contain larger fuel particles, fire spread still tends to be dominated by the fine, thermally thin, components (Rothermel 1972).

When the temperature of the hypothetical particle reaches about 100°C, the moisture held by the particle will begin rapidly to boil away. The amount of energy that must be absorbed by the particle during this phase of heating may be quite large because of the high latent heat of vaporization of water. The desiccated particle continues to absorb heat and its temperature continues to rise as it approaches the edge of the flaming zone.

As the temperature of the particle reaches about 200°C, some material begins to exude from the particle as gas (Shafizadeh and others 1977). The gas consists partly of volatilized constituent waxes, oils, resins, etc., and partly of the products of decomposition--pyrolysis--of the particle fibre. The rate of mass loss increases with increasing temperature until a maximum is achieved (in some cases, two maxima are exhibited), usually between 300° and 400°C (Muhlenkamp and others 1977). Gas production continues at a decreasing rate until particle

temperature reaches 450-500°C, at which point the only thing remaining of the original particle is a solid carbonaceous char. The energy necessary to heat a unit mass of dry solid fuel to 500°C has been measured in the laboratory for a wide variety of forest fuel types (Muhlenkamp and others 1977).

In a wildland fire situation, between the temperature at which the particle begins to exude gases and the temperature at which it is reduced totally to char, it will have become immersed in flame. The attachment of a flame to a solid particle occurs when the rate of combustible gas generation by the particle is sufficient to maintain a flame. This usually happens at a temperature between 300°C and 380°C (Fons 1950; Martin 1964; Simms 1960, 1961, 1963). Recent findings (Mutch 1964; Stockstad 1975, 1976) indicate that the temperature for flame attachment, or piloted ignition, is approximately 325°C.

So at or about 325°C the hypothetical particle will have entered the zone of flaming combustion at the edge of the fire. And when it has reached about 500°C it will have contributed all its combustible volatilizable material to the flow of gas that burns as a free flame above the fuelbed. (Some of the char formed in this process may also have been burned by the time the particle consists solely of char--more on this possibility follows.) The intent of the effort here is to devise a means of calculating the bulk properties of this fuel gas, contributed by all the fuel particles in the vicinity of the edge of the fire as they undergo the process just described. The flames that are attached to the individual fuel particles most often cannot consume all of the combustible gas liberated by the heating of the particle because the rate of release is higher than the local rate of oxygen supply.¹ So some unburned combustible gas mixes with the products of the partial combustion occurring within the fuelbed--and the water vapor driven from the unignited particles--and issues from the fuelbed to burn in a free flame.

The heat of combustion available from this mixture, its temperature, and its stoichiometric mass ratio for combustion in air are the properties sought. To derive these quantities it is necessary to write down the heat and mass balances implicit in the process just described. These relationships will then provide a mathematical model allowing the prediction of the desired values from intrinsic properties of the fuel material and an estimate of the efficiency of the radiant heat transfer to the fuel ahead of the fire.

Structure of the Fuel Gas-Generating Zone

The volume of space in which the processes described take place can be defined in terms of an idealization of the processes. Rothermel and Anderson (1966) discuss these processes and their localization with respect to the edge of a fire. Berlad and others (1971) described fire spread in fine fuel arrays in terms of a

¹The rate of oxygen supply to this gas-producing zone is a rate-limiting factor implicit in the model developed here. The model presented here is independent of the rate at which the processes occur, but any of a host of factors impose rate limits. Later in the development of the model it is assumed that the combustion occurring in the fuelbed below the free flame takes place at the fuel rich limit, so is limited in rate by the availability of air. Gas sampling during large scale compartment fires indicates that this process is at play in stationary fire situations not unlike what is pictured here (Harmathy 1978B).

wave of fuel volatilization and combustion propagating along and into the fuelbed. Rothermel (1972) idealized the processes and introduced the concept of a "reaction zone" at the edge of a spreading fire. Rothermel's reaction zone is in rough coincidence with the physical volume envisioned here.

The forward boundary of the volume in question is taken to be the surface within the unignited fuelbed along which the temperature of the fuel particles begins to rise "significantly." This surface is presumed to lie parallel to the surface on which ignition or flame attachment occurs, a short distance away from it. This latter surface can be inclined at a large angle from the vertical for rapidly spreading fires but will be nearly vertical for fires spreading very slowly (Thomas 1967; Frandsen 1971; Rothermel 1971).

The lower boundary of the zone of gas generation will be considered to be the bottom of the fuelbed. For open fuel arrangements, such as grass or shrubs, this surface would be the ground or the top of the litter lying on the ground. For compact fuelbeds, such as forest litter, the lower boundary can be much more difficult to define, since in many cases only the loose upper portion of the layer will be involved in the flame gas production associated with the spreading fire. In this case it is necessary to define the lower boundary as the imaginary surface that separates the fuel into two portions. The upper portion is ignited during the time the flame-production zone (or Rothermel's reaction zone) passes over a point. The lower portion is the fuel that is ignited only after the passage of the zone, if at all. The only difficulty caused in the mathematical description of the process by this definition is in the lack of a clearly specified fuelbed depth. This problem is not severe in terms of the uncertainty it causes in the quantities calculated.

The upper surface of the gas fuel generation zone is simply the top of the fuelbed. This surface forms the imaginary orifice through which the fuel flows into the free flame.

The rearward surface of the zone, however, must be defined in terms not specifiable before the fact. The rearward edge of the zone from which combustible gas issues must be coincident with the surface upon which the fuel particles reach 500°C and so have been reduced to char. But since the fuel particles may not all be exactly the same size nor experience exactly the same history on passing through the flame-producing zone, this surface may exist at a variety of places at the same time. Mathematically one would say that the region is not simply connected. Physically this means that it must be considered that some fuel particles will have been partially or totally consumed (even the char) by the time that most of them have ceased to produce combustible gas. The release of heat from char combustion can be an important component of the heat budget for the flame-producing zone and the products of any char combustion must be included in the bulk fuel gas flow. So the rearward boundary of the zone can be taken to be the surface upon which "most" fuel particles have ceased to emit combustible gases, but ahead of which some fuel particles may have been completely consumed. This surface, in other words, is a mathematical artifice that may not have a geometrical counterpart in reality. The degree to which real situations conform to this conceptualization will be one of the limiting factors on the validity of the model.

Two limiting cases can be considered in which the rearward boundary is clearly definable, if not easily located in space. In the first case, it is postulated that there exists a rearward surface forward of which all fuel particles are emitting gas and none have yet been reduced to char but behind which all particles are pure char and none emit combustible gas. In the second case it is postulated that the rearward surface is also a boundary behind which all the fuel particles are reduced to char at 500°C, but in this case a fraction of the fuel ahead of the surface

will have been completely consumed and the remainder will not as yet have been reduced to char. The fraction in question is determined by equating the heat required to accomplish the volatilization to the heat released by the burning of the whole fuel, as is described below.

Mass Balance

If the volume of space described above is considered to be fixed to a steadily advancing flame front, the mass flow of the idealized processes described above can be represented schematically by the sketch shown in figure 2. In this figure solid fuel, with its associated moisture, enters the process volume along with air. Enough air must be present to accomplish the combustion needed to satisfy the heat balances detailed below or the process will not be in steady state. The process is self-adjusting if a wind acts on the fire. A wind-driven fire will spread faster as the windspeed increases, thus raising the mass flow rate of fuel into the volume. In a backing fire, the process volume shrinks in response to increasing windspeed, and some char may be burned in the volume shown. So windspeed affects the mass flow rates, but not the balance. Some air may pass through the process volume without interacting with the fuel or entering into any combustion process. This air is ignored in the mass balance and heat balance formulations. If the quantity of non-interacting air becomes a large fraction of the air needed for combustion, its neglect in the heat balance probably will lead to significant error, since it should carry away some heat even if it does not react in the process zone.

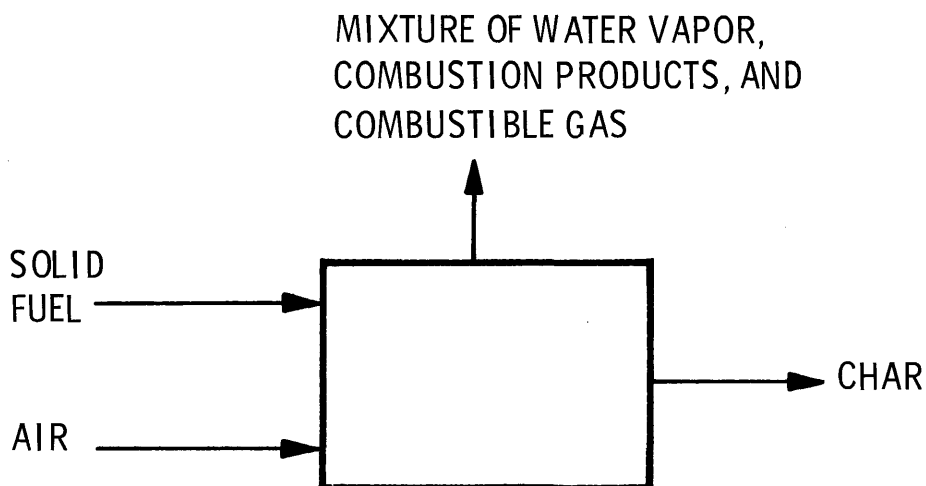


Figure 2.--Schematic mass flow diagram of the process to be analyzed.

Out of this volume flows the hot combustible gas that will fuel the free flame and the char remnants of the solid fuel that may later burn by glowing combustion. The combustible gas consists of the unburned pyrolyzate from the charred solid fuel, the products of all combustion that takes place in the process volume, and the initial moisture of the solid fuel.

The fraction of the initial dry weight of solid fuel that is converted to char appears to be a characteristic of the type of fuel being burned and a very weak function, at most, of its rate of heating. Several investigators have established this fact for temperature rise rates up to $160^{\circ}\text{C}/\text{min}$ (see, e.g., Leu 1975). Recent experiments by Susott (data on file at NFFL, Dec. 1978) have shown that this relationship is maintained when predried samples are suddenly immersed in a furnace at 500°C , establishing temperature rise rates of at least $3000^{\circ}\text{C}/\text{min}$. These later experiments more closely approximate conditions in a spreading fire (Rothermel and Anderson 1966; Rothermel 1972) than any previously done and so clearly yield data suitable for use in this model.

The mass of air that enters into reaction with either the volatile fuel or the char can be related to the mass of volatile or char reacted by the chemical balance required of the reaction. The ratio of the mass of oxygen (hence air) to the mass of fuel burned is the stoichiometric mass ratio, a constant fixed by the relative abundance of hydrogen and carbon in the fuel component. The stoichiometric mass ratio of the volatilized fuel is a property of the solid fuel from which it was produced,² and can be determined by experiment. Thus by using one or the other of the two special-case definitions of the rearward boundary of the process zone described above, the mass of air involved can be related to the mass of fuel consumed, either in the volatile phase only or *en toto*. The sum of the reacted fuel mass, the air needed to burn it, and the moisture makes up a diluting flow of noncombustible gas that is mixed with the combustible volatiles released. As the proportion of burned gas diluent increases, the heat of combustion of the mixture declines, along with its stoichiometric mass ratio. The proportions of these two components are determined by satisfying the heat balance described in the following section.

Heat Balance

By following a unit (dry) mass of fuel through the process zone, we can calculate the amount of heat that it must absorb in order to go from its initial state to its final state. This amount is simply the sum of the quantities of heat needed to:

- 1) Raise the temperature of the (wet) fuel from ambient to the boiling point of water (100°C).
- 2) Boil away the water held by the fuel at 100°C .
- 3) Raise the temperature of the solid dry fuel from 100° to 500°C , and in the process reduce it to char and volatile components.

This sum represents a quantity of heat that must be supplied to the fuel as it passes through the process volume. The requirement of steady state conditions dictates that this heat requirement be satisfied by the energy release from an

²This fact has been established experimentally by R. A. Susott in an extensive series of tests using the oxygen coulometer at the Northern Forest Fire Laboratory. These data will be reported in forthcoming publications by Susott.

equal mass of fuel within or near the process volume. We posit, for this model, that this energy is supplied by combustion within the process volume.

Additional heat is required, though, as we can determine from a closer inspection of the process outlined above. The sources of additional heat demand included here are the following:

- 1) Only part of the radiant energy emitted from the burning region into the fuelbed ahead of the ignition surface is absorbed by fuel particles. That which passes through the fuelbed into the air above or the solid surface below is lost from the system. So the energy demand of a unit mass of fuel, as it goes from ambient temperature to ignition temperature ($\approx 325^{\circ}\text{C}$), must be increased to include this leakage of energy. The other boundaries of the burning region are the same as those of the process volume and are assumed to be in radiation balance. So no additional energy loss is attributed to those surfaces.

- 2) The hot gas issuing from the upper surface of the process volume will have a mass-averaged temperature in excess of 500°C , which temperature represents a rough lower limit for visible radiation from the gas. The energy needed to raise the steam, the volatilized solid fuel, and the reaction products to this average temperature must be supplied by the partial combustion occurring within the process volume. A means of establishing the mass-averaged temperature is spelled out in appendix I, based on a more detailed examination of the combustion occurring within this zone.

