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V Short Course on

# Fire Behaviour

## Held at the V International Conference on Forest Fire Research

**25/26 November 2006**

Centro de Artes e Espectáculos

Figueira da Foz - PORTUGAL

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Organization:

Associação para o Desenvolvimento da Aerodinâmica Industrial
*Association for the Development of Industrial Aerodynamics*

Universidade de Coimbra / University of Coimbra

**Centro de Estudos sobre Incêndios Florestais**
***Forest Fire Research Centre***

LMSR

## CONTENTS

## Speaker | Martin Alexander

Marty Alexander is an Adjunct Professor of wildland fire science & management with the University of Alberta. He was one of the architects of the Canadian Forest Fire Behaviour Prediction System, a co-coordinator of the International Crown Fire Modelling Experiment, and has been extensively involved in fire behaviour training on a national an international basis. He received the International Wildland Fire Safety Award in 2003.

*V Short Course on Fire Behaviour Modelling*
*November 25-26, 2006 – Figueira da Foz, Portugal*

# Models for Predicting Crown Fire Behavior – A Review

**M.E. Alexander**[1]
Adjunct Professor – Wildland Fire Science & Management
Department of Renewable Resources, University of Alberta
Edmonton, Alberta
mea2@telus.net

This presentation will provide an overview of existing empirical and semi-physical theories and models for predicting the development and spread of crown fires in conifer forests at the stand level, including their limitations and performance, with emphasis on practical applications in fire and fuel management. The following publications authored or co-authored by the lecturer listed below are being provided to those attending the short course in support of the formal presentation.

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Alexander, M.E. 1988. Help with making crown fire hazard assessments. In: Fischer, W.C. and Arno, S.F. (compilers). Protecting People and Homes from Wildfire in the Interior West: Proceedings of the Symposium and Workshop. USDA Forest Service, Intermountain Research Station, Ogden, Utah. General Technical Report INT-251. pp. 147-156.

Alexander, M.E. 1991. Fire behaviour in Canadian pine plantations in relation to two Australian fire danger indexes. Paper presented at Bureau of Meteorology and Australian Disaster College sponsored Fire Weather Workshop (June 16-20, 1991, Mount Macedon, Victoria). 12 p.

Alexander, M.E. 2005. Long-term experiment takes some of the mystery out of crown fires. Fire Management Today 65(3): 36-37.

Alexander, M.E.; Cruz, M.G. 2006. Evaluating a model for predicting active crown fire rate of spread using wildfire observations. Canadian Journal of Forest Research 36: in press.

Alexander, M.E.; Cruz, M.G.; Lopes, A.M.G. 2006. CFIS: A software tool for simulating crown fire initiation and spread. In: Viegas, D.X. (editor). Proceedings of V International Conference on Forest Fire Research. Elsevier, Meppel, Netherlands. CD-ROM. 13 p.

[1] Full-time affiliation: Senior Fire Behavior Research Officer, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, Canada T6H 3S5; E-mail: malexand@nrcan.gc.ca

Alexander, M.E.; Stefner, C.N.; Mason, J.A.; Stocks, B.J.; Hartley, G.R.; Maffey, M.E.; Wotton, B.M.; Taylor, S.W.; Lavoie, N.; Dalrymple, G.N. 2004. Chartacterizing the jack pine-black spruce fuel complex of the International Crown Fire Modelling Experiment (ICFME). Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Information Report NOR-X-393. 49 p.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2002. Predicting crown fire behavior to support forest fire management decision-making. In: Viegas, D.X. (editor). Forest Fire Research & Wildland Fire Safety, Proceedings of the IV International Conference on Forest Fire Research/2002 Wildland Fire Safety Summit. Millpress Scientific Publications, Rotterdam, Netherlands. CD-ROM. 11 p.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2003a. Definition of a fire behavior model evaluation protocol: A case study application to crown fire behavior models. In: Omi, P.N. and Joyce, L.A. (technical editors). Fire, Fuel Treatments, and Ecological Restoration: Conference Proceedings. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. Proceedings RMRS-P-29. pp. 49-67.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2003b. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. International Journal of Wildland Fire 12: 39-50.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2003c. Assessing the probability of crown fire initiation based on fire danger indices. Forestry Chronicle 79: 976-983.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2004. Modeling the likelihood of crown fire occurrence in conifer forest stands. Forest Science 50: 640-658.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2005. Development and testing of models for predicting crown fire rate of spread in conifer forest stands. Canadian Journal of Forest Research 35: 1626-1639.

Cruz, M.G.; Butler, B.W.; Alexander, M.E.; Forthofer, J.M.; Wakimoto, R.H. 2006. Predicting the ignition of crown fuels above a spreading surface fire. Part I: Model idealization. International Journal of Wildland Fire 15: 47-60.

Cruz, M.G.; Butler, B.W.; Alexander, M.E. 2006. Predicting the ignition of crown fuels above a spreading surface fire. Part II: Model behavior and evaluation. International Journal of Wildland Fire 15: 61-72.

Cruz, M.G.; Butler, B.W.; Alexander, M.E.; Viegas, D.X. 2006. Development and evaluation of a semi-physical crown fire initiation model. In: Viegas, D.X. (editor). Proceedings of V International Conference on Forest Fire Research. Elsevier, Meppel, Netherlands. CD-ROM. 17 p.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada, Ottawa, Ontario. Information Report ST-X-3. 63 p.

Stocks, B.J.: Alexander, M.E.; Lanoville, R.A. 2004. Overview of the International Crown Fire Modelling Experiment (ICFME). Canadian Journal of Forest Research 34: 1543-1547.

Stocks, B.J.; Alexander, M.E.; Wotton, B.M.; Stefner, C.N.; Flannigan, M.D.; Taylor, S.W.; Lavoie, N.; Mason, J.A.; Hartley, G.R.; Maffey, M.E.; Dalrymple, G.N.; Blake, T.W.; Cruz, M.G.; Lanoville, R.A. 2004. Crown fire behaviour in a northern jack pine – black spruce forest. Canadian Journal of Forest Research 34: 1548-1560.

Taylor, S.W.; Wotton, B.M.; Alexander, M.E.; Dalrymple, G.N. 2004. Variation in wind and crown fire behaviour in a northern jack pine – black spruce forest. Canadian Journal of Forest Research 34: 1561-1576

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A copy of the following is also being provided to the short course participants:

Cruz, M.G.; Lopes, A.M.G.; Alexander, M.E. 2005. CFIS: Simulation of crown fire initiation and spread. Version 3.0.0. Associação para o Desenvolvimento da Aerodinâmica Industrial, Coimbra, Portugal and Forest Engineering Research Institute, Wildland Fire Operations Research Group, Hinton, Alberta. Visual Basic Software.

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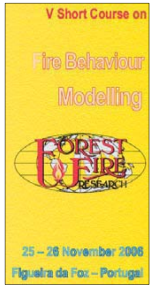
Please note that the following crown fire related papers are included on the Proceedings of the V International Conference on Forest Fire Research CD-ROM:

Cohen, J.D.; Finney, M.A.; Yedinak, K.M. 2006. Active spreading crown fire characteristics: Implications for modeling. In: Viegas, D.X. (editor). Proceedings of V International Conference on Forest Fire Research. Elsevier, Meppel, Netherlands. CD-ROM. 12 p.

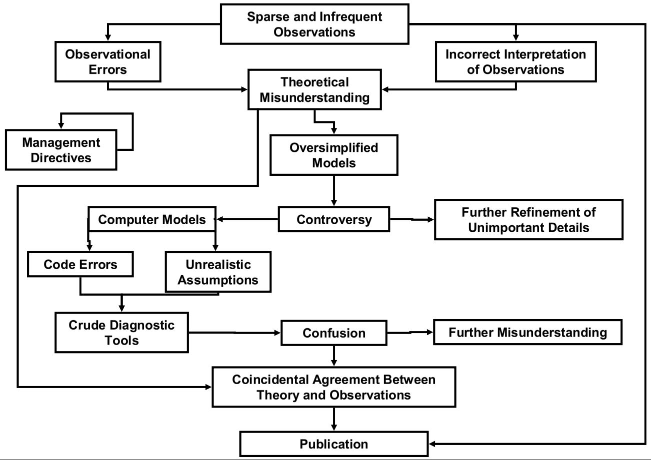
Tachajapong, W.; Zhou, X.; Mahalingam, S.; Weise, D. 2006. Experimental and numerical modeling of crown fire initiation. In: Viegas, D.X. (editor). Proceedings of V International Conference on Forest Fire Research. Elsevier, Meppel, Netherlands. CD-ROM. 17 p.

# Models for Predicting Crown Fire Behavior – A Review

**Marty Alexander, PhD, RPF**
Adjunct Professor
Department of Renewable Resources, University of Alberta
Edmonton, Alberta, Canada
mea2@telus.net




## The Course of Wildland Fire Behavior Prediction Science?



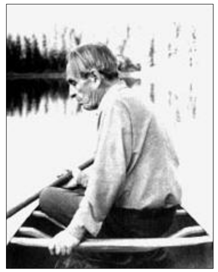

## Outline of Presentation

- **I.** **Why are Crown Fires Significant?**
- **II.** **Nature and Characteristics of Crown Fires**
- **III.** **Early Work and References to Crown Fires**
- **II.** **Understanding Crown Fire Behavior From Experimental Fires**
- **III.** **Crown Fire Initiation**
- **IV.** **Crown Fire Propagation**
- **V.** **Crown Fire Rate of Spread**
- **VI.** **Crown Fire Intensity and Growth**
- **VII.** **Spotting from Active Crown Fires**
- **VIII.** **Plume- or Convection-Dominated vs. Wind-driven Crown Fires**
- **IX.** **Working Towards Practical Applications**
- **X.** **Researching Crown Fires**
- **XI.** **Recent and Current Research on Crown Fires**
- **XII.** **Key Take-home Messages**

## Why are Crown Fires Significant?

On how Crown Fires were handled in the early part of the 20th century by the U.S. Forest Service:

*"By the time they reached the fire, it had spread all over the map, and had jumped into the crowns of trees, and for a lot of years a prospective ranger taking his exam had said the last word on crown fires … When asked on his examination, "What do you do when a fire crowns?" he had answered, "Get out of the way and pray like hell for rain"."*



Norman Maclean (1976)
***A River Runs Through and Other Stories***

## Nature and Characteristics of Crown Fires


**A “Crown Fire” is defined as:**

*A fire that advances through the crown fuel layer, usually in conjunction with the surface fire.  Crowning can be classified according to the degree of dependence on the surface fire phase.*

**“Crowning” is defined as:**

*A fire ascending into the crowns of trees and spreading from crown to crown.*

**from Merrill and Alexander (1987) – *Glossary of Forest Fire Management Terms***

## Why are Crown Fires Significant?

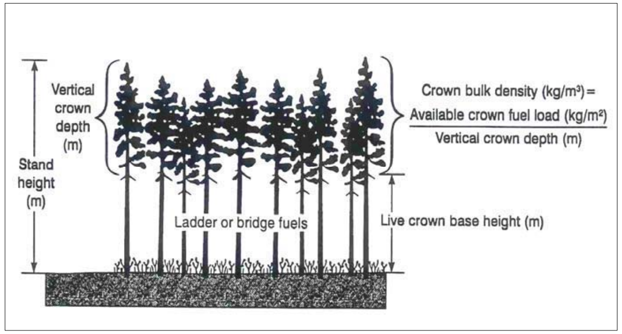
The transition from a surface fire to a crown fire is obviously of great interest and concern to fire managers since crown fires represent a level of fire behavior that normally precludes any direct fire suppression action.

Furthermore, the forward spread of the fire typically at least doubles its rate of advance and in turn the area burned for a given period of time is at least four times greater in size because the area burned is proportional to:

(Rate of Spread increase)$^2$

## Why are Crown Fires Significant?

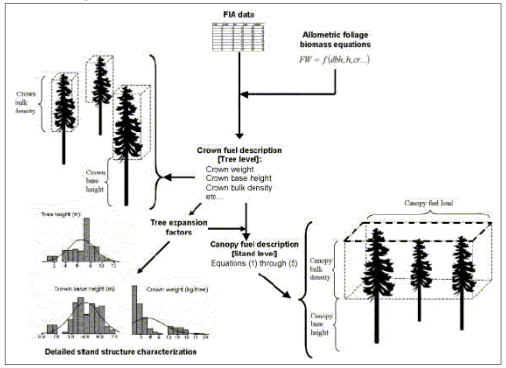
## Aerial (Crown or Canopy and Ladder) Fuel Properties




**Ladder Fuels:** bark flakes, lichens, needle drape, boles branches (live & dead), understory conifers, tall shrubs

**Available Crown Fuel Load:** needle foliage, lichens, small dead and live (a proportion) twigs < 1 cm in diameter

## Flow diagram illustrating linkages used to estimate canopy fuel characteristics from forest inventory data biomass equations




from Cruz, Alexander and Wakimoto (2003) – *Int. J. Wildland Fire*

## Type of Crown Fire:

## Passive, Intermittent or Dependent

**Passive Crown Fires can occur under two broad situations:**

- Canopy base height and canopy bulk density are considered optimum but fuel moisture and wind conditions are not quite severe enough to induce full-fledged crowning

- Canopy base height and canopy bulk density are, respectively, above and below the thresholds generally considered necessary for crowning so that even under severe burning conditions full-fledged crowning is not possible, although vigorous, high-intensity fire behavior can occur.

## Type of Crown Fire:

## Active, Running or Continuous

**An Active Crown Fire is most likely to occur in forests that have:**

- Ground and surface fuels that permit development of a substantial surface fire
- A moderately high canopy or crown base height
- A fairly continuous crown layer of moderate to high bulk density and low to normal foliar moisture content

**Reported cases in which strong winds coupled with low amounts of available fuel (either because of light pre-burn fuel quantities and/or moisture conditions) have limited the degree of crowning, in spite of the fact that the surface fire behavior characteristics exceeded accepted threshold conditions for crown fire initiation.**

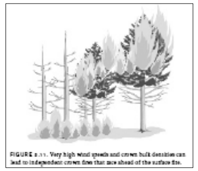
**Some examples:**

- 1967 Tasmanian Fires (Luke & McArthur 1978)
- 1972 Burnt Fire, Arizona (Dieterich 1979)
- 1988 Bemm River Fire, Victoria (Buckely 1992)
- 1991 Myalup Fire, Western Australia (Smith 1992)
- 1991 Spokane Wash. Firestorm (NFPA 1992)

## Type of Crown Fire:

## Independent

**?**



**Van Wagner (1977) on the Independent Crown Fire:**

*"The crown phase will … no longer depend in any way on the surface phase and can run ahead on its own."*

**North slope** *of the South Mowich fire on the northwest flank of Mount Rainier is shown here as it looked on June 3, 1987, 27 days after the fire started. Many of the tall trees have sparse crowns from being burned and snow still remains between the tree clusters.*

**Incidents of crown fires spreading over top of small to moderate size snowdrifts in conifer forest stands on steep slopes during the spring have been reported.**

**For example:**

Mowich Fire – May 7, 1987
Mount Rainier National Park
Washington

Huff (1988) *Park Science* 8(3): 22-23.

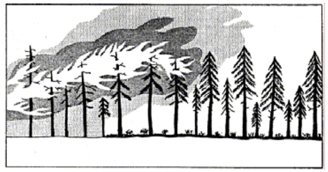
**Panther River Fire – Banff National Park – May 27, 1999**

Originated from a spot fire produced from prescribed burning. Fire spread more than 7 km in ~ 90 min (ROS: ~78 m/min or 4.7 km/h) through mature spruce-fir forest on a north-facing slope. The top 1/3 of the slope was still snow covered and the bottom 2/3rds had a full saturated duff layer. Little or no surface fuel consumption in most areas. Park personnel were "very surprised".

Air temperature 17$^{o}$C
Relative Humidity 17%
10-m Open Wind speed
20 km/h

Mottus & Pengelly (2004)
Proc. 22$^{nd}$ Tall Timbers
Fire Ecol. Conf.

