Prescribed Fire Aerial Ignition Strategies

Douglas J. McRae

1996

NODA • EDNO
CANADA ONTARIO
Northern Ontario Development Agreement
Entente de développement du nord de l'Ontario
Forestry • Foresterie

Funding for this report has been provided through the Northern Ontario Development Agreement's Northern Forestry Program.

Canadian Cataloguing in Publication Data

McRae, Douglas J.

Prescribed fire aerial ignition strategies

(NODA/NFP technical report ISSN 1195-2334; TR-33
Includes an abstract in French.
Includes bibliographical references.
"Funding for this report has been provided through the Northern Ontario Development Agreement's Northern Forestry Program."
ISBN 0-662-24952-6
DSS cat. no. Fo29-42/33-1996E

1. Slashburning.
2. Slashburning in forestry.
I. Great Lakes Forestry Centre.
II. Title.
III. Series.

SD421.43M32 1996 634.9'55 C96-980356-7

Catalogue No. Fo29-42/33-1996E
ISBN 0-662-24952-6
ISSN 1195-2334

Copies of this publication are available at no charge from:
Publications Services
Natural Resources Canada
Canadian Forest Service
Great Lakes Forestry Centre
P.O. Box 490
Sault Ste. Marie, Ontario
P6A 5M7

Microfiche copies of this publication may be purchased from:
Micro Media Inc.
Place du Portage
165, Hotel-de-Ville
Hull, Quebec J8X 3X2

This report was produced in fulfillment of the requirements for NODA/NFP Project No. 4121 "Prescribed fire ignition strategies for northern Ontario".

TABLE OF CONTENTS

McRae, D.J. 1996. Prescribed fire aerial ignition strategies. Nat. Resour. Can., Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, ON. NODA/NFP Tech. Rep. TR-33. 27 p.

ABSTRACT

The ability to control and manipulate fire behavior during the ignition phase of a prescribed burn is discussed. Specifically, the use of aerial ignition devices on harvested forest sites (slash clear-cuts) is outlined. This publication is an attempt to bridge the knowledge gap left by many prescribed burn manuals, which simply describe common ignition patterns without characterizing the proper buildup required to ensure safe fire control. Rules for conducting a proper ignition are also described.

RÉSUMÉ

L'ouvrage traite de la capacité de maîtriser et de gérer le comportement d'un incendie dirigé durant la phase d'allumage, plus particulièrement de l'utilisation de dispositifs d'allumage aérien sur des sites forestiers exploités (rémanents de coupes à blanc). Il vise à combler les lacunes de nombreux manuels traitant des feux dirigés, qui décrivent seulement les méthodes d'allumage courantes sans donner de précisions sur la quantité de combustible disponible qui permet de maîtriser les feux en toute sécurité. De plus, il explique les règles à respecter pour procéder à un allumage adéquat.

Important Note: This manual has been expressly written for Ontario Ministry of Natural Resources (OMNR) personnel based on their prescribed burning procedures (Ontario Ministry of Natural Resources 1987). The ignition procedures discussed pertain only to harvested forest sites (i.e., clear-cuts) where fuels consist of woody slash and duff. Some ignition techniques described in this report could cause considerable damage to overstory trees if applied during an understory pine prescribed burn. Proper procedures for igniting an understory prescribed burn are contained in McRae et al. (1994).

PRESCRIBED FIRE AERIAL IGNITION STRATEGIES

INTRODUCTION

The use of prescribed fire as a cost-effective site preparation technique for forest, vegetation, and wildlife management purposes has been increasing throughout Canada in recent years (Weber and Taylor 1992). Helping this revival has been the ecological compatibility of using prescribed fire as a tool in resource management. However, prescribed fire can only be useful when applied correctly. When employed improperly, it can result in costly escapes outside the planned burn perimeter. The greatest fear of managers responsible for conducting prescribed burns is an escaped fire. Repeated escapes can result in the formation of long-term, negative attitudes among local resource managers—attitudes that are very hard to change. Ultimately, prescribed fire may be lost as a feasible treatment alternative because of the belief that fire escapes are a common occurrence.