With these additional heat demands included we have a rather complete accounting of the debit side of the energy budget for a hypothetical unit mass of dry fuel. In order for the process described to continue in a steady state, this budget must be balanced by combustion of part of a unit mass of dry fuel.

The greater is the total of energy requirements the greater will be the fraction of fuel consumed to satisfy the needs of the process. As a result, less energy will be available in the form of unburned volatile fuel to feed the free flame. (Another way of looking at this is to realize that the combustion process must go farther toward completion within the fuelbed, leaving less to be burned above the bed.) For example, if the moisture content of the fuel is increased, more heat is needed to boil the water and heat the steam associated with a unit mass of dry fuel. So a greater fraction of the unit mass would have to be burned to provide this energy. Of course, as more fuel is burned, more air must be used, so an additional demand for heat is incurred to raise the products of combustion to the average temperature of the effluent gas. This compounding effect amplifies the influence of an incremental change in the basic heat requirement.

The effect of a change in fuel arrangement can also be inferred from the list above. If the fuel is deep and compact so that little radiation can pass through the bed and escape, the energy loss by escaped radiation will be small. But if the fuelbed is open and shallow, more radiant energy will be required to heat the fuel to ignition, since much would escape. An implication of this model then, is that a deep, compact fuelbed should be able to support a free flame at greater fuel moisture content than could a shallow, open bed of the same fuel particles.

An implicit assumption evident here is that the fuelbed is not so compact as to restrict the flow of air to the extent that flaming combustion cannot be maintained in the process volume. Some compact forest litter mats may exhibit such an oxygen starvation effect; these would then burn mainly by smoldering (unless aided by wind) with no free flame.

The energy to be supplied by combustion in the process volume will be generated by the burning of some of the volatilized fuel and perhaps some of the char. Two cases are considered here: In the first case it is assumed that only volatile fuels are burned to balance the heat budget. In the second case it is assumed that equal fractions of char and volatile fuel are burned. The first case is thought to be representative of rapidly spreading fires, in which the flame-producing zone passes quickly over a fuel particle, leaving it nearly whole, with glowing combustion to occur after the flame zone has passed. Some grass and shrub fires exhibit this character. The second case is thought to be more representative of slowly spreading fires, in which some fuel particles are totally consumed within the flame-producing zone. Fires in conifer litter sometimes show this trait. Hopefully these two special cases will serve to "bracket" the behavior of fires in many real situations.

SIMPLIFYING ASSUMPTIONS AND APPROXIMATIONS

A mathematical description of the processes described is readily produced in symbolic form (see appendixes), but a large number of parameters must be specified in order to calculate the desired quantities. To minimize this demand for data and to simplify the computations, some empirical relationships and approximations are introduced. Because the physical processes represented by the equations are themselves highly simplified approximations of reality, the use of approximate values in them does not weaken the model. In other words, any inaccuracies caused by the approximations should be overshadowed by the approximations that the equations themselves represent. As more experimental data are accumulated it may result that some properties treated as fuel-specific in this model can be replaced by constants, so further simplifications may be made. For the present, the following set of assumptions are used in the model and are introduced without discussion in the mathematical development:

The specific heat capacities (at constant pressure) of air, gaseous fuel, and combustion products are considered to be constant with temperature and equal to each other. This approximation is fairly accurate in the temperature range of interest in this problem (Weast 1967).

The specific heat capacity of steam (from fuel moisture only--not combustion products) is also taken to be constant and equal to twice the value for the other gases. This, too, is a fair approximation (Weast 1967).

The volatilized fuel gas emitted from the heated solid fuel is emitted at different rates as the temperature of the solid increases, as described in the previous section. For the purpose of estimating the additional heat required to raise the gas to a common temperature, the rate-versus-temperature curve is approximated by two straight lines. The ascending line (rate increasing with increasing temperature) rises from zero at 200°C to a maximum at 350°C; from the maximum a descending line reaches zero again at 450°C. By this crude approximation, a modest correction to the experimentally determined heat required to pyrolyze the solid fuel (Muhlenkamp and others 1977) can be calculated.

The stoichiometric air/fuel mass ratio for the volatile fuel gas and for char is assumed to be proportional to the heat of combustion (high heat value) of the fuel. This empirical rule has long been known to be rather accurate (Thornton 1917)

and has recently been confirmed for a wide variety of fuels (Susott and others 1979). The ratio of the heat of combustion to the stoichiometric air/fuel mass ratio was found in the later work to be nearly constant at 3270 J/gm air. This value is used in the model presented here.

Conventional determination of the heat of combustion by bomb calorimetry provides what is called the high heat value of the fuel. For combustion processes in which the latent heat of vaporization of the water in the combustion products is not recovered, the heat of combustion must be reduced by this amount, to give what is called the low heat value of the fuel. The correction term is readily computed if one knows the relative abundance of hydrogen in the fuel. Elemental analysis of a variety of natural fuels (Susott and others 1975) has revealed that a hydrogen content of 6.3 percent of the ash-free whole fuel weight is quite representative, so this figure is used to derive the correction term for heat of combustion. The volatilized fuel contains about 7.2 percent hydrogen by weight (Susott and others 1975) and this figure is used also. The corrections are modest, and the high heat value is used only to obtain the stoichiometric mass ratio, so the model is not very sensitive to these fractions in any case.

The heat of combustion of whole fuel can be expressed as the sum of the heats of combustion of the volatile and char components. Since the heat of combustion of ash-free char from rapidly heated samples of various forest fuels has been found to be virtually constant at 31,200 J/gm (Susott and others 1975), the heat of combustion of the volatile component can be calculated from this relationship if the fraction of whole fuel converted to char is known, along with the ash fraction and the heat of combustion of whole fuel. These latter parameters are readily measured and tabulated while the heat of combustion of the volatile material is difficult to obtain experimentally. So even though no reduction in the number of input variables is achieved, the model is made easier to apply by using this relationship.

In formulating the heat balance described above, matter enters the process volume at ambient temperature and leaves it as char at 500°C or at a mass-average gas temperature to be determined. The latter temperature is found through an intermediate step. First, all the mass (solid fuel, volatiles, moisture, and air) is presumed to be heated to 500°C. Then the fraction of fuel that burns in the process volume is assumed to produce gaseous products with a final temperature of 1100°C. Along with this fraction an equal fraction of the moisture (as steam) is assumed to be heated to 1100°C, serving as a diluent of the reacting components. This two-temperature mixture contains all the sensible heat of the effluent gas, so a mass-averaged uniform temperature is readily calculated. The choice of 1100°C for the final temperature of the combustion products is based upon the empirical rule that both lean and rich limits of premixed flame propagation tend to occur at this final temperature for a wide variety of fuels and diluents (Gaydon and Wolfhard 1960).

The process of heat loss through radiation leakage was discussed above. This component of the energy balance is calculated in terms of the energy required to raise the temperature of a unit mass of fuel to the flame-attachment temperature of 325°C from ambient. To make this calculation, the interface between burning and unignited fuel is assumed to be a radiating plane panel tilted at a fixed angle to the horizontal. The fraction of the energy emitted through this plane that escapes the fuelbed is computed by treating the fuelbed as an absorbing layer with a constant extinction coefficient. The extinction coefficient is proportional to the product of the fuelbed packing ratio and the surface/volume ratio of the fuel particles (Anderson 1969; Thomas 1967; Rothermel 1971; Telisin 1974). The critical assumptions here are that the shape of the interface surface is planar, the fuelbed is homogeneous, and that the process volume radiation loss can be adequately characterized by that from a radiating surface. The sensitivity of the results (fraction of energy lost) to the tilt angle of the hypothetical plane surface indicates that

the shape is not a critical factor in the loss process. The homogeneity required of the fuelbed implies a restriction on model applicability. The use of a radiating surface to characterize loss from a volume is strictly valid only if the volume is opaque to radiation over the spectrum containing a large fraction of the radiant power. It is a good approximation for the sooty flames from natural fires if the integrated soot concentration through the flame exceeds about 1 gm/m^2 (Beer 1974). That is, for a particulate concentration of 1 gm/m^3 , a flame 1 m deep would be virtually opaque. A fraction of a meter thickness would suffice to make natural fire flames virtually opaque, if the flame continually occupied all the volume considered. The phenomenon of intermittency (temporary local extinction, sometimes called "flickering" or "pulsating") lowers the time-averaged emissivity of the flame volume, weakening this approximation.

More serious sources of inaccuracy no doubt lie in neglecting radiation from the free flame to the unignited fuel (Anderson 1969) as an additional heat source and in neglecting radiation losses through other boundaries of the process volume. The first source of error is more important for rapidly spreading fires with large flames while the second source no doubt becomes important for fires nearing the condition of extinction. So, if there were no other uncertainties, the model should be expected to predict a heat of combustion of gaseous fuel that is too low for low fuel moisture and too high for high fuel moisture.

EXAMPLES OF MODEL RESULTS AND DISCUSSION

Using the equations assembled at the end of appendix I and the data displayed in table 1, some numerical examples were calculated. A computer program facilitated the effort, so both fuel moisture content and radiation loss fraction were varied parametrically. In addition, the char fraction formed by excelsior³ was varied parametrically up to 0.60, to illustrate the influence of typical flame retardants on the combustible gas properties (Williams 1974; George and Blakely 1972). Results are given graphically in this section.

There is a uniform and consistent difference in the results between the two methods of computation described. When the heat budget is balanced using combustion of whole fuel (as opposed to volatile component only) the predicted properties of the combustible volatiles are those of a slightly more energetic fuel. The mass fraction of unburned fuel in the gas mixture is slightly higher, so the heat of combustion and the stoichiometric air/fuel mass ratio are higher. Also the mass-averaged temperature is slightly lower as is the ratio of gas produced to fuel load lost. Figures 3-7 illustrate these differences for the five fuel types considered, with plots of gaseous fuel properties versus solid fuel moisture content for a nominal value of radiation leakage fraction of 0.3 (see appendix II).

³Excelsior is a commercial product available in bulk, widely used for packing around fragile items for shipment and as a stuffing for upholstery. It is made by shaving wood (typically aspen or poplar) into long, curled filaments of cross-sectional dimension in the range of 0.5 mm.

Table 1.--Fuel properties data used for example calculations

Fuel material	Heat of combustion (low heat value) J/gm	Heat required to raise temp. from 25°C		Ash content fraction	Char formed fraction
		To 325°C J/gm	To 500°C J/gm		
Poplar excelsior	18,234	441	772	0.0046	0.1328
Ponderosa pine dead needles	21,548	603	1,017	.0405	.2717
Cellulose	15,992	440	954	.00075	.0418
Chamise foliage (green, freeze-dried)	20,686	600	767	.0045	.3036
Manzanita foliage (green, freeze-dried)	20,413	605	778	.0369	.3023
NOTES	(1)	(2)	(3)	(4)	(5)

NOTES

- (1) Data on file at Northern Forest Fire Laboratory. High heat values corrected for assumed 6.3% H content; ash-free basis; 25°C ref. temp.
- (2) Data taken from Muhlenkamp and others (1977); dry weight, ash included; 160°C/min heating rate.
- (3) Data extrapolated from source (2), same basis.
- (4) Data on file at Northern Forest Fire Laboratory. Dried sample immersed suddenly in 500°C furnace, N₂ atmosphere. Ash formed by introducing air to hot sample, temperature raised to 600°C at 20°C/min; ash weighed at 600°C; average of 3 samples.
- (5) Data from source (4); char fraction determined at 30 s from time of immersion in furnace (stable weight achieved).

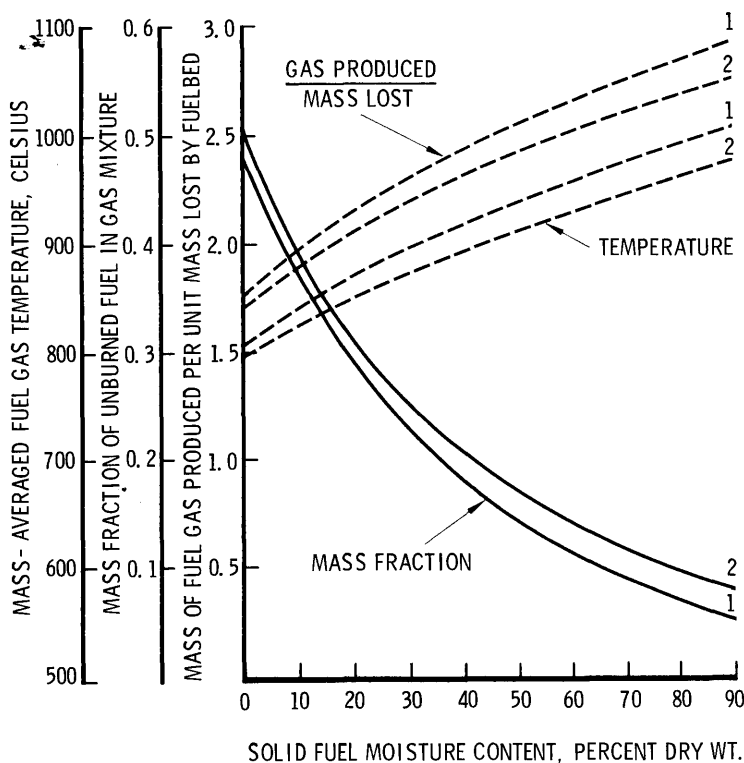


Figure 3.--Variation of gaseous fuel properties with moisture content of solid fuel. Curves labeled "1" are based upon balancing the heat budget by combustion of volatile fuel only; "2" signifies burning of whole fuel. Fuel in this figure is poplar excelsior (see properties shown in table 1). Radiation leakage fraction assumed to be 0.30. To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,320 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.47.