**Independent crown fire runs are undoubtedly a short-lived phenomena. In any event, how far ahead of the surface fire can we expect the crowning phase to advance?**



- A distance of 40 m was observed on the 1955 Balmoral Forest Fire in New Zealand (Prior 1958).
- Kurbatsky (1969) reported ~150 m.

Van Wagner (1977) indicated that stand conditions favouring development of independent crown fire runs are, presumably, a continuous crown layer of low to moderate bulk density and an abnormally low foliar moisture content.

"*The concept of independent crown fire remains dubious … true independent crown-fire spread ahead of the surface phase could only proceed if the flame front from crown base to flame tip were titled well forward, perhaps so much as to approach the horizontal. In other words, the spread of crown fire independent of any surface fire is essentially ruled out as a stable phenomenon on level terrain. The concept may still have value in rough or steep terrain and as a short-term fluctuation under the most extreme conditions …*" **– Van Wagner (1993)**

1979 Ship Island Fire, Idaho

From video ***Look Up, Look Down, Look Around***

## Basic Features of a Crown Fire

- Fierce radiation due to flame heights (up to 50+ m)
- Sustained runs possible (e.g., 64 km in 10 hrs)
- Wide range in rate of spread (0.6 - 12 km/h)
- Narrow range in fuel consumption (1.5 - 6 kg/m$^2$)
- Very wide range in fire intensities (2500 – 100,000 kW/m)
- Flame front residence time in tree crowns at least half that of ground surface
- Contributes to medium and long-range spotting and in turn breaching of major barriers to fire spread
- High amounts of convective energy produce massive convection columns

## Fire Intensity Spectrum

10 kW/m – Lower limit of surface fire spread

100 kW/m – Prescribed underburns

1000 kW/m – Limit of suppression capability by hand crews

10 000 kW/m – Active crown fires have developed

100 000 kW/m – Major conflagrations

## Fire Intensity (Byram 1959)

$$I = H \times W \times R$$

| $I$ | $H$ | $W$ | $R$ |
|---|---|---|---|
| **Fire Intensity (kW/m)** | **Heat of Combustion (18 000 kJ/kg)** | **Fuel Consumed (kg/m$^2$)** | **Rate of Fire Spread (m/sec)** |

Fire intensity is the rate of energy release, or rate of heat release, per unit time per unit length of fire front

## Flame Front Residence Times in Crown Fires

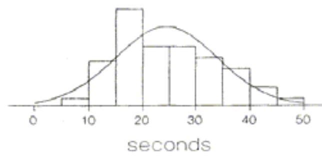



**Figure 1.** Distribution of flame duration in burning crowns of lodgepole pine trees and stands. Curve represents a normal distribution.

Old Faithful Inn fire run – Sept. 8, 1988

Despain *et al.* (1996) determined the duration of flaming combustion in lodgepole pine crowns averaged 25±10 seconds (range: 5-48) based on analysis of videotape footage taken during the 1988 Yellowstone fires.

## Early Work and References to Crown Fires

**Molchanov (1957) conclusions based on calculation of heat balances and visual evidence:**

• Crown fires are increasingly difficult to start as the crown base increase in height aboveground

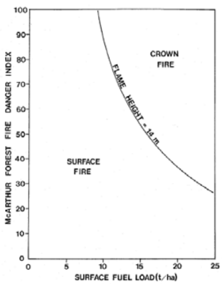
• Crown fires generally required a surface fire to supply part of the heat needed for lateral spread

• Only in a very strong wind and when crown conditions are ideal can the crown phase spread by itself, and such behavior is erratic.

**McArthur (1965)**

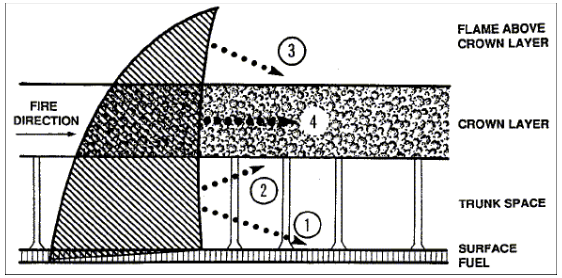
Case study analysis of the effects of low pruning on the development of crown fires in radiata pine plantations

**McArthur (1967)**




On the back of his Forest Fire Danger Meter, the conditions for crown fire development in eucalypt forests were defined in terms of fuel quantity and fire danger index

**Van Wagner (1968)**




Schematic diagram illustrating the four components of forward radiated heat transfer in an active crown fire: trunk space radiates to (1) surface fuels and (2) crown fuels; flame above the canopy radiates to (3) crown fuels; and flame within the crown fuel layer radiates (4) throughout the layer.

**Fahnestock (1970):**
"*No technique is available for calculating the mathematical probability that a fire will crown under given conditions*."

Developed dichotomous key ranks crowning potential on a scale of 0 to 10 based on ladder fuels and general tree crown characteristics

**Sando *et al.* (1970)**
"*What fuel-weather combinations are required to produce a propagating crown fire in northern flatland forests*?"

**Kerr *et al.* (1971)**
"*In the foreseeable future there is little prospect of predicting the behavior of a fast spreading crown fire in timber over any extended period of time.*"

**Taylor et al. (1975) survey**

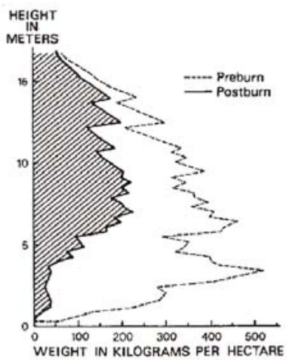
*"Will fire in a thinned stand tend to stay on the ground as opposed to crowning? What the effects of various spacings? What spacing inhibits spread of [crown] fire?"*

"*Crown fires are quite a threat in the ponderosa pine of the Black Hills. Extreme burning conditions may cause crowning any time of the day or night. Based on slope, what tree spacing would allow full stocking and yet be most desirable for separating tree crown to preclude crown fire ignition?*"

"*How many tons/acre of fuel are required to support a crown fire in ponderosa pine and in mixed conifer forest in the Southwest?*"

"*What stand and crown density is required to carry a fire in standing pinyon-juniper stands?*"

**Kilgore and Sando (1975)**




Authors quantified the effect of a prescribed fire on the crowning potential in the understory conifers beneath a giant sequoia stand

**McArthur (1977)**

"*The 1972 U.S. National Fire Danger Rating System states quite definitely that it only considers an 'initiating fire'. This is defined as a fire which is not behaving erratically and is spreading without spotting through fuels which are continuous with the ground (no crowning) …*"

"*After fourty years of research into fire weather and fire behaviour, it is shocking admission of the inadequacy of the research program if we must eliminate that segment of the fire danger/fire behavior spectrum which includes all major fires which probably account for around 90-95 per cent of the fire damage in a severe fire season.*"

Mature Jack Pine Stand,
Northeastern Ontario

Mature Jack Pine Stand,
Northeastern Alberta

**Immature Jack Pine Stand, Northeastern Ontario**

**Red Pine Plantation, Petawawa, Ontario**

**Lodgepole Pine Stand, central British Columbia**

Lowland Black Spruce Stand, North-central Alberta


Spruce-budworm Killed Balsam Fir Stand,
Northeastern Ontario

Spruce-Lichen Woodland Stand,
Northwest Territories

### Crown Fire Prediction in mid 90s – Limitations:

- Canada – empirical approach couldn't be sustained indefinitely
- United States – interim model only following the 1988 fire season in Yellowstone (Rothermel 1991 considered his methods as "first order approximations of crown fire behavior")

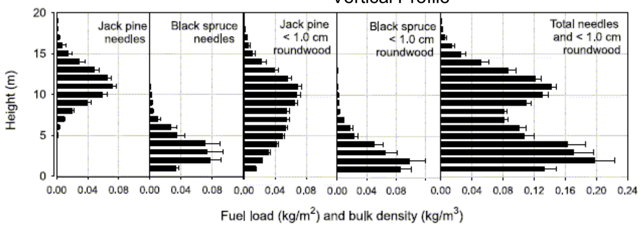
**This led to the birth of International Crown Fire Modelling Experiment (ICFME)**

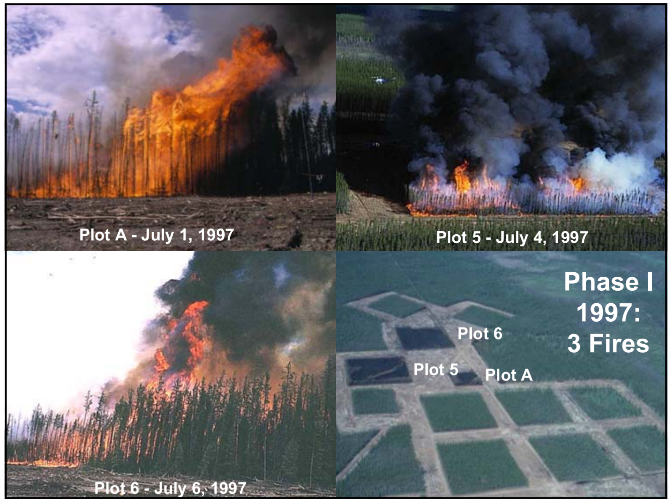


### ICFME Fuel Complex

13-m tall Jack Pine Overstory with a shorter Black Spruce Understory

Vertical Profile





**Phase II 1998: Only 2 Fires!!!**

**1998 certainly tested our resolve**




**Phase III
1999**

Continued …




**Phase III
1999:
6 Fires
total**




**Phase IV
2000**

Continued …



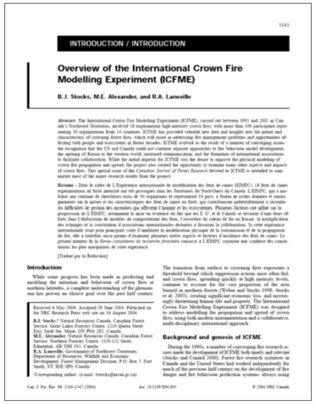

**Phase IV
2000:
7 Fires
total**

## Characteristics of ICFME Fires

- Typical of Active Crown Fires in the Boreal Forest
- Rate of Advance: 1- 4 km/h (16-70 m/min)
- Fuel Consumed: 4-5 kg/m$^2$
- Fire Intensities: 13,000 - 93,000 kW/m
- Flame Front: 2-3 Times Tree Height
- Well-defined Convection Columns
- Spotting: prolific; up to 200-300 m
- 10 Primary Fires & 8 Secondary Fires

NO Escapes!


*Fire Management Today*
**Summer 2005**




*Canadian Journal of Forest Research*
**July 2004**


## Van Wagner's (1977) Theory on Initiation of Crowning: Starting with Two Basic Equations

Temperature rise ($\Delta T$) at height $z$
over a line heat source, $I$
(after Thomas 1963)

$$\Delta T \propto I^{2/3}/z$$

Heat of ignition ($h$ – kJ/kg) in relation to
foliar moisture content ($m$ - %)
(from Van Wagner 1968)

$$h = 460 + 25.9 \cdot m$$

## Van Wagner's (1977) Theory on Initiation of Crowning: The Transformation of Equations

Assumptions: $\Delta T$ required for crown ignition at arbitrary value of $h$ we will call $h_o$ and the actual $\Delta T$ at $z$ or the crown base height (m) varies with the ratio $h/h_o$. Thus:

$$\Delta T \cdot (h/h_o) \; \alpha \; I^{2/3}/z$$

Replacing $\Delta T/h_o$ with an empirical quantity $C$ yields:

$$I_o = (C \cdot z \cdot h)^{3/2}$$

where $I_o$ is the critical surface intensity (kW/m) needed to initiate crowning and $C$ is a criterion for initial crown combustion

## Van Wagner's (1977) Criterion for Initial Crown Combustion

"*The quantity* $C$ *is best regarded as an empirical constant of complex dimensions whose value is to be found from field observations.*"

A value of 0.010 was derived for $C$ from an experimental fire in a red pine plantation ($z$ = 6 m and $m$ = 100%)exhibiting an intensity of ~ 2500 kW/m just prior to crowning as follows:

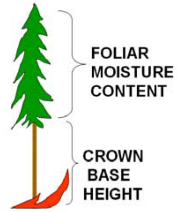
$$C = I_o/(z \cdot h)^{3/2}$$

$$C = 2500/(6 \cdot (460 + 26 \cdot (100)))^{3/2}$$

$$C = 0.010$$

## Van Wagner's (1977) Crown Fire Initiation Model

Vertical fire spread into the overstory canopy will occur when the surface fire intensity ($I_s$) attains the critical value $I_o$ as determined by $z$ and $m$.




$I_s < I_o$: Surface Fire

$I_s \sim I_o$: Surface Fire - Crown Fire Transition

$I_s > I_o$: Crown Fire

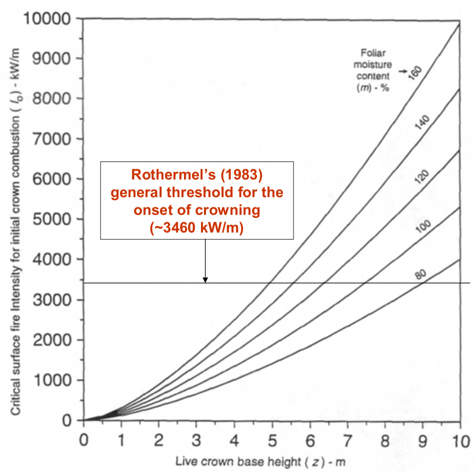
## Van Wagner's (1977) Crown Fire Initiation Model
Assumptions

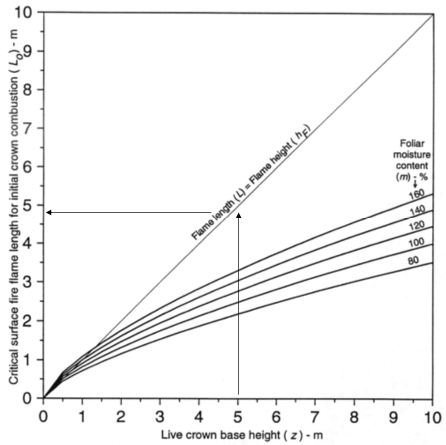
- "*Vertical spread of fire into the overstory canopy is for practical purposes independent of the canopy bulk density*".
- "*… bridge fuels must presumably be present in sufficient quantity to intensify the surface fire appreciably as well as to extend the flame height*".

### Minimum Crown Bulk Density to Define the $z$ or Canopy Base Height

Various estimates but little or no laboratory research to quantify threshold value.

- Sando and Wick (1972 – 0.037 kg/m$^2$
- Williams (1977) – 0.074 kg/m$^2$
- Scott and Reinhardt (2001) – 0.011 kg/m$^2$




Assuming Byram's (1959) flame length-fire intensity relation is valid and flame height = flame length, then we can see that the flames of a surface fire don't have to necessarily reach into the tree crowns to initiate crowning

**Van Wagner's (1977) Crown Fire Initiation Model: Strengths and Weaknesses**

**Simplicity:**

Only two crown fuel properties (***z*** and ***m***) and an estimate of potential surface fire intensity required as inputs

**Limitations**:

- Truth of the matter is, that separate ***C*** values are required for distinctly different fuel complexes – furthermore, currently used value (0.010) is essentially based on a single observation.
- Doesn't allow for variable duration of heating (presently flame front residence time a constant 50 sec) – thus, quite possible for two fires to have the same intensity but significantly different residence times (e.g., grass vs. conifer needle forest floor).
- Surface burning conditions (i.e., temp, RH, plus in-stand wind and thus fire plume angle) a constant rather than a variable.

**Van Wagner's (1977) Crown Fire Initiation Model**

Presently implemented in the Canadian FBP System and in turn *PROMETHEUS* – the Canadian Wildland Fire Growth Model

http://www.firegrowthmodel.com/

And all major fire behavior decision support systems used in the U.S. (***BehavePlus***, ***FARSITE***, ***NEXUS***, ***Fire and Fuels Extension*** to the ***Forest Vegetation Simulator***, ***FlamMap***, and the ***Fuels Management Analyst***).


