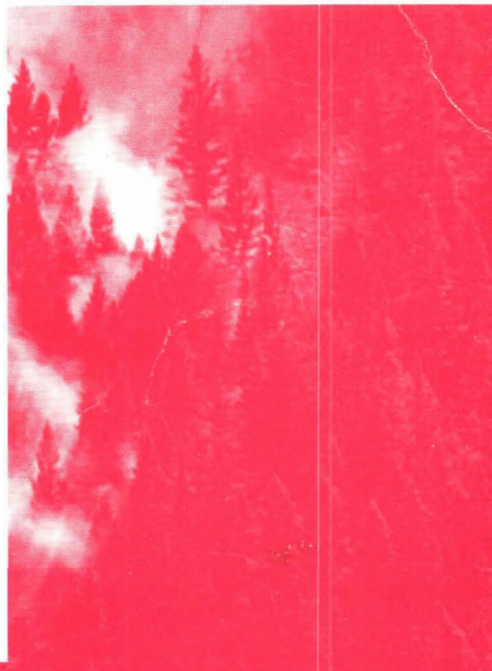
ESTIMATING WILDFIRE BEHAVIOR AND EFFECTS

Frank A. Albini



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ABSTRACT

This paper presents a brief survey of the research literature on wildfire behavior and effects and assembles formulae and graphical computation aids based on selected theoretical and empirical models. The uses of mathematical fire behavior models are discussed, and the general capabilities and limitations of currently available models are outlined.

Rothermel's fire spread model is used to develop nomographs for estimating rate of spread, reaction intensity, and flame length for a variety of "typical" fuel complexes, under widely variable conditions. Factors affecting spread rate and overall shape of a fire are quantified, as well as some fire effects such as crown scorching and duff removal.

Appendices give more details of the formulations presented graphically in the text, including the definitions of terms used to quantify fire behavior and effects and tables of numerical factors for converting values to different units of measurement.

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INTRODUCTION

This document is an outgrowth of a short course in fire behavior estimation.[1] It is not intended to be an exhaustive survey or even a thorough introduction to the material, but a starting point from which the interested reader may venture into the literature of fire behavior modeling. Some theoretical and empirical relationships are presented, along with computation aids that may prove to be useful to those concerned with wildland fire behavior and effects.

Although fire behavior prediction is by no means a new field, the use of complex mathematical models for this purpose has only recently begun. The availability of computers has made the use of very complicated models a routine procedure in research, and allows complex calculations to be done by machines instead of people. The result is that more powerful models are now easy to use.

The purpose of this report is to introduce fire behavior specialists to some tools being developed in research which may be useful for predicting fire behavior. Through the process of constructive "feedback," research efforts can be tailored better to fit the needs of those who use research results. The continuation of such a dialogue about fire behavior modeling is actively being sought here.

USES OF FIRE BEHAVIOR MODELS

Potential uses of fire behavior models span the spectrum of fire-related decision-making. From land use planning to prescribed fire design, models are used to aid decisionmakers. The nature of the decisions being made, and the consequences of errors, determine the types of predictions and the degree of accuracy required of the model output. Here we review some model uses and indicate the type of output needed and the general level of accuracy each requires.

Fire-Danger Rating

Fire-danger rating is a management tool used to establish the degree of fire hazard and the risk of fire outbreak. On the basis of such assessments, decisions are made concerning land use and fire control readiness. The National Fire-Danger Rating System (NFDRS) (Deeming and others 1974) is a multiple-index scheme designed to provide fire control and land management personnel with a systematic means of assessing various aspects of fire danger on a day-to-day basis.

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[1]Albini, Frank A. Advanced Fire Management Training Course, National Fire Training Center, Marana Air Park, Marana, Arizona, November 11-22, 1974.

Although easy to use because of its tables of indices, the system is based on complicated models of fire behavior. The multiple-index concept allows the assessment of different aspects of fire behavior (Deeming and others 1974; USDA Forest Service 1962). For example, in the National Fire-Danger Rating System, the spread component is calculated from predicted forward rate of spread, the energy release component from a rate of heat release per unit area, and the burning index from an estimate of flame length.

Model outputs need not be highly accurate for this use. It is important that the system of models (fire behavior models and fuel models) properly rank the fire behavior variables estimated and that they respond to changes in weather consistently and with sufficient sensitivity to permit decision boundaries to be established. For these purposes, stylized fuel models are entirely adequate, and indices of *relative* severity of fire behavior are sufficient.

Fire Control Planning

Fire control planning is a complex job of resource allocation. When, where, and to what level to man stations; the rules for initial attack dispatching; and the material to include in a fireline handbook may sound like unrelated questions, but to be answered they have a common need for data--estimation of fire behavior.

Although the estimation of wildfire behavior is a significant ingredient in the planning of fire control activities and the allocation of fire control resources, it is by no means the only (and frequently not even the principal) ingredient. Considerations such as resource value threatened, relative risk of ignition, transportation, communications, equipment capabilities, etc., often dominate the problem of manning stations and initial attack dispatching. The experienced fireman on the scene of a fire must be the source of predictions of potential fire behavior. The potential fire behavior entries in handbooks and training aids are only for purposes of quick, preliminary assessment.

Models that predict fire behavior can be useful in manning and dispatching planning if they are no more precise than the stylized models of the NFDRS; indeed, danger-rating indices themselves are used for these purposes. So the accuracy requirements for fire behavior estimation for these planning efforts are no more stringent than for fire-danger rating. This same general level of precision is probably adequate for fireline handbooks and similar training aids as well, but instead of indices, the models should provide actual estimates of forward rate of spread, perimeter growth, intensity, flame length, etc.

These same kinds of estimates, except with slightly better accuracy (say, "factor-of-two" accuracy?), might be useful to fire behavior officers. For quantitative estimation, if the models are easy enough to use under field conditions, and if they offer at least enough resolution between fuel types to exhibit significant differences, models may be useful additions to the tools of the fire behavior officer's trade.

A set of working charts for estimating forward rate of spread, intensity, flame length, and crown scorch height are included in this document. This is done in hopes that those concerned will try them and communicate to the author their assessments of the utility and accuracy of the charts. They are also intended for use as training aids and may be useful in some dispatching activities. Comments on these kinds of applications are also solicited.

Prescribed Fire Planning

Prescribed fires are used in many areas and for many purposes (Peet 1965; USDA Forest Service 1971; Fahnestock 1973; USDA Forest Service, n.d.). Hazard reduction (Pagni and others 1971; Green 1970; Schimke and Green 1970), species control (Pechanec and Blaisdell 1954), habitat improvement (Cushwa and others 1969; Leege 1968), silviculture (Roe and others 1971; Beaufait 1966), reduction of air pollution from wildfire smoke (Hall 1972; Mobley and others 1973; USDA Forest Service, n.d.), etc., are objectives of prescribed burning.

To plan prescribed fires to achieve stated objectives, to minimize cost of control and mopup, and to reduce the risk of escape or undesirable behavior, a firm basis of fire behavior estimation must be established. This basis should include not only the gross behavior of the fire but its effects on the surrounding environment. So, predictive models that allow the estimation of spread rate, intensity, flame length, etc., should be useful in prescription formulation but may not suffice to prejudge relevant fire effects such as fuel reduction, smoke generation, soil conditioning, and others.

Because specific effects are sought and specific sites are burned under preselected conditions to achieve them, in many cases prescribed burning poses the most stringent requirements for fire behavior prediction models. The use of preestablished fuel bed descriptions (such as the fuel models of the NFDRS) may be inappropriate for accurate prediction as the specific site being burned may differ substantially from the assumed fuel bed. But such "stylized" or "typical" models may be useful in establishing *roughly* what the fire behavior will be before the first burn, or for estimating what the sense and magnitude of *changes* in fire behavior will be as the burning conditions vary. The computation aids presented later in this document are offered with these intended applications in mind. There is no substitute for experience, but these tools may be useful aids in extrapolating from known to slightly different conditions when coupled with experience and careful observation.

CAPABILITIES AND LIMITATIONS OF SOME AVAILABLE MODELS

There are many mathematical models of varying scope and complexity that deal with many of the elements mentioned above. Most of these models reside in the literature, but some have been put into a form useful to nonresearch personnel. We will concentrate on a few models and mention others only in passing. The purpose of this cursory review is to introduce the reader not active in fire research to the literature of this field and to indicate roughly the present state-of-the-art of fire behavior modeling.

Scope of Predictions Possible

Mathematical models exist that relate physical and chemical properties of fuel arrays to specific fire behavior, such as forward rate of spread, fire intensity, flame length, burning time, and others. The environmental variables of windspeed and slope are also required to operate the models, as well as fuel moisture content.

Rates of fire spread and growth.--Using mathematical models published by the authors listed below, it is possible to calculate forward rates of spread for various fuel complexes.

Author(s)	*Publication date*	*Type of fuel array considered*
Fons	1946	Light forest fuels
Fons, Clements & George	1963	Laboratory wood cribs
Thomas & Simms	1963	Forest fuels (grass, brush)
Hottel, Williams & Steward	1965	Arrays of paper sheets
Albini	1967	Brush
Anderson	1969	Uniform porous bed
Fang & Steward	1969	Randomly packed fine particles
Thomas	1971	Cribs, gorse, and heather
Steward	1971	Mathematically describable bed
Frandsen	1971	Uniform porous bed
Rothermel	1972	General (uniform) wildland fuels
Pagni & Peterson	1973	Uniform porous bed

Of the models listed above, Rothermel's wildland fuel spread model (1972) is the most comprehensive and robust to date. It has been subjected to some direct verification tests in logging slash assembled fuel beds (Brown 1972) and both prescribed and wild grass fires (Sneeuwjagt 1974). Stevenson and others (1975) were also able to match observations and after-the-fact predictions of spread rate in mixed chaparral-like fuels using the Rothermel model in conjunction with an area-growth computer algorithm (Kourtz and O'Regan 1971). We will focus on this model at length in this paper.

The forward rate of spread of a wildland fire is only one descriptor of growth.[2] The growth rate of the perimeter of a large fire, as well as its area and the shape of the perimeter, are also useful quantities to predict.

A computer-based model of great mathematical elegance, but with a voracious appetite for data, has been developed by Kourtz and O'Regan (1971) and will be used in the FIRESCOPE computer-assisted Multi-Agency Coordination Center (Hanna and others 1974) to assess fire growth potential. The data that this model uses include the rate of spread from point-to-point; these quantities are generated by Rothermel's model in the application cited.

A much simpler model assembled by Anderson[3] from data taken by Fons[4] allows one to estimate roughly the shape, size, rate of perimeter increase, and rate of area growth of a wind-driven wildland fire using only the forward rate of spread and windspeed as

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[2]Both George Fahnestock and Clive Countryman have pointed out to the author (private communications, 1975) that the term "rate of spread" has often been used to connote "rate of perimeter growth." The term "forward rate of spread" should be used to indicate head fire linear rate of advance. Current usage seems to favor the shorter phrase "rate of spread" for head fire rate of advance, but this unfortunate confusion of terms will no doubt persist for some time. Here we shall be explicit when referring to perimeter (or area) growth and use the phrase "rate of spread" for head fire rate of advance.

[3]Anderson, Hal E. Memorandum to R. C. Rothermel and W. C. Fischer on file at the Northern Forest Fire Laboratory, Missoula, Montana, August 10, 1973.

[4]Fons, Wallace L. Unpublished data on rate of growth and fire shape. On file at Pacific Southwest For. and Range Exp. Stn., For. Fire Lab., Riverside, Calif. [n.d.].

inputs. Van Wagner (1969) proposed a very similar method that predicts the same quantities; this method uses three rates of advance of the fire front--heading, flanking, and backing.

Fire intensity and related effects.--Byram (1959) defined a rather basic measure of fire intensity which has been proven very useful. Byram's fireline intensity has been used in describing the difficulty of controlling a fire because of the heat it produces (Hodgson 1968) and to predict or correlate flame length (Byram 1959), the height of scorching of conifer crowns (Van Wagner 1973), and the occurrence of spotting (Hodgson 1968). These relationships make this measure of intensity very valuable in fire behavior prediction. This intensity is defined as the rate of heat release per unit length of fire edge, and so is proportional to the rate of advance perpendicular to the edge.

Using a simple relationship between fuel particle size and burning time (Anderson 1969), or flame residence time, Rothermel's model can be used to predict Byram's intensity and the related aspects of fire intensity correlated to it.

Rothermel (1972) and Anderson (1969) make use of a different measure of intensity--the rate of heat release per unit area burning. This quantity appears directly in Rothermel's spread model and can be used in Thomas' (1963) equations correlating flame length and height with fire mass release rate. Thomas' equations are somewhat difficult to use in describing wildland fire flame behavior but usually predict a flame length approximately equal to that given by the equation given by Byram if one uses the flame width predicted by Anderson's relation as the characteristic dimension D in Thomas' equations.

Limitations on Accuracy of Predictions

The mathematical models cited above permit one to calculate various features of fire behavior. Some are easy to use, some very complicated, but all will be found to produce results which do not always agree with observed fire behavior. In some instances, the disagreement can be quite significant (Brown 1972; Lawson 1972).

There are three principal reasons for such disagreement, no matter which models are used:

1. The model may not be applicable to the situation.

2. The model's inherent accuracy may be at fault.

3. The data used in the model may be inaccurate.

Model applicability.--If one applies a model in a situation for which the model was not intended to be used, the "error" in the model's prediction can be very large. All the models discussed and cited above have the following limitations and should not be expected to predict what they do not pretend to represent:

1. The fuel bed modeled is continuous, uniform, and homogeneous. The more the real fuel situation departs from this ideal, the more erratic the predictions will be when compared to real fire behavior.

2. The fuel bed is a single layer and is contiguous to the ground, not an aerial layer, such as the crowns of coniferous trees. Although brush fires may technically be considered "crown fires" and have been treated by some of the above-mentioned models, a large-scale conifer crown fire is *not* specifically modeled and would probably be poorly predicted.

3. Fire spread by spotting (flying embers or firebrands) is not modeled by any of the models mentioned above, so fire spread rate in those situations where spotting is important will likely be poorly estimated.

4. Fire whirlwinds and similar extreme, fire-induced atmospheric disturbances are not modeled. Countryman (1971) provides guidance as to when such phenomena are to be expected, but actual predictions are not yet within the state-of-the-modelers'-art.

Accuracy of model relationships.--Wildland fires, being infrequent, unpredicted, and often occurring in inconvenient locations, are not ideal candidates for instrumentation and measurement. As a consequence, data to test theoretical or empirical formulae for wildfire behavior accumulate slowly. Model testing probably will continue to rely mostly on laboratory experiments and prescribed fire data, with occasional "windfall" wildfire observations.

The relationships between variables in all of the models must be viewed as weakly tested, semiempirical, and subject to exception. Where tests have been possible with sufficient rigor to test model relationship accuracy, they have usually shown the prediction errors to be within a few tens of percent on the average. Fire behavior varies over many orders of magnitude, and model builders consider models successful if the relationships predict fire behavior within a factor of two or three over a range of two or three decades. This can be taken as roughly representative of the current state-of-the-art in fire behavior model accuracy, including both the effects of applicability and internal accuracy. So until the limitations of model applicability outlined above are relaxed by further research, improvements in model relationship accuracy beyond the current level are unlikely to increase the overall accuracy of predictions.

The most important source of error in any particular prediction may be difficult to pin down to model applicability, model accuracy, or data accuracy. But the *internal consistency* of a well-disciplined mathematical model allows one to use it to assess the impact of changes in important variables for specific situations, even if the model overpredicts or underpredicts systematically, whether due to model inapplicability, model inaccuracy, or data errors.

For example, the effect of a 5 mi/h windspeed *increase* on the rate of spread in a grass-type fuel can be predicted to within a few tens of percent using Rothermel's (1972) model, but a specific prediction of spread rate at one windspeed in the same fuel type may be a factor of two high or low (Sneeuwjagt 1974).

Accuracy of data.--Fire behavior models should be sensitive to those parameters known to affect fire behavior, such as variations in fuel moisture, windspeed, slope, fuel bed depth, and others. If these data are not known accurately enough, model output may be significantly in error. It is easy to recognize the nature of and the effects of errors in data such as the windspeed, the slope, or the fuel moisture content. More subtle, yet equally important descriptors, such as fuel particle surface/volume ratios, the loading of fuel components in each size class, and the proportions of live and dead components, must also be specified accurately in order to predict fire behavior realistically. Rothermel's (1972) figures 24 and 25 illustrate dramatically the importance of these fuel bed descriptors in determining predicted fire intensity and forward rate of spread.

Because models of phenomena as complex as wildfire are, generally, quite nonlinear, the output may be highly sensitive to a particular parameter over one range of values and nearly insensitive to the same parameter in a different value range. For this reason, it is difficult to make a valid quantitative statement about the relationship between input data accuracy and output accuracy. The model in question must be used to establish its requirements for data accuracy, considering the range of values of the variables used for input.

If any general rule is valid, however, it is that most likely data accuracy will not be the factor which limits the validity of behavior model predictions. The usually dominating error source is that the fuel complex is not uniform, continuous, homogenous, and consolidated into a single layer. Nor is the windspeed constant, the slope everywhere the same, nor the fuel moisture content the same from place to place. After model applicability, probably the next most important error source is inherent model accuracy. If standard fuel inventory techniques are followed (Brown 1971, 1974; Van Wagner 1968b; USDA Forest Service 1959), it is unlikely that data accuracy would be the dominant error source. If no measurements are made, however, but estimates from observations are used, the accuracy of the estimates may cause errors as large as the first two sources, or even larger.

SOME FIRE BEHAVIOR COMPUTATION AIDS

In this section, some graphical results from the physical and mathematical relationships that make up some specific fire behavior prediction models are presented, and the reader is referred to some others. The presentation here will be brief by necessity. The interested reader is urged to consult the original documentation for a better understanding of the various models.

To apply models predicting fire behavior, it is necessary to have in hand specific definitions of the terms used to describe the phenomena. Appendix I discusses phenomena and defines their descriptive terms, and gives some tables showing conversion factors between various common units of measurement.

Appendix II presents and discusses the various models used in calculating the results given here. The discussions are brief, but the equations are given for the interested reader.

Rothermel's Spread Rate Model

Frandsen (1973a) programed a Hewlett-Packard Model 9820 minicomputer to calculate intensity and rate of spread from Rothermel's model. Recently, this program has been revised and extended by Ms. Patricia Andrews of the Northern Forest Fire Laboratory. In its current version, the program will not only solve a single problem, but will produce graphs of spread rate versus windspeed and/or reaction intensity versus fuel moisture. Written instructions on the operation of the new program can be obtained by writing to Ms. Andrews.

The Northern Forest Fire Laboratory maintains a computer-based library of fire behavior models at the Lawrence Berkeley Laboratories computer facility on the campus of the University of California at Berkeley. A Users' Manual (Albini 1976) is in preparation; draft copies are available from the author. Listing and card images of the FORTRAN IV source code are also available.

Nomographs for Stylized Fuel Models

By using Rothermel's equations (appendix II) and some stylized fuel models similar to those employed in the NFDRS (Deeming and others 1974), a set of graphs has been drawn that together can be used to estimate fire behavior in a wide variety of situations. A set of graphs has been constructed and organized for easy use. The fuel models used are described in detail in table 7, appendix III.

These sets of graphs, or working charts, are technically called nomographs, meaning graphical aids for the computation of numbers. The nomographs are collected at the end of this section.

The mathematical basis for the nomographs is the rate of spread model (Rothermel 1972) with minor modifications, as discussed in appendix III. Thus, the fire behavior described by the nomographs pertain to the leading edge of a spreading surface fire. *It does not include* spread by spotting (firebrands or embers), crown fire (spread through coniferous tree crowns), or the long-term residual fire intensity.

How to Use the Nomographs

1. Determine the best fuel model to use. The 13 fuel models contained in the set of nomographs are grouped into four general fuel community groups:

Grass and Grass-Dominated Fuel Complexes
Chaparral and Shrubfields
Timber Litter
Logging Slash

Although identified by an explicit, short name, the model usually will apply to more than one fuel situation. For example, fuel model 2, labeled "Timber (Grass and Understory)," also can be used for fire behavior assessment of southern pine clearcut slash. And fuel model 4, labeled "Chaparral (6 ft)," can also be used for heavy fresh "red" conifer logging slash.

Each of the fuel models in each general group has a set of brief descriptions of applicable "best-fits" fuel types and "can-also-be-used-for" fuel types. The reader is urged to skim over the four pages separating the groups of fuel models to become familar with the variety of models available and fuel communities to which they are intended to apply.

2. Determine the "variable" factors: windspeed, terrain slope, and fuel moistures. A working chart in the lower left-hand quadrant of each fuel model allows one to combine the measured 20-ft windspeed and the slope tangent to obtain an "effective windspeed." The procedure is explained in the text accompanying the chart on each figure.

For fires not driven by the prevailing wind (e.g., backing or flanking fire), use zero windspeed.

Fuel moisture for the dead fuel components can be taken from fire-danger rating assessments, fuel stick measurements on site, or from any other appropriate source. For models 1-5 and 8-10, use the 1-hour timelag fuel moisture. For models 6 and 7, if the data are available, combine the three moisture contents as follows:

$$\begin{aligned}\text{"Dead Fuel Moisture"} = {} & 0.89 \times (\text{1-hour timelag moisture}) \\ & + 0.09 \times (\text{10-hour timelag moisture}) \\ & + 0.02 \times (\text{100-hour timelag moisture}).\end{aligned}$$

For the logging slash models, 11-13, combine the three moisture contents as follows:

"Dead Fuel Moisture" = 0.76 × (1-hour timelag moisture)

+ 0.18 × (10-hour timelag moisture)

+ 0.06 × (100-hour timelag moisture).

Live fuel moisture (foliage moisture) is required for models 2, 4, 5, 7, and 10. If data are unavailable for estimating such moisture, the following rough estimates based on the stage of the dominant cover species in its annual cycle can be used:

300 percent--Fresh foliage, annuals developing, early in growth cycle.

200 percent--Maturing foliage, still developing, with full turgor.

100 percent--Mature foliage, new growth complete and comparable to older perennial foliage.

50 percent--Entering dormancy, coloration starting, some may have dropped from stems.

3. Proceed to calculate fire behavior using the nomograph with the appropriate effective windspeed range. For each fuel model, there are two nomographs--one for low and one for high windspeeds.

A. Enter the nomograph, via the upper right-hand scale, at the appropriate "Dead Fuel Moisture." Draw a horizontal line across the page at that point.

If only dead fuel is present in the fuel model, determine the point of intersection of this horizontal line with the S-shaped curve in the upper right-hand quadrant. From this point of intersection, draw a vertical line down through the lower right-hand quadrant. Call this "line A." Go on to step B, skipping the following steps.

If both live and dead fuels are present in the fuel model, determine the point of intersection of the horizontal line with the curve in the upper right-hand quadrant, which corresponds to the live fuel (foliage) moisture. Interpolate if necessary. These curves are labeled and also distinguished by different dot-and-dash patterns. From this point of intersection, draw a vertical line down through the lower right-hand quadrant. Call this "line A." *Continue the horizontal line* through the upper left-hand quadrant, connecting it to the "Dead Fuel Moisture" scale on the upper left-hand scale at the same value used to enter the nomograph on the upper right-hand scale.

The curves in the upper left-hand quadrant are labeled with the various live fuel moistures and are drawn with the same dot-and-dash patterns as their corresponding curves in the upper right-hand quadrant. *If the horizontal line intersects* the curve in the upper left-hand quadrant for the live fuel moisture being used, *then draw a straight line* through this point of intersection to the lower right-hand corner of this quadrant. Call this "line K." You will use this constructed line later, in step D. *If the horizontal line does not intersect* the curve of live fuel moisture being used, *you will not need to use a constructed line* in step D.

B. Line A, constructed in step A, extends vertically into the lower right-hand quadrant, crossing the lines labeled "Effective Windspeed" in that quadrant. You should already have determined the value of the effective windspeed using the small graph inset in the lower left-hand quadrant. If not, do so before proceeding; the

instructions are printed below the graph on each page. Determine the point of intersection of the vertical line with the line labeled with the value of the effective windspeed, interpolating if necessary. From this point of intersection, draw a horizontal line across the bottom of the nomograph, extending through the lower left-hand quadrant.

C. Determine the point of intersection of the horizontal line constructed in step B with the diagonal line in the lower left-hand quadrant. From this point of intersection, draw a vertical line into the upper left-hand quadrant, passing through the lines drawn in that quadrant.

D. *If only dead fuel is present in the fuel model*, then determine the point of intersection of the vertical line constructed in step C with the line labeled with the appropriate 1-hour timelag fuel moisture, interpolating if necessary. From this point of intersection, draw a horizontal line back through the upper right-hand quadrant. Call this "line D." Go on to step E and read results.

If both live and dead fuels are present in the fuel model, then the next step depends upon whether or not you constructed line K in step A. *If line K was constructed*, determine its intersection with the vertical line constructed in step C. From this point of intersection, draw a horizontal line back through the upper right-hand quadrant. Call this "line D." Go on to step E and read results. *If you did not have to construct line K* in step A, then locate the curve labeled with the value of live fuel moisture used in step A, interpolating if necessary. From where this curve intersects the vertical line constructed in step C, draw a horizontal line to the right, through the upper right-hand quadrant. Call this "line D."

E. Read results at three places:

(1) Line A crosses the horizontal axis separating the two right-hand quadrants. Read the scale at that point to determine the reaction intensity (see appendixes I and II) of the fire.

(2) Line D crosses the vertical axis separating the two upper quadrants. Read the scale at that point to determine the forward rate of spread of the fire.

(3) Line A (extended upward if necessary) and line D intersect in the upper right-hand quadrant. The flame length at the front of the fire can be determined from this intersection point. Interpolate between the hyperbolic curves (those that run from upper left to lower right in a rounded L shape), which are labeled with the values of flame length.

Examples

Two examples are worked out step-by-step on the following pages, one step per page. Each page is marked with the letter of the step in the instruction sequence just above. To follow the steps in the construction of the solution to each example, match the letter of the instruction steps (A-E) with the page. On each page, the lines constructed in that step are shown dashed, previously completed lines solid. The data for the two examples are given below:

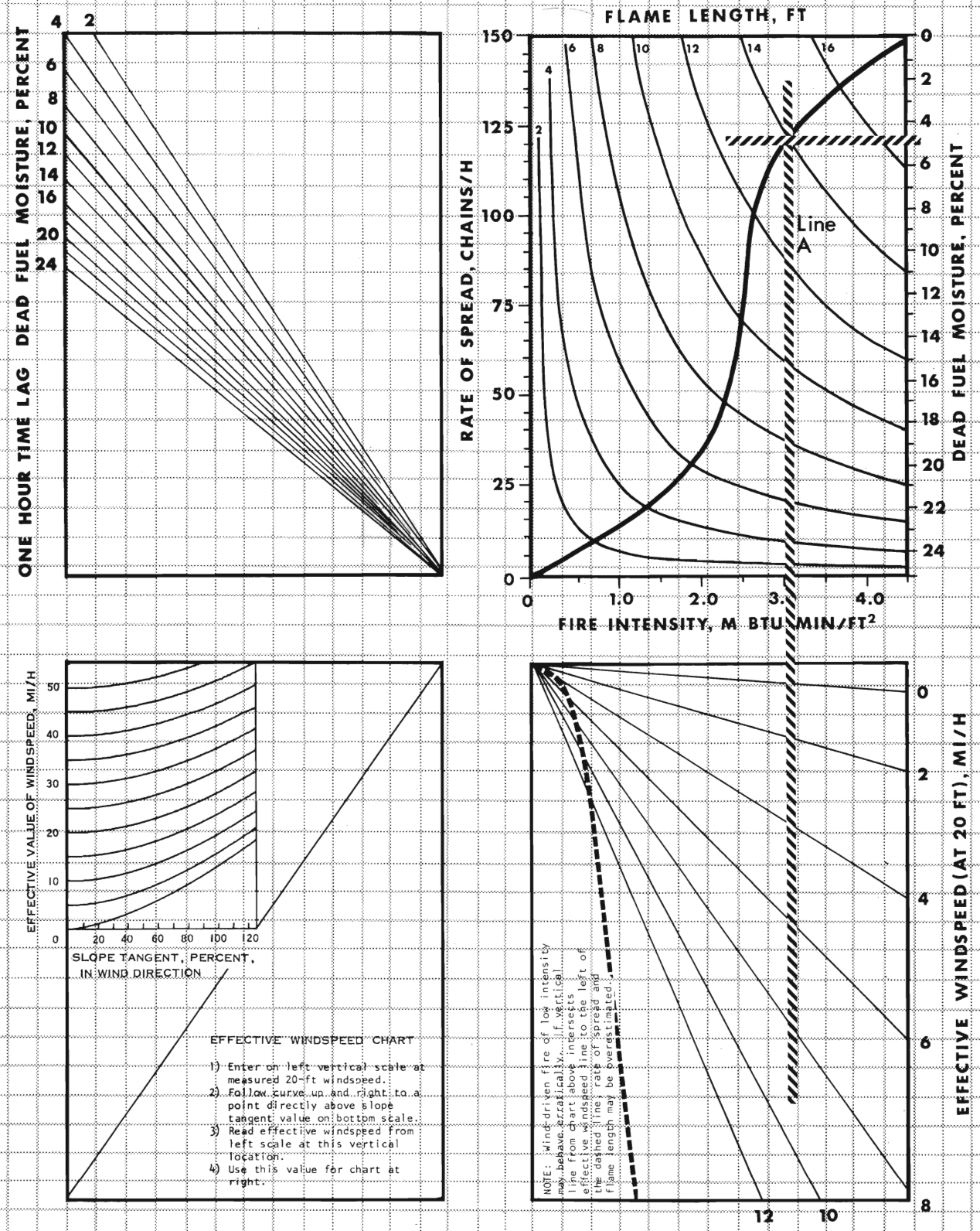
Example 1 (fig. 1).--Estimate the fire intensity, forward rate of spread, and the flame length of a fire in cured broomsedge, given a fuel moisture content of 5 percent and a windspeed (at 20-ft height) of 8 mi/h, on level ground.

Solution 1.--Verify that the appropriate fuel model is number 3--Tall Grass (2.5 ft). The chart to use is the "low windspeed" member of the pair. The results of the construction illustrated on the following pages are: fire intensity, 3,000 Btu/min/ft^2; rate of spread, 97 chains per hour; flame length, 12.5 ft.

Figure 1.--Example 1, parts A through E.