Figure 4.--Variation of gaseous fuel properties with moisture content of solid fuel. Curves labeled "1" are based upon balancing the heat budget by combustion of volatile fuel only; "2" signifies burning of whole fuel. Fuel in this figure is dead ponderosa pine needles (see properties shown in table 1). Radiation leakage fraction assumed to be 0.30. To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 18,490 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 6.14.

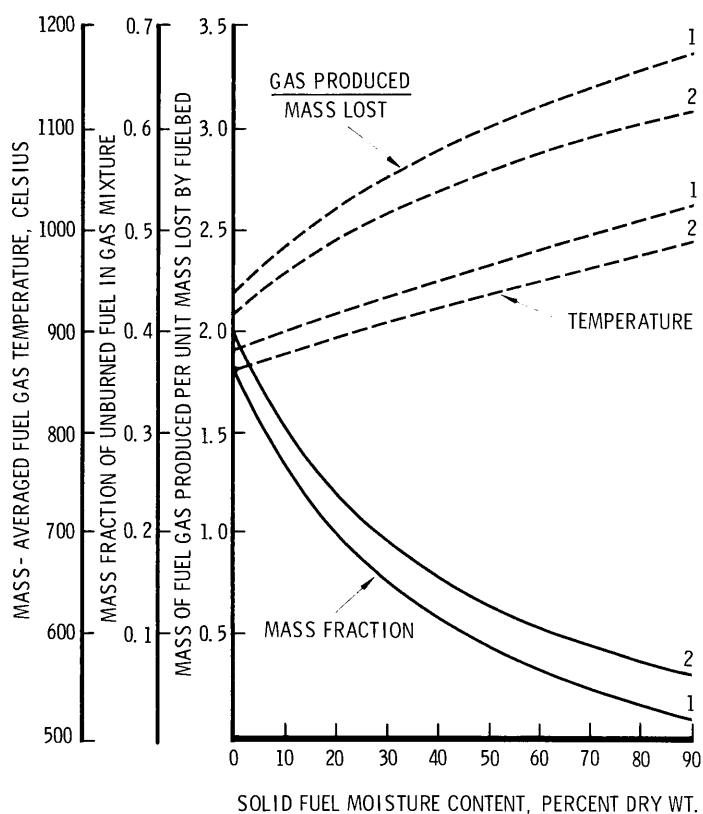
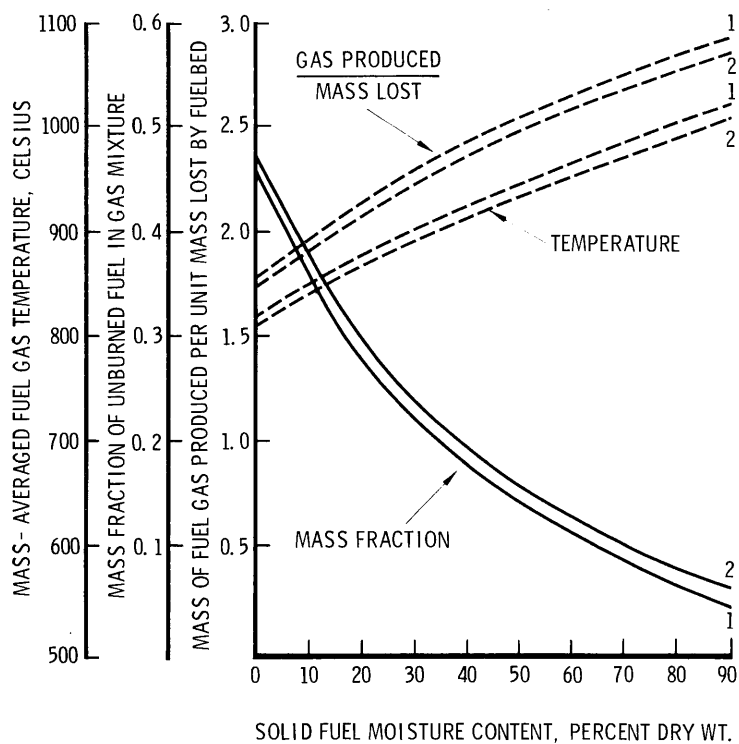


Figure 5.--Variation of gaseous fuel properties with moisture content of solid fuel. Curves labeled "1" are based upon balancing the heat budget by combustion of volatile fuel only; "2" signifies burning of whole fuel. Fuel in this figure is cellulose (see properties shown in table 1). Radiation leakage fraction assumed to be 0.30. To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 15,340 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.17.



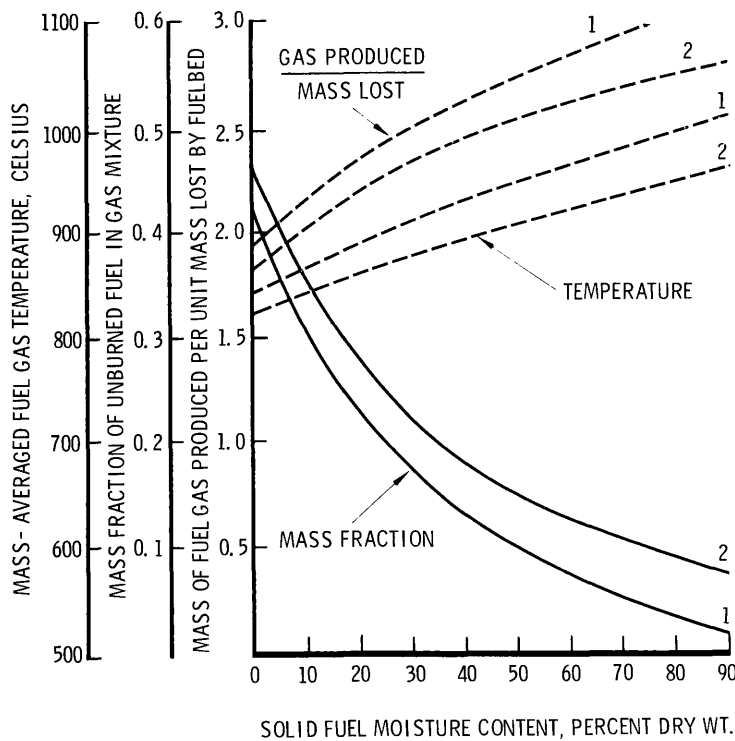


Figure 6.--Variation of gaseous fuel properties with moisture content of solid fuel. Curves labeled "1" are based upon balancing the heat budget by combustion of volatile fuel only; "2" signifies burning of whole fuel. Fuel in this figure is green chamise foliage (see properties shown in table 1). Radiation leakage fraction assumed to be 0.30. To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,770 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.61.

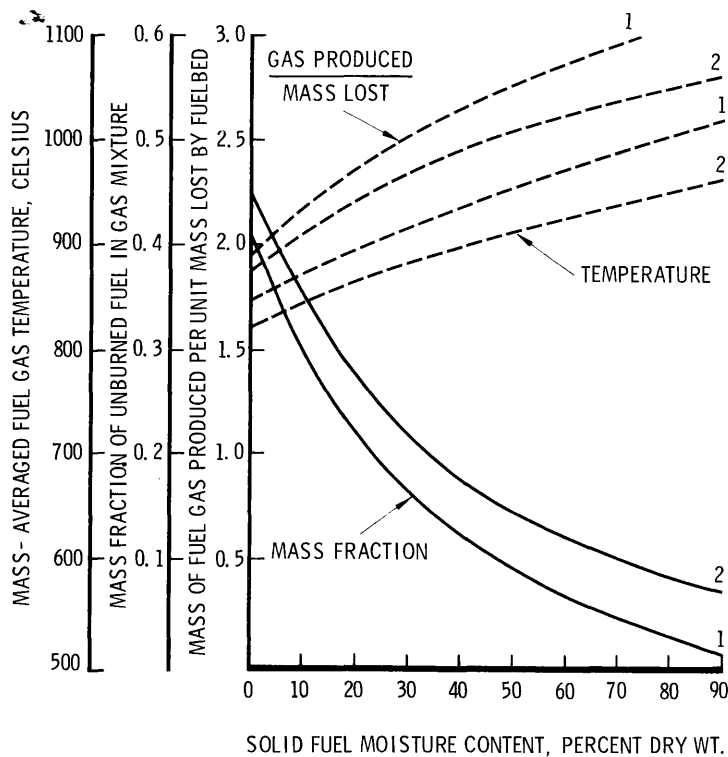


Figure 7.--Variation of gaseous fuel properties with moisture content of solid fuel. Curves labeled "1" are based upon balancing the heat budget by combustion of volatile fuel only; "2" signifies burning of whole fuel. Fuel in this figure is green manzanita foliage (see properties shown in table 1). Radiation leakage fraction assumed to be 0.30. To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,310 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.47.

This series of figures also serves to illustrate the influence of moisture content on the properties of the gaseous fuel generated by a spreading fire. Note that the temperature (mass-averaged basis) of the fuel gas increases as the moisture content rises. This seeming paradox can be readily understood if one realizes that more energy is demanded by the fuelbed to release the volatile fuel as the moisture increases. Hence the combustion process must go further toward its ultimate completion to satisfy this requirement, and less unburned fuel is available to feed the free flame standing above the fuelbed. That is, the top of the flame is getting closer and closer to the top of the fuelbed as the flame shrinks. Because we have modeled a process with no excess air, the more fuel consumed, the greater the temperature. The decline of the stoichiometric air/fuel mass ratio with increasing fuel moisture content tells this story.

The effect of fuelbed geometry, as reflected in the radiation leakage fraction, is illustrated in the series of figures 8 through 12. There are two versions of each figure; version A is based on volatile fuel combustion only and version B is based on whole fuel combustion. The general appearance of these figures illustrates that radiation leakage plays much the same role, and has a similar influence, as fuel moisture content. The similarity of the curves for such disparate fuels as those used here indicates that the use of surrogate fuels in research activities may not introduce substantial distortion when the results are interpreted to describe fire behavior in forest fuels.

Figures 13-15 illustrate the dramatic influence that the char fraction has on flaming combustion behavior of excelsior. Excelsior is often used to test fire retardant effectiveness (George and Blakely 1972) so was chosen to illustrate this effect here. Any of the other fuels would have exhibited approximately the same behavior. Since the fraction of fuel mass converted to char appears to be a function of the concentration of flame retardant (Browne and Tang 1962), the influence of retardant chemicals in reducing flaming combustion may be explainable by the process modeled here.

This series of figures shows that the greatest impact of an increase in the char fraction formed is on the heat of combustion of the fuel gas mixture. This occurs because the heat value of the nascent volatile fuel declines as well as does the mass fraction of unburned fuel in the mixture. The indication is, then, that as the level of retardant application increases, a rapid transition from flaming fire spread to smoldering should occur as a critical level of char fraction is achieved. If such a critical value exists, it would probably be a function of fuelbed geometry and moisture content.

The effect of fuel moisture on volatile fuel properties for elevated char fractions is shown in figures 16-18, which show unburned fuel mass fraction and gas production per unit load loss versus moisture content. In these figures, as in 3-12, the heat of combustion of the gas mixture is a constant multiple of the unburned fuel mass fraction. The multiplier is 15,070 J/gm for figure 16, declining to 12,760 for figure 17 and to 9,690 for figure 18. Assuming for illustrative purposes that a "critical" heat of combustion value is 3,000 J/gm (3KJ/gm), this value would be achieved at a moisture content of 36 or 47 percent (a mass fraction of 0.2 in either case, but the moisture level depends upon which process is assumed) for a char fraction of 0.2 (fig. 16). But if the char fraction were 0.3 (fig. 17), the mass fraction figure would have to be $3,000/12,760$ or 0.235; this would be achieved at 18 or 33 percent fuel moisture. And if the char fraction were 0.4 (fig. 18), the required mass fraction would be 0.31, which would occur at 2 or 15 percent fuel moisture. So there appears to be a synergistic effect in the combination of fuel moisture content and flame retardant (i.e., char fraction formed) according to the model. This phenomenon has been noted for natural fuels (Rothermel and Hardy 1965) but the data do not permit quantitative comparisons with results predicted here.

