CFFDRS

User Guide to the

Canadian Forest Fire Behavior Prediction System

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USER GUIDE TO THE

CANADIAN FOREST FIRE BEHAVIOR PREDICTION SYSTEM:

Rate of Spread Relationships

Interim Edition

Prepared by the Canadian Forestry Service Fire Danger Group

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PREFACE

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Persons involved with making fire behavior predictions are encouraged to communicate their assessment of this interim edition report on the Canadian Forest Fire Behavior Prediction System to the authors. Inquiries and/or comments should be directed to the appropriate CFS Fire Danger Group representative listed below.

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ABSTRACT

This report represents the interim edition of the rate of spread (ROS) component of the Canadian Forest Fire Behavior Prediction (FBP) System. The principal input variable is the Initial Spread Index (ISI) of the Canadian Forest Fire Weather Index System. Head fire ROS/ISI relationships are presented for 14 major Canadian fuel types in equation, graphical, and tabular form. Written descriptions of each fuel type are included. Instructions for adjusting the Fine Fuel Moisture Code (FFMC) for time of day and topography, and the effect of ground slope on fire spread rates are also included. Procedures for projecting fire growth from a point ignition or an active perimeter source are described. Guidelines for documenting observations of wildfire behavior are presented. Details regarding the technical development of the FBP System's spread component are provided. The fire spread relationships in the FBP System are interpreted in terms of fuel complex characteristics and wind effects.

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INTRODUCTION

The Canadian Forest Fire Danger Rating System (CFFDRS) has been under development in its present form since 1968, when the Canadian Forestry Service (CFS) adopted a modular approach to a new national system of fire danger rating (Muraro 1969). The first major sub-system of the CFFDRS is the Canadian Forest Fire Weather Index (FWI) System. It has been in operational use by fire management agencies across the country since 1971. The FWI System provides numerical ratings of relative fire potential. Its components have been regionally calibrated for use by fire management agencies as guides to the evaluation of fire danger. Documentation of the FWI System's structure is provided in Van Wagner (1974), a computer program and equation list in Van Wagner and Pickett (1984), and the current tables for FWI System calculations (Canadian Forestry Service 1984).

The other major sub-system of the CFFDRS was conceived, in the original modular approach, as being a collection of regionally developed and published quantitative indexes of actual fire behavior (e.g., rate of spread in m/min) in specific fuel types. This sub-system has been variously termed a series of Burning Indexes (BI) (Kiil 1971; Lawson 1972; Van Wagner 1974), then later a family of Fire Behavior Indexes (FBI) (Lawson 1977b; Stocks 1977; Quintilio 1978). Together with the FWI System, the BIs or FBIs conceptually formed a national system of fire danger rating called the Canadian Forest Fire Behavior (or Behavior Rating) System. A number of regional BIs and FBIs were developed during the 1970s. Some were issued in the form of Regional Supplements to the three CFS regional versions of the Canadian Forest Fire Behavior System distributed by Pacific and Yukon Region (Supplement BC-3, [Muraro 1971] developed but not officially distributed), Western and Northern Region (Supplement NFRC-1) and Ontario Region (Supplements ONT-1 and ONT-2). As well quantitative measures of one or more fire behavior characteristics in a number of fuel types were published by Van Wagner (1973), with later experimental or developmental work on quantitative fire behavior appearing for both logging slash (e.g., Muraro 1975; Stocks and Walker 1973; McRae 1980), and for standing timber fuel types (e.g., Lawson 1973; Quintilio et al. 1977).

The concept of BIs and FBIs is now being replaced by the new sub-system of the CFFDRS described here, the Canadian Forest Fire Behavior Prediction (FBP) System. (The old term, Canadian Forest Fire Behavior System, encompassing both FWI System and BIs or FBIs was officially changed in favor of CFFDRS in 1975 [CCFFC 1976].) In practice, it is expected that the new FBP System will augment existing user agency fire management decision aids (e.g., BC Ministry of Forests 1983) which, in some cases, have incorporated local modifications of the former BIs or FBIs to suit particular management applications.

Philosophically, the FBP System reflects the long-established CFS approach to fire behavior research, as described by Van Wagner (1971). Field observation and documentation of readily measured variables on experimental fires, followed by analysis of the data using rather simple mathematical models and correlation techniques, are the basis of the CFS approach. Well-documented operational prescribed fires and wildfires have been used as well, the latter being particularly useful to determine the extreme end of the fire behavior scale where experimental fires are difficult to manage. Laboratory-based fire research in moisture physics and heat transfer theory provides the models and framework by which field data are analyzed and explained.

Structurally, the FBP System consists of three fire behavior components as primary outputs; rate of spread, fuel consumption and fire intensity (Fig. 1). This interim edition contains only the rate of spread component; the other two major components are under development for inclusion in the published edition of the FBP System, which will be issued as a CFS Forestry Technical Report in 1986.

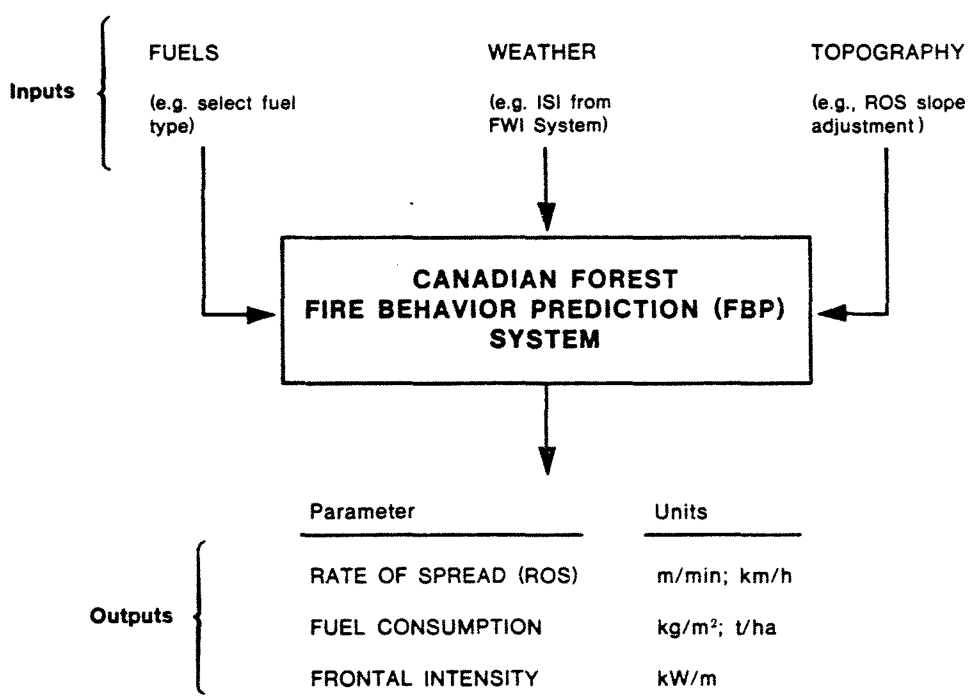

Figure 1. Simplified structure of Canadian Forest Fire Behavior Prediction (FBP) System.

FBP System inputs are drawn from the three major groups of variables affecting fire behavior, namely fuels, weather and topography. The rate of spread component of the FBP System specifically draws on three inputs: fuel type (selected from a list of 14 discrete fuel type descriptions, in this interim edition), Initial Spread Index (ISI), a component of the FWI System, and topographic slope.

The output from the spread component of the FBP System is forward, linear, head fire rate of spread (ROS) on level terrain under equilibrium conditions. By defining ROS as the forward movement of the fire front per unit time after having reached an equilibrium steady-state, crowning and spotting are automatically accounted for, in terms of their influence on the overall spread rate in fuel types subject to these fire behavior phenomena. Crown fire thresholds are indicated as part of the basic ROS output of the system.

The spread component of the FBP System is presented for 14 broadly defined Canadian fuel types. Fuel types are described mainly qualitatively, emphasizing obvious properties of stand structure and composition, and surface and ground fuels important to fire behavior. Terminology is used in the fuel type descriptions which allows semiquantitative comparison of characteristics among fuel types to assist a user in selecting the most appropriate fuel type. The 14 fuel types described do not cover the entire spectrum of Canadian forest and rangeland fuel complexes, but reflect a wide range of the variation experienced and the limits of presently available fire behavior data. Further expansion and refinement of fuel types is anticipated as fire behavior research continues.

Predicted fire behavior varies from one fuel type to another at the same FWI System component (ISI) rating. This is the key conceptual difference between the FBP System (variable fuel type) and the FWI System (standard fuel type), in addition to the basic difference of the former providing quantitative fire behavior outputs while the latter outputs relative indexes. However, fire spread predicted for one fuel type at any given ISI level may not be statistically or significantly different from all other fuel types; this was not a criterion in differentiating fuel types. Expected usefulness of the fuel type descriptions to the fire manager takes precedence over statistical uniqueness. The user is required to "fit" his fuel complex of concern to one of the 14 fuel types provided; no provision is made for "adjusting" ROS for a fuel type which has characteristics in between two of the discrete fuel types provided.

ROS/ISI relationships are presented in equation, table and graph form for level to gently undulating terrain. However, topographic slope and its mechanical effect on ROS can be accounted for by applying a relative spread factor to the predicted ROS. This and other adjustments for topographic slope and aspect and for time of day are included in a separate section of the report. The latter two are handled as adjustments to the Fine Fuel Moisture Code (FFMC), an input into the

ISI, and hence are made before entering the FBP System for a ROS prediction.

Application of outputs from the spread component of the FBP System could include a number of fire presuppression and suppression activities involving a wide range of planning time horizons, from near-real time suppression tactics to strategic planning for a major ongoing fire, to fire control resource allocation and deployment schedules. Procedures for calculating fire growth from a point ignition using an elliptical fire growth model or an active perimeter source and FBP System ROS predictions are described to assist the user with practical applications of system outputs.

To improve the application of ROS predictions from the FBP System in fire management and to strengthen the available data base (described in Appendix I), a section of the report is devoted to documentation of wildfire spread rates, giving a number of suggestions regarding methodology which can be employed by the practitioner in the field, as well as by the researcher. This section is intended to help the fire manager evaluate, adjust for, and solve problems associated with fire behavior predictions.

FUEL TYPE DESCRIPTIONS

Fuel type has been defined as "an identifiable association of fuel elements of distinctive species, form, size, arrangement, or other characteristics that will cause a predictable rate of fire spread or difficulty of control under specified burning conditions" (CCFFC 1976). More specifically, a fuel type is a recognizable fuel complex of sufficient homogeneity of characteristics and horizontal (areal) extent that steady-state equilibrium fire behavior can be predicted and be expected to be maintained over a considerable period of time. This edition of the FBP System recognizes 14 discrete fuel types, organized into five major groups as follows:

Group	Identifier	Descriptive Name
	C-1	Spruce - Lichen Woodland
	C-2	Boreal Spruce
	C-3	Mature Jack or Lodgepole Pine
Coniferous	C-4	Immature Jack or Lodgepole Pine
	C-5	Red and White Pine
	C-6	Red Pine Plantation
	C-7	Ponderosa Pine - Douglas-fir
Deciduous	D-1	Leafless Aspen
Mixedwood	M-1	Boreal Mixedwood - leafless
	M-2	Boreal Mixedwood - summer
	S-1	Jack or Lodgepole Pine Slash
Slash	S-2	Spruce - Balsam Slash
	S-3	Coastal Cedar - Hemlock - Douglas-fir Slash
Open	O-1	Grass

Users are required to select from the list of 14, the fuel type best suited to the particular situation of concern. The above list represents as broad a range of conditions in Canadian fuel types as allowed by the existing fire behavior data base. In addition, some fuel types for which sound empirical Canadian fire behavior data do not presently exist have been included because of their significance to one or more provinces and territories (e.g., boreal mixedwood and grass). However, the present list of 14 fuel types is not intended to be comprehensive or fixed for the future; additions and refinements should be expected as sufficient data become available.

Fuel types in the FBP System are described mainly qualitatively, rather than quantitatively, using terms describing stand structure and composition, surface and ladder fuels, and the forest floor cover and organic (duff) layer. The major distinguishing features of each fuel

Table 1. Brief summary of Canadian Forest Fire Behavior Prediction (FBP) System Fuel Type characteristics.

Fuel Type	Forest Floor & Organic Layer	Surface & Ladder Fuels	Stand Structure & Composition
C-1	Continuous reindeer lichen; organic layer absent or shallow, uncompacted.	Very sparse/herb shrub cover and down woody fuels; tree crowns extend to ground.	Open black spruce stands with dense clumps; assoc. spp. jack pine, white birch; well-drained upland sites.
C-2	Continuous feather moss and/or cladonia; deep, compact organic layer.	Continuous shrub, e.g. Labrador tea common; low to moderate down woody fuels; tree crowns extend nearly to ground; arboreal lichens, flaky bark.	Moderately well-stocked black spruce stands on both upland and lowland sites; sphagnum bogs excluded.
C-3	Continuous feather moss; moderately deep, compact organic layer.	Sparse conifer understory may be present; sparse down woody fuels; tree crowns separated from ground.	Fully-stocked jack or lodgepole pine stands; mature.
C-4	Continuous needle litter; shallow, moderately compacted organic layer.	Moderate shrub/herb cover; continuous vertical crown fuel continuity; heavy standing dead and dead and down woody fuel.	Dense jack or lodgepole pine stands; immature.
C-5	Continuous needle litter; moderately shallow organic layer.	Moderate herb & shrub, e.g. hazel; moderate dense understory, e.g. red maple, balsam fir; tree crowns separated from ground.	Moderately well-stocked red & white pine stands; mature; assoc. spp. white spruce, white birch, aspen.
C-6	Continuous needle litter; moderately shallow organic layer.	Absent herb/shrub cover; absent conifer understory; tree crowns separated from ground.	Fully-stocked red pine plantations; complete crown closure regardless of mean stand ht.; mean stand ht. controls ROS & crowning.
C-7	Continuous needle litter; absent to shallow organic layer.	Discontinuous grasses, herbs, except in conifer thickets where absent; light woody fuels; tree crowns separated from ground except in thickets.	Open ponderosa pine - Douglas-fir stands; mature uneven-aged; assoc. spp. western larch, lodgepole pine; understory conifer thickets.
D-1	Continuous leaf litter; shallow uncompacted organic layer.	Moderate medium to tall shrubs & herb layers; absent conifer understory; sparse dead and down woody fuels.	Moderately well-stocked trembling aspen stands; semi-mature; leafless (i.e., spring and fall).
M-1 & M-2	Continuous leaf litter in deciduous portions of stands; discontinuous feather moss and needle litter in conifer portions of stands; organic organic layers shallow, uncompacted to moderately compacted.	Moderate shrub and continuous herb layers; low to moderate dead and down woody fuels; conifer crowns extend nearly to ground; scattered to moderate conifer understory.	Moderately well-stocked mixed stands of boreal conifers (black/white spruce, balsam/subalpine fir) and deciduous species (trembling aspen, white birch). Fuel types are differentiated by season and % conifer:deciduous spp. composition.
S-1	Continuous feather moss; discontinuous needle litter; moderately deep compact organic layer.	Continuous slash, moderate loading and depth; high foliage retention; absent to sparse shrub & herb cover.	Slash from clearcut logging mature jack or lodgepole pine stands.
S-2	Continuous feather moss and needle litter; moderately deep compact organic layer.	Continuous to discontinuous slash (due to skid trails); moderate foliage retention; moderate loading & depth; moderate shrub & herb cover.	Slash from clearcut logging mature or overmature white spruce - subalpine fir or balsam fir stands.
S-3	Continuous feather moss or compact old needle litter below fresh needle litter from slash; moderately deep to deep compact organic layer.	Continuous slash, high foliage retention (cedar), moderate for other spp.; heavy loading, deep slash; sparse to moderate shrub & herb cover.	Slash from clearcut logging mature or overmature cedar-hemlock - Douglas-fir stands.
O-1	Continuous dead grass litter; organic layer absent to shallow and moderately compacted.	Continuous standing grass (current yr. crop). 'Standard' loading is 3 t/ha, other loadings can be accommodated; % cured or dead must be ocularly estimated. Sparse or scattered shrubs and down woody fuel.	Scattered trees, if present, do not appreciably affect fire behavior.

type are briefly summarized in Table 1 and are described in more detail below by major groups. It is recognized that these fuel type descriptions will be used in practice to classify fuel types from forest inventory type descriptions, usually coded by species, age, stocking, stand height and site quality. Our fuel type descriptions do not rigorously or quantitatively follow this pattern. However, knowledgeable fire managers will be able to develop their own schemes to classify their land base and vegetation data for fire planning, or allocate their real-time fuels data on potential or going fires, to an appropriate FBP System fuel type(s). The final version of the FBP System will contain representative photographs for each fuel type to assist the user with selecting and verifying fuel types for fire behavior prediction.

Coniferous Group

Fuel Type C-1 (Spruce - Lichen Woodland)

This fuel type is characterized by open, park-like black spruce stands occupying well-drained uplands in the subarctic zone of western and northern Canada. Jack pine and white birch are minor associates in the overstory. Forest cover occurs as widely-spaced individuals and dense clumps. Tree heights vary considerably but bole branches (live and dead) uniformly extend to the forest floor and layering development is extensive. Woody surface fuel accumulation is very light and scattered. Shrub cover is exceedingly sparse. The ground surface is fully exposed to the sun and covered by a nearly continuous mat of reindeer lichens averaging 3-4 cm in depth above mineral soil.

Fuel Type C-2 (Boreal Spruce)

This fuel type is characterized by pure, moderately well-stocked black spruce stands on lowland (excluding Sphagnum bogs) and upland sites. Tree crowns extend to or near the ground and dead branches are typically draped with bearded lichens. The flaky nature of the bark on the lower portion of stem boles is pronounced. Low to moderate volumes of downed woody material are present. Labrador tea is often the major shrub component. The forest floor is dominated by a carpet of feather mosses and/or ground-dwelling lichens (chiefly cladonia). Sphagnum mosses may occasionally be present but they are of little hinderance to surface fire spread. A compact organic layer commonly exceeds a depth of 20-30 cm.

Fuel Type C-3 (Mature Jack or Lodgepole Pine)

This fuel type is characterized by pure, fully-stocked (1000 to 2000 stems/ha) jack pine or lodgepole pine stands that have matured at least to the stage that crown closure is complete and the base of live crown is substantially separated from the ground. Dead surface fuels are light and scattered. Ground cover is basically feather moss over a moderately deep (approximately 10 cm) compact organic layer. A sparse conifer understory may be present.

Fuel Type C-4 (Immature Jack or Lodgepole Pine)

This fuel type is characterized by pure, dense jack pine or lodgepole pine stands (10,000 to 30,000 stems/ha) in which natural thinning mortality results in a large quantity of standing dead stems and dead and down woody fuel. Vertical and horizontal fuel continuity is characteristic of this fuel type. Surface fuel loadings are greater than in Fuel Type C-3; organic layers are shallower and less compact. Ground cover is mainly needle litter, partially elevated and suspended within a low (vaccinium) shrub layer.

Fuel Type C-5 (Red and White Pine)

This fuel type is characterized by mature stands of red and white pine in various proportions, sometimes with small components of white spruce, and old white birch or aspen. The understory is of moderate density, usually red maple or balsam fir. A shrub layer, usually beaked hazel, may be present in moderate proportions. The ground surface cover is a combination of herbs and pine litter. The organic layer is usually 5 to 10 cm deep.

Fuel Type C-6 (Red Pine Plantation)

This fuel type is characterized by pure plantations of red pine, fully stocked so that crowns are closed and no understory or shrub layer is present. The forest floor is covered by needle litter with an underlying duff layer of up to 10 cm in depth. The rate of spread relationships accommodate three ranges in mean stand height: 1) from 4 to 9.9 m, 2) from 10 to 20 m, and 3) more than 20 m.

Fuel Type C-7 (Ponderosa Pine - Douglas-fir)

This fuel type is characterized by uneven-aged stands of ponderosa pine and Douglas-fir in various proportions. Western larch and lodgepole pine may be significant stand components on some sites and elevations. Stands are open with occasional clumpy thickets of multi-aged Douglas-fir and/or larch as a discontinuous understory. Canopy closure is less than 50 percent overall, although thickets are closed and often dense. Woody surface fuel accumulations are light and scattered. Except within Douglas-fir thickets, the forest floor is dominated by perennial grasses, herbs and scattered shrubs. Within tree thickets, needle litter is the predominant surface fuel. Duff layers are non-existent to shallow (less than 3 cm).

Deciduous Group

Fuel Type D-1 (Leafless Aspen)

This fuel type is characterized by pure, semimature trembling aspen stands prior to "green-up" in the spring or following leaf fall and curing of lesser vegetation in the autumn. A conifer understory is noticeably absent but a well-developed medium to tall shrub layer is typically present. Dead and down roundwood fuels are a minor component of the fuel complex. The principal fire-carrying fuels consist chiefly of deciduous leaf litter and cured herbaceous material which are directly exposed to wind and solar radiation. In the spring, the duff mantle (F and H horizons) seldom contributes available fuel for combustion due to its generally high moisture content.

Mixedwood Group

Fuel Types M-1 (Boreal Mixedwood - leafless) and M-2 (Boreal Mixedwood - summer)

These fuel types are characterized by stand mixtures consisting of the following coniferous and deciduous tree species in varying proportions: black spruce, white spruce, balsam fir, subalpine fir, trembling aspen, and white birch. Within any combination, individual species can be present in or absent from the mixture; i.e., one or both of the broadleaf species can occur, and one, two or all of the conifers. In addition to the diversity in species composition, stand mixtures exhibit wide variability in stand structure and development but are generally confined to moderately well-drained upland sites. Two phases associated with the seasonal variation in the flammablity of the boreal mixedwood forest are recognized: leafless stage - spring and fall periods (Fuel Type M-1) and summer period (Fuel Type M-2). Rate of spread in both fuel types is weighted according to the proportion (expressed as percentage) of softwood (S) and hardwood (H) components. In the summer, after the deciduous overstory and understory vegetation have leafed out, fire spread is greatly reduced with maximum spread rates possibly only one-fifth as fast as spring or fall fires under similar burning conditions.

Slash Group

Fuel Type S-1 (Jack or Lodgepole Pine Slash)

This fuel type is characterized by slash resulting from tractor or skidder clearcut logging of mature jack pine or lodgepole pine stands. Slash is typically one to two seasons old, retaining up to 50 percent of the foliage, particularly on branches closest to the ground.

No post-logging treatment has been applied and slash fuels are continuous. Tops and branches left on site result in moderate loadings and depths of fine and medium woody fuels (fuel depth 0.5 m to 1.0 m). Ground cover is continuous feather moss mixed with discontinuous fallen needle litter. Organic layers are moderately deep (8 to 12 cm) and fairly compact.

Fuel Type S-2 (Spruce - Balsam Slash)

This fuel type is characterized by slash resulting from tractor or skidder clearcut logging of mature to overmature stands of white spruce and subalpine fir or balsam fir. Slash is typically one to two seasons old, retaining from 10 to 50 percent of the foliage on the branches. No post-logging treatment has been applied. Fuel continuity may be broken by skid trails unless winter logged. Tops have been left on site and most branch fuels have broken off during skidding of logs to landings, resulting in moderate loading and depths of fine and medium woody fuels (fuel depth 0.5 m to 1.0 m). Quantities of shattered large and rotten woody fuels may be significant. Ground cover is feather moss with considerable needle litter fallen from the slash. Organic layers are moderately deep (10 to 15 cm) and compact.