## Other U.S. Applications

Keyes and O'Hara (2002) Flow Chart for Targeting Canopy Base Height and Bulk Density to Resist Crown Fire Initiation and Spread

---

**Calculation of Fire Intensity per Byram (1959)**

$$I = H \cdot W \cdot R$$

**Calculation of Byram's Fire Intensity in the context of Rothermel (1972)**

$$H \cdot W = H_A$$

$$H_A = I_R \cdot t_r$$

$$I = I_R \cdot t_r \cdot R$$

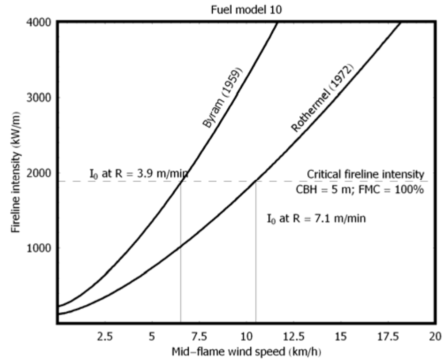
where $H_A$ is the heat per unit area (kJ/m$^2$), $I_R$ is the reaction intensity (kW/m$^2$) as per Rothermel (1972), and $t_r$ is the flame front residence time (sec) as per Anderson (1969) relation based on the characteristic surface-area-to-volume ratio for the fuelbed.

**Result:**

$I$ values calculated via Rothermel (1972) are up to ~1/2 to 2/3 lower compared to Byram (1959)

---

Thus, when Van Wagner's (1977) crown fire initiation model is implemented in the context of the various U.S. fire behavior decision support systems, it is grossly underestimating the presumed onset of crowning.




Fuel moistures:

1-hr TL – 7%
10-hr TL – 8%
Woody – 30%

Slope steepness:

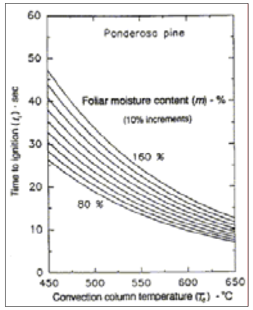
Level terrain

---

**Xanthopoulos (1990) Crown Fire Initiation Model**

Comprised principally of two laboratory experiments:

- Time to ignition – convection temperature – moisture relationships for foliage of 3 conifers (ponderosa pine, Douglas-fir, and lodgepole pine); see Xanthopolous and Wakimoto (1993) →




- Time-temperature profiles at different heights based on flame and convection column temperature measurements in wind tunnel fires (questions of scale effects, realism of the wind tunnel environment and real-world evaluation)

## Alexander (1998) Crown Fire Initiation Model

Based on a combination of physical insights and mathematical modelling coupled with relevant field and laboratory experiments -- Exemplifies the art & science of fire behavior modelling. Goal was to develop a simple algorithm to predict the onset of crowning in exotic pine plantations of Australasia.

The temperature (ºC) at the live crown base height z (m) is calculated from the following equation (after Yih 1951, Thomas 1963, Van Wagner 1973, 1975):

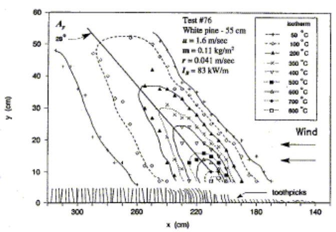
$$T_c = T_a + \frac{k \cdot I^{2/3} \cdot \sin A_P}{z}$$

where $k$ is a fuel complex specific proportionality constant (dimensionless), $I$ is fire intensity (kW/m), $A_P$ is the fire plume angle (º), and $z$ is the live crown base height (m).

## Alexander (1998) Crown Fire Initiation Model

$A_P$ is calculated as follows where $U$ is the in-stand wind speed (m/s) based on a model developed from data extracted from wind tunnel fires (Fendell *et al.* 1990):

$$A_P = \tan^{-1} \cdot (0.209 \cdot (I/U^3)^{0.286})$$




## Alexander (1998) Crown Fire Initiation Model

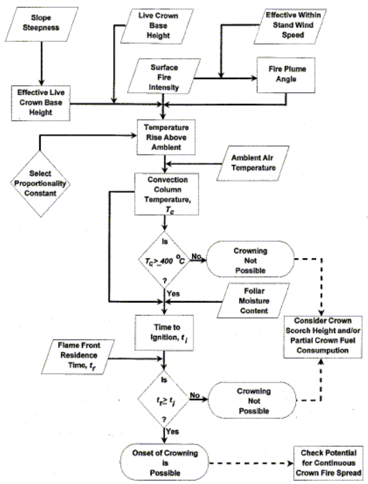
If $T_c$ < 400 ºC, then presumably crowning is not possible.
If $T_c \geq$ 400 ºC then the time to ignition ($t_i$ – sec) is calculate as follows were $m$ is the foliar moisture content (from Xanthopolous and Wakimoto 1993):

$$t_i = 291.917 \cdot exp(-0.00664 \cdot T_c + 0.00729 \cdot m)$$

If the flame front residence time $t_r$ is < $t_i$ then presumably crowning is not possible. If $t_r \geq t_i$ then crown fire initiation is possible.

"*The general underlying assumption … is that the convective heating by the surface fire supported by radiation drives off sufficient moisture in the lower tree crowns to enable the ignition or initial crown combustion to take place from a pilot flame source(s) thereby "triggering" an uninhibited chain reaction.*"– Alexander (1998)

## Alexander (1998) Crown Fire Initiation Model




The constant $k$ = 16 for needle fuelbeds and $k$ = 9 for thinning slash & dense understory vegetation; developed methodology for using crown scorch heights to derive $k$.

Model tested favourably against 8 experimental fires (QLD,WA, ACT and NSW) and one detailed wildfire case study (QLD).


Definition of a Fire Behavior Model Evaluation Protocol: A Case Study Application to Crown Fire Behavior Models

Miguel G. Cruz, Martin E. Alexander, and Ronald H. Wakimoto

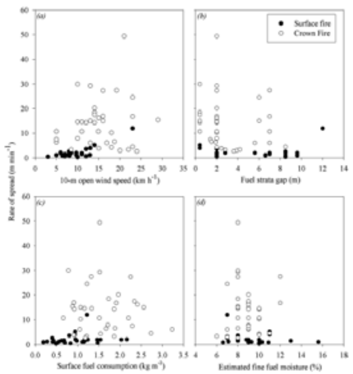
Introduction

Cruz, Alexander and Wakimoto (2003) proposed a model evaluation protocol that encompasses five aspects:

- Model conceptual validity
- Data validation
- Sensitivity analysis
- Predictive validation
- Model comparison

## Cruz, Alexander and Wakimoto (2004)
## Crown Fire Occurrence Probability Model

(based initially on Cruz 1999 MSc Thesis; Cruz *et al.* 2002)




- Comprehensive review of the literature
- Number of variables examined
- Data available for 34 surface fires & 37 crown fires (principally Canadian but a few fires from Portugal and Australia)

## Cruz, Alexander and Wakimoto (2004)
## Crown Fire Occurrence Probability Model


Modeling the Likelihood of Crown Fire Occurrence in Conifer Forest Stands

Miguel G. Cruz, Martin E. Alexander, and Ronald H. Wakimoto

October 2004 – *Forest Science*

Logistic regression model requires three environmental inputs:

- 10-m open wind speed (***$U_{10}$***);
- Fuel strata gap (***FSG***);
- Estimated fine fuel moisture (***EFFM***);

and one fire behavior description:

- Surface fuel consumption (***SFC***) class (<1, 1-2, >2 kg/m$^2$)

**Threshold for Crown Fire Occurrence judged to be 50% Probability.**

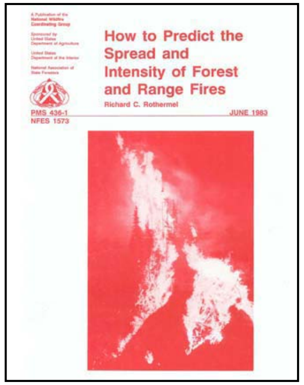
## Cruz, Alexander and Wakimoto (2004)
## Crown Fire Occurrence Probability Model

The ***FSG*** represents the vertical distance between the top of the surface fuelbed and the lower limit of the aerial or crown fuel layer constituted by ladder and canopy fuels capable of sustaining vertical fire propagation (e.g., bark flakes, dead tree bole branches).

For example, in immature jack pine stands described by Stocks (1987), the measured canopy base height (***CBH***) was 4 m (Van Wagner 1993). However, a FSG value of 2 m (i.e., ½ of the ***CBH***) was assigned by the basis of the abundance of ladder fuels present in the trunk space.

Admittedly, in some conifer forest stands, the ***FSG*** would be equivalent to the ***CBH***.

## Effective Fine Fuel Moisture (*EFFM*)
(from Rothermel 1983)

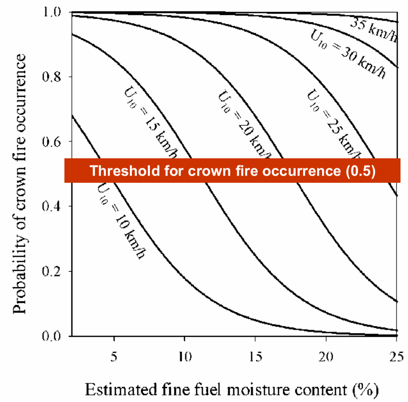



Determined from:
- Air temperature
- Relative Humidity
- Time of Year
- Time of Day
- Degree of Shading (cloud cover & canopy coverage)

Tabular version

Software


## Cruz, Alexander and Wakimoto (2004) Crown Fire Occurrence Probability Model

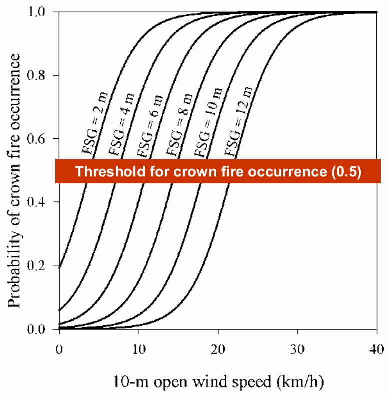



**Effect of Estimated Fine Fuel Moisture (*EFFM*) under variable 10-m Open Wind Speeds (*$U_{10}$*)**

Assume:

*FSG* = 6 m
*SFC* = 1-2 kg/m$^2$

## Cruz, Alexander and Wakimoto (2004) Crown Fire Occurrence Probability Model

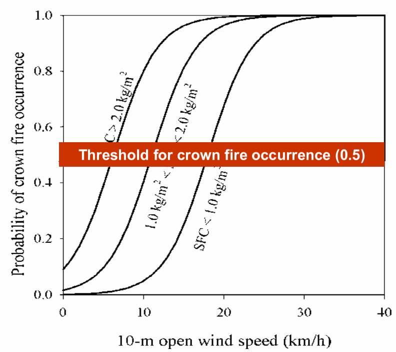



**Effect of 10-m Open Wind Speed (*$U_{10}$*) under variable Fuel Strata Gap (*FSG*)**

Assume:

*EFFM* = 6%
*SFC* = 1-2 kg/m$^2$

## Cruz, Alexander and Wakimoto (2004) Crown Fire Occurrence Probability Model




**Effect of Surface Fuel Consumption (*SFC*) under variable 10-m Open Wind Speeds (*$U_{10}$*)**

Assume:

*EFFM* = 6%
*FSG* = 6 m

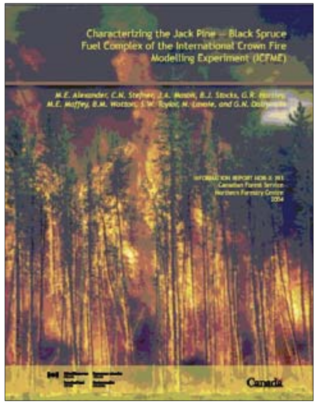
## Evaluation Against Independent Dataset: Porter Lake Project


Alexander *et al.* (1991) Alexander and Lanoville (1989)

## Cruz, Alexander and Wakimoto (2004) Crown Fire Occurrence Probability Model: Evaluation Results

| Observed | Predicted: Surface fire | Predicted: Crown fire | Correctly predicted (%) |
|---|---|---|---|
| Data set used in logistic model development | | | |
| Surface fire | 29 | 5 | 85.3 |
| Crown fire | 6 | 31 | 83.8 |
| Porter Lake experimental fires (Alexander et al. 1991) | | | |
| Surface fire | 0 | 0 | 100 |
| Crown fire | 0 | 8 | 100 |
| ICFME experimental fires (Stocks et al. 2004) | | | |
| Surface fire | 0 | 0 | 100 |
| Crown fire | 0 | 11 | 100 |

## Evaluation Against Independent Dataset: ICFME





## Cruz, Alexander and Wakimoto (2003) Crown Fire Initiation Probability Models


Sep./Oct. 2003 – *Forestry Chronicle*

Four different logistic regression models that use crown base height (***CBH***) and/or 10-m open wind speed (***$U_{10}$***) and components of the Canadian Forest Fire Weather Index System:

1: ***CBH***, FFMC, ***$U_{10}$***, DC
2: ***CBH***, ISI, DC
3: ***CBH***, ISI, BUI
4: ISI, DC

**Cruz, Alexander and Wakimoto (2003) Crown Fire Initiation Probability Models: Evaluation Results**

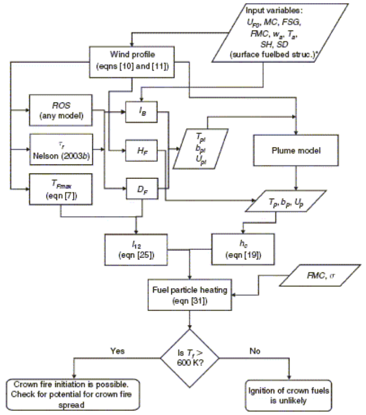
Against Dataset Used in Model Development ($n$ = 63)

| | | LOGIT1 | LOGIT2 | LOGIT3 | LOGIT4 |
|---|---|---|---|---|---|
| Correctly Predicted | Surface fire | 90% | 80% | 83.3% | 74.3% |
| | Crown fire | 91% | 88% | 85% | 58.3% |

Against Independent Datasets

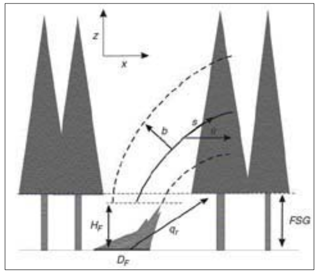
| Model | Type of fire | Porter Lake (Pred./Obs.) | ICFME (Pred./Obs.) |
|---|---|---|---|
| LOGIT1 | Surface fires | 0 / 0 | 1 / 0 |
| | Crown fires | 8 / 8 | 10 / 11 |
| LOGIT2 | Surface fires | 0 / 0 | 2 / 0 |
| | Crown fires | 8 / 8 | 9 / 11 |
| LOGIT3 | Surface fires | 0 / 0 | 3 / 0 |
| | Crown fires | 8 / 8 | 8 / 11 |
| LOGIT4 | Surface fires | 0 / 0 | 2 / 0 |
| | Crown fires | 8 / 8 | 9 / 11 |

**Cruz *et al.* (2006a) Crown Fuel Ignition Model (CFIM)**




- CFIM links several sub-models
- Final model output is the temperature of the crown fuel particles
- A fuel ignition temperature of > 600K is assumed to be required for crown fire initiation

**Cruz (2004 PhD Thesis) Crown Fuel Ignition Model (CFIM)**
(Cruz *et al.* 2006a, b *IJWF* articles & 2006c *VICFFR* paper)




Schematic diagram of the buoyant plume and radiative heat source dimensions in CFIM. Pertinent variables: $D_F$ = flame depth, $H_F$ – flame height, *FSG* = fuel strata gap, and $q_r$ = radiative heat flux