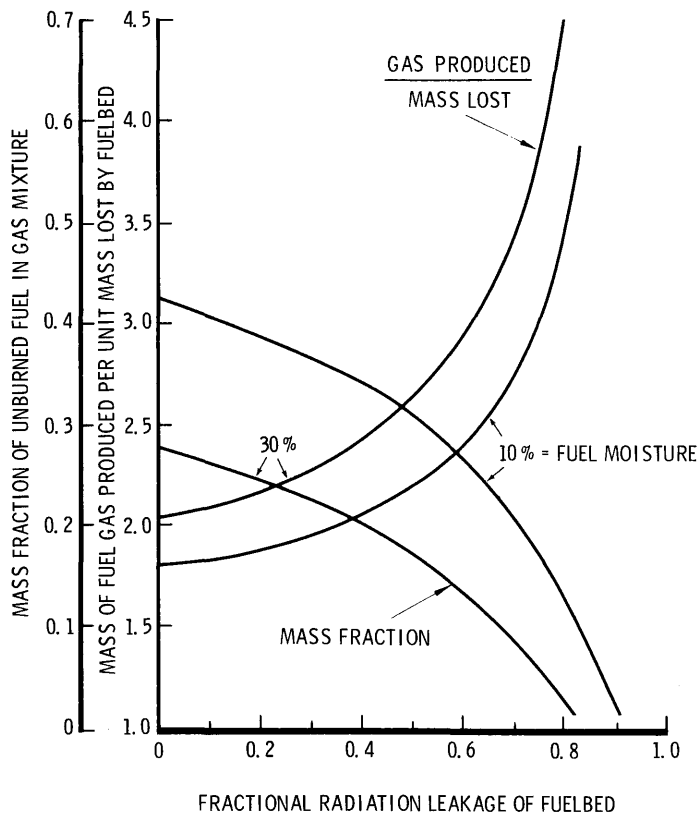


Figure 8A.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of volatile products only. Fuel in this figure is poplar excelsior (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,320 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction by 5.47.

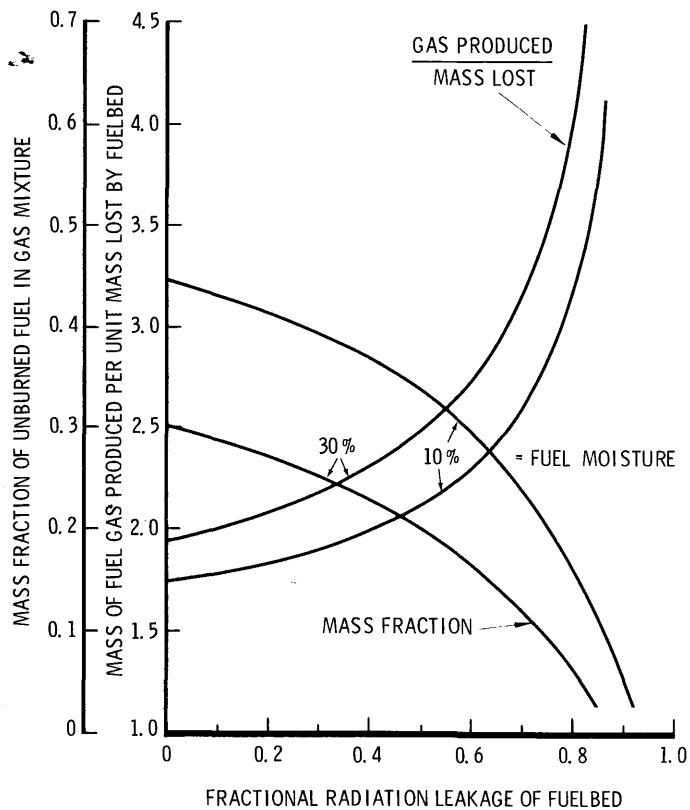


Figure 8B.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of whole fuel. Fuel in this figure is poplar excelsior (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,320 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.47.

Figure 9A.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of volatile products only. Fuel in this figure is dead ponderosa pine needles (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 18,490 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction by 6.14.

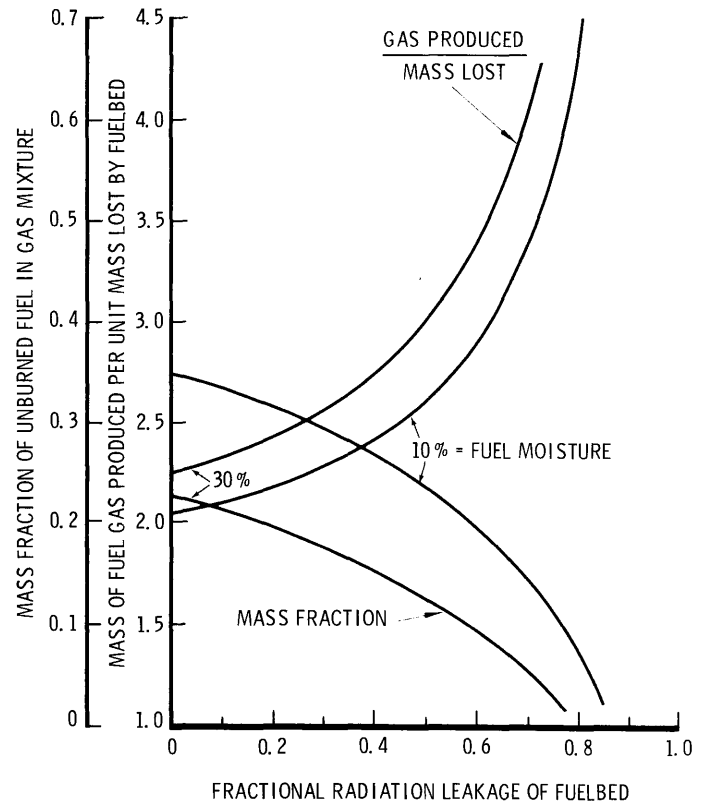
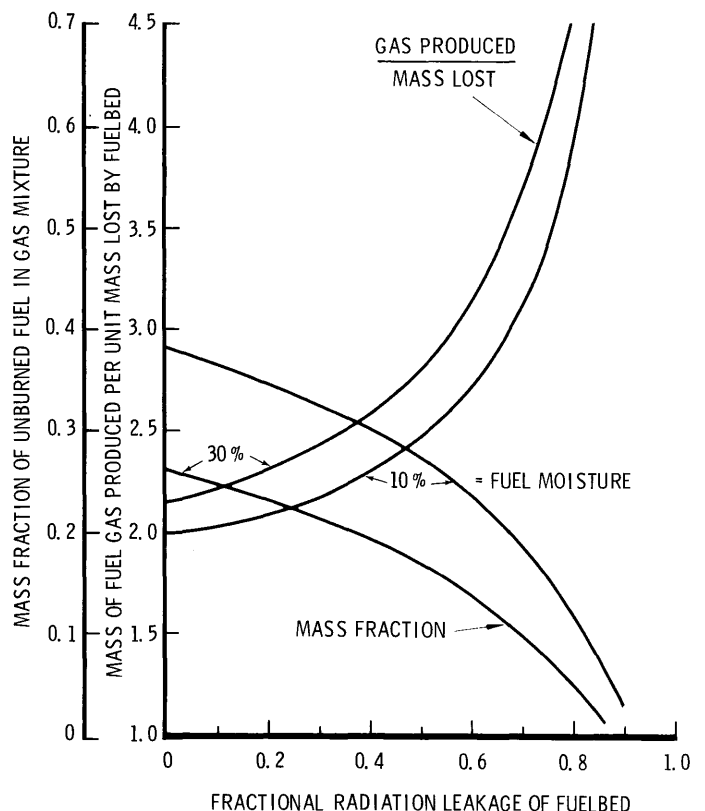


Figure 9B.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of whole fuel. Fuel in this figure is dead ponderosa pine needles (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 18,490 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 6.14.



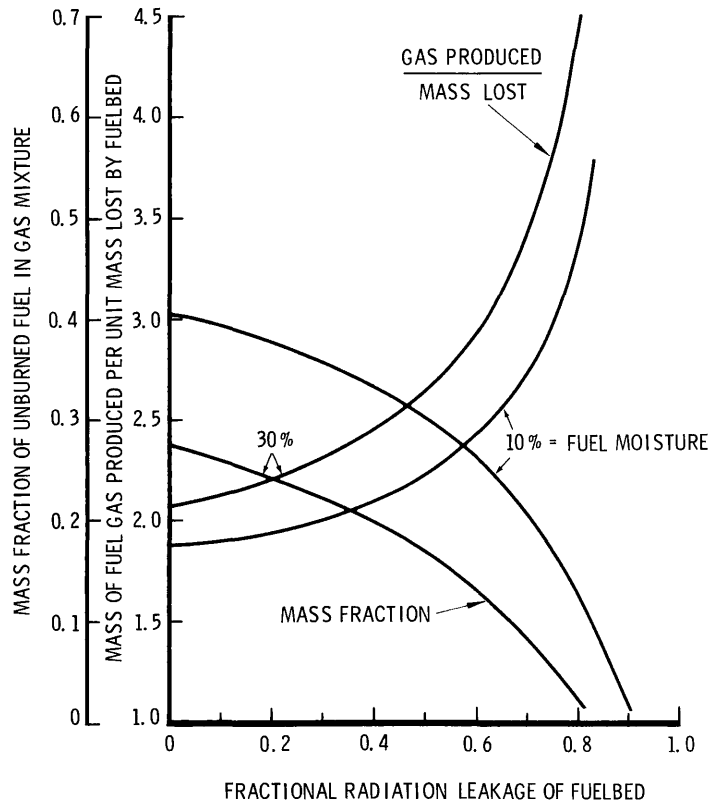


Figure 10A.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of volatile products only. Fuel in this figure is cellulose (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 15,340 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction by 5.17.

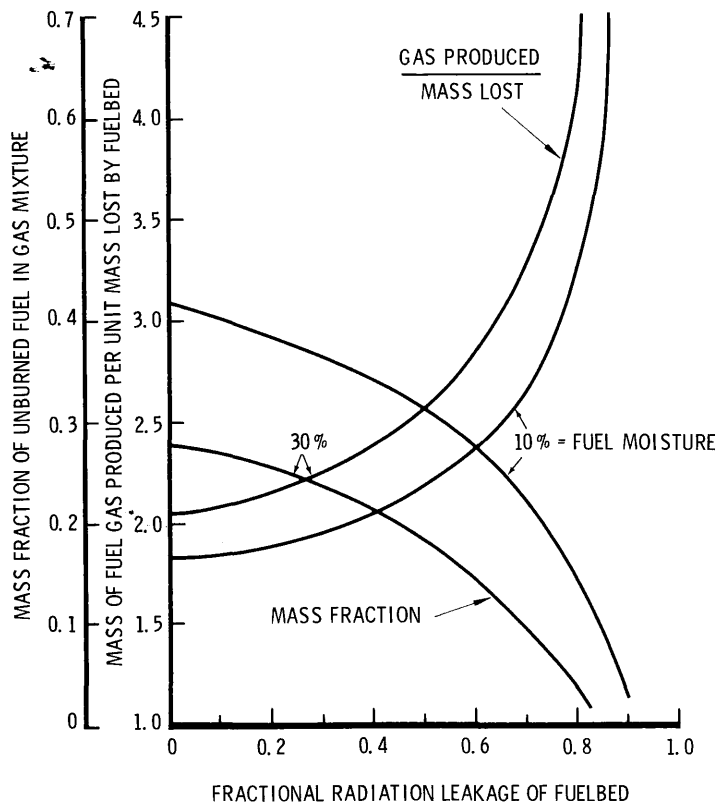


Figure 10B.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of whole fuel. Fuel in this figure is cellulose (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 15,340 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.17.

Figure 11A.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of volatile products only. Fuel in this figure is green chamise foliage (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,770 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction by 5.61.