Fuel Type S-3 (Coastal Cedar - Hemlock - Douglas-fir Slash)

This fuel type is characterized by slash resulting from high-lead clearcut logging of mature to overmature coastal British Columbia mixed conifer stands. Predominant species are western red cedar, western hemlock and Douglas-fir. Slash is typically one season old, with the cedar component retaining all its foliage in a cured condition on the branches, while hemlock and Douglas-fir components will have dropped up to 50 percent of their foliage. Slash fuels tend to be continuous and uncompacted, because of cable yarding and the bucking of logs and trimming of branches on-site. Very large loadings of broken and rotten unmerchantable material may be present, depending on degree of stand decadence. Total slash fuel depths may range from 0.5 to 2.0 m. Ground cover may be feather moss or just compact old needle litter under significant quantitites of recent needle litter fallen from the slash. Organic layers are moderately deep to deep (10 to 25 cm) and compact. Minor to moderate shrub and herbaceous understory components may be present. This fuel type may also be applied to coastal and interior B.C. wet belt decadent cedar-hemlock slash, where the Douglas-fir component is absent.

Open Group

Fuel Type O-1 (Grass)

This fuel type is characterized by continuous grass cover, with no more than occasional trees or shrub clumps that do not appreciably affect fire behavior. The grass is fully developed, and has a dry weight of 3 t/ha in the stylized standard grass fuel type. However, rate of spread in grass is proportional to fuel loading, so variable grass fuel weight can be accommodated, if known or estimated. The proportion of cured or dead material may vary, and must be ocularly estimated with care, since it has a pronounced effect on fire spread in grasslands. This factor, as expressed as percent of grass cured or dead, is then applied in the rate of spread equation or graph.

RATE OF SPREAD EQUATIONS

For computerized use of the FBP System, a list of equations for predicting rate of spread for all 14 fuel types described in the previous section is presented here. However, a complete computer program is not included in this interim edition of the system. Rate of spread output is given in metres per minute (m/min), as recommended by Van Wagner (1978) for general usage. Conversion factors for expressing rate of spread in other commonly used units are given in the Adjustments and Procedures section of this report.

The principal input variable used in the rate of spread equations is the Initial Spread Index (ISI). Certain stand (mean height and species composition) and fuel (proportion of cured or dead grass and weight) characteristics are required for some fuel types. Some of the fuel types require two or more equations, depending on the ISI range and input variables. Analytical details regarding derivation of Equations (1) to (14) and the corresponding statistics are documented in Appendix I.

The effect of slope steepness on fire spread as derived by Van Wagner (1977a) is represented by Equation (15). This relationship refers to fires burning upslope and is recommended for use only up to 60% slope. It is not valid for downslope fires which spread more slowly than fires on level to gently undulating ground; the exact relation is difficult to document in the field except with backing fires.

All quantities used in the list of numbered equations are given below. Rate of spread on level to gently undulating ground is represented in this section by the single letter 'R' rather than 'ROS' which is used in the following sections of this report. Rate of spread on upsloping ground is represented by 'R_ϕ' where the subscript 'ϕ' denotes percent slope.

List of Symbols and Abbreviations

ISI - Initial Spread Index

h - mean stand height, m

S - softwood species composition, %

H - hardwood species composition, %

C - proportion of cured or dead fuel, %

W - fuel weight, t/ha

ϕ - slope of ground, %

R - rate of spread on level to gently undulating ground, m/min

R_ϕ - rate of spread on ground of slope ϕ, m/min

List of Equations

Fuel Type C-1 (Spruce - Lichen Woodland)

$$R = 0.0788\ ISI^{1.883} \quad ,ISI \leq 20 \qquad (1a)$$

$$R = 85\left[1 - e^{-0.0378\ (ISI - 12)}\right] \quad ,ISI > 20 \qquad (1b)$$

Fuel Type C-2 (Boreal Spruce)

$$R = 112.8\left(1 - e^{-0.0323\ ISI}\right)^{1.863} \qquad (2)$$

Fuel Type C-3 (Mature Jack or Lodgepole Pine)

$$R = 100.3\left(1 - e^{-0.0509\ ISI}\right)^{3.53} \qquad (3)$$

Fuel Type C-4 (Immature Jack or Lodgepole Pine)

$$R = -8.67 + 145.5\left(1 - e^{-0.01689\ ISI}\right)^{1.000} \qquad (4)$$

Fuel Type C-5 (Red and White Pine)

$$R = 0.01544\ ISI^{2.16} \quad ,ISI \leq 18 \qquad (5a)$$

$$R = 30\left[1 - e^{-0.0440\ (ISI - 11)}\right] \quad ,ISI > 18 \qquad (5b)$$

Fuel Type C-6 (Red Pine Plantation)

$$R = -8.67 + 145.5\left(1 - e^{-0.01689\ ISI}\right)^{1.000} \quad ,h < 10 \qquad (6a)$$

$$R = 100.3\left(1 - e^{-0.0509\ ISI}\right)^{3.53} \quad ,10 \leq h \leq 20 \qquad (6b)$$

$$R = 0.01544\ ISI^{2.16} \quad ,ISI \leq 18 \text{ and } h > 20 \qquad (6c)$$

$$R = 30\left[1 - e^{-0.0440\ (ISI - 11)}\right] \quad ,ISI > 18 \text{ and } h > 20 \qquad (6d)$$

Fuel Type C-7 (Ponderosa Pine - Douglas-fir)

$$R = 0.0201\ ISI^{1.879} \quad ,ISI \leq 35 \qquad (7a)$$

$$R = 40\left[1 - e^{-0.0341\ (ISI - 20)}\right] \quad ,ISI > 35 \qquad (7b)$$

Fuel Type D-1 (Leafless Aspen)

$$R = 0.0518\ ISI^{1.574} \quad ,ISI \leq 30 \qquad (8a)$$

$$R = 30\left[1 - e^{-0.0305\ (ISI - 15)}\right] \quad ,ISI > 30 \qquad (8b)$$

Fuel Type M-1 (Boreal Mixedwood - leafless)

$$R = (S/100)\,112.8\left(1 - e^{-0.0323\,ISI}\right)^{1.863} + (H/100)\,0.0518\,ISI^{1.574} \quad ,ISI \le 30 \tag{9a}$$

$$R = (S/100)\,112.8\left(1 - e^{-0.0323\,ISI}\right)^{1.863} + (H/100)\,30\left[1 - e^{-0.0305\,(ISI - 15)}\right] \quad ,ISI > 30 \tag{9b}$$

Fuel Type M-2 (Boreal Mixedwood - summer)

$$R = (S/100)\,112.8\left(1 - e^{-0.0323\,ISI}\right)^{1.863} + (H/100)\,0.01036\,ISI^{1.574} \quad ,ISI \le 30 \tag{10a}$$

$$R = (S/100)\,112.8\left(1 - e^{-0.0323\,ISI}\right)^{1.863} + (H/100)\,6\left[1 - e^{-0.0305\,(ISI - 15)}\right] \quad ,ISI > 30 \tag{10b}$$

Fuel Type S-1 (Jack or Lodgepole Pine Slash)

$$R = 1.486\,ISI \quad ,ISI \le 30 \tag{11a}$$

$$R = 75\left[1 - e^{-0.0501\,(ISI - 12)}\right] \quad ,ISI > 30 \tag{11b}$$

Fuel Type S-2 (Spruce - Balsam Slash)

$$R = 0.770\,ISI \quad ,ISI \le 40 \tag{12a}$$

$$R = 40\left[1 - e^{-0.0980\,(ISI - 25)}\right] \quad ,ISI > 40 \tag{12b}$$

Fuel Type S-3 (Coastal Cedar - Hemlock - Douglas-fir Slash)

$$R = 0.1011\,ISI^{1.992} \quad ,ISI \le 10 \tag{13a}$$

$$R = 55\left[1 - e^{-0.0481\,(ISI - 6)}\right] \quad ,ISI > 10 \tag{13b}$$

Fuel Type O-1 (Grass)

$$R = 4.88\,ISI^{0.626}\,(C/100)^{4.364} \quad ,W = 3.0 \tag{14a}$$

$$R = 1.625\,ISI^{0.626}\,(C/100)^{4.364}\,W \tag{14b}$$

Upslope Effect on Rate of Spread

$$R_{\phi} = R\,e^{3.533\,(\phi/100)^{1.2}} \quad ,0 \le \phi \le 60 \tag{15}$$

RATE OF SPREAD GRAPHS

This section contains separate graphs of rate of spread (ROS) versus Initial Spread Index (ISI) by fuel type, generated from the equations presented in the preceding section. A master graph, outlining the relative shape and position of curves for all fuel types, is given at the end of this section of the report, but the user should derive rate of spread predictions from the individual graphs presented here.

For each graph the solid line represents plotted equation values based on observed data, while the broken, or dashed, line represents an extrapolation beyond our data limits. The shaded area around each curve is a subjective confidence interval and observed spread rates can be expected to fall within this shaded area approximately 2/3 of the time. Threshold values of ISI, indicating the transition from surface to crown fire, are shown for some fuel types. Crown fire development was considered unlikely under most circumstances in certain fuel types (i.e., C-5, C-6 >20 m, D-1, M-1 <50S, and M-2 < 50S) and simply not applicable in others (i.e., S-1, S-2, S-3, and O-1).

Each graph presents ROS in both metres/minute (m/min) and kilometres/hour (Km/h) on level to gently undulating ground. The former unit is better suited to documenting slow-spreading fires over short time intervals, and the latter being more suitable when monitoring fast-spreading fires over long time periods. All graphs are plotted to a maximum ISI of 70, and the user is cautioned against extrapolating ROS values beyond this point.

Figure 16 shows ISI/ROS relationships for all 14 FBP System fuel types, displayed in four major groups. Interpretation of individual curves is briefly discussed in Appendix I.

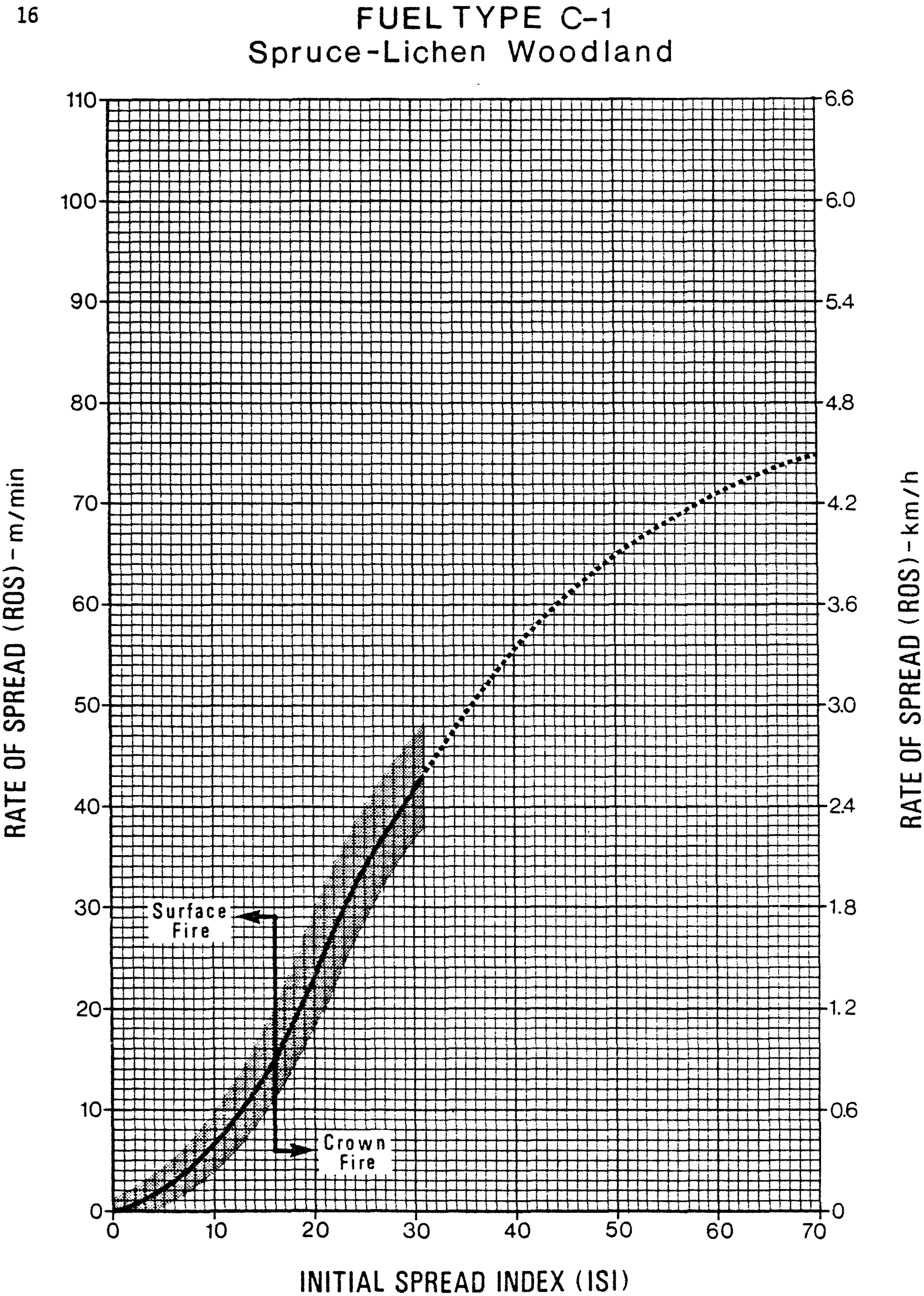

Figure 2. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for the Spruce-Lichen Woodland Fuel Type (C-1) with 70% confidence limits (shaded area), crowning threshold, and limit of observed data (dashed line) indicated.

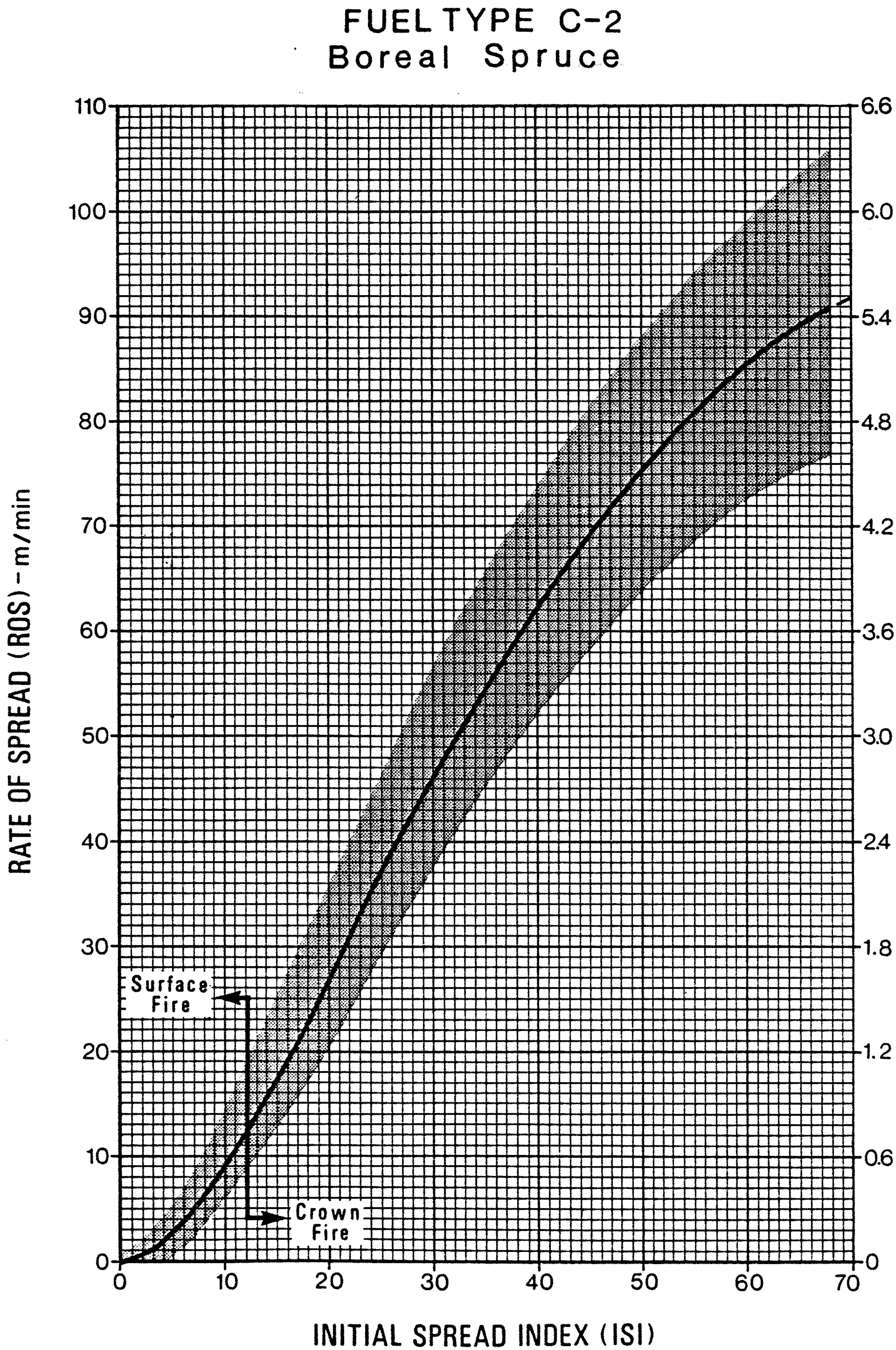

Figure 3. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for the Boreal Spruce Fuel Type (C-2) with 70% confidence limits (shaded area), crowning threshold, and limit of observed data (dashed line) indicated.

FUEL TYPE C-3
Mature Jack or Lodgepole Pine

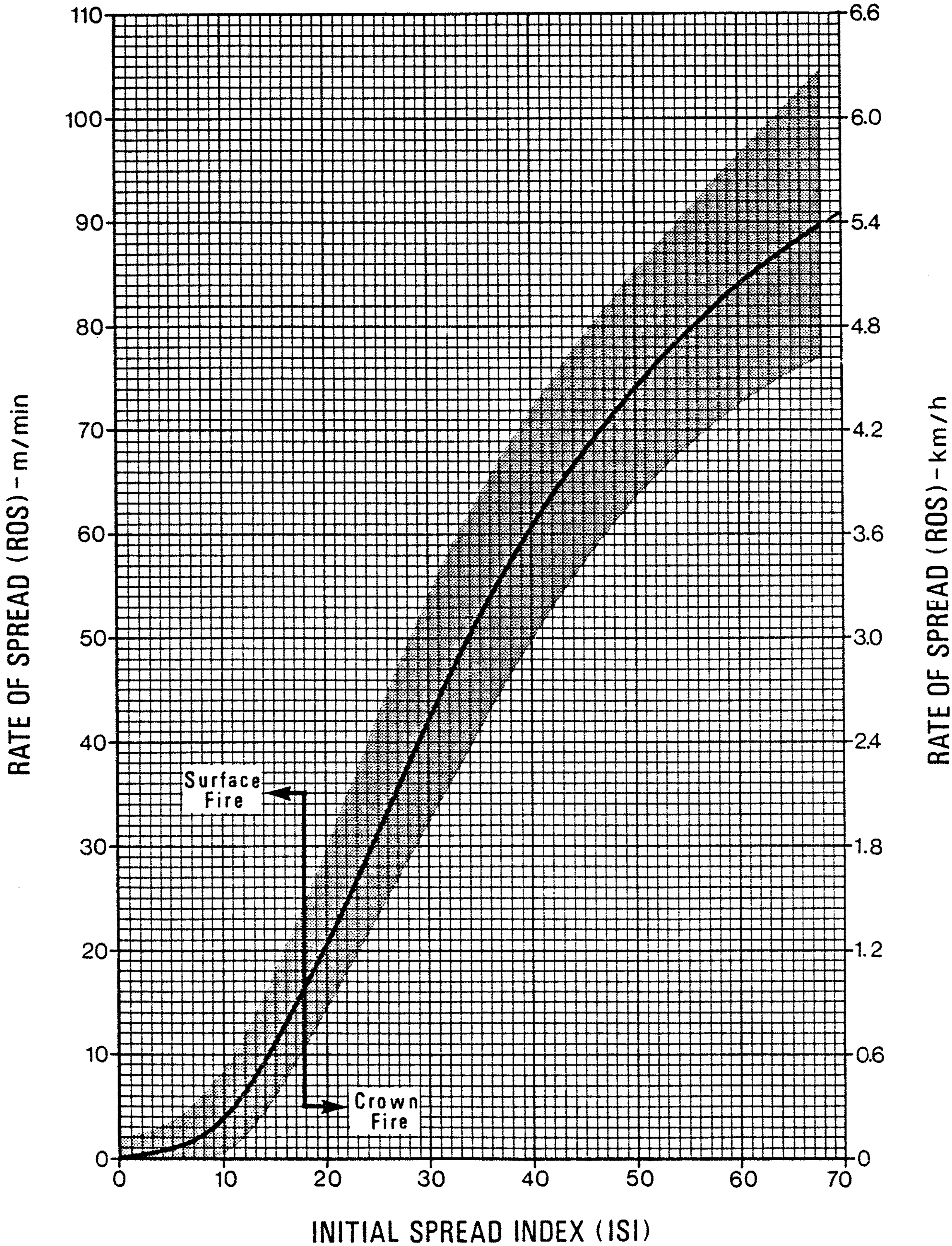

Figure 4. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for the Mature Jack or Lodgepole Pine Fuel Type (C-3) with 70% confidence limits (shaded area), crowning threshold, and limit of observed data (dashed line) indicated.

FUEL TYPE C-4
Immature Jack or Lodgepole Pine

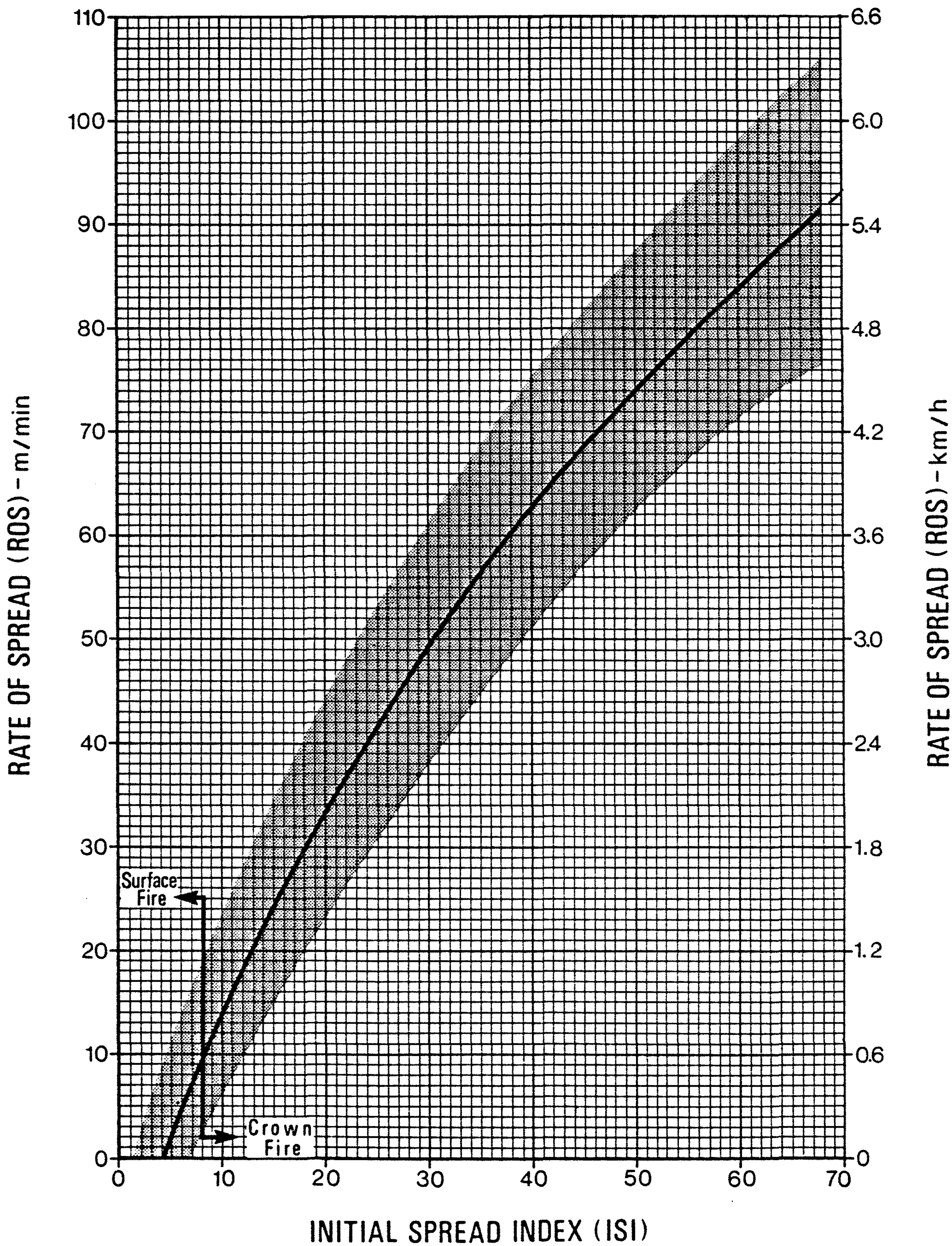

Figure 5. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for the Immature Jack or Lodgepole Pine Fuel Type (C-4) with 70% confidence limits (shaded area), crowning threshold, and limit of oberved data (dashed line) indicated.