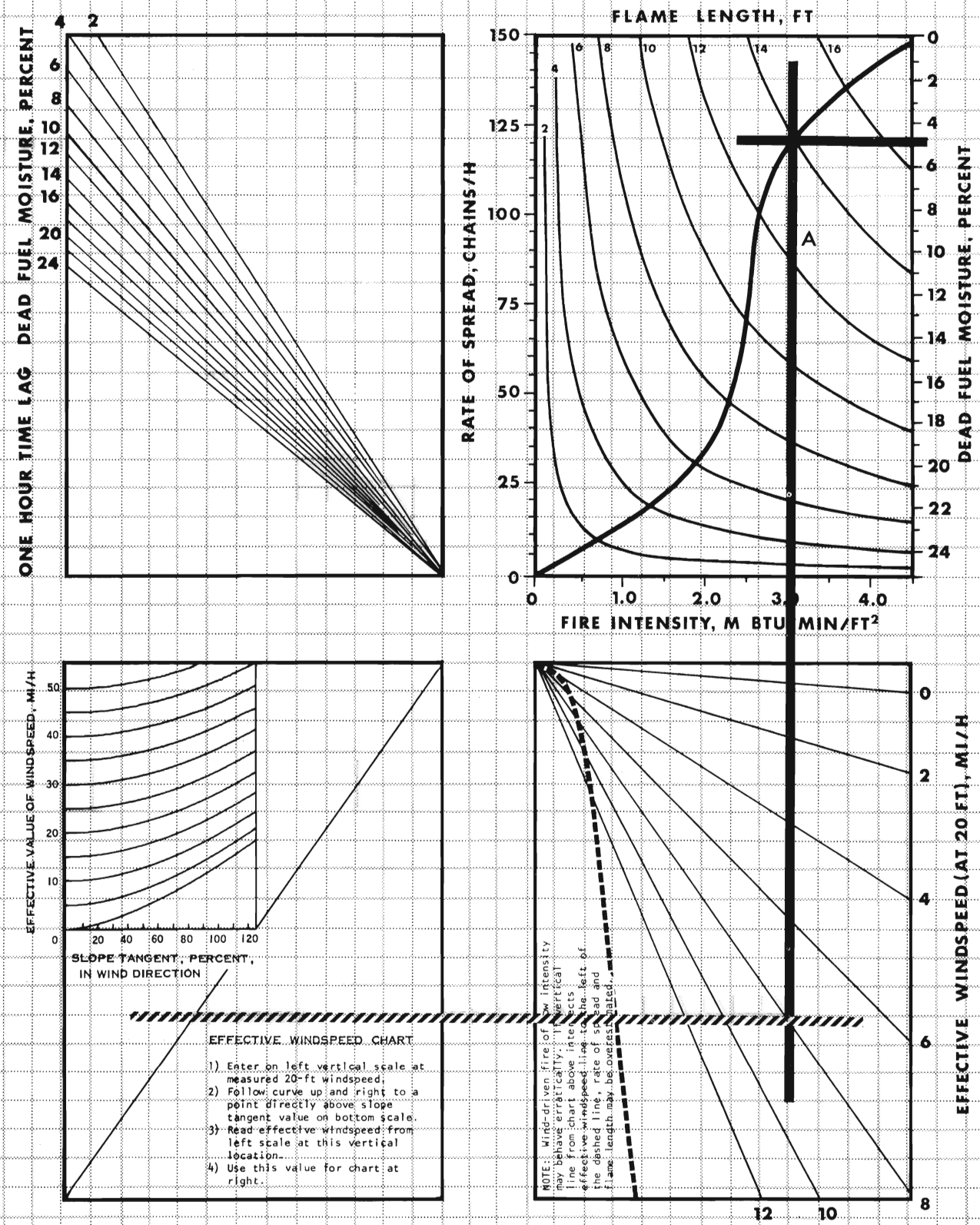
3. TALL GRASS (2.5 FT)-LOW WINDSPEEDS

Ex 1 A



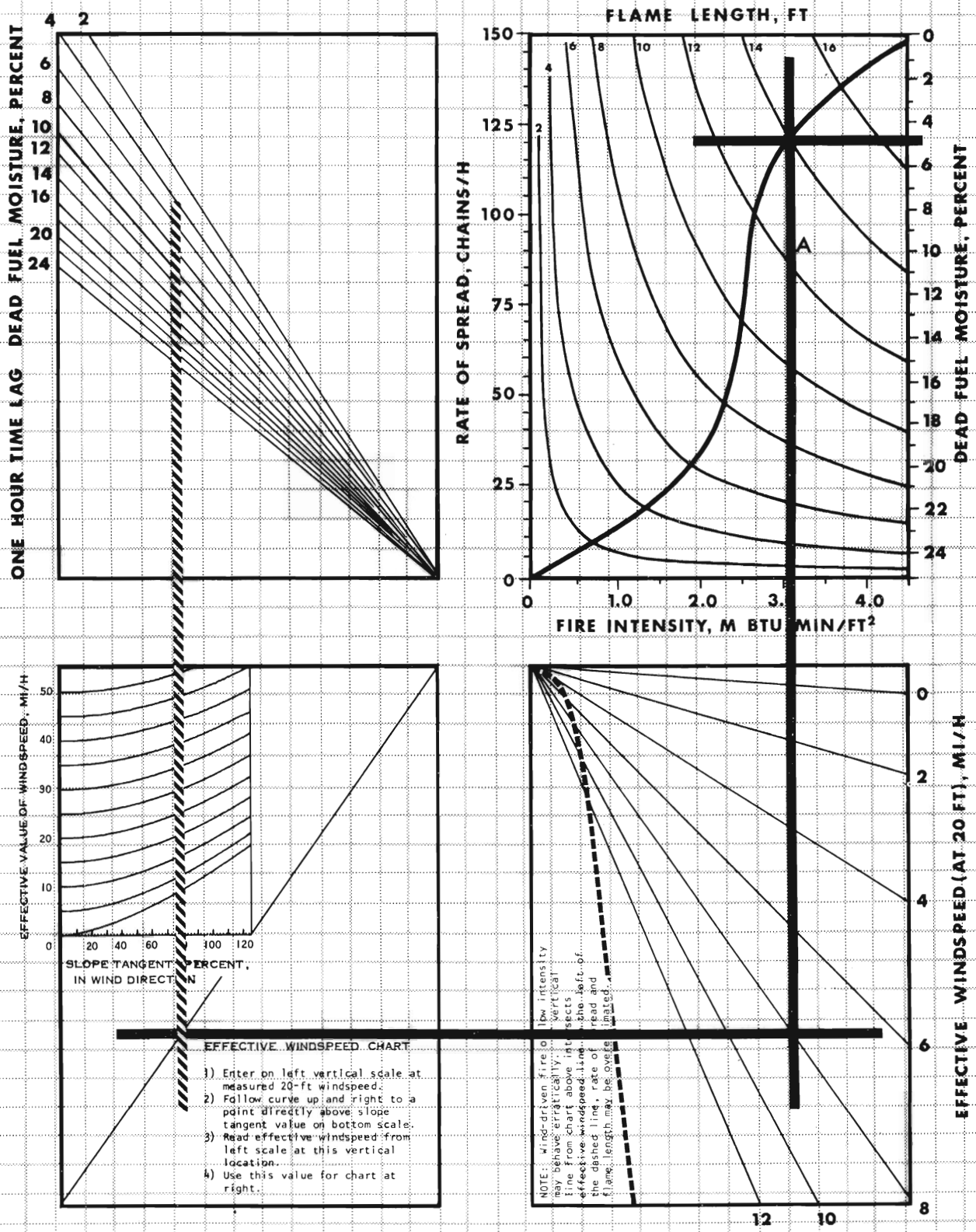
3. TALL GRASS (2.5 FT) - LOW WINDSPEEDS

Ex 1B



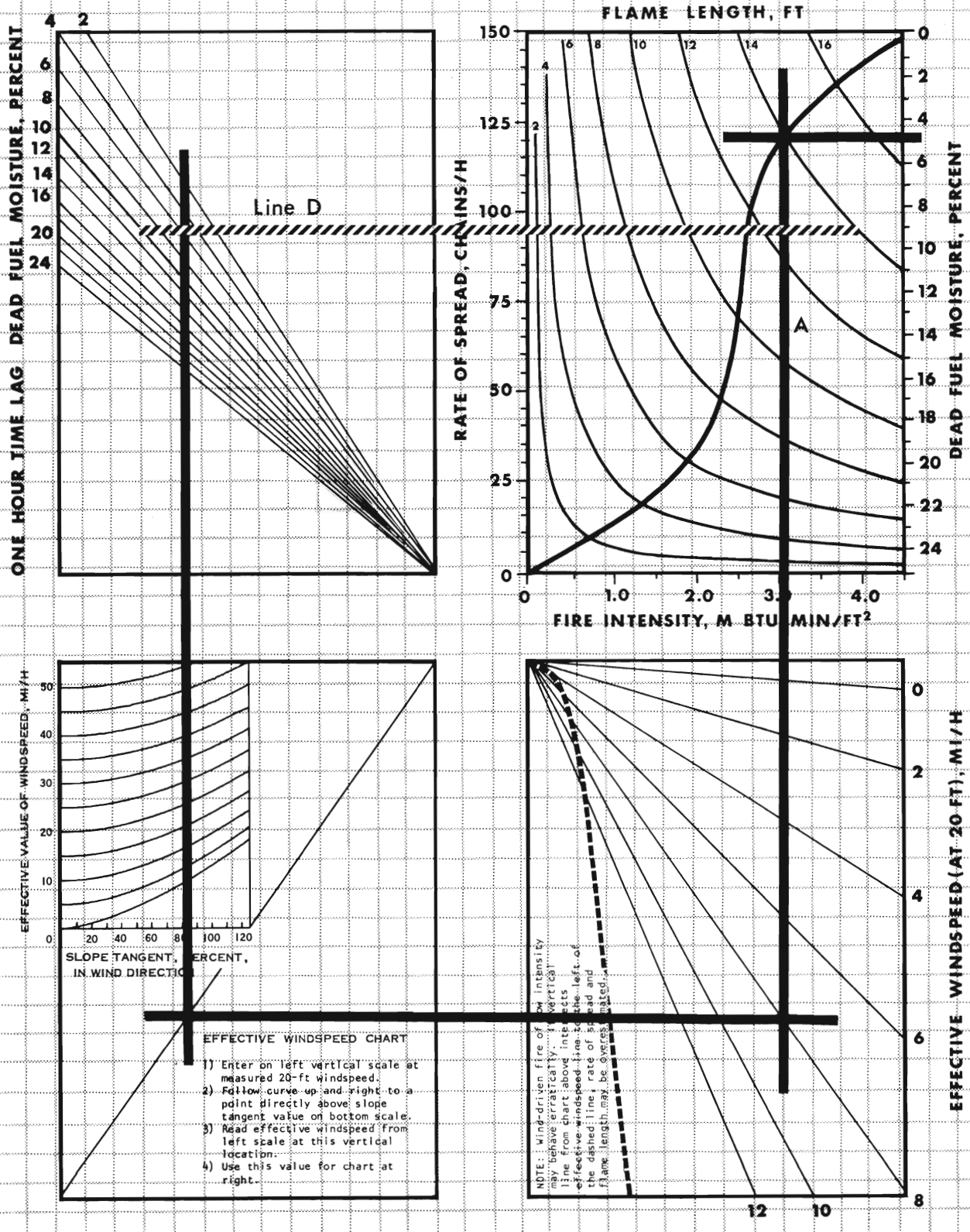
3. TALL GRASS (2.5 FT)-LOW WINDSPEEDS

Ex 1C



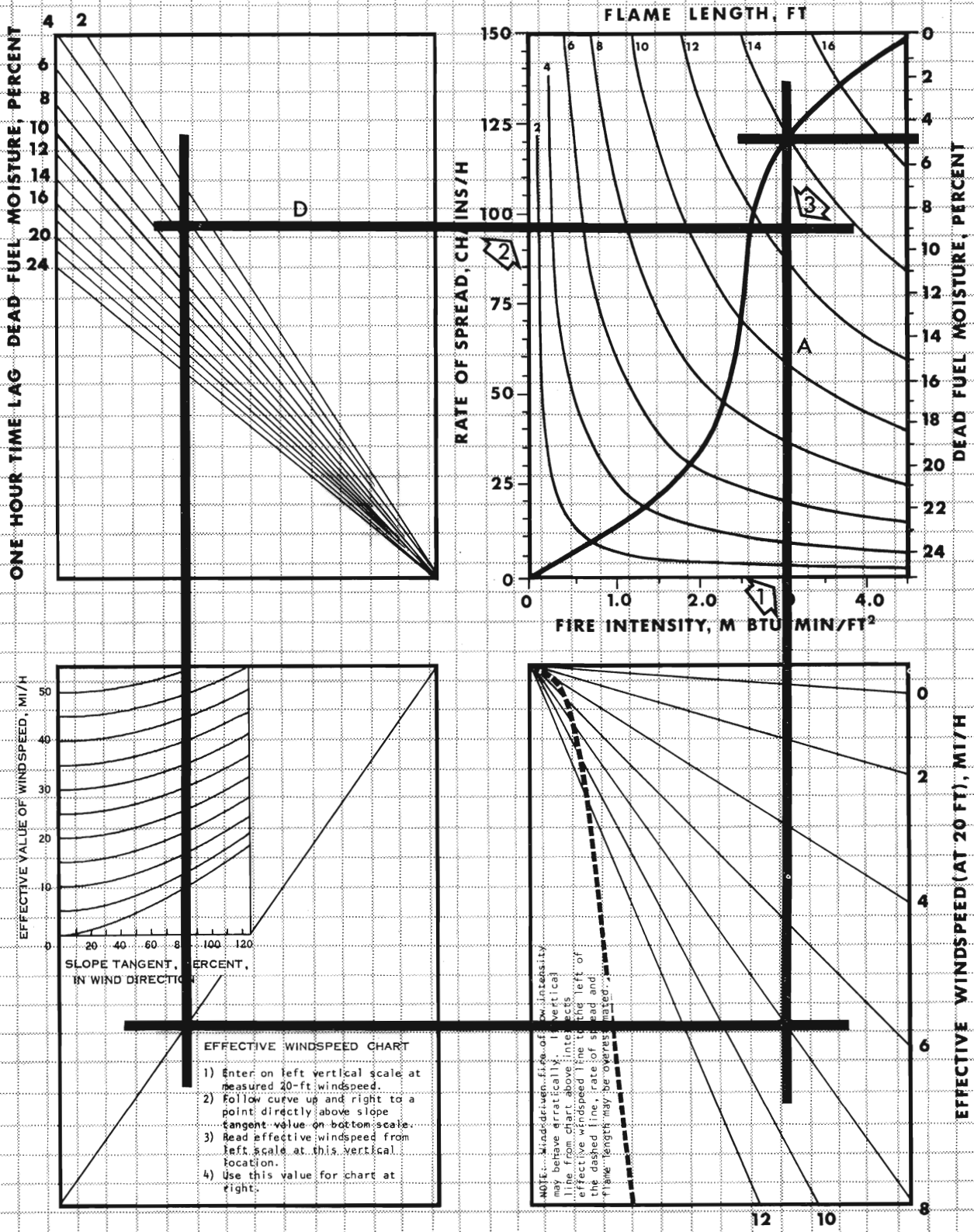
3. TALL GRASS (2.5 FT)-LOW WINDSPEEDS

Ex 1D



3. TALL GRASS (2.5 FT) - LOW WINDSPEEDS

Ex 1E

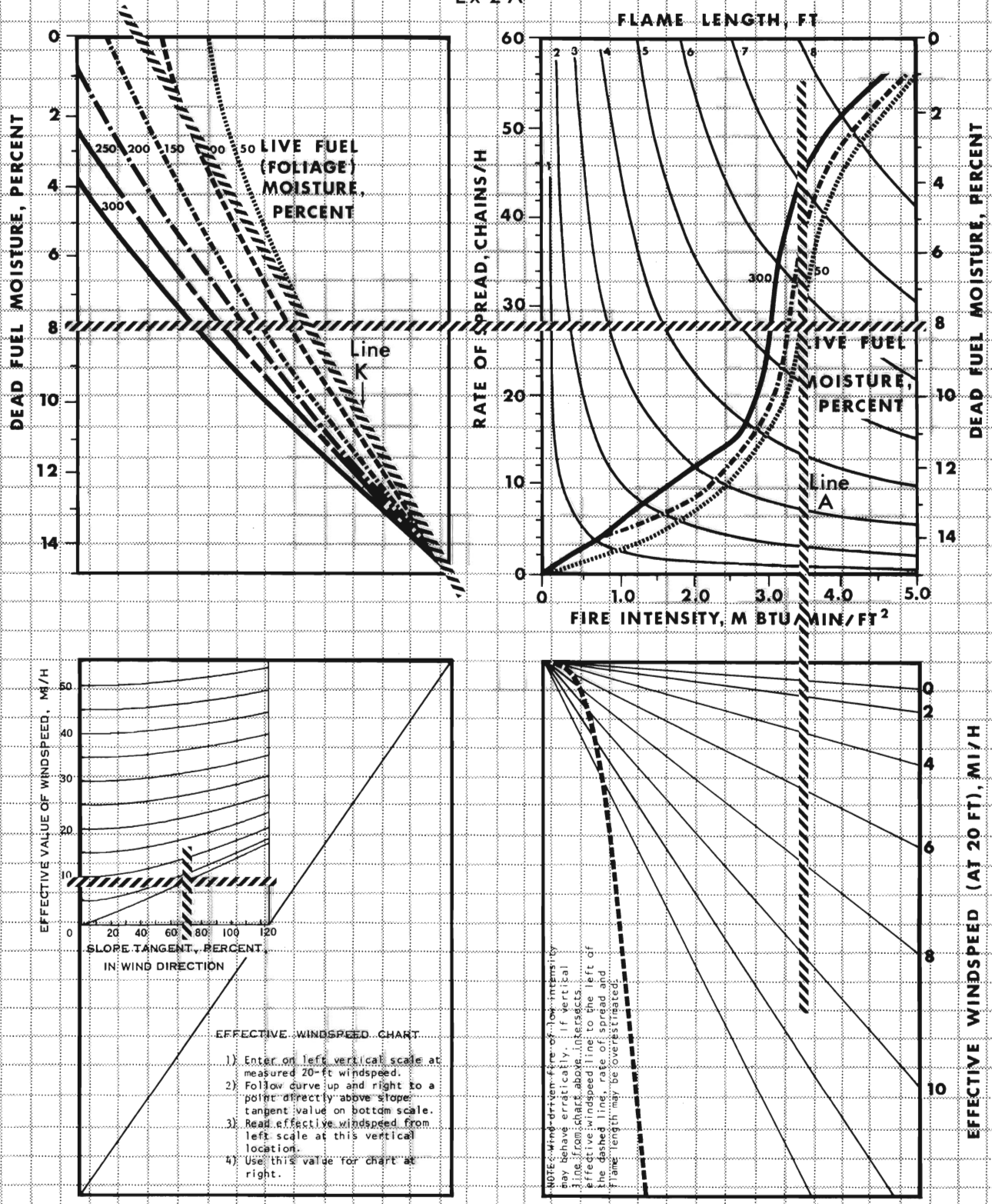


Example 2 (fig. 2).--Estimate the fire intensity, forward rate of spread, and the flame length of a fire in a wiregrass/scrub oak association, when the fine dead fuel moisture is 8 percent, the live foliage moisture about 50 percent, the wind is calm, and the slope is 70 percent.

Solution 2.--Verify that the proper fuel model to use is number 2, Timber (Grass and Understory). The chart to use is once again the "low windspeed" version. Using the small chart inset in the lower left-hand quadrant of this nomograph, verify that the effective windspeed is 9 mi/h. The results of the construction illustrated on the following pages are: fire intensity, 3,500 Btu/min/ft^2; rate of spread, 34 chains per hour; flame length, 6.2 ft.

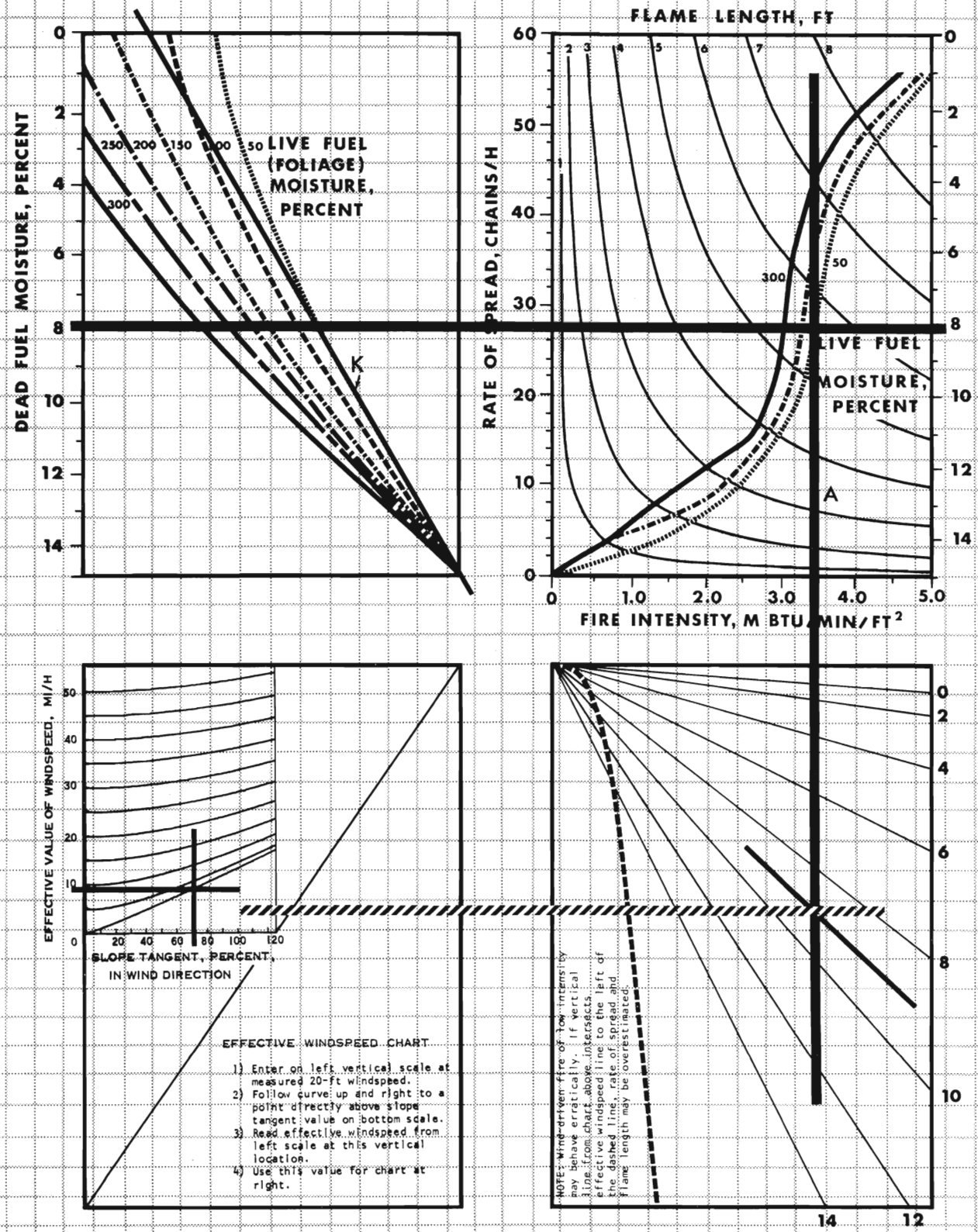
2. TIMBER (GRASS & UNDERSTORY) - LOW WINDSPEEDS

Ex 2 A



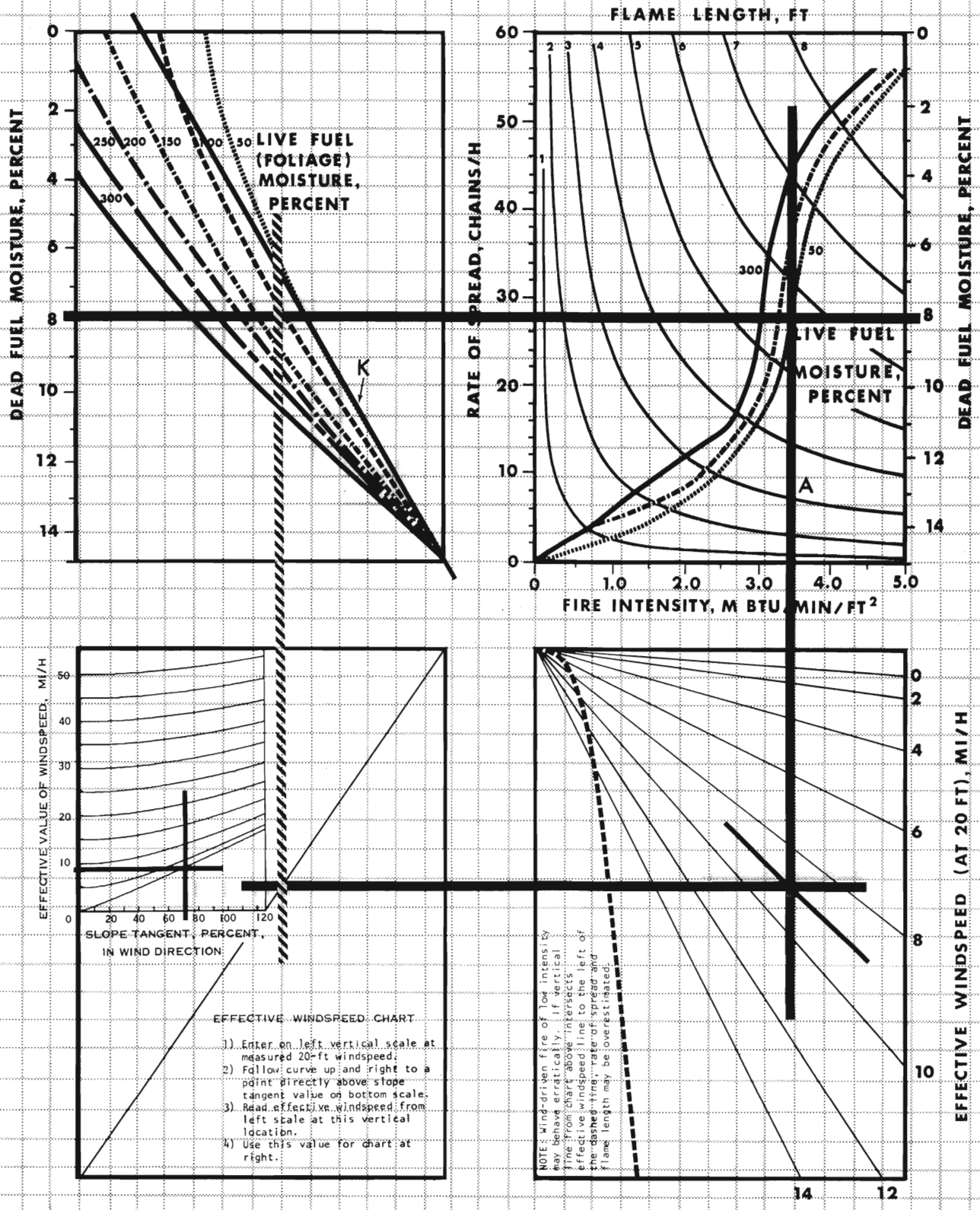
2. TIMBER (GRASS & UNDERSTORY) - LOW WINDSPEEDS

Ex 2B



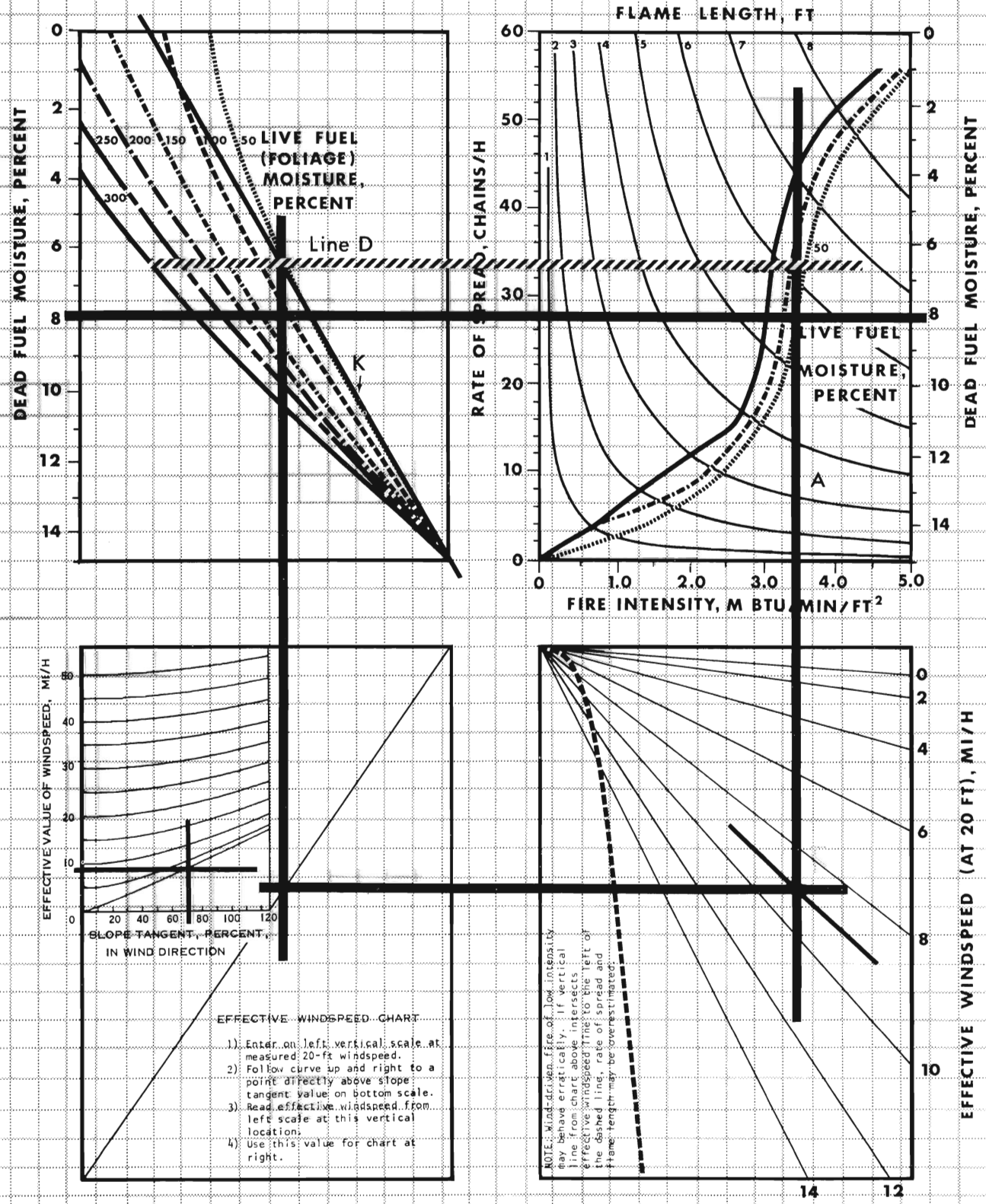
2. TIMBER (GRASS & UNDERSTORY) - LOW WINDSPEEDS

Ex 2C



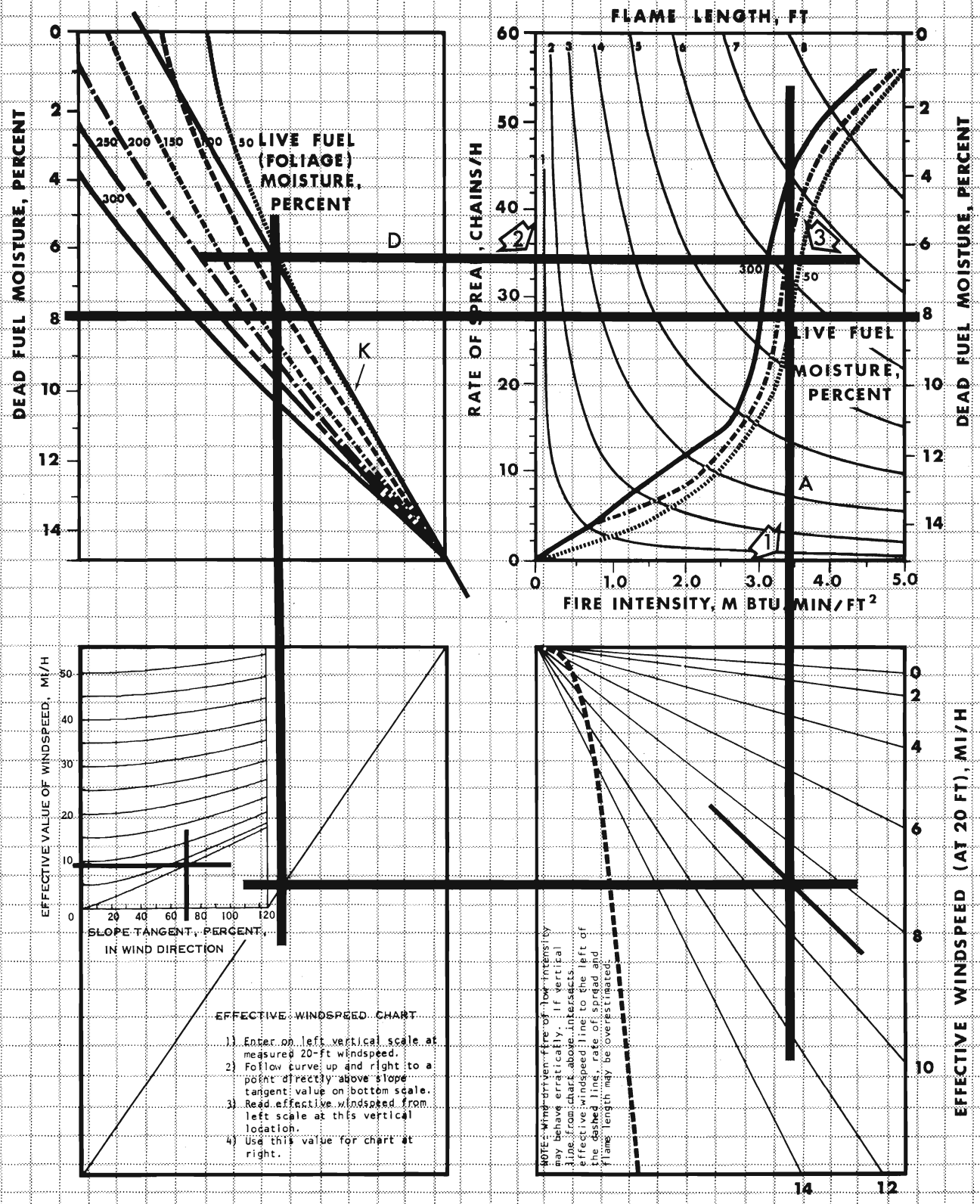
2. TIMBER (GRASS & UNDERSTORY) - LOW WINDSPEEDS

Ex 2D



2. TIMBER (GRASS & UNDERSTORY) - LOW WINDSPEEDS

Ex 2E



Fire Behavior Estimation Charts

Chart Numbers	*General Fuel Description*
1 - 3	Grass and Grass-Dominated Complexes
4 - 7	Chaparral and Shrubfields
8 - 10	Timber Litter
11 - 13	Logging Slash

These charts are based on stylized "typical" fuel models, much like those used in the National Fire-Danger Rating System, but with some important differences. Estimates made from these charts are not intended to be precise, but rather to provide rough estimates for planning and hazard assessment purposes. The fuel complex descriptions are given in detail in table 7, appendix III.

Fire Behavior Estimation Charts for Grass and Grass-Dominated Complexes

1. Short Grass (1 ft)

   Best fits: Western grasslands, not grazed.

   Also use for: Western savannah types, stubble, grass tundra.

   NOTE: Cured fuels only.

2. Timber (Grass and Understory)

   Best fits: Open pine grassy understory, wiregrass/scrub oak associations.

   Also use for: Timber/sagebrush/grass associations, southern pine clearcut slash.

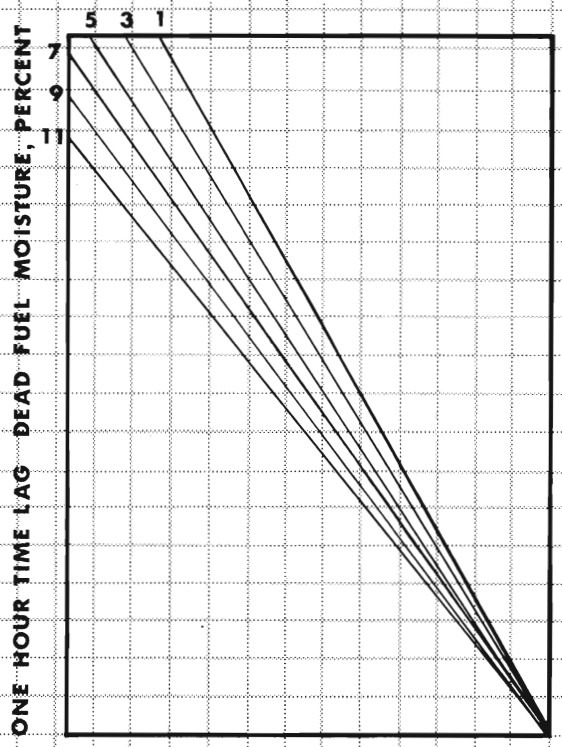
3. Tall Grass (2.5 ft)

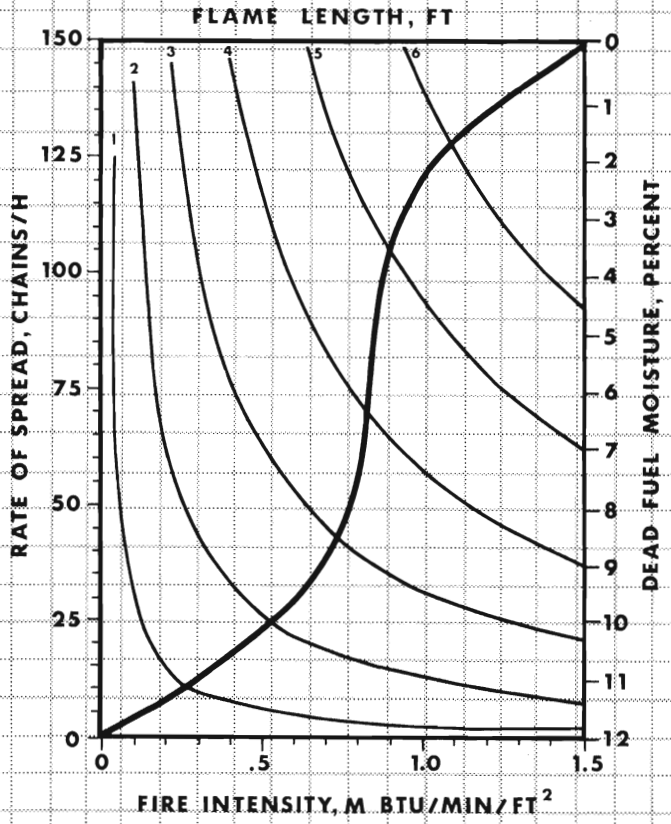
   Best fits: Bluebunch wheatgrass, bluestems, galleta, Indiangrass, broomsedge, switchgrass, pineland three-awn, panicgrass, etc.

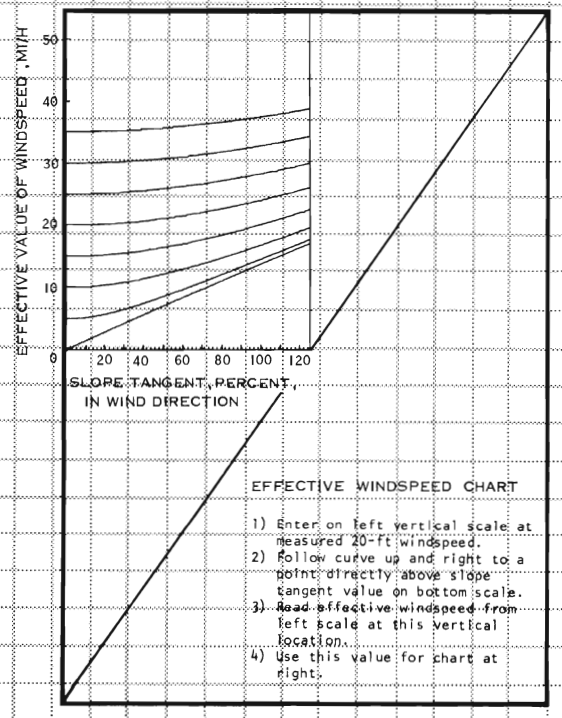
   Also use for: Wild or cultivated grains (cured, not harvested), tall sawgrass, eastern marsh vegetation.

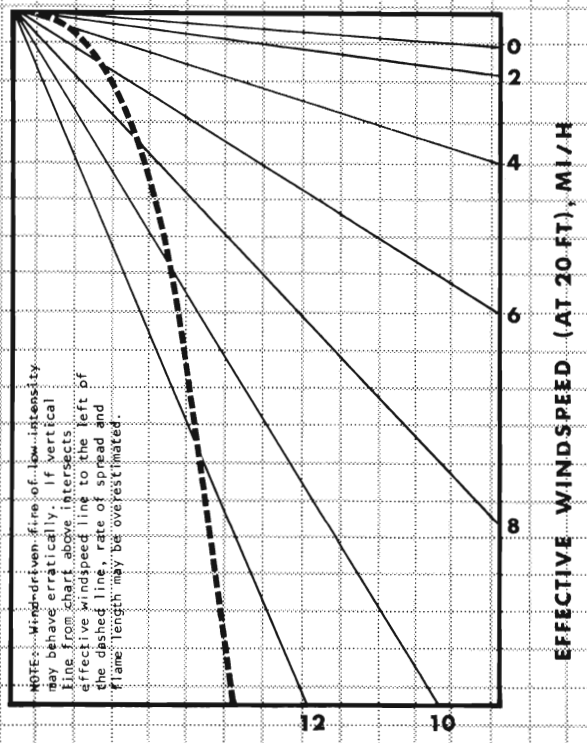
   NOTE: Cured fuels only.