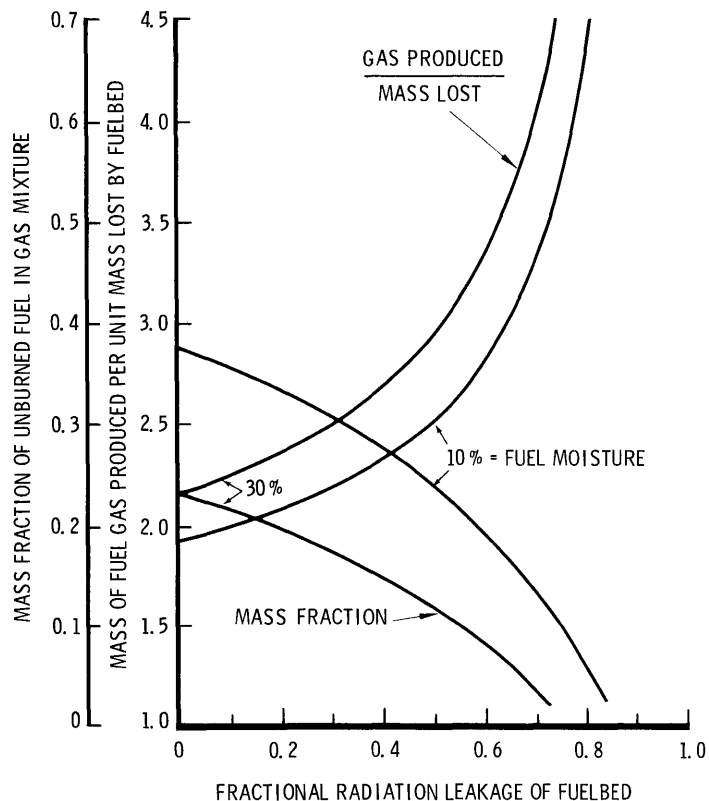
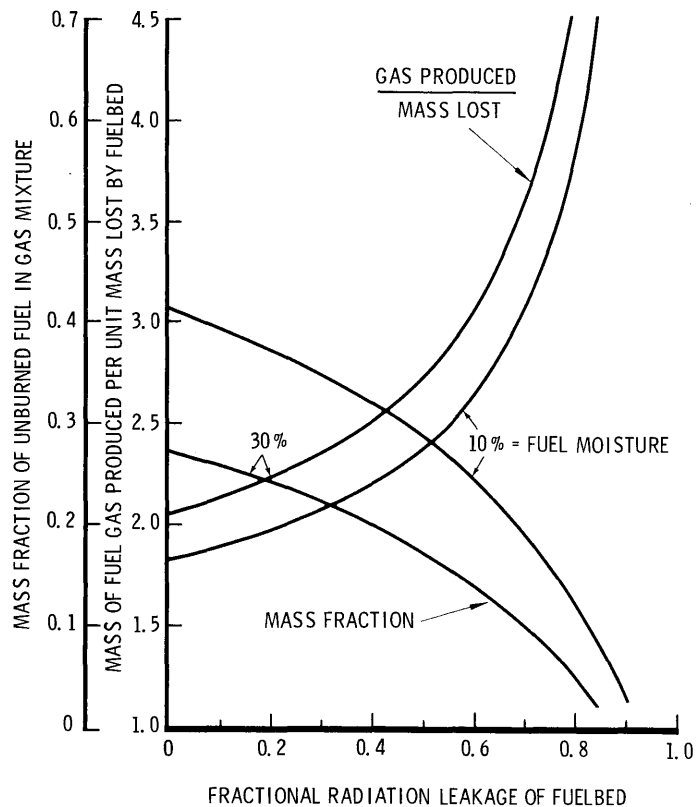


Figure 11B.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of whole fuel. Fuel in this figure is green chamise foliage (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,770 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.61.



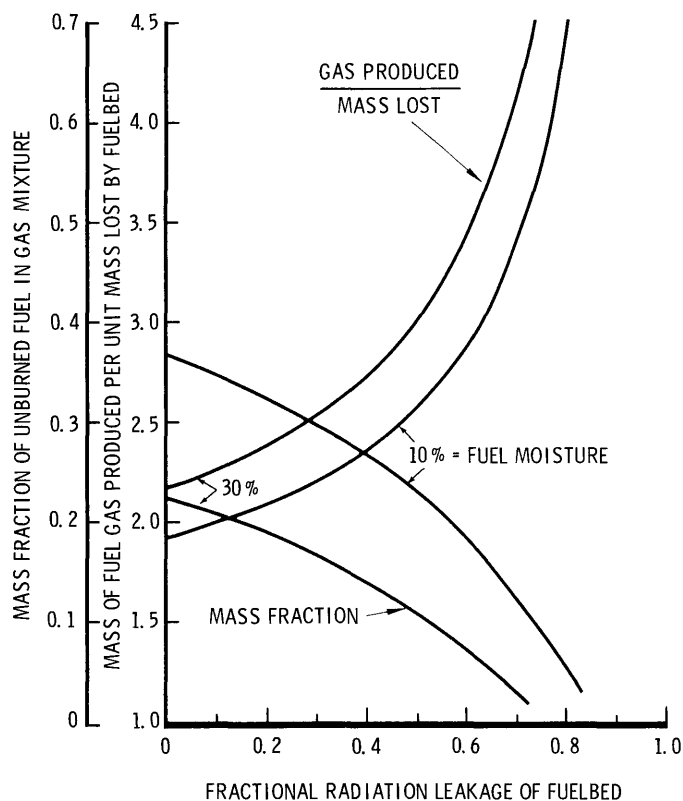


Figure 12A.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of volatile products only. Fuel in this figure is green manzanita foliage (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,310 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction by 5.47.

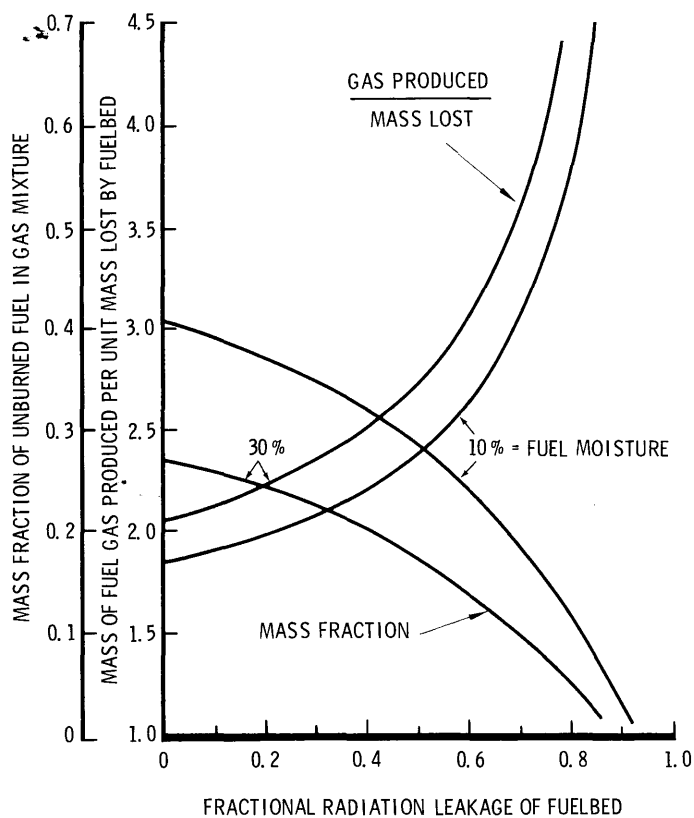


Figure 12B.--Variation of gaseous fuel properties with radiation leakage fraction. Curves are based upon balancing heat budget by combustion of whole fuel. Fuel in this figure is green manzanita foliage (see properties shown in table 1). To find the heat of combustion of the gaseous fuel produced, multiply the mass fraction values by 16,310 J/gm. The stoichiometric air/fuel mass ratio is found by multiplying the mass fraction values by 5.47.

Figure 13.--Variation of fuel gas properties with the char fraction formed from the solid fuel. Curves marked "1" are derived from a heat balance based upon burning of released volatiles only; curves marked "2" are based upon burning of whole fuel. The fuel is poplar excelsior, a surrogate forest fuel that has been often used to test the effectiveness of flame retardant chemicals. The principal influence of such chemicals is to increase char formation. The fuel moisture content in this case is set at 6 percent, typical of retardant test conditions. The radiation leakage fraction here is 0.1.

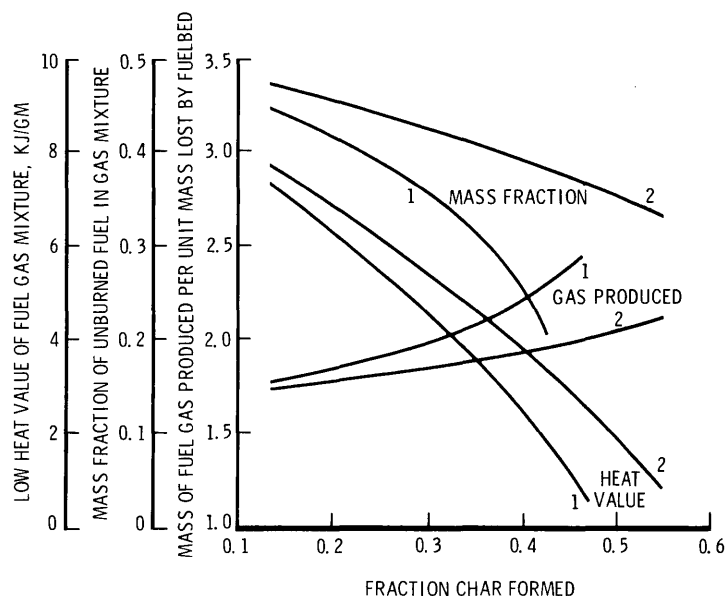
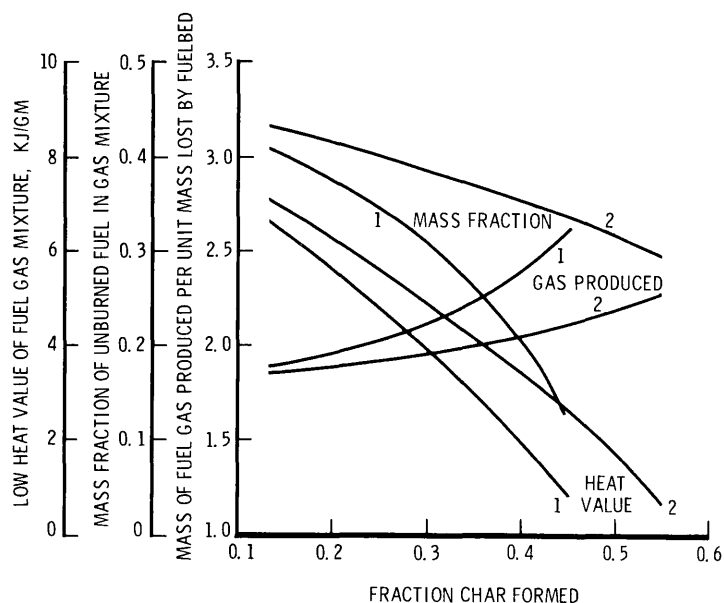


Figure 14.--Variation of fuel gas properties with the char fraction formed from the solid fuel. Curves marked "1" are derived from a heat balance based upon burning of released volatiles only; curves marked "2" are based upon burning of whole fuel. The fuel is poplar excelsior, a surrogate forest fuel that has been often used to test the effectiveness of flame retardant chemicals. The principal influence of such chemicals is to increase char formation. The fuel moisture content in this case is set at 6 percent, typical of retardant test conditions. The radiation leakage fraction here is 0.3.



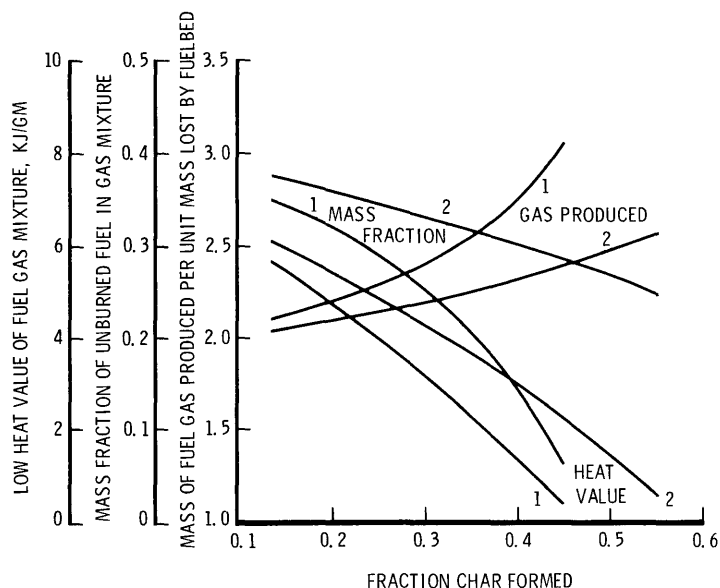


Figure 15.--Variation of fuel gas properties with the char fraction formed from the solid fuel. Curves marked "1" are derived from a heat balance based upon burning of released volatiles only; curves marked "2" are based upon burning of whole fuel. The fuel is poplar excelsior, a surrogate forest fuel that has been often used to test the effectiveness of flame retardant chemicals. The principal influence of such chemicals is to increase char formation. The fuel moisture content in this case is set at 6 percent, typical of retardant test conditions. The radiation leakage fraction here is 0.5.

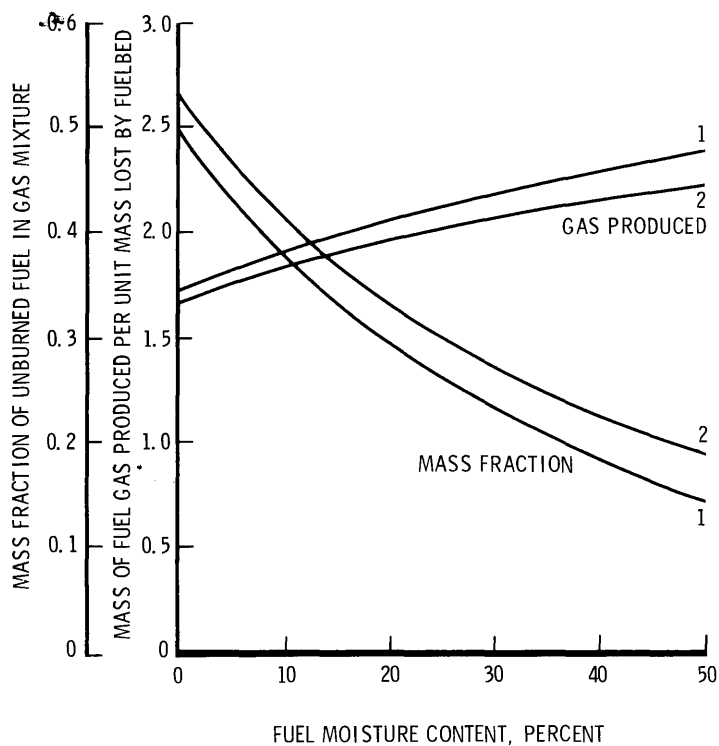


Figure 16.--Variation of fuel gas properties with moisture content for poplar excelsior treated with retardant to increase char fraction to 0.2. Radiation leakage fraction here assumed to be 0.1, typical of retardant test fuelbed geometry. To find the low heat value of the fuel gas mixture, multiply the mass fraction values by 15,070 J/gm. Similarly, the stoichiometric air/fuel mass ratio for the mixture is 5.09 times the mass fraction.