- Based on heat transfer theory and first principles
- Integrates characteristics of the heat source as defined by surface fire, the heat sink as dictated by the crown fuels, and the energy transferred to the crown fuels

**Cruz *et al.* (2006b) Crown Fuel Ignition Model (CFIM): Evaluation Protocol**

- Sensitivity analysis of input parameters
- Comparison against other models (Van Wagner 1977; Alexander 1998; Cruz, Alexander and Wakimoto 2004)
- Experimental fires (correctly predicted 14 of the 15 fires)

| Fire name | $H_F$ (m) | $FSG-H_F$ (m) | $D_F$ (m) | $\tau_r$ (s) | $b_{pi}$ (m) | $U_{pi}$ (m s$^{-1}$) | Max. $T_f$ (K) | Crowing activity CFIM (Y/N) |
|---|---|---|---|---|---|---|---|---|
| VW67_R3 | 2.3 | 4.7 | 3.4 | 66 | 1.7 | 3.3 | 547 | N |
| VW67_R4 | 1.1 | 5.9 | 2.3 | 65 | 1.1 | 2.8 | 392 | N |
| VW67_R5 | 1.3 | 5.7 | 2.9 | 51 | 1.4 | 3.1 | 415 | N |
| VW67_R1 | 2.9 | 4.1 | 6.2 | 57 | 3.1 | 3.9 | >600 | Y |
| BW&B_P1 | 1.8 | 0.6 | 3.8 | 77 | 1.9 | 3.4 | >600 | Y |
| BW&B_P2 | 1.9 | 0.5 | 4.3 | 77 | 2.2 | 3.5 | >600 | Y |
| BW&B_P3 | 1.7 | 0.7 | 3.3 | 75 | 1.6 | 3.2 | >600 | Y |
| McA66 | 1.9 | 8.1 | 6.9 | 104 | 3.4 | 4 | 490 | N |
| VL&L_A2 | 1.4 | 0.4 | 2.1 | 55 | 1 | 2.8 | >600 | Y |
| VL&L_A4 | 0.9 | 0.9 | 0.88 | 52 | 0.44 | 2 | 492 | N |
| VL&L_C2 | 0.3 | 1.5 | 0.53 | 53 | 0.26 | 1.7 | 398 | N |
| PF&al_UN | 2.1 | 2.6 | 5.9 | 98 | 2.9 | 4 | >600 | Y |
| PF&al_RX13 | 1.5 | 2.5 | 2.9 | 92 | 1.5 | 3.1 | 600 | Y |
| PF&al_RX3 | 0.83 | 4.6 | 1.7 | 39 | 0.84 | 2.7 | 416 | N |
| BS&al_Plot8b | 1.6 | 3 | 4.5 | 48 | 2.2 | 3.8 | >600 | Y |

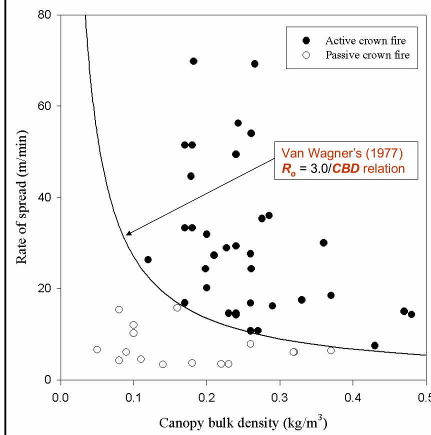

**Van Wagner's (1977)**
**Criteria for Solid Crown Flame**

Based on rearranging a simple heat balance equation (cf. Thomas *et al.* 1964) for fire spread in wildland fuel the following relation was proposed:

$$R_o = S_o/CBD$$

Where $R_o$ is the critical minimum spread (m/min) in order to sustain a continuous flame front within the crown fuel layer, $S_o$ is the critical mass flow rate for solid crown flame (kg/m²-min), and ***CBD*** is the canopy bulk density (kg/m³).

$S_o$ is regarded as an empirical constant to be derived from field observations. Best available estimate (3.0) based on experimental fires in red pine plantations.

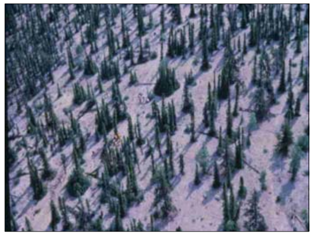



**from Cruz, Alexander and Wakimoto (2005)**

Experimental crown fires used in the development of the Canadian FBP System plotted.

Points of note:

- No passive crown fires with ***CBD*** < 0.05 kg/m³
- No active crown fires with ***CBD*** < 0.11 kg/m³



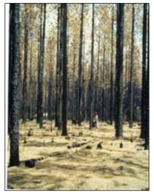
Alexander et al. (1991) found in the Porter Lake Project that Van Wagner's (1977) $R_o$ relation worked reasonably well in a fuel type that you would consider as discontinuous or non-uniform from a crown fuel layer perspective, at least as the stand level.

## Toolara No. 7 Wildfire – SE Queensland – 22 Sep. 1991

**Weather Conditions:** 31 °C, 12% RH, 10-m Open Winds 28 km/h, and 37 days since rain

**Fuel Type:** 19-20 year old Slash Pine Plantations with variable stand tending

Active Crown Fire



Surface Fire

Head Fire Rate of Spread during the major run average 22.5 m/min.

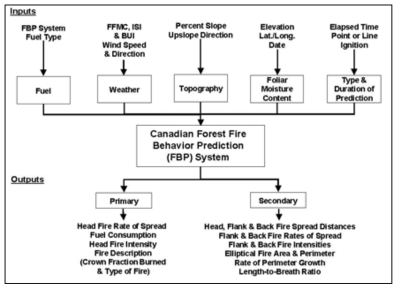
Stands with ***CBD*** ~ less than 0.13 kg/m$^3$ did experience any crowning, although was full crown scorch.


## Van Wagner (1977) Relation vs. ICFME Fires

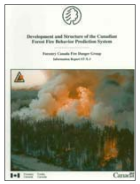
| ICFME Plot | *CBD** (kg/m$^3$) | $R_o$ (m/min) | Obs. ROS (m/min) | Comments |
|---|---|---|---|---|
| A | 0.18 | 16.7 | 56.2 | |
| 1 | 0.24 | 12.5 | 35.3 | |
| 2 | 0.13 | 23.1 | 15.8 | Passive Crown Fire |
| 3 | 0.11 | 27.3 | 24.3 | Active Crown Fire |
| 4 | 0.11 | 27.3 | 44.6 | |
| 5 | 0.15 | 20.0 | 28.9 | |
| 6 | 0.24 | 12.5 | 36.0 | |
| 7 | 0.25 | 12.0 | 69.2 | |
| 8 | 0.19 | 15.8 | 30.7 | |
| 9 | 0.14 | 21.4 | 69.8 | |

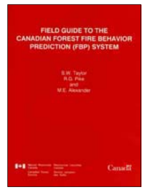
*Needles & roundwood < 1 cm in diameter

## Canadian FBP System

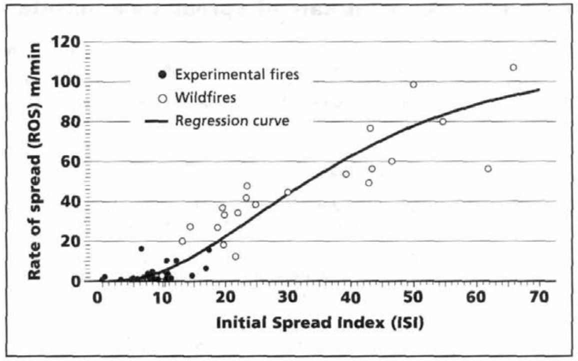



- Interim edition in 1984
- First complete edition in 1992



## Canadian FBP System:
## Surface & Crown Rate of Spread
## (Natural Forest Stands)




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


## Stephan Bridge Road Fire Michigan May 8, 1990

**The following comparisons are based on the major run of the Stephan Bridge Road Fire that occurred between 1540 and 1930 hours EDT on May 8, 1990 using FBP System Fuel Type C-4, a 0% Slope and 100% Foliar Moisture Content:**

| Fire Behavior Characteristic | Predicted | Observed |
|---|---|---|
| Head Fire Rate of Spread (m/min) | 53 | 56 |
| Head Fire Intensity (kW/m) | 51 400 | N/A |
| Forward Spread Distance (km) | 11.6 | 12.9 |
| Area Burnt (ha) | 2885 | 1817 |
| Fire Perimeter (km) | 25.5 | 24.8 |

**Predicted Type of Fire at the "Head" :**

**Continuous Crown Fire (100% Crown Fuel Involvement)**

$$I = H \cdot W \cdot R$$

Assuming that $H$ = 18 000 kJ/kg and $R$ (m/sec) x 60 gives the rate of spread ($R_{m/min}$) in m/min, we have:

$$I = 300 \cdot W \cdot R_{m/min}$$

The critical surface fire rate of spread (call it ***RSO***) associated with the onset of crowning is found by replacing the critical surface intensity (call it ***CSI***) for crown combustion for fire intensity in the above equation and working backwards, gives the following result were W is replaced by the surface fuel consumption (SFC):

$$RSO = \frac{CSI}{300 \cdot SFC}$$

**Canadian FBP System**
**Type of Fire Classification Scheme**

| CFB* | Type of Fire |
|---|---|
| < 0.1 | Surface Fire |
| 0.1-0.89 | Intermittent Crown Fire |
| ≥ 0.9 | Continuous Crown Fire |

*Crown Fraction Burned (***CFB***): Degree of potential crown fuel involvement expressed as a proportion of the total number of tree crowns involved in the crown combustion process.

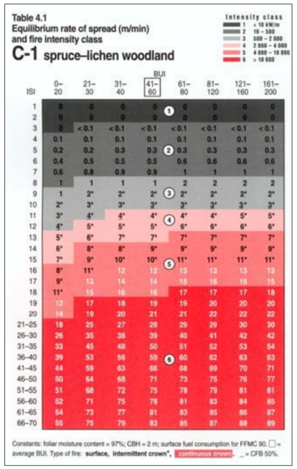


Table 4.1
Equilibrium rate of spread (m/min) and fire intensity class
C-1 spruce–lichen woodland

Intensity class: 1 < 10 kW/m; 2 10 – 500; 3 500 – 2 000; 4 2 000 – 4 000; 5 4 000 – 10 000; 6 > 10 000

| ISI | BUI 0–20 | 21–30 | 31–40 | 41–60 | 61–80 | 81–120 | 121–160 | 161–200 |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| 4 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| 5 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| 6 | 0.4 | 0.5 | 0.5 | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 |
| 7 | 0.6 | 0.8 | 0.9 | 0.9 | 1 | 1 | 1 | 1 |
| 8 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 |
| 9 | 1 | 2* | 2* | 2* | 2* | 2* | 2* | 2* |
| 10 | 2* | 3* | 3* | 3* | 3* | 3* | 3* | 3* |
| 11 | 3* | 4* | 4* | 4* | 4* | 4* | 5* | 5* |
| 12 | 4* | 5* | 5* | 5* | 6* | 6* | 6* | 6* |
| 13 | 5* | 6* | 7* | 7* | 7* | 7* | 7* | 7* |
| 14 | 6* | 8* | 8* | 9* | 9* | 9* | 9* | 9* |
| 15 | 7* | 9* | 10* | 10* | 11* | 11* | 11* | 11* |
| 16 | 8* | 11* | 12 | 12 | 13 | 13 | 13 | 13 |
| 17 | 9* | 13 | 14 | 14 | 15 | 15 | 15 | 15 |
| 18 | 11* | 15 | 16 | 16 | 17 | 17 | 17 | 18 |
| 19 | 12 | 17 | 18 | 19 | 19 | 20 | 20 | 20 |
| 20 | 14 | 19 | 20 | 21 | 21 | 22 | 22 | 22 |
| 21–25 | 18 | 25 | 27 | 28 | 29 | 29 | 30 | 30 |
| 26–30 | 26 | 35 | 38 | 39 | 40 | 41 | 42 | 42 |
| 31–35 | 33 | 45 | 48 | 50 | 51 | 52 | 53 | 54 |
| 36–40 | 39 | 53 | 56 | 59 | 60 | 62 | 63 | 63 |
| 41–45 | 44 | 59 | 63 | 66 | 68 | 69 | 70 | 71 |
| 46–50 | 50 | 64 | 68 | 71 | 73 | 75 | 76 | 77 |
| 51–55 | 51 | 68 | 72 | 75 | 78 | 79 | 81 | 81 |
| 56–60 | 52 | 71 | 75 | 78 | 81 | 83 | 84 | 85 |
| 61–65 | 54 | 73 | 77 | 81 | 83 | 85 | 86 | 87 |
| 66–70 | 55 | 75 | 79 | 83 | 85 | 87 | 88 | 89 |

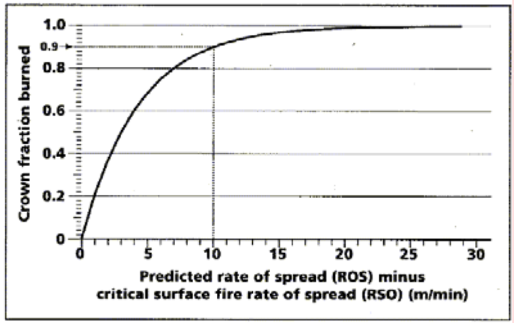
Constants: foliar moisture content = 97%; CBH = 2 m; surface fuel consumption for FFMC 90. □ = average BUI. Type of fire: **surface**, **intermittent crown***, continuous crown. _ = CFB 50%.

Sample page from FBP System "Red Book"

For a given fuel type, each table provides the following:

- Head fire rate of spread;
- Type of fire (surface, intermittent crown or continuous crown); and
- 50% CFB threshold.

A transition function was scaled so that the degree of crowning was 90% complete when the predicted rate of spread exceeded the ***RSO*** by 10 m/min.




It's worth noting that this function is not based on any data but rather on expert opinion (Van Wagner 1989).

**Crown Fraction Burned (CFB) Transition Function**
(Van Wagner 1989; Forestry Canada Fire Danger Group 1992)

$$CFB = 1 - exp\,(-a \cdot (ROS - RSO))$$

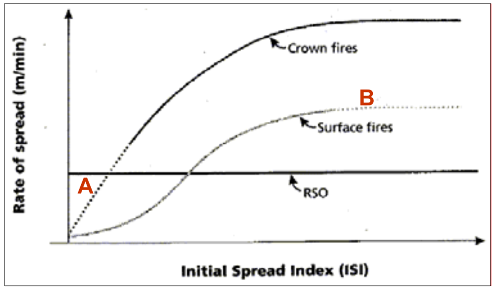
where ***ROS*** is the predicted rate of fire spread. The ***a*** coefficient equals 0.23 when ***CFB*** = 0.9 and ***ROS*** exceeds ***RSO*** by 10 m/min.

Later on Van Wagner (1993) proposed the following equation in order to calculate the ***a*** coefficient for variable canopy fuel characteristics:

$$a = \frac{-ln\,(0.1)}{(0.9(R_o - RSO)}$$

Both approaches allow for a gradual transition from surface to crown fire (note that this is an assumption).