FUEL TYPE C-5
Red and White Pine

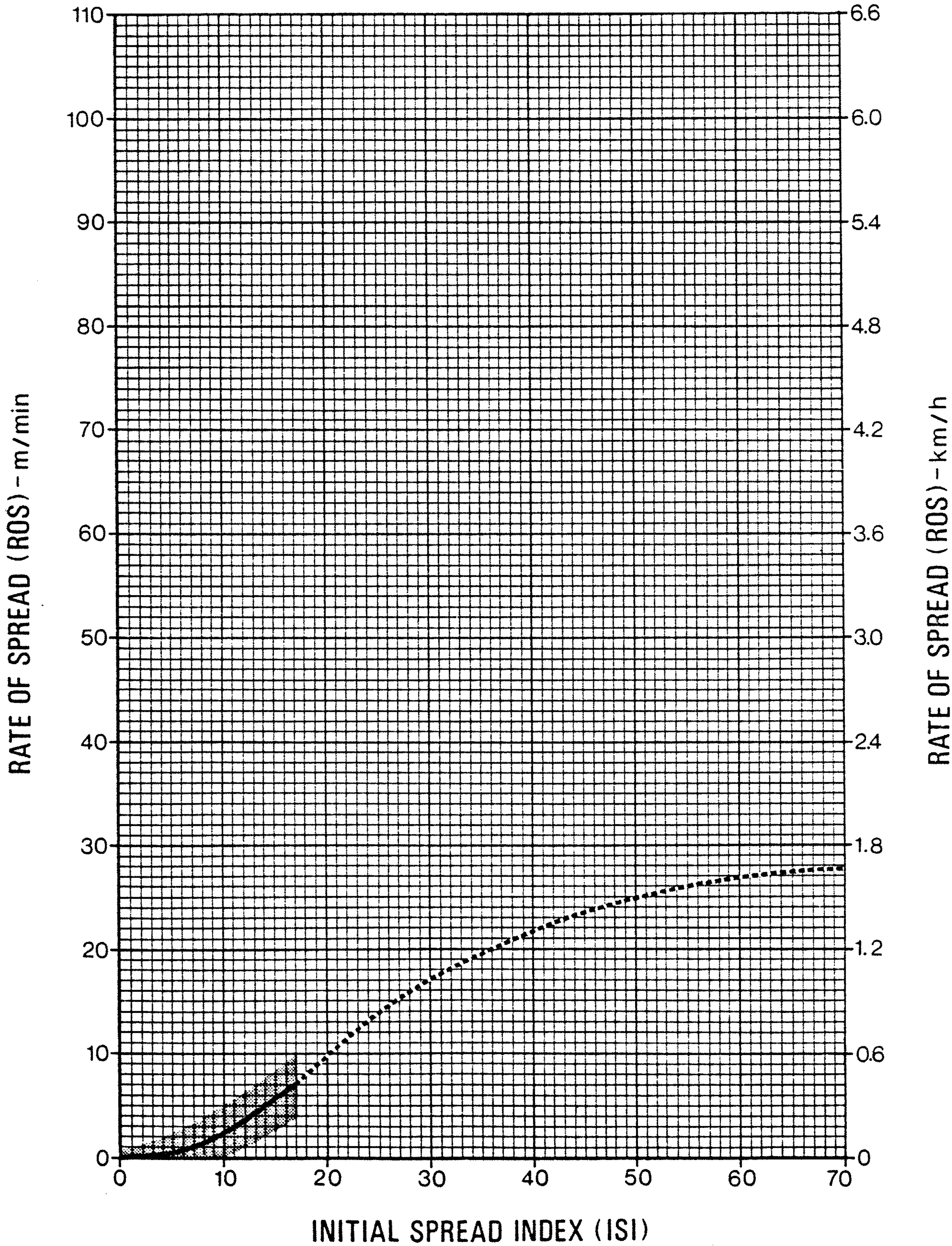

Figure 6. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for the Red and White Pine Fuel Type (C-5) with 70% confidence limits (shaded area) and limit of observed data (dashed line) indicated.

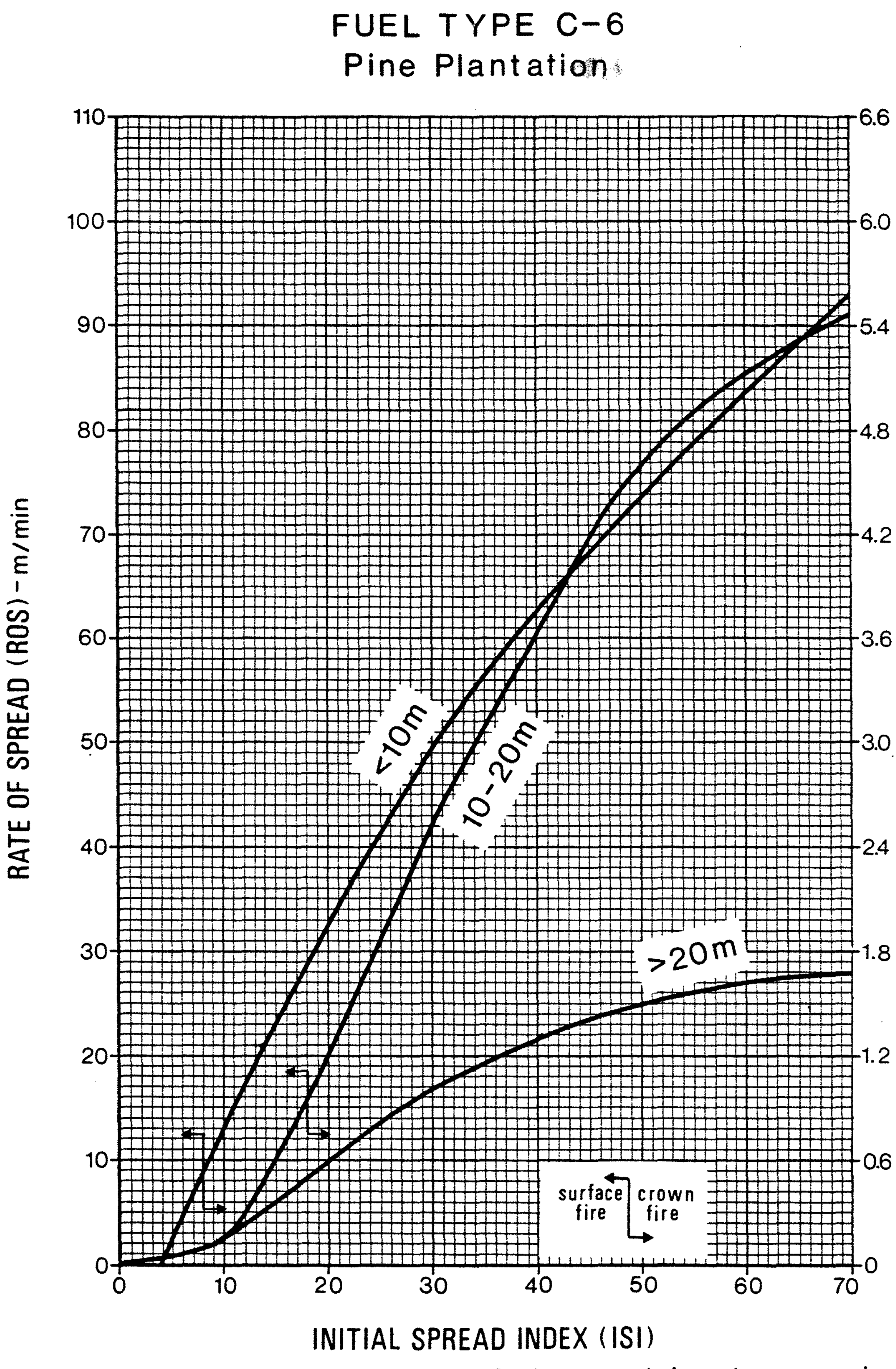

Figure 7. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for the three mean stand height ranges of the Red Pine Plantation Fuel Type (C-6) with crowning thresholds indicated.

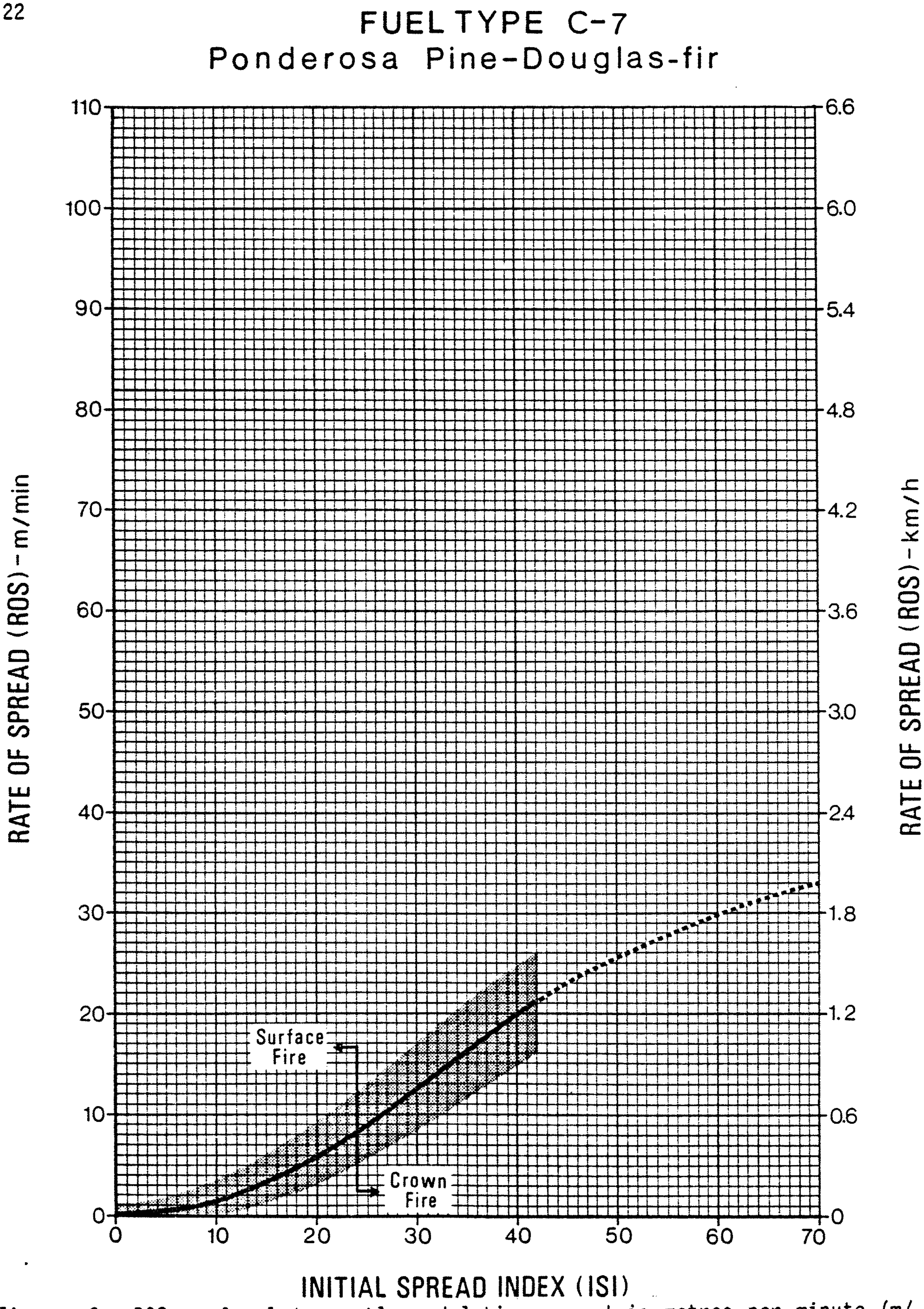

Figure 8. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for the Ponderosa Pine - Douglas-fir Fuel Type (C-7) with 70% confidence limits (shaded area), crowning threshold, and limit of observed data (dashed line) indicated.

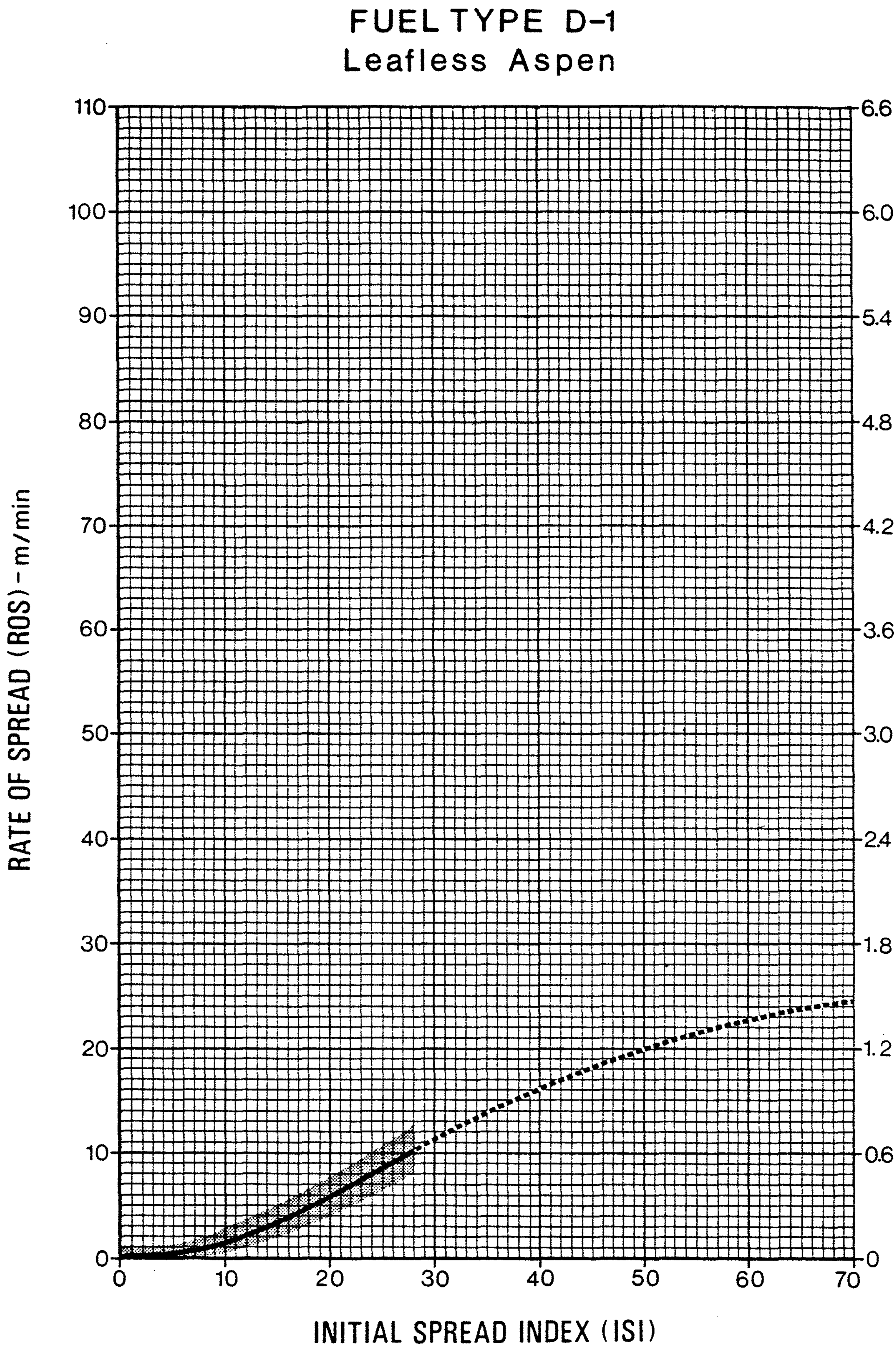

Figure 9. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for the Leafless Aspen Fuel Type (D-1) with 70% confidence limits (shaded area) and limit of observed data (dashed line) indicated.

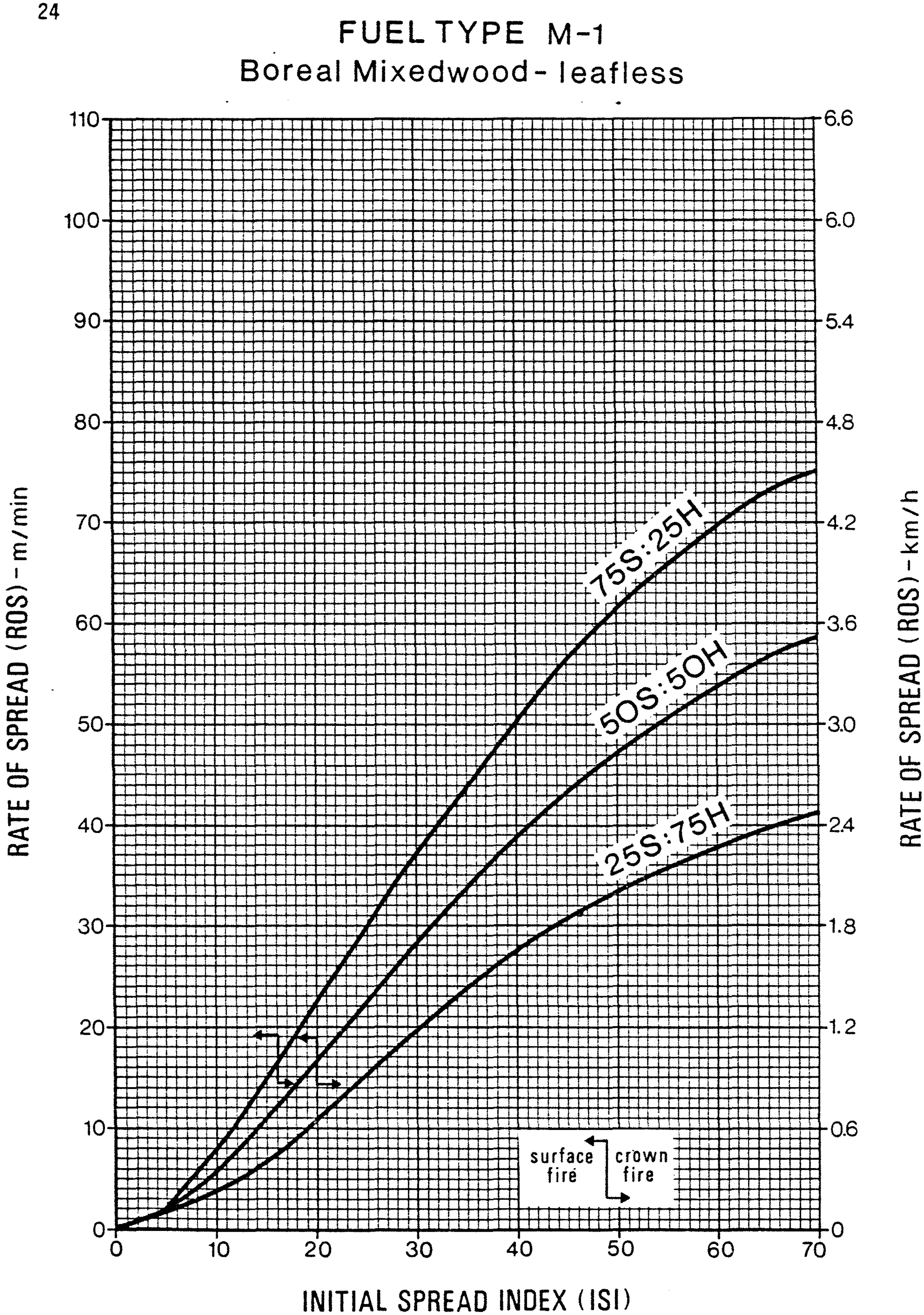

Figure 10. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for three softwood (% S) and hardwood (% H) species composition combinations of the Boreal Mixedwood Fuel Type during the spring and fall period (M-1) with crowning threshold indicated.

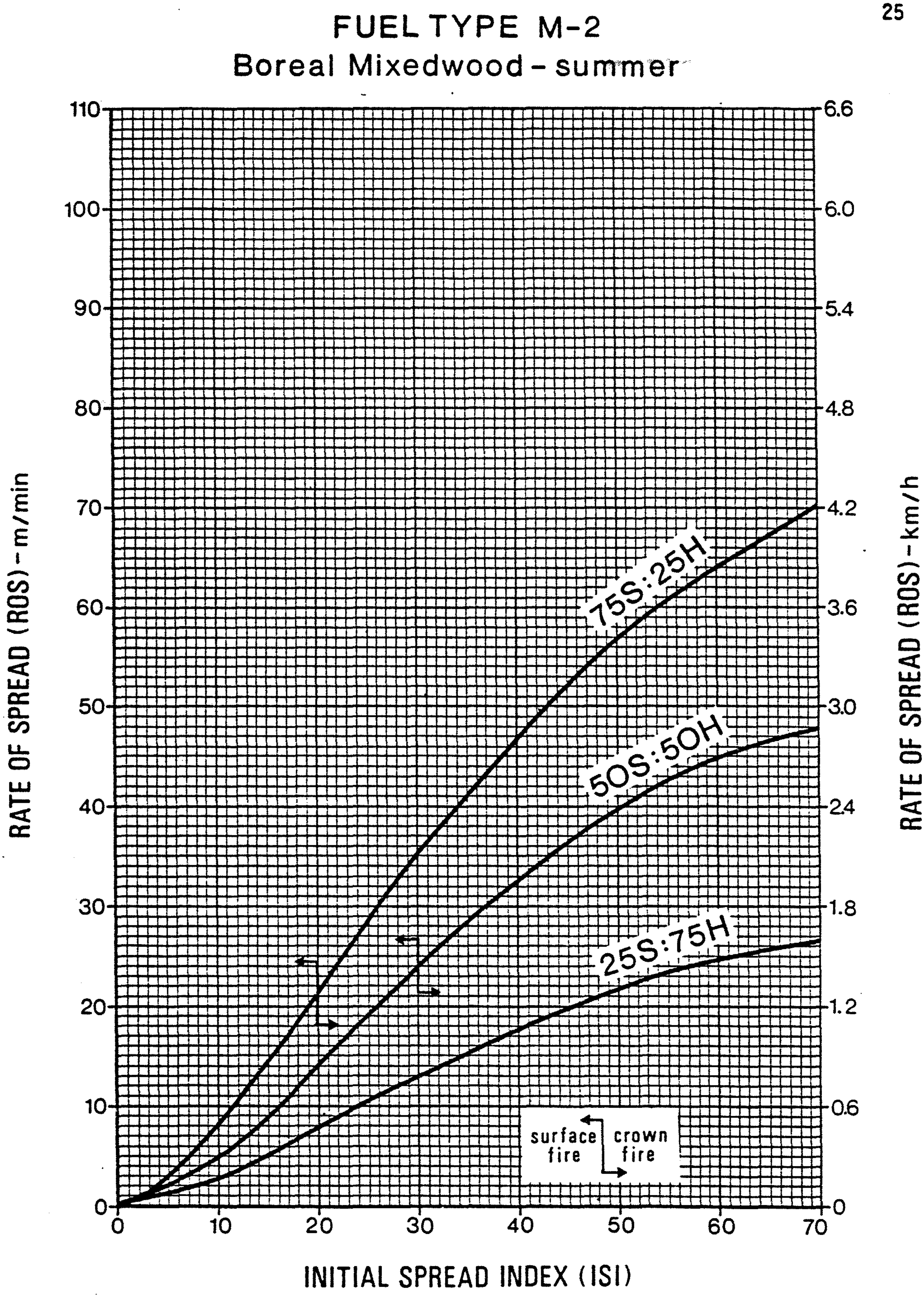

Figure 11. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for three softwood (% S) and hardwood (% H) species composition combinations of the Boreal Mixedwood Fuel Type during the summer period (M-2) with crowning thresholds indicated.