1. SHORT GRASS (1 FT) – LOW WINDSPEEDS

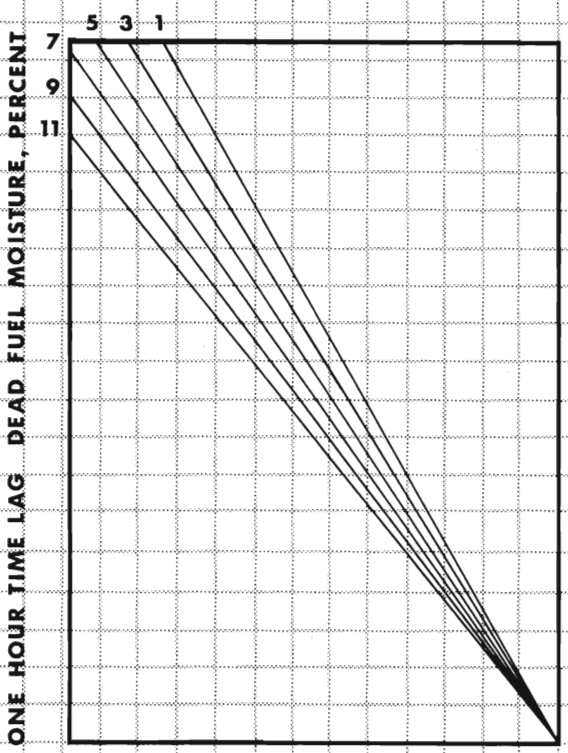


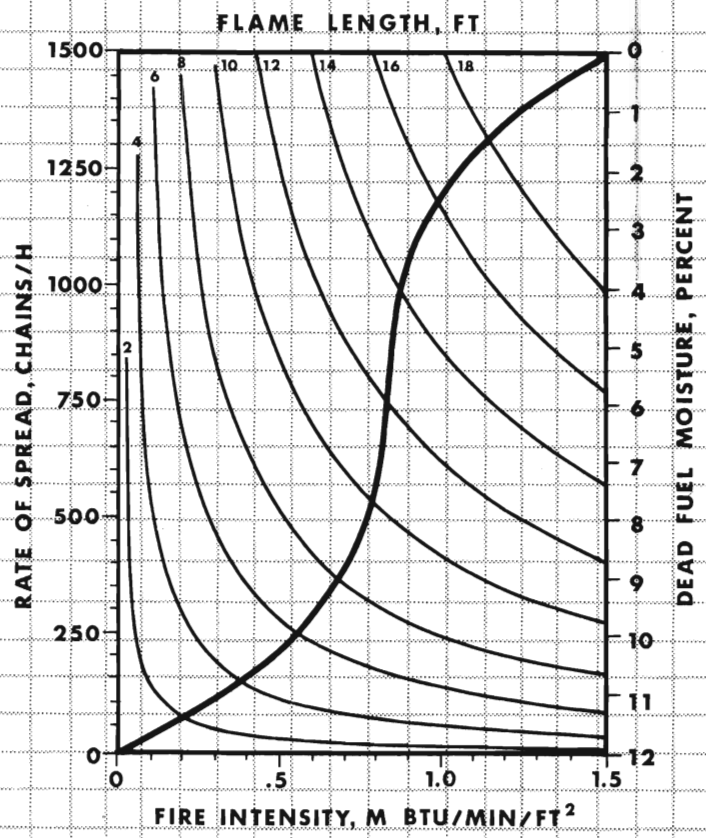


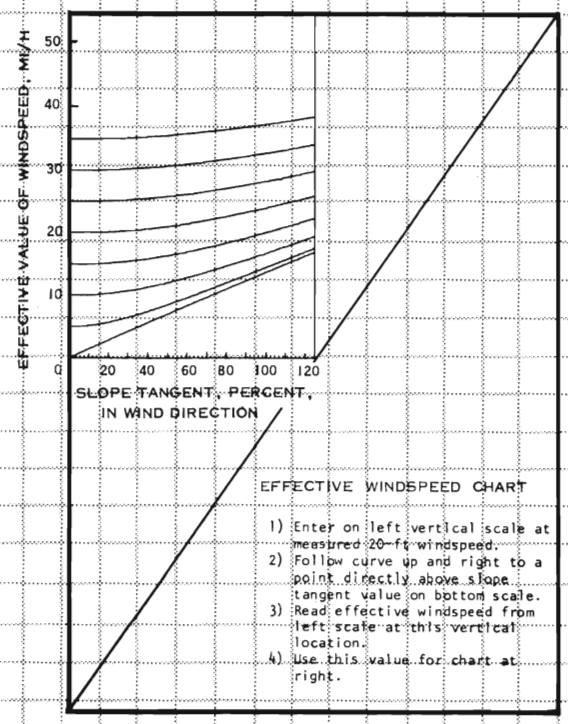


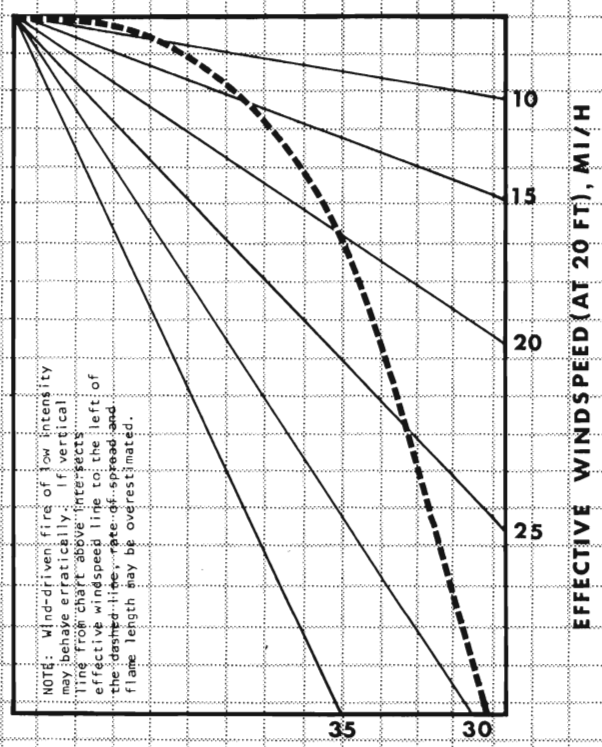


1. SHORT GRASS (1 FT) - HIGH WINDSPEEDS

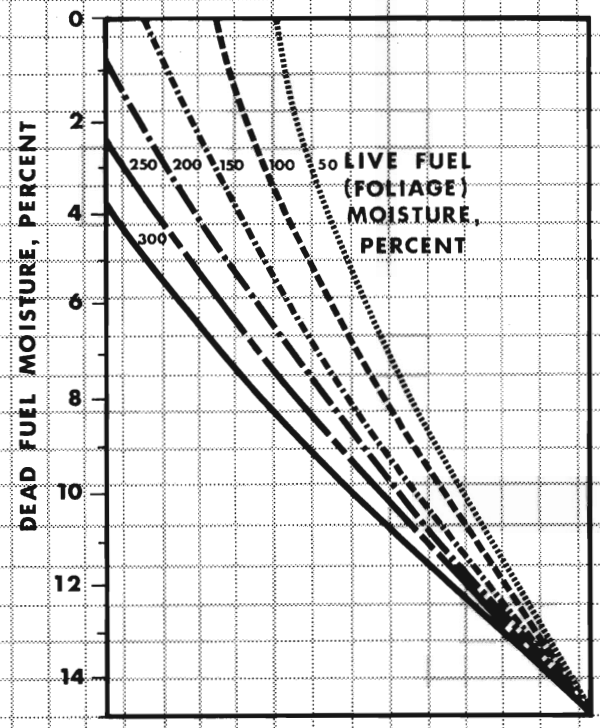


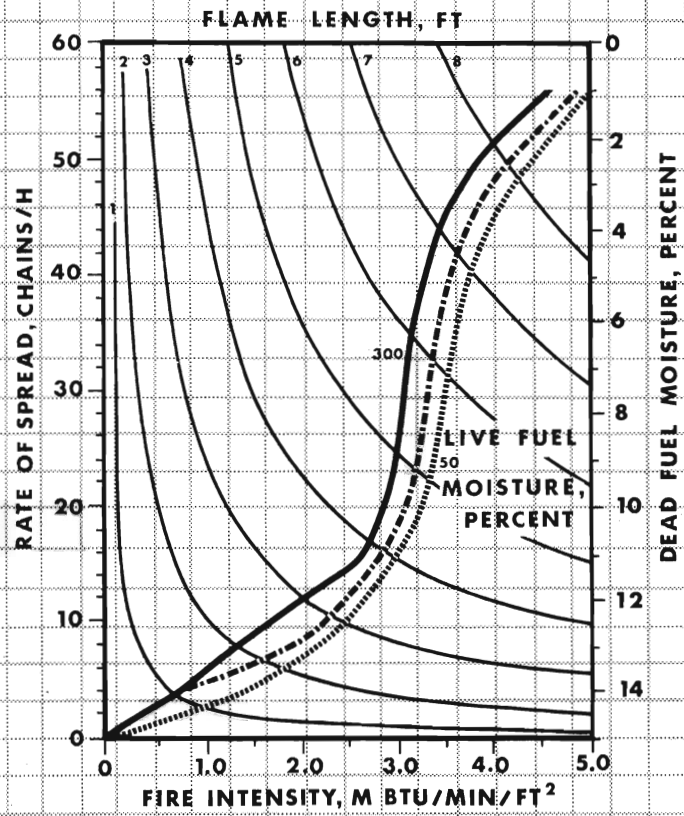


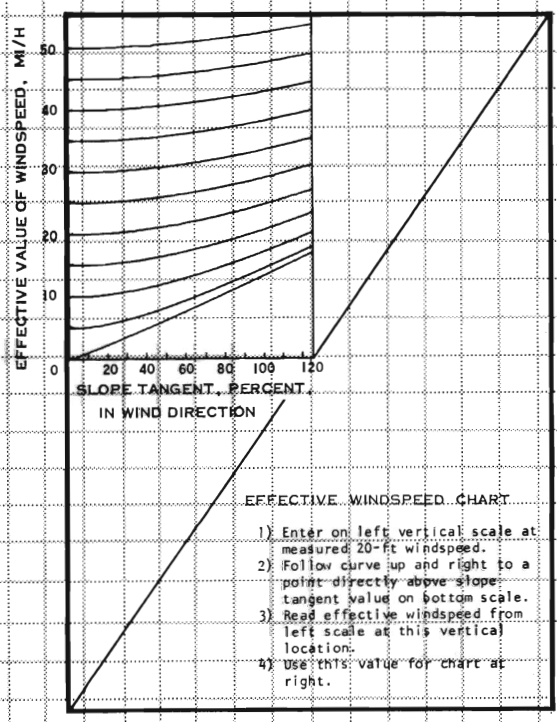


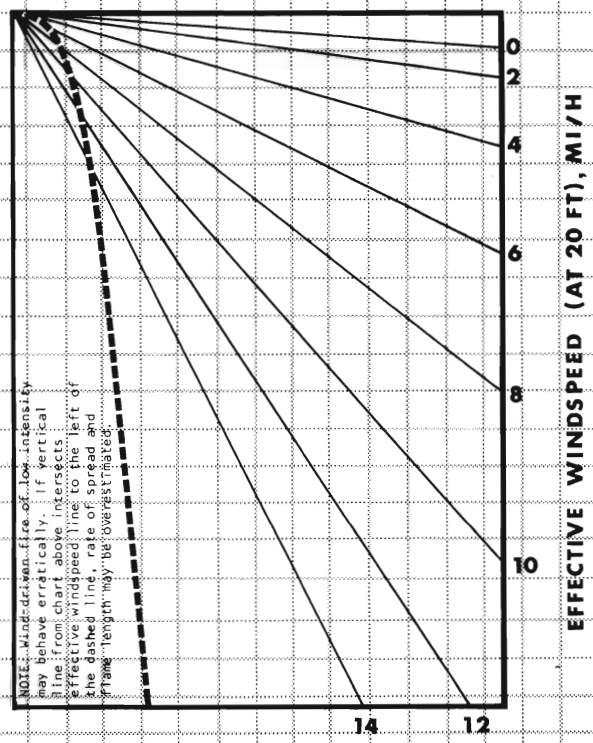


2. TIMBER (GRASS & UNDERSTORY) - LOW WINDSPEEDS

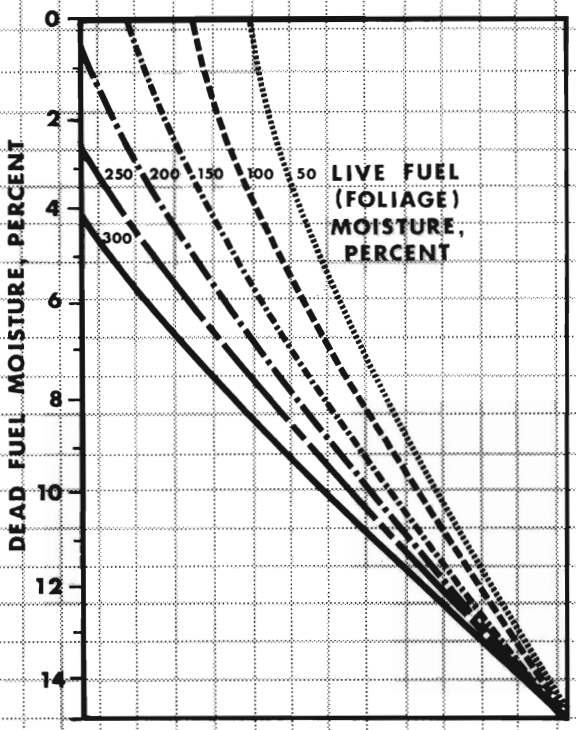


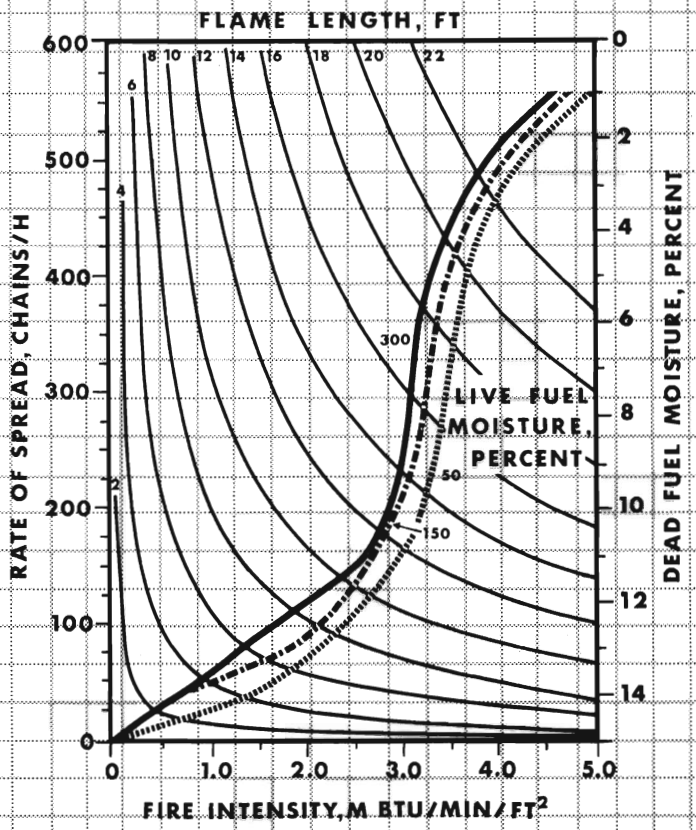


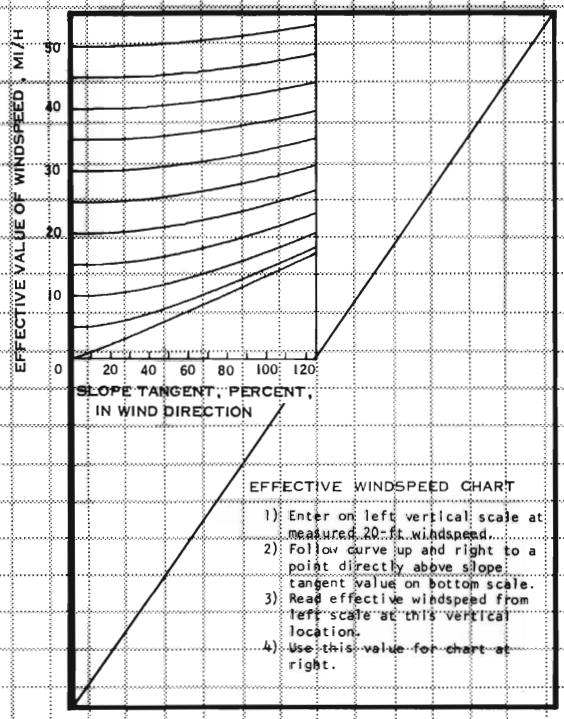


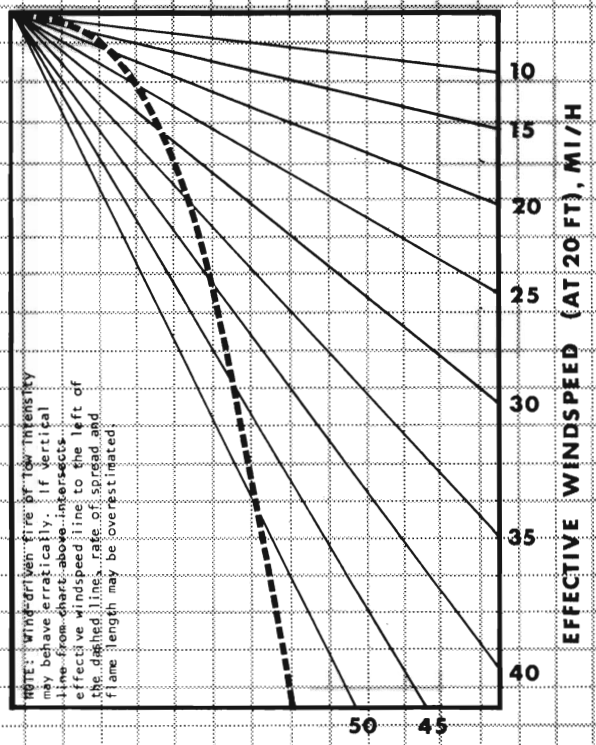


2. TIMBER (GRASS & UNDERSTORY) - HIGH WINDSPEEDS

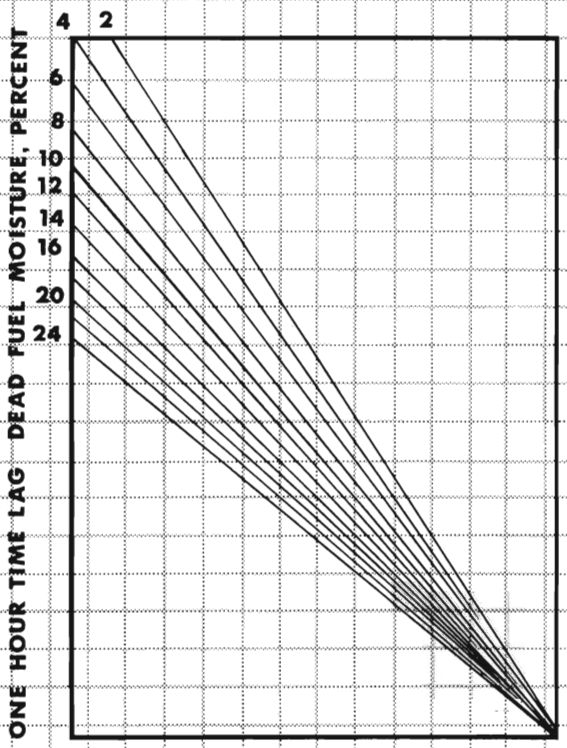


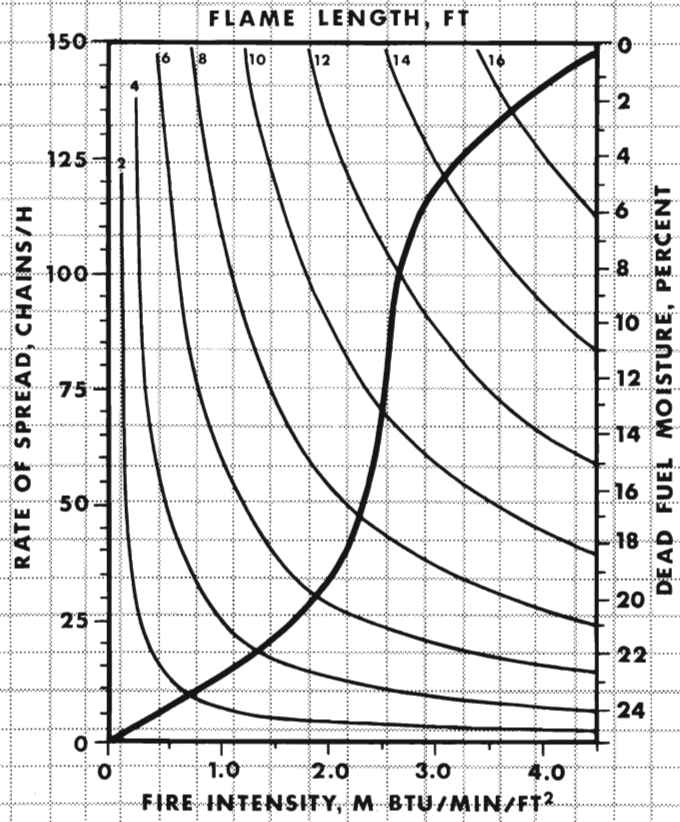


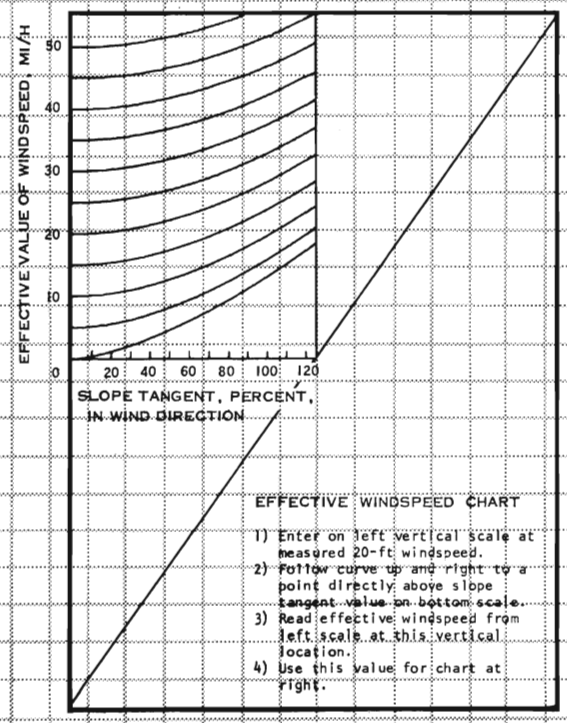


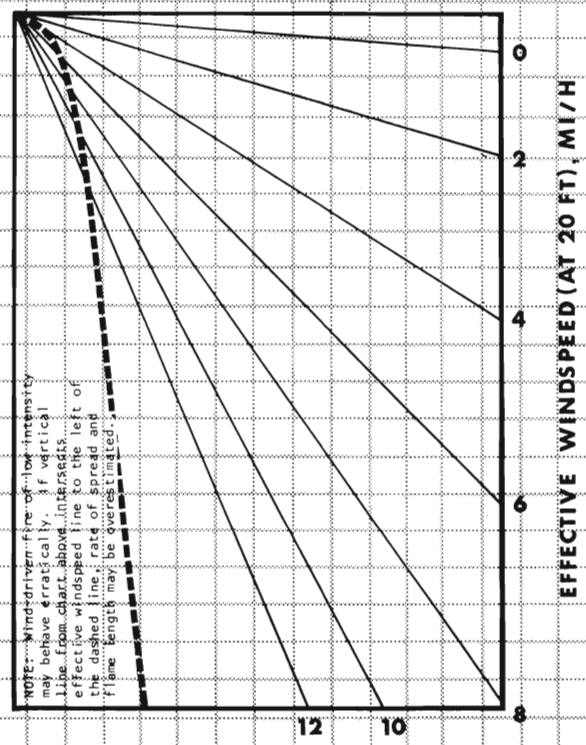


3. TALL GRASS (2.5 FT) - LOW WINDSPEEDS

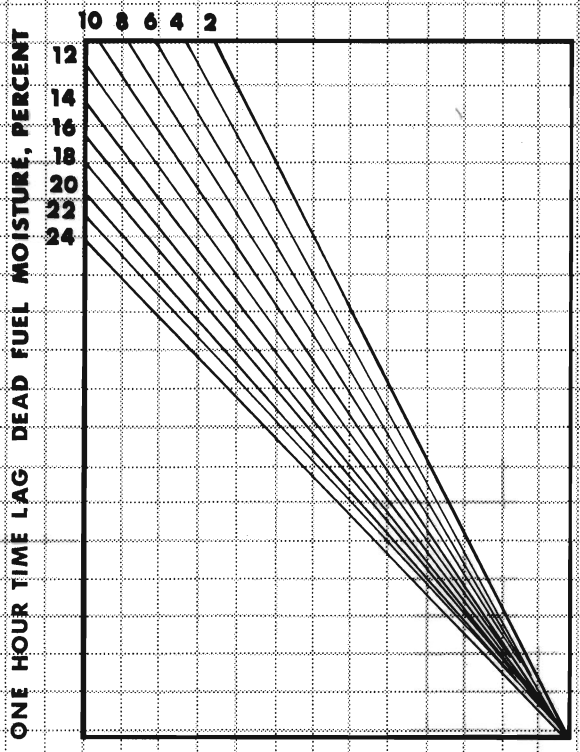


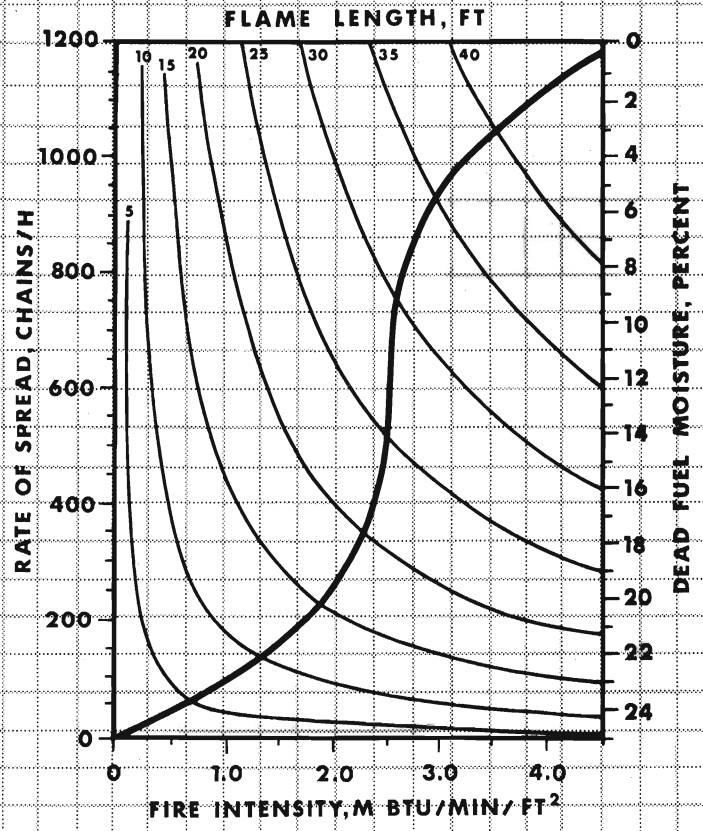


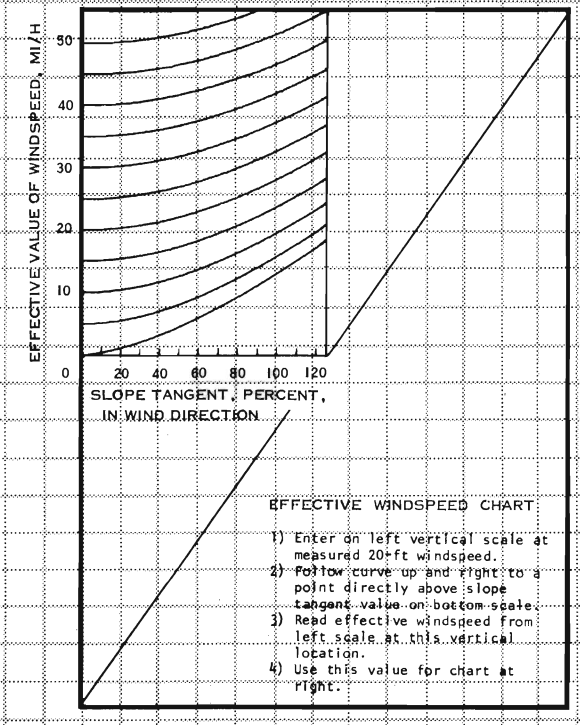


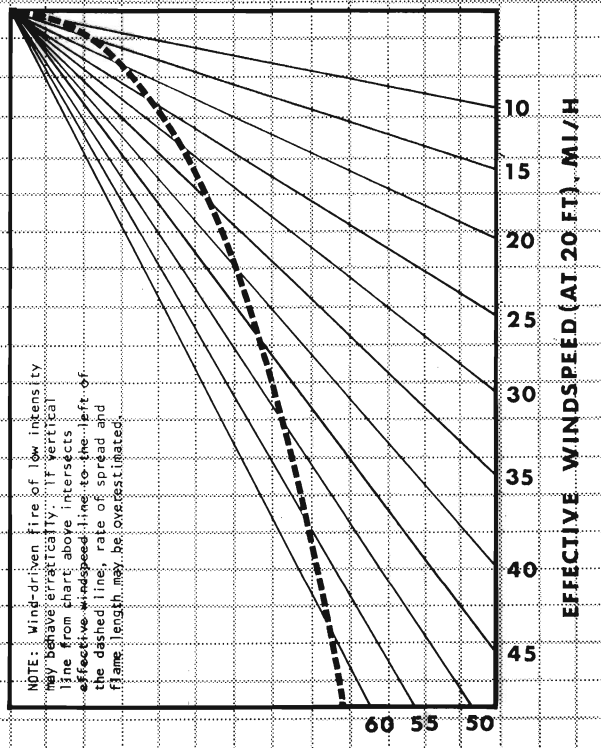


3. TALL GRASS (2.5 FT) - HIGH WINDSPEEDS









4. Chaparral (6 ft)

   Best fits: Mature (at least 10 to 15 years old) chaparral, manzanita, chamise.

   Also use for: High pocosins, heavy (more than 120 tons per acre) "red" conifer slash.

5. Brush (2 ft)

   Best fits: Laurel, salal, vine maple, alder, mountain mahogany.

   Also use for: Young chaparral, manzanita, chamise.

6. Dormant Brush, Hardwood Slash

   Best fits: Low pocosins (dormant), Alaskan spruce taiga, shrub tundra.

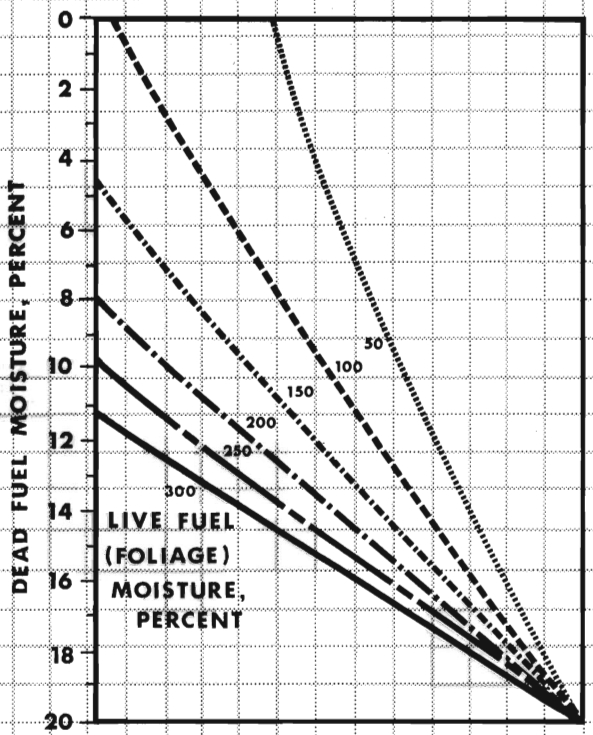
   Also use for: Fresh hardwood logging slash (40 tons per acre or less).

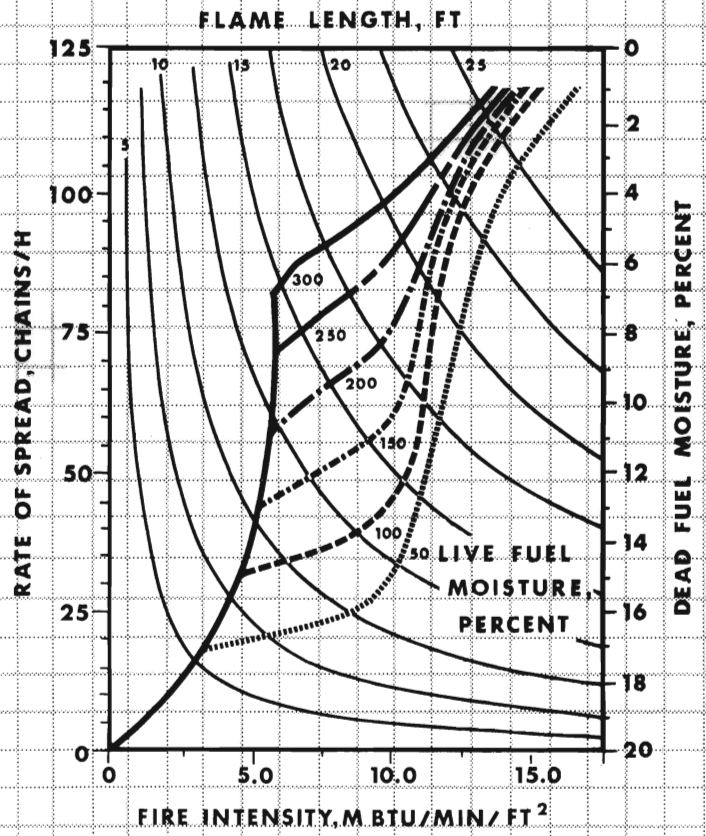
7. Southern Rough

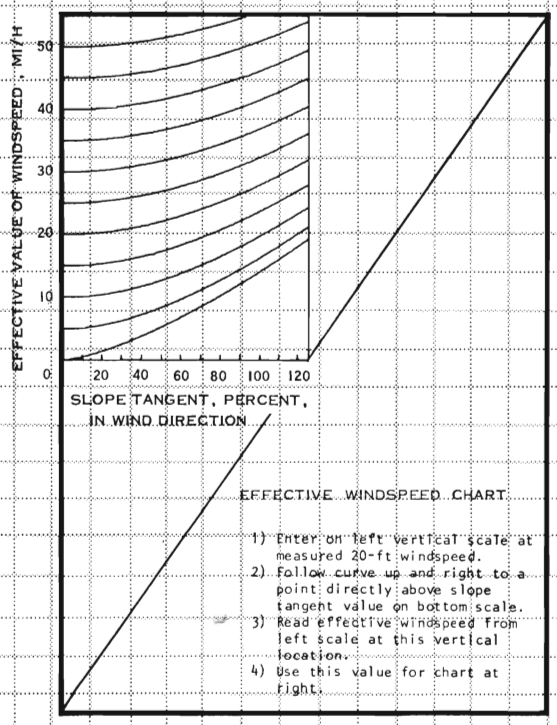
   Best fits: Southern rough (2 years), palmetto-gallberry communities.

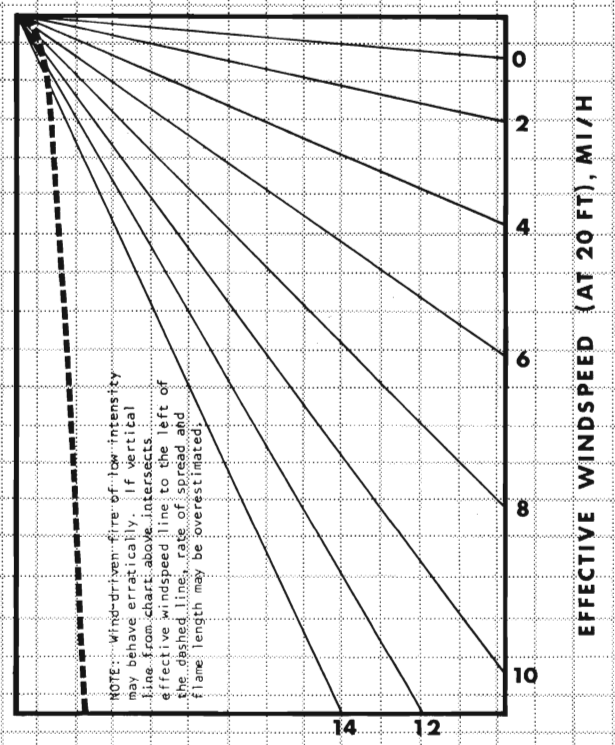
   Also use for: Low pocosins (not dormant).