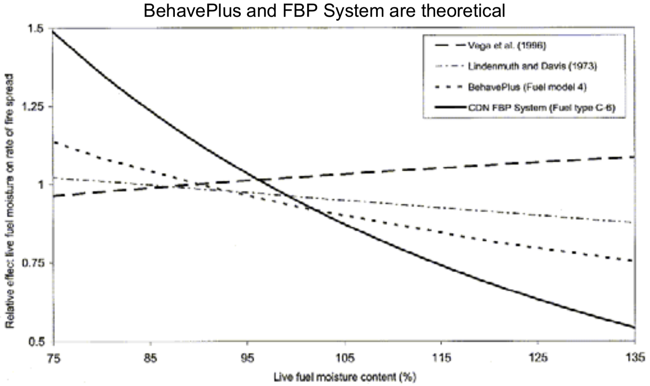
## Canadian FBP System: Dual Rate of Spread (ROS) Model Form (Conifer Plantation (C-6) Fuel Type)




**The lower (A) and upper (B) portions of the surface and crown fire ROS curves, respectively, are unlikely to be used.**

## Relative Effect of Live Fuel Moisture on Crown Fire Rate of Spread in Shrublands and Conifer Forests

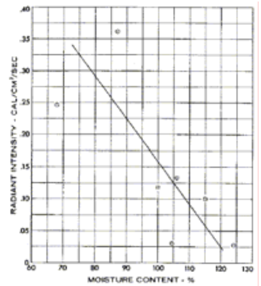
Vega *et al.* (1996) and Lindenmuth & Davis (1973) are empirical and BehavePlus and FBP System are theoretical




## Foliar Moisture Content (*m*) Effect on Crown Fire Rate of Spread

There has certainly been a number of "Christmas Tree" studies carried out in the laboratory which have quite dramatically shown the influence of needle moisture content on the flammability of individual trees.

However, what about a stand of trees and specifically the effect of ***m*** on the spread rate Of crowning forest fires?



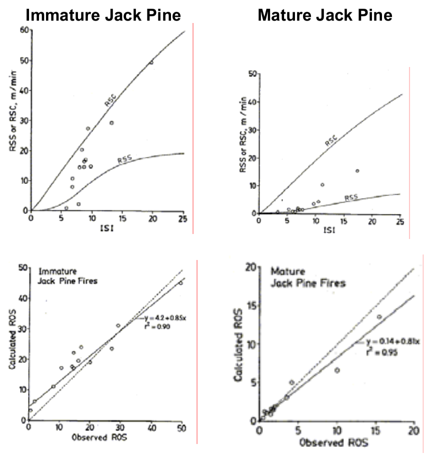

**Effect of *m* on maximum radiant intensity 0.9 m from single 1.5 m high burning white spruce trees (from Van Wagner 1967).**

## Foliar Moisture Content (*m*) Effect on Crown Fire Rate of Spread

"*Ideal evidence to substantiate this theory would be a set of crown fire spread data in some uniform conifer fuel types under similar weather of weather and surface fuel, foliar moisture content being the only variable. This is a very tall order.*" – Van Wagner (1974)

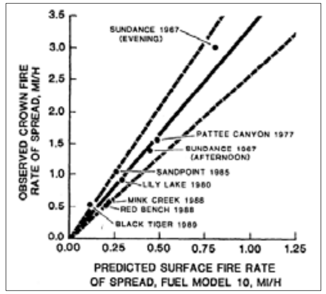
Red Pine Plantation Experimental Fires (***SH*** = 15 m) (after Van Wagner 1974)

| Exp. Fire | Spread Rate (m/min) | Fire Intensity (kW/m) | ***m*** (%) | Flame Height (m) |
|---|---|---|---|---|
| C4 | 16.8 | 21,000 | 135 | 19.8 |
| C6 | 27.4 | 22,500 | 95 | 30.5 |

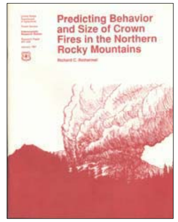



Van Wagner (1993) showed the utility of this approach based on datasets from experimental fires carried out in immature (Stocks 1987) and mature (Stocks 1989) jack pine stands in NE Ontario.

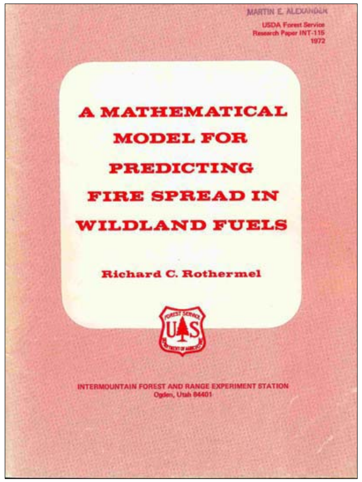
## Rothermel (1991) Rate of Spread "Model" for Wind-driven Crown Fires




A statistical correlation between the predicted surface fire rate of spread for Fuel Model 10 (wind reduction factor 0.4) and 8 western U.S. wildfire observations




**Ave. Crown Fire ROS = 3.34 x Surface Fire ROS**
**Max. Crown Fire ROS = 1.7 x Ave. Crown Fire ROS**

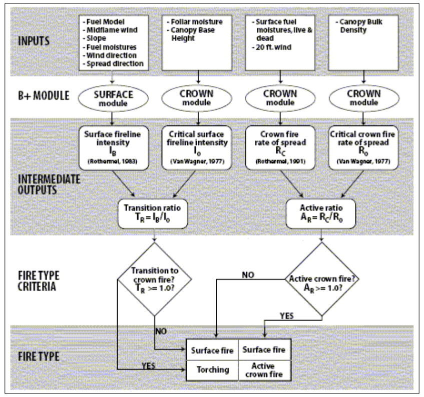



"*The nature and mechanisms of heat transfer in a crown fire are considerably different than those for a ground [surface] fire. Therefore, the model developed in this paper is not applicable to crown fires.*"

Rothermel (1972)

## Crown Fire Logic in *BehavePlus* Version 3.0

(Andrews *et al.* 2005)




Incorporates Van Wagner's (1977) crown fire initiation model and Rothermel's (1991) crown fire rate of spread model but there no transition function for scaling rate of spread between surface fire and active crown fire, although ratios are outputted.

**From BehavePlus Training Lesson 13 – Crown Fire (www.fire.org)**

## Coupling Rothermel's Surface Fire (1972) and Crown Fire (1991) Rate of Spread Models

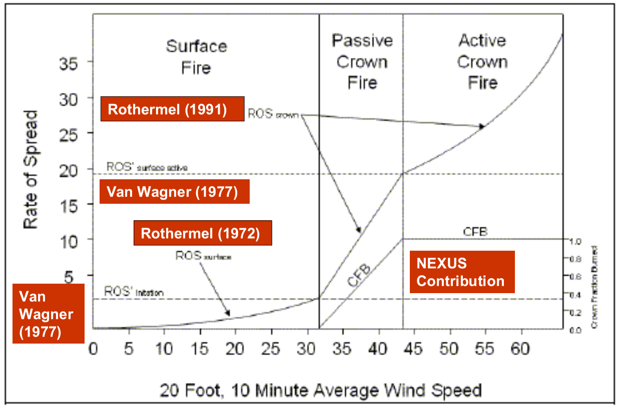
• ***FARSITE*** and ***FlamMap*** uses the Van Wagner (1993) approach (i.e., a unique ***a*** coefficient to calculate ***CFB*** as dictated by the critical surface fire spread rate (based on ***SFC***, ***CBH*** and ***m***) for the onset of crowning and critical minimum spread rate for active crowning (based on ***CBD***).

• ***NEXUS*** (and in turn the ***FFE-FVS***) uses a linear relation between the critical surface fire spread rate (based on ***SFC***, ***CBH*** and ***m***) for the onset of crowning and critical minimum spread rate for active crowning (based on ***CBD***).

• ***Fuels Management Analyst*** includes both the ***FARSITE***/***FlamMap*** and ***NEXUS***/***FFE-FVS*** methods

For copy of user guide see:
http://www.fireps.com/software/ug_cm3.pdf

## NEXUS Simulation (Scott and Reinhardt 2001)




## CFB Transition Functions: Comparison Against ICFME Fires

- ***NEXUS*** (Scott and Reinhardt 2001) – predicted that all 10 ICFME fires would advance as intermittent crown fires (***CFB*** range 0.12-0.84)

- ***FARSITE*** (Finney 1998) – predicted all 10 ICFME fires would advance as intermittent crown fires (***CFB*** range 0.09-0.46)

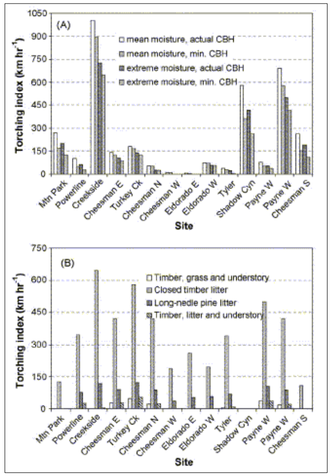
Cruz, Alexander and Wakimoto (2005) Crown Fire Rate of Spread Model predicted that nine of the 10 ICFME fires would advance as active or fully developed crown fires (***CAC*** for Plot 2 = 0.68).

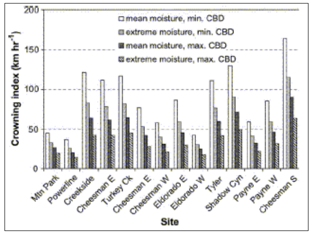
## NEXUS: Two Indices of Crown Fire Hazard
(Scott and Reinhardt 2001)

The **Torching Index** (**TI**) is the 6.1-m open wind speed at which crown fire is expected to initiate based on Rothermel's (1972) surface fire model and Van Wagner's (1977 crown fire initiation model. The **TI** is a function of surface fuel characteristics (fuel model), ***m***, ***CBH***, slope steepness, and wind reduction by the canopy.

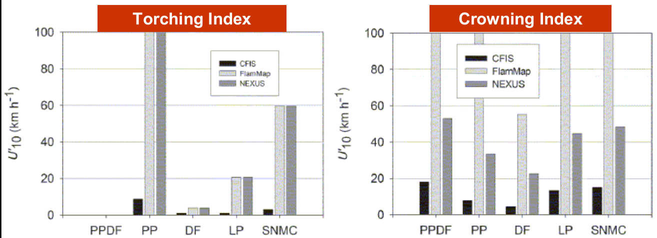
The **Crowning Index** (**CI**) is the 6.1-m open wind speed at which active crowning is possible based on Rothermel's (1991) crown fire rate of spread model and Van Wagner's (1977) criterion for active crown fire spread. The **CI** is a function is a function of ***CBD***, slope steepness and surface fuel moisture content.

The under-predictions in the critical surface fire intensity for the onset of crowning coupled with the under-predictions in Rothermel's (1991) crown fire rate of spread model have lead to highly questionable results (e.g., Hall and Burke 2006).



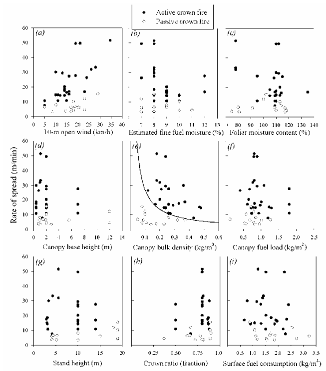

"*Wind speeds above 100 km h⁻¹ occur so rarely that crown fire can be considered nearly impossible to initiate for U10 > 100 km h⁻¹*". – Scott (2006)




| | PPDF | PP | DF | LP | SNMC |
|---|---|---|---|---|---|
| Stand | Ponderosa Pine/ Douglas-fir | Ponderosa Pine | Douglas-fir | Lodgepole Pine | Mixed Conifer |
| ***CBH*** (m) | 0 | 5 | 1 | 1 | 2 |
| ***CBD*** (kg/m$^3$) | 0.089 | 0.166 | 0.257 | 0.112 | 0.101 |

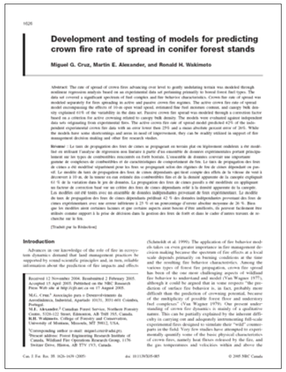
## Cruz, Alexander and Wakimoto (2005)
## Crown Fire Rate of Spread Models

(based initially on Cruz 1999 MSc Thesis; Cruz *et al.* 2002)




- Comprehensive review of the literature
- Number of variables examined
- Data available for 24 active crown fires and 13 passive crown fires

## Cruz, Alexander and Wakimoto (2005)
## Crown Fire Rate of Spread Models




***Canadian Journal of Forest Research***
**August 2005**

Separate models for predicting passive and active crown fire spread rates based on three environmental inputs:

- 10-m open wind speed (***$U_{10}$***)
- Canopy bulk density (***CBD***)
- Estimated fine fuel moisture (***EFFM***)

**Cruz, Alexander and Wakimoto (2005)**
**Crown Fire Rate of Spread Models: The Equations**

$$CAC = \frac{CROS_A}{3/CBD}$$

***Active Crown Fires*: CAC ≥ 1.0**

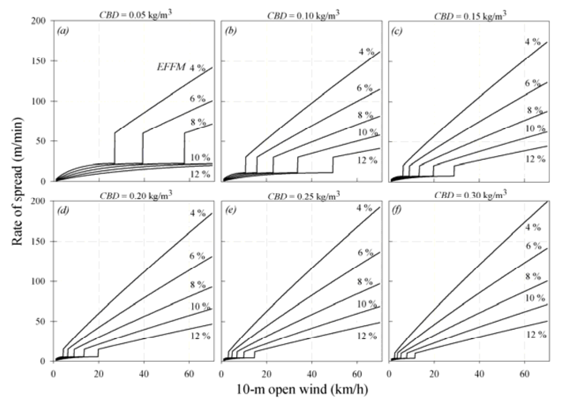
$$CROS_A = 11.02 \cdot (U_{10})^{0.9} \cdot CBD^{0.19} \cdot exp(-0.17 \cdot EFFM) \quad , U_{10} > 0.0$$

***Passive Crown Fires*: CAC < 1.0**

$$CROS_P = CROS_A \cdot exp(-CAC)$$

where ***CAC*** is the criterion for active crowning dimensionless), ***CBD*** is the canopy bulk density ($kg/m^3$), $U_{10}$ is the 10-m open wind speed km/h), ***EFFM*** is the estimated fine fuel moisture (%), $CROS_A$ is the active crown fire rate of spread (m/min), and $CROS_P$ is the passive crown fire rate of spread (m/min).

**Cruz, Alexander and Wakimoto (2005)**
**Crown Fire Rate of Spread Models**




**Cruz, Alexander and Wakimoto (2005)**
**Crown Fire Rate of Spread Models:**
**Major Underlying Assumption**

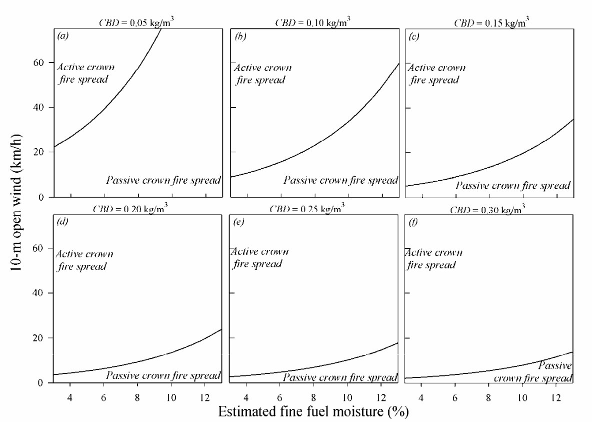
The abrupt changes or sudden increases in behavior (i.e., spread rate and fire intensity) that occurs when a fire crowns has been has been incorporated into the modelling.

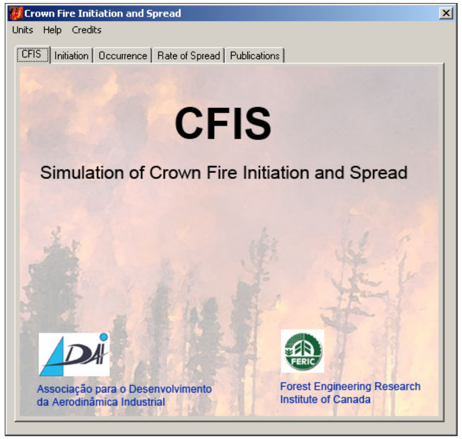
There is plenty of observational evidence to support this claim. For example, while observing the behavior of a series of experimental fires in a maritime pine plantation in Western Australia, Burrows *et al.* (1988) reported that:

"*… when crowning did occur, then fire spread rates were 2-5 times that of ground [surface] fires*".