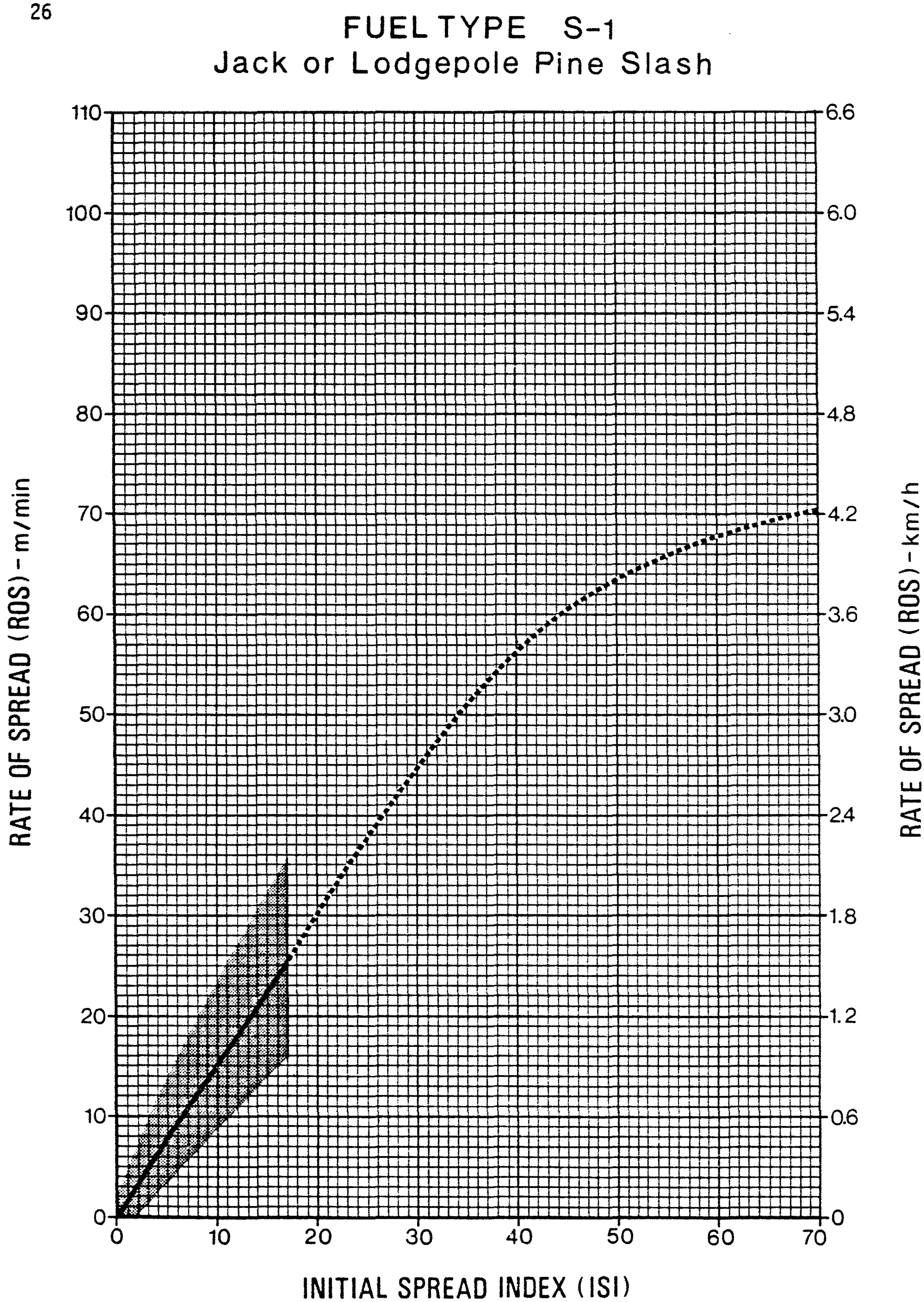

Figure 12. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for the Jack or Lodgepole Pine Slash Fuel Type (S-1) with 70% confidence limits (shaded area) and limit of observed data (dashed line) indicated.

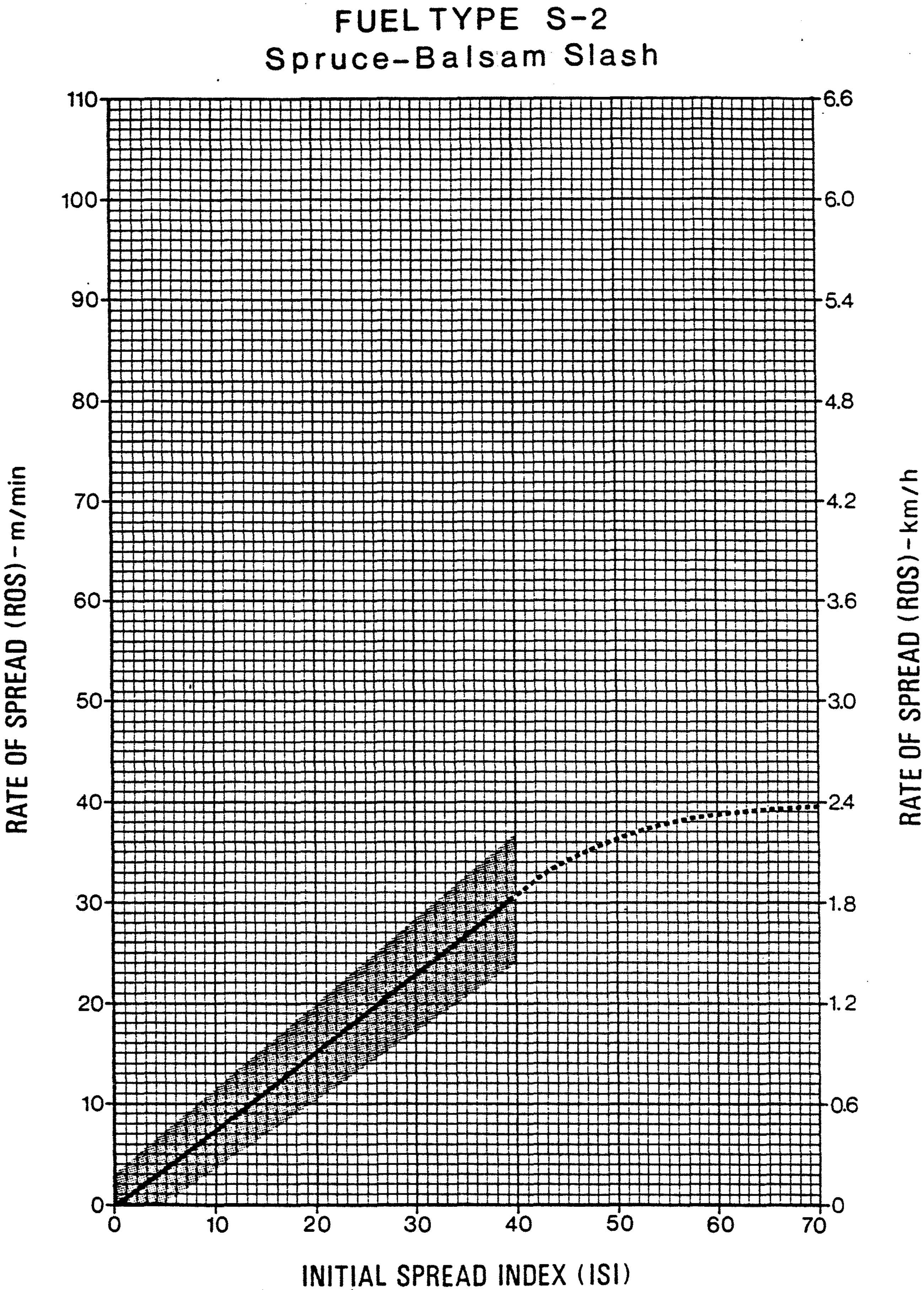

Figure 13. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for the Spruce - Balsam Slash Fuel Type (S-2) with 70% confidence limits (shaded area) and limit of observed data (dashed line) indicated.

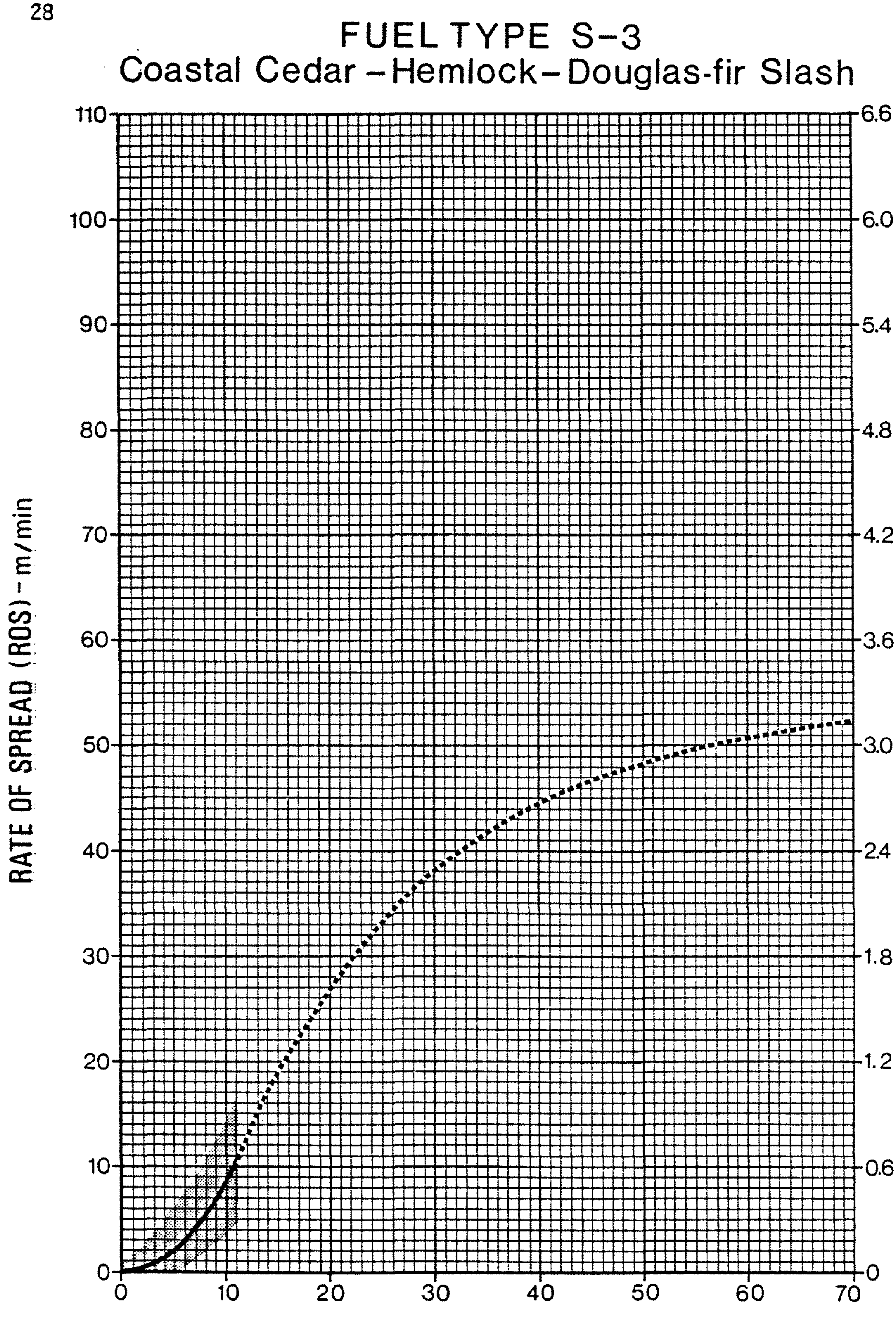

Figure 14. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI for the Coastal Cedar - Hemlock - Douglas-fir Slash Fuel Type (S-3) with 70% confidence limits (shaded area) and limit of observed data (dashed line) indicated.

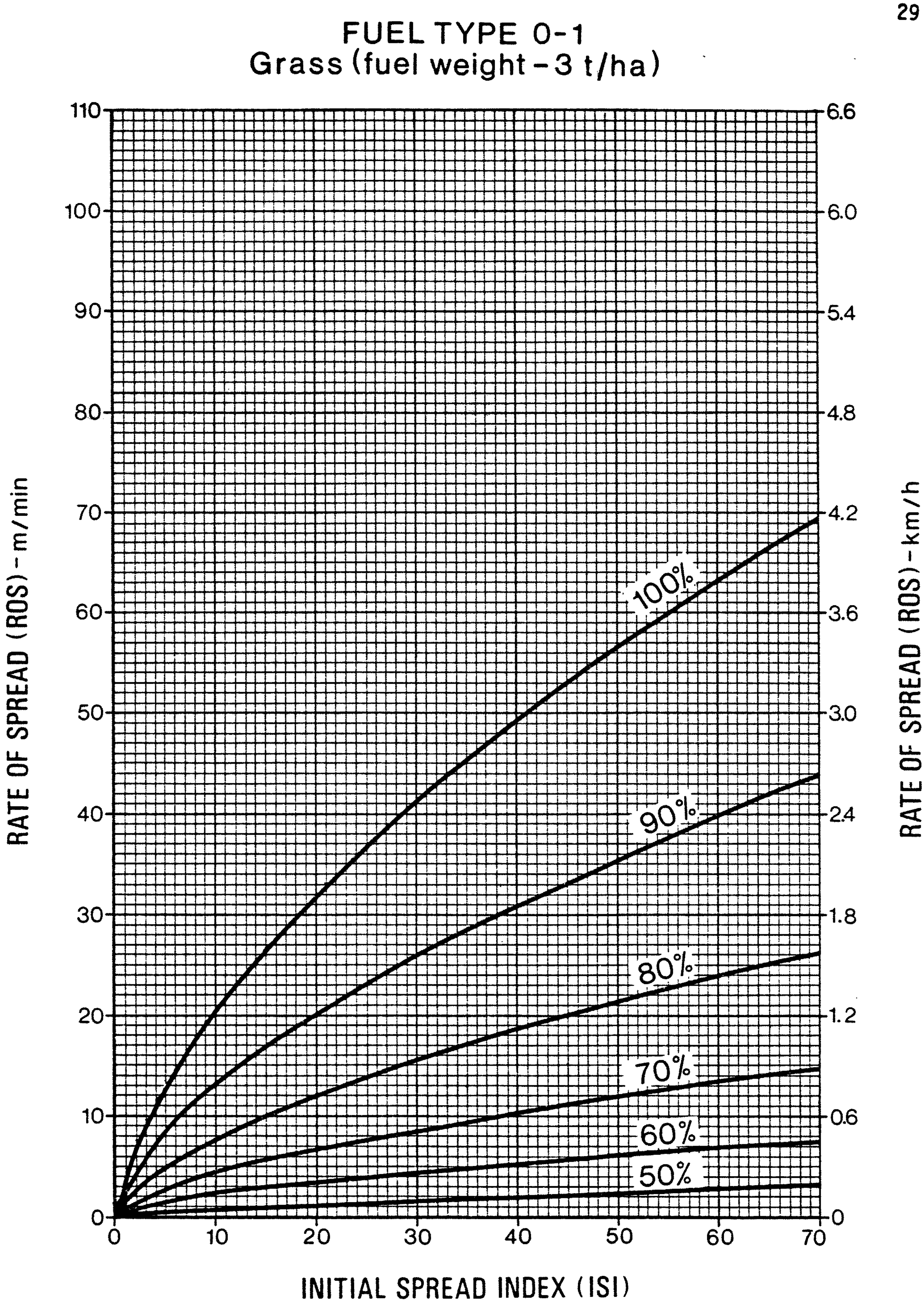

Figure 15. ROS on level to gently undulating ground in metres per minute (m/min) and kilometres per hour (km/h) as a function of the ISI and proportion of cured or dead fuel for the Grass Fuel Type (O-1) having a fuel weight of 3.0 t/ha.

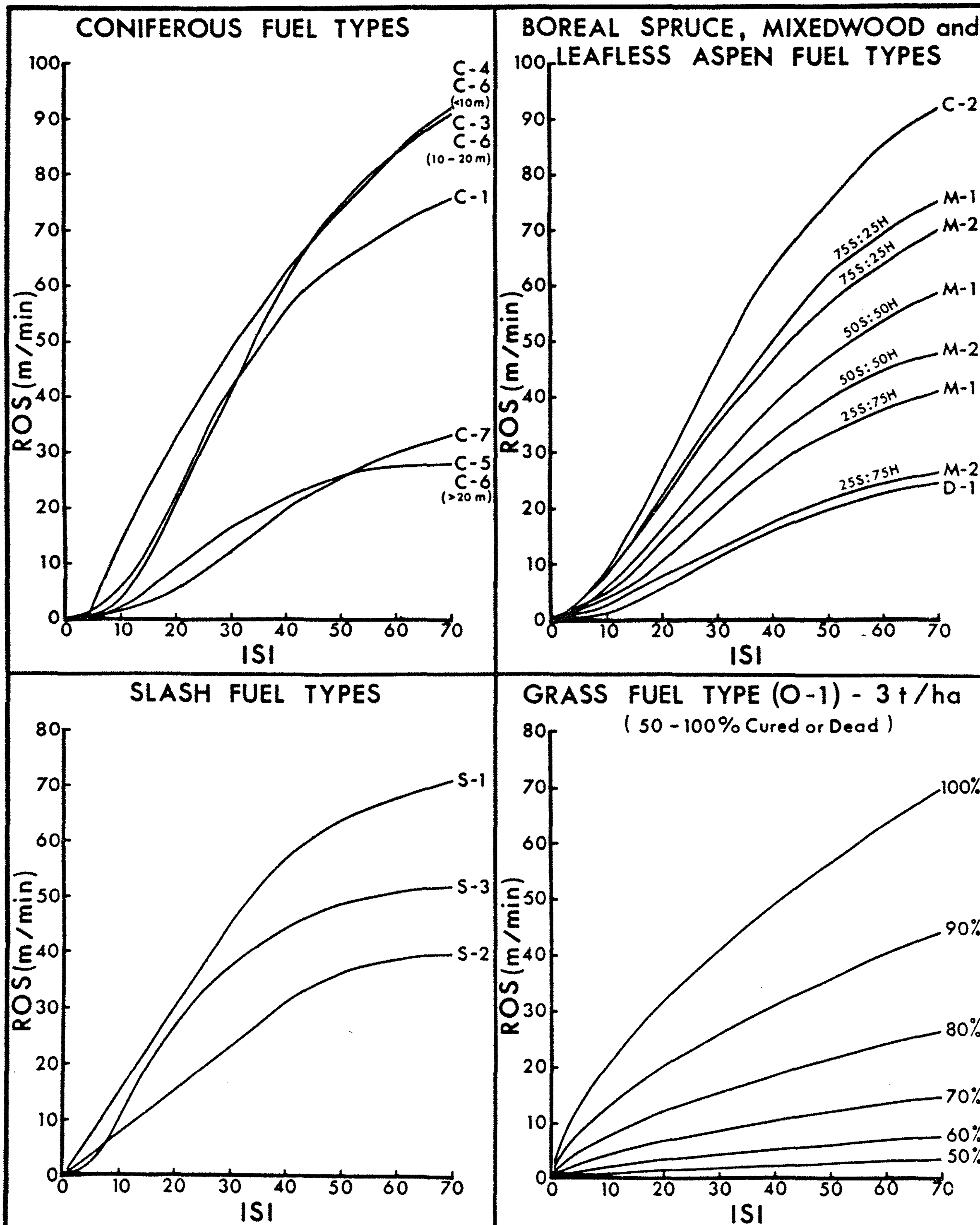

Figure 16. Initial Spread Index (ISI) versus rate of spread (ROS) relationships for the 14 fuel types embodied in the 1984 interim edition of the Canadian Forest Fire Behavior Prediction (FBP) System. ROS is given in metres per minute (m/min) on level to gently undulating ground.

RATE OF SPREAD TABLES

This section contains tables for predicting rate of spread (ROS) by fuel type from the Initial Spread Index (ISI). The four ROS tables presented here were prepared for operational field use and should be viewed as an alternative to the series of graphs displayed in the previous section. ROS is expressed in metres per minute (m/min) and kilometres per hour (km/h) in separate tables for all 14 fuel types described earlier. For the Boreal Mixedwood Fuel Types M-1 (leafless) and M-2 (summer), three commonly accepted softwood/hardwood species composition combinations were selected. In the case of Fuel Type 0-1 or Grass, the proportion of cured or dead fuel and weight was set at 100 percent and 3.0 t/ha, respectively. The content of the four ROS tables is summarized below:

Tables 2a (m/min) & 2b (km/h) - Coniferous (C) and Deciduous (D) Fuel Type Groups

C-1 Spruce - Lichen Woodland
C-2 Boreal Spruce
C-3 Mature Jack or Lodgepole Pine
C-4 Immature Jack or Lodgepole Pine
C-5 Red and White Pine
C-6 Red Pine Planation:
 < 10 m mean stand height
 10-20 m mean stand height
 > 20 m mean stand height
C-7 Ponderosa Pine - Douglas-fir
D-1 Leafless Aspen

Tables 3a (m/min) & 3b (km/h) - Mixedwood (M), Slash (S), and Open (O) Fuel Type Groups

M-1 Boreal Mixedwood - leafless:
 75% softwood (S):25% hardwood (H)
 50% softwood (S):50% hardwood (H)
 25% softwood (S):75% hardwood (H)
M-2 Boreal Mixedwood - summer:
 75% softwood (S):25% hardwood (H)
 50% softwood (S):50% hardwood (H)
 25% softwood (S):75% hardwood (H)
S-1 Jack or Lodgepole Pine Slash
S-2 Spruce - Balsam Slash
S-3 Coastal Cedar - Hemlock - Douglas-fir Slash
0-1 Grass (100% cured or dead and 3.0 t/ha)

The ROS values contained in each table are based on the equations that were listed earlier in this report and represent the head fire spread rate to be expected on level to gently undulating ground. The procedure to adjust ROS for percent slope is given in the next section. The ISI values between 0.5 and 70 that were selected for inclusion in the ROS tables should be sufficient for practical purposes. An ISI of 70 is consistent with the maximum limit set for the ROS graphs.

Crown fire spread rates are identified in the tables by shading. The boundary between the two sections of a table represents the threshold ISI value for crown fire development. Certain fuel types were judged to be incapable of supporting and/or sustaining continuous fire spread through a crown fuel layer under all but the most severe weather, while others simply lacked overstory tree cover.

Table 2a. Rate of spread (ROS) on level to gently undulating ground in metres per minute (m/min) versus Initial Spread Index (ISI) for the coniferous and deciduous fuel type groups.