4. CHAPARRAL (6 FT) - LOW WINDSPEEDS

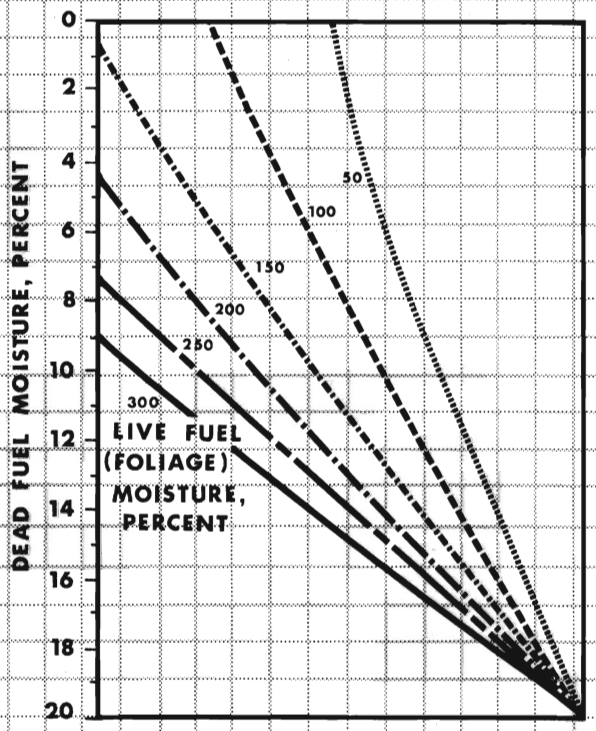


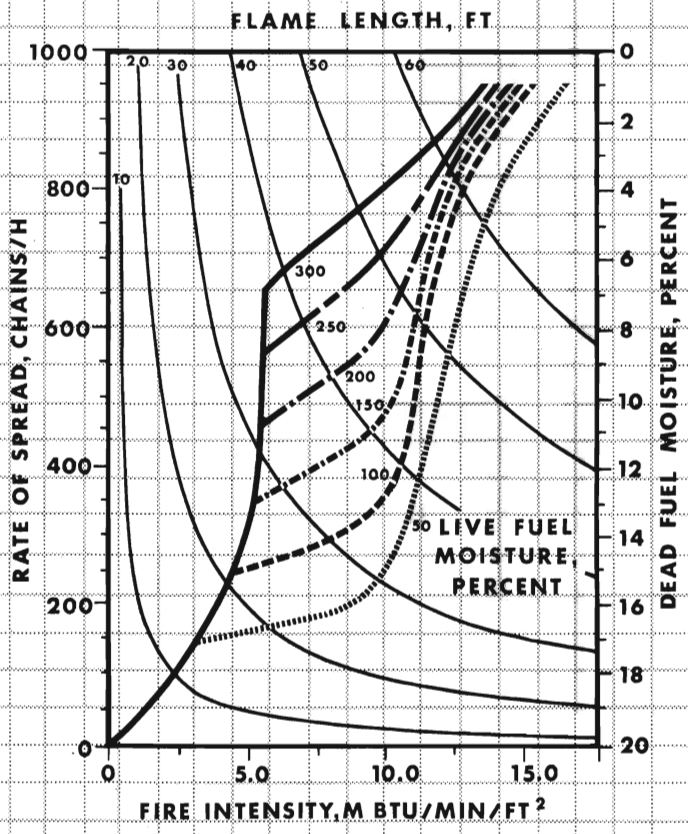


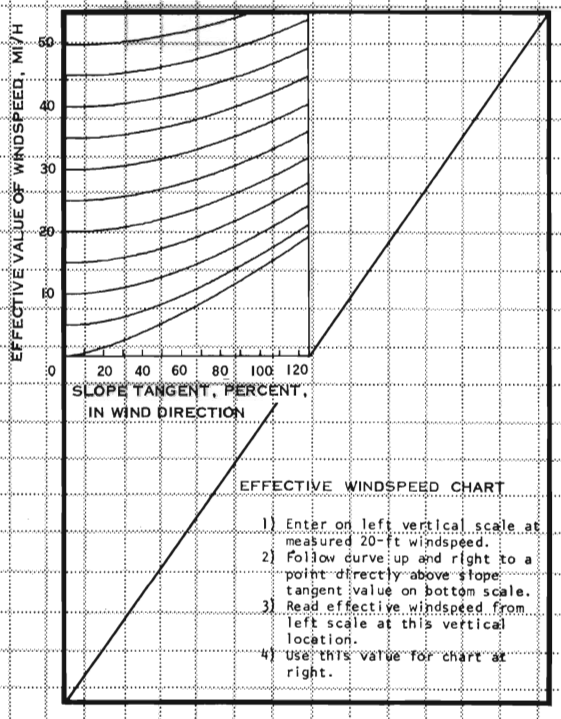


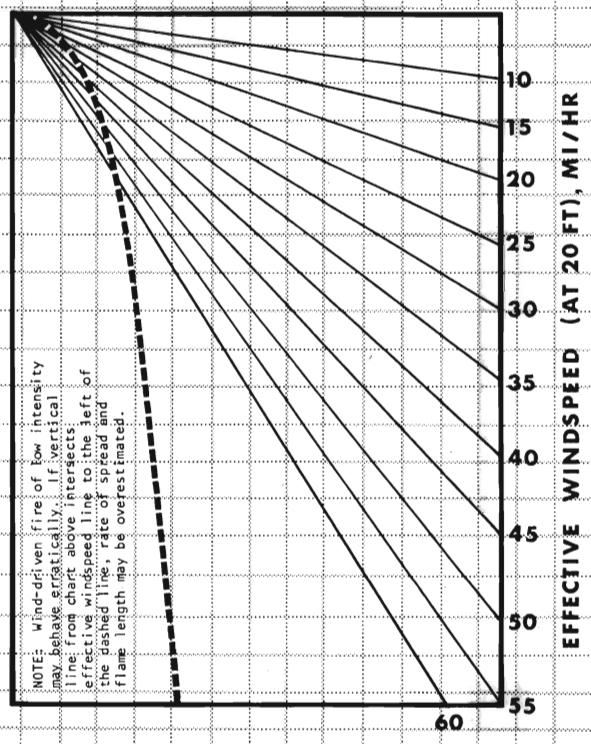


4. CHAPARRAL (6 FT) - HIGH WINDSPEEDS

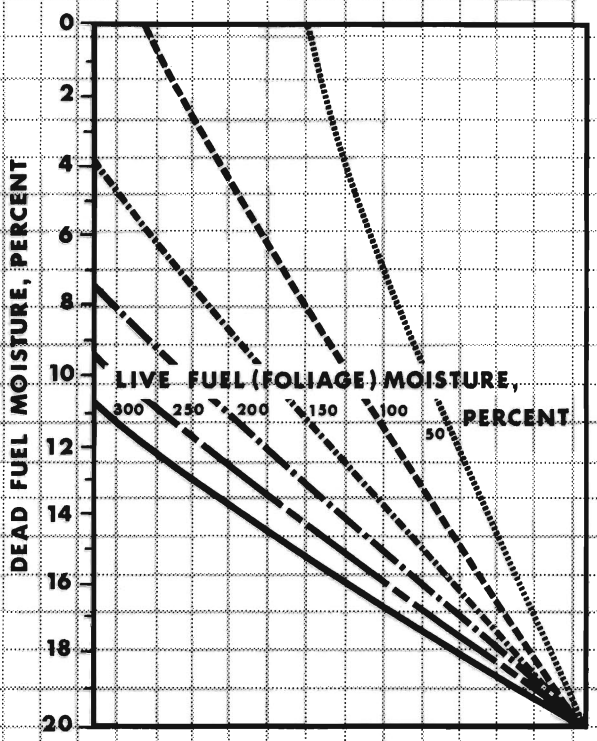


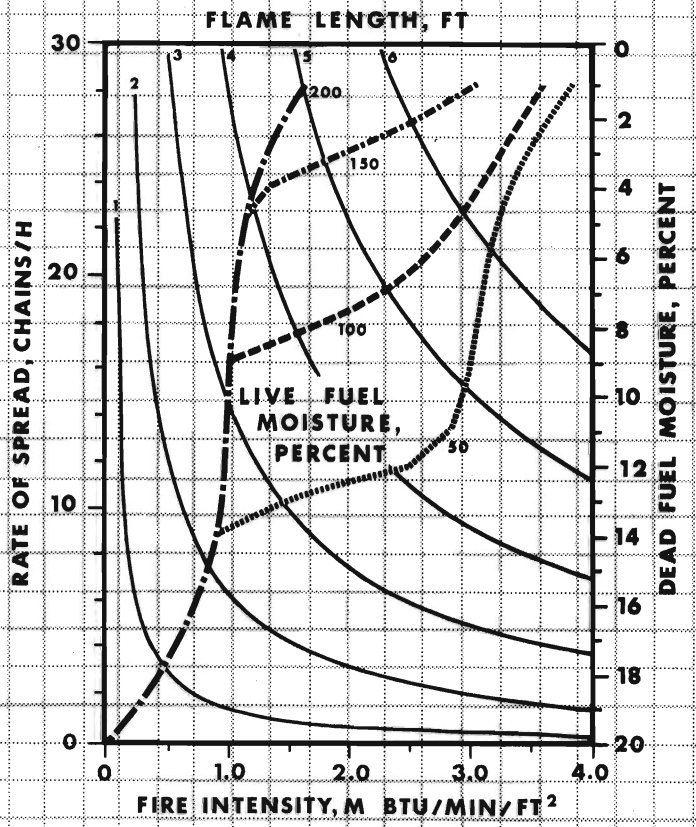


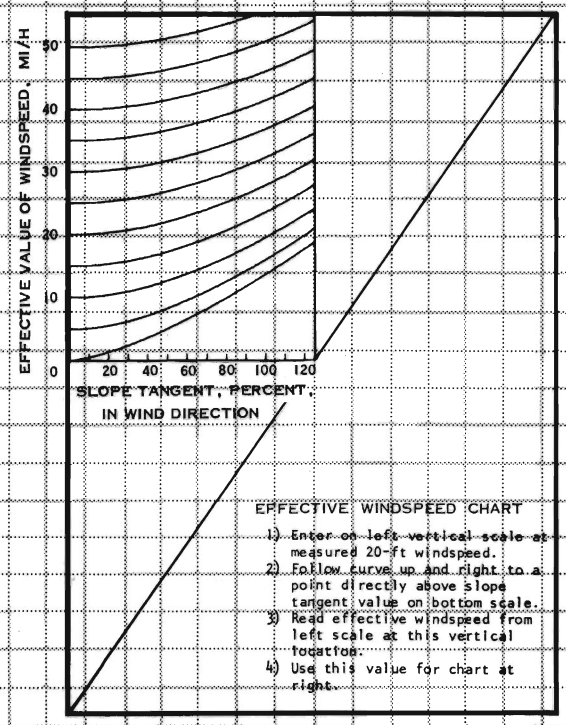


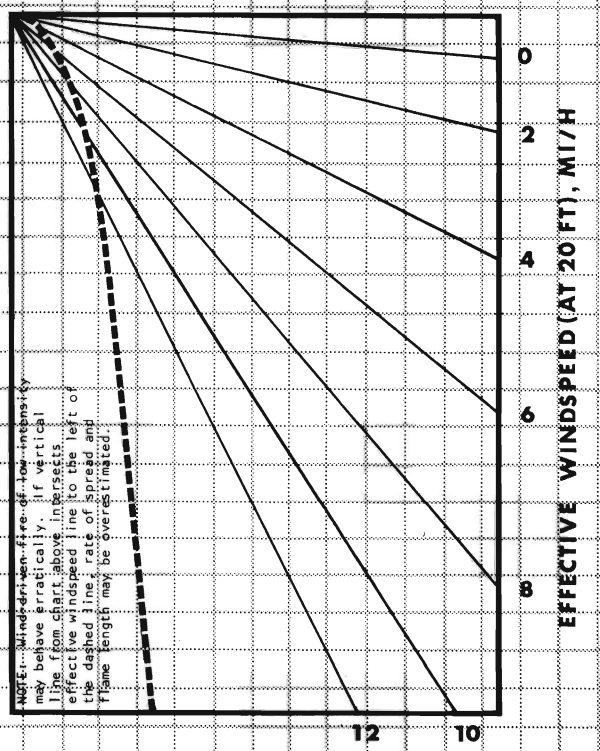


5. BRUSH (2 FT) - LOW WINDSPEEDS

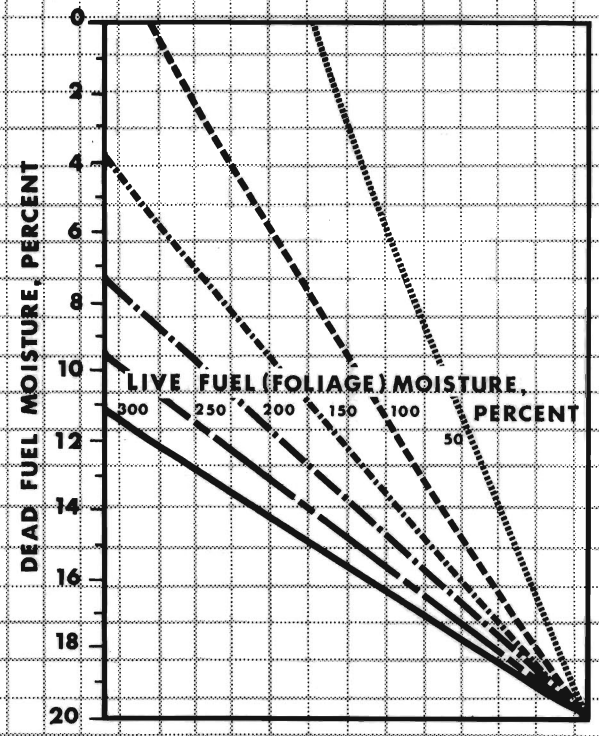


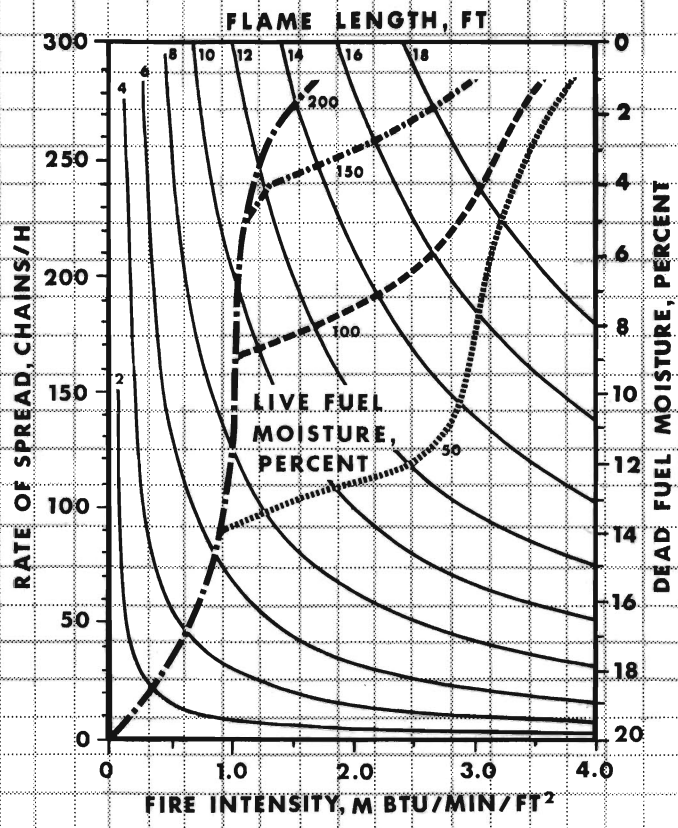


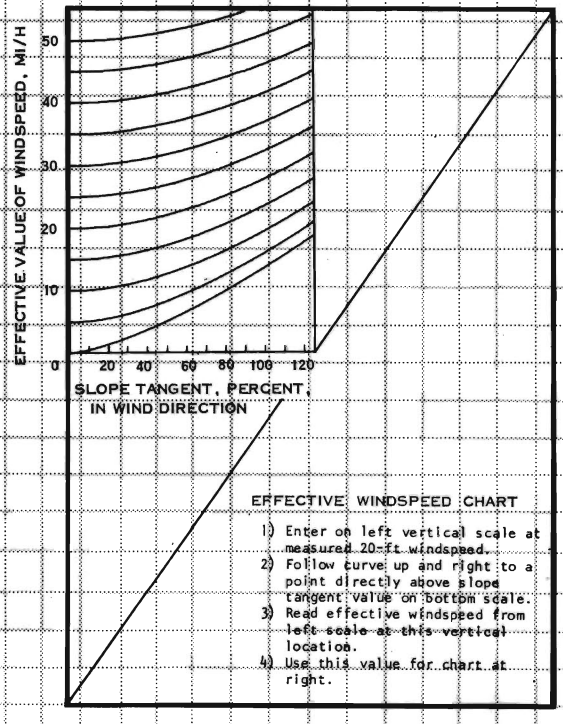


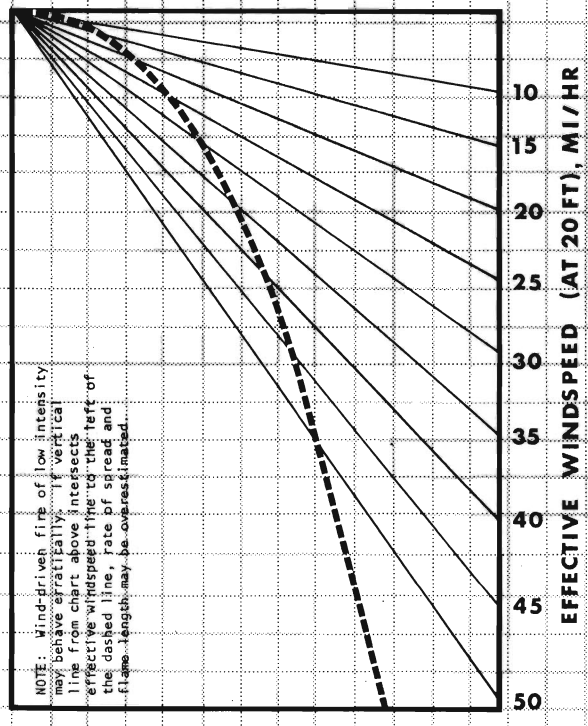


5. BRUSH (2 FT) - HIGH WINDSPEEDS

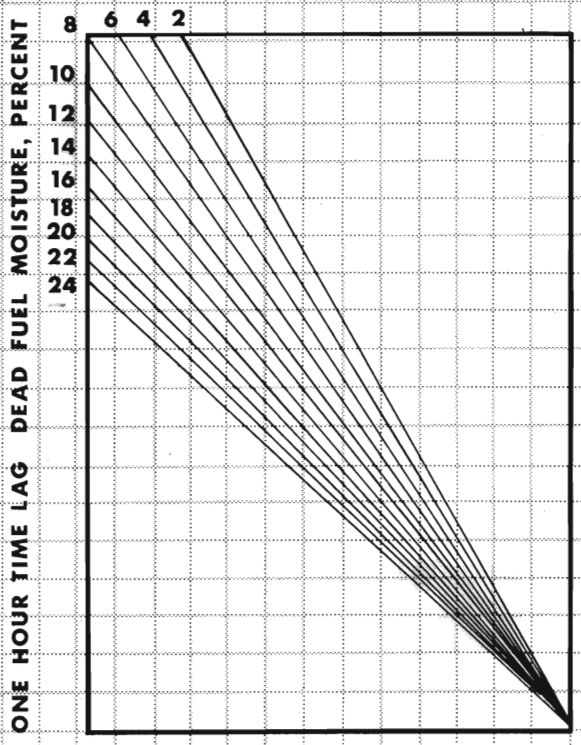


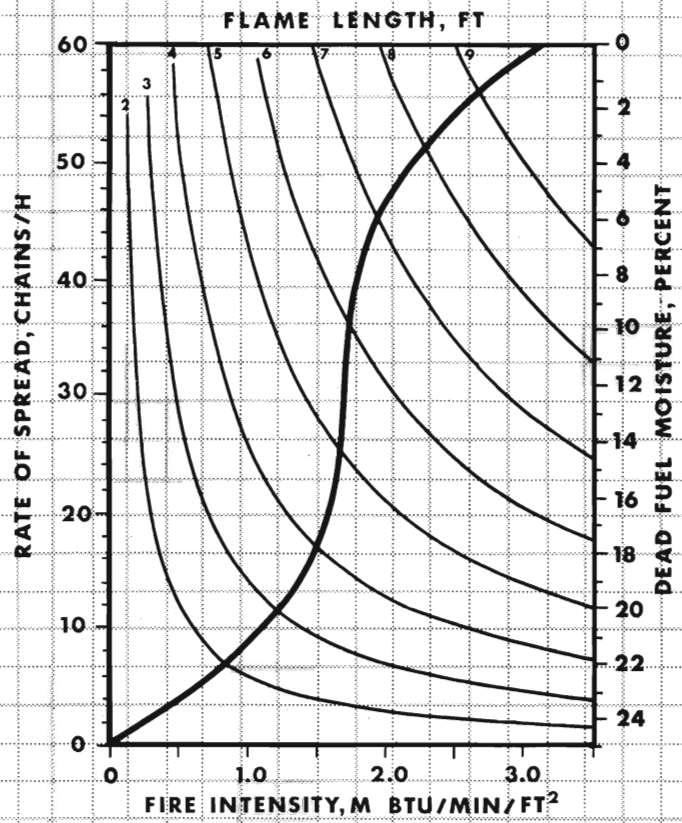


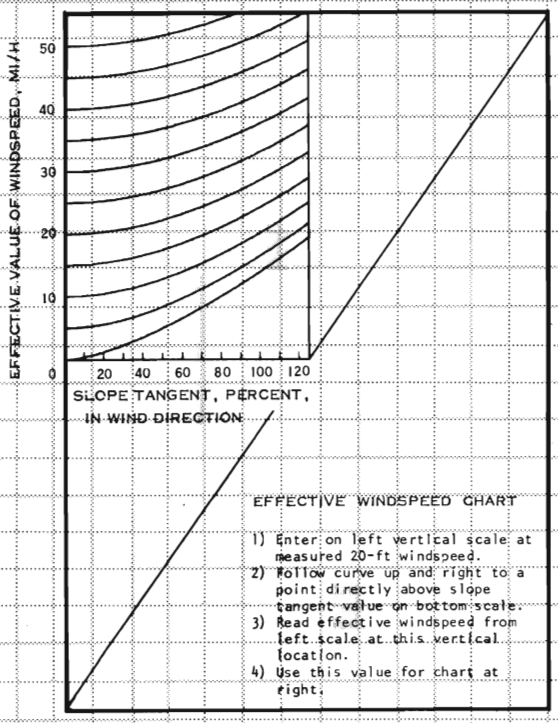


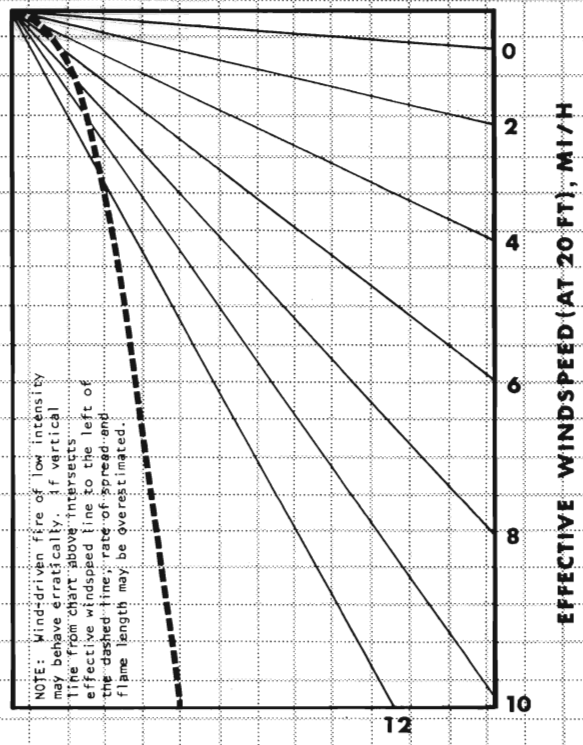


6. DORMANT BRUSH, HARDWOOD SLASH – LOW WINDSPEEDS

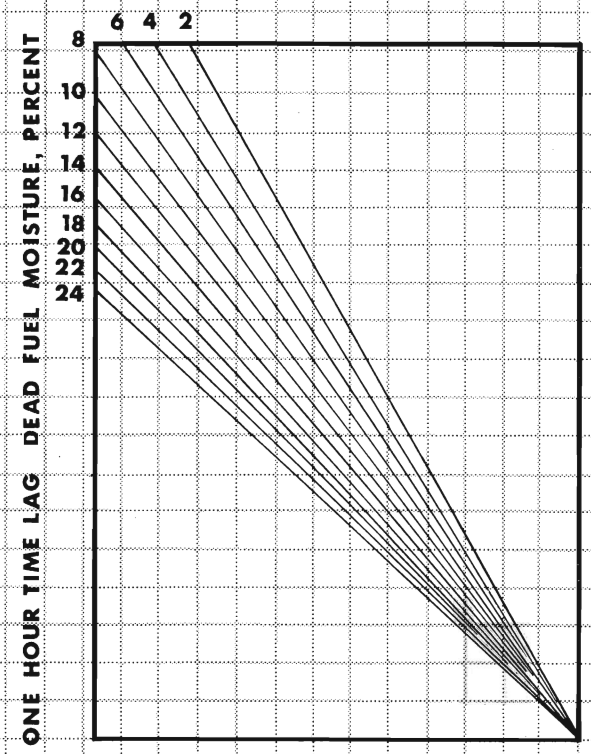


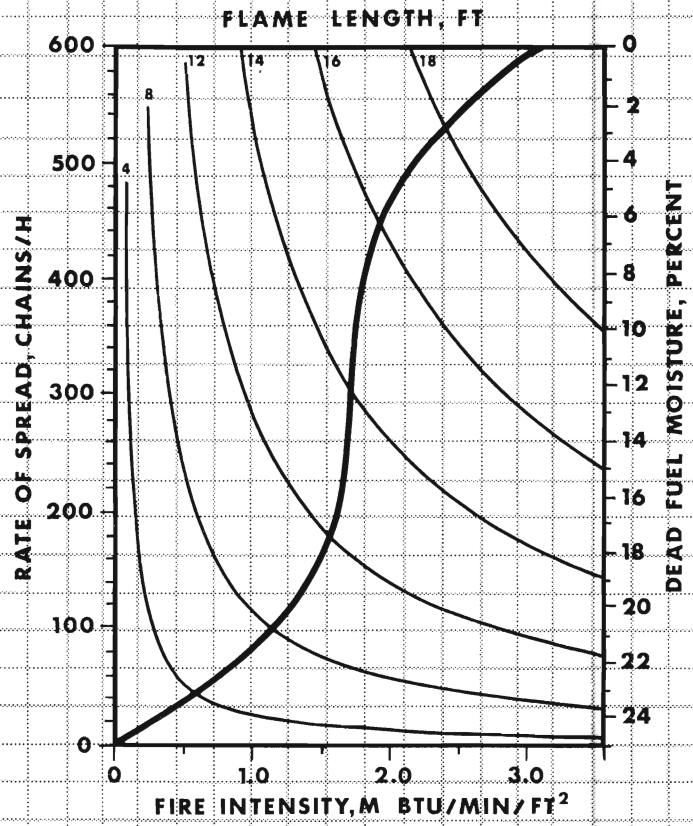


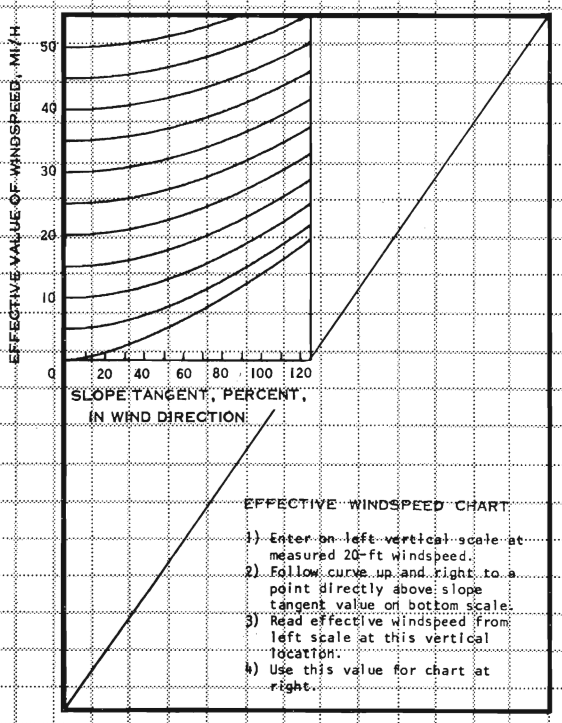


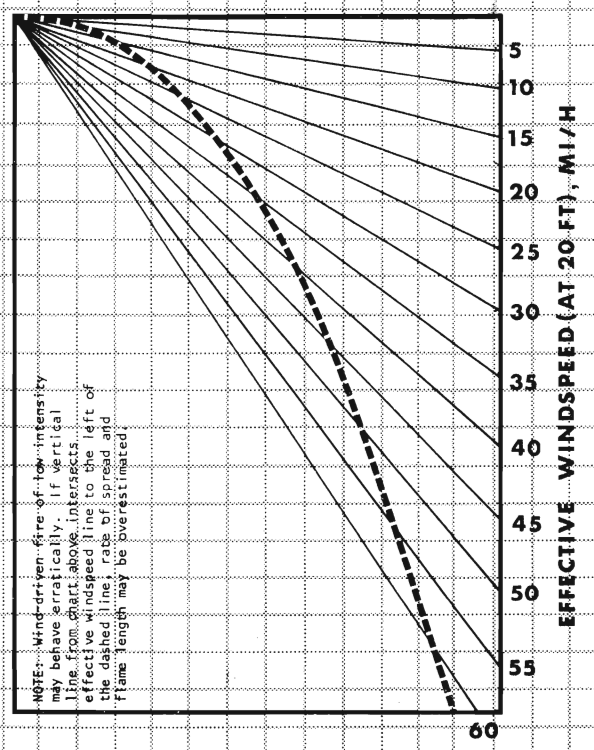


6. DORMANT BRUSH, HARDWOOD SLASH–HIGH WINDSPEEDS

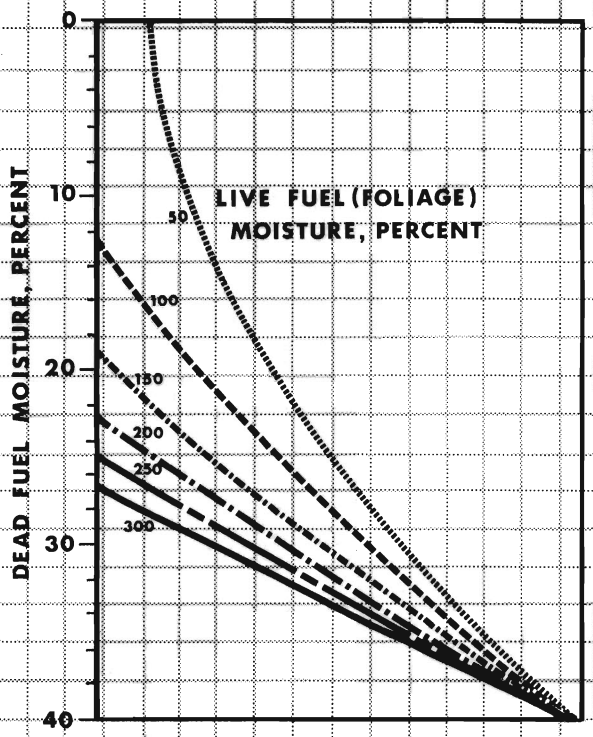


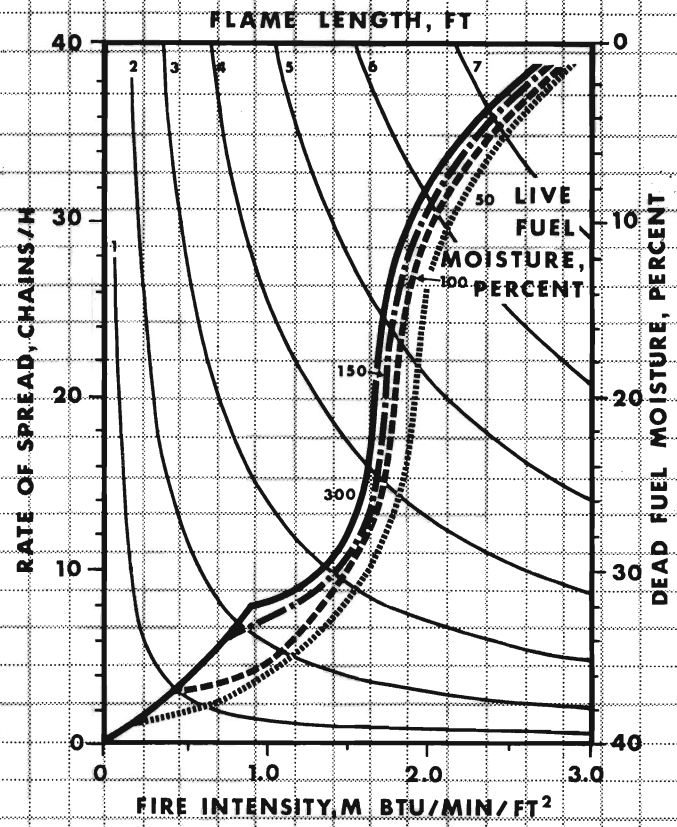


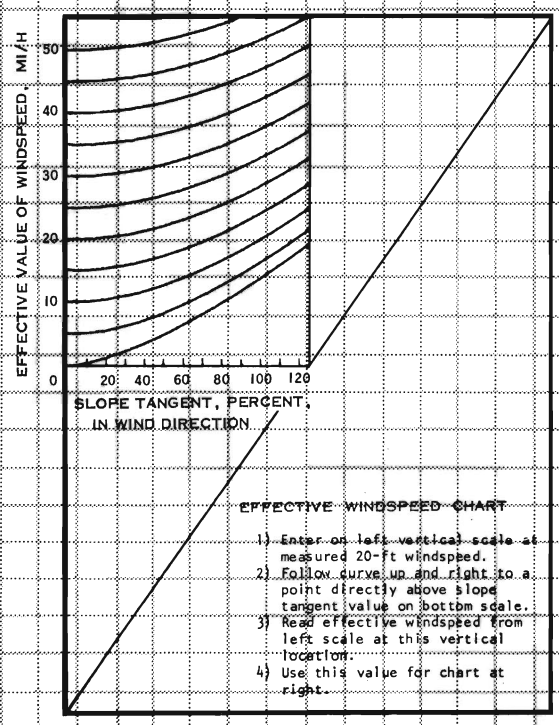


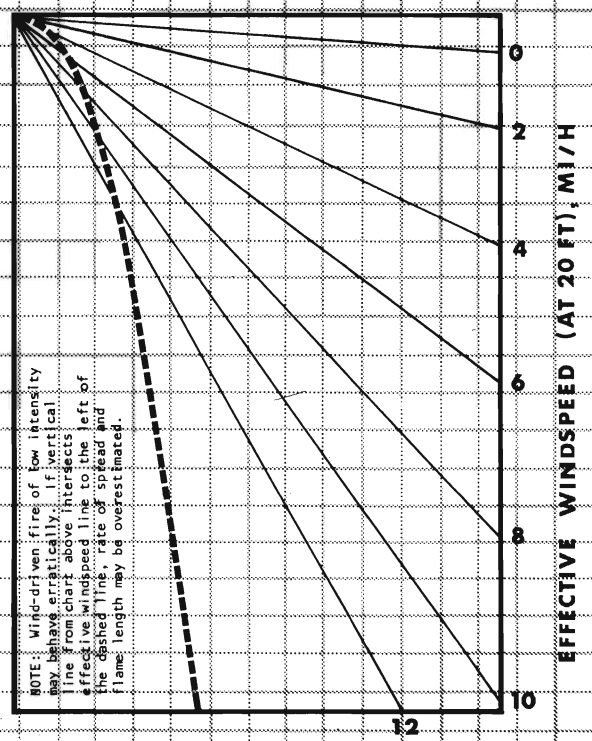


7. SOUTHERN ROUGH - LOW WINDSPEEDS

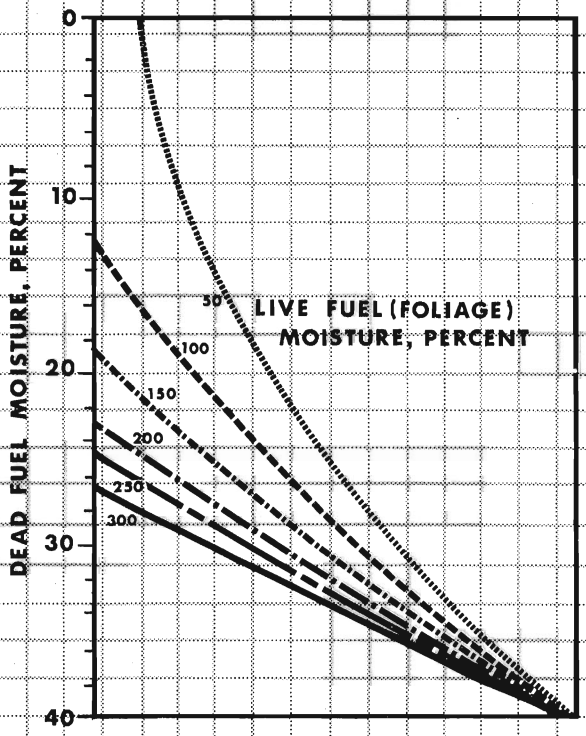


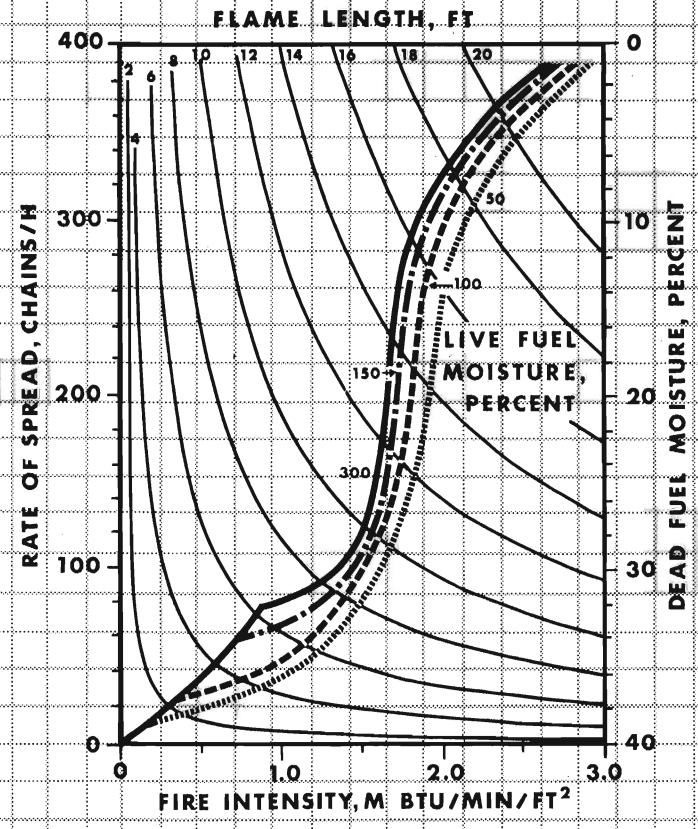


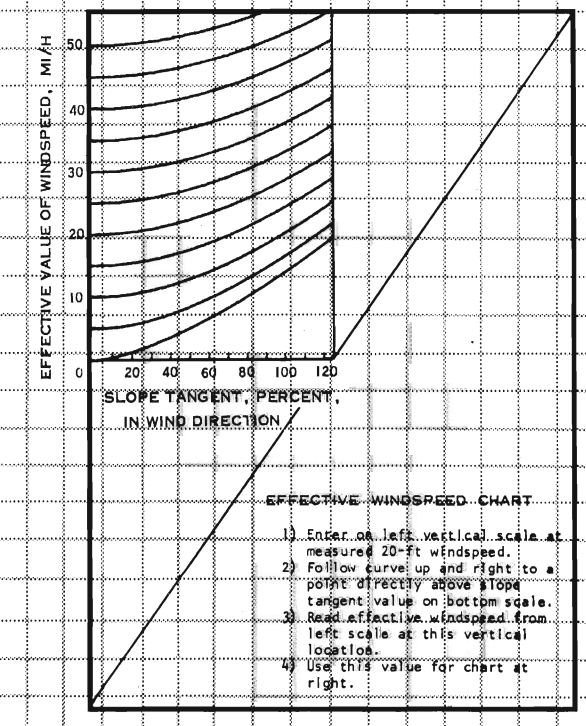


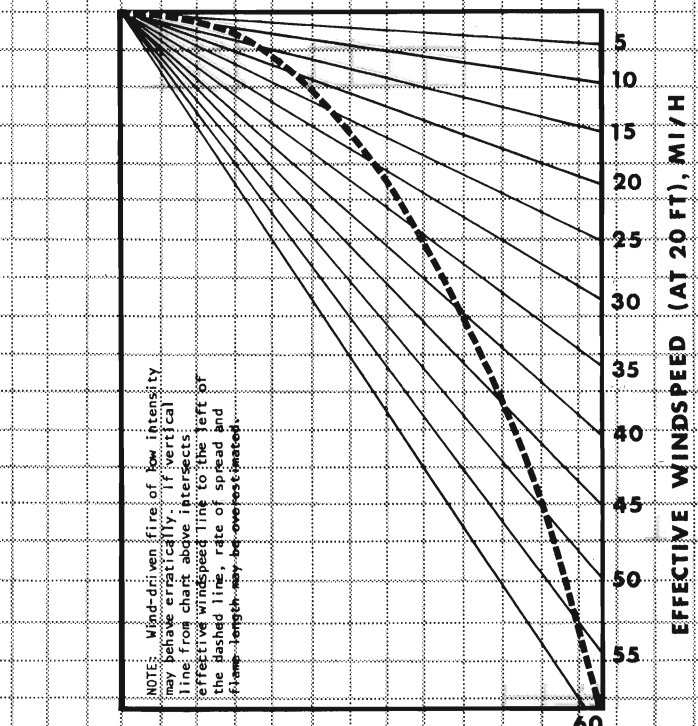


7. SOUTHERN ROUGH - HIGH WINDSPEEDS









Fire Behavior Estimation Charts for Timber Litter

8. Closed Timber Litter

   Best fits: compact litter in closed, short-needle conifer stands.

   Also use for: Compact hardwood litter (see 9 also).

9. Hardwood Litter

   Best fits: Fresh, uncompacted oak/hickory litter.

   Also use for: Fresh, uncompacted litter under maple, tulip poplar, aspen, etc.

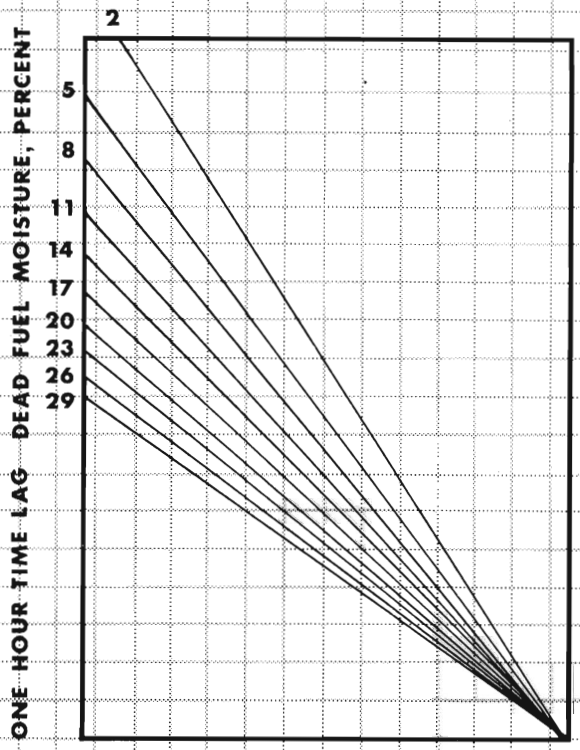
   NOTE: Blown, burning leaves may increase spread rate above chart predictions.