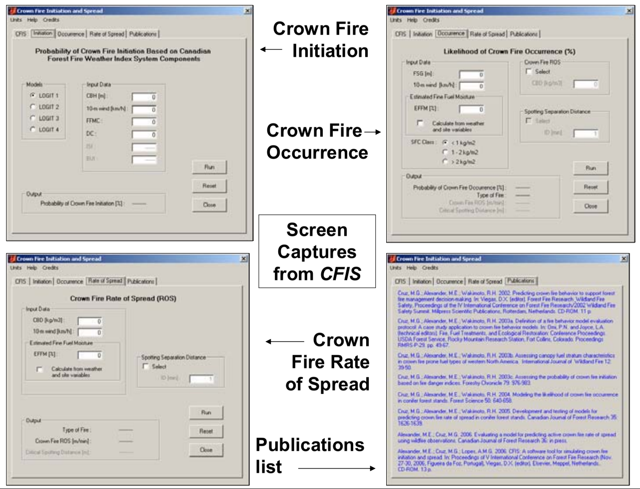
**Mount Muirhead Fire, South Australia - 16 February 1983**
Radiata Pine Plantation Fuel Types
Head Fire ROS 207 m/min (12.4 km/h) with winds >80 km/h
Model predictions for 80 km/h winds: 212 m/min (12.7 km/h)

## Cruz, Alexander and Wakimoto (2005) Crown Fire Rate of Spread Models




**Cruz, Alexander and Wakimoto (2003, 2004, 2005) crown fire behavior models have now been incorporated into a software package.**




The models comprising ***CFIS*** are considered most valid for free-burning fires that have reached a pseudo steady-state, burning in live, boreal or boreal-like conifer forests (i.e., they are <u>not</u> applicable to insect-killed stands).

Level terrain is assumed as the ***CFIS*** does <u>not</u> presently consider the mechanical effects of slope steepness on crown fire behavior.

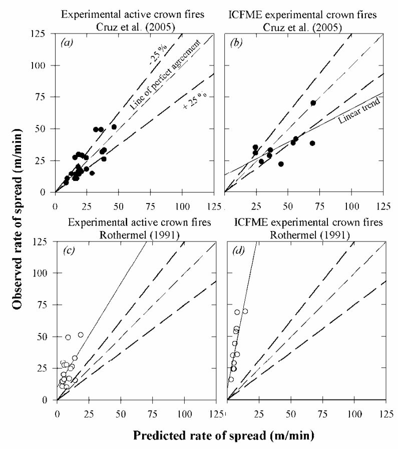
The models underlying the ***CFIS*** are <u>not</u> applicable to prescribed fire or wildfire situations that involve strong convection activity as a result of the ignition pattern.

## On Validating *NEXUS*

"*Due to a lack of high-quality validation data, this and similar methods have not been validated … Gathering high-quality data from prescribed and wild fires for building and testing models of fire behavior should be made a high priority*". – Scott and Reinhardt (2001)

## On Management Implications of Crown Fire Modelling Systems (FlamMap, NEXUS and CFIS)

"*… the output from these systems must be compared with observation and experience to determine the suitability of the system … this analysis compares the modeling systems only with each other, not with the truth;" we do no know the truth.*"– Scott (2006)



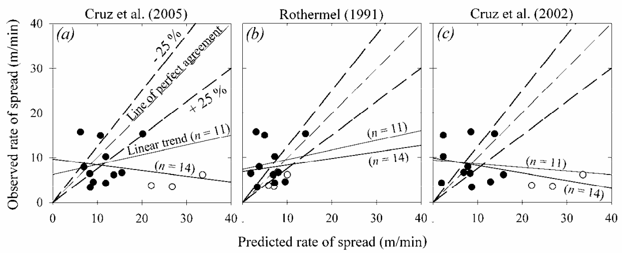

Crown Fire Rate of Spread Models: Evaluation Against Experimental Active Crown Fires

Rothermel (1991) under-predicts by a factor of 2-5 and shows little sensitivity to burning conditions.

from Cruz, Alexander and Wakimoto (2005)

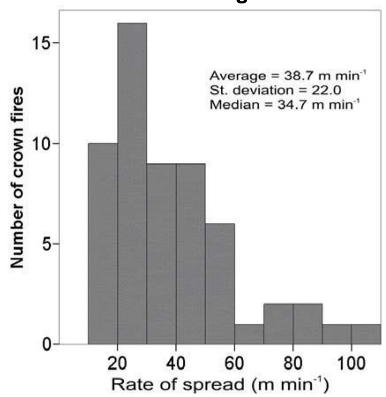
## Crown Fire Rate of Spread Models: Evaluations Against Experimental Passive Crown Fires

The 3 open circles (o) represent Porter Lake experimental fires. Analysis was carried out with and without these fires.




from Cruz, Alexander and Wakimoto (2005)

## Crown Fire Rate of Spread Models: Evaluations Against Wildfire Observations

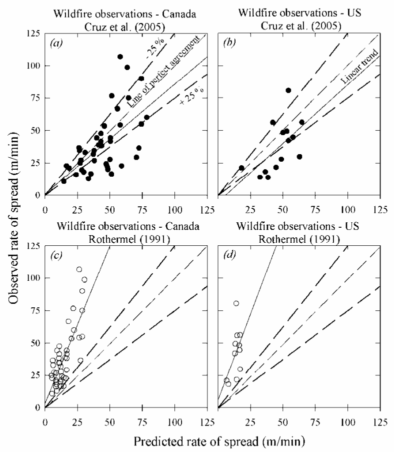



Canadian dataset consisted of 43 observations; composed chiefly of fires in boreal forest fuel types.

U.S. dataset consisted of 14 observations (some from Rothermel 1991); mostly fires in pine stands in the interior Rocky Mountains, the Lake States, and SE U.S.

from Alexander and Cruz (2006)

## Crown Fire Rate of Spread Models: Evaluations Against Wildfire Observations




from Alexander and Cruz (2006)

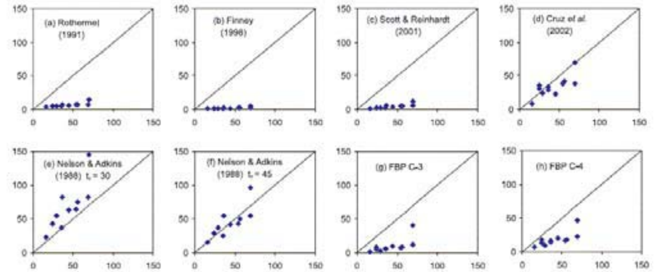
Total of 57 observations

Few data on ***CBD*** (judgement therefore required)

Rothermel (1991) under-predicts by a factor of 2.5-3 and shows little sensitivity to burning conditions.

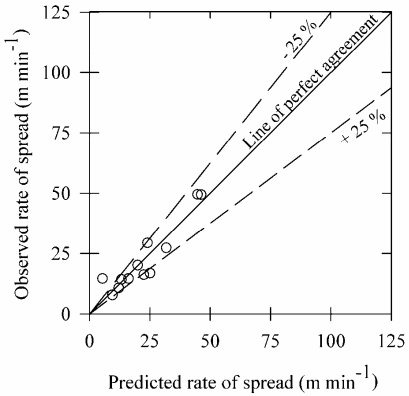
## Summary Comparison of Rothermel (1991), *FARSITE* (Finney 1998), *NEXUS* (Scott & Reinhardt 2001), Cruz *et al.* (2002), Nelson & Adkins (1988), and Canadian FBP System (C-3 & C-4 Fuel Types) Predictions vs. ICFME Fires

**Fig. 6.** Observed forward spread rates (*x*-axis; m/min) of the ICFME fires in comparison to predictions (*y*-axis) from a number of North American fire behaviour prediction systems and models.




From Stocks, Alexander, Wotton et al. (2004)

## Cruz, Alexander and Wakimoto (2005) Model Form (less the *CBD*) applied to Stocks (1987) Experimental Data




from Alexander and Cruz (2006)

***CBD*** averaged 0.235±0.031 kg/m$^3$

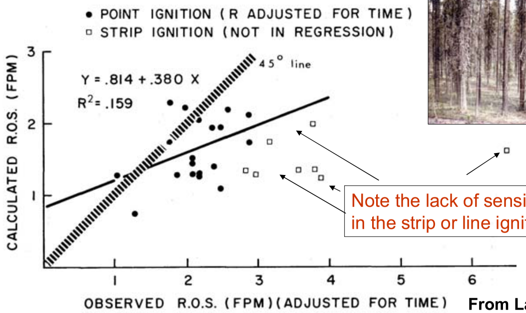
Immature Jack Pine, NE Ontario

## Why is it that Rothermel's (1991) Crown Fire Rate of Spread Model Appears to be Under-predicting and is Relatively Insensitive to Burning Conditions?

- The fires selected for evaluation are not "*Applicable to the Northern Rocky Mountains or mountainous areas with similar fuels and climate*" ???
- The 7 wildfires used in the model development encompass a wide range in fuel complex structure and composition (difficult to critically assess as formal case study documentation is only available for 2 of the 8 fires).
- Only 4 of the 8 observations used in the model development involve level terrain.
- The representativeness of the winds in complex terrain.
- The overall average observed rate of spread for 6 of the 9 observations used in the model development was 25 m/min (1.5 km/h) which seems reasonable. However, 3 fires were around 13.5 m/min (0.8 km/h) which raises the issue about the stage or degree of crown fire activity associated with each wildfire (i.e., developing active crown fire vs. a well developed active crown fire).

Perhaps it's just pure luck that there was any sort of reasonable correlation at all?

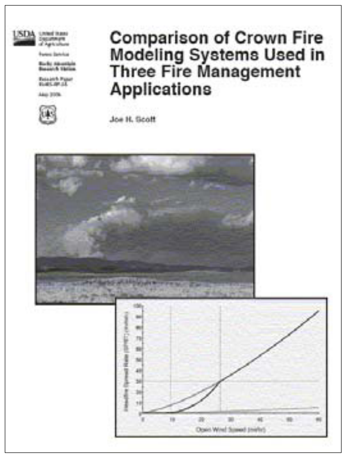
There have admittedly been a few validation studies of Rothermel's (1972) model carried out in slash, grass, and shrubs. However, Lawson's (1972) study in lodgepole pine in NE British Columbia is the only one that involved a relatively compacted forest floor layer.




**From Lawson (1972)**

## Principal Misconceptions about *CFIS* in Scott (2006)

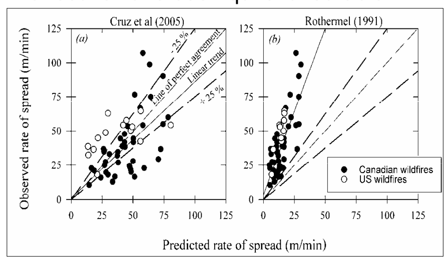
• The experimental crown fires used in the model development were classed as either passive or active on the basis of visual observation and/or photographic evidence (see Cruz, Alexander and Wakimoto 2005, p. 1627).
• The fireguards associated with the experimental fires used in the model development were relatively narrow, typically ~ 10 m wide – see, for example, Stocks (1987, Fig. 2) and Stocks (1989, Fig. 2).
• Abrupt changes in spread rate as wind speed increases does not represent "curious behavior" but is in fact is reality (see Cruz, Alexander and Wakimoto 2005, p. 1632).
• The two phases of active crown fire spread separated by a lull in the gradient wind associated with ICFME Plot 8 (Stocks, Alexander, Wotton *et al.* 2004, p. 1553; Taylor *et al.* 2004, Fig. 4) serves to illustrate that these fires were ignited under conditions that were also conducive to crown fire initiation.




*"Across the range of inputs used in these comparisons, CFIS predicted the highest incidence of crown fire and the highest resulting spread rates, whereas FlamMap predicted the lowest crown fire incidence and lowest spread rates. NEXUS predictions fell between those two systems."*– Scott (2006)

## Model Evaluation

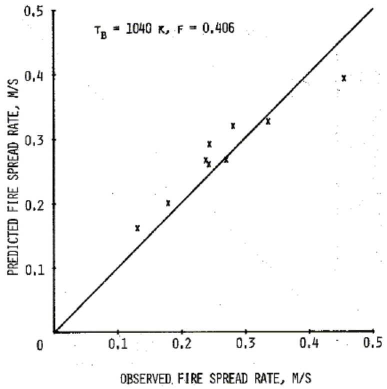
The Cruz, Alexander and Wakimoto (2003, 2004, and 2005) model outputs have been compared to two independent experimental datasets (ICFME & Porter Lake) as well as 57 wildfire observations (43 Canadian & 14 U.S.) obtained from case studies. The results have been quite favourable.





**From Alexander, Cruz and Lopes (2006)**

## Albini and Stocks (1986)
## Physically-based Model for Crown Fire Rate of Sread




Comparisons against the active crown fires in immature jack pine (Stocks 1987) were very good. However, submodels were needed for several parameters (e.g., flame height and tilt angle) in order to achieve model closure.

A radiation-driven model for crown fire spread[1]

B.W. Butler, M.A. Finney, P.L. Andrews, and F.A. Albini

*Canadian Journal of Forest Research*
**July 2004**

In the mid to late 90s Dr.Frank Albini was supported by the Canadian Forest Service and USDA Forest Service to develop a new physically-based rate of spread model for crown fires. The testing and calibration of this model was largely the impetus for ICFME.

**Dr. Frank Albini**
**ICFME 1997**

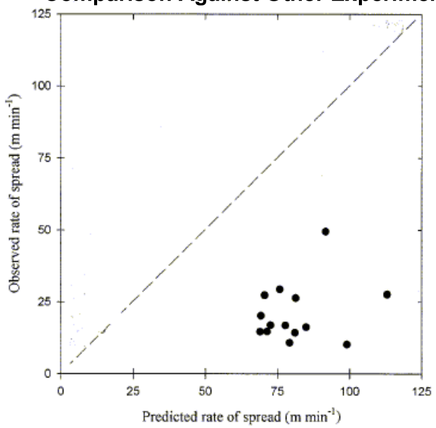
## Albini Physically-based Crown Fire Rate of Spread Model: Comparison Against ICFME Fires

"*Results of the comparison indicate that the model … accurately predicts the relative response of fire spread rate to fuel and environment variables but overpredicts the magnitude of fire spread rates.*" – Butler *et al.* (2004)

| Plot | Effective radiometric temperature (K) | Radiation ratio | Predicted rate of spread (m·min$^{-1}$) | Measured spread rate (m·min$^{-1}$) |
|---|---|---|---|---|
| A | 1200 | 0.30 | 34 | 56 |
| A | 1200 | 0.35 | 62 | 56 |
| A | 1250 | 0.325 | 91 | 56 |
| 5 | 1200 | 0.35 | 61 | 29 |
| 5 | 1250 | 0.325 | 89 | 29 |
| 6 | 1200 | 0.35 | 86 | 36 |
| 6 | 1250 | 0.325 | 127 | 36 |
| 7 | 1200 | 0.35 | 74 | 69 |
| 7 | 1250 | 0.325 | 104 | 69 |
| 8 | 1200 | 0.35 | 121 | 24–54 |

Note sensitivity to temperature and radiation

## Albini Physically-based Crown Fire Rate of Spread Model: Comparison Against Other Experimental Crown Fires




This included experimental active crown fires in immature jack pine, red pine plantation, and black spruce-lichen woodland.

Model output showed large over-predictions.

Measurements of radiant emissive power and temperatures in crown fires[1]

Variation in wind and crown fire behaviour in a northern jack pine – black spruce forest[1]

Canadian Journal of Forest Research
July 2004


All of the current systems for predicting fire behavior that include a crown fire component, except for ***CFIS***, provide for the calculation of fire intensity. Thus, the ***W*** in $I = H \cdot W \cdot R$ includes an estimate of crown fuel consumption (***CFC***) that generally takes the following form:

$$CFC = CFL \cdot CFB$$

where ***CFL*** = available crown fuel load.