Figure 17.--Variation of fuel gas properties with moisture content for poplar excelsior treated with retardant to increase char fraction to 0.3. Radiation leakage fraction here assumed to be 0.1, typical of retardant test fuelbed geometry. To find the low heat value of the fuel gas mixture, multiply the mass fraction values by 12,760 J/gm. Similarly, the stoichiometric air/fuel mass ratio for the mixture is 4.38 times the mass fraction.

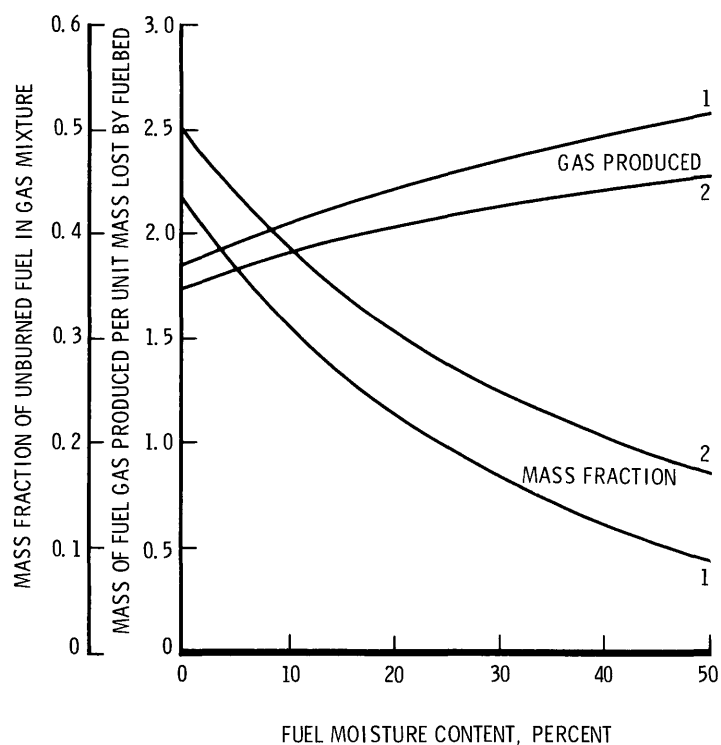
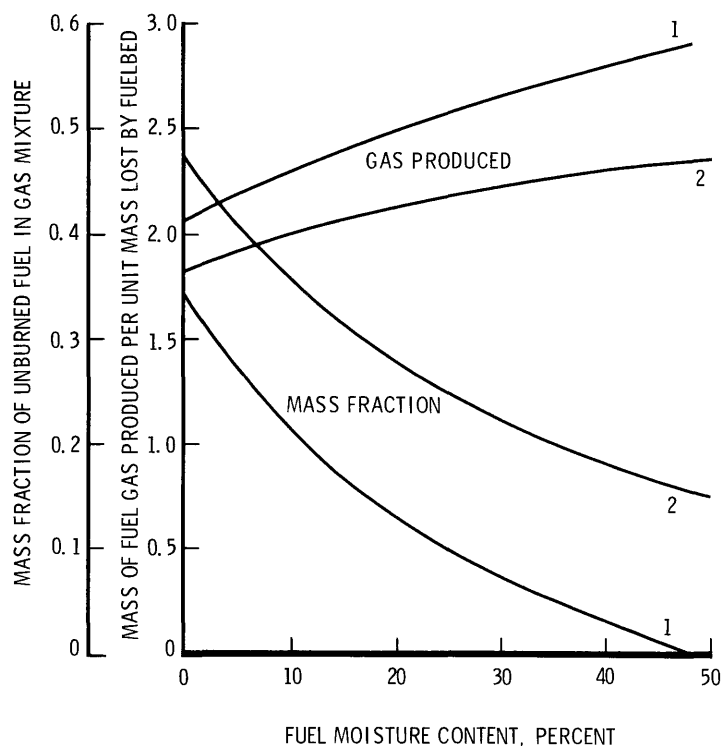


Figure 18.--Variation of fuel gas properties with moisture content for poplar excelsior treated with retardant to increase char fraction to 0.4. Radiation leakage fraction here assumed to be 0.1, typical of retardant test fuelbed geometry. To find the low heat value of the fuel gas mixture, multiply the mass fraction values by 9,690 J/gm. Similarly, the stoichiometric air/fuel mass ratio for the mixture is 3.45 times the mass fraction.



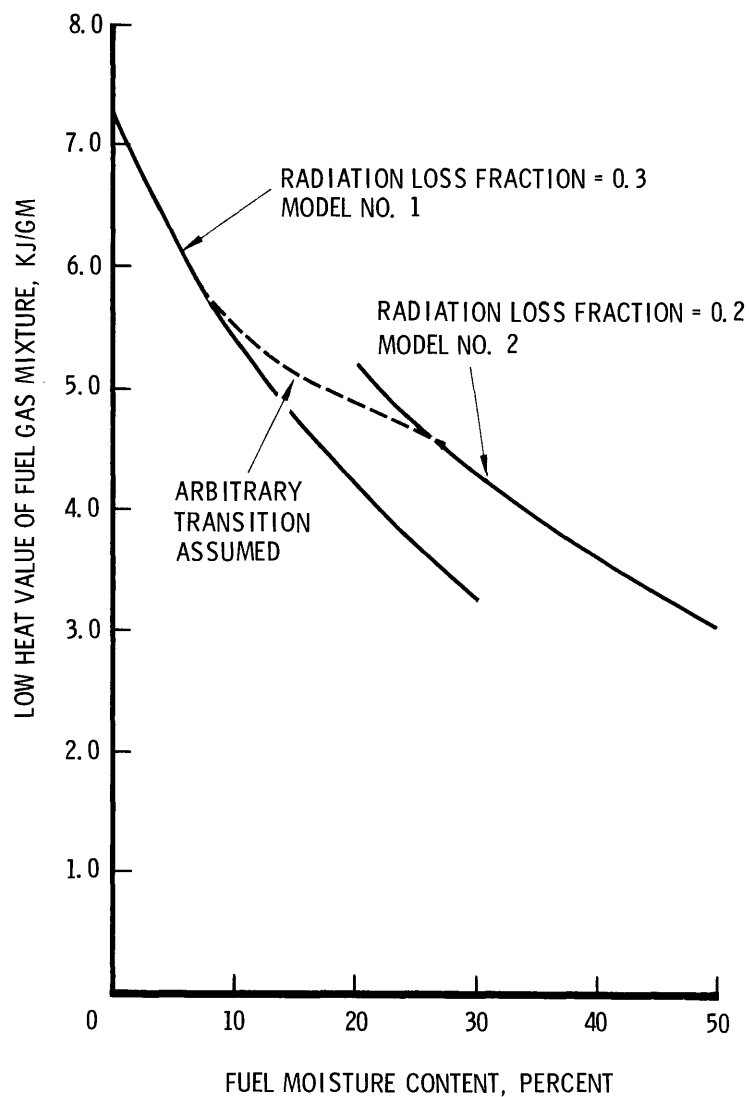
The model presented here is not a predictive tool in that a complete description of the fuel (in terms of the intrinsic properties of the fuel particle material, particle size, and fuelbed loading) does not permit the calculation of the thermochemical properties of the flame gases that would be generated if the fuel were burned. Not only does one have to specify the flame-fuel surface inclination angle (see appendix II) to derive a radiation leakage fraction, but one also must choose which of the two models to use. At this stage of development no way is seen to predict either the interface angle or which model to use. But, as was discussed above, fires that are spreading rapidly should exhibit large flame-fuel interface angles and might be expected to admit of little char burning in the flame-generating zone at the head of the fire. And fires propagating near the limit of extinction are known to exhibit near vertical flame-fuel interface orientations and more complete fuel consumption in the flaming zone.

If these two principles are tentatively accepted, then one might expect a fuelbed burned under very low moisture content conditions to be described by the first model (only volatile fuel burning in the flame-producing zone) and to exhibit a large radiation leakage fraction. The same fuelbed, burned at a moisture content such that it would barely qualify for description by the models given here, might have a vertical flame-fuel interface (hence showing the smallest radiation leakage fraction possible for the fuelbed) and might be best described using the second model. For conditions between these extremes, neither model would apply adequately by itself and the radiation leakage fraction would have intermediate values. So a graph showing the heat of combustion of bulk fuel gas versus fuel moisture content might follow a curve such as that shown in figure 19, drawn for a fuelbed of dead ponderosa pine needles arranged in a loose mat (opacity factor ≈ 2.5 --see appendix II). The two solid curves show the behavior expected under the limiting conditions and the dashed line connecting the two is included only to illustrate that a smooth transition between the two is to be expected over some range of fuel moisture content. The shape of the composite curve, including the dashed line, is reminiscent of the "moisture damping" coefficient curves given by Rothermel (1972) based upon experimental measurements. Such similarity is encouraging but cannot be construed as supportive of this theoretical work.

Experimental confirmation or refutation of the theoretical developments presented here will be very difficult to obtain, since none of the predicted quantities are readily measured. It is tempting to speculate, however, that there exists a critical value of the heat of combustion or the stoichiometric air/fuel mass ratio of the fuel gas mixture below which the flaming combustion zone would collapse as a coherent structure. If so, perhaps the fuel intrinsic properties, moisture content, and fuelbed opacity parameter (hence radiation loss fraction--see appendix II) combinations that lead to this condition could be used to correlate and to predict the occurrence for other fuel/moisture/fuelbed opacity combinations. Controlled-condition laboratory fires near the extinction limit are both difficult and time consuming, but work in progress at present⁴ may lead to sufficient data to test the concept.

⁴Ralph Wilson, "Moisture damping of fires under variable fuel loading conditions." USDA For. Serv. Study Plan 2103-12; Intermt. For. and Range Exp. Stn., Northern For. Fire Lab., Missoula, MT, Line Project FS-INT-2103, Fire Fundamentals, 22 July 1977.

Figure 19.--Variation of heat of combustion of fuel gas mixture with fuel moisture content. Fuel is ponderosa pine needles arranged in a loose mat, so the radiation loss fraction lies between 0.2 and 0.3 for all values of fuel-fire interface angle between 10 and 90 degrees (see appendix II). The two solid curves show the behavior expected in the extreme conditions; the dashed line indicates that a smooth transition between the two is to be expected over some range of moisture contents. Model 1 implies combustion of volatile fuels only in the flame-producing zone while model 2 implies combustion of whole fuel.



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APPENDIX I: HEAT AND MASS BALANCE MODEL

This appendix presents the mathematical formulation of the models described in the text, with some elaboration. Assumptions and approximations discussed in the text will not be reiterated here, but will be briefly indicated as they are introduced. First the "debit" side of the heat budget is developed for a unit mass of dry solid fuel. Then two alternative forms of the energy supply budget are derived, as outlined in the text. Symbols are defined as they are introduced, for the sake of clarity.

Heat Required by a Unit Mass of Fuel

The heat energy needed to raise the temperature of a unit mass of dry solid fuel from ambient to 500°C, reducing it to char and liberating the volatilizable component, is a measurable quantity that seems to be a property of the fuel material. Example values of this quantity are tabulated in the text. Let this quantity of heat be represented by H_D .

Before the fuel reaches the char state, it will have become involved in flaming combustion, as described in the text. In order to take account of the loss of energy by radiation leakage, it is necessary to estimate the amount of heat absorbed by the fuel before flame attachment. This amount of heat, H_i , can be expressed, approximately, as follows:

$$H_i = M(C_{pW}(T_B - T_A) + L) + H_i'$$

where

M = moisture content of fuel (fraction dry weight)

C_{pW} = specific heat capacity of water = 4.18 J/gm/deg C

T_B = boiling temperature of water = 100°C

T_A = ambient temperature (assumed = 25°C)

L = latent heat of vaporization of water = 2260 J/gm

H_i' = heat required to raise the temperature of a unit mass of dry solid fuel to ignition temperature (a measured value--see tables in text)

so

$$H_i = H_i' + 2570M \quad \text{J/gm.}$$

Now if a fraction, F , of the energy radiated into the fuelbed ahead of the flame/fuel interface is lost (see appendix II), then the amount of heat required to raise a unit mass of fuel to ignition temperature is approximately H_I , where

$$H_I = H_i / (1 - F).$$

This is the energy output demanded from the process volume.