ISI	C-1	C-2	C-3	C-4	C-5	C-6 <10 m	C-6 10-20 m	C-6 >20 m	C-7	D-1
	ROS (m/min)									
0.5	*	0.1	*	0	*	0	*	*	*	*
1.0	0.1	0.2	*	0	*	0	*	*	*	0.1
1.5	0.2	0.4	*	0	*	0	*	*	*	0.1
2.0	0.3	0.6	*	0	0.1	0	*	0.1	0.1	0.2
2.5	0.4	1.0	0.1	0	0.1	0	0.1	0.1	0.1	0.2
3	0.6	1.3	0.1	0	0.2	0	0.1	0.2	0.2	0.3
4	1.1	2.2	0.3	0.8	0.3	0.8	0.3	0.3	0.3	0.5
5	1.6	3.3	0.5	3.1	0.5	3.1	0.5	0.5	0.4	0.7
6	2.3	4.4	0.9	5.4	0.7	5.4	0.9	0.7	0.6	0.9
7	3.1	5.7	1.4	7.6	1.0	7.6	1.4	1.0	0.8	1.1
8	4.0	7.2	2.1	9.7	1.4	9.7	2.1	1.4	1.0	1.4
9	4.9	8.7	2.9	12	1.8	12	2.9	1.8	1.2	1.6
10	6.0	10	3.9	14	2.2	14	3.9	2.2	1.5	1.9
12	8.5	14	6.3	18	3.3	18	6.3	3.3	2.1	2.6
14	11	17	9.3	22	4.6	22	9.3	4.6	2.9	3.3
16	15	21	13	26	6.2	26	13	6.2	3.7	4.1
18	18	25	17	29	7.9	29	17	7.9	4.6	4.9
20	22	28	21	33	9.8	33	21	9.8	5.6	5.8
25	33	38	31	41	14	41	31	14	8.5	8.2
30	42	46	42	49	17	49	42	17	12	11
35	49	55	52	56	20	56	52	20	16	14
40	56	62	61	63	22	63	61	22	20	16
45	61	69	69	69	23	69	69	23	23	18
50	65	75	75	74	25	74	75	25	26	20
55	68	80	80	79	26	79	80	26	28	21
60	71	84	85	84	27	84	85	27	30	22
65	74	88	88	88	27	88	88	27	31	23
70	76	92	91	92	28	92	91	28	33	24

Notes: Shaded area indicates crown fire spread. The three values listed in the column heading under Fuel Type C-6 (Red Pine Plantation) refer to mean stand height ranges. ROS values greater than 0.0 m/min but less than 0.05 m/min are indicated by an asterisk (*).

Table 2b. Rate of spread (ROS) on level to gently undulating ground in kilometres per hour (km/h) versus Initial Spread Index (ISI) for the coniferous and deciduous fuel type groups.

ISI	Fuel Type C-1	C-2	C-3	C-4	C-5	C-6 <10 m	C-6 10-20 m	C-6 >20 m	C-7	D-1
	ROS (km/h)									
0.5	*	*	*	0	*	0	*	*	*	*
1.0	*	0.01	*	0	*	0	*	*	*	*
1.5	0.01	0.02	*	0	*	0	*	*	*	0.01
2.0	0.02	0.04	*	0	*	0	*	*	*	0.01
2.5	0.03	0.06	*	0	0.01	0	*	0.01	0.01	0.01
3	0.04	0.08	0.01	0	0.01	0	0.01	0.01	0.01	0.02
4	0.06	0.13	0.02	0.05	0.02	0.05	0.02	0.02	0.02	0.03
5	0.10	0.20	0.03	0.19	0.03	0.19	0.03	0.03	0.02	0.04
6	0.14	0.27	0.05	0.32	0.04	0.32	0.05	0.04	0.03	0.05
7	0.18	0.34	0.09	0.45	0.06	0.45	0.09	0.06	0.05	0.07
8	0.24	0.43	0.13	0.58	0.08	0.58	0.13	0.08	0.06	0.08
9	0.30	0.52	0.18	0.71	0.11	0.71	0.18	0.11	0.07	0.10
10	0.36	0.62	0.23	0.84	0.13	0.84	0.23	0.13	0.09	0.12
12	0.51	0.82	0.38	1.1	0.20	1.1	0.38	0.20	0.13	0.16
14	0.68	1.0	0.56	1.3	0.28	1.3	0.56	0.28	0.17	0.20
16	0.88	1.2	0.76	1.6	0.37	1.6	0.76	0.37	0.22	0.24
18	1.1	1.5	0.99	1.8	0.48	1.8	0.99	0.48	0.28	0.29
20	1.3	1.7	1.2	2.0	0.59	2.0	1.2	0.59	0.34	0.35
25	2.0	2.3	1.9	2.5	0.83	2.5	1.9	0.83	0.51	0.49
30	2.5	2.8	2.5	3.0	1.0	3.0	2.5	1.0	0.72	0.66
35	3.0	3.3	3.1	3.4	1.2	3.4	3.1	1.2	0.96	0.82
40	3.3	3.7	3.7	3.8	1.3	3.8	3.7	1.3	1.2	0.96
45	3.6	4.1	4.1	4.1	1.4	4.1	4.1	1.4	1.4	1.1
50	3.9	4.5	4.5	4.5	1.5	4.5	4.5	1.5	1.5	1.2
55	4.1	4.8	4.8	4.8	1.5	4.8	4.8	1.5	1.7	1.3
60	4.3	5.1	5.1	5.0	1.6	5.0	5.1	1.6	1.8	1.3
65	4.4	5.3	5.3	5.3	1.6	5.3	5.3	1.6	1.9	1.4
70	4.5	5.5	5.4	5.5	1.7	5.5	5.4	1.7	2.0	1.5

Notes: Shaded area indicates crown fire spread. The three values listed in the column heading under Fuel Type C-6 (Red Pine Plantation) refer to mean stand height ranges. ROS values greater than 0.0 km/h but less than 0.005 km/h are indicated by an asterisk (*).

Table 3a. Rate of spread (ROS) on level to gently undulating ground in metres per minute (m/min) versus Initial Spread Index (ISI) for the mixedwood, slash, and open fuel type groups.

ISI	M-1 75S:25H	M-1 50S:50H	M-1 25S:75H	M-2 75S:25H	M-2 50S:50H	M-2 25S:75H	S-1	S-2	S-3	O-1
	ROS (m/min)									
0.5	*	*	*	*	*	*	0.7	0.4	*	3.2
1.0	0.2	0.1	0.1	0.1	0.1	0.1	1.5	0.8	0.1	4.9
1.5	0.3	0.2	0.2	0.3	0.2	0.1	2.2	1.2	0.2	6.3
2.0	0.5	0.4	0.3	0.5	0.3	0.2	3.0	1.5	0.4	7.5
2.5	0.8	0.6	0.4	0.7	0.5	0.3	3.7	1.9	0.6	8.7
3	1.1	0.8	0.6	1.0	0.7	0.4	4.5	2.3	0.9	9.7
4	1.8	1.3	0.9	1.7	1.2	0.6	5.9	3.1	1.6	12
5	2.6	2.0	1.3	2.5	1.7	0.9	7.4	3.9	2.5	13
6	3.6	2.7	1.8	3.4	2.3	1.2	8.9	4.6	3.6	15
7	4.6	3.4	2.3	4.4	3.0	1.6	10	5.4	4.9	16
8	5.7	4.3	2.8	5.4	3.7	2.0	12	6.2	6.4	18
9	6.9	5.2	3.4	6.6	4.5	2.4	13	6.9	8.0	19
10	8.2	6.1	4.0	7.8	5.3	2.9	15	7.7	9.9	21
12	11	8.1	5.3	10	7.1	3.8	18	9.2	14	23
14	14	10	6.8	13	8.9	4.8	21	11	18	25
16	17	12	8.3	16	11	5.8	24	12	21	28
18	20	15	9.8	19	13	6.9	27	14	24	30
20	23	17	11	21	15	7.9	30	15	27	32
25	30	23	16	29	20	11	37	19	33	37
30	38	29	20	35	24	13	45	23	38	41
35	44	34	24	42	29	16	51	27	41	45
40	51	39	28	47	33	18	57	31	44	49
45	56	43	31	52	36	20	61	34	47	53
50	61	47	33	57	39	22	64	37	48	56
55	65	50	36	61	42	23	66	38	50	60
60	69	53	38	64	44	24	68	39	51	63
65	72	56	40	67	47	26	70	39	52	67
70	75	58	41	70	48	27	71	40	52	70

Notes: Shaded area indicates crown fire spread. The values listed in the column heading under Fuel Types M-1 (Boreal Mixedwood - leafless) and M-2 (Boreal Mixedwood - summer) refer to the percent softwood (S) and hardwood (H) species composition. The proportion of cured or dead fuel and weight in Fuel Type O-1 (Grass) is 100 percent and 3.0 t/ha, respectively. ROS values greater than 0.0 m/min but less than 0.05 m/min are indicated by an asterisk (*).

Table 3b. **Rate of spread (ROS) on level to gently undulating ground in kilometres per hour (km/h) versus Initial Spread Index (ISI) for the mixedwood, slash, and open fuel type groups.**

ISI	M-1 75S: 25H	M-1 50S: 50H	M-1 25S: 75H	M-2 75S: 25H	M-2 50S: 50H	M-2 25S: 75H	S-1	S-2	S-3	O-1
	ROS (km/h)									
0.5	*	*	*	*	*	*	0.04	0.02	*	0.19
1.0	0.01	0.01	0.01	0.01	0.01	*	0.09	0.05	0.01	0.29
1.5	0.02	0.01	0.01	0.02	0.01	0.01	0.13	0.07	0.01	0.38
2.0	0.03	0.02	0.02	0.03	0.02	0.01	0.18	0.09	0.02	0.45
2.5	0.05	0.04	0.02	0.04	0.03	0.02	0.22	0.12	0.04	0.52
3	0.06	0.05	0.03	0.06	0.04	0.02	0.27	0.14	0.05	0.58
4	0.11	0.08	0.05	0.10	0.07	0.04	0.36	0.18	0.10	0.70
5	0.16	0.12	0.08	0.15	0.10	0.05	0.45	0.23	0.15	0.80
6	0.21	0.16	0.11	0.20	0.14	0.07	0.53	0.28	0.22	0.90
7	0.28	0.21	0.14	0.26	0.18	0.10	0.62	0.32	0.29	0.99
8	0.34	0.26	0.17	0.33	0.22	0.12	0.71	0.37	0.38	1.1
9	0.41	0.31	0.20	0.40	0.27	0.14	0.80	0.42	0.48	1.2
10	0.49	0.37	0.24	0.47	0.32	0.17	0.89	0.46	0.60	1.2
12	0.65	0.49	0.32	0.62	0.42	0.23	1.1	0.55	0.83	1.4
14	0.82	0.61	0.41	0.78	0.53	0.29	1.2	0.65	1.1	1.5
16	1.0	0.75	0.50	0.95	0.65	0.35	1.4	0.74	1.3	1.7
18	1.2	0.88	0.59	1.1	0.77	0.41	1.6	0.83	1.4	1.8
20	1.4	1.0	0.68	1.3	0.88	0.48	1.8	0.92	1.6	1.9
25	1.8	1.4	0.93	1.7	1.2	0.64	2.2	1.2	2.0	2.2
30	2.3	1.7	1.2	2.1	1.5	0.79	2.7	1.4	2.3	2.5
35	2.7	2.0	1.4	2.5	1.7	0.94	3.1	1.6	2.5	2.7
40	3.0	2.3	1.7	2.8	2.0	1.1	3.4	1.8	2.7	2.9
45	3.4	2.6	1.8	3.1	2.2	1.2	3.6	2.1	2.8	3.2
50	3.7	2.8	2.0	3.4	2.4	1.3	3.8	2.2	2.9	3.4
55	3.9	3.0	2.1	3.7	2.5	1.4	4.0	2.3	3.0	3.6
60	4.1	3.2	2.3	3.9	2.7	1.5	4.1	2.3	3.1	3.8
65	4.3	3.4	2.4	4.0	2.8	1.5	4.2	2.4	3.1	4.0
70	4.5	3.5	2.5	4.2	2.9	1.6	4.3	2.4	3.2	4.2

__Notes:__ Shaded area indicates crown fire spread. The values listed in the column heading under Fuel Types M-1 (Boreal Mixedwood - leafless) and M-2 (Boreal Mixedwood - summer) refer to the percent softwood (S) and hardwood (H) species composition. The proportion of cured or dead fuel and weight in Fuel Type O-1 (Grass) is 100 percent and 3.0 t/ha, respectively. ROS values greater than 0.0 km/h but less than 0.005 km/h are indicated by an asterisk (*).

ADJUSTMENTS AND PROCEDURES

This section of the report provides the user with suggested methods and procedures for adjusting FBP System inputs (Wind, Fine Fuel Moisture Code [FFMC], Initial Spread Index [ISI]) (Fig. 17), principal output (Rate of Spread [ROS]), and for calculating and plotting predicted fire sizes from the adjusted ROS. A computer program, or list of equations for all these adjustments and procedures is not provided in this interim edition, so the user must use the tables and graphs included to make ROS calculations and fire area projections. The flow chart (Fig. 18) indicates the sequence of steps involved. An FBP System Worksheet is provided to assist the user with organization of the required information to use this section. A calculator would be of assistance in performing some of the calculations.

It is useful for the user to appreciate the interrelationships between the ISI inputs Wind and FFMC, in order to understand the importance of using the suggested adjustments to these inputs before determining ROS predictions from the FBP System. ROS is predicted from ISI as shown in Figure 18, but ISI is highly dependent on wind and the FFMC, as shown graphically in Figure 17. The ISI doubles in value for each increase of 13 km/h in wind (Turner and Lawson 1978). It is important when calculating ISI for ROS predictions to determine the most accurate 10 m open windspeed measurement, estimate or forecast value for the time and area of interest. Methods to correct windspeed observations taken at non-standard heights, as well as guides for estimating windspeeds, are contained in Turner and Lawson (1978). The main point is that windspeed updates to the time(s) of interest for ROS predictions (may be hourly throughout the afternoon or simply a single mid-afternoon update of the noon observation) will improve ROS prediction accuracy.

Fine Fuel Moisture Code Adjustments

All possible adjustments to the Fine Fuel Moisture Content (FFMC) for use in fire behavior prediction are not presented in this interim edition, for various reasons. For example, a procedure exists for calculating FFMC for any hour throughout the diurnal cycle for any observed weather pattern (Van Wagner 1977b; also revised and unpublished computer program, 1984) but was felt to be too weather data-demanding to be practical for operational use. Instead, the simplest approach to FFMC adjustments was selected for inclusion here. One simple table (Table 4) is used to adjust a standard daily FFMC for times throughout the afternoon (1200 h to 2000 h, local standard time). This table requires no additional weather observations for these times of interest; the table assumes a "normal" or "standard" afternoon pattern of change in temperature and relative humidity. Table 4 is derived from previously published versions (Van Wagner 1972; Canadian Forestry Service 1973, 1974; Alexander 1982a), but has been restricted to afternoon hours for simplicity of data requirements and to stress only the times and FFMC ranges normally of most interest to fire behavior prediction problems.

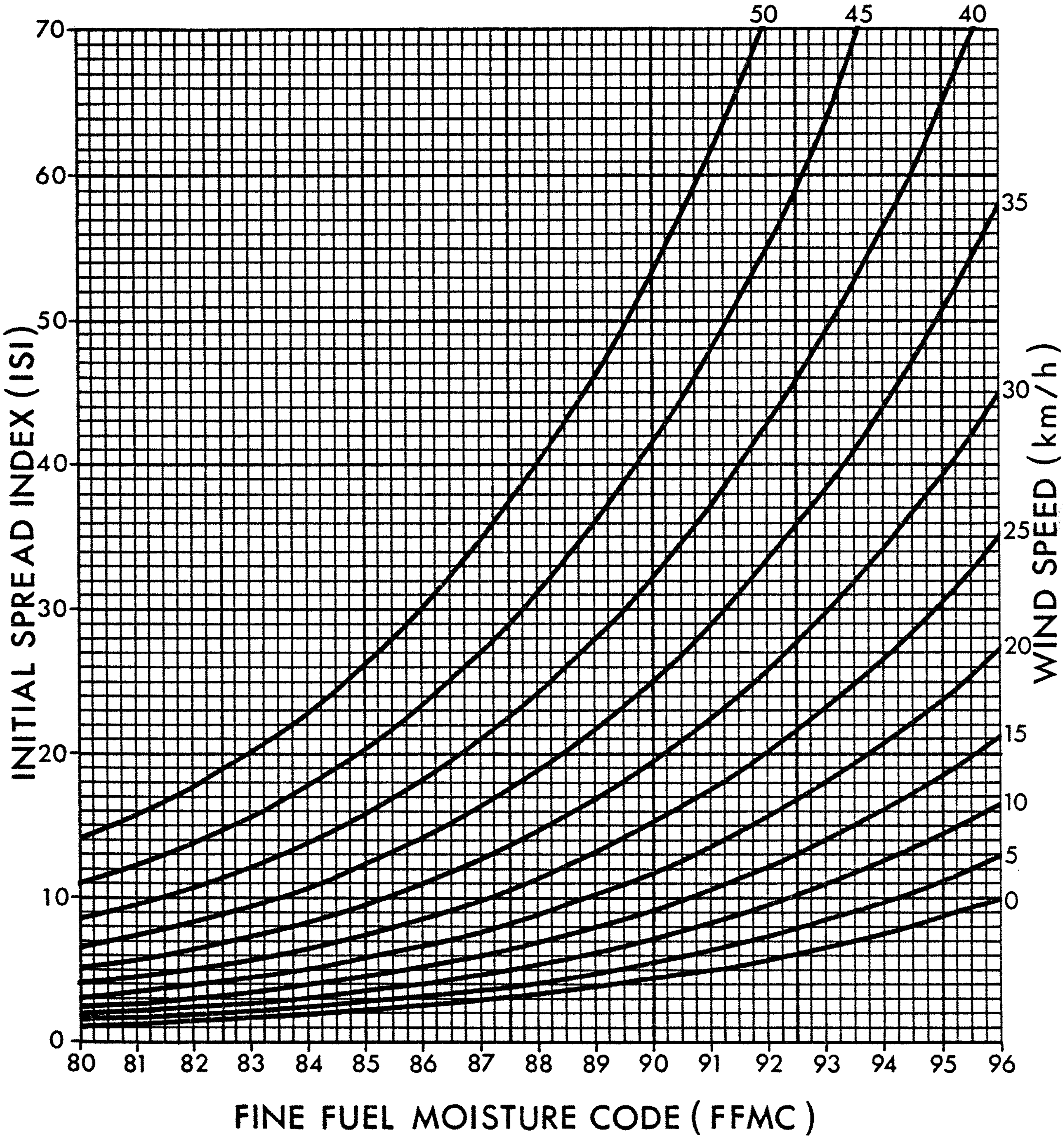

Figure 17. Initial Spread Index as a function of the Fine Fuel Moisture Code and wind speed (at a height of 10 m in the open on level terrain) in the 1984 version of the Canadian Forest Fire Weather Index System.

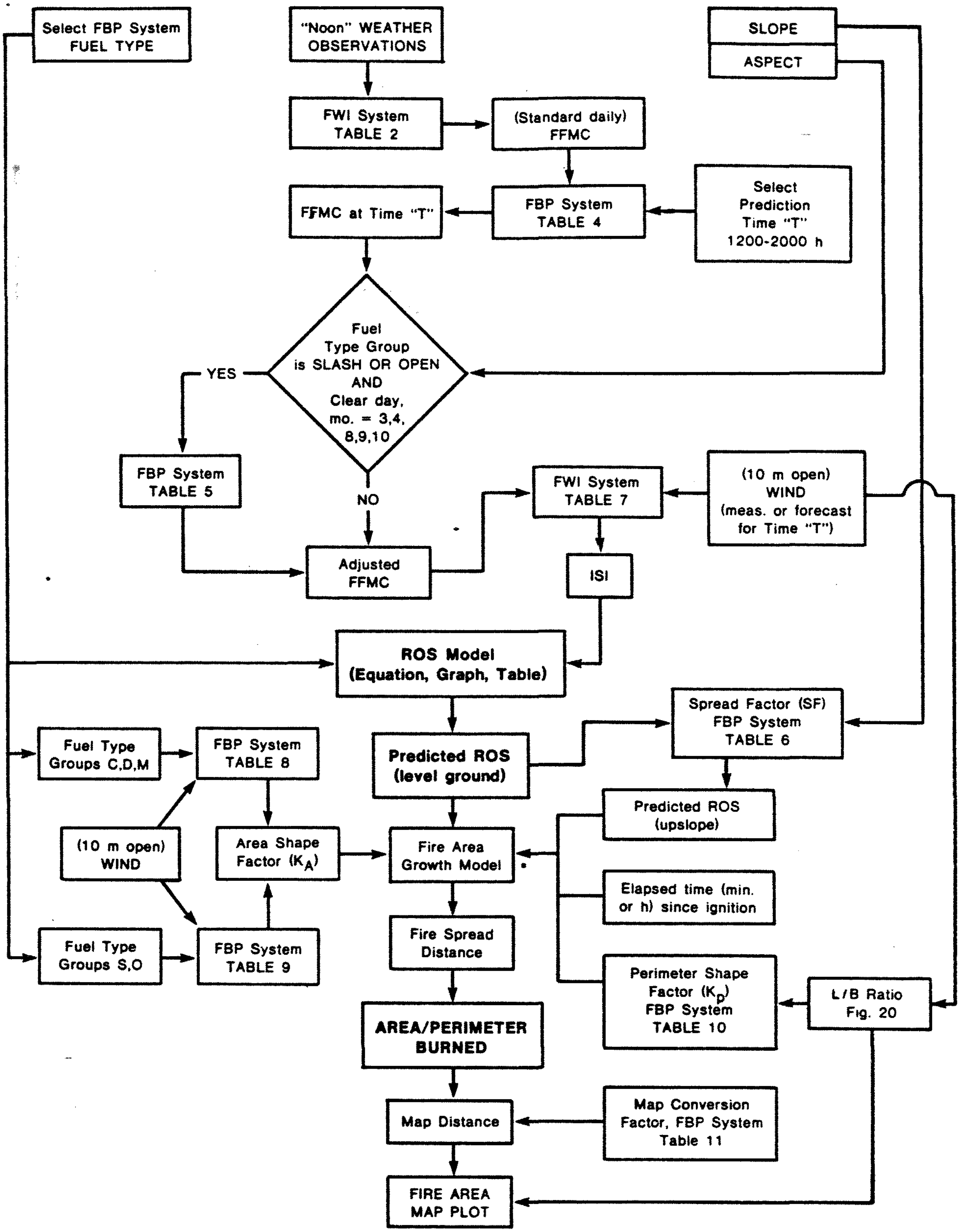

Figure 18. Flow chart of Adjustments and Procedures, 1984 Interim Edition of Canadian Forest Fire Behavior Prediction (FBP) System.

A second table (Table 5) is used, under restricted circumstances, to adjust FFMC for slope and aspect, if the standard daily FFMC was determined from weather observations taken on different topographic conditions from those at the fire behavior prediction point. As illustrated in the flow diagram (Fig. 18), Table 5 is required only for adjusting non-forested fuel types (Slash and Open fuel type groups) on clear or partly cloudy afternoons in early spring and late summer and fall, i.e., March, April, August, September and October. The months of May, June and July, all cloudy to overcast days, and standing timber fuel types do not experience significant enough fuel moisture differences among various slopes and aspects to warrant adjusting FFMC for normal FBP System applications. Table 5 was derived from an unpublished file report[1], which drew heavily on the coastal British Columbia slash moisture field research findings of Williams (1964).

Table 4. Adjustment of Fine Fuel Moisture Code (FFMC) for times ("T") throughout the afternoon.

Time "T" (h, LST*)	Standard daily FFMC																			
	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99
	FFMC at time "T"																			
1200	69	70	72	74	76	79	81	83	85	87	88	89	90	91	92	93	94	95	96	97
1400	76	77	79	81	82	83	84	85	86	88	89	90	91	92	93	94	95	96	97	98
1600	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99
1800	80	81	82	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98
2000	78	79	80	81	82	82	83	84	85	86	87	88	89	90	91	92	92	93	94	95

To use table, find the column heading value of today's standard daily FFMC, as determined from "noon" (1200 h, LST) weather observations. Then find the row heading for time "T" for which an adjusted FFMC is desired. Read the desired FFMC at time "T" at the column and row intersection. Interpolate between adjacent rows if desired afternoon time "T" is not listed. **FFMC at time "T"** from the table becomes **Adjusted FFMC**, unless additional adjustment for slope and aspect is required (Table 5).