**Canadian FBP System Fuel Type Characteristics**

| Fuel Type | Max. Surface Fuel Consumption (t/ha) | Crown Base Height (m) | Crown Fuel Load (t/ha) |
|---|---|---|---|
| C-1 Spruce-Lichen Woodland | 15.0 | 2.0 | 7.5 |
| C-2 Boreal Spruce | 50.0 | 3.0 | 8.0 |
| C-3 Mature Jack or Lodgepole Pine | 50.0 | 8.0 | 11.5 |
| C-4 Immature Jack or Lodgepole Pine | 50.0 | 4.0 | 12.0 |
| C-5 Red and White Pine | 50.0 | 18.0 | 12.0 |
| C-6 Conifer Plantation | 50.0 | 7.0 | 18.0 |
| C-7 Ponderosa Pine/Douglas-fir | 35.0 | 10.0 | 5.0 |
| D-1 Leafless Aspen | 15.0 | - | - |
| M-1 Boreal Mixedwood-Leafless | 50.0 | 6.0 | 8.0 |
| M-2 Boreal Mixedwood-Green | 50.0 | 6.0 | 8.0 |
| M-3 Dead Balsam Fir/Mixedwood-Leafless | 50.0 | 6.0 | 8.0 |
| M-4 Dead Balsam Fir/Mixedwood-Green | 50.0 | 6.0 | 8.0 |
| S-1 Jack or Lodgepole Pine Slash | 80.0 | - | - |
| S-2 Spruce/Balsam Slash | 160.0 | - | - |
| S-3 Coastal Cedar/Hemlock/Douglas-fir Slash | 320.0 | - | - |
| O-1a Matted Grass | 3.0 | - | - |
| O-1b Standing Grass | 3.0 | - | - |

**Summary on Crown Fuel Consumption for the 10 Primary ICFME Fires Based on Post-burn Crown Weight Sampling**
(from Stocks, Alexander, Wotton *et al.* 2004)

Needles – 100%

< 0.5 cm roundwood (overstory & understory – 86%

0.5-1.0 cm roundwood (overstory) – 70%

0.5-1.0 cm roundwood (understory) – 80%

1.0-3.0 cm (overstory) – 42%

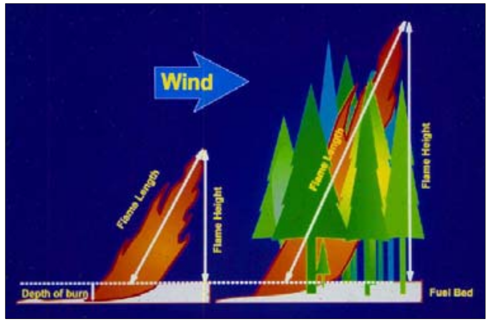


Flame heights in high-intensity crown fires generally <u>average</u> up to 50 m or so with momentary flashes often extending to much greater heights. Sutton (1984) documented a ~192 m flame burst in a radiata pine plantation in South Australia on 16 February 1983.

**Byram (1959) Fire Intensity-Flame Length Relationship**

$$L = 0.0775 \cdot (I)^{0.46}$$

where $L$ is flame length (m) and $I$ is fire intensity (kW/m).




Is this relation valid for crown fires ?

Byram (1959) indicated that his fire intensity-flame length equation would under-predict the flame length for "… *high intensity crown fires because much of the fuel is a considerable distance above the ground*."

He suggested, on the basis of personal visual estimates, that "… *this can be corrected for by adding one-half of the mean canopy height* …" to the flame length value obtained by his equation. Thus, the equation for crown fire flame lengths ($L_c$) taking into account stand height (***SH***) becomes :

$$L_c = 0.0775 \cdot (I)^{0.46} + (SH/2)$$

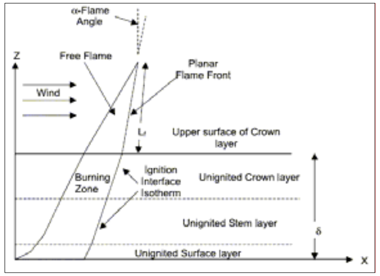
Rothermel (1991) suggested using Thomas' (1963) relation to estimate the flame lengths of crown fires from fire intensity:

$$L_c = 0.0266 \cdot (I)^{2/3}$$

More recently Butler *et al.* (2004) proposed the following relation for calculating the flame lengths of crown fires from fire intensity:

$$L_f = 0.0175 \cdot (I)^{2/3}$$

Where $L_f$ is the flame length measured from the upper surface of the fuel array.




None of these methods seem to work consistently well based on comparisons against experimental crown fires undertaken in Canada. Take, for example, the following experimental crown fires in red pine plantations (*SH* = 15 m) documented by Van Wagner (1977).

| Exp. Fire | Obs. $L_c$ (m) | ------------- Predicted $L_c$ (m) --------- Byram (1959) | Thomas (1963) | Butler *et al.* (2004) |
|---|---|---|---|---|
| C4 | 19.8 | 15.1 | 20.2 | 28.8 |
| C6 | 30.5 | 15.3 | 21.2 | 29.4 |

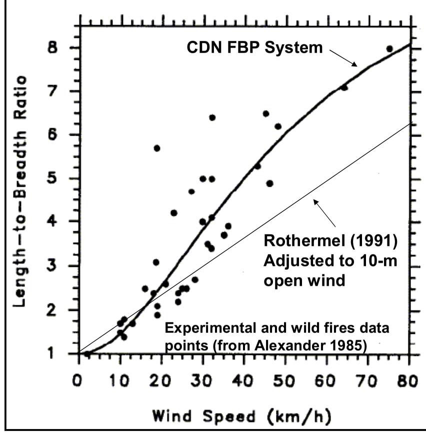
**General Observation Based on Experimental Crown Fires:**

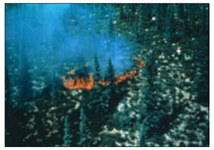
The flame front depth increases as fire intensity increases rather than a corresponding increase in the vertical flame length.

ICFME Plot 9 – Fire Intensity ~93,000 kW/m

**Alexander's Simple Rule of Thumb for Crown Fire Flame Heights: 2-2.5 x Stand Height for Active Crown Fires**

## Wind-driven Crown Fire Shape



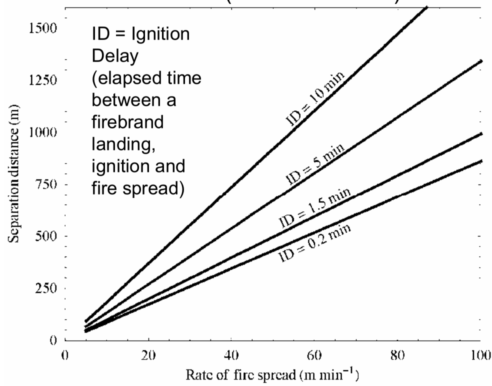



Rothermel's (1991) L/B – wind speed relation does not produce realistic results in light of observational evidence whereas the Canadian FBP System does.

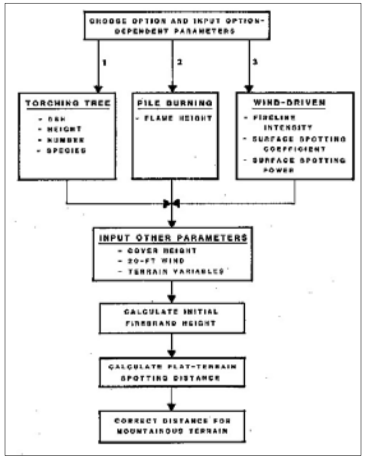

The effect of spotting on a fire's overall rate of advance is implicitly accounted for in the FBP System and in the Rothermel (1991) crown fire rate of spread model as a result of the empirical nature of their development.

## Alexander and Cruz (2006) Spotting Separation Distance Model

(included in ***CFIS***)




Assuming a nominal spread rate of 35 m/min (2.1 km/h), spotting distances would have to exceed 300-700 m in order to increase the overall rate of advance. In-draft effects are not considered.




**Albini Maximum Spotting Distance Models**

**<u>3 Firebrand Sources</u>**

- **Torching tree(s)**
- **Pile Burning**
- **Wind-driven Surface Fires**

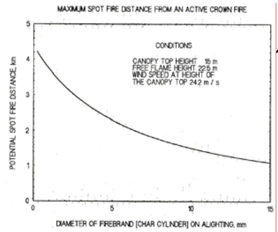
**Albini Spotting Model for Active Crown Fires**
(applicable to level terrain only)

Developed under contract in 1998 based on financial support from several Canadian fire management agencies (coordinator: M.E. Alexander). Effort currently underway to publish in a scientific journal.

<u>Inputs</u>:
- Average Crown Top Height of Forest Cover
- Average Height of Flame Above Canopy Top (observed/estimated <u>or</u> inferred from Fire Intensity)
- Mean Wind Speed at Canopy Top <u>or</u> at Some Height in the " Open" (e.g., 10-m open wind) in which case the Measured Height is entered
- Minimum Diameter of Char Cylinder Firebrand Reaching the Surface or Size Upon Alighting
- Maximum Firebrand Diameter Alighting Diameter

**Albini Spotting Model for Active Crown Fires**

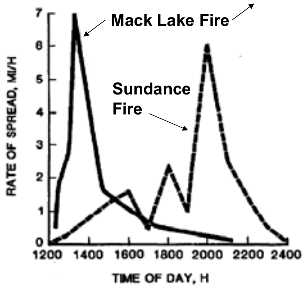
A firebrand of 10 mm in diameter upon reaching the surface "… *should be expected to start spot fires promptly upon alighting*" and that firebrands as small as 1 mm in diameter "… *often will not start spot spot fires [immediately], but they may initiate smouldering combustion in the duff or litter (fermentation layer) on the forest floor, to emerge as flaming fire starts after a considerable delay*." -- Frank Albini (1998)




Sample simulation

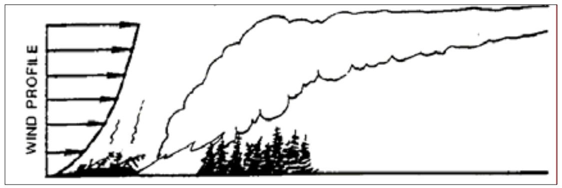

In his publication, Rothermel (1991) identified 3 plume-dominated crown fires:

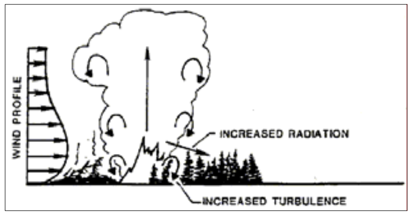
- 1980 Mack Lake Fire, Michigan
- 1985 Butte Fire, Idaho
- 1990 Dude Fire, Arizona




In the case of the Mack Lake Fire, the fire was observed to spread at a rate of 188 m/min (11.3 km/h) over a 20-min period. This was considered as evidence of a plume-dominated crown fire run. I view it simply as a chance observation with no associated wind speeds.

Wind-driven Crown Fire




Plume- or Convection-dominated Crown Fire

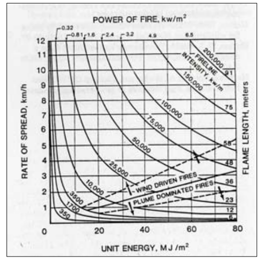
From Rothermel (1991) – 11th Conference on Fire and Forest Meteorology

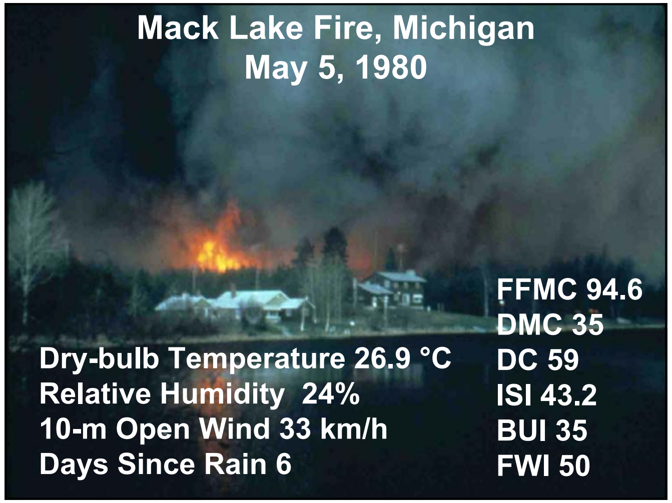
**Rothermel (1991) on Plume-Dominated Crown Fires**

"*The expected spread rate of a plume-dominated fire is not yet predictable …*"

"*The expected spread rates and intensity of plume-dominated fires can be greater than indicated …*"

Rothermel (1991) included Byram's (1959) "Power of the Fire/Power of the Wind" ratio for blow-up fires into his nomograms as an aid to assessing the possible occurrence of plume-dominated crown fires on the basis of the 20-ft open wind speed. According to Byram, the ratio would have to be > 1.0 for at least 300 m above the fire not just at the surface.



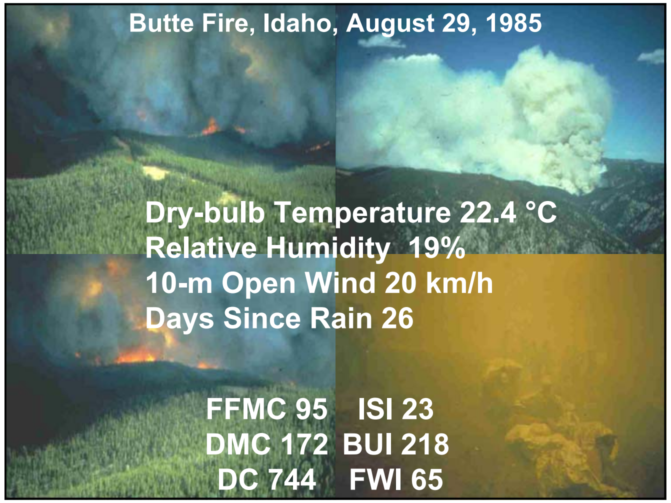
## Mack Lake Fire, Michigan May 5, 1980

**The following comparisons are based on the major run of the Mack Lake Fire that occurred between 1230 and 1600 hours EDT on May 5, 1980 using FBP System Fuel Type C-4, a 0% Slope and 100% Foliar Moisture Content:**

| Fire Behavior Characteristic | Predicted | Observed |
|---|---|---|
| Head Fire Rate of Spread (m/min) | 57 | 56 |
| Head Fire Intensity (kW/m) | 33 660 | 30 440 |
| Forward Spread Distance (km) | 11.5 | 12.1 |
| Area Burnt (ha) | 2534 | 2743 |
| Fire Perimeter (km) | 24.8 | 20.0 |

**Predicted Type of Fire at the "Head" :**

**Continuous Crown Fire (100% Crown Fuel Involvement)**




## Butte Fire, Idaho, August 29, 1985

**The following comparisons are based on the major run of the Butte Fire that occurred between 1430 and 1610 hours MDT on August 29, 1985 using FBP System Fuel Type C-3, a 9% slope and 105% Foliar Moisture Content:**

| Fire Behavior Characteristic | Predicted | Observed |
|---|---|---|
| Head Fire Rate of Spread (m/min) | 22.3 | 24.7 |
| Head Fire Intensity (kW/m) | 43 326 | N/A |
| Forward Spread Distance (m) | 2200 | 2460 |

**Predicted Type of Fire at the "Head" :**

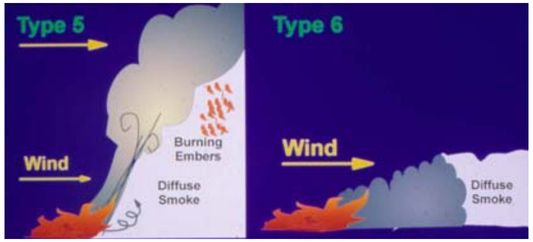
**Continuous Crown Fire (>99% Crown Fuel Involvement)**

### Major Run of the Chisholm Fire – Central Alberta May 28, 2001

Fromm and Servranchx (2003) documented that the fire's convection column reached 13 km in height. In other words, the thermal energy emitted by the fire was sufficient to "punch" through the normally resistant tropopause and into the upper troposphere and lower stratosphere.