After the fuel has entered the flaming zone, the energy required to complete the char/volatilization process, H_p , is given by

$$H_p = H_D - H_1'$$

This energy will liberate the volatiles at a temperature-dependent rate as described in the text. To raise the temperature of the volatiles to a uniform temperature T^* ($= 500^\circ\text{C}$) requires an additional increment of heat, H_R . Assuming the bilinear rate of evolution described in the text, this quantity can be derived as follows:

Let $m(t)$ = the mass of gas evolved from a unit mass of solid fuel at time t after the gassification starts. Then

$$\frac{dm}{dt} = \left(\frac{dm}{dt}\right)_{\max} \cdot \begin{cases} (T - T_1)/(T_2 - T_1), & T_1 \leq T \leq T_2 \\ (T_3 - T)/(T_3 - T_2), & T_2 \leq T \leq T_3 \end{cases}$$

where

$$\begin{aligned} \left(\frac{dm}{dt}\right)_{\max} &= \text{the maximum rate of gas evolution, which occurs at temperature } T = T_2 \\ T_1 &= \text{temperature at which gas liberation starts } (\sim 200^\circ\text{C}) \\ T_2 &= \text{temperature at peak gas evolution rate } (\sim 350^\circ\text{C}) \\ T_3 &= \text{temperature at which gas evolution is complete } (\sim 450^\circ\text{C}). \end{aligned}$$

The rate at which energy (E) would have to be supplied to the evolved gas to bring it instantly up to the reference temperature T^* would be given by

$$\frac{dE}{dt} = \frac{dm}{dt} C_p (T^* - T)$$

where

C_p = specific heat capacity of volatiles.

Assuming that the temperature-versus-time curve for the fuel particle is adequately approximated by a straight line over the range $T_3 \leq T \leq T_1$,

$$dE = \left(\left(\frac{dm}{dt}\right)/\left(\frac{dT}{dt}\right)\right) C_p (T^* - T) dT$$

where

$$\frac{dT}{dt} \doteq \text{constant.}$$

The total mass of gas evolved is given by Δm , where

$$\begin{aligned} \Delta m &= \int_{T_1}^{T_3} \left(\left(\frac{dm}{dt}\right)/\left(\frac{dT}{dt}\right)\right) dT \\ &= \left(\left(\frac{dm}{dt}\right)_{\max} / \left(\frac{dT}{dt}\right)\right) \frac{1}{2} (T_3 - T_1) \end{aligned}$$

so the energy demand per unit mass of evolved gas is

$$\int_{T_1}^{T_3} \frac{dE}{dT} dT / \Delta m = \frac{2C_p}{T_3 - T_1} \int_{T_1}^{T_3} (T^* - T) \left\{ \frac{(dm)}{(dt)} / \left(\frac{dm}{dt} \right)_{\max} \right\} dT$$

and hence

$$H_R = (1 - \gamma) \frac{2C_p}{T_3 - T_1} \int_{T_1}^{T_3} (T^* - T) \frac{\left(\frac{dm}{dt} \right)}{\left(\frac{dm}{dt} \right)_{\max}} dT.$$

Here γ is the fraction of dry fuel converted to char (so $1 - \gamma$ is the fraction converted to volatiles).

$$H_R = \frac{2(1-\gamma)C_p}{T_3 - T_1} \left\{ \int_{T_1}^{T_2} (T^* - T) \frac{T - T_1}{T_2 - T_1} dT + \int_{T_2}^{T_3} (T^* - T) \frac{T_3 - T}{T_3 - T_2} dT \right\}$$

$$H_R = \frac{(1-\gamma)C_p}{T_3 - T_1} \left\{ (T_2 - T_1) \left[(T^* - T_1) - \frac{2}{3}(T_2 - T_1) \right] + (T_3 - T_2) \left[(T^* - T_3) + \frac{2}{3}(T_3 - T_2) \right] \right\}$$

Inserting the numerical values

$$C_p = 1.05 \text{ J/gm/deg C}$$

$$T_1 = 200^\circ\text{C}$$

$$T_2 = 350^\circ\text{C}$$

$$T_3 = 450^\circ\text{C}$$

$$T^* = 500^\circ\text{C}$$

this becomes simply

$$H_R = 175(1 - \gamma) \text{ J/gm.}$$

The steam (water driven off before ignition temperature is reached) must also be heated to the reference temperature T^* since it forms part of the effluent gas from the process volume also. The heat required by this component is H_s , where

$$H_s = MC_{ps}(T^* - T_B)$$

and

$$C_{ps} = \text{the mean specific heat capacity of water vapor in the temperature range } 100^\circ\text{-}1000^\circ\text{C} (= 2.09 \text{ J/gm/deg C})$$

$$H_s = 836M \text{ J/gm.}$$

The sum of the components listed above gives the heat, H_N , required to desiccate, heat, and decompose a unit mass of solid fuel and heat the char and gases (water and volatilized fuel) to the reference temperature T^* :

$$H_N = H_I + H_p + H_R + H_s.$$

Heat Available Through Partial Combustion

The net sensible heat demand H_N is to be met by the combustion of some of the fuel (either as gas or as whole fuel, gas plus char) within the process volume. In turn, the combustion product mass (air + consumed fuel) must be heated to the rich-limit combustion temperature, T_C , which process demands additional sensible heat. An equal fraction of the liberated moisture is assumed to be heated to T_C also.

Assume first that only volatile fuel is burned in the process volume. Let the fraction of the volatile fuel that is burned be X_1 and the heat of combustion (low heat value) of the volatile fuel be ΔH_V . Then if the stoichiometric air/fuel mass ratio of the volatile fuel is N_V , the net sensible heat released by this combustion, per unit mass of dry solid fuel is H_{A1} , where

$$H_{A1} = X_1(1-\gamma)(\Delta H_V - C_p(T_C - T^*) - N_V C_p(T_C - T_A) - MC_{ps}(T_C - T^*)).$$

Since we assume equal specific heat capacities for the volatile fuel, air, and combustion products, the heat of combustion of the volatiles need not be corrected for temperature.

Using the numerical values employed before, this reduces to

$$H_{A1} = X_1(1 - \gamma)(\Delta H_V - 630 - 1130N_V - 1255M) \quad \text{J/gm.}$$

Equating H_{A1} and H_N gives the equation for X_1 , the fraction of the volatile fuel burned in the process volume. The mass-averaged temperature, T_{M1} , of the gaseous fuel mixture leaving the process volume is readily expressed in terms of X_1 :

$$(MC_{ps} + (1-\gamma)(1+X_1N_V)C_p)(T_{M1} - T^*) = (1-\gamma)X_1(MC_{ps} + (1+N_V)C_p)(T_C - T^*).$$

This equation expresses a sensible heat balance in the gas phase. Solving for the mass-averaged temperature gives

$$T_{M1} = T^* + \frac{(T_C - T^*)(1 - \gamma)X_1(MC_{ps} + (1 + N_V)C_p)}{MC_{ps} + (1 - \gamma)(1 + X_1N_V)C_p}$$

or

$$T_{M1} = 500 + \frac{600(1 - \gamma)X_1(2M + 1 + N_V)}{2M + (1 - \gamma)(1 + X_1N_V)} \quad \text{deg C.}$$

The fraction of the mass of the exiting gas that consists of unburned volatile fuel vapor, Y_1 , is also simply expressed in terms of X_1 :

$$Y_1 = (1 - \gamma)(1 - X_1)/(M + (1 - \gamma)(1 + X_1N_V)).$$

The numerator is simply the fraction of the dry weight of a unit mass of fuel that leaves the volume unburned while the denominator is the mass of gas generated per unit (dry) mass of fuel processed. If the denominator is divided by the mass loss (as would be sensed by a weighing system under the fuelbed) per unit mass of dry fuel processed, we find the ratio of gaseous fuel mass evolved per unit mass loss by the fuelbed within the process volume, μ_1 :

$$\mu_1 = (M + (1 - \gamma)(1 + X_1 N_V)) / (M + 1 - \gamma).$$

The heat of combustion ΔH_{F1} of the gas mixture leaving the control volume, treated as a diluted fuel, is simply the product of Y_1 and ΔH_V . Similarly, the stoichiometric air/fuel mass ratio N_{F1} for this mixture is Y_1 times N_V .

In the second case discussed in the text, whole fuel is consumed in the process volume (i.e., equal fractions of char and volatile components) rather than just some of the volatiles. The development of the equations proceeds along the same lines as just above. Let the fraction of the whole fuel that is burned be X_2 , the low heat value of the (ash-free) whole fuel be ΔH_O , and the stoichiometric mass ratio of the (ash-free) whole fuel be N_O . The net sensible heat released by this partial combustion is H_{A2} , where

$$H_{A2} = X_2 \left((1 - \epsilon) (\Delta H_O - C_p (T_C - T^*) - N_O C_p (T_C - T_A)) - MC_{ps} (T_C - T^*) \right)$$

$$H_{A2} = X_2 \left((1 - \epsilon) (\Delta H_O - 630 - 1130 N_O) - 1255 M \right) \quad \text{J/gm.}$$

The parameter ϵ in this equation is the fraction of whole fuel (dry) weight that is mineral ash. This fraction is not converted to volatile (it is included in γ) but neither is it burned when the char burns. Again, equating H_{A2} and H_N gives the equation for X_2 , in terms of which the mass-averaged temperature, T_{M2} , of the mixture can be expressed:

$$T_{M2} = T^* + \frac{(T_C - T^*) X_2 (MC_{ps} + (1 - \epsilon)(1 + N_O) C_p)}{MC_{ps} + \left(1 - \gamma + X_2 (N_O (1 - \epsilon) + \gamma - \epsilon) \right) C_p}$$

$$T_{M2} = 500 + \frac{600 X_2 (2M + (1 - \epsilon)(1 + N_O))}{2M + 1 - \gamma + X_2 (N_O (1 - \epsilon) + \gamma - \epsilon)}.$$

The fraction of the exiting gas that consists of unburned volatile fuel vapor, Y_2 , in this case, is given by:

$$Y_2 = (1 - \gamma)(1 - X_2) / (M + 1 - \gamma + X_2 (N_O (1 - \epsilon) + \gamma - \epsilon)).$$

As before, the heat of combustion of the gas mixture, ΔH_{F2} , is $Y_2 \Delta H_V$ and the stoichiometric air/fuel mass ratio, N_{F2} , is $Y_2 N_V$.

The ratio of gaseous fuel mass produced to fuelbed mass lost in the process volume, μ_2 , can be expressed in terms of X_2 also:

$$\mu_2 = \frac{M + 1 - \gamma + X_2(N_O(1 - \epsilon) + \gamma - \epsilon)}{M + 1 - \gamma + X_2(\gamma - \epsilon)}$$

In the expression for H_{A2} above, the heat of combustion of the whole fuel, ΔH_O , should be corrected for the difference in enthalpy changes between reactants and products due to the temperature shift between the posited reference temperature T^* and the temperature at which the heat of combustion is measured (usually $\sim 25^\circ\text{C}$). But this difference would be composed only of product of γ , the difference between the specific heat capacities of solid and gas phase reactants, and the temperature shift, plus the heat of reaction (including phase change) associated with the pyrolysis process. This "latent heat" term is known to be very small, but it is not clear whether the process is generally exothermic or endothermic (Roberts 1971). In any case the difference between the heat of reaction at the elevated reference temperature and the usual laboratory temperature of determination is small and will be neglected here.

Simplification and Summary of Equations

The number of input variables required to use the equations given above is quite large. Fortunately, additional simplifications are possible by using the approximations and empirical relationships discussed in the text.

The heat of combustion of the volatile component, ΔH_V , can be calculated from the equation for the whole fuel heat of combustion, ΔH_O , and the heat of combustion of the (ash-free) char, ΔH_C .

$$(1 - \epsilon)\Delta H_O = (1 - \gamma)\Delta H_V + (\gamma - \epsilon)\Delta H_C,$$

so

$$\Delta H_V = ((1 - \epsilon)\Delta H_O - (\gamma - \epsilon)\Delta H_C)/(1 - \gamma)$$

where all heats of combustion are low heat values and ΔH_C is taken to be constant at 31,200 J/gm.

The high heat value of the volatile fuel, $\Delta H_V'$, is calculated from ΔH_V and the estimate that these volatiles contain 7.2 percent hydrogen. Similarly, the whole fuel high heat value $\Delta H_O'$ is calculated assuming a 6.3 percent hydrogen fraction by weight.

$$\Delta H_V' = \Delta H_V + 1580 \quad \text{J/gm}$$

$$\Delta H_O' = \Delta H_O + 1380 \quad \text{J/gm}$$

These values are used to calculate the stoichiometric air/fuel mass ratios, using the figure 3270 J/gm air as an empirical constant (see discussion in text):

$$N_V = \Delta H_V'/3270$$

$$N_O = \Delta H_O'/3270.$$

Other constants used in the calculations leading to the figures presented in the text were introduced above as the need arose. The set of equations used is assembled here for ready reference, with numerical values inserted.