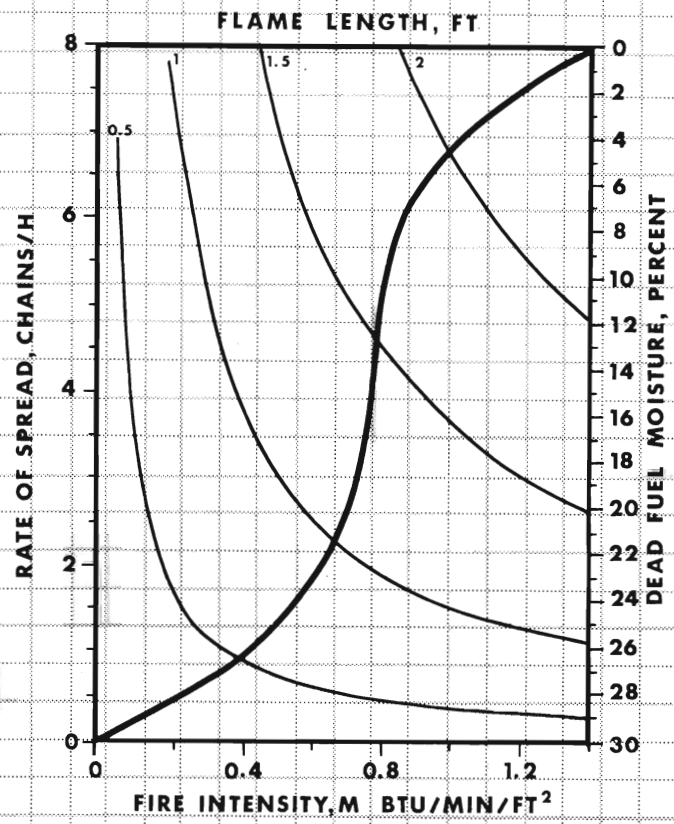
10. Timber (Litter and Understory)

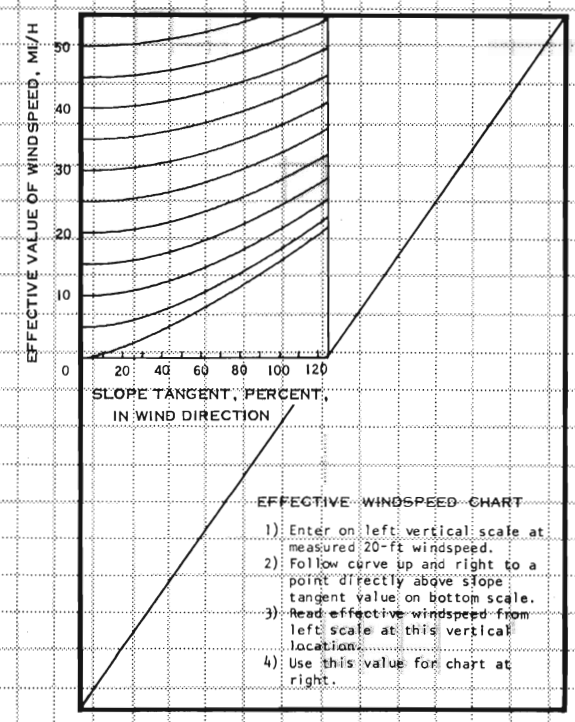
    Best fits: Overmature conifer stands with high loadings of dead, down woody fuel, including shrub understory or conifer reproduction.

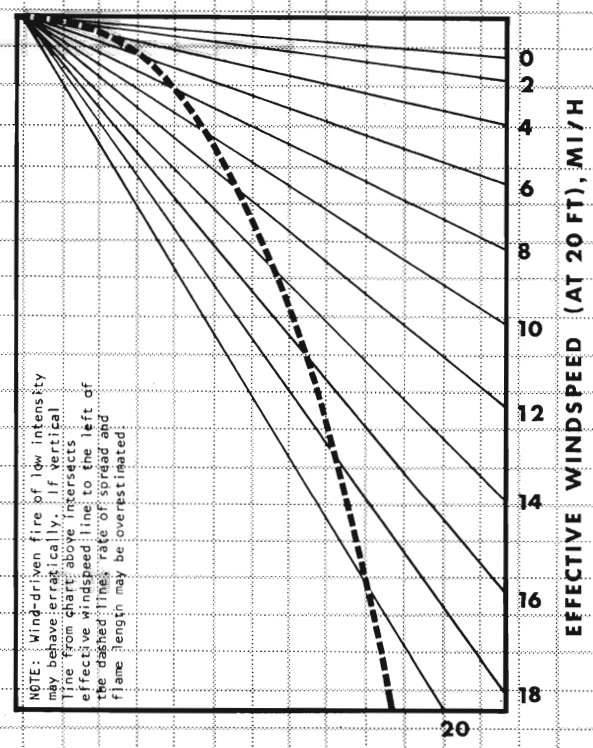
    Also use for: Settled thinning or partial-cut conifer slash, with needles fallen, overgrown by shrubs or conifer reproduction.

8. CLOSED TIMBER LITTER - LOW WINDSPEEDS

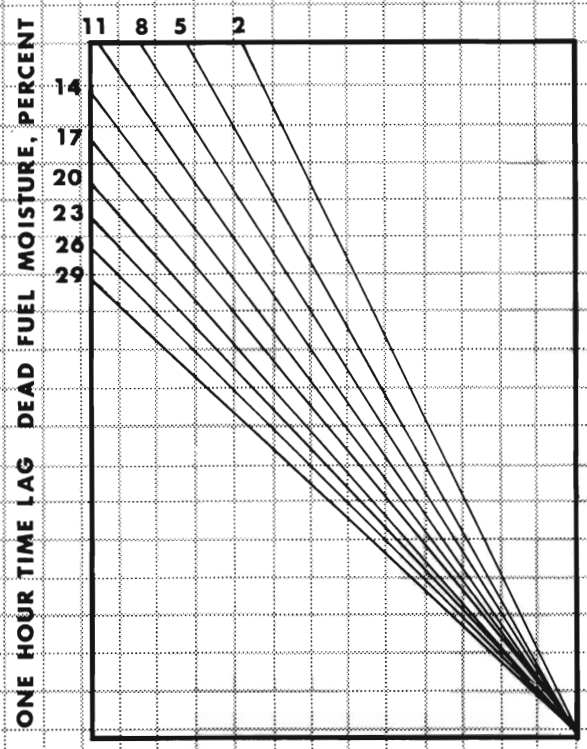


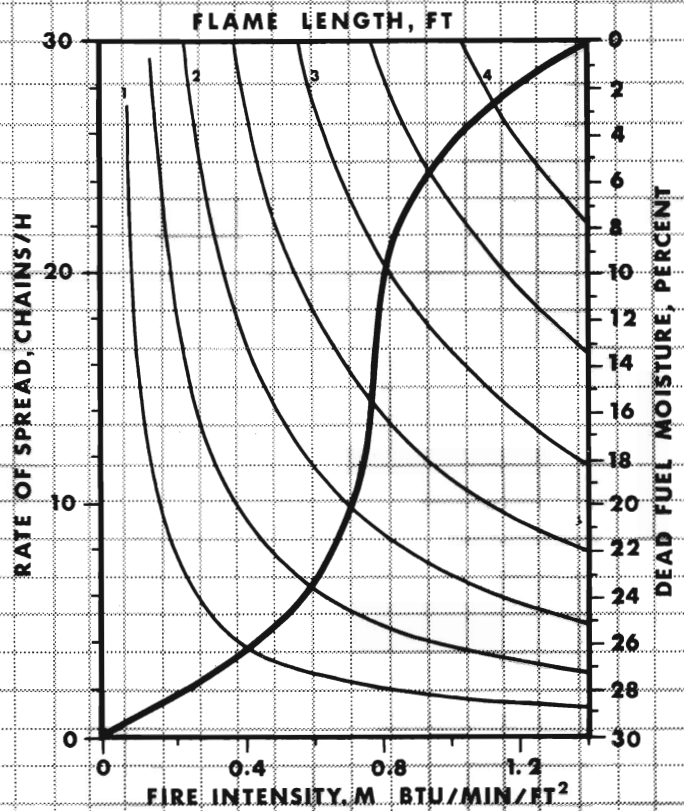


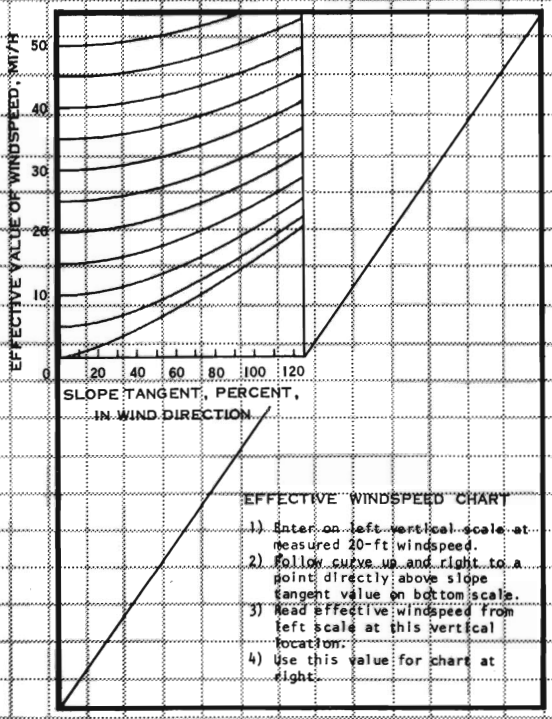


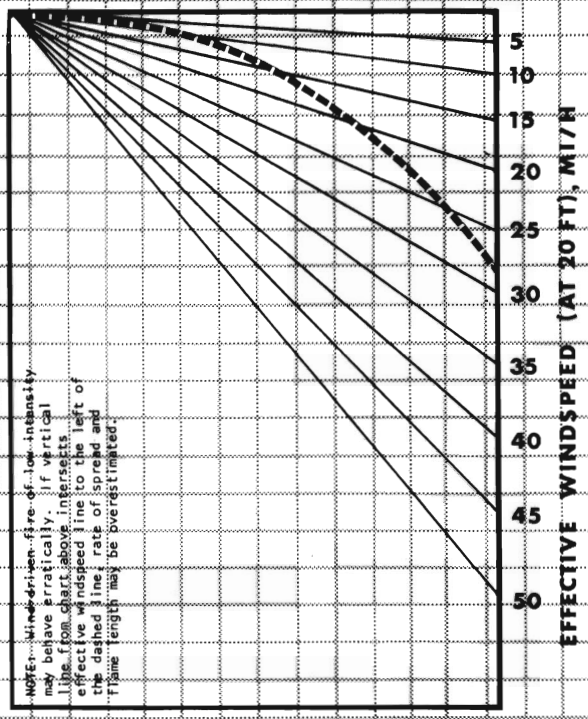


8. CLOSED TIMBER LITTER-HIGH WINDSPEEDS

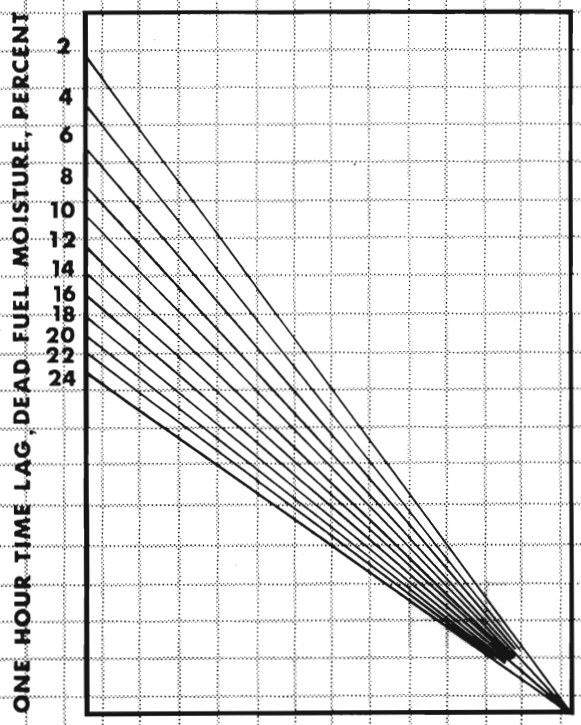


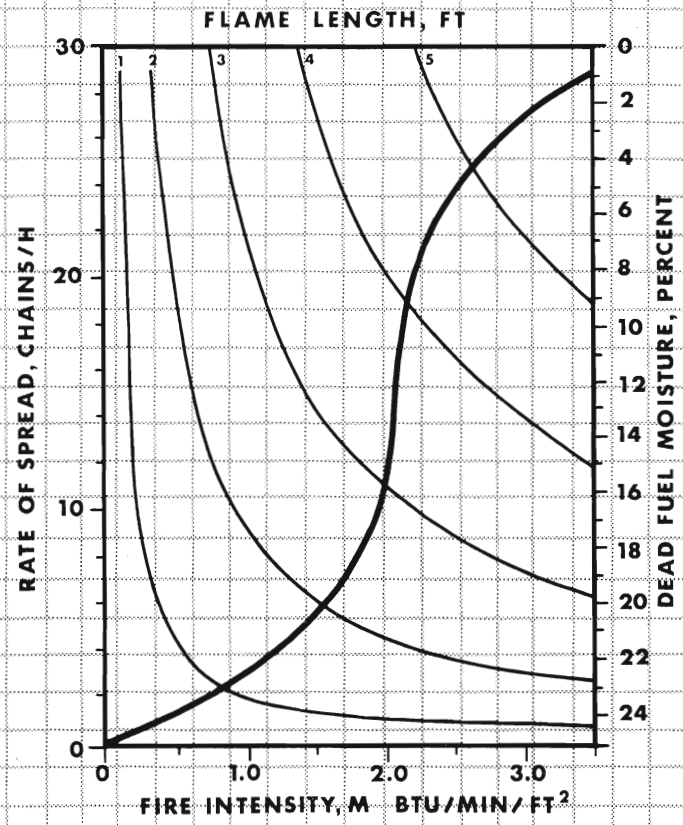


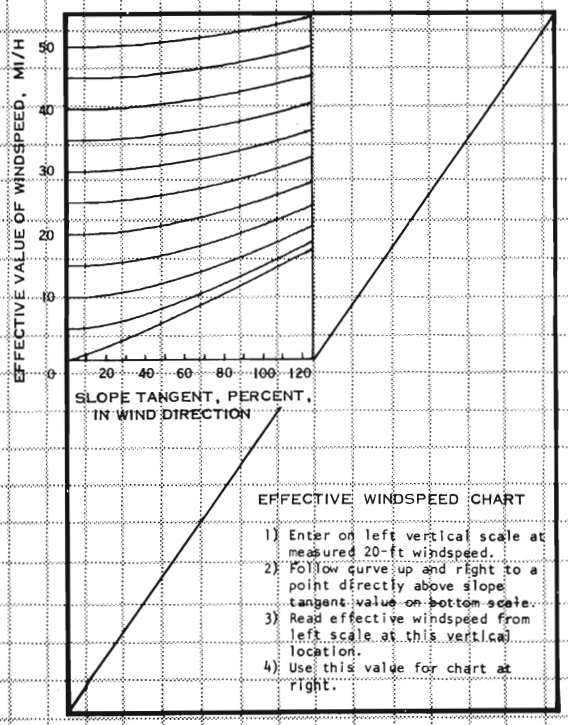


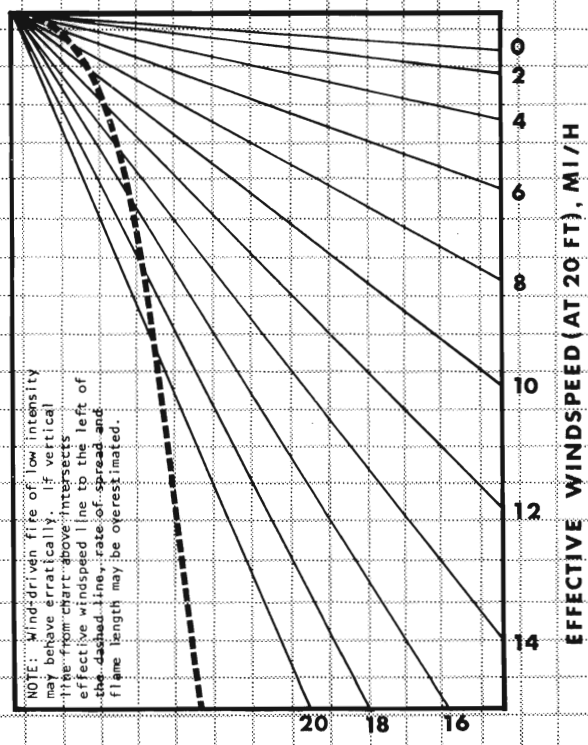


9. HARDWOOD LITTER - LOW WINDSPEEDS

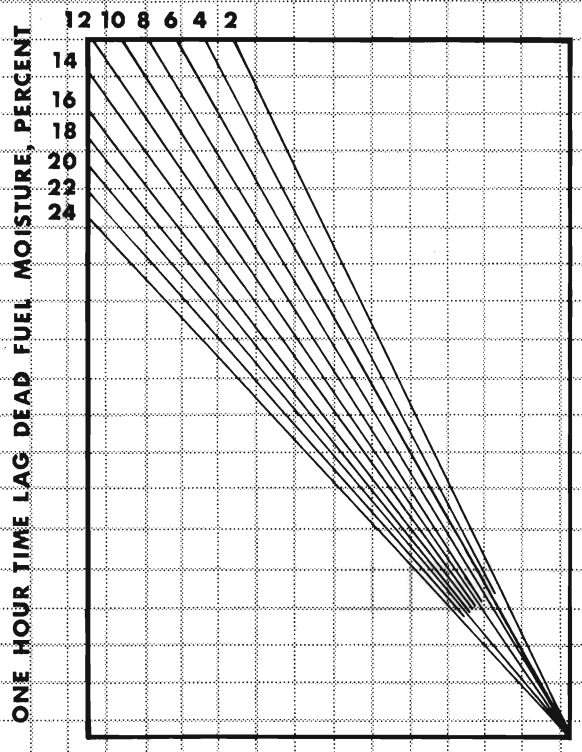


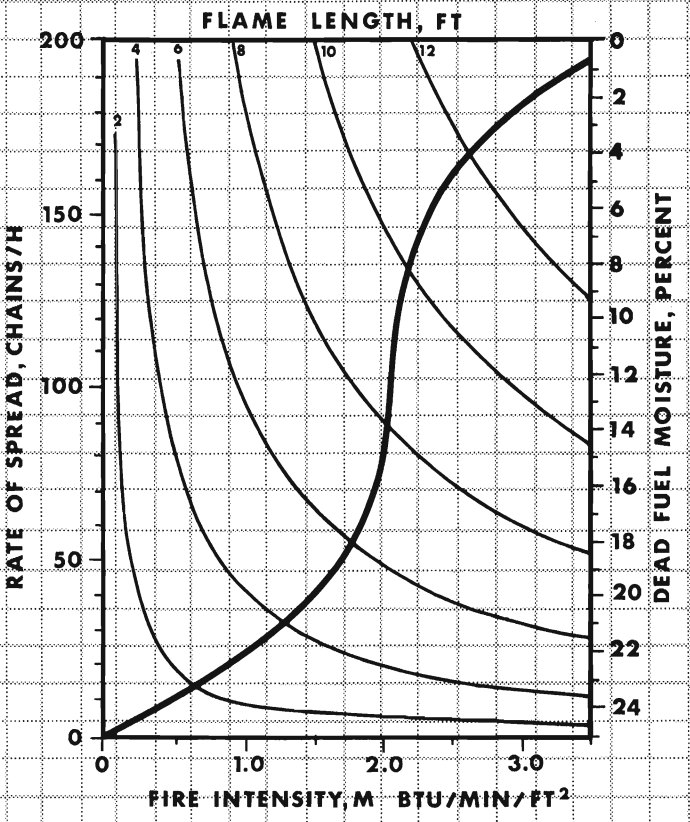


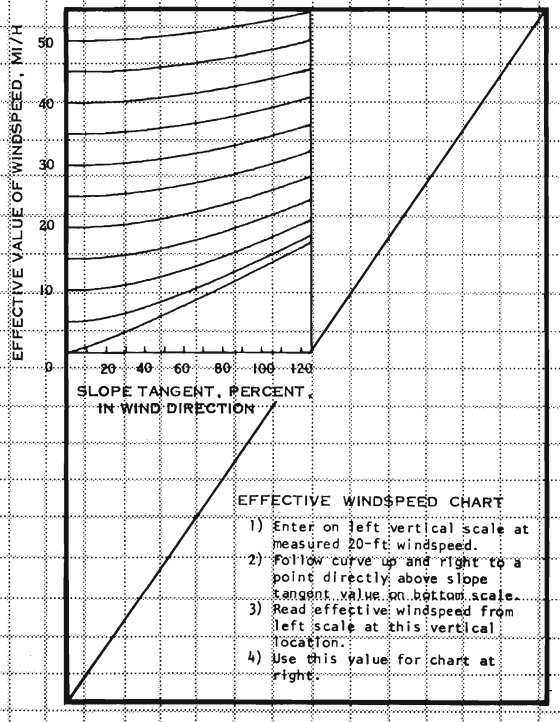


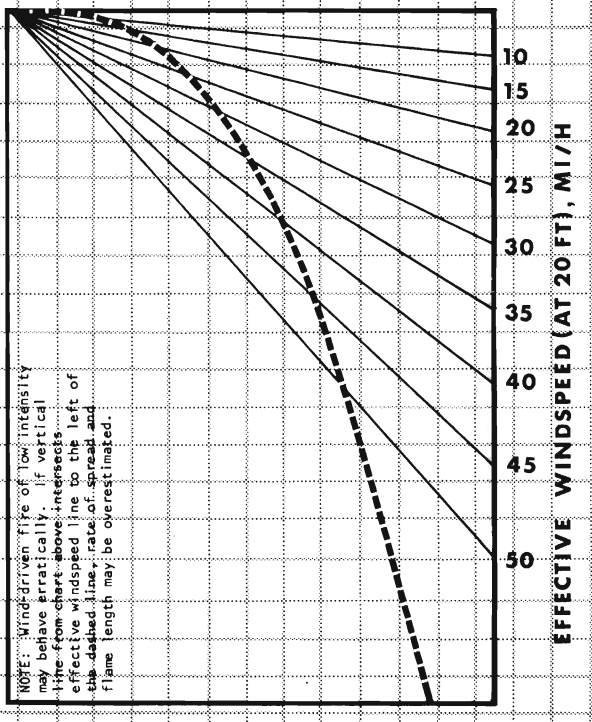


9. HARDWOOD LITTER - HIGH WINDSPEEDS

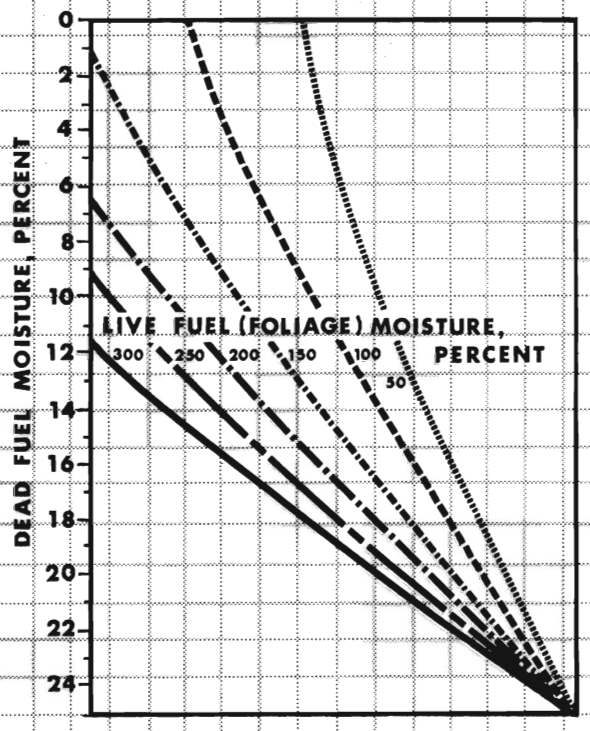


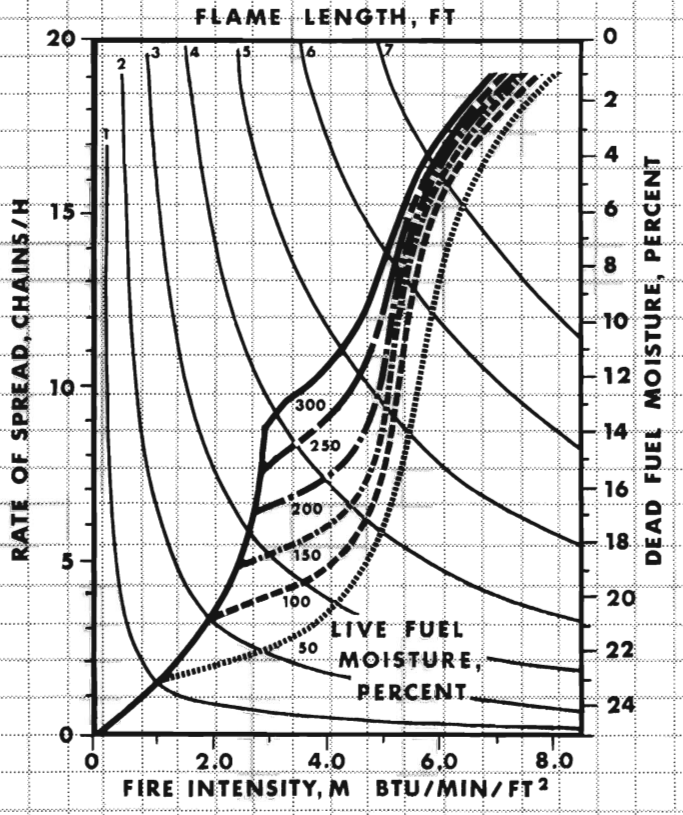


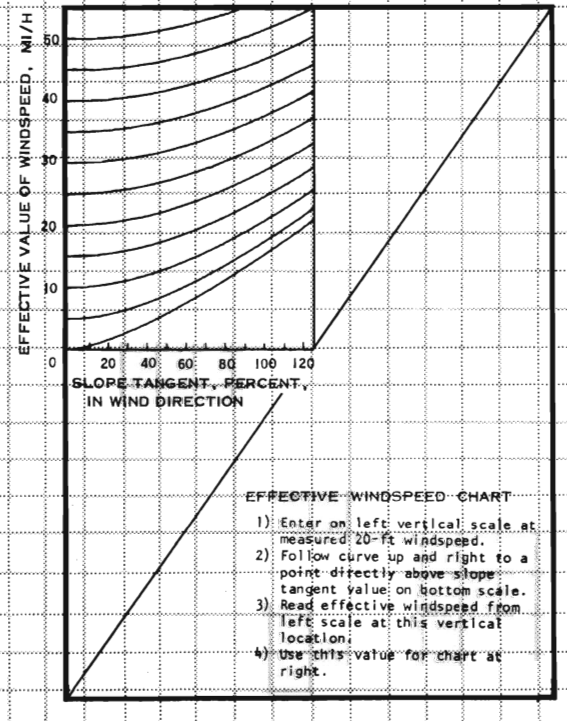


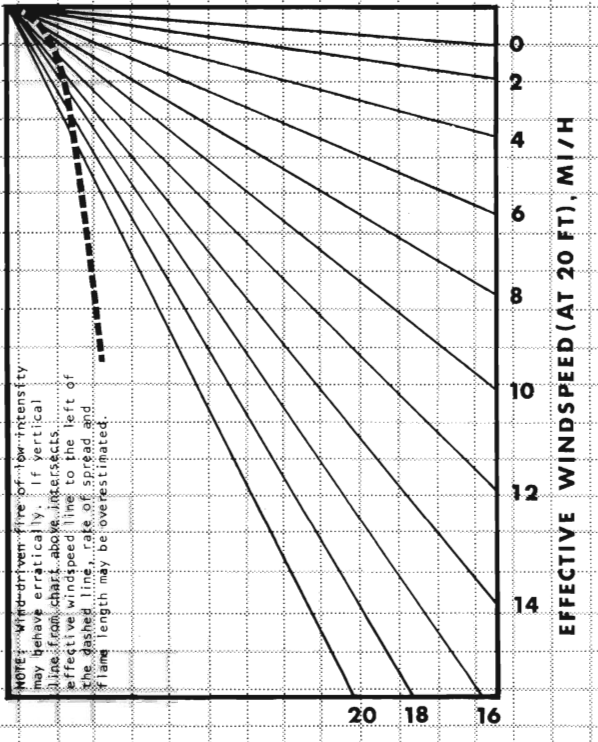


10. TIMBER (LITTER & UNDERSTORY)-LOW WINDSPEEDS

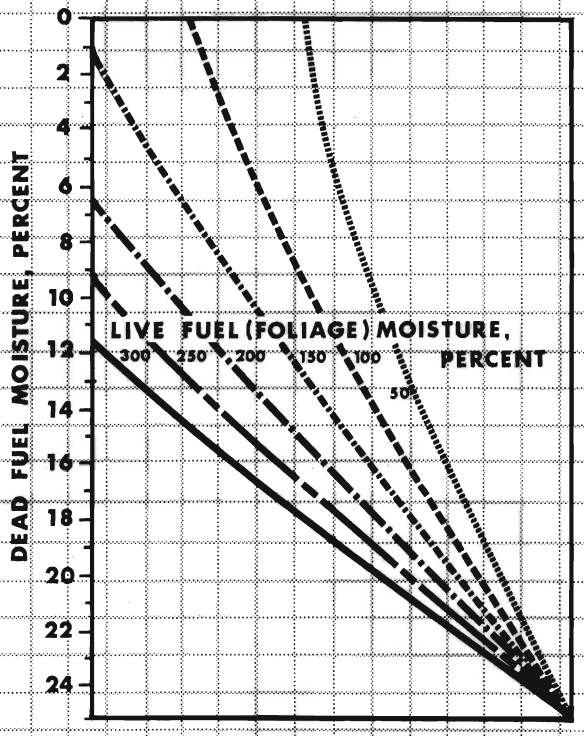


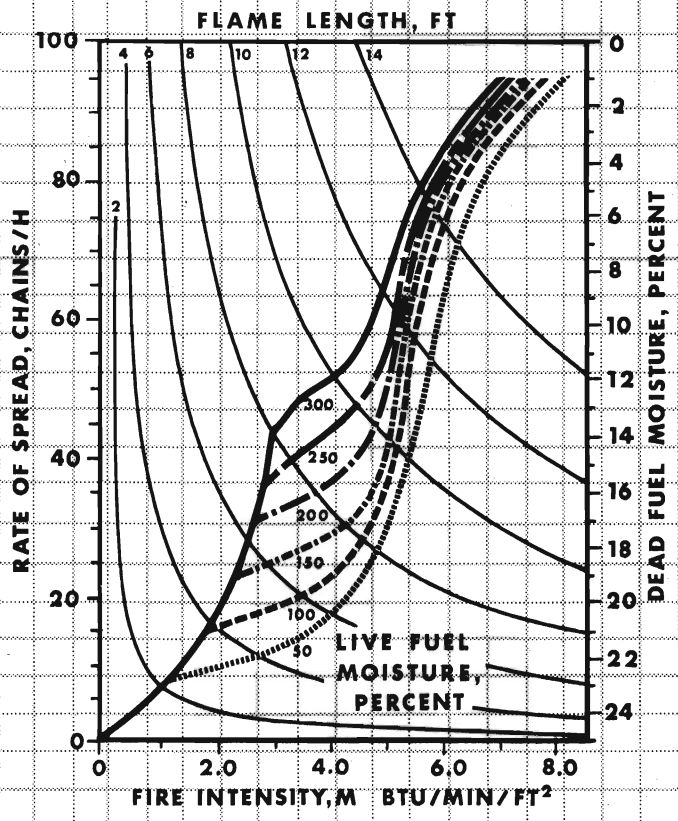


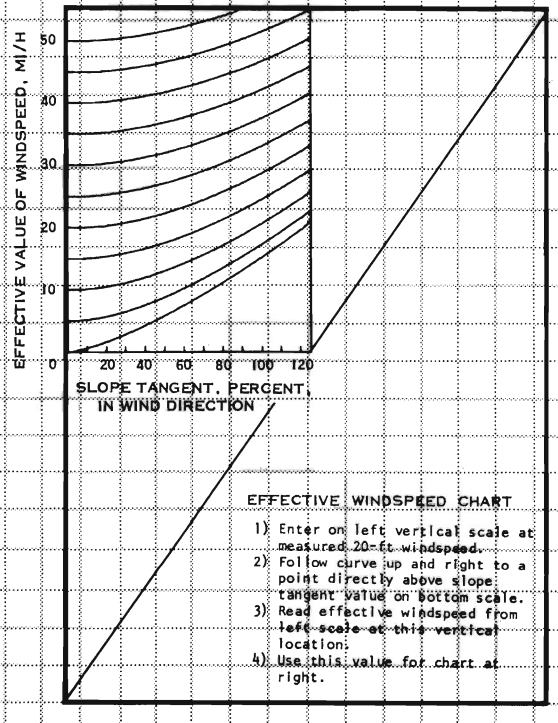


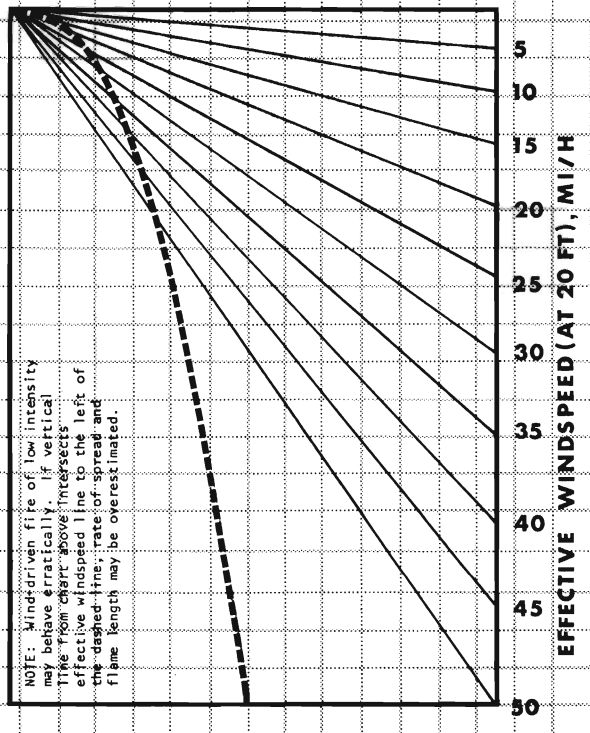


10. TIMBER (LITTER & UNDERSTORY)-HIGH WINDSPEEDS









11. Light Logging Slash

Best fits: Light (under 40 tons per acre) logging slash from partial or clearcut western mixed conifers. Most needles have fallen, slash somewhat compact.

12. Medium Logging Slash

Best fits: Medium (40 to 120 tons per acre) logging slash from clearcut western mixed conifers. Most needles have fallen, slash somewhat compact.

Also use for: Light "red" slash, with needles attached.

13. Heavy Logging Slash

Best fits: Heavy (more than 120 tons per acre) logging slash from clearcut western mixed conifers. Most needles have fallen, slash somewhat compact.

Also use for: Medium "red" slash, with needles attached.