Quintilio *et al.* (2001) documented a three hour run in which the observed spread rate was 90 m/min vs. a FBP System predicted spread rate of 92 m/min.

**Smoke Pattern/Convection Column Types**
(from Kerr et al. 1971)

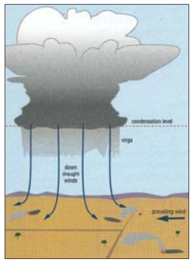


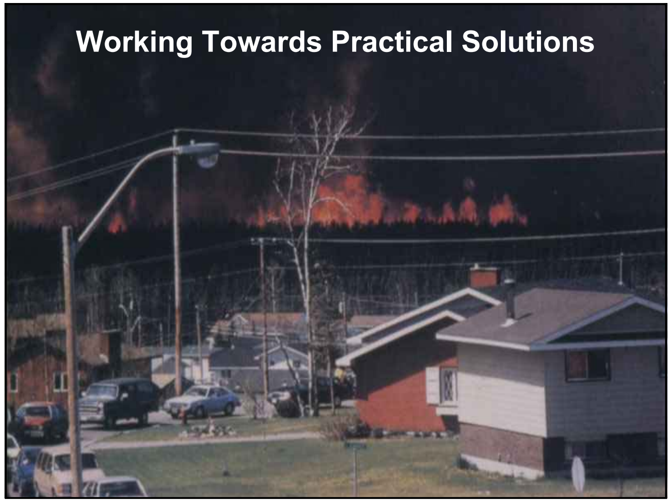

- **Learning convection column with moderate surface winds that strengthen with height.**
- **Rapid, erratic spread with both short- and long-distance spotting.**

- **No rising convection column under strong surface winds.**
- **Very rapid spread driven by combined fire and wind energy; frequent close-in spotting.**

Goens and Andrews (1998) undertook a hindsight analysis of the 1990 Dude Fire in terms of the situation just before, during, and then sometime after the downburst winds that caused the major escalation in the fire's behavior. They indicate that the results from Rothermel's (1991) crown fire rate of spread model "closely agree with the observed fire behavior".

The specific location, timing, duration and strength of downburst winds, including those resulting from collapsing convection columns, are always going to be difficult to forecast as is many other types of mesoscale weather phenomena.

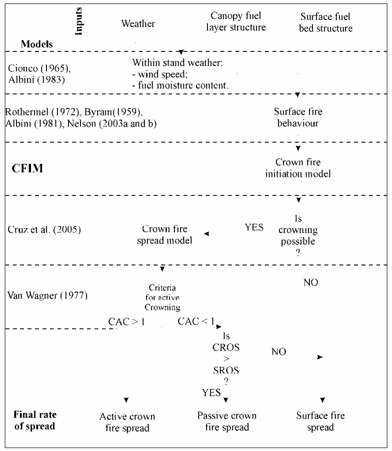





There is a great deal of interest nowadays in applying fire behavior models and systems to issues related to fuel treatments at the stand and landscape level.

Fire managers are seeking answers to questions such as:
- How much ground and surface fuel is acceptable or can be tolerated?
- How high should I prune?
- How much thinning should I do or should I thin at all?
- What percentage of area has to be treated?

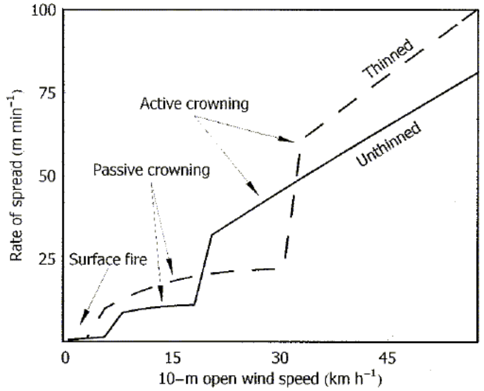
Note that these kinds of questions are not that much different from those poised 30 years ago. The difference is that we have now reached the stage were some of these kinds of questions can be attacked more analytically.




Example of a proposed system for predicting fire behavior potential based on integrating Crown Fuel Ignition Model (**CFIM**) with other models related to predicting surface and crown fire behavior characteristics.

**From Cruz, Butler, Alexander and Viegas (2006)**

**Sample Simulation of Fire Behavior Potential in 12 y.o. Radiata Pine Planations (per Williams 1978)**



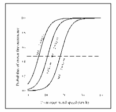

**Thinned***
***W*** **= 1.1 kg/m²**
***FSG*** **= 1.7 m**
***CBD*** **= 0.05 kg/m³**
***EFFM*** **= 5 %**

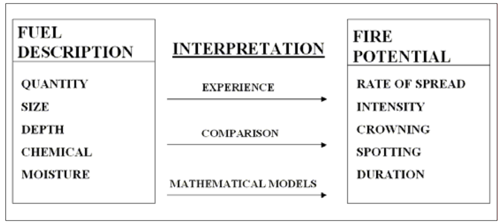
***50% basal area reduction**

**Unthinned**
***W*** **= 0.5 kg/m²**
***FSG*** **= 0.6 m**
***CBD*** **= 0..1 kg/m³**
***EFFM*** **= 7 %**

**From Cruz, Butler, Alexander and Viegas (2006)**

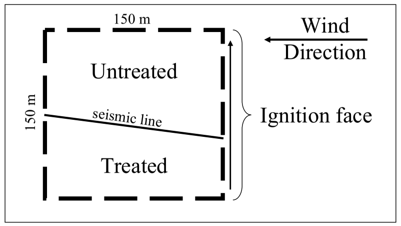
The most effective means of appraising or evaluating potential fire behavior is considered to be the coupling of mathematical modelling with experienced judgement (e.g., “expert opinion”), and comparison against other situations (e.g., published case study knowledge on experimental, wild and prescribed fires).



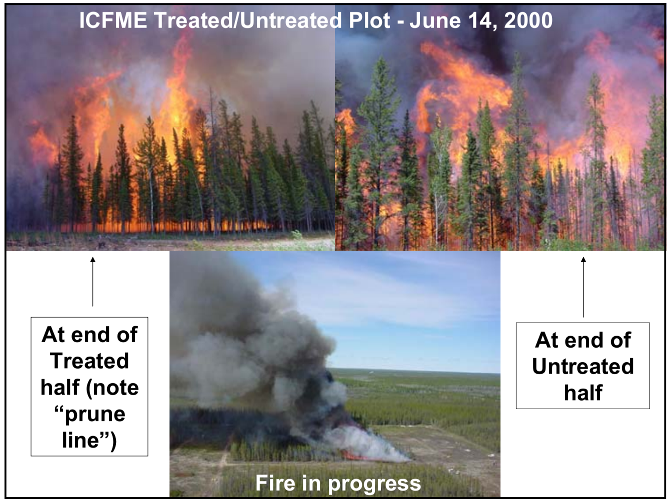


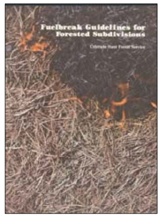

**From Brown (1972)**

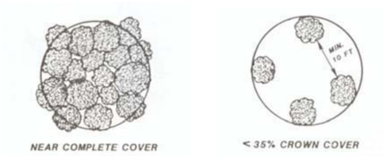
Each approach has its own inherent limitations.

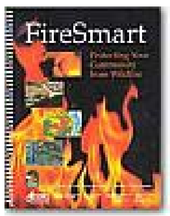




**ICFME Treated/Untreated Plot June 14, 2000**




A 10-ft or 3-m spacing between crowns has been a recommended fuel treatment measure to prevent active crown fire development for some 25 years or so.

Surprisingly, there appears to be no technical or scientific basis for this wildland-urban interface standard.

Surely "one size doesn't fit all".


Mitsopoulos, I.D. 2005. Crown fire analysis and management in Pinus halepensis forests of Greece. PhD Dissertation, Aristotle University of Thessaloniki. (articles to appear in *Int. J. Wildland Fire* and *Ann. For. Sci.* shortly)

Fuel Characteristic Classification System (USDA Forest Service, PNW Research Station, FERA Team, Seattle, WA): Schaaf, M.D.; Sandberg, D.V.; Riccardi, C.L.; Schreuder, M.D. A conceptual model of crown fire potential using the reformulated Rothermel wildland fire behaviour model. (see http://www.fs.fed.us/pnw/fera/fccs/manuscripts/Schaaf_et_al.pdf)

W. Tachajapong, PhD Candidate, University of California, Riverside (supported by USDA Forest Service)
See preliminary work (in VICFFR Procs.): Tachajapong, W.; Zhou, X.; Mahalingam, S.; Weise, D. 2006. Experimental and numerical modeling of crown fire initiation.

## Researching Crown Fires

**Topics Considered Worthy of Investigation/Study:**

- ❑ Vertical fire spread (critical ***CBD***) into the overstory canopy and ladder fuel effects (e.g., bark flakes).
- ❑ Foliar moisture content (***m***) effect on crown fire rate of spread
- ❑ Crown fuel consumption by size class
- ❑ Crown fire flame height model
- ❑ Additional emphasis placed on the prediction of surface fire rate of spread and flame front characteristics (e.g., residence time, intensity).

"*The prediction of surface fire behavior is, in fact, probably more difficult that the prediction of crowning potential, because of the multiplicity of possible forest floor and understory fuel complexes.*" – Van Wagner (1979)

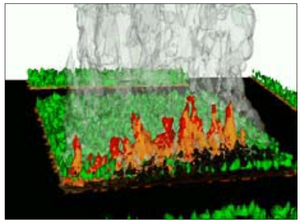
J.D. Cohen, PhD Candidate (and USDA Forest Service, Missoula Fire Lab), University of Idaho, Moscow

Research focusing on convective heat transfer in active spreading crown fires.

"*Preliminary laboratory experiments indicate that radiation heat transfer is not sufficient to sustain fire spread in live fuels.*"– J.D. Cohen (2006, pers. comm.).

See preliminary work (in VICFFR Procs.): Cohen, J.D.; Finney, M.A.; Yedinak, K.M. 2006. Active spreading crown fire characteristics: Implications for modeling.

R. Linn et al., Los Alamos National Laboratory, New Mexico
Testing of HIGRAD/FIRETEC numerical models against the ICFME fires



Graphical simulation

ICFME Plot 5

R. Mell, S. Manzello and A. Maranghides, NIST Building and Fire Research Laboratory, Gaithersburg, Maryland
Testing of WFDS-FDS numerical models against the ICFME fires

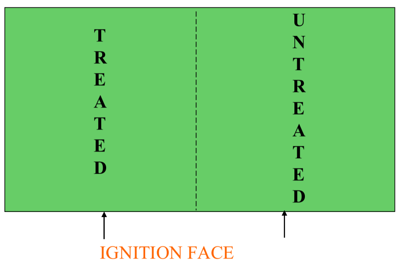
**Some Other Thoughts:**

❑ Physically-based models (e.g., Grishin 1997; Porterie *et al.* 2003, Dupuy and Morvan 2005; Linn *et al.* 2005; Pimont *et al.* 2006) could definitely play a critical role in gauging the effectiveness of fuel treatments in relation to crown fire cessation.

❑ Place a greater emphasis on a more systematic approach to wildfire documentation as opposed to a "snap shot" methodology, including rigorous fuel characterization work (e.g., ***CBH*** and ***CBD***).

❑ Continue to carry out field experimental fires but pay attention to the planning (i.e., have realistic scenarios). Consult widely for opinions.

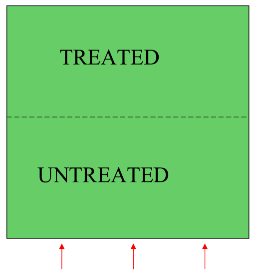
e.g., ICFME Treated/Untreated Plot - burnt June 14, 2000




Strengths:
• Any differences should be readily apparent
• Lull in wind speed not a problem

Limitations:
• Plot face exposure problem (fuel moisture)
• Subject to shift in wind direction after ignition
• Question of one half influencing the other

Alternative Approach to Conducting Experimental Fires for Gauging Fuel Treatment Effectiveness

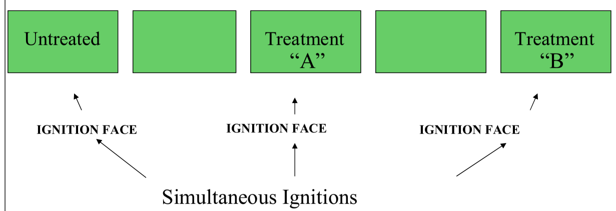



Strength:
• Provided wind speed remains relatively constant, provides direct evidence of treatment effect

Limitation:
• Subject to shift in wind direction after ignition

• Winds could drop off at or near the interface boundary between the two plots

Alternative Approach to Conducting Experimental Fires for Gauging Fuel Treatment Effectiveness




Strengths:
• Lull in wind speed not a problem
• Provides direct evidence of treatment effect

Limitation:
• Subject to shift in wind direction after ignition

"*Fire behavior predictions may not be infinitely valuable; but as long as the forest fire people continue to want better ones, and there are researchers to work on them, it is safe to say that next year's predictions will be better than last year's.*" – Van Wagner (1985)

Keep in mind though the "Fire Behavior Paradox" (Rothermel 1987):

- The models and systems aren't accurate enough.
- The models and systems are too complicated.

Presumably, crude but reliable decision aids are needed at the field level.

Most undertake and support the fundamental research that forms the basis for operational products.

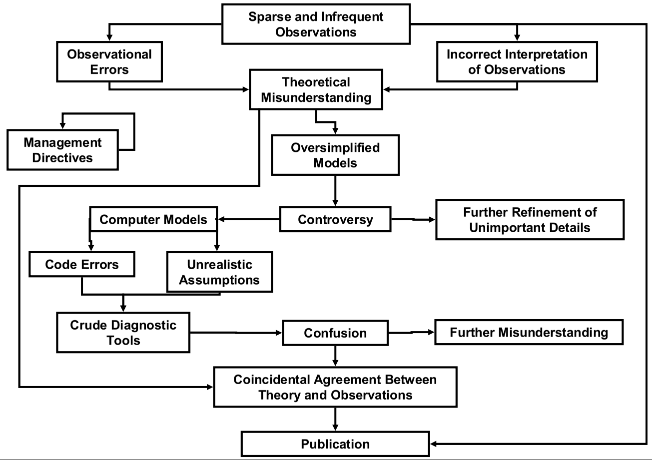

- Know the literature, including the "older stuff".
- Question things.  Be skeptical.
- Insist on realism (Do these results make sense?  Is this what I would expect given the burning conditions?).
- Appreciate that fire researchers and fire modellers are often reluctant to point out the weaknesses in their models and systems for fear of them not being accepted.  Point out the "warts".
- If you are a researcher or modeller, ensure that you try and obtain first-hand experience in the field.
- And if you are a researcher or modeller, bear in mind that you have a social responsibility when it comes to your work.
- Emphasize the dynamics of crown fires in training and technology transfer (a single number hardly does the phenomena justice).

**On the Limitations in Fire Models**

"*All fire models simulate reality but fall short of it in varying degrees.  In meeting the objective of simplifying relationships, minor factors are neglected and the model is usually based on a single set of idealized conditions.  If fire-modeling laws are observed, this will permit approximations close enough for many purposes, but it is easy to forget that they are approximations only. Consequently, there is a strong tendency to apply models beyond their field of usefulness.  To avoid this, the assumptions on which they are based and the range of conditions under which the model is valid need to be carefully defined and frequently rechecked.*"

A.A. Brown & K.P. Davis (1973)
***Forest Fire: Control & Use.*** 2nd Edition

## The Course of Wildland Fire Behavior Prediction Science?




**Questions?**

**Comments?**

## Acknowledgment

Fire Research Scientist, Ensis Bushfire Research, Ensis – Forest Biosecurity and Protection, CSIRO, Canberra, Australia

**CORRIGENDUM**

On page 190 in the lower right-hand corner, all the three $kg/m^2$ should be replaced by $kg/m^3$.