A major reason for escaped prescribed fires in Canada is poor ignition techniques. Large-scale, convection-style burns in Ontario (M^c^Rae and Stocks 1987), usually ignited quickly by some type of aerial ignition device (Mutch 1984), often result in the generation of extremely erratic fire behavior. This is caused by complex fire interactions between different ignition lines (Fig. 1). Reported ignition line lengths exceeding 7 km on broadcast burns conducted in Ontario indicate the extensive amount of fire that can develop in a very short time using aerial ignition techniques (M^c^Rae and Stocks 1987). Erratic fire behavior can cause major spotting of firebrands outside the prescribed burn perimeter; it can even result in the development of large fire whirlwinds (M^c^Rae and Flannigan 1990). Such behavior can create major suppression problems. While general techniques for planning an overall prescribed burn are available (Fischer 1978, Ontario Ministry of Natural Resources 1987, Hirsch 1988, Wade and Lungsford 1989, Alberta Forest Service 1990, Laframboise 1991), only superficial attention is given to the detail required to properly plan the ignition phase. The text of many of these planning manuals, while adequately explaining the various ignition methods and patterns, fails to provide detailed information on the actual application of fire to the burn site. Application rates, preferred distances between ignition lines, and proper positioning of ignition lines are not stressed. Most operational ignition plans, contained in the overall prescribed burn plan, explain the ignition procedure by showing the arbitrary placement of ignition lines on a map. These maps are no more detailed than the diagrams given in many general articles on ignition. They provide some idea of what is likely to occur during the burn (e.g., circles drawn to indicate a center fire ignition), but provide no real details (i.e., exact location of ignition lines, the distance between ignition lines, etc.). While some flexibility must exist to deal with weather changes and fuel flammability during the burn, the ignition plan should contain significantly more detail. This lack of quantifying ignition procedures has been partly the fault of the prescribed fire research community, which has not provided operational users of prescribed fire with an adequate explanation of proper ignition methodology. The complexity of the mass-ignited prescribed fire has made this a difficult procedure to both document and model. Therefore, ignition is often based on the personal experience of the ignition boss, and not on the actual ignition plan.

Ignition of a prescribed burn involves the application of fire to the burn site, often in set patterns based on weather, fuel, topography, and ignition system, to achieve specific objectives in a safe manner. In other words, the fire must carry over the burn site, accomplish the desired effects (objectives), and do so without exorbitant expense for ignition and containment (suppression).

Simple ignition models or fire behavior guidelines are used by many Canadian prescribed fire managers in developing their ignition plans (Stocks and Walker 1972, Muraro 1975, Canadian Forestry Service 1987, Forestry Canada Fire Danger Group 1992). Most of these guidelines relate equilibrium (steady-state) rates of spread (m/min) for a single-line ignition with the Initial Spread Index (ISI) of the Canadian Forest Fire Weather Index (FWI) System (Canadian Forestry Service 1987, Van Wagner 1987). These aids were not designed with mass ignition in mind, but for a single fire front on a wildfire. The interactive fire behavior on prescribed burns is complex and dependent on many variables. The amount of area on fire at any one time, the fire intensity, the rate of application, and in particular, junction-zone effects make the modeling of these mass-ignited fires very difficult. Junction-zone effects are created when the fire accelerates as it approaches the preceding ignition line or main fire body due to the development of a strong convection column with strong fire induced surface indrafts. This phenomena can be effectively demonstrated by bringing two lighted matches close together. As they meet the flame length (intensity) will increase. Many factors influence the strength of the junction-zone effect, including the fireline's equilibrium rate of spread and the strength of the fire-induced indraft.

In turn, this depends on the total intensity produced by the flaming combustion of the main fire body, which the fireline is approaching. This junction-zone effect has been a difficult aspect of fire spread to document and model.

Another problem related to guideline development is that the simpler spread models used by ignition bosses look at the ignition (fire) process as a two-dimensional rather than a three-dimensional problem. However, ignition involves not only the on-ground fire behavior, but also convection column dynamics and atmospheric conditions. Ignoring this three-dimensional process has caused prescribed fire control problems, for example, when strong ambient winds aloft are brought down to ground level.

While research has been, or is being, undertaken to understand the ignition process (Johansen 1987, McRae et al. 1991), there are presently no in-depth ignition guidelines for operational prescribed burning. The closest product for broadcast prescribed burning is the proposed Prescribed Fire Ignition Expert System (PFIES) being developed by Natural Resources Canada (M[c]Rae et al. 1991). This computerized expert system is designed for use in planning the ignition of any prescribed burn that utilizes the FWI System for setting the weather prescription. The idea for an expert system on ignition has developed because of the complexity and interrelationship of the many decision processes involved. The main goals of the PFIES would be to: (1) improve fire coverage over the burn area so that burn objectives can be realized, and (2) improve safety (i.e., control) of the burn. A flowchart of the different components contained in the PFIES is shown in Figure 2. Development of this flowchart made it quite apparent that numerous decisions must be considered in planning the ignition of a prescribed burn. Many decisions are presently made during the prescribed burn, without a proper ignition plan and often on the spur-of-the-moment, by an experienced ignition boss. However, ignition bosses lacking experience may not understand the implication of some of their actions, and this can result in serious control problems. Even experienced bosses, because of the number of considerations, may make mistakes when certain principles are forgotten and improper decisions are made during the hectic period of ignition.