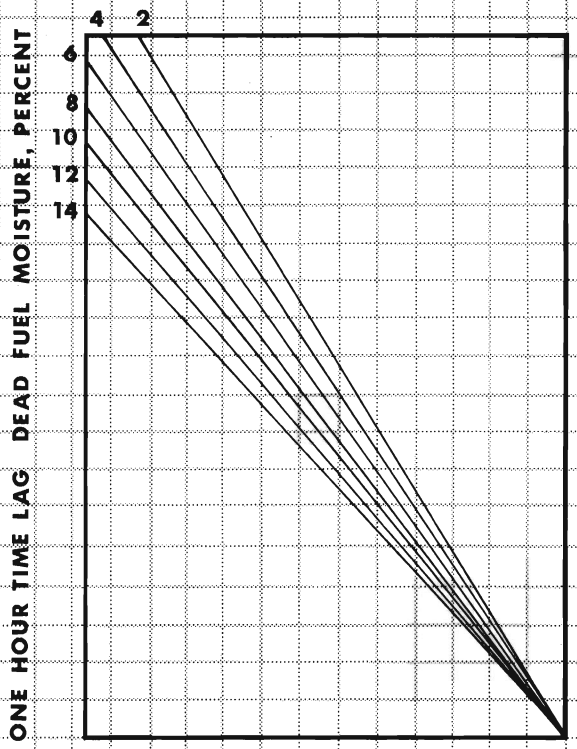
NOTES: Hardwood slash - see model 6

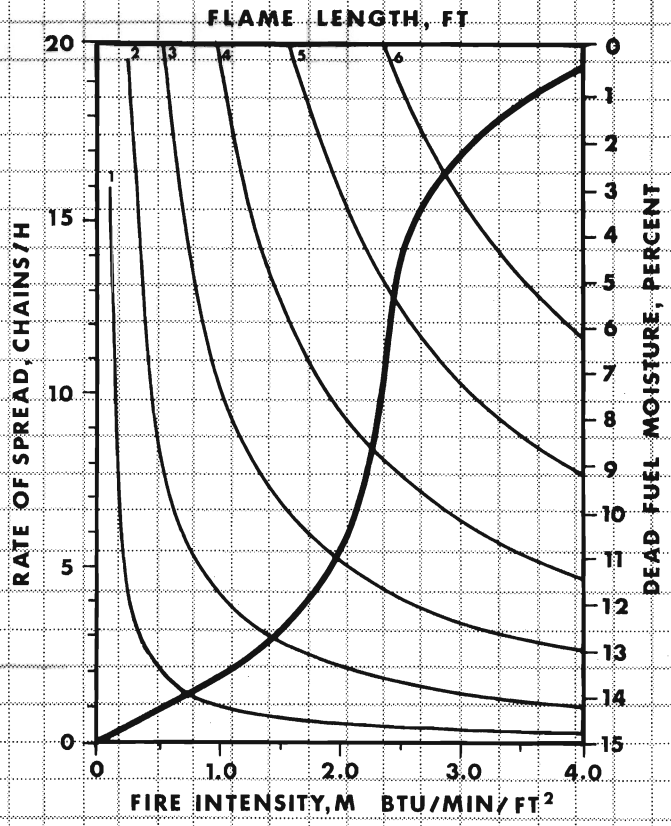
Heavy "red" slash - see model 4

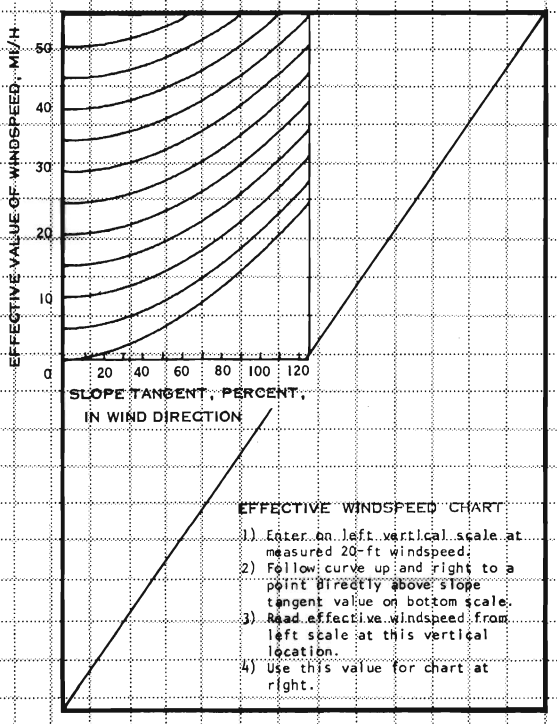
Overgrown slash - see model 10

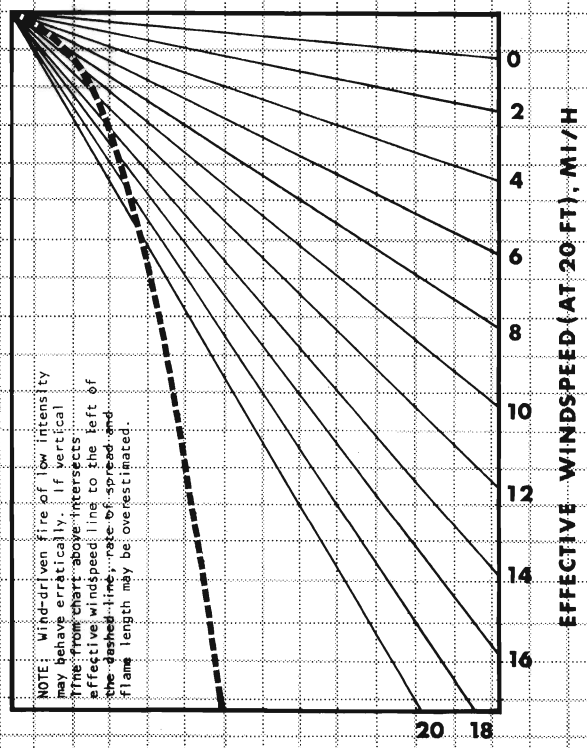
Southern pine clearcut slash - see model 2

11. LIGHT LOGGING SLASH-LOW WINDSPEEDS

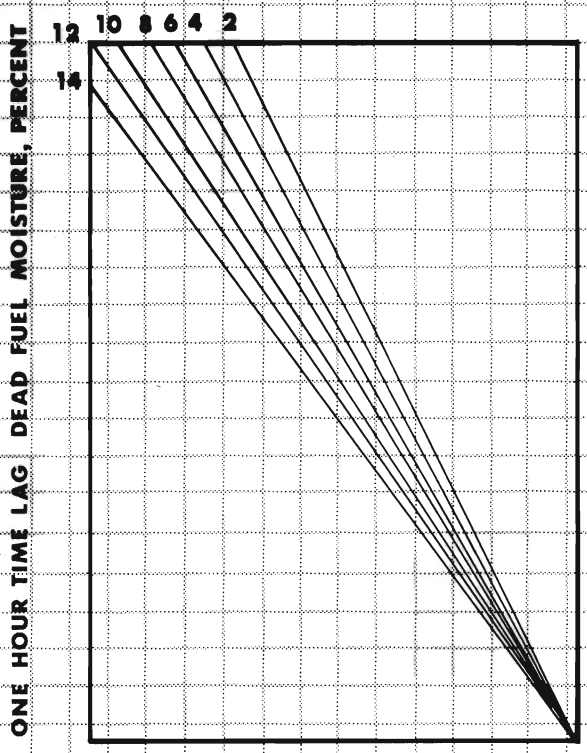


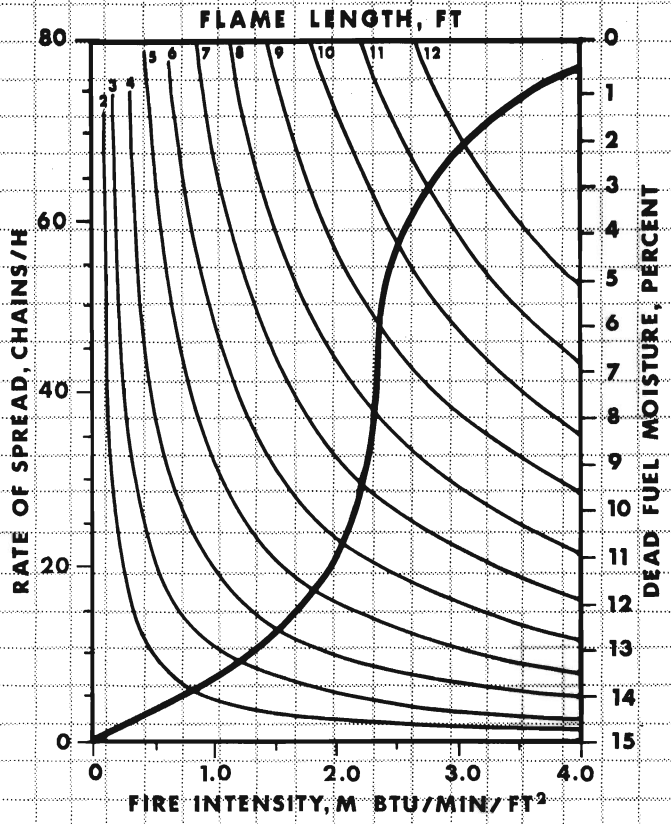


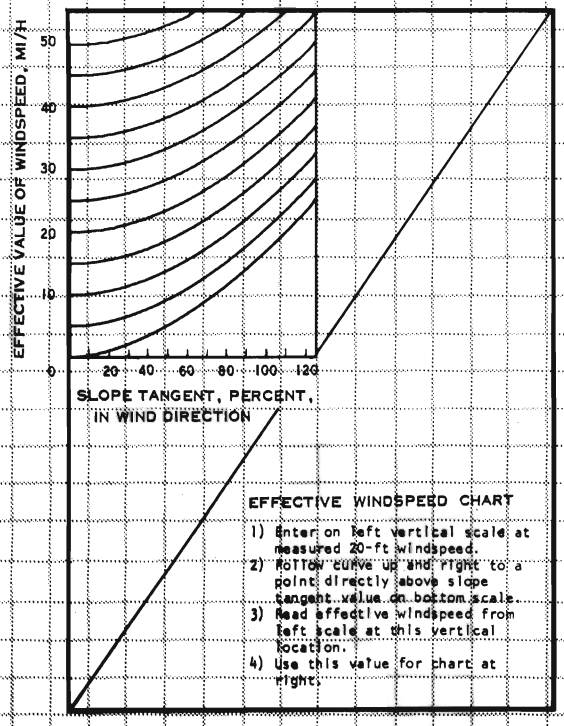


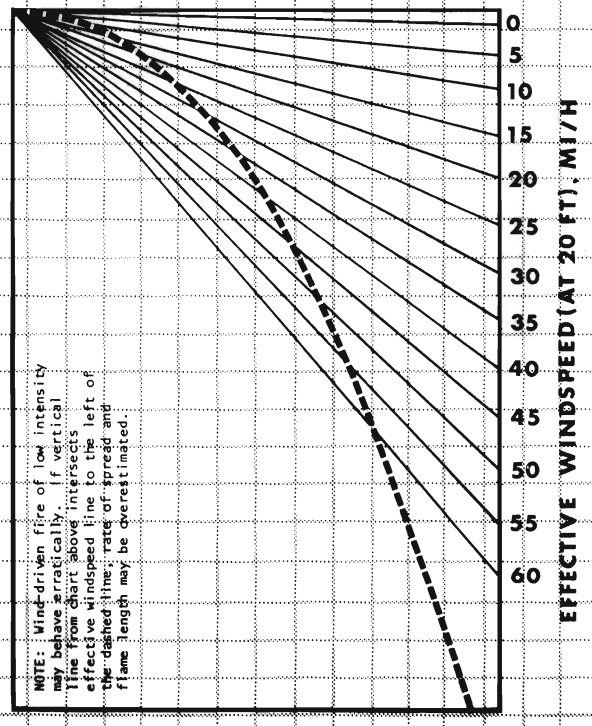


11. LIGHT LOGGING SLASH-HIGH WINDSPEEDS

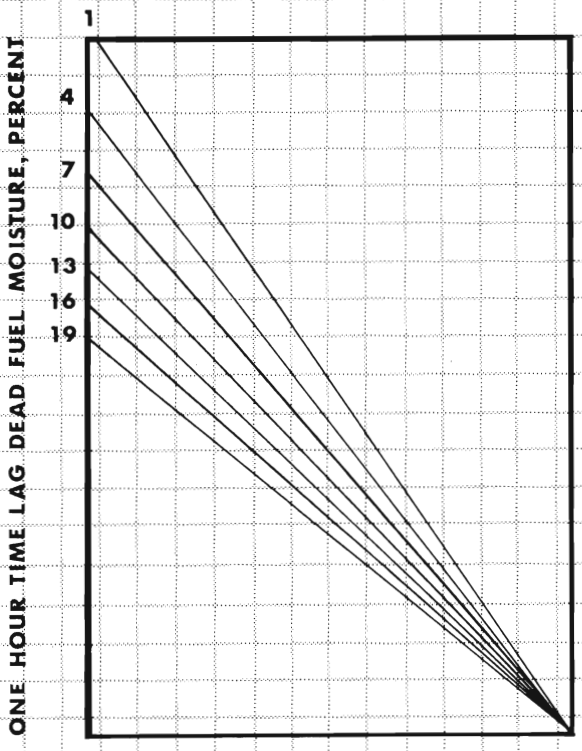


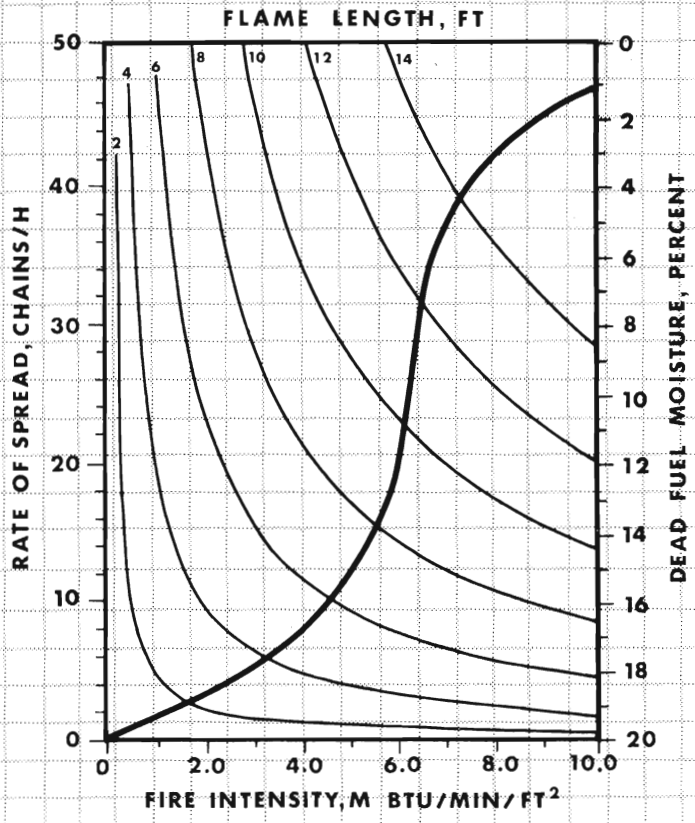


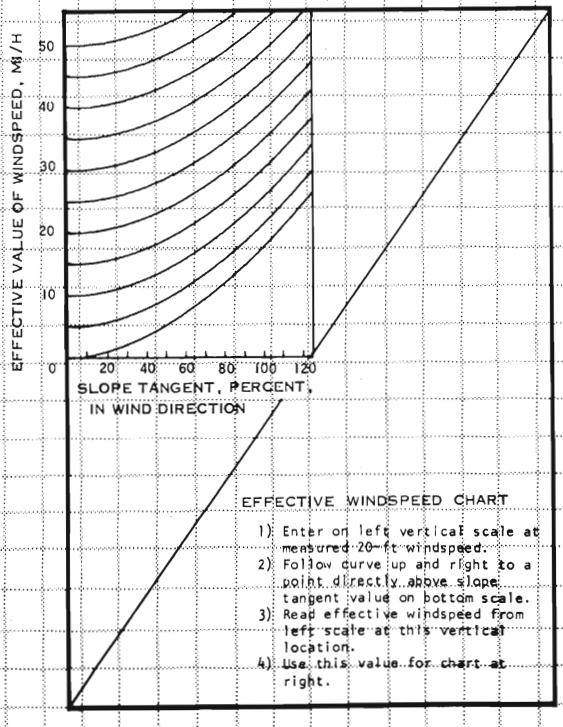


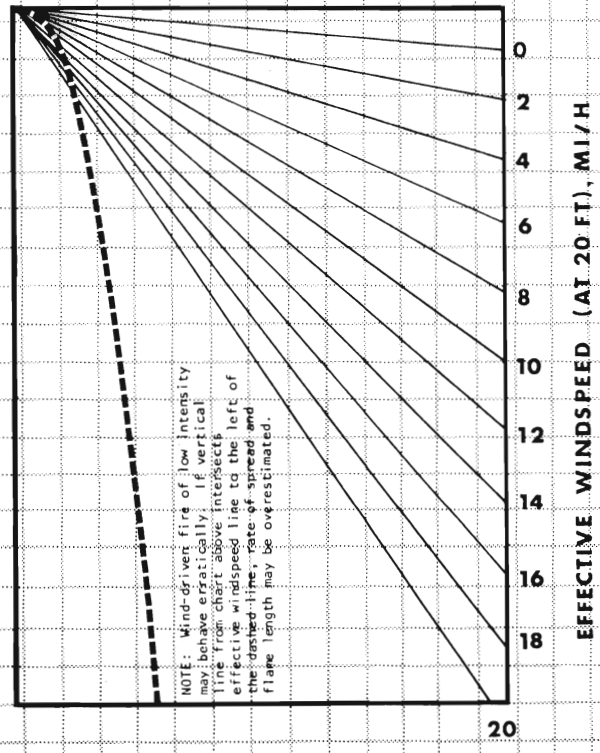


12. MEDIUM LOGGING SLASH - LOW WINDSPEEDS

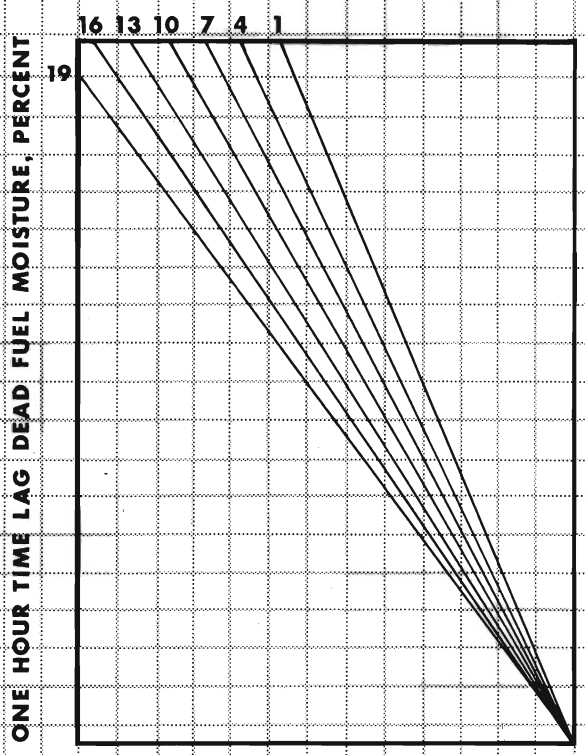


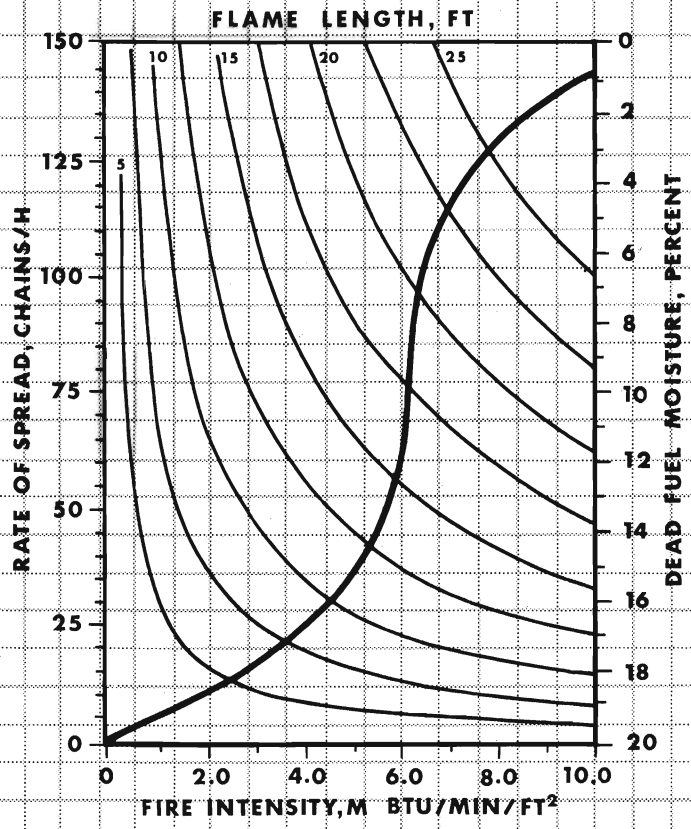


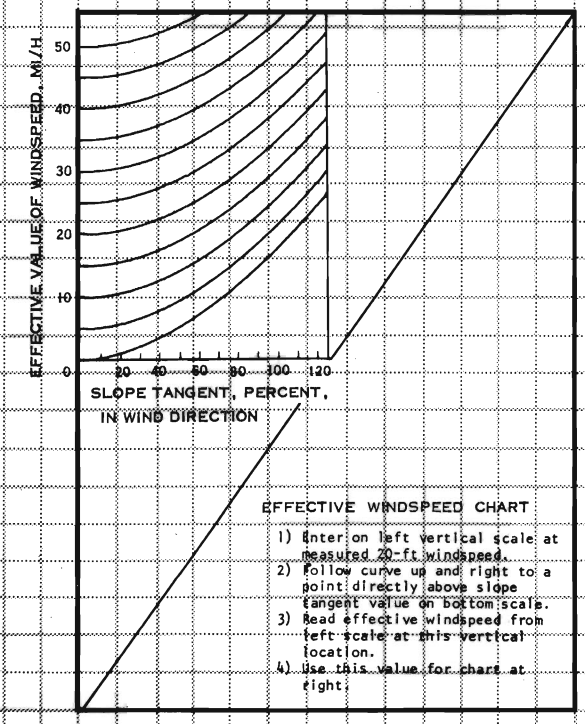


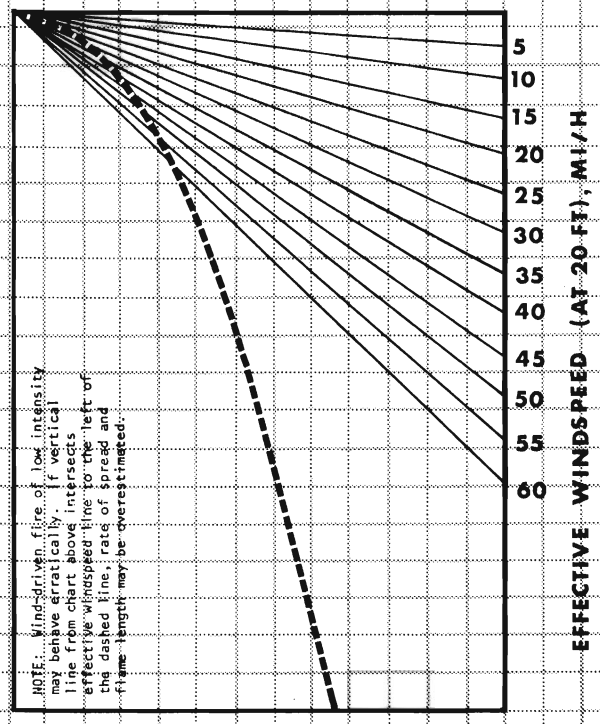


12. MEDIUM LOGGING SLASH-HIGH WINDSPEEDS

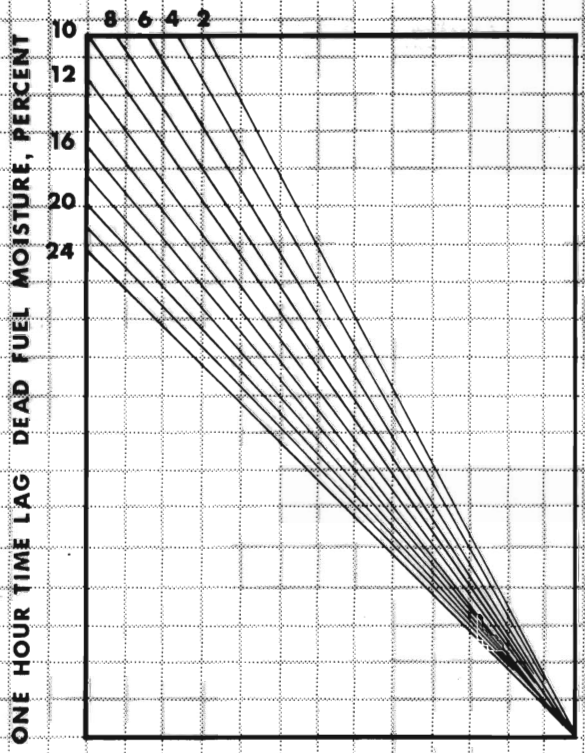


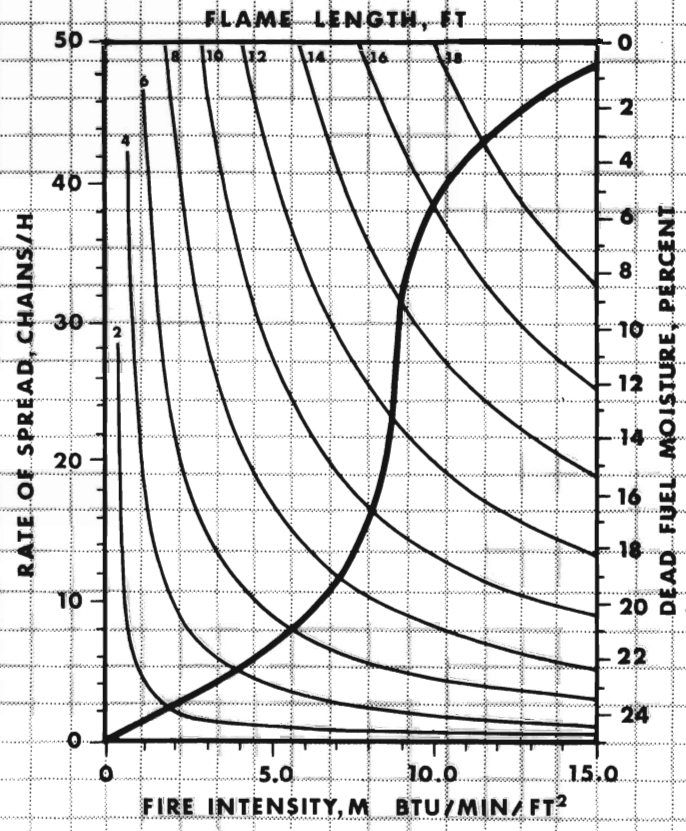


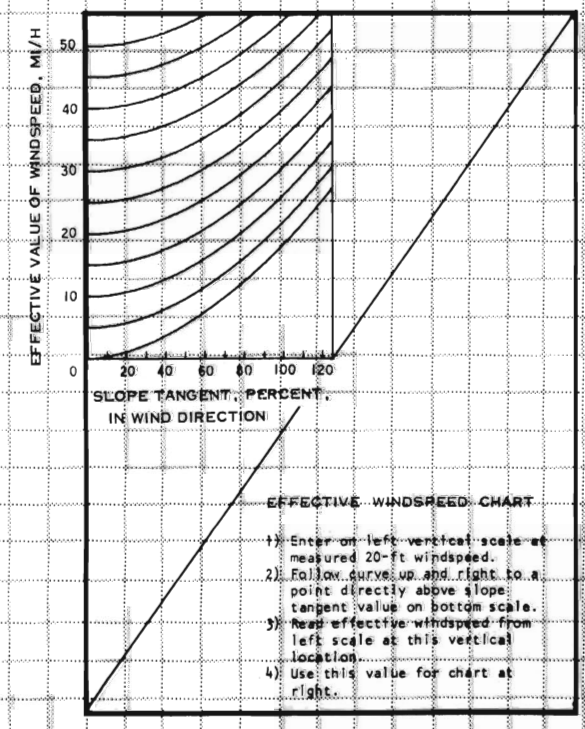


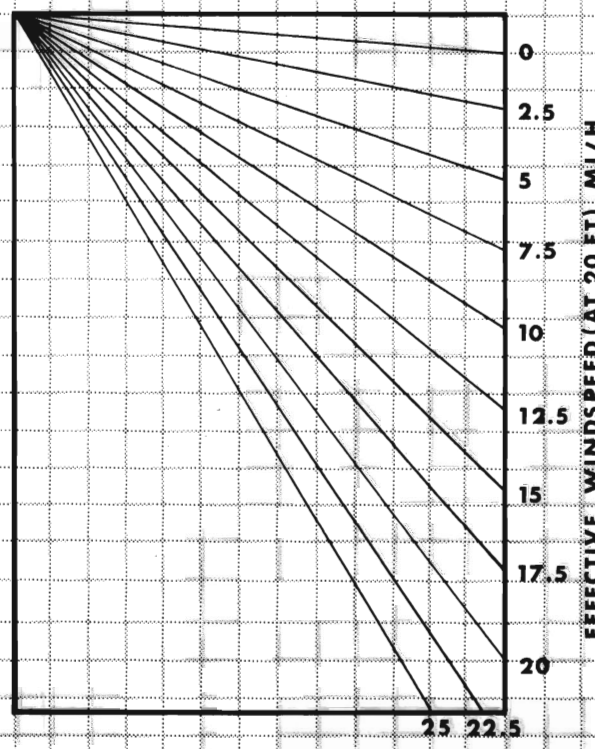


13. HEAVY LOGGING SLASH-LOW WINDSPEEDS

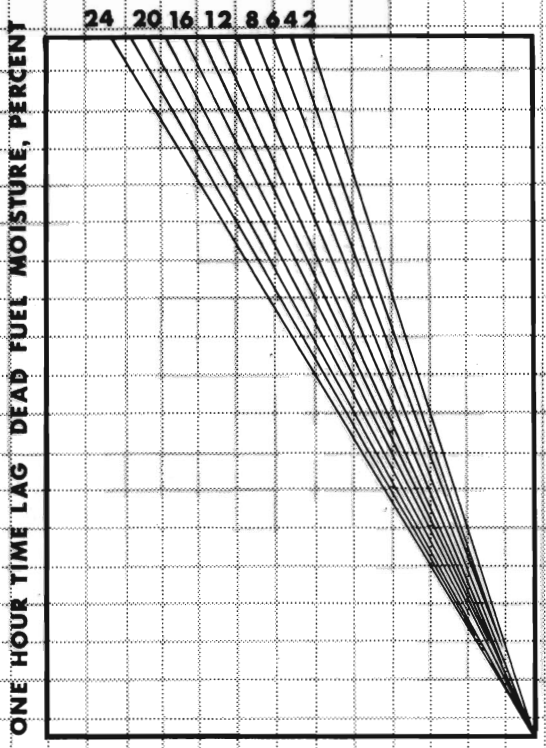


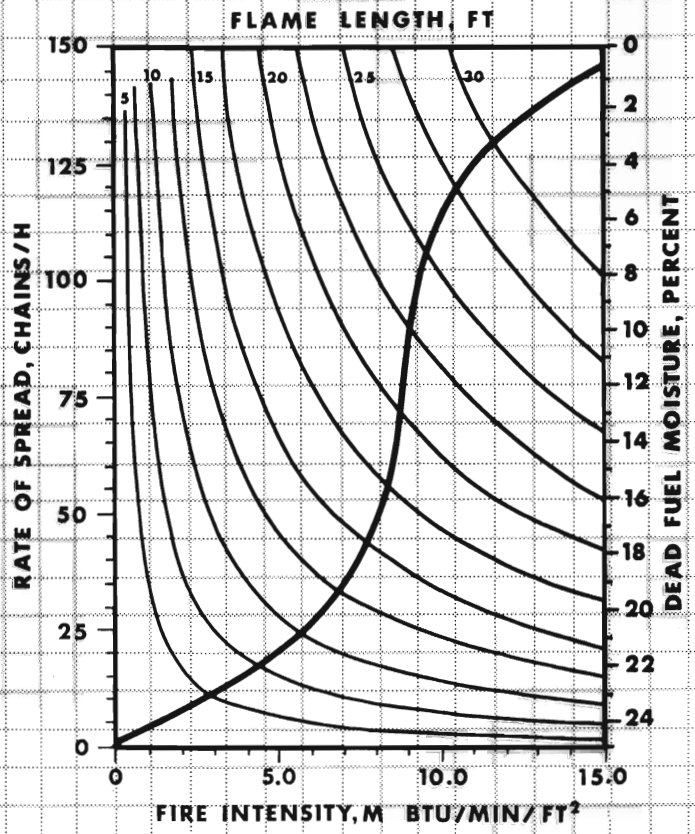


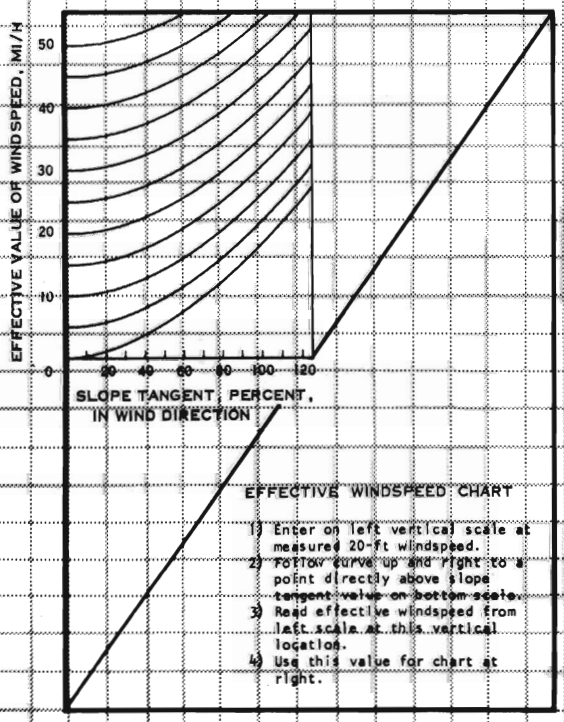


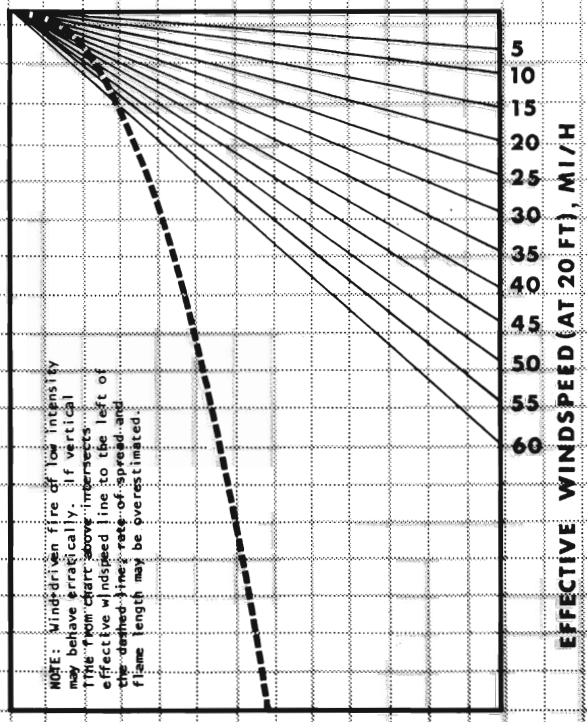


13. HEAVY LOGGING SLASH - HIGH WINDSPEEDS









Rate of Growth Factors

Effects of Wind and Slope on Forward Rate of Spread

The computer-based versions of Rothermel's spread model and the nomographs presented above allow one to incorporate the effects of wind and slope, either separately or combined. The stylized fuel models were used to establish the fuel bed properties, which influence spread rate sensitivity to wind and slope (appendix II), shown in figures 3 and 4. These figures provide estimates of the effects of slope or wind on a fire burning in a fuel that resembles one of the 13 stylized models used here.

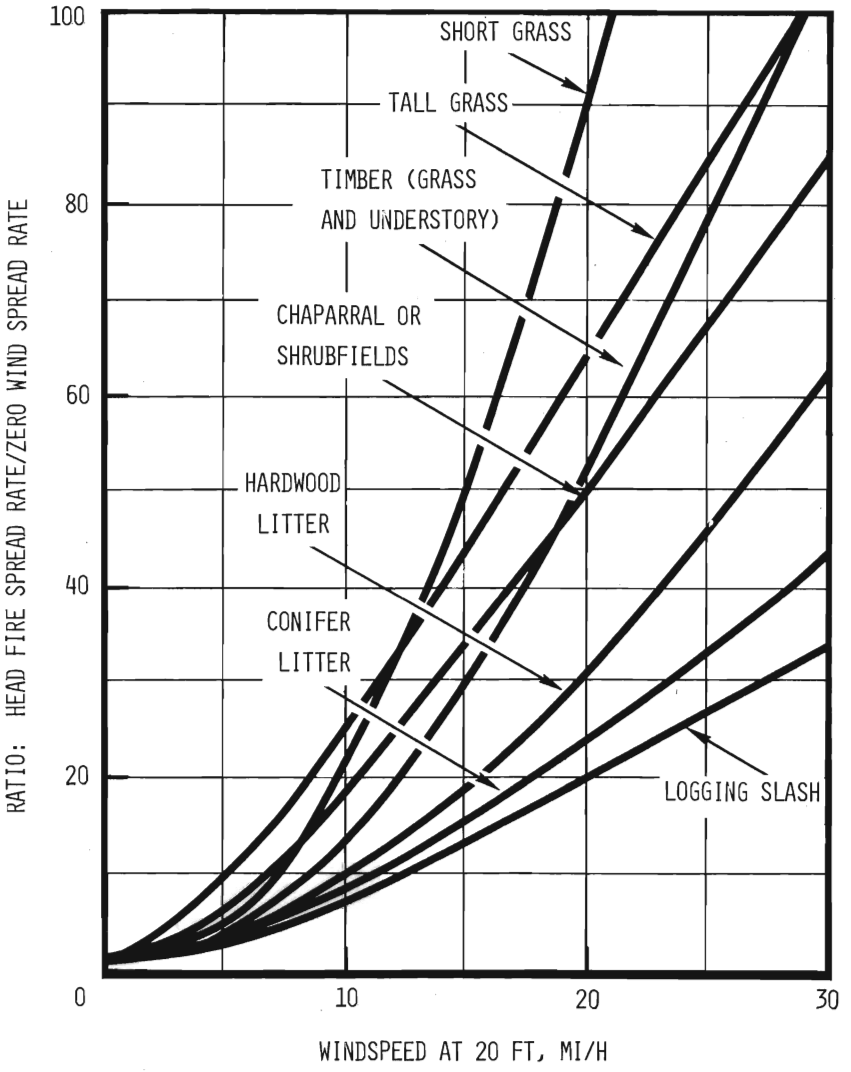
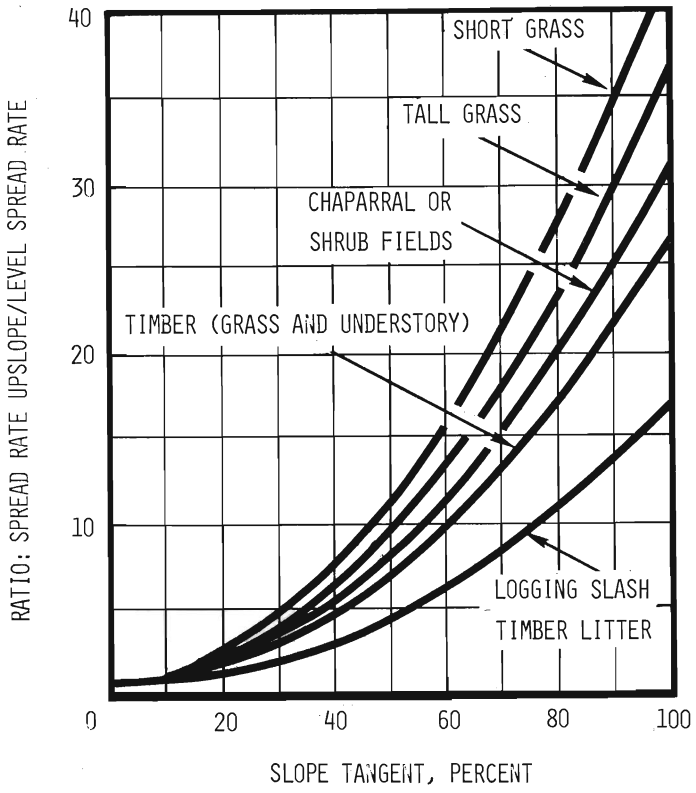


Figure 3.--Ratio of forward rate of spread downwind to the rate under calm conditions. Level terrain is assumed in both cases. Fuel models correspond to those used in the nomographs.

Figure 4.--Ratio of forward rate of spread upslope to the rate on level terrain. Zero windspeed is assumed in both cases. Fuel models correspond to those used in the nomograph.



Shape and Growth of Wind-Driven Fires

The shape of a wind-driven fire can be approximated by joining two ellipses.[5] Relationships between area, perimeter, and length of downwind travel from the point of origin are given as formulae in appendix II. The parameters that describe the elliptical shapes can be derived from these formulae also. But these quantities convey little in the way of a visual impression of the shape represented.

Figure 5 shows the shapes predicted by the equations in appendix II, for fires driven by 5-, 10-, 15-, 20-, and 30-mi/h winds. In each case, the fire is presumed to start where the two straight lines cross, and the wind blows from left to right. The typical elongated egg shape has been noted even for very large fires.[6]

The length of the perimeter of a wind-driven fire depends on how long it has been burning. By using the shapes predicted by Anderson's equations (like those shown in fig. 5), all we need to know to compute the perimeter is the length of the downwind run. On the diagrams of figure 5, this length of run is from the intersection of the two straight lines to the right-hand edge of the fire outline. Figure 6 plots the perimeter of the fire divided by length of run. To compute the perimeter length of the elliptical shapes, read the vertical axis of figure 6 for the ratio of perimeter to downwind run distance. Multiply this number by the length of the downwind run, which is simply the forward rate of spread multiplied by the time since ignition.

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[5]Reference footnote 3.

[6]Anderson, Hal E. Private communication of data on file at the Northern Forest Fire Laboratory, Missoula, Montana, December 1974.