DATA REQUIRED

H_D = heat required to raise unit mass of dry fuel to 500°C, J/gm

H_i' = heat required to raise unit mass of dry fuel to 325°C, J/gm

γ = fraction of fuel (dry weight) converted to char, ash included

ϵ = fraction of fuel (dry weight) that is mineral ash

ΔH_O = low heat value of ash-free whole fuel (dry weight basis)

M = fuel moisture content, fraction of dry weight

F = fraction of heat radiated into fuelbed from process volume that is lost to the environment (calculated in appendix II)

EQUATION SUMMARY

$$H_i = H_i' + 2570M$$

$$H_I = H_i / (1 - F)$$

$$H_P = H_D - H_i'$$

$$H_R = 217(1 - \gamma)$$

$$H_S = 836M$$

$$H_N = H_I + H_P + H_R + H_S$$

$$\Delta H_V = ((1 - \epsilon)\Delta H_O - (\gamma - \epsilon)31,200)/(1 - \gamma)$$

$$\Delta H_V' = \Delta H_V + 1580$$

$$\Delta H_O' = \Delta H_O + 1380$$

$$N_V = \Delta H_V' / 3270$$

$$N_O = \Delta H_O' / 3270$$

$$X_1 = H_N / ((1 - \gamma)(\Delta H_V - 630 - 1130N_V - 1255M))$$

$$T_{MI} = 500 + \frac{600(1 - \gamma)X_1(2M + 1 + N_V)}{2M + (1 - \gamma)(1 + X_1N_V)}$$

$$Y_1 = (1 - \gamma)(1 - X_1) / (M + (1 - \gamma)(1 + X_1N_V))$$

$$\mu_1 = (M + (1 - \gamma)(1 + X_1 N_V)) / (M + 1 - \gamma)$$

$$\Delta H_{F1} = Y_1 \Delta H_V$$

$$N_{F1} = Y_1 N_V$$

$$X_2 = H_N / ((1 - \epsilon)(\Delta H_O - 630 - 1130N_O) - 1255M)$$

$$T_{M2} = 500 + \frac{600X_2(2M + (1 - \epsilon)(1 + N_O))}{2M + 1 - \gamma + X_2(N_O(1 - \epsilon) + \gamma - \epsilon)}$$

$$Y_2 = (1 - \gamma)(1 - X_2) / (M + 1 - \gamma + X_2(N_O(1 - \epsilon) + \gamma - \epsilon))$$

$$\mu_2 = \frac{M + 1 - \gamma + X_2(N_O(1 - \epsilon) + \gamma - \epsilon)}{M + 1 - \gamma + X_2(\gamma - \epsilon)}$$

$$\Delta H_{F2} = Y_2 \Delta H_V$$

$$N_{F2} = Y_2 N_V$$

APPENDIX II: RADIATION LEAKAGE CALCULATION

In this appendix we calculate an approximate value for the fraction of radiant energy emitted from the ignition surface into the fuelbed that escapes being intercepted by fuel particles. To do this we approximate the radiating surface (actually the boundary of the radiating volume) as a plane, inclined at an angle, α , to the horizontal. Assuming that this surface radiates energy in accordance with Lambert's cosine law (Gebhart 1961) and that the problem can be considered two dimensional (i.e., that the fire front is extremely long compared to the extent of the flaming zone in the direction of spread and compared to the depth of the fuelbed), the calculation reduces to a relatively simple problem.

The fuelbed is treated as an absorbing continuum; scattering and reradiation are ignored. The extinction of a ray along its straight line path can be expressed as an exponential decay of intensity:

$$I(s) = I(0)\exp(-ks)$$

where

s = distance along the (straight) ray path

$I(s)$ = intensity of radiation at distance s along ray path

$I(0)$ = intensity of radiation leaving the plane surface in the direction of the ray

k = the extinction coefficient, a property of the fuelbed.

Using this functional form we merely calculate the relative intensity of radiation reaching the fuelbed upper and lower surfaces from each point of the flame interface and integrate over the interface to determine the total fractional leakage.

Consider a differential element dL of the radiating plane surface, located a distance L from the lower boundary of the fuelbed, L being measured along the inclined surface. From this element of surface is radiated, in the direction $(\theta, \theta+d\theta)$ measured from the outward normal to the surface, the differential fraction d^2f of the total power radiated by the surface:

$$d^2f = (dL \sin \alpha / \delta) (\cos \theta \, d\theta / 2)$$

where δ is the depth of the fuelbed (so $\delta / \sin \alpha$ is the length of the interface). The fraction of this power that reaches a boundary of the fuelbed is $\Phi(L, \theta)$, where

$$\Phi(L, \theta) = \exp(-kD)$$

where D is the distance from the surface, at L , to the boundary in the direction θ . Since the surface is inclined at angle α to the horizontal and the depth of the fuelbed is δ , we can express D as:

$$D = \begin{cases} L \sin \alpha / \cos(\theta - \alpha), & \alpha - \pi/2 \leq \theta \leq \pi/2 \\ -(\delta - L \sin \alpha) / \cos(\alpha - \theta), & -\pi/2 \leq \theta \leq \alpha - \pi/2. \end{cases}$$

The first form represents loss to the lower boundary and the second represents loss to the upper boundary.

The net fractional energy loss is given by F, where

$$F = \int_{L=0}^{\delta/\sin\alpha} \int_{-\pi/2}^{\pi/2} \frac{\cos \theta}{2} \frac{\sin \alpha}{\delta} \exp(-kD) d\theta dL.$$

Carrying out the integral over L first, this becomes

$$F = \frac{1}{2k\delta} \left\{ \int_{-\pi/2}^{\alpha-\pi/2} (\exp(k\delta/\cos(\alpha-\theta)) - 1) \cos \theta \cos(\alpha-\theta) d\theta \right. \\ \left. + \int_{\alpha-\pi/2}^{\pi/2} (1 - \exp(-k\delta/\cos(\theta-\alpha))) \cos \theta \cos(\theta-\alpha) d\theta \right\}.$$

Changing to the variable $x = \alpha - \theta - \pi/2$ in the first integral and $x = \alpha + \pi/2 - \theta$ in the second gives the form

$$2k\delta F = \int_0^{\alpha} \sin x \sin(\alpha-x) (1 - \exp(-k\delta/\sin x)) dx \\ + \int_{\alpha}^{\pi} \sin x \sin(x-\alpha) (1 - \exp(-k\delta/\sin x)) dx.$$

Replacing $k\delta$ by C and differentiating the expression above twice with respect to the angle α gives

$$2C \frac{d^2 F}{d\alpha^2} = 2 \sin \alpha (1 - \exp(-C/\sin \alpha)) - 2CF.$$

By this device it is possible to evaluate the integrals indirectly, by solving the differential equation numerically. The set of equations then is:

$$\begin{aligned}
CF|_{\alpha=\pi/2} &= \frac{1}{2} \left\{ \int_0^{\pi/2} \sin x \cos x (1 - \exp(-C/\sin x)) dx \right. \\
&\quad \left. - \int_{\pi/2}^{\pi} \sin x \cos x (1 - \exp(-C/\sin x)) dx \right\} \\
&= \frac{1}{2} \left\{ 1 - \int_0^1 u \exp(-C/u) du + \int_1^0 v \exp(-C/v) dv \right\} \\
&= \frac{1}{2} \left\{ 1 - 2C^2 \int_C^{\infty} (1/t^3) \exp(-t) dt \right\} \\
&= \frac{1}{2} \left\{ 1 - (1 - C) \exp(-C) - C^2 E_1(C) \right\}
\end{aligned}$$

where $E_1(C)$ is the exponential integral (Abramowitz and Stegun 1964)

$$\begin{aligned}
E_1(C) &\equiv \int_C^{\infty} \exp(-t) dt/t \\
\frac{d}{d\alpha}(CF)|_{\alpha=\pi/2} &= 0 \\
\frac{d^2}{d\alpha^2}(CF) &= \sin \alpha (1 - \exp(-C/\sin \alpha)) - CF.
\end{aligned}$$

The differential equation was solved numerically using a standard Runge-Kutta integration program coded for the CDC-7600 computer at the Lawrence Berkeley Laboratories computer facility on the University of California, Berkeley, campus. A polynomial approximation for the exponential integral (Abramowitz and Stegun 1964) was used to establish the initial condition for various values of the parameter C . Figure II-1 is a plot showing the variation of the radiation loss fraction, F , as a function of the fuelbed opacity parameter, C , for two values of the tilt angle (α) of the flame interface surface.

The parameter C can be related to familiar fuelbed descriptors, since the extinction coefficient, k , is given by Anderson (1969)

$$k = \sigma\beta/4$$

where

σ = fuel particle surface area/volume ratio
 β = fuelbed packing ratio, the fraction of fuelbed volume filled with solid fuel particles.

From this form we have

$$C = \sigma\beta\delta/4$$

which has values in the range from about 0.5 (e.g., for sparse grass) to perhaps 5.0 or more (e.g., for pine litter). This range of values gives rise to potential radiation leakage fractions of 0.1 to 0.7 (see fig. II-1) and greater variability is readily conceivable.

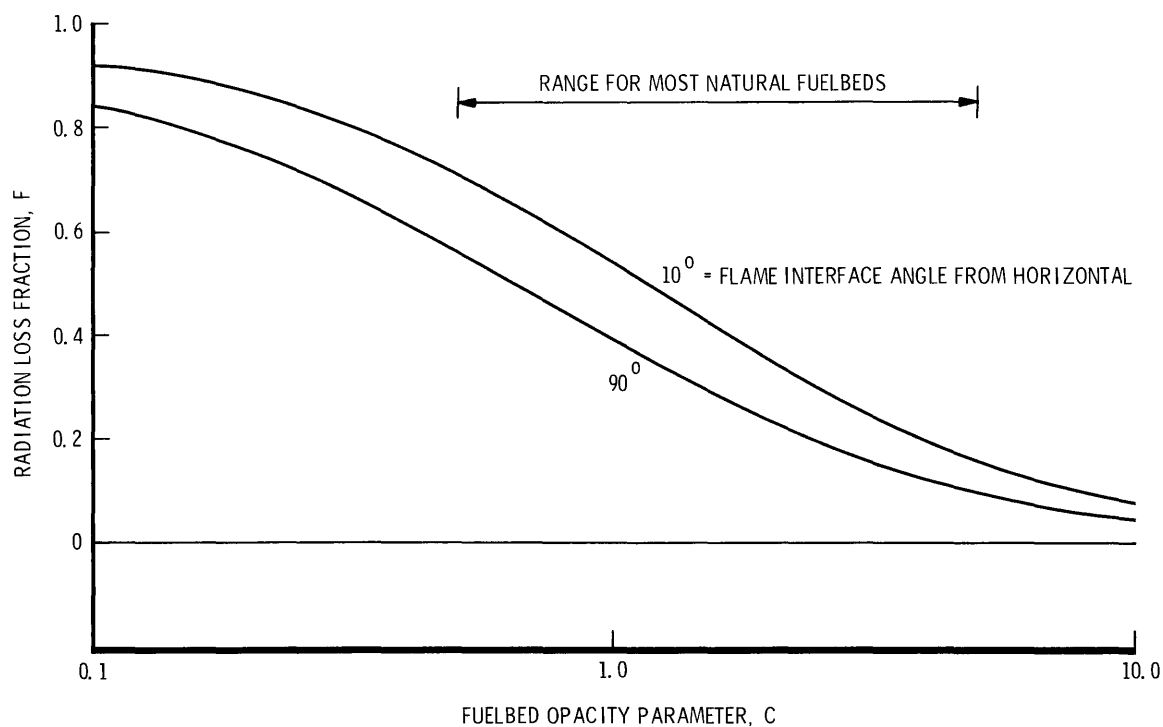


Figure II-1.--Variation of the radiation loss fraction, F , with fuelbed opacity parameter, C .

The dependence of the chemical properties of the gases fueling the free flame upon the geometrical properties of the fuelbed raises the possibility that the elusive "moisture of extinction" variable (Rothermel 1972; Albini 1976) may be predictable from such considerations.

The equation for C can be written also in terms of w , the weight loading (for single size class fuelbeds) and ρ , the density of the fuel particles. Since

$$\beta = w/\rho\delta$$

$$C = \sigma w/4\rho.$$

For fuelbeds with more than one size class, the value of C is to be found by summing the values for each of the individual components.

Albini, Frank A.

1979. Thermochemical properties of flame gases from fine wildland fuels. USDA For. Serv. Res. Pap. INT-243, 42 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Describes a theoretical model for calculating thermochemical properties of the gaseous fuel that burns in the free flame at the edge of a spreading fire in fine forest fuels. Predicted properties are the heat of combustion, stoichiometric air/fuel mass ratio, mass-averaged temperature, and mass fraction of unburned fuel in the gas mixture emitted from the flame-producing zone. These variables depend upon readily determined intrinsic properties of the fuel, the fuel moisture content, fuel particle surface/volume ratio, particle mass density, and fuel loading. Numerical examples are given for several fuel types, exploring the sensitivity to moisture content, char fraction formed (an inherent property of the fuel that can be modified by fire retardants), and an energy-leakage fraction related to fuelbed opacity. All the equations are given in appendixes.

KEYWORDS: flame, heat of combustion, stoichiometry, fuel moisture content, char, volatiles, burning characteristics, combustion properties.

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The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

The Intermountain Station includes the States of Montana, Idaho, Utah, Nevada, and western Wyoming. About 273 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

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Provo, Utah (in cooperation with Brigham Young University)

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