For example, today's standard daily FFMC is determined to be 94. For a desired time "T" of noon (1200 h, LST), the FFMC is determined from the table to be 92. This is **Adjusted FFMC**, unless Table 5 is required.

* LST = Local Standard Time. Add one hour for Daylight Saving Time, in effect from last Sunday in April to last Sunday in October.

[1] Muraro, S.J. 1978. Adjustment procedures for moisture codes of the Canadian Forest Fire Weather Index System applicable to prescribed fire behavior prediction. Environ. Can., Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Draft File Rep.

Table 5. Adjustment of Fine Fuel Moisture Code (FFMC) for slope and aspect differences between weather observation point and fire behavior prediction point. Table applies only to FFMC calculated for times between 1200 h and 2000 h (LST), on clear days in March, April, August, Sept. or Oct., and for elevation differences of less than 300 m between points. Table applies only to Slash and Open fuel type groups.

	Ground Slope and Aspect															
	1 to 15%				16 to 30%				31 to 45%				46 to 60%			
Level	N	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W
	FFMC															
80	78	79	82	80	77	78	82	80	74	77	83	81	72	76	84	81
82	80	81	84	82	79	80	84	82	76	79	85	83	74	78	85	83
84	83	83	85	84	81	82	86	84	79	81	87	84	76	80	88	84
86	85	85	87	86	83	84	88	86	81	83	89	86	78	82	90	86
87	86	86	88	87	84	85	89	87	82	84	90	87	80	83	90	87
88	87	87	89	88	85	87	90	88	83	86	91	88	82	85	91	88
89	88	88	90	89	87	88	91	89	85	87	91	89	83	86	92	89
90	89	89	91	90	88	89	92	90	86	88	92	90	84	87	93	90
91	90	90	92	91	89	90	92	91	87	89	93	91	86	88	93	91
92	91	91	93	92	90	91	93	92	88	90	94	92	87	89	94	92
93	92	92	94	93	91	92	94	93	89	91	95	93	88	90	95	93
94	93	93	95	94	92	93	95	94	91	92	96	94	90	92	96	94

To use table, determine column which best describes slope and aspect of weather observation point. Find FFMC at time "T" in that column and then move horizontally to column best describing prediction point and read **Adjusted FFMC**.

For example, a weather stn. on a 15% slope/east aspect provided an FFMC at time "T" of 92. For predicting fire behavior on a 50% slope/south aspect, the table would give an **Adjusted FFMC** of 95.

(a) Time of Day

The flow chart (Fig. 18) indicates that, once a standard daily FFMC has been calculated from noon weather observations, a prediction time "T" is selected from 1200 to 2000 h. In practice, ROS predictions may be desired hourly throughout the afternoon or calculated from a single set of "noon" weather observations, perhaps with a mid-afternoon windspeed update. If the desired prediction time "T" or Time interval is other than the 1600 to 1700 h maximum peak of daily fire danger, to which standard FFMC applies, then it is necessary to determine one or more adjusted FFMC values from Table 4 for prediction times "T". If fire behavior predictions for morning hours are desired, adjusted FFMC for times betwen 0600 and 1000 h can be obtained from tables contained in Van Wagner (1972), Canadian Forestry Service (1973, 1974) or Alexander (1982a); however, the previous day's standard FFMC and the relative humidity for time "T" is then required.

(b) Topography

Once the appropriate FFMC at time "T" has been determined from Table 4, a further adjustment of fine fuel moisture may be required to correct for the effects of variation in topography (slope and aspect) between the points where the weather observations were taken and where they are to be applied. As shown in Figure 18, Table 5 provides the adjustment required to FFMC for slope and aspect differences, but the use of the table is required only when significant topographic differences exist and all of the following conditions are met:

Fuel Type Group: Slash or Open
Month: Mar.-Apr. (03-04); Aug.-Sept.-Oct. (08-09-10).
Day: essentially clear, sunny or partly cloudy.
Hour: 1200 to 2000 h, LST.

If all these conditions apply, enter Table 5 with FFMC at time "T" and determine Adjusted FFMC for the slope and aspect of concern. If all the conditions for use of Table 5 do not apply, use FFMC at time "T" as Adjusted FFMC.

Slope Adjustments

The procedure discussed for updating windspeed and adjusting FFMC for times of interest and for topographic effect on fine fuel moisture permit the user to enter Table 7 of the FWI System Tables with these adjusted inputs and determine an ISI (Fig. 18). If the ROS prediction is desired for level to gently undulating terrain, the appropriate FBP System ROS model (equation, graph or table) for the fuel type best matching the fuels ahead of the prediction point of interest is entered with the ISI, and the ROS is read or calculated.

If terrain is sloping, adjustments must be made to the predicted ROS for level ground to account for the mechanical effects of slope on fire spread rate. For the simplest case of a fire spreading upslope with the wind, the user must determine the ground slope (percent) on the area of interest (ocularly estimated or measured on the ground with a clinometer or calculated from a topographic map using the procedure described below) and derive the appropriate spread factor (SF) from Table 6. The SF is used as a multiplier with the predicted ROS on level ground to determine the predicted upslope ROS. An upslope ROS can also be calculated directly from Equation (15) in the Rate of Spread Equations section. The SF relationship in Table 6 was adapted from the work of Van Wagner (1977a) which examined relative fire spread factors from various literature references to fire danger rating systems and field and laboratory studies of fire behavior on slopes. SF (Table 6) and Equation (15) are recommended for use only on slopes up to 60% and for fires burning upslope.

The ground slope between two points is simply the change in elevation (±) between the two points divided by the horizontal distance between them. This ratio multiplied by 100 gives ground slope in percent. To compute ground slope from a topographic map or other map with elevation contours, follow these step-by-step procedures:

Step 1. Determine the contour interval (i.e., the elevation change between adjacent contour lines) in metres or feet.

Step 2. Determine the map scale conversion factor in terms of the number of metres each centimetre (m/cm), OR number of feet each inch (ft/in), on the map represents.

Step 3. Determine the vertical rise or fall in elevation in metres or feet by counting the number of contour lines between the two points and then multiplying by the contour interval found in Step 1.

Step 4. Determine the horizontal ground distance between the two points with a graduated ruler and convert to equivalent number of metres or feet by multiplying by the map scale conversion factor determined in Step 2.

Step 5. Divide the vertical rise or fall in elevation determined in Step 3 by the horizontal ground distance determined in Step 4 and then multiply by 100:

$$\text{\% Ground Slope } (\pm) = \frac{\text{Rise or Fall in Elevation}}{\text{Horizontal Ground Distance}} \times 100$$

In computing ground slope, learn to disregard undulations that are of little consequence with respect to fire size or are of minor importance in comparison to the duration of the prediction time interval.

In addition to the procedures described for determining upslope fire spread rate when wind direction is upslope or upward cross-slope[2], suggested procedures are included for three other combinations of wind and fire spread direction relative to ground slope (Table 7). All four cases of wind and fire spread direction relative to slope are described in procedural steps below and summarized in Table 7.

Case 1: Fire spread direction upslope; wind direction upslope or upward cross-slope.

[2] Definitions of wind direction relative to slope are given in Table 7.

USER NOTE: ***For further information on the concept of determining ROS in relation to direction fire is spreading with respect to wind and slope, refer to the supplemental illustrations following page 73 of this report.***

Table 6. Relative spread factors (SF) by percent slope for fires burning upslope.

Ground Slope (%)	0	1	2	3	4	5	6	7	8	9
	SF									
0	1.00	1.01	1.03	1.05	1.08	1.10	1.13	1.16	1.19	1.22
10	1.25	1.28	1.32	1.36	1.40	1.44	1.48	1.52	1.57	1.62
20	1.67	1.72	1.78	1.83	1.89	1.95	2.02	2.08	2.15	2.23
30	2.30	2.38	2.46	2.54	2.63	2.72	2.82	2.92	3.02	3.13
40	3.24	3.36	3.48	3.61	3.74	3.88	4.02	4.17	4.32	4.49
50	4.65	4.83	5.01	5.20	5.40	5.61	5.82	6.05	6.28	6.53

Note: e.g., Ground Slope = 14% and SF = 1.40.

Step 1. Calculate ISI (FWI System Table 7) from adjusted FFMC and 10 m open wind speed, measured, estimated or forecasted for time of prediction.

Step 2. Determine ROS on level to gently undulating ground by entering appropriate FBP System ROS model (equation, graph or table) for fuel type of concern with ISI as calculated in Step 1.

Step 3. Multiply ROS from Step 2 by Spread Factor (SF) (Table 6) for percent gound slope in direction fire is spreading. In effect, head fire rate of spread is reinforced by both wind and slope.

Case 2: Fire spread direction downslope; wind direction upslope or upward cross-slope.

Step 1. Calculate ISI from adjusted FFMC and zero wind speed.

Step 2. Determine ROS on level to gently undulating ground by entering appropriate FBP System ROS model for fuel type of concern with ISI as calculated in Step 1.

Step 3. Multiply ROS from Step 2 by Spread Factor (SF) (Table 6) for 0% ground slope (i.e., by 1.00). In effect, a fire backing downslope into the wind is predicted to spread downslope at the same rate as a fire spreading with zero wind on level ground; wind and slope effects cancel each other.

Case 3: Fire spread direction upslope; wind direction downslope or downward cross-slope.

Step 1. Calculate ISI from adjusted FFMC and zero wind speed.

Step 2. Determine ROS on level to gently undulating ground by entering appropriate FBP System ROS model for fuel type of concern with ISI as calculated in Step 1.

Step 3. Multiply ROS from Step 2 by Spread Factor (SF) (Table 6) for percent ground slope in direction fire is spreading. In effect, a fire spreading upslope into the wind is predicted to spread at the same rate as a fire spreading upslope with zero wind; the wind effect is cancelled but the slope effect remains.

Case 4: Fire spread direction downslope; wind direction downslope or downward cross-slope.

Step 1. Calculate ISI from adjusted FFMC and 10 m open wind speed, measured, estimated or forecasted for time of prediction.

Step 2. Determine ROS on level to gently undulating ground by entering appropriate FBP System ROS model for fuel type of concern with ISI as calculated in Step 1.

Step 3. Multiply ROS from Step 2 by Spread Factor (SF) (Table 6) for 0% ground slope (i.e., by 1.00). In effect a fire spreading downslope with the wind is predicted to spread at the same rate as a fire spreading with the wind on level ground; the slope effect is cancelled but the wind effect remains.

Crown Fire Thresholds

The criteria for crown fire development given in the ROS Graphs and Tables sections are in terms of the ISI for head fire spread on level to gently undulating ground. These values are listed in Appendix I and are also applicable to fires burning downslope (Cases 2 and 4). the corresponding spread rates for those fuel types subject to crowning are:

Fuel Type	C-1	C-2	C-3	C-4	C-6		C-7	M-1	M-2
					$<$10m	10-20m		$\geq$50S	$\geq$50S
ROS(m/min)	15	14	17	9	9	17	8	17	21
(km/h)	0.90	0.84	1.02	0.54	0.54	1.02	0.48	1.02	1.26

For fires burning upslope (Cases 1 and 3), the threshold conditions for crowning should be based on the slope adjusted ROS rather than the ISI.

Table 7. Procedures for determining rate of spread (ROS) in relation to direction fire is spreading with respect to wind and slope (ISI = Initial Spread Index and SF = relative Spread Factor in Table 6). Case numbers refer to discussion in text.

Direction of Fire Spread	Wind Direction	
	Upslope or Upward Cross-slope	Downslope or Downward Cross-slope
Upslope Side of Fire	ROS on level to gently undulating ground from ISI (using measured, forecasted or estimated wind speed) X SF for % ground slope in direction fire is spreading (Case 1).	ROS on level to gently undulating ground from ISI (using zero wind speed) X SF for % ground slope in direction fire is spreading (Case 3).
Downslope Side of Fire	ROS on level to gently undulating ground from ISI (using zero wind speed) X SF for 0% ground slope (Case 2).	ROS on level to gently undulating ground from ISI (using measured, forecasted or estimated wind speed) X SF for 0% ground slope (Case 4).

Notes: Definitions of wind direction follow Rothermel and Rinehart (1983).
Upslope wind is within a ± 30° quadrant of the maximum ground slope.
Downslope wind is within ± 30° quadrant of the maximum fall line.
Cross-slope wind consists of all remaining angles that are not upslope or downslope.

Fire Size Calculations

To calculate the approximate size of potential fires requires consideration of fire shape. Wind velocity largely determines the general shape of fires spreading through continuous, uniform fuels and across homogeneous topography. Fires spreading under calm wind conditions tend to be circular in shape. Provided wind direction remains fairly constant, wind-driven fires typically assume an elliptical shape (Anderson 1983). Since directional variation in wind generally decreases with increasing velocity, the higher the wind speed the more narrow and elongated the fire shape (Fig. 19). The ratio of the total length to the maximum breadth or width of a free-burning fire having an elliptical shape (Fig. 19) can be expressed as a function of wind speed (Fig. 20). Note that an ellipse with a length-to-breadth ratio (L/B) equal to 1.0 is a circle (i.e., zero wind speed).

Assuming that a fire attains a steady-state condition in a homogeneous fire environment after a short period of time, and that the

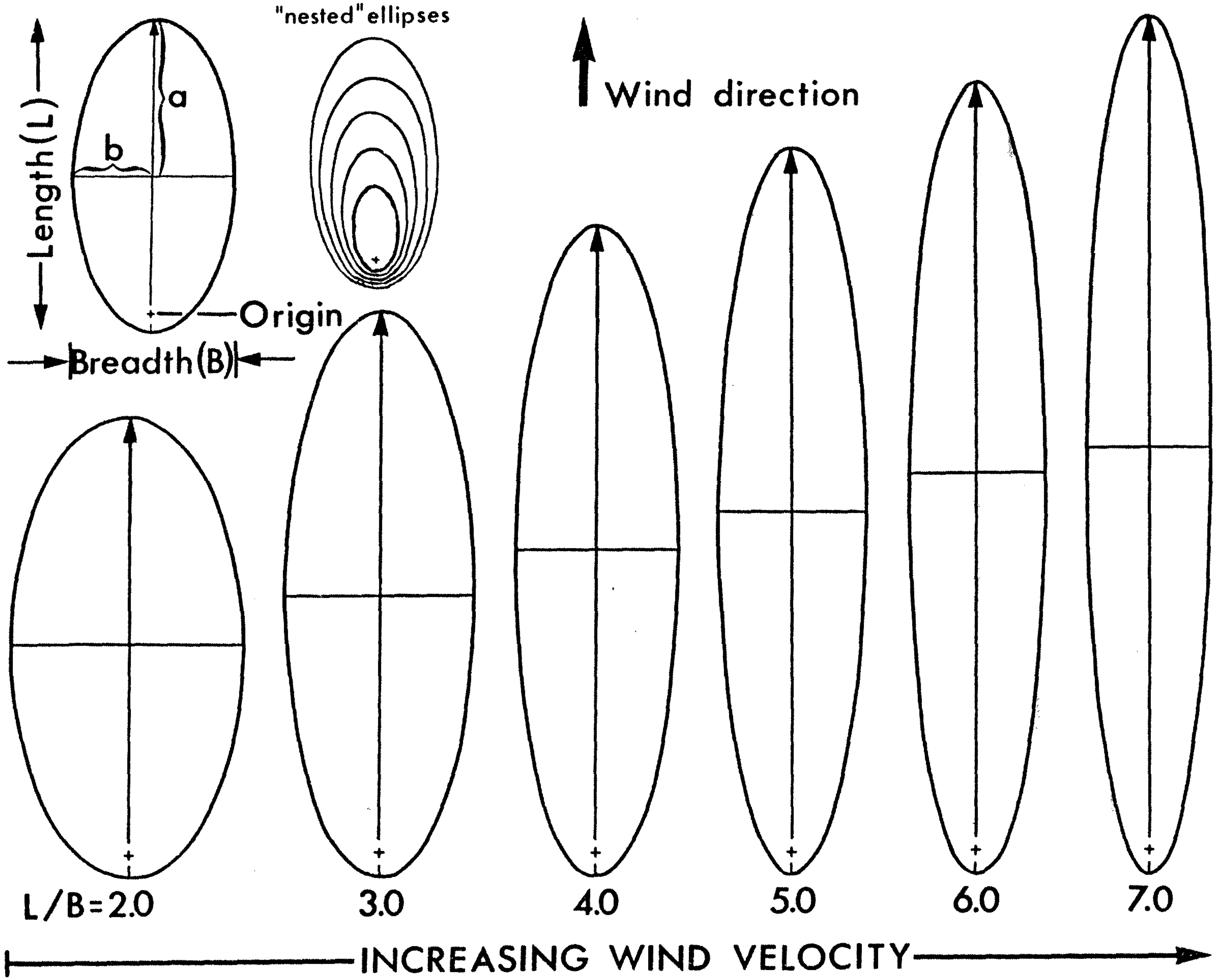

Figure 19. Idealized elliptical shapes of various length-to-breadth (L/B) ratios having the same area for free-burning fires spreading under the influence of increasing wind velocity (L/B = 2.0 to 7.0). Backfire spread assumed to be essentially negligible in all cases.

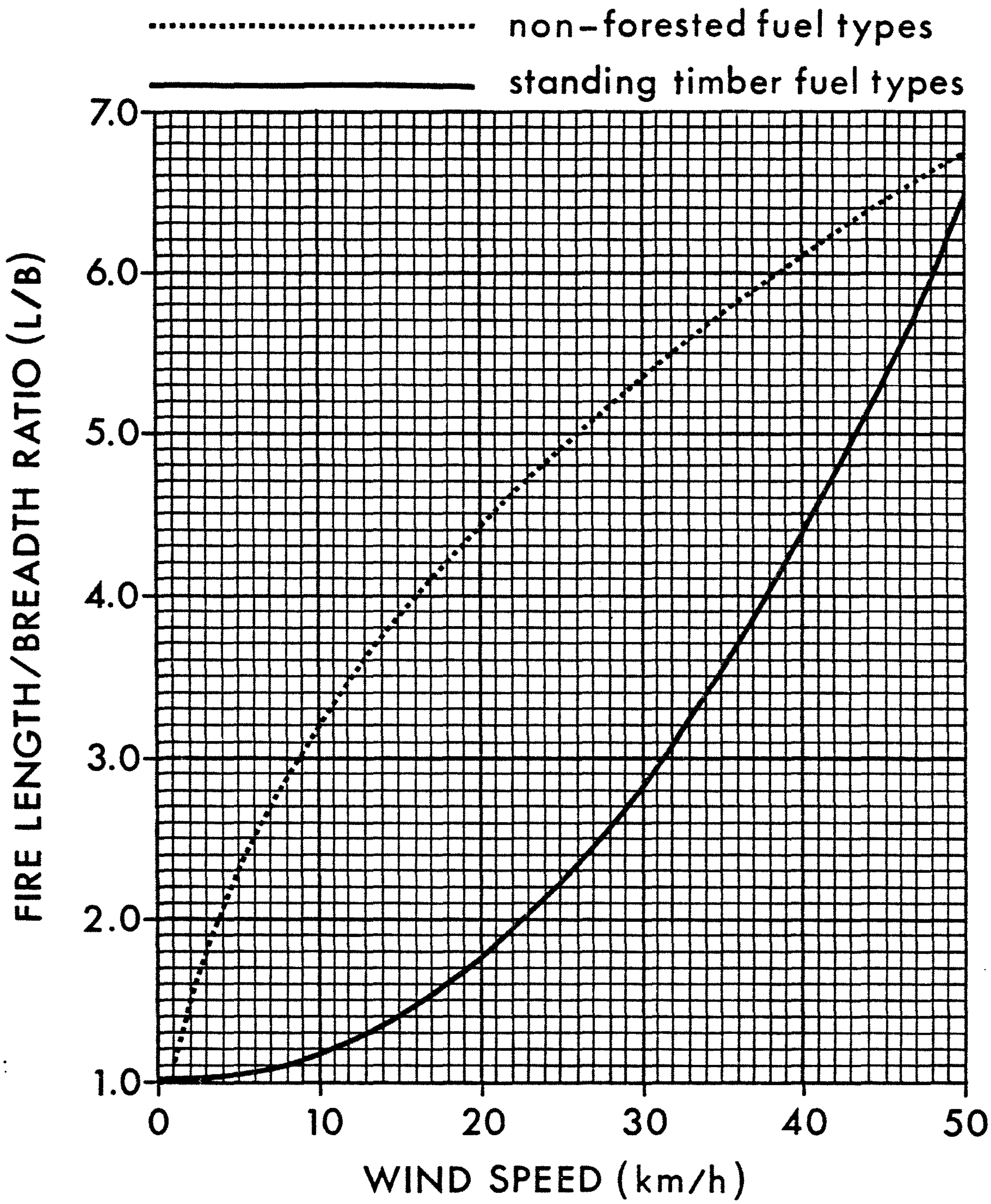

Figure 20. Relationship between wind speed at a height of 10 m in the open and the length-to-breadth (L/B) ratio of free-burning fires in two broad fuel type catagories.

backfire spread is negligible for practical purposes, a rough approximation of fire size can be made on the basis of the simple elliptical fire shape using the following formula (after Van Wagner 1969; McArthur et al. 1982):

$$A = K_A(ROSxT)^2 \quad (16)$$

where, A = probable fire area after time T, m^2 or km^2

K_A = area shape factor, $\pi/[4\ (L/B)]$

ROS = rate of spread, m/min or km/h

T = elapsed time since ignition, min or h

To convert area to hectares (ha), divide the number of square metres (m^2) by 10,000 or multiply the number of square kilometers (km^2) by 100. Values of K_A versus wind speed for standing timber and non-forested fuel types are contained in Tables 8 and 9. The units of ROS and T used in Equation (16) must be compatible (i.e., m/min or min or km/h and h). The multiplication of ROSxT represents the actual length of the fire or the Spread Distance (m or km).

Rate of area growth does not remain constant with time. Rather, it increases in direct proportion to time. Provided suppression action is ineffective in restricting fire growth and head fire ROS remains constant, total area burned increases as the square of time since ignition (e.g., the area 2 h after ignition will be 4 times the area after 1 h). Rate of area growth (Ag) can be quoted as area per unit time (e.g., hectares/hours) at time T, provided this is understood to apply to the current moment only (i.e., $Ag = 2KxROS^2xT \times 100$, ha/h).

An analysis of fire growth would not be complete without consideration of perimeter. The perimeter of a smooth, simple elliptical fire shape can be estimated from the following formula:

$$P = K_P\ D \quad (17)$$

where, P = probable fire perimeter after time T, m or km

K_P = perimeter shape factor (refer to Table 10)

D = fire spread distance (ROSxT), m or km

The actual length of the perimeter tends to be underestimated by this procedure because natural irregularities in the fire edge are not considered in Equation (17). In contrast to rate of perimeter growth, the rate of perimeter growth (Pg) or increase does remain constant with time provided the head fire ROS does not change (i.e., $Pg = K_P \times ROS$, m/min or km/h).

Table 8. Area shape factors (K_A) versus wind speed at a height of 10 m in the open on level terrain for free-burning fires in standing timber fuel types.

Wind speed (km/h)	0	1	2	3	4	5	6	7	8	9
					K_A					
0	0.79	0.78	0.78	0.78	0.77	0.76	0.74	0.73	0.71	0.69
10	0.67	0.65	0.63	0.60	0.58	0.56	0.53	0.51	0.49	0.47
20	0.45	0.43	0.41	0.39	0.37	0.35	0.34	0.32	0.31	0.29
30	0.28	0.27	0.25	0.24	0.23	0.22	0.21	0.20	0.19	0.19
40	0.18	0.17	0.16	0.16	0.15	0.15	0.14	0.14	0.13	0.13

Note: e.g., Wind Speed = 15 km/h and K_A = 0.56.

Table 9. Area shape factors (K_A) versus wind speed at a height of 10 m in the open on level terrain for free-burning fires in non-forested fuel types.