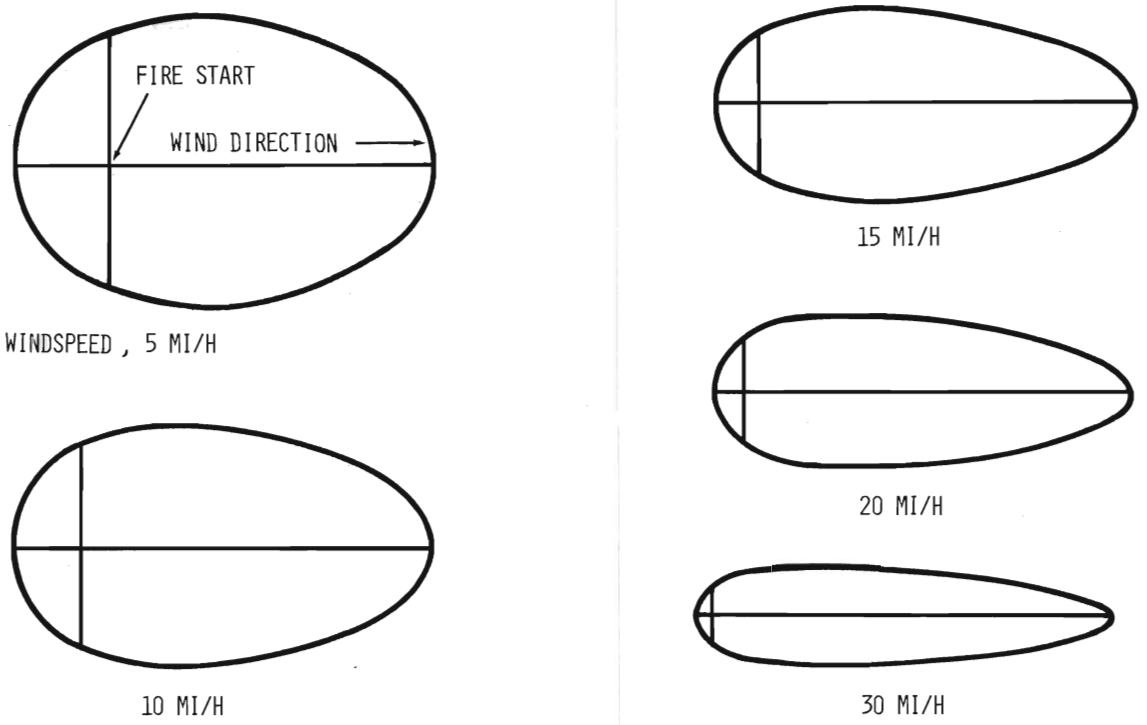


Figure 5.--Approximate fire shapes (not sizes, the scales are arbitrary) for windspeeds of 5, 10, 15, 20, and 30 mi/h.

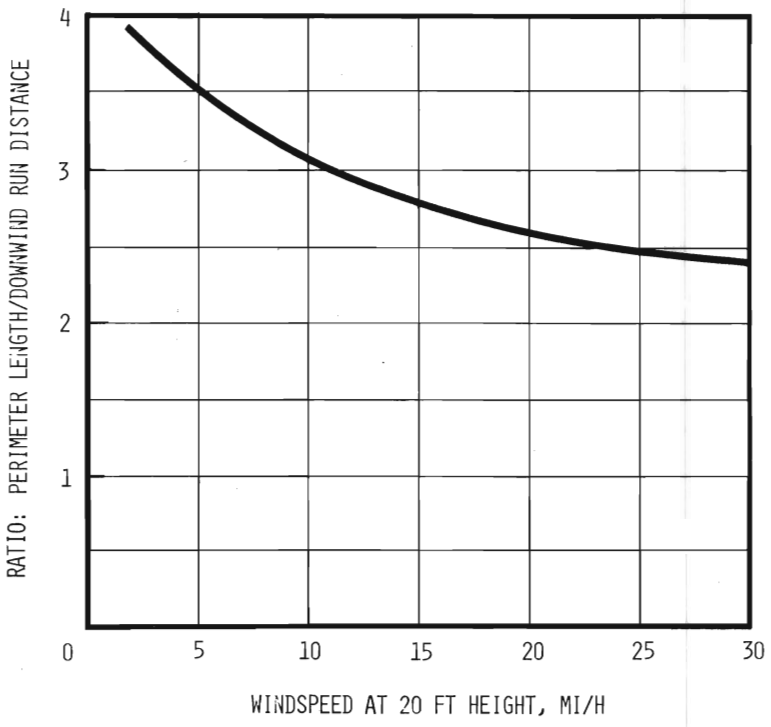
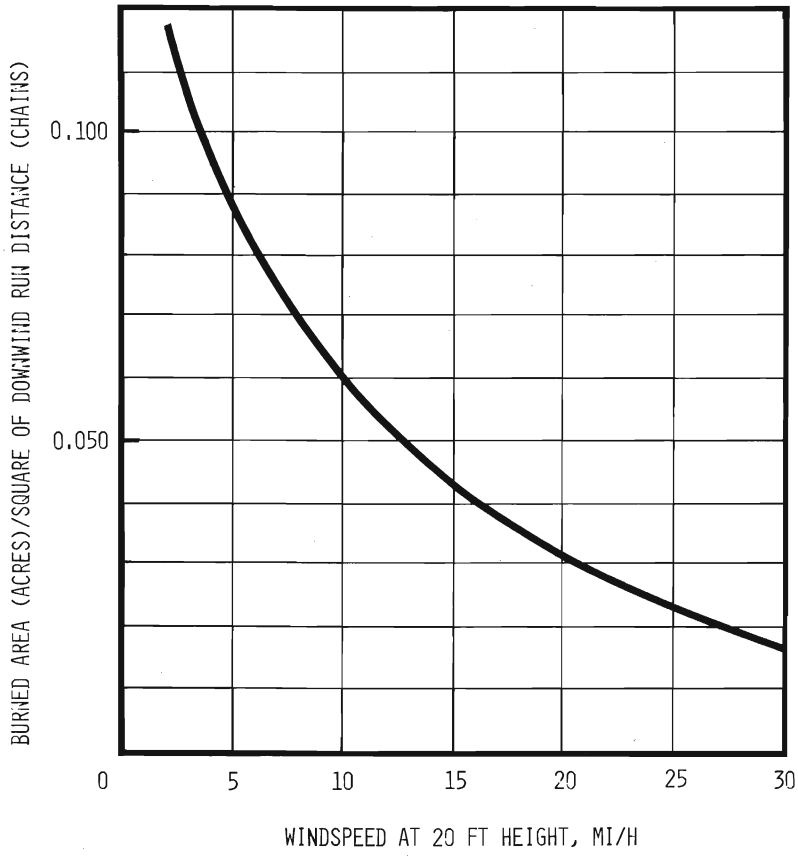


Figure 6.--Ratio of approximate fire perimeter length to the distance from point of origin to the head of the fire (based on Anderson's double-ellipse formulae in appendix II).

Figure 7.--Approximate area of wind-driven fires, using Anderson's double-ellipse formulae in appendix II. In this figure, the area within the approximate perimeter (acres) has been divided by the squared distance (in chains) from the point of origin to the head of the fire. Thus, this ratio decreases with windspeed while the area itself actually increases.



Note that the curve in figure 6 underestimates the fire perimeter for extremely low windspeeds. It appears from this figure that at zero windspeed (when the fire shape would be a circle) the ratio of perimeter to radius would be just greater than four, while the proper value is, of course, 6.28. The data from which the equations for figure 6 and 7 were derived were for windspeeds of about 5 mi/h and above, and the extrapolation of the curves to lower windspeeds produces some error.

The area enclosed by this approximate perimeter affords a measure of the area of the fire. To express this area, we divide the acreage burned by the square of the downwind run length so that all fires can be represented on a single graph. In figure 7, the burned area is plotted, and divided by the square of the length of the downwind run in chains. Again, note the underestimation of fire area for very low windspeeds. The zero-wind ratio of area to square of radius would be 0.314 in the units used in figure 7.

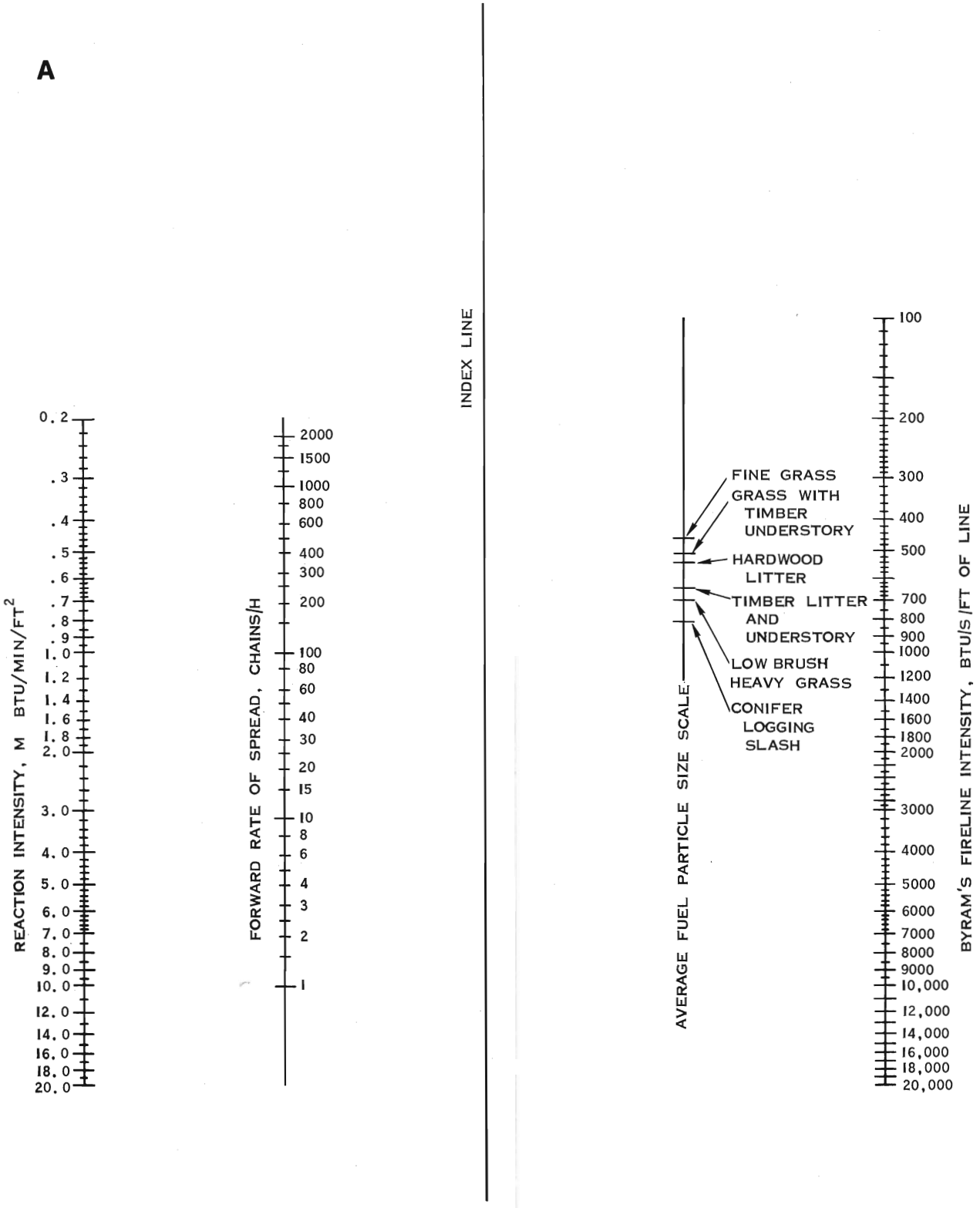
Flame Front Characteristics and Some Fire Effects

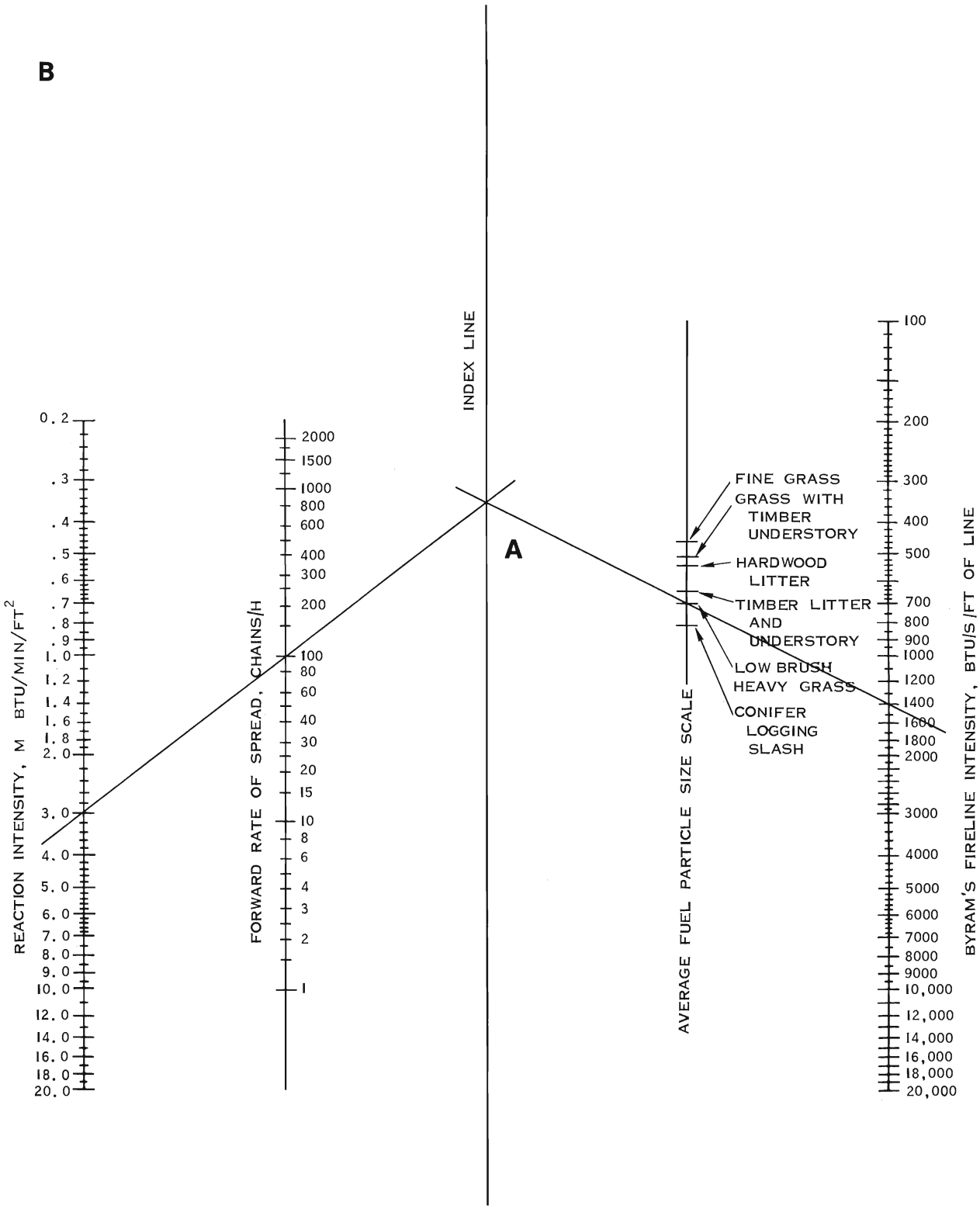
Byram's Intensity

Many researchers have used Byram's measure of intensity (appendixes I and II) to correlate observed fire behavior phenomena. This important parameter is also, by itself, a useful gage of fire intensity or resistance to control (Hodgson 1968). Figure 8 is a different type of nomograph that allows one to estimate Byram's intensity from the rate of spread and the reaction intensity (as taken from the previous nomographs), and the mean size of the fire-propagating fuel particles.

Figure 8.--A nomograph for determining Byram's intensity from the rate of spread and Rothermel's reaction intensity. B, an example of how to use A, using the results of example 1 of the nomograph explanation, 97 chains per hour and 3,000 Btu/min/sq ft.

A




B
INDEX LINE
A
REACTION INTENSITY, M BTU/MIN/FT^2
0.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.2
1.4
1.6
1.8
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
12.0
14.0
16.0
18.0
20.0
FORWARD RATE OF SPREAD, CHAINS/H
2000
1500
1000
800
600
400
300
200
100
80
60
40
30
20
15
10
8
6
4
3
2
1
AVERAGE FUEL PARTICLE SIZE SCALE
FINE GRASS
GRASS WITH TIMBER UNDERSTORY
HARDWOOD LITTER
TIMBER LITTER AND UNDERSTORY
LOW BRUSH HEAVY GRASS
CONIFER LOGGING SLASH
BYRAM'S FIRELINE INTENSITY, BTU/S/FT OF LINE
100
200
300
400
500
700
800
900
1000
1200
1400
1600
1800
2000
3000
4000
5000
6000
7000
8000
9000
10,000
12,000
14,000
16,000
18,000
20,000

To use figure 8, follow these steps:

1. Determine the reaction intensity (e.g., from the previous nomographs) and locate this value on the scale at the far left.

2. Determine (or select) the rate of spread, and locate this value on the scale next to farthest left.

3. Draw a straight line through the two points located in the previous two steps and determine the intersection of this line with the index line of figure 8 (the center line). Call this point A.

4. Determine the mean fuel particle size, from the fuel complex descriptions shown on the line next to far right.

5. Draw a straight line from point A through the fuel particle size scale at the point representing the fuel complex of interest and extend the line to intersect the far right-hand scale.

6. Where the line intersects the far right-hand scale in step 5, read off Byram's intensity.

An example is shown (fig. 8*B*), using the results of example of the nomograph explanation, 97 chains per hour and 3,000 Btu/min/ft^2.

Flame length

Figures 9 and 10 are plots of Byram's flame length formula given in appendix II. Using the value determined from the nomograph of figure 8, the average flame length

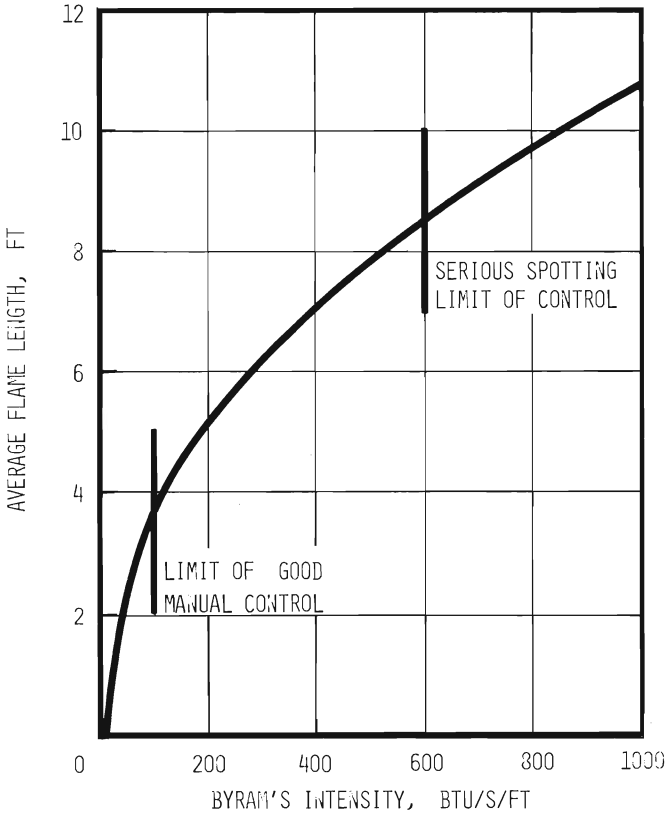
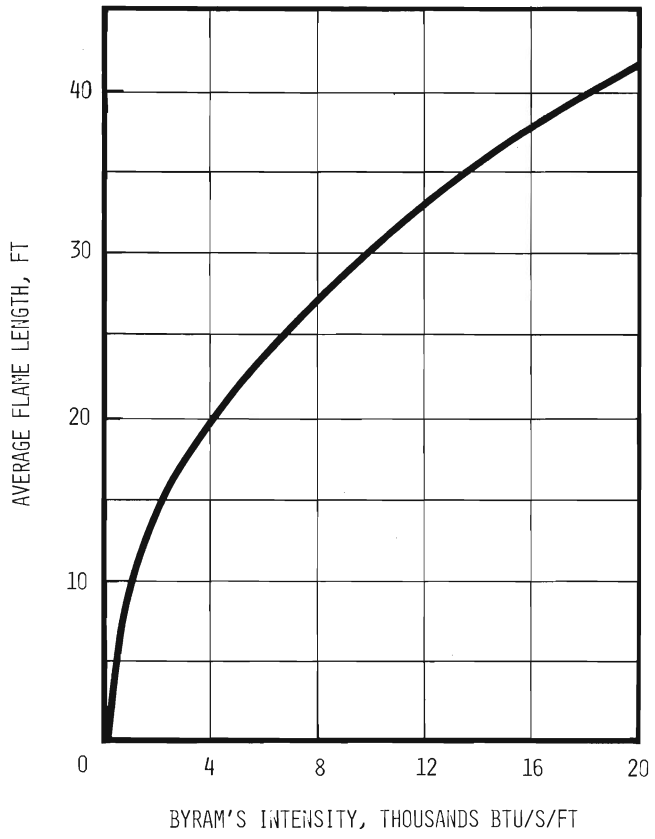


Figure 9.--Flame length versus Byram's intensity. The limits of control indicated on the figure are from Hodgson (1968).

Figure 10.--Flame length versus Byram's intensity for high-intensity fires.



can be estimated directly by reading the graphs of figure 9 or 10. On figure 9, Hodgson's (1968) limits of controllability are marked. Note the flame lengths associated with these intensities. Good manual control ceases with flame lengths greater than about 3.5 feet, and serious spotting (limit of control) is to be expected when flame lengths exceed about 8.5 feet.

Crown Scorch Height

Figures 11 and 12 plot Van Wagner's (1973) equations for the height of crown scorch versus Byram's intensity for various windspeeds on a 77° F day. (The use of the 77° F day as a standard for this calculation is discussed in the mathematical presentation of appendix II.) The sharp decrease in scorch height with windspeed for a fixed value of Byram's intensity is due to cooling of the hot plume by entrained ambient air. This is somewhat deceiving, as Byram's intensity usually increases rapidly with windspeed. (This is so because Byram's intensity is proportional to rate of spread, see appendix II and fig. 8).

Crown scorching is an important consideration in prescribed fire design, and the effect of windspeed can be an overriding factor in many cases. Due to the fact that the windspeed under a timber canopy is often nearly constant with height above the ground (Countryman 1956; Curry and Fons 1940) and significantly lower than the windspeed measured in the open, as at a nearby weather station, the value of the crown scorch height predicted by the use of the charts presented in figures 11 through 13 can be either high or low, depending on how the measured windspeed values are interpreted. The proper way to use these charts is to enter the value of Byram's intensity as determined from the previous graphs, using the 20-ft windspeed as measured in the open. But when using figures 11 through 13, use the value of windspeed *to be expected in the timber stand*. Typically, this windspeed will be half the open area windspeed or less.

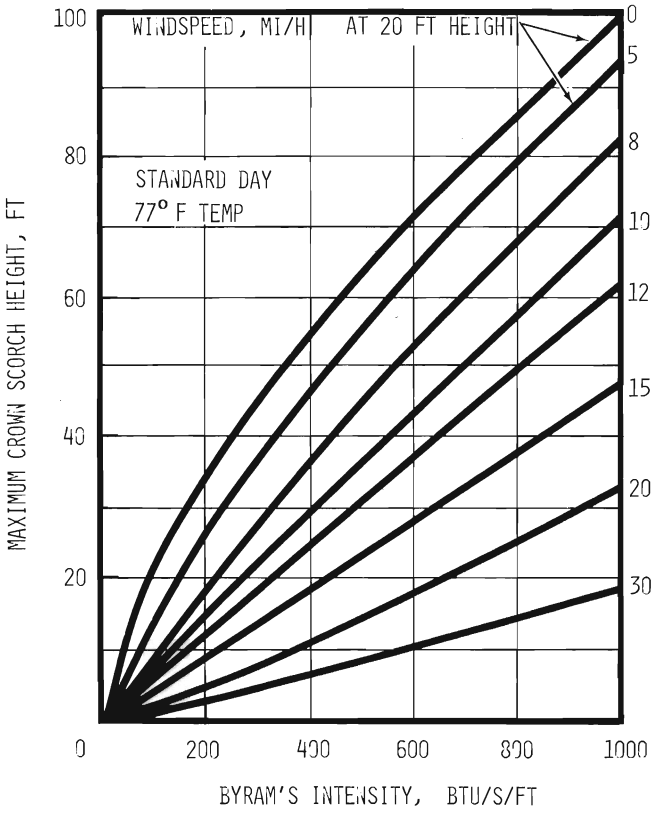


Figure 11.--Crown scorch height versus Byram's intensity (low-intensity range).

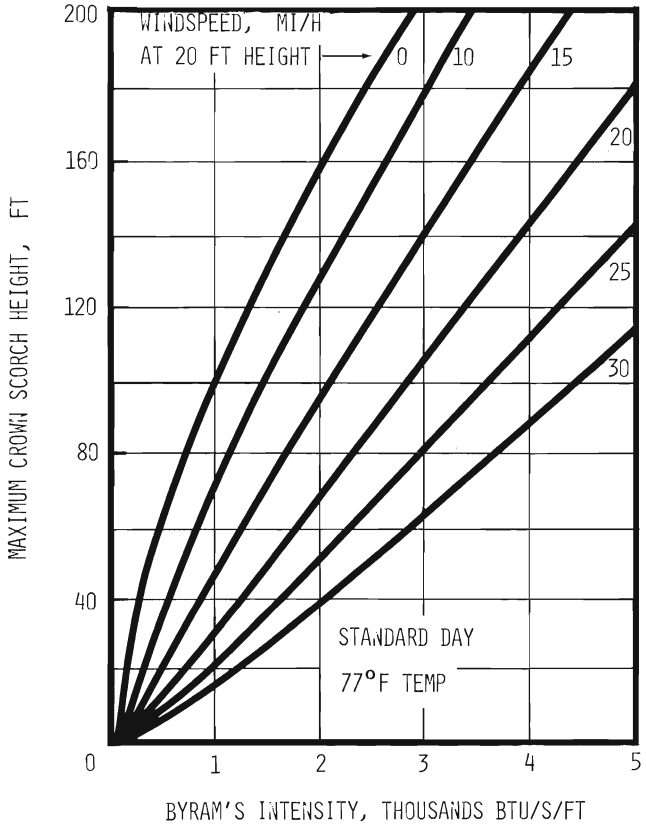
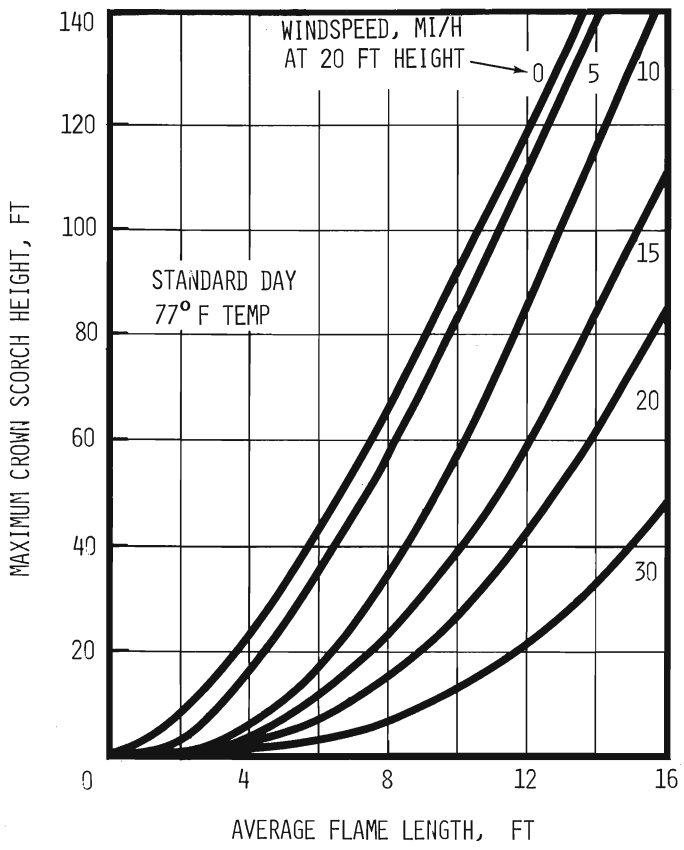


Figure 12.--Crown scorch height versus Byram's intensity (high-intensity range).

Figure 13.--Maximum height of crown scorch on a 77° F day versus average flame length. Both quantities are predicted by Byram's intensity and so are directly related.



Using Byram's intensity, determined by using the nomograph of figure 8 or from reading figures 9 and 10 backwards (using the flame length determined from the rate of spread nomographs), figures 11 and 12 can be read to estimate the maximum height of lethal scorching of coniferous tree crowns over the fire, assuming that the ambient temperature is 77° F. Figure 11 is for relatively low values of Byram's intensity, such as might be encountered in prescribed burns. Figure 12 is for much higher values of Byram's intensity, such as might be encountered in severe wildfires.

Figure 13 shows the relationship between the flame length predicted by Byram's equation and the maximum height of crown scorch on a 77° F day. Using this figure, one can go directly from the flame lengths, as given by the nomographs, to an estimate of maximum crown scorch height.

By using figure 14, the scorch height determined from figures 11 through 13 can be adjusted for any ambient temperature. The vertical scale of figure 14 is the ratio of the scorch height on a day with ambient temperature, T, to the scorch height on a day with ambient temperature 77° F. For the temperature of interest, on the horizontal scale, read off the ratio on the vertical scale. Multiply this value by the 77° F day scorch height from any of figures 11, 12, or 13 to determine the scorch height on the day of interest.

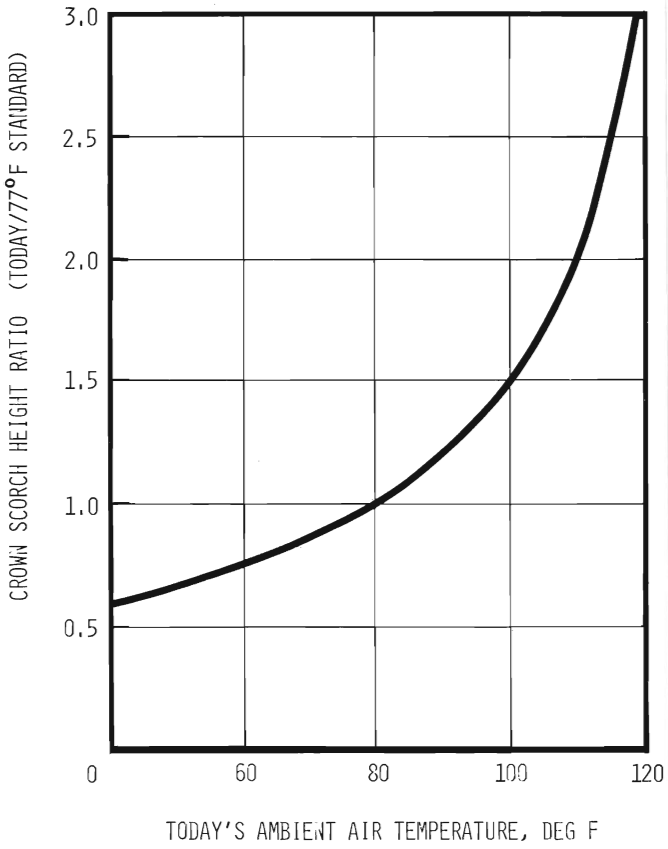


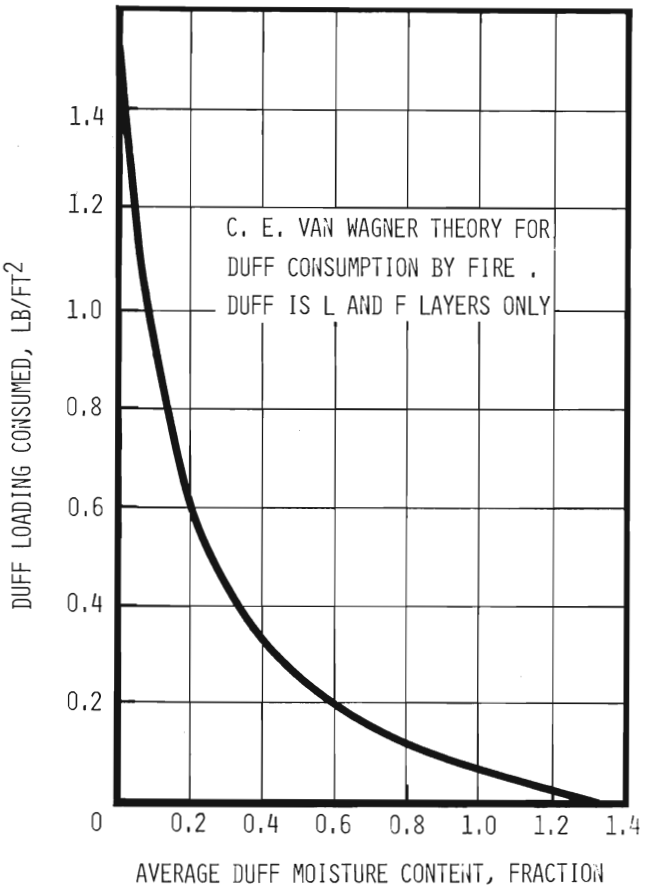
Figure 14.--Variation of scorch height with burning-day temperature. Multiply the ordinate value from this figure by the heights read from figure 11, 12, or 13 to determine maximum scorch height.

Duff Burnoff

The consumption by fire of the litter and fermentation layers of the duff mantle of the forest floor was investigated by Van Wagner (1972). A brief discussion of this work is given in appendix II. Duff consumption is achieved largely by burning after the passage of the initiating fire front, but Van Wagner found a strong correlation of the duff loading reduction to the duff moisture content, using a simple spreading-fire phenomenological model to guide the choice of functional form for the relationship.

Figure 15 is a plot of the relationship found by Van Wagner. The *reduction* in L and F layer duff loading is plotted against the average moisture content (fraction of dry weight) of these layers combined. Of course, if the total L and F layer loading is less than that predicted by figure 15, the proper interpretation is that whatever loading is present would be consumed.

Figure 15.--Duff consumption by fire, as predicted by Van Wagner (1972) from average duff moisture content. Only the L and F layers of the duff mantle are considered here.



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APPENDIX I

FIRE BEHAVIOR DESCRIPTION AND QUANTIFICATION

Because there are many aspects to fire behavior, there are also many quantitative descriptors of fire behavior. This appendix presents some of these quantities and appropriate units of measurement.

Measures of Growth

The shape, or map outline, of a free-burning fire is often highly irregular in detail, but the overall pattern usually resembles an ellipse. Particularly in the case of wind-driven fires, an elongated ellipse can be drawn that corresponds roughly to the outline of the burned area.

The rate of advance of the "head" of such a fire is called the forward rate of spread. The distance around the fire, encircling the head, along both flanks, and around the backing fire at the "tail" is called the perimeter. The area enclosed by the perimeter we will call the area, or the burned area. So long as conditions remain unchanged, including the fuel being burned, the perimeter will increase linearly with time and the area quadratically.

Rates of Spread

A rate of spread, whether it be the forward rate, the rate of spread against a flank, or a backing rate, has the dimensions of velocity. The most common such velocity measurement unit in United States forestry is "chains per hour." Many other units are used, however, particularly in research circles. Table 1 shows the numerical equivalence of various units of velocity measurement.

The rate of increase of the perimeter of a fire is also measured in units of velocity. Again, United States foresters rely on "chains per hour," but all other units in table 1 could equally well be used.

Table 1.--*Equivalence of various units used to measure the rate of spread of a fire*

If units are:	Multiply by:	To obtain:
Chains per hour	1.100	Feet per minute
Chains per hour	.0183	Feet per second
Chains per hour	.0125	Miles per hour
Chains per hour	.3353	Meters per minute
Chains per hour	.5588	Centimeters per second
Chains per hour	.02012	Kilometers per hour
Feet per minute	.9091	Chains per hour
Feet per second	54.54	Chains per hour
Miles per hour	80.0	Chains per hour
Meters per minute	2.982	Chains per hour
Centimeters per second	1.79	Chains per hour
Kilometers per hour	49.7	Chains per hour

Area and Area Growth

The area of a fire is most commonly measured in acres in the United States, but the metric hectare is becoming more common in the literature. Other units of area are also used. Table 2 shows the numerical equivalence of various measures of area.

Area growth rate is measured in units of area per time, such as acres/h, ft^2/min, etc. Table 3 shows the numerical equivalence of such units of measurement.

Table 2.--*Equivalence of various units used to measure the area of a fire*

If units are:	Multiply by:	To obtain:
Acres	43,560	Square feet
Acres	0.001563	Square miles
Acres	4,047	Square meters
Acres	.4047	Hectares
Acres	.004047	Square kilometers
Square feet	.0000230	Acres
Square miles	640	Acres
Square meters	.0002471	Acres
Hectares	2.471	Acres
Square kilometers	247.1	Acres

Table 3.--*Equivalence of various units used to measure the rate of area growth of a fire*

If units are:	Multiply by:	To obtain:
Acres per hour	726	Square feet per minute
Acres per hour	12.10	Square feet per second
Acres per hour	11,241	Square centimeters per second
Acres per hour	67.45	Square meters per minute
Acres per hour	.4047	Hectares per hour
Acres per hour	.0971	Square kilometers per day
Acres per hour	.0375	Square miles per day
Square feet per minute	.001377	Acres per hour
Square feet per second	.08264	Acres per hour
Square centimeters per second	.0000890	Acres per hour
Square meters per minute	.01483	Acres per hour
Hectares per hour	2.471	Acres per hour
Square kilometers per day	10.30	Acres per hour
Square miles per day	26.67	Acres per hour

Measures of Intensity

Perhaps no descriptor of wildfire behavior is as poorly defined or as poorly communicated as are measures of fire intensity. Technically, the term intensity implies some measure of a rate of energy transmission, but the term has also been applied to many aspects of wildfire behavior and effects such as peak flame temperature, convection column height, maximum soil temperature, fraction of standing timber killed, and others.

Here we shall define two explicit but virtually unobservable measures of intensity. Through various models (empirical relationships), these measures can be related to directly observable fire phenomena which can themselves serve as indirect measures of intensity.

Reaction Intensity

Reaction intensity is defined as the rate of heat release per unit area of ground beneath the fuel bed. As the front of the flaming zone moves over some point on the ground, the reaction intensity increases from zero to some maximum value and then decreases to zero (much more slowly than it increased usually), as the available fuel is consumed.

Appropriate units for this measure of intensity are (heat energy/area/time), such as Btu/ft^2/min, or Kcal/m^2/s.[7] Table 4 gives conversion factors between various units for reaction intensity.

Table 4.--*Equivalence of various units used to measure the reaction intensity of a fire*

If units are:	Multiply by:	To obtain:
Btu/square foot/minute	0.01667	Btu/square foot/second
Btu/square foot/minute	1,055	Joules/square foot/minute
Btu/square foot/minute	.004521	Calories/square centimeter/ second
Btu/square foot/minute	.04521	Kilocalories/square meter/ second
Btu/square foot/minute	1.890×10^5	Ergs/square centimeter/ second
Btu/square foot/second	60	Btu/square foot/minute
Joules/square foot/minute	.000948	Btu/square foot/minute
Calories/square centimeter/ second	221.2	Btu/square foot/minute
Kilocalories/square meter/ second	22.12	Btu/square foot/minute
Ergs/square centimeter/second	5.292×10^{-6}	Btu/square foot/minute

[7]A Btu is a British thermal unit, which is the amount of heat energy required to raise the temperature of 1 pound of water (1 pint), by 1° Fahrenheit. A Kcal is a kilogram-calorie which is the amount of heat energy required to raise the temperature of 1 kilogram of water (1 liter) by 1° Celsius (Centigrade).