Wind speed (km/h)	0	1	2	3	4	5	6	7	8	9
					K_A					
0	0.79	0.71	0.52	0.43	0.38	0.34	0.31	0.29	0.27	0.26
10	0.25	0.23	0.23	0.22	0.21	0.20	0.20	0.19	0.19	0.18
20	0.18	0.17	0.17	0.17	0.16	0.16	0.16	0.15	0.15	0.15
30	0.15	0.15	0.14	0.14	0.14	0.14	0.14	0.13	0.13	0.13
40	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.12	0.12	0.12

Note: e.g., Wind Speed = 15 km/h and K_A = 0.20.

Table 10. Perimeter shape factors (Kp) versus length-to-breadth ratios (L/B) for free-burning wildland fires.

L/B	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
					Kp					
1	3.14	2.93	2.84	2.77	2.71	2.66	2.62	2.58	2.55	2.53
2	2.50	2.48	2.46	2.45	2.43	2.42	2.40	2.39	2.38	2.37
3	2.36	2.35	2.35	2.34	2.33	2.33	2.32	2.31	2.31	2.30
4	2.30	2.29	2.29	2.29	2.28	2.28	2.27	2.27	2.27	2.27
5	2.26	2.26	2.26	2.25	2.25	2.25	2.25	2.24	2.24	2.24
6	2.24	2.24	2.23	2.23	2.23	2.23	2.23	2.23	2.22	2.22

Note: e.g., L/B = 2.0 and Kp = 2.50.

Fire Area Plotting

The perimeter of a free-burning fire is often highly irregular in detail but the overall pattern can usually be represented by a smooth ellipse. the elliptical fire shape that can be drawn or plotted on a map should correspond roughly to the actual outline of the burned area and the approximation of fire size. Use the following procedures to plot the projected fire area:

Step 1. Calculate the Map Distance (mm or cm) by multiplying the Spread Distance by the Map Conversion Factor (see Table 11) appropriate to the scale of the map being used to plot fire area OR determine the Map Distance using the map scale bar as a reference guide.

Step 2. Assess the most likely direction of fire spread considering wind direction and topographic features.

Step 3. Mark the known or a suspected ignition point on the map with a "+".

Step 4. Draw a line on the map in the direction of probable fire spread and equal in length to the Map Distance. Place an arrow at the end of the line to indicate the direction of fire spread. The resulting line represents the Length (L) of the ellipse (see Fig. 19).

Step 5. Determine the Length/Breadth Ratio (see Fig. 20) of the elliptical fire shape based on the wind speed at a height of 10 m in the open.

USER NOTE: ***Tabular versions of Figure 20 are presented as supplemental aids following Page 73 of this report.***

Step 6. Calculate the map equivalent length of the ellipse's maximum Breath (B) or width (see Fig. 19) by dividing the length of the L line by the Length/Breadth Ratio. A clear plastic ruler (metric scale) will serve as a handy aid in drawing the L and B lines.

Step 7. Draw the B line on the map starting at the midpoint of and perpendicular to the L line. The length of the B line on either side of the L line should be ½ the total length calculated in Step 6 above.

Step 8. Using the elliptical shapes illustrated in Figure 19 as a guide, sketch in the outline of the fire's perimeter using both ends of the L and B lines as reference points.

Fire growth for successive time intervals could be represented by a series of "nested" ellipses (see Fig. 19) using the above procedures. This would involve computing a ROS prediction and repeating Steps 1-8 for each time interval selected.

The procedures for portraying fire growth on a map as described above are for the most part applicable to the initial spread pattern exhibited by wildfires during their first major burning period, spot or jump fires, or at "excursion" points along the controlled line of campaign fire (i.e., point ignitions). In such cases, the wind is generally pushing the fire in one principal direction. Any fire which remains out of control for days or weeks is likely to be subjected to considerable changes in wind direction and in other fire weather elements, fuel type differences, and topographic variations which collectively determine the direction of fire spread, growth, etc. on any particular day. Under these circumstances, a large portion of the fire perimeter may remain active for an extended time period. Rothermel (1983) has described the concept and techniques involved in projecting area growth and spread from the uncontrolled edge of a large, irregular shaped wildfire. There are no "cookbook" procedures to this aspect of fire behavior prediction. Instead, the following guidelines are offered, some of which are also applicable to point ignition fires. These consist of five steps:

Step 1. Assembling Fire Environment Data and Information.--Gather together all relevant data and information required to make fire behavior predictions such as cover or fuel type maps, topographic maps, area and spot fire weather forecasts, current fire progress map, fire weather observations and fire danger ratings, intelligence reports, etc.

Step 2. Selection of Prediction Points.--Pick a few points along the perimeter that are likely to experience the most significant fire spread. Forecasted weather and surrounding fuel/terrain conditions will influence the number and location of prediction points.

Step 3. Determination of Prediction Time Interval(s).--Choose time intervals when burning conditions are expected to be reasonably constant. Concentrate on the period of major fire activity (i.e., 1200-2000 h). Predictions can be made for sequential time periods (e.g.,

Table 11. Conversion factors for medium- and large-scale cover type and topographic maps commonly used in forest fire management.

Map Scale		Map Conversion Factor	
Ratio	in./mile	cm/m	cm/km
1:126 720	0.5	0.00079	0.79
1:125 000	0.507	0.0008	0.8
1:100 000	0.634	0.001	1.0
1:63 360	1.0	0.00158	1.58
1:50 000	1.267	0.002	2.0
1:40 000	1.584	0.0025	2.5
1:31 680	2.0	0.00316	3.16
1:25 000	2.534	0.004	4.0
1:20 000	3.168	0.005	5.0
1.15 840	4.0	0.00631	6.31
1:15 000	4.224	0.00667	6.67
1:10 000	6.336	0.01	10.0
1:5 000	12.67	0.02	20.0

Notes: Map Conversion Factor (cm/m) = 100/Map Scale Ratio and Map Conversion Factor (cm/km) = 100 000/Map Scale Ratio.

1200-1400, 1400-1600, etc.). Be aware of forecasted changes in wind speed and direction. To determine the time required for the fire to advance from one fuel type to another, divide the width of fuel type zone by the predicted rate of spread.

Step 4. Calculations of Fire Spread.--From each prediction point, calculate the fire's Spread Distance (predicted rate of spread X time interval). Then calculate or estimate the Map Distance (Spread Distance X Map Conversion Factor or use map scale bar). Indicate the direction of fire spread from each prediction point with an arrow line equal in length to the Map Distance.

Step 5. Plotting Position of Fire Perimeter.--Using the prediction point arrow lines as reference guides, sketch in the probable location of the fire front at the end of each time interval taking into account natural fuel-breaks that could hinder lateral fire spread (e.g., lakes, aspen stands after leaf flush). Total fire size and growth during the prediction time interval could be determined with a dot grid or planimeter. Similarly, perimeter could be determined manually with a map measurer.

Persons making predictions should be extremely cognizant of amendments to fire weather forecasts and revise their projections accordingly.

Projecting fire growth from a line source is obviously a complex process. The amount of detail that can be achieved and the degree of accuracy that can be expected will depend upon the time available for making predictions, availability of timely and reliable weather forecasts, the heterogeneity in the fuel type mosaic and terrain, fire size, etc.

Conversion Factors

Making predictions of fire behavior usually involves conversion of values from one system of measurement to another. This unit conversion process must be done carefully to avoid major errors in interpreting the results of fire behavior prediction exercises. All units of measurement in the FBP System are given in the International System (SI) to conform with national forestry sector standards. Table 12 has been provided to assist the user with conversion of values in SI units to comparable units in the English system. Conversion factors are provided for units of rate of spread, spread distance, rate of perimeter increase, perimeter length, rate of area growth, and area burned. Conversion factors are given in Table 12 to five significant digits, unless the conversion factor is exact with a lesser number of digits.

FBP System Worksheet

The FBP System Worksheet included on page 60 (blank copy included for photocopying) provides a step by step recording of input data, results of Fine Fuel Moisture Code (FFMC) adjustments for time and slope/aspect, rate of spread (ROS) calculations, fire size calculations and fire area plotting information. Lines 1 through 13 document the input data required for predicting rate of spread with the FBP System. Lines 14-27 of the worksheet are intended to present the results of calculations, and display results needed for plotting fire area. Data inputs and fire behavior prediction outputs are described briefly below, line by line, to assist in correct use of the worksheet.

Heading. Enter Fire Number and/or Name; Date and Time calculations are made (24 hour clock, standard time or daylight saving time when in effect); Prediction Date and Time Interval. All calculations made on one sheet should be for the same time interval. Use a new sheet for each successive or new time interval.

Table 12. International System (SI)/English unit conversion factors for various quantities commonly used to describe the rate of spread (linear and perimeter growth or increase), rate of area growth, spread distance, perimeter, and area of wildland fires.

If Units Are:	Multiply by:	To Obtain:	Inverse Factor*
Metres per minute (m/min)	0.06	Kilometres per hour (km/h)	16.667
Metres per minute (m/min)	3.2808	Feet per minute (ft/min)	0.3048
Metres per minute (m/min)	2.9826	Chains per hour (ch/hr)	0.33528
Metres per minute (m/min)	0.03728	Miles per hour (mi/hr)	26.822
Kilometres per hour (km/h)	54.680	Feet per minute (ft/min)	0.018288
Kilometres per hour (km/h)	49.709	Chains per hour (ch/hr)	0.020117
Kilometres per hour (km/h)	0.62137	Miles per hour (mi/hr)	1.6093
Hectares per hour (ha/h)	2.4711	Acres per hour (ac/hr)	0.40469
Metres (m)	0.001	Kilometres (km)	1000.0
Metres (m)	3.2808	Feet (ft)	0.3048
Metres (m)	0.049709	Chains (ch)	20.117
Metres (m)	0.00062137	Miles (mi)	1609.5
Kilometres (km)	3280.8	Feet (ft)	0.0003048
Kilometres (km)	49.709	Chains (ch)	0.020117
Kilometres (km)	0.62137	Miles (mi)	1.6093
Hectares (ha)	2.4711	Acres (ac)	0.40469

*Note: To convert English (or SI) values to SI, multiply by the inverse factor in the right-hand column.

Line 1. Prediction Point. This is a place from which fire spread rate and fire area and perimeter growth will be predicted. Record the number of a prediction point at the top of a column and place the same number at the corresponding prediction point on the fire map. All subsequent data in the column should pertain to fire spread from that point. Specify whether the Prediction Point refers to a point ignition (P.I.) or active perimeter source (A.P.S.).

Lines 2 to 6. Fuel Type Information.

Line 2. FBP System Fuel Type. Enter the Fuel Type Identifier (e.g., C-2) which best applies to the fuels expected to be encountered by the fire ahead of the prediction point. In the case of Fuel Type C-6 (Red Pine Plantation), specify the mean stand height in brackets; e.g., C-6 [10-20m]. If a fuel type change is encountered or expected, begin a new column with a new prediction point.

Lines 3 and 4. Softwood and Hardwood Species Composition (%). If Fuel Type is M-1 (Boreal Mixedwood-leafless) or M-2 (Boreal Mixedwood-summer) specify and enter the percent tree species composition of the stand by softwood (S) and hardwood (H) components. These proportions are required for later use as inputs when the appropriate ROS model (equation, table or graph) is entered (Line 16). The sum of Lines 3 and 4 must total 100%.

Line 5. Cured/Dead Grass (%). If Fuel Type is O-1 (Grass), specify and enter the proportion (as percent) of the current year standing crop of grass that is cured or dead, based on ocular estimate. This value is used as an input to the Grass ROS model (Line 16).

Line 6. Grass Fuel Weight (t/ha). If Fuel Type is O-1 (Grass), the total weight of grass, living and dead (dry weight basis) is specified and entered as either 3 t/ha, as in the standardized grass fuel type description, or some other proportional weight, known or estimated. Grass fuel weights other than 3 t/ha can be accommodated only in the equation form of the ROS model for Fuel Type O-1; the graph and table forms present ROS only for the standard fuel weight of 3 t/ha.

Lines 7 to 12. Fine Fuel Moisture Code (FFMC) Time & Slope/Aspect Adjustments.

Line 7. Standard Daily FFMC. Enter the calculated value of FFMC determined from the standard "noon" weather observations taken on the day for which an afternoon rate of spread prediction is desired. (If morning hour rate of spread predictions are desired, the previous day's standard daily FFMC is required and an observation or estimate of the morning relative humidity at the time of prediction.) Standard daily FFMC can be calculated from tables for the FWI System or from an appropriate computer program for the FWI System.

Line 8. Time "T". Select and enter an hour between 1200 and 2000 Local Standard Time (LST) for calculation of adjusted FFMC. If fire behavior predictions are desired over an interval of several hours duration, additional times "T" can be selected and entered in successive columns on Line 8, in effect each successive Time "T" defining a new prediction point (Line 1). Alternatively, Time "T" can be selected as 1600 to coincide with the daily peak of fire danger, as built in to the standard daily FFMC.

Line 9. FFMC at Time "T". Enter FFMC at time "T" as determined from Table 4. (See Time of Day section for procedures if Time "T" is other than 1200 to 2000 h.)

Line 10. Aspect (N, E, S, *or* W). Enter the letter standing for the cardinal direction most closely representing the direction that the area ahead of the prediction point faces (north, east, south *or* west). If FFMC topographic adjustment is required, record the aspect of the weather observation point in brackets (use 'L' for Level); e.g., S[E].

Line 11. Ground Slope (%). Enter the estimated or measured percent slope of the ground ahead of the prediction point, disregarding minor fluctuations. If FFMC topographic adjustment is required, record the slope of the weather observation point in brackets (use 'L' for Level; e.g., 50[15]. Slope can also be determined from a topographic map of the area (see **Slope Adjustments**). The value in Line 11 is used both in FFMC adjustments (if necessary) and in ROS calculations.

Line 12. Adjusted FFMC. If Fuel Type Group is Slash or Open, month is Mar., Apr., Aug., Sept., Oct., day is clear to partly cloudy, Time "T" is between 1200 and 2000 and significant differences exist in slope and aspect between point where weather observations were taken and the prediction point, determine Adjusted FFMC from Table 5 and enter it here. If all the above conditions are not met, enter FFMC at Time "T" as Adjusted FFMC.

Lines 13 to 17. Rate of Spread (ROS) Calculations.

Line 13. 10-m Wind Speed (km/h). Enter the measurement, estimate or forecast value of the 10-m open windspeed for the prediction point and time interval of the prediction. Ideally, this will be an updated value from the standard "noon" observation if the prediction is for the afternoon. Record in brackets, beside 10-m Wind Speed value, the case number for direction of fire spread relative to wind and slope (see **Slope Adjustments** and Table 7); e.g., 15[1].

Line 14. Initial Spread Index (ISI). Enter the ISI as calculated from: a) 10-m Wind Speed given at Line 13 (Cases 1 and 4) **OR** zero windspeed (Cases 2 and 3) and b) Adjusted FFMC (Line 12) using Table 7 of the FWI System Tables. If the fuel type is subject to crowning and the fire is spreading on level to gently undulating ground or downslope, denote crown fire spread with an asterisk (*), if applicable (see **Crown Fire Thresholds**); e.g., 16*.

Line 15. Spread Factor (SF). Using Ground Slope (Line 11), and Table 6, derive the appropriate Spread Factor (SF) to adjust ROS for fires burning upslope. Table 6 is valid only for slopes up to 60%. For fires burning downslope or on level to gently undulating ground, let SF = 1.00. Enter SF in Line 15.

Line 16. ROS on Level (m/min *or* km/h). Using the appropriate Fuel Type Information (Lines 2 to 6) and ISI (Line 14), determine the ROS on Level to gently undulating ground from the appropriate ROS model (equation, graph or table) for the Fuel Type of concern (Line 2). ROS equations yield output in m/min; ROS tables and graphs are readable in units of m/min or km/h. Enter ROS on Line 16, indicating units chosen.

Line 17. ROS[16] X SF[15] (m/min *or* km/h). By multiplying ROS on Level ground (Line 16) by SF (Line 15), ROS adjusted for slope is calculated (i.e., upslope fire spread). Alternatively, Equation (15) in the Rate of Spread Equations section can be used with ROS on Level ground (Line 16) and percent ground slope (Line 11) to calculate upslope ROS in m/min. Enter ROS adjusted for slope in Line 17, indicating units chosen. If the fuel type is subject to crowning and the fire is spreading upslope, denote crown fire spread with an asterisk (*), if applicable (see **Crown Fire Thresholds**); e.g., 19.6*.

Lines 18 to 24. Fire Size Calculations.

Line 18. Elapsed Time (min *or* h). Enter Elapsed Time, corresponding to the Prediction Time Interval, indicating units of either min or h, making sure that the units are compatible with those used for ROS (Line 17); i.e., m/min and min or km/h and h.

Line 19. Spread Distance (m *or* km). Multiply the ROS calculated at Line 17 by Elapsed Time (Line 18) to obtain Spread Distance (m or km), representing the actual length of the fire in (horizontal) ground distance. Enter Spread Distance in Line 19, indicating units chosen.

Line 20. Area Shape Factor (K_A). If predicting fire growth for a point ignition, determine K_A by entering either Table 8 (for standing timber fuel types) or Table 9 (for non-forested fuel types) with 10-m Wind Speed (Line 13). K_A is a unitless value derived from the length-to-breadth ratio of a simple ellipse as determined by the fuel type and prevailing wind velocity. Enter K_A in Line 20. If projecting fire growth from an active perimeter source, leave this line blank.

Line 21. Area Burned (ha). If predicting fire growth for a point ignition, multiply K_A (Line 20) by the square of the product of ROS (Line 17) times Elapsed Time (Line 18) using Equation (16). The result is area burned in m^2 or km^2, depending on units used for ROS and Elapsed Time, assuming an elliptical fire shape. Convert this result to Area Burned in ha by dividing m^2 by 10,000 or multiplying km^2 by 100. If projecting fire growth from an active perimeter source, determine the burned area with a dot grid or planimeter. Enter Area Burned (ha) in Line 21.

Line 22. Length/Breadth Ratio (L/B). The ratio of total length to maximum breadth (L/B) of a free-burning fire having an elliptical shape depends on wind speed in a given fuel type. Relationships are presented (Fig. 20) for two broad fuel type categories: non-forested and standing timber. If predicting fire growth for a point igntion, determine from Figure 20 the L/B ratio for the 10-m open wind speed (Line 13) and appropriate fuel type category. Enter L/B in Line 22. If projecting fire growth from an active perimeter source, leave this line blank.

USER NOTE: ***Tabular versions of Figure 20 are presented as supplemental aids following page 73 of the report.***

Line 23. Perimeter Shape Factor (Kp). If predicting fire growth for a point ignition, determine Kp by entering Table 10 with the L/B ratio (Line 22). Kp is a unitless value derived from the length-to-breadth ratio of a simple ellipse based on its circumference. Enter Kp in Line 23. If projecting fire growth from an active perimeter source, leave this line blank.

USER NOTE: ***It will be necessary to interpolate between adjacent columns and rows to determine K_p when entering Table 10 with a L/B value obtained from the tabular versions of Figure 20 that are presented as supplemental aids following Page 73 of this report.***

Line 24. Perimeter Length (m *or* km). Perimeter Length for a point ignition fire having a burned area as determined in Line 21 can be approximated by multiplying Kp (Line 23) by Spread Distance (Line 19) using Equation (17). This procedure tends to underestimate actual fire perimeter length because of irregularities in the fire edge not accounted for in the formula. If projecting fire growth from an active perimeter source, determine the length of the perimeter with a map measurer. Enter Perimeter Length in Line 24, indicating units chosen.

Lines 25 to 27. Fire Area Plotting. Note Map Scale (ratio or in./mile).

Line 25. Map Conversion Factor. Determine the Map Conversion Factor from Table 11 appropriate to the topographic or cover type map being used to plot the predicted fire size and area burned. Enter Table 11 with Map Scale expressed either as a ratio or in./mile and determine the appropriate Map Conversion Factor, either as cm/m or cm/km. Enter the Map Conversion Factor in Line 25, indicating units chosen (cm/m or cm/km) in parentheses.

Line 26. Map Distance (cm). Calculate Map Distance (cm) by multiplying Spread Distance (Line 19) by Map Conversion Factor (Line 25), making sure that the units are compatible; i.e., m and cm/m or km and cm/km. When plotting fire area for a point ignition, this distance represents the length (L) of the elliptical fire area map plot. When plotting fire area from an active perimeter source, this distance represents the fire spread from an individual prediction point. If plotting fire area for a point ignition, calculate the map equivalent length of the ellipse's maximum Breadth (B) by dividing length of the L line by the L/B ratio (Line 22). Enter the Map Distance values of both L and B lines for point ignition fires (e.g., 6.2/3.1) or single value for active perimeter source fires in Line 26.

Line 27. Wind Direction. Record Wind Direction to guide plotting of fire spread direction from Prediction Point.

USER NOTE: ***Five worksheet sample calculations are given at the end of this report.***

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CANADIAN FOREST FIRE BEHAVIOR PREDICTION (FBP) SYSTEM WORKSHEET

Fire Number/Name ______________________ Date & Time __________

Prediction Date & Time Interval ____________ from ________ to ________

1	Prediction Point					
	Fuel Type Information					
2	FBP System Fuel Type					
3	Softwood Species Composition (%)					
4	Hardwood Species Composition (%)					
5	Cured/Dead Grass (%)					
6	Grass Fuel Weight (t/ha)					
	Fine Fuel Moisture Code (FFMC) Time & Slope/Aspect Adjustments					
7	Standard Daily FFMC					
8	Time "T"					
9	FFMC at Time "T"					
10	Aspect (N, E, S, *or* W)					
11	Ground Slope (%)					
12	Adjusted FFMC					
	Rate of Spread (ROS) Calculations					
13	10-m Wind Speed (km/h)					
14	Initial Spread Index (ISI)					
15	Spread Factor (SF)					
16	ROS on Level (m/min *or* km/h)					
17	ROS[16] x SF[15] (m/min *or* km/h)					
	Fire Size Calculations					
18	Elapsed Time (min *or* h)					
19	Spread Distance (m *or* km)					
20	Area Shape Factor (K_A)					
21	Area Burned (ha)					
22	Length/Breadth Ratio (L/B)					
23	Perimeter Shape Factor (K_P)					
24	Perimeter Length (m *or* km)					
	Fire Area Plotting					
25	Map Conversion Factor ( )					
26	Map Distance (cm)					
27	Wind Direction					

DOCUMENTATION OF WILDFIRE SPREAD RATES

While a number of well-documented wildfires were used in developing this interim edition of the FBP System, much more information remains to be collected in order to evaluate the ROS relationships outlined, and to allow for the future expansion of the FBP System to include other important Canadian fuel types. The purpose of this section is to provide guidance and methodology to user agencies in gathering ROS data in a systematic and reliable fashion on wildfires in order to rationally verify and adjust their fire behavior predictions. This is not an easy task at all, primarily because wildfire occurrence is unpredictable as to time and place, and numerous logistical problems arise when attempting to observe and monitor wildfire behavior. However, fire suppression personnel are generally in a position to make a few key observations on wildfires and, if properly trained, to document these observations in a systematic fashion. An excellent outline of the principles of wildfire documentation is provided by Rothermel and Rinehart (1983).

Rate of Spread Monitoring

The forward rate of spread is the most important fire behavior parameter to measure on a wildfire. Identification of the position of the head fire at various times throughout the peak late afternoon-early evening burning period would be optimum. Even marking the beginning and end points of major, sustained runs (e.g., ROS in excess of 2 km/h for more than 3 hours) would be most useful information. The most common weakness with conventional mapping on campaign wildfires is that it is usually not done at the time when the fire is actively spreading. Maps and records officers traditionally map the fire perimeter in the early morning and/or late evening. Mapping during peak spread periods is difficult due to turbulence and visibility problems caused by large volumes of smoke and significant convective activity. Conversely, "blow-up" fire periods are too dangerous for suppression activities and this time could be used for documentation.