Byram's Fireline Intensity

This measure of intensity is commonly used to describe wildland fire in the United States. This intensity, as defined by Byram (1959), is the product of the available heat of combustion per unit area of the ground and the rate of spread of the fire. The dimensions of this product are heat energy/length/time, such as Btu/ft/s or Kcal/m/s. This measure of intensity can be interpreted as the heat released per unit of time for each unit of length of fire edge.

Byram's intensity parameter has proved to be very useful in wildland fire behavior descriptions and as a general index to what most people seem to visualize when they speak loosely of "fire intensity." For example, Australian researchers have found (Hodgson 1968) that a heat output rate per unit of fireline length should not exceed 100 Btu/ft/s in order to maintain good control over prescribed burns. Hodgson also states that if Byram's intensity exceeds 600 Btu/ft/s, spotting becomes serious and the fire is, to all intents and purposes, uncontrollable. Van Wagner (1973) found that the height of lethal scorching of coniferous tree crowns could be very well correlated with Byram's intensity. Table 5 gives conversion factors for different units which can be used to measure this intensity.

Table 5.--*Equivalence of various units used to measure Byram's fireline intensity*

If units are:	Multiply by:	To obtain:
Btu/foot/second	60	Btu/foot/minute
Btu/foot/second	1,055	Joules/foot/second
Btu/foot/second	8.268	Calories/centimeter/second
Btu/foot/second	.8268	Kilocalories/meter/second
Btu/foot/second	3.461×10^{8}	Ergs/centimeter/second
Btu/foot/minute	.01667	Btu/foot/second
Joules/foot/second	.000948	Btu/foot/second
Calories/centimeter/second	.1209	Btu/foot/second
Kilocalories/meter/second	1.209	Btu/foot/second
Ergs/centimeter/second	2.889×10^{-9}	Btu/foot/second

Flame Length

Byram also found (1959) that the average length of the flame at the edge of a free-burning fire could be predicted by the fireline intensity. Because of this relationship, flame length can be considered to be an alternative form of quantifying Byram's intensity. But flame length itself is both a meaningful parameter[8] and a good general index to the elusive meaning of fire intensity (Van Wagner 1968a, 1973; Lawson 1972; Sneeuwjagt 1974).

Units of length measurement are easily converted if one recalls the English-to-Metric conversion factor "1 foot = 0.3048 meter" or its inverse "1 meter = 3.281 feet."

[8]Flame length, for example, gives a rough minimum width of an effective fireline and a rough guide as to the likelihood of crowning of a ground fire under timber.

Site and Environmental Effects

The effects of a wildland fire on the site over which it burns and on the surrounding area can be many and varied. Here we mention a few effects, note the ways in which they are quantified, and point out their relationships to descriptors of the fuel complex, the environment, or other fire-behavior variables.

Total Heat Release

The amount of heat released by burning a unit area of a given fuel bed is a rough measure of the impact that the fire would have on the site at the location of that unit area. Because the heat produced by burning a pound of almost any forest fuel is about the same (∿8,000 Btu), the total heat released by burning is nearly a direct measure of the total fuel load loss. This being so, the larger size fuel pieces can be important in determining total heat release, because they contribute so much to total loading per unit area whenever they occur in any significant quantity. Another important fuel under timber or slash is the duff (or litter and duff) layer (Van Wagner 1968a, 1972).

Norum (in press) has found initial fuel loadings to be important variables, as well as duff moisture content, in predicting total load loss in burns under standing timber. Stocks and Walker (1972) found slash fuel consumption (hence total heat release) to be correlated to Canadian Fire-Danger Rating indexes which are closely related to duff moisture. Hough (1968) found fuel moisture important in predicting available fuel energy in backing fires, and Van Wagner (1972) found duff moisture to give a fair prediction of (L and F) duff layer burnoff under standing timber.

Units that would be used in total heat release are (heat energy/area). Table 6 gives some conversion factors for different units for this measure of site impact.

Table 6.--*Equivalence of various units used to measure total heat release by a fire*

If units are:	Multiply by:	To obtain:
Btu/square foot	0.2713	Calories/square centimeter
Btu/square foot	2.713	Kilocalories/square meter
Btu/square foot	1,055	Joules/square foot
Btu/square foot	1.134×10^{7}	Ergs/square centimeter
Calories/square centimeter	3.687	Btu/square foot
Kilocalories/square meter	.3687	Btu/square foot
Joules/square foot	.000948	Btu/square foot
Ergs/square centimeter	8.818×10^{-8}	Btu/square foot

Duff Removal

As mentioned above, the burning of duff[9] can contribute substantially to total heat release. Also, because duff is in intimate contact with the soil, it can serve either as an insulating cover for the soil if it is not largely consumed by the fire. Or it can serve as the greatest single source of heat input to the soil itself if it is completely or nearly completely consumed. Because duff removal is sometimes the effect sought by prescribed burning, the secondary effect of soil heating may be very important.

Duff consumption can be measured either in terms of load reduction (loss of so many pounds per square foot, for example) or in terms of depth reduction. For many considerations, the thickness of the duff mantle is more important than its weight per unit area, but for fire behavior estimations, both parameters can be important.

The units of measurement of duff removal would be either weight/area or depth, depending upon how the investigator chose to determine or express it. Because the duff mantle is often nonuniform in the vertical direction, with the bulk density of the material changing substantially from top to bottom, the two measures cannot usually be related simply. In other words, knowledge of one such measure of duff reduction does not necessarily allow one to infer the other, without a relationship linking the two variables.[10]

Height of Crown Scorch

The maximum height of lethal scorching of conifer needles is an immediate effect of fire and an important parameter in establishing prescriptions for burning under timber. A completely scorched tree may be delayed in growth or even killed. Van Wagner has found (1973) this height to be a strong function of Byram's intensity, ambient temperature, and windspeed. Evidence has been put forth[11] that the height of lethal scorch may correlate with the height to which spruce budworm larvae are killed (or at least the number which are killed), by heat from a fire under timber.

The mechanism by which lethal needle scorching occurs is probably simply killing the live tissue, as it seems to be strongly correlated to an air temperature of about 140° F, which proximate temperature level has been noted to be lethal to conifer foliage on exposures of 30 seconds to 1 minute (Hare 1961).

Maximum scorch height would be measured in units of length, vertically from the base of the tree to the height in the tree crown at which needles have survived the fire. This effect may not be easily detected for a week or two after a fire, but when evident is usually noted as a distinct height in the crown. Below this height all the needles are brown and dead; above it, live and green.

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[9]Here we use the term "duff" loosely to represent the total forest floor accumulation of detritus, from fresh litter (L layer), the decomposing layer underlying this fresh layer (the fermentation, or F layer), and the lower layer which is decaying to organic soil (the humus, or H layer). When it is important to be specific, the designators L, F, and H are used explicitly.

[10]Norum, Rodney A. 1974. Correlation data relating duff depth and weight loading on file at Northern Forest Fire Laboratory, Missoula, Mont.

[11]Caldwell, W. D. The effect of understory burning in a larch-fir stand on larval populations of the spruce budworm, *Choristoneura occidentalis*. Intermt. For. and Range Exp. Stn., North. For. Fire Lab., Missoula, Mont. (Unpublished manuscript, 1974.)

Particulate Production

The mechanisms of smoke (particulate) production have been studied for many years since it was learned that a smoking fire was a sign of inefficient combustion. It is known that wildland fires tend to produce more smoke when burning in mixed live and dead fuel than in dead fuel only, or when wind driven as opposed to backing or flanking (Hall 1972; USDA Forest Service, n.d.; Brown and Davis 1973; Biswell 1973).

There seem to be differing views on the relationship between fire intensity and smoke production. Most smoke is particulate matter, about half solid (containing lots of carbon) and half liquid (again, containing lots of carbon). On this basis one can say that much potential fuel energy is "lost" in smoke rather than released in the fire.[12] This means that a fire that produces a lot of smoke is not converting the stored energy of the fuel into heat energy as efficiently as possible. So this lost energy might reduce the reaction intensity of a smoky fire.

On the other hand, the only way that a lot of smoke can be produced in a short time is for a lot of fuel to be involved. So a fire that is producing lots of smoke is involving a lot of fuel and therefore might also be said to be very intense.

Paradoxically, a fire may be of fairly low intensity when measured by the rate of heat release per unit of ground area (reaction intensity), yet be of rather high intensity when measured by the rate of heat release per unit of fire perimeter (Byram's intensity), as in the case of a wind-driven grass fire. Or a lot of green fuel may be "involved" by the burning dead fuel, but not itself burned well, if at all.

Particulate production is usually quantified as an emission factor. This is a dimensionless number, the ratio of particulate-matter-weight-generated per unit-weight-of-fuel-consumed-by-fire. It is sometimes expressed as a fraction, sometimes as a percentage, and sometimes as a ratio of dissimilar weight measures, such as pounds per ton or grams per kilogram, etc. The emission factor generally increases as reaction intensity decreases, so more particulate matter is generated (per pound of fuel burned) when burning conditions are poor than when they are good. But because the rate at which fuel is consumed (on the whole) may increase rapidly as burning conditions improve, or if the fire is wind-driven, the rate of smoke generation by the fire as a whole will frequently increase.

Smoke, like many other aspects of wildfire, is probably not all bad. Current literature contains speculation about links between smoke and insect mortality and between smoke and the inhibition of fungus growth (Parmeter and Uhrenholdt (in press); Biswell 1973).

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[12]Susott, R. A. 1974. Effective heat content of forest fuels. Unpublished final report on Study Plan 2103-08 on file at Northern Forest Fire Laboratory, Missoula, Mont.

APPENDIX II

SELECTED FIRE BEHAVIOR PREDICTION MODELS

In this appendix, some fire behavior prediction models are presented and briefly discussed. The equations used to calculate the results shown in the text are given. The reader is urged to consult the cited sources for more thorough discussions of the underlying theories, data, assumptions, restrictions, etc.

Rothermel's Spread Rate Model

Rothermel (1972) published so far the most comprehensive spread rate model for wildland fuels. The basic relationship of the model is an expression of conservation of energy (Thomas and Simms 1963; Frandsen 1971). The model deals solely with uniform, homogeneous beds of fuel contiguous to a smooth earth. Figure 16 shows such an idealized fuel bed and explains some of the nomenclature used in discussing the model.

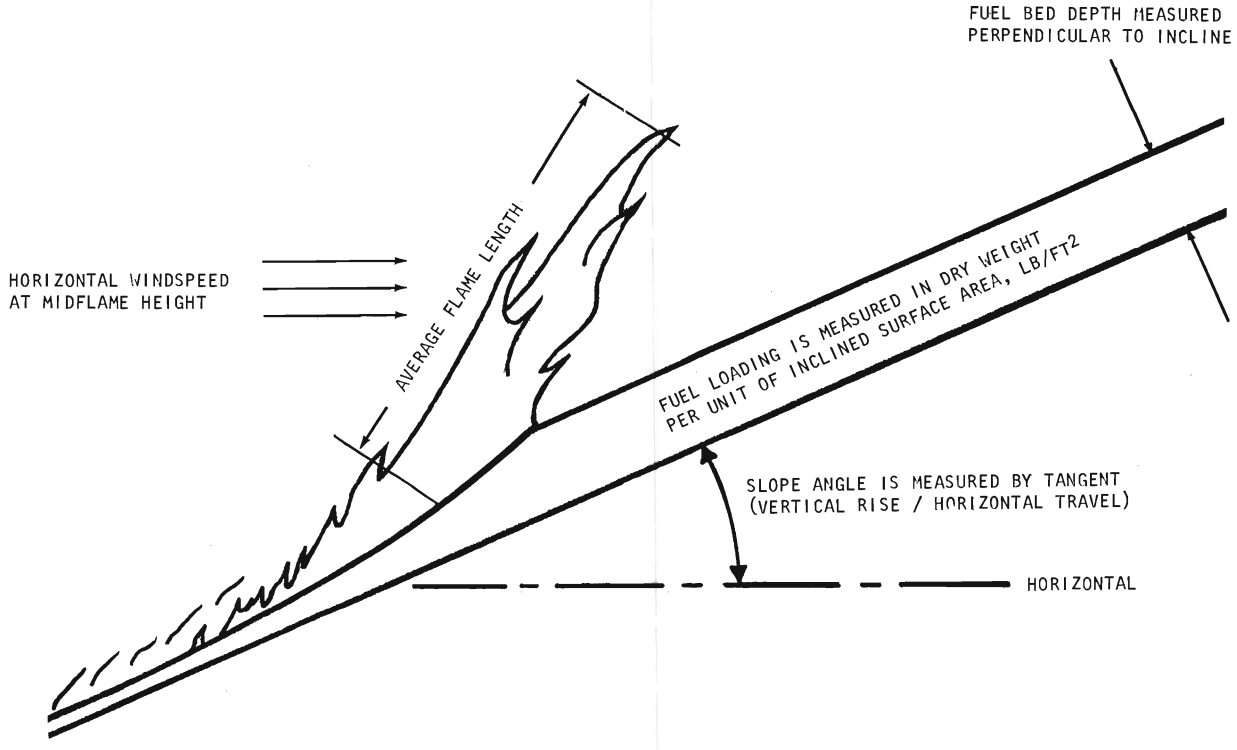

Figure 16.--Explanation of some nomenclature used in describing fire spread model and input variable definitions.

The model assumes that fire spreads by a sequence of ignitions (of the fine fuel in a mixed bed). The continued burning of a unit area of the bed proceeds largely from top to bottom, at a rate fixed mostly by the size and arrangement of the fuel particles. This burning provides the heat necessary to ignite adjacent fine fuels, and the process cycle is complete. This model is discussed here only in general terms; the equations are too complicated to be presented in detail, so the reader is urged to visit the original sources for details.

Reaction Rate and Intensity

The rate of heat release per unit area of ground (the reaction intensity) is given by a simple formula:

$$I_R = \eta_m \eta_s \Gamma' \tilde{h} \tilde{w} \qquad (1)$$

where

$\tilde{w}$ = net loading of combustible fuel (dry weight, lb/ft^2)

$\tilde{h}$ = heat of combustion of fuel (Btu/lb, dry weight)

Γ' = maximum rate of combustion of the fuel complex, as determined by size of fuel particles and bulk density of fuel bed (min^{-1})

η_s = a factor reflecting the effect of minerals on slowing down the rate of pyrolysis of woody fuels (Philpot 1968) (dimensionless)

η_m = a factor reflecting the effect of free moisture content of the fuels on slowing down the rate of combustion (Rothermel 1972) (dimensionless)

I_R = the reaction intensity ($Btu/min/ft^2$).

For a single size class fuel bed, the indicated calculation is simple, but the computing of weighted averages of fuel properties for beds with a mixture of fuel particle sizes gets a bit complicated. The only parameters which needed determination in the laboratory in this equation were the damping coefficients η_m and η_s and the reaction velocity term, Γ'. Rothermel (1972) and Rothermel and Anderson (1966) determined these empirical parameters.

Heat Required for Ignition

A fundamental problem in predicting rate of spread of a free-burning fire is determining the amount of heat that must be absorbed by the fuel bed to cause ignition. Not all of the mass of a fuel particle, only part of its surface, must be heated to flame-attachment temperature. In an extremely tedious but careful set of experiments, Frandsen (1973b) discovered that the fraction of the total loading of fuel which is heated to ignition temperature is a function of the surface area/volume ratio of the fuel particles:

$$\varepsilon = \exp(-138/\sigma) \qquad (2)$$

where

ε = fraction of fuel loading heated to ignition temperature

σ = surface/volume ratio of fuel particles, ft^{-1}

With this information, one can write an expression for the total amount of heat that must be absorbed by a unit volume of the fuel bed in order to allow ignition in that unit volume:

$$Q^*_{ig} = \varepsilon\rho_b Q \tag{3}$$

where

Q = the heat required to bring a unit mass of fuel to ignition temperature (e.g., Btu/lb). This heat includes the latent heat of vaporization of all the moisture in a pound of fuel, plus the sensible heat absorbed by the fuel in raising its temperature to the point of flame attachment or "pilot ignition," about 325° C in many cases (Anderson 1970; Stockstad 1975, 1976).

ρ_b = the bulk density (lb/ft^3) of the fuel bed considered as a unit

Q^*_{ig} = the heat which must be absorbed by a unit volume of the fuel bed to bring it to the point of pilot ignition (Btu/ft^3).

Heat Flux and Rate of Spread

We have an expression for the rate of heat release per unit area of fuel bed, I_R, and an expression for the heat required to ignite a unit volume of the fuel bed, Q^*_{ig}. The missing parameter is the amount of the heat released per unit area which is absorbed by the fuel in the bed just ahead of the flame front. This quantity, represented by the symbol, ξ, (Rothermel 1972), is used to define the propagating flux, I_p, the rate of heat absorption per unit area of the fuel bed:

$$I_p = \xi I_R \tag{4}$$

Of course, ξ depends not only upon the geometrical properties of the fuel bed and particle sizes but also upon wind and slope. If the wind drives the flames into the unburned fuel bed, one would expect that a large fraction of the heat released in the burning zone would be absorbed in the unburned fuel ahead of the burning zone. Similarly, because flames tend to rise vertically, if the fuel bed is tilted, the flames will lie closer to, perhaps even touching, the top surface of the fuel bed, again increasing the value of ξ.

With these relationships, the conservation of energy equation gives an equation for the rate of spread (Thomas and Simms 1963; Frandsen 1971; Rothermel 1972):

$$I_p = RQ^*_{ig} \tag{5}$$

where R is the rate of spread in ft/min using the units mentioned here. This equation simply states that the rate at which energy is absorbed by the fuel bed per unit area (I_p) is equal to the rate at which energy per unit area is required to achieve ignition (RQ^*_{ig}). The propagating flux is the energy conserved in this relationship.

Moisture of Extinction

In Rothermel's model there exists some value of fuel moisture content for which a fire would not spread. This is called the "moisture of extinction" and must be specified by the model user. For cases in which only dead fuel components are present, the moisture of extinction has been experimentally evaluated (although not for a wide range of situations) and seldom exceeds 30 percent of dry fuel weight. Thirty percent represents a fiber-saturation condition (Stamm 1964), but fuel moisture can exceed this value.

The moisture of extinction is probably a function of the fuel type and the geometry of the fuel bed (Byram and others 1966). For light, airy fuels (such as fine grass), a moisture of extinction of about 12 percent[13] to 15 percent (Sneeuwjagt 1974) is suggested. Brown (1972) found 15 percent worked well for open beds of assembled slash fuel, while for beds of pine needles, 25 to 30 percent has been observed (Rothermel and Anderson 1966). Prescribed fires in the Southeast have been reported in pine litter, burning under conditions in which the moisture exceeded the 30 percent level[14] (Blackmarr 1972).

When both live and dead fuels are present, the moisture of extinction of the live component is calculated from the ratio of dead-to-live fine fuel loadings and the moisture content of the fine dead fuel. The calculation is complicated, but internal to the workings of the model (Albini 1976), so need not concern the user.

When sufficient fine dead fuel exists and the dead fuel moisture content is low enough relative to its moisture of extinction, both live and dead fuel will burn, according to the model. In this case, the reaction intensities from the burning of the two fuels are added together.

If the fine dead fuel loading is too light relative to that of the live fuel, or the dead fuel is too moist, the live fuel moisture of extinction may be less than the live fuel moisture content. In this case, only the dead fuel produces a reaction intensity, but because both dead and live fuel must be heated to the point of ignition, the fire spreads relatively slowly.

If there is no dead fuel, or if it is more moist than its moisture of extinction, Rothermel's model predicts no spread and no reaction intensity. Because in some cases live fuel alone may propagate a fire (e.g., crowning in conifer stands), this restriction can be viewed as an area of incompleteness in the model.

The moisture of extinction parameter can be very important in influencing predicted wildfire behavior. The moistures of extinction used in the stylized fuel models discussed in the text can be used as a guide to the selection of approximate values, but direct data are to be preferred.

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[13]Countryman, C. M. Manuscript review (memorandum dated February 9, 1971, to James K. Brown, on file at Northern Forest Fire Laboratory, Missoula, Mont.

[14]Hough, W. A. Personal communication to F. A. Albini and R. C. Rothermel at the Fuel Modeling Workshop held at the Southern Forest Fire Laboratory, Macon, Georgia, June 24-28, 1974.

Growth Models

Equation (5) can be used to calculate the forward rate of spread once the fuel bed is described using the additional equations in Rothermel (1972) to compute the terms in the equations given above. In this section we briefly examine the effect of wind and slope on forward rate of spread and give relationships for the shape and size of a wind-driven, free-burning fire.

Influence of Wind on Rate of Spread

The formulation of Rothermel (1972), based on experimental and theoretical work (Rothermel and Anderson 1966; Anderson and Rothermel 1965) and field data by McArthur (1969), expresses the effect of wind in the form of a factor, ϕ_w, which increases the value of the propagating flux parameter, ξ, and thus the rate of spread:

$$\xi_{\text{with wind}} = (1 + \phi_w)\xi_{\text{without wind}} \tag{6}$$

The quantity, ϕ_w, is related to the geometrical properties of the fuel particles and fuel bed. The complete set of equations is in Rothermel (1972) but the form of the equation is:

$$\phi_w = AU^B \tag{7}$$

where U is the windspeed (ft/min) at midflame height and A and B are "constants" depending on the fuel complex. In general, A is small for fine fuels and for tightly packed fuels and large for big and/or loosely packed fuels, while B is large for fine fuels and small for larger fuels.

The net effect of these conflicting effects is that ϕ_w is small for fine fuels at low windspeeds, but increases rapidly with increasing windspeeds. The opposite trend is true for larger fuels: ϕ_w increases rapidly for very low windspeeds but quickly "saturates" and stays nearly constant as higher windspeeds are imposed.

Examples are given in the text for several stylized wildland fuel complexes.

Beaufait (1965) obtained experimental evidence that backing fires spread at virtually the same rate as fires under still conditions. This observation has been made by others under field conditions (Van Wagner 1968a; Thomas and others 1963; Thomas 1971).

Influence of Slope on Rate of Spread

In a manner exactly analogous to the wind coefficient, a slope coefficient, ϕ_s, is used as a multiplier of the parameter, ξ, in Rothermel's model.

$$\xi_{\text{with wind and slope}} = (1 + \phi_w + \phi_s)\xi_{\text{without wind or slope}} \tag{8}$$

The dependence of the slope coefficient on fuel bed properties is much simpler than that of the wind coefficient:

$$\phi_s = 5.275\ \beta^{-0.3}\tan^2\theta \tag{9}$$

where

β = packing ratio = fraction of fuel bed volume occupied by fuel particles

$\tan\theta$ = slope tangent = vertical rise/horizontal travel.

Overall Shape of Wind-Driven Fire

Empirical data taken by Fons were correlated and condensed to a few equations by Anderson[15] with the following general results:

1. The overall shape of the perimeter of a wind-driven wildland fire can often be approximated by two ellipses with a common semiminor axis. One ellipse will have an elongated semimajor axis in the downwind direction. The other ellipse has a shorter semimajor axis representing the progress of the backing fire.

The shape of the perimeter does not depend on the size of the fire in this formulation but only on the windspeed. Because of this fact, it is most convenient to express all distances in terms of the distance of downwind travel from the point of origin of the fire. So in the equations below, all distances are expressed relative to this length, which is simply the product of the forward rate of spread and the time since ignition if conditions remain constant.

Let W be the windspeed at 20-ft height, mi/h, and assume that this is twice the midflame height windspeed used by Anderson[15] in the correlation equations. Let B be the distance traveled upwind (backing) from the point of origin, relative to the downwind distance. Then:

$$B = 0.46 \exp(-0.04325W) \tag{10}$$

Let C be the maximum distance traveled crosswind (perpendicular to the wind direction) relative to the distance from the point of origin to the head of the fire. Then, from Anderson's formulae:

$$C = 0.748 \exp(-0.03608W) \{(1 + B)/(1 + Q)\}^{1/2} \tag{11}$$

where

$$Q = 1.16 \exp(0.04325W).$$

2. The perimeter of the elliptical shape which roughly outlines the burned area, expressed in ratio to the distance from the point of origin to the head of the fire is given by P,

where, approximately

$$P \doteq \{\frac{\pi}{\sqrt{2}} (C^2 + (1 + B)^2/(1 + Q)^2)^{1/2} + (C^2 + Q^2(1 + B)^2/(1 + Q)^2)^{1/2}\},$$

or

$$P \doteq \frac{\pi}{\sqrt{2}} C \{(1 + S)^{1/2} + (1 + QS)^{1/2}\} \tag{12}$$

where

$$S = 3.19 C^2 \exp(0.14432W).$$

3. The area enclosed by the smooth, double-ellipse shape, divided by the square of the distance from the point of origin to the head of the fire, is given by A,

where

$$A = \pi C (1 + B)/2. \tag{13}$$

---

[15]Reference footnote 3.

Examples of wind-driven fire shapes, as predicted by these formulae, as well as graphs of the perimeter length (equation 12) and burned area (equation 13) are given in the text.

The simple formulae given by Van Wagner (1969) require three values of the rate of spread (heading, flanking, and backing) but don't use the windspeed explicitly. The shapes and rates of increase predicted by his method should be very similar to those given by Anderson's formulae.

Flame Front Characteristics

As mentioned earlier, several fire behavior descriptors have been related to Byram's fireline intensity. Rothermel's model deals with reaction intensity, but a simple relationship found by Anderson (1969) allows one to transcribe the reaction intensity to Byram's intensity.

Residence Time and Flame Depth

The depth, or front-to-back distance, of the actively flaming zone of a free-spreading fire can be determined from the rate of spread and the particle-residence time. Anderson (1969) found that fuel particles with diameter d (in inches) actively flamed for a time, t, where

$$t(\text{minutes}) = 8d\ (\text{inches}) \tag{14}$$

Clearly, the product of the rate of spread and the flaming time should give the depth, D, of the flaming zone:

$$D = Rt. \tag{15}$$

Byram's Intensity

Byram's intensity, I, is the rate of heat release per unit of fire edge. The reaction intensity, I_R, provided by Rothermel's spread model is the rate of energy release per unit area in the actively flaming zone. So, in terms of the depth of the flaming zone, D, described above:

$$I = I_R D/60 \tag{16}$$

The factor 60 is to convert from Btu/ft/min to Btu/ft/s.

Flame Length

Byram's formula (1959) makes it easy to calculate the average flame length from I, if I is in Btu/ft/s:

$$L = 0.45(I)^{0.46} \tag{17}$$

where

L = flame length, ft

I = Byram's intensity, Btu/ft/s.

Thomas (1963, 1970) found a very similar formula, but he used the rate of fuel consumption per unit length of fire edge rather than the intensity, I, to express his results. If we assume that the heat of combustion of the fuel particles is 8,000 Btu/lb, we can rewrite Thomas' equation in terms of I, with the result:

$$L = 0.20\ I^{2/3}$$

There are theoretical reasons to prefer the 2/3 exponent of Thomas' equation, and some experiments (Thomas 1963, 1970; Thomas and others 1963; Putnam 1965; Anderson and others 1966) tend to confirm this power law, but Byram's equation seems to give more realistic results over a wide range of intensities (Brown and Davis 1973) and is used here to predict flame length.

Crown Scorch Height

Van Wagner's formula (1973) for maximum height of lethal scorch can be written in English units as:

$$H_s = (63/(140 - T))\ (I^{7/6}/(I + W^3)^{1/2}) \qquad (18)$$

where

W = windspeed at 20 ft height, mi/h

I = Byram's intensity, Btu/s/ft

T = ambient air temperature, °F

H_s = maximum height of lethal scorch, ft.

Because there are three variables in equation (18), it is possible to deal with two equations which are each simpler. Note, for example, that if the temperature (T) were 77° F, we would have a simpler formula:

$$(H_s)_{77°\ F} = I^{7/6}/(I + W^3)^{1/2} \qquad (19)$$

So we can pick a standard day as being a 77° F day, and refer all other crown scorch heights to this standard. If the intensity (I) and the windspeed (W) were the same for two different days, but the temperatures were different, the scorch heights would be in the ratio:

$$\frac{(H_s)_{\text{Temperature T}}}{(H_s)_{77}} = \frac{63}{140-T} \qquad (20)$$

Duff Burnoff

Van Wagner (1972) conducted experimental burns under standing pines in eastern Canada to determine the amount of duff burned off under various conditions. He found that the weight loading (dry weight, lb/ft^2) of combined L and F layers consumed by fire was strongly related to the average moisture content of these duff layers. The equation derived by Van Wagner included theoretical justification based on the variation of flame emissivity with water content. In units used herein, this equation is:

$$W = 0.1926\ (1.418 - M)/(0.1774 + M) \qquad (21)$$

where

W = duff loading burned off, lb/ft^2

M = duff (L + F) average moisture content, fraction of dry weight. This equation is graphed in the text.

APPENDIX III

BASIS FOR CONSTRUCTION OF THE NOMOGRAPHS

Mathematical Basis

The nomographs represent a graphical means of performing the computations specified by Rothermel (1972) for determining reaction intensity and rate of spread, with minor modifications. The computations were performed July 25, 1974, on the CDC 7600 computer at the Lawrence Berkeley Laboratories Computer Center (BKY) located on the campus of the University of California at Berkeley. The program used was the FIREMODS library (Albini 1976) of computer subroutines maintained on permanent storage at BKY by the Northern Forest Fire Laboratory.

The modifications of the equations (Rothermel 1972) which are significant in the computations resulting in these nomographs are outlined briefly below. Other revisions have been made, but are inconsequential for these computations (Albini 1976).

1. The dry-weight loading of any particular fuel element, W_o, includes the noncombustible mineral fraction, S_T. The loading of combustible fuel is $W_o(1 - S_T)$, not $W_o/(1 + S_T)$, as in Rothermel (1972).

2. The equation for reaction velocity, Γ', includes an exponent A, calculated from equation (39) (Rothermel 1972):

$$A = (4.77\ \sigma^{0.1} - 7.27)^{-1}.$$

In the computer-based model, this equation is replaced by

$$A = 133\ \sigma^{-0.7913}$$

to prevent divergence of results as σ approaches $(7.27/4.77)^{10}$. The differences are small but noticeable between the two methods of computation.

3. The calculation of the moisture of extinction of the live fuel loading (Fosberg and Schroeder 1971) is described by Rothermel's (1972) equation (88), which can be written as

$$(M_x)_{living} = 2.9\ W(1 - (M_f)_{dead}/0.3) - 0.226 \quad \text{(minimum value 0.3)}$$

where

$(M_x)_{living}$ = Moisture of extinction of living fuel

W = Ratio of "fine" fuel loadings, dead/living

$(M_f)_{dead}$ = Moisture content of "fine" dead fuel.

In the computer-based model, this equation is replaced by

$$(M_x)_{living} = 2.9\ W'(1 - (M'_f)_{dead}/(M_x)_{dead}) - 0.226$$

$$\text{(minimum value } (M_x)_{dead})$$

where

$$W' = (\Sigma_{dead} W_{o,j} \exp(-138/\sigma_j))/(\Sigma_{live} W_{o,j} \exp(-500/\sigma_j))$$

$$(M'_f)_{dead} = (\Sigma_{dead} W_{o,j} M_{f,j} \exp(-138/\sigma_j))/(\Sigma_{dead} W_{o,j} \exp(-138/\sigma_j))$$

and

$W_{o,j}$ = dry weight loading of size class j

σ_j = surface/volume ratio of size class j

$M_{f,j}$ = moisture content of size class j

The exponential weighting factors, developed by W. H. Frandsen[16] make explicit the calculation of "fine" fuel properties for an arbitrary fuel description, and replacement of 0.3 by $(M_x)_{dead}$ stabilizes model behavior over a wide range of moisture-of-extinction of the dead fuel.

4. In Rothermel's equation (58), the reaction intensity of the dead and living fuel categories were combined by forming a weighted average where the weighting factor was the fraction of fuel surface area per unit of ground area contributed by each category. In the computer-based model the intensities are simply added together. This change is due to a revision in the method of categorizing fuel components; only two categories (live and dead) are now employed, while at the time Rothermel published his findings (1972), it was felt that categorization by species might be more useful.

Nomograph Organization

The nomographs are organized into three functional quadrants: the two right-hand quadrants and the upper left-hand quadrant; an auxiliary working chart is inset in the lower left-hand quadrant above the lone index line.

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[16]Unpublished results, discussed in Albini (1976).

The upper right-hand quadrant represents a graph of reaction intensity (right horizontal axis) versus dead fuel moisture (right vertical axis). For the fuel models presented here, the dead fuel moisture can be taken to be the 1-hour fuel moisture in all cases except models 11-13 (conifer slash), models 6 (dormant brush or hardwood slash), and 7 (southern rough). For these models, one can use an average moisture computed from Rothermel's (1972) area-weighted formula:

$$(M_{fuel})_{dead} = 0.76(M_{1-h}) + 0.18(M_{10-h}) + 0.06(M_{100-h}) \text{ Models 11-13}$$

or

$$(M_{fuel})_{dead} = 0.89(M_{1-h}) + 0.09(M_{10-h}) + 0.02(M_{100-h}) \text{ Models 6, 7}$$

For those models that include live fuel, only the foliage moisture is used, and only the foliage component is included in the fuel loadings.

The lower right-hand quadrant represents the combined effect of wind and slope on amplifying the propagating flux, which is proportional to the reaction intensity. The wind coefficient, ϕ_w, and the slope coefficient, ϕ_s, are combined using the auxiliary working chart in the lower left-hand quadrant to produce an effective windspeed which, when used in the formula for the wind coefficient, produces an amplification factor equal to the sum of the two coefficients:

$$\phi_w \text{ (effective windspeed)} = \phi_w \text{ (measured windspeed)} + \phi_s \text{ (slope)}$$

The lower right-hand quadrant is thus a plot of straight lines of slope $(1 + \phi_w)$ relating amplified propagating flux to reaction intensity. In all cases it is assumed that the windspeed at midflame height is half the measured windspeed at 20 feet above ground.

The lower left-hand quadrant is nonfunctional, serving only to translate the propagating flux to the horizontal axis of the upper left-hand quadrant.

The upper left-hand quadrant represents a plot of the rate of spread (center vertical axis) versus the propagating flux (left horizontal axis, running right to left). The relationship plotted is (Rothermel 1972; Frandsen 1971):

$$R = I_p/Q^*_{ig}$$

where R is spread rate, I_p is propagating flux, and Q^*_{ig} is the bulk heat of preignition. For models that have dead fuel only, Q^*_{ig} is simply a function of the dead fine fuel (1-h) moisture content.

For models that contain both live and dead fuel components, Q^*_{ig} is the function of both the dead fine fuel moisture and the live foliage moisture, so the slope of the appropriate line $(1/Q^*_{ig})$ relating the two variables must be constructed for each combination of interest. Because the right-hand vertical axis is essentially the 1-hour timelag dead fuel moisture for these models, a curve for constant live foliage moisture can be constructed in the upper left-hand quadrant which represents the locus of end points of straight lines of slope $(1/Q^*_{ig})$ drawn from the origin to the vertical location of the dead fuel moisture. This allows the simple construction of the appropriate straight line of slope $1/Q^*_{ig}$ for the combination of live and dead fuel moistures.

The flame length curves in the upper right-hand quadrant are based on the simple approximation for depth of flaming zone, D:

$$D = (\text{rate of spread}) \times (\text{flaming zone residence time}) = Rt_R$$

where

$t_R = 384/\tilde{\sigma}$ = particle residence time in flaming zone, minutes.

The correlation of particle size, as represented by $\tilde{\sigma}$, a composite surface/volume ratio for the fuel bed, with flaming zone residence time is according to Anderson (1969).

The product of flaming zone depth, D, and reaction intensity, I_R, represents an approximate value of Byram's fireline intensity, I.

$$I = I_R D$$

This intensity can be used to estimate flame length, L, from the correlation equation (Byram 1959):

$$L = 0.45\ I^{0.46} \text{ (L in ft, I in Btu/ft/s)}$$

Combining these equations yields a family of hyperbolae of the form

$$RI_R = K(L)^{1/0.46}$$

Where K is a proportionality constant incorporating the numerical factors and rationalizing the systems of units employed in the above equations.

The Stylized Fuel Models

The descriptions of the fuel models used in constructing the nomographs are given in table 7. The other variables needed to complete the descriptions for use in the fire spread model are held constant for the entire set. These variables are:

Ovendry fuel density	:	32 lb/ft^3
Heat of combustion (low heat value)	:	8,000 Btu/lb
Total mineral content	:	5.55 percent
Silica-free ash content (effective mineral content)	:	1.00 percent

These fuel models are very similar to the nine stylized fuel models (A - I) employed in the National Fire-Danger Rating System (Deeming and others 1974), but there are some important differences. The accuracy with which any particular situation in the field is reproduced by one of these stylized models is highly variable. The user is urged to note discrepancies between fuel situations in the field and the stylized models used here in order to better interpret results obtained by using the nomographs given in the text.

Table 7.--*Description of fuel models used in constructing the nomographs*

Model	Typical fuel complexes	Surface-to-volume ratio (ft^{-1})/Loading (lb/ft^2)				Depth (ft)	Moisture of extinction, dead fuel (percent)
		Dead fuel			Live fuel		
		1-h	10-h	100-h	(Foliage)		
				GRASS AND GRASS-DOMINATED			
1	Short grass (1 ft)	3500/.034	--	--	--	1.0	12
2	Timber (grass and understory)	3000/.092	109/.046	30/.023	1500/.023	1.0	15
3	Tall grass (2.5 ft)	1500/.138	--	--	--	2.5	25
				CHAPARRAL AND SHRUBFIELDS			
4	Chaparral (6 ft)	2000/.230	109/.184	30/.092	1500/.230	6.0	20
5	Brush (2 ft)	2000/.046	109/.023	--	1500/.092	2.0	20
6	Dormant brush, hardwood slash	1750/.069	109/.115	30/.092	--	2.5	25
7	Southern rough	1750/.052	109/.086	30/.069	1550/.017	2.5	40
				TIMBER LITTER			
8	Closed timber litter	2000/.069	109/.046	30/.115	--	0.2	30
9	Hardwood litter	2500/.134	109/.019	30/.007	--	.2	25
10	Timber (litter and understory)	2000/.138	109/.092	30/.230	1500/.092	1.0	25
				LOGGING SLASH			
11	Light logging slash	1500/.069	109/.207	30/.253	--	1.0	15
12	Medium logging slash	1500/.184	109/.644	30/.759	--	2.3	20
13	Heavy logging slash	1500/.322	109/1.058	30/1.288	--	3.0	25

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