The position of the head and flanks of a fire, and the direction of spread, should be plotted on a map in relation to major identifiable landmarks and topographic features (e.g., rivers, lakes, ridges, roads, seismic lines, power lines). Flank fire position, when combined with head fire location, will allow calculation of the fire's length-to-breadth (L/B) ratio. The use of topographic maps (1:50 000 scale or larger) or forest cover type maps would provide additional information of value. Additional equipment, such as a hand-held portable tape recorder and a camera with a "data back" timing attachment, would prove very useful in documenting fire spread. The interviewing of suppression personnel and pilots during the fire, and the examination of radio log records can also provide valuable information.

Fire Weather Observations

Ideally, a fire weather station located at the fire site should be used to monitor the fire weather parameters (temperature, relative humidity, wind speed, precipitation) used in calculating the component codes and indexes of the FWI System relative to that particular fire. A variety of portable and/or electronic fire weather stations are available, at a reasonable cost, for temporary installation at a fire camp. The station location should be representative of the fire area, and the station should be established according to the criteria outlined in Turner and Lawson (1978). Weather observations should be recorded every hour during periods of major fire activity.

In most cases, however, major fire runs occur before fire camps are in place and weather stations set up. In these situations, an observer documenting fire behavior must resort to using a portable belt weather kit which will allow him to measure local fire weather parameters in a reasonably accurate manner. A sling psychrometer and a hand-held anemometer are the main components in each kit. The Beaufort Wind Scale (Turner and Lawson 1978) is also a quite useful means of estimating wind velocity in this type of situation. Ideally, the observer should collect some moisture content samples for selected fuels for later analysis.

In the absence of on-site weather observations during periods of major fire spread, it is necessary to collect weather data from the nearest permanent weather station. Each province has a broad network of fire weather stations from which 1200 h LST data can be obtained. In addition, the Atmospheric Environment Service (AES) has a number of synoptic weather stations across Canada which provide hourly observations of numerous weather parameters.

Every attempt should be made to collect, from any source, as much accurate and representative weather data as possible for correlation with observed fire behavior parameters. Good weather data is invaluable to a proper understanding and explanation of the behavior of wildfires.

Well-documented cases of high wildfire spread rates will be invaluable in evaluating and expanding this version of the FBP System. The CFS Fire Danger Group would appreciate receiving this type of information, including copies of ROS maps, written accounts, weather data and weather station location, etc. This data could be sent to the appropriate member listed in the Preface of this report.

FIRE BEHAVIOR PREDICTION

This interim edition of the FBP System represents the best available information on fire spread in Canada. Hence, the fire manager would appear to be in a good position to predict head fire rate of spread with reasonable assurance under a variety of fuel and fire weather conditions. However, any system for predicting fire behavior is a mechanical scheme and will not give an exact answer every time. Many variables determine fire behavior and these are interrelated in complex ways. Prediction accuracy is dependent upon the skill and knowledge of the user and the degree of uniformity in environmental conditions.

The FBP System is intended to supplement, rather than replace, the experience, local knowledge, and judgement of fire managers. Persons combining, in a systematic fashion, the products of the FBP System with their own fire experience can be expected to make the most accurate fire behavior predictions. Practice and experienced judgement in assessing the fire environment, coupled with a systematic method of calculating fire behavior, can yield surprisingly good results. Predicting quantitative rates of fire spread and other features of fire behavior in wildland vegetation complexes remains an art. It must be done at the fire site by a highly trained and experienced fire specialist who must observe a vast number of interacting parameters and evaluate them in his mind in view of existing and predicted short term changes in fuel, weather, and topographic factors of the fire environment.

The FBP System provides Canadian forest fire managers with site-specific fire behavior information for fuel types of major concern. It will be a number of years before all important Canadian fuel types are properly covered. This edition will assist in meeting the present day planning and immediate operational requirements of Canadian fire management agencies primarily concerned with fire behavior in major standing timber fuel types.

The future development and effective use of more sophisticated procedures for fire behavior prediction dictate improved weather data collection and weather forecasting procedures, an increased data-handling capability by the operational agency, and some indication that the fire manager's ability to predict changes in fire behavior over short time spans and on small areas is of real practical importance in relation to suppression activities, and will contribute to a saving in fire management costs and fire damages.

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APPENDIX I - DERIVATION AND INTERPRETATION OF MATHEMATICAL FUNCTIONS

The rate of spread (ROS) equations for most fuel types were developed by grouping into appropriate subsets data from a larger data set consisting of 290 fire observations for which spread rate and necessary weather information were available. This data base comprises 245 experimental and operational prescribed fire observations, and 45 wildfire observations from all available Canadian sources[3] (e.g., Van Wagner 1963, 1964, 1965, 1966, 1968, 1973, 1977c; Howard 1968; Kiil 1970, 1975; Muraro 1971; Quintilio 1972; Stocks and Walker 1972, 1973; Walker and Stocks 1972; Lawson 1973, 1977a, 1982; Stocks 1975, 1977; Stocks and Alexander 1980; Alexander 1983; Alexander et al. 1983; Newstead and Alexander 1983; Quintilio et al. 1984) as well as from adjacent states of the U.S. (e.g., Johnson 1962; Randall 1966; Sando 1972; Sando and Haines 1972; Perala 1974; Alexander 1982b, 1984; Dyrness and Norum 1983; Simard et al. 1983). Some large wildfires known to have burned through several forest types were included in more than one fuel-type subset.

For all equations derived directly from the data base, the independent variable is the Initial Spread Index (ISI). Because this index is a compound quantity, comprising functions of fine fuel moisture and wind, all fuel-type subsets were tested for multiple correlation of ROS with these two variables expressed separately. No advantage was found over the ISI alone. An effect of Buildup Index (BUI) on ROS (Van Wagner 1973) was also tested for but not found. The ISI was therefore retained as sole independent variable for these fuel types. Table 13 shows various statistics, including ranges of ROS, ISI, BUI, numbers of fires, as well as the correlation coefficients (r^2) between actual versus calculated ROS values for all data-based fuel types. Figure 16 (page 30) shows the comparative position of ROS/ISI curves for all 14 fuel types.

The final equation forms were chosen after some trial and judgement. Special attention was paid to reasonable fit with data at low ISI, and for consistency among fuel types. The principle that ROS probably levels off at very high ISI was adopted as an appropriate conservative approach in the absence of firm knowledge on this point. Some fuel types are served by two equations for lower and upper ranges of ISI, with a smooth junction at the ISI changeover value. Where data existed for a low range of ISI only, the curves were extrapolated by judgement and informal experience.

Because of the empirical nature of the data, the transition from surface fire to crown fire among the coniferous fuel types is accounted for automatically in the ROS equations. Among the boreal coniferous fuel types especially (C-1, C-2, C-3, and C-4), the steeper section of

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[3] Donors of unpublished fire spread data are thanked especially. These include R.A. Lanoville (Indian and Northern Affairs Canada, Regional Fire Centre, Fort Smith, N.W.T.) and A.H. Johnson (formerly with Faculty of Forestry, University of British Columbia, Vancouver).

the curves at intermediate ISI represents this process. Crowning is considered unlikely in type C-5 and occurs only at very high ISI levels in type C-7, due to the very open nature of the forest in these fuel types. All ROS curves were forced through the origin, with the exception of type C-4 where the dense nature of the stands precluded fire spread at ISI values below 4. ISI crowning thresholds were set by informal experience (Table 13). Fuel type C-6 is dealt with below.

Several equations were not derived directly from the data base:

a) The Boreal Mixedwood Fuel Types (M-1 and M-2), which occur widely throughout Canada, are served by a blend of the ROS equations for Boreal Spruce (C-2) and Leafless Aspen (D-1). Fuel Type M-1 (leafless-for spring and fall periods) uses these two equations directly in proportion to the amount of softwood (S) and hardwood (H). Fuel Type M-2 (for summer period) is similar except that the ROS equation for Fuel Type D-1 is used at 1/5 strength. The influence of hardwood composition on ROS and crowning potential is taken into account.

b) The Red Pine Plantation Fuel Type (C-6) utilizes the ROS equations of other coniferous fuel types for three mean stand height ranges. This approach was adopted in view of 1) the importance of height to plantation fire behavior, and 2) the limited number of ROS observations in this fuel type.

c) The Grass Fuel Type (O-1) equation is based on the Australian grassland fire danger/behavior research of McArthur (1962, 1966, 1977), with supporting evidence from early Canadian grass fire research (Wright and Beall 1938). The basic ROS equation assumes a fuel load of 3 t/ha (1.3 T/ac) and is for use in instances where actual grass loading is unknown. For cases in which grass loading is known, a second equation which utilizes fuel weight as a variable, is provided. Both equations provide for incorporating an estimate of the proportion of cured or dead fuel.

The fuel-type subsets into which the main data base is divided are not all significantly different. Some of the ROS curves, therefore, resemble each other to some degree. This was allowed on grounds that it was better to identify and distinguish the important fuel types rather than to pool certain large types together. This separation provides also for collecting further fire behavior data and assigning them logically.

Fire length-to-breadth ratio versus wind speed relationships (Fig. 20) are presented in this interim edition of the FBP System for two broad fuel type categories:

<u>Non-forested Fuel Types</u>

$$L/B = 1.1\, W^{0.464} \qquad , W \geq 1 \qquad (18)$$

Standing Timber Fuel Types

$$L/B = 1 + 0.0012W^{2.154} \qquad ,W \leq 50 \quad (19)$$

where, L/B = length-to-breadth ratio and W = wind speed at a height of 10 m in the open on level terrain, km/h. It is recommended that Equation (18) be used for winds greater than 50 km/h, regardless of the fuel type.

Equation (18) is from Cheney (1981) based on McArthur's (1966) original empirical work on Australian grassland fires. A graph of the relationship also appears in Luke and McArthur (1978). Equation (19) was derived using the Initial Spread Index (ISI) component of the FWI System (Van Wagner and Pickett 1984) and by assuming for reasons of simplicity that flank fire spread is independent of wind speed. L/B ratios were computed for wind speeds between 0 and 50 km/h as follows: L/B = (ISI at zero wind + ISI at given wind)/2 (ISI at zero wind). The resulting L/B ratios were plotted over wind and fitted to the equation form $Y = 1 + aX^b$ so that L/B = 1.0 when wind = 0. Comparisons of predicted L/B ratios for Equation (19) with actual values from published case histories of selected wildfires in natural and man-made forests (e.g., Van Wagner 1965; McArthur et al. 1966; Stocks and Walker 1973; Geddes and Pfeiffer 1981; Alexander et al. 1983; Simard et al. 1983) show good agreement.

The perimeter shape factors (Kp) contained in Table 10 were formulated by using the approximate expression for the circumference (C) of an ellipse:

$$C = 2\pi\sqrt{(a^2 + b^2)/2} \qquad (20)$$

where, a and b are the long and short semiaxes of the ellipse (Fig. 19). The following empirical equation linking Kp to the length-to-breadth ratio (L/B) of a simple ellipse was derived:

$$K_p = (L/B)/[-0.14145 + 0.47034(L/B)] \qquad (21)$$

The resulting Kp values, which varied from 2.22 (L/B = 7.0) to 2.92 (L/B = 1.1), were consistent with general rules of thumb (i.e., Kp = 2.5) for estimating perimeter length and/or rate of perimeter growth (McArthur 1966; Anderson 1983).

Table 13. **Statistics and related information associated with the data base and rate of spread (ROS) functions embodied in the 1984 interim edition of the Canadian Forest Fire Behavior Prediction (FBP) System. The r^2 values refer to the correlation between actual and equation spread rates (ISI = Initial Spread Index, FFMC = Fine Fuel Moisture Code, and BUI = Buildup Index).**

Fuel type	Number of fires (n)	ROS range (m/min)	ISI range	FFMC range	Wind[1] range (km/h)	BUI			Correlation coefficient (r^2)	ISI crowning threshold[2]
						$\bar{X}$	SD	Range		
C-1	8	0.6- 51.4	3.2-31.1	80.0-93.0	14.5-34.6	71	4.6	63- 75	0.95	16
C-2	43	0.3-107.0	2.5-68.0	84.8-96.2	2.8-51.0	78	39.3	30-160	.91	12
C-3	56	0.4-107.0	3.3-68.0	87.2-96.2	3.0-51.0	59	24.8	24-128	.91	18
C-4	29	0.7-107.0	5.8-68.0	89.0-96.2	6.0-51.0	61	27.6	27-128	.84	8
C-5	15	0.3- 7.5	3.0-18.0	81.0-92.0	3.0-25.0	48	23.2	17- 97	.91	--
C-6	12	0.9- 27.4	5.0-13.0	87.0-93.0	7.0-19.0	60	20.5	34-109	--	8/18/--
C-7	12	0.3- 26.8	7.0-41.0	89.0-97.5	0.0-40.0	97	37.1	33-135	.92	25
D-1	34	0.3- 10.7	3.2-28.1	87.0-95.0	3.0-28.0	29	12.8	13- 57	.69	--
S-1	53	0.6- 37.7	1.0-16.4	72.4-95.2	4.8-32.2	38	20.6	7- 87	.60	N/A
S-2	52	0.1- 31.7	1.0-38.8	56.0-95.2	2.3-32.0	75	18.5	45-114	.74	N/A
S-3	12	0.4- 12.0	1.0-11.0	74.0-92.0	2.0-32.0	32	14.4	13- 65	.69	N/A

[1] As measured at 10 m in the open on level terrain.

[2] Crown fire spread in the Boreal Mixedwood Fuel Types M-1 (leafless) and M-2 (summer) was judged to occur, in forest stands having at least a 50 percent softwood component, when the ROS is ≥17 m/min and ≥21 m/min, respectively. Thus, the ISI crowning thresholds for the three softwood (S)/hardwood (H) species composition combinations used in the ROS Graphs and Tables sections of this report are as follows: M-1 75S:25H - 16, M-1 50S:50H and M-2 75S:25H - 20, M-2 50S:50H - 30, and M-1 25S:75H and M-2 25S:75H - crowning unlikely.

SUPPLEMENTS

Users may find the graphical (Fig. 20) or equation method of determining length-to-breadth ratio (L/B) inconvenient. Tabular summaries of Equations (18) and (19) are presented below. L/B can also be approximated by using Tables 8 or 9 and the following formula: $L/B = \pi/[4K_A]$.

Length-to-breadth ratios (L/B) versus wind speed at a height of 10 m in the open on level terrain for free-burning fires in standing timber fuel types.

Wind speed (km/h)	0	1	2	3	4	5	6	7	8	9
	L/B									
0	1.00	1.00	1.01	1.01	1.02	1.04	1.06	1.08	1.11	1.14
10	1.17	1.21	1.25	1.30	1.35	1.41	1.47	1.54	1.61	1.68
20	1.76	1.85	1.93	2.03	2.13	2.23	2.34	2.45	2.57	2.70
30	2.82	2.96	3.10	3.24	3.39	3.54	3.70	3.86	4.03	4.21
40	4.39	4.57	4.76	4.96	5.16	5.37	5.58	5.80	6.02	6.25

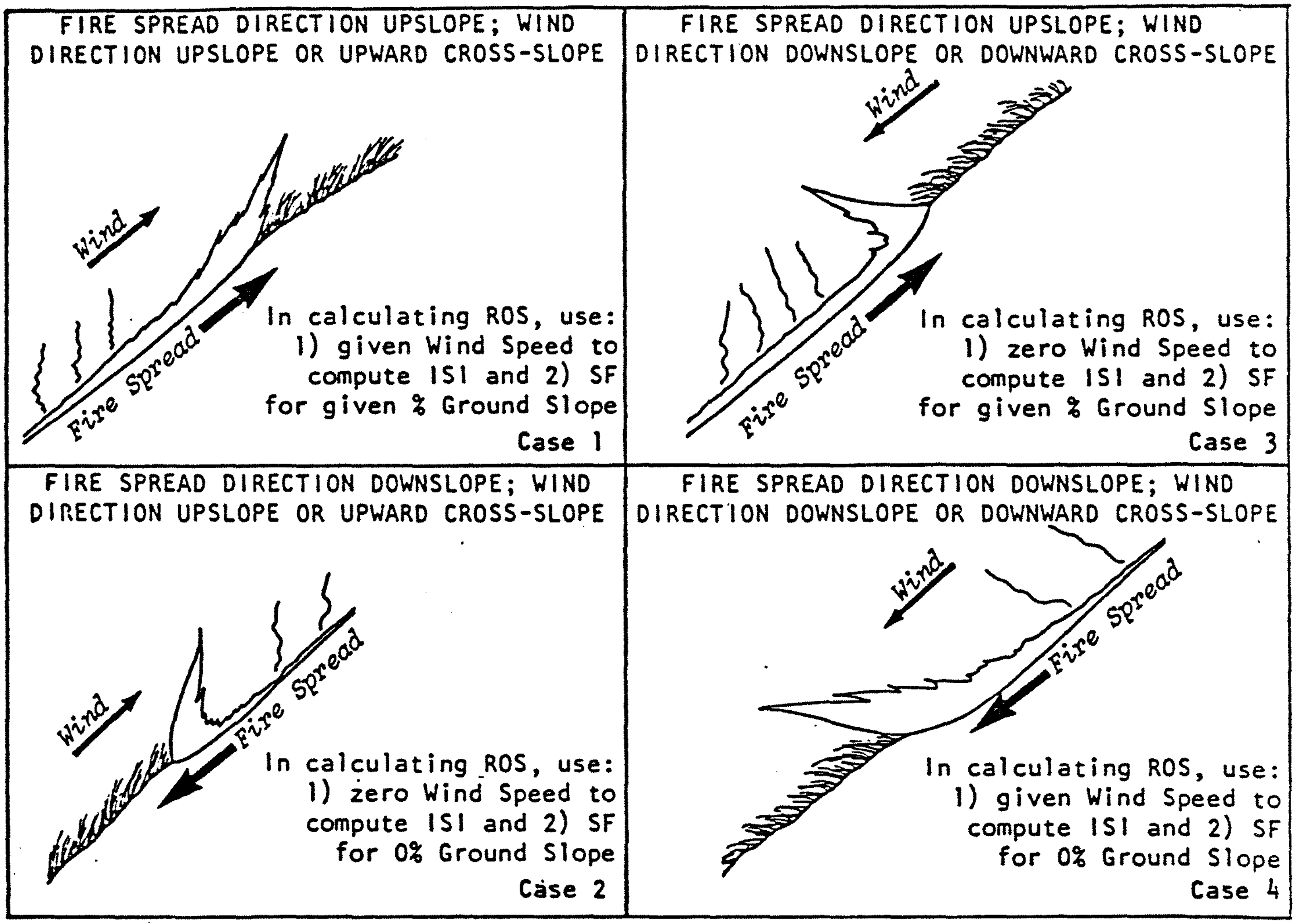
Note: e.g., Wind Speed = 15 km/h and L/B = 1.41.

Length-to-breadth ratios (L/B) versus wind speed at a height of 10 m in the open on level terrain for free-burning fires in non-forested fuel types.

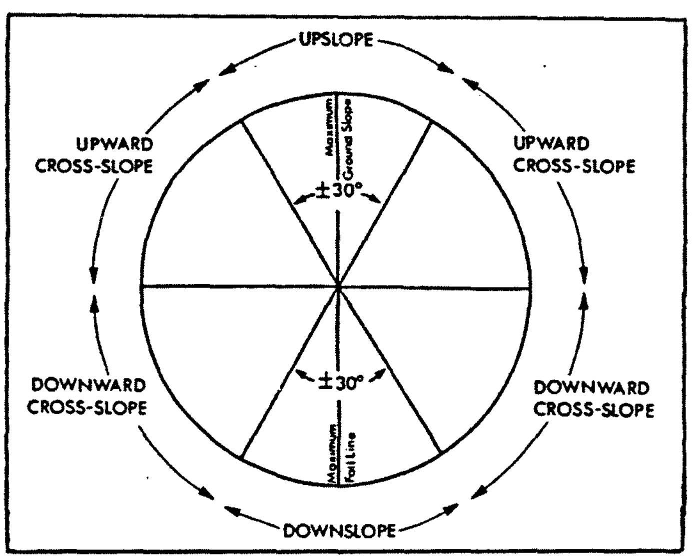
Wind speed (km/h)	0	1	2	3	4	5	6	7	8	9
	L/B									
0	1.00	1.10	1.52	1.83	2.09	2.32	2.53	2.71	2.89	3.05
10	3.20	3.35	3.48	3.62	3.74	3.86	3.98	4.10	4.21	4.31
20	4.42	4.52	4.62	4.71	4.81	4.90	4.99	5.08	5.16	5.25
30	5.33	5.41	5.49	5.57	5.65	5.73	5.80	5.88	5.95	6.02
40	6.09	6.16	6.23	6.30	6.37	6.43	6.50	6.57	6.63	6.69

Note: e.g., Wind Speed = 15 km/h and L/B = 3.86.

The following illustrations have been prepared to further assist users in determining rate of spread in relation to direction fire is spreading with respect to wind and slope (see **Slope Adjustments** and Table 7 in the text, pgs. 42-46).



The four cases of fire spread direction with respect to wind direction and slope (adapted from Rothermel and Rinehart 1983) and input information for determining rate of spread (ROS) in regards to the Initial Spread Index (ISI) and relative Spread Factor (SF).



The four types of slope winds according to Rothermel and Rinehart's (1983) definitions:

Upslope Wind is within a ± 30° quadrant of the maximum ground slope.

Downslope Wind is within a ± 30° quadrant of the maximum fall line.

Upward and Downward Cross-slope Winds consist of all remaining angles that are not upslope or downslope.

CANADIAN FOREST FIRE BEHAVIOR PREDICTION (FBP) SYSTEM WORKSHEET

Fire Number/Name SAMPLE CALCULATIONS Date & Time 29/04/84 1600 LST

Prediction Date & Time Interval 30/04/84 from 1200 to 1300 LST

1	Prediction Point	1	2	3	4	5
		P.I.	P.I.	A.P.S.	A.P.S.	P.I.
	Fuel Type Information					
2	FBP System Fuel Type	C-4	M-1	D-1	S-2	O-1
3	Softwood Species Composition (%)	-	75	-	-	-
4	Hardwood Species Composition (%)	-	25	-	-	-
5	Cured/Dead Grass (%)	-	-	-	-	95
6	Grass Fuel Weight (t/ha)	-	-	-	-	3
	Fine Fuel Moisture Code (FFMC) Time & Slope/Aspect Adjustments					
7	Standard Daily FFMC	93	95	88	94	94
8	Time "T"	1200	1200	1200	1200	1200
9	FFMC at Time "T"	91	93	88	92	92
10	Aspect (N, E, S, or W)	-	N	E	S [E]	W [L]
11	Ground Slope (%)	0	14	10	50 [15]	18 [L]
12	Adjusted FFMC	91	93	85	95	92
	Rate of Spread (ROS) Calculations					
13	10-m Wind Speed (km/h)	23	15 [1]	3 [2]	5 [3]	15 [4]
14	Initial Spread Index (ISI)	16*	14	2.0	9	12
15	Spread Factor (SF)	1.00	1.40	1.00	4.65	1.00
16	ROS on Level (m/min or km/h)	26	14	0.2	6.9	19
17	ROS[16] x SF[15] (m/min or km/h)	26	19.6*	0.2	32.1	19
	Fire Size Calculations					
18	Elapsed Time (min or h)	60	60	60	60	60
19	Spread Distance (m or km)	1560	1176	12	1926	1140
20	Area Shape Factor (K_A)	0.39	0.56			0.20
21	Area Burned (ha)	95	77			26
22	Length/Breadth Ratio (L/B)	2.0	1.41			3.86
23	Perimeter Shape Factor (K_p)	2.50	2.72			2.30
24	Perimeter Length (m or km)	3900	3199			2622
	Fire Area Plotting 1:25000					
25	Map Conversion Factor (cm/m)	0.004	0.004	0.004	0.004	0.004
26	Map Distance (cm)	6.2/3.1	4.7/3.3	0.1	7.7	4.6/1.2
27	Wind Direction	S-SW	NW	SE	N	E