The key for implementing the PFIES will be the development of a multi-ignition fire growth model. This model, along with other inputs, will help to determine the energy-release rates of the fire, and whether or not critical threshold energy levels, which might jeopardize the safety of the burn, have been surpassed. With an ability to change the ignition techniques at this planning stage, the user could modify key variables in the PFIES to alter the ignition so as to produce safer energy-release rates. The PFIES will allow for better quantification of ignition procedures in the planning stage (i.e., it is better to correct the mistakes in the planning stage rather than to create problems during actual ignition). It is hoped that the PFIES will eventually be a subsystem of a larger prescribed fire expert system for Canada that will encompass all of the decision processes required to plan a prescribed burn.

Igniting a prescribed burn is a complex process due to many interacting factors. When not accounted for, these factors can cause major problems associated with meeting burn objectives, cost, and safety. The number of factors shown in the PFIES flowchart (Fig. 2) clearly illustrates this complexity. Even with the development of recent prescribed burn planning manuals (Ontario Ministry of Natural Resources 1987, Alberta Forest Service 1990, Laframboise 1991), the ignition boss is left with meager strategic instructions as to how to generate the proper fire behavior necessary to maintain good fire and convection-column control and thus reduce escapes. Written plans, based on these manuals, reflect this lack of information. Because of this, it is conceivable that various ignition bosses, reading the same ignition plan, could ignite the burn quite differently. In turn, this could result in completely different fire behavior characteristics for the same prescribed burn.

The purpose of this handbook is to investigate present knowledge and the ability to control and manipulate fire behavior during the ignition phase of a prescribed burn, conducted on a harvested forest site (slash clear-cut), so that safe, beneficial results will occur. The final development of ignition models, such as the PFIES, is still some time in the future, yet ignition bosses need a sound knowledge base now to carry out their ignition strategies. A number of recommendations on proper ignition procedures are given. Since almost all ignition in Ontario is aerial, most of these recommendations are based on this method. It is hoped that the primary outcome of this publication will be a better appreciation of various principles for safely igniting burns, and for achieving desired results.

IGNITION PROCEDURES

Ignition is more than just applying fire; it is a precise procedure based on science and experience. Yet, often this knowledge base can be forgotten as the ignition boss gets absorbed in "dropping" fire onto the site. Common decisions faced by the ignition boss of a large-scale, convection-style prescribed burn may be categorized into the following areas:

1) ignition system (e.g., hand, helitorch, or Ontario Aerial Ignition Device);

2) ignition patterns (e.g., back fire, center fire, perimeter, strip head fire, etc.);

3) ignition line characteristics (e.g., solid line versus spot ignition);

4) spacing and placement of ignition lines; and

5) ignition rates.

The development of ignition strategies in this manual will concentrate on these categories as they are the ones most easily controlled by the ignition boss. The focus will be on how each can be used to affect the ignition process. In this discussion, some assumptions have been made that may pertain to ignition practices carried out exclusively by the OMNR. These assumptions are that either the helitorch or the Ontario Aerial Ignition Device (OAID or "ping-pong ball" machine) is the main ignition system used, and that strip head fire and center fire ignition are the two most common ignition patterns used in the prescribed burning of woody-slash fuels found on harvested boreal forest sites. However, many of the principles developed can be easily applied to hand ignition. Steep slopes and aspects have not been emphasized as they are not a major concern in Ontario due to relatively flat terrain. However, if steep slopes are a concern on the rate of spread then the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) should be referred to in planning strategies.

Importance of Fire Intensity

Recognizing the importance of fire intensity and its effect on prescribed fire control is critical for the ignition boss. Without this recognition erratic fire behavior and fire escapes will prevail, and areas of concern, particularly forested reserves left standing inside the burn as shelter for wildlife, will continue to be damaged. Knowledge on how fire intensity can be used to maintain the convection column to prevent its premature collapse and possible fire escape is essential.

Wildfire managers are well acquainted with the following equation (*from* Byram 1959):

$$FFI = Hwr \qquad [1]$$

where FFI is frontal fire (fireline) intensity (kW/m), H is low heat of combustion (kJ/kg), w is fuel consumption (kg/m^2), and r is rate of spread (m/sec). Frontal fire intensity is defined by Merrill and Alexander (1987) as: "The rate of heat energy released per unit time per unit length of fire front." Equation [1] was rewritten in the FBP System (Forestry Canada Fire Danger Group 1992) as:

$$FFI = 300\,(wr) \qquad [2]$$

where the constant 300 is used since a low heat of combustion (H) of 18 000 kJ/kg divided by 60 minutes allows the units for rate of spread (r) to be expressed in meters per minute (m/min), which is how it is normally stated by the OMNR. Frontal fire intensity pertains to intensities developed only in the flaming phase of combustion. In a forest fire, the equation is easily used, as there is generally only one fire front (compared to the mass fire of a prescribed burn), and smoldering combustion time is small, as generally only live trees and the forest floor are involved. Extensive smoldering may occur only when the Duff Moisture Code (DMC) or the Drought Code (DC) of the FWI System are high, and then it only occurs in the deeper duff (forest floor) fuel components. However, prescribed burns, because of the vast amounts of dead, dry, often sun-exposed, large diameter slash fuels and duff fuels involved, smolder for a considerable length of time after flaming combustion has ended. The smoldering phase of combustion on a prescribed burn can produce a large proportion of the fire's total intensity. Concerns on the applicability of Equation [2] in prescribed burn planning, because of the problem in quantifying the proportion of w involved in the flaming combustion phase only, have been raised by fire personnel. Because of this difficulty, Equation [2] has never been stressed by many organizations in their prescribed burning guidelines.

A strategy to quantify total intensity on prescribed burns was developed for the Canada/United States Cooperative Mass Fire Behavior and Atmospheric Environmental Impact Study (Stocks and M^{c}Rae 1991). In this approach, both flaming and smoldering phases of combustion were considered. To estimate intensity by this method, prescribed fire managers need to use the following equation:

$$I_T(t) = I_F(t) + I_S(t) \qquad [3]$$

where I_T is the total intensity (kW) for the entire prescribed fire at time (t), I_F is the total intensity (kW) produced by flaming combustion for the entire prescribed fire at time (t), and I_S is the total intensity (kW) produced by smoldering combustion for the entire prescribed fire at time (t). Equation [3] can be expanded to:

$$I_T(t) = Hw_F a_F(t) + Hw_S a_S(t) \qquad [4]$$

where w is the rate of fuel consumption (kg/m^2 per sec) at time (t), and a is the area (m^2) involved at time (t). Note that this equation must be solved separately for both phases of combustion, flaming and smoldering, and hence use of the subscripts $_F$ and $_S$ as in Equation [3]. Calculations are made even more difficult because two values must be considered for smoldering combustion, which takes longer to complete for the duff fuel component than for the slash fuel component.

Table 1 is an example of the area of an actual prescribed fire broken down according to the phase of combustion. From this, it can be seen that within just a few minutes of ignition (i.e., 7.8 minutes after ignition in Table 1), the

Table 1. The proportion of the Hill Township prescribed burn (10 August 1989), which was ignited using a center fire, in terms of area of flaming and smoldering combustion.

Time since ignition (min)*	Area (m^2) in flaming combustion (a_F)	Area (m^2) in smoldering combustion (a_S)* *	Total area (m^2)
2.0	16 845	0/0	16 845
3.8	46 984	0/0	46 984
4.9	64 340	16 845/16 845	81 185
6.7	63 421	46 984/46 984	110 405
7.8	60 321	81 185/81 185	141 506
10.9	87 811	141 506/141 506	229 317
14.9	34 697	229 317/229 317	264 014
17.9	36 164	264 014/264 014	300 178
19.8	72 106	272 894/272 894	345 000
23.5	50 000	334 123/344 123	394 123
26.5	50 000	379 299/394 123	444 123
30.0	20 000	362 938/444 123	464 123
33.0	0	322 617/464 123	464 123
36.0	0	256 759/420 967	420 967
39.0	0	222 662/359 412	359 412
42.0	0	191 229/259 555	259 555
45.0	0	141 634/234 806	234 806
48.0	0	95 214/200 109	200 109
52.0	0	20 000/155 104	155 104
55.0	0	0/107 412	107 412
60.0	0	0/20 000	20 000
63.0	0	0/0	0

*Areas given between 2.0 and 19.8 minutes are actual measurements obtained from infrared images, areas for 23.5 and 26.5 minutes are estimates obtained from aerial photography, and the area at 30.0 minutes is an estimate. All other estimates are based on consumption times for the two phases of combustion (*see* footnote below).

**Two area values are given for smoldering combustion; the first is for the woody slash fuel component and the second is for the duff fuel component. Smoldering times for the two fuels are 22 and 30 minutes, respectively. Flaming combustion, on the other hand, lasted for only 2.9–3.2 minutes.

area of smoldering combustion (a_S) can become much greater than the area of flaming combustion (a_F). The contribution of the smoldering portion of the prescribed burn toward I_T for the entire burn should not be underestimated (Table 2), especially when prolonged smoldering may occur due to dry conditions. In fact, smoldering combustion can be the greatest contributor to the overall total energy release of the prescribed fire and can have major influences on the convection column dynamics when a_F is small. This can easily occur if ignition should be curtailed during or at the end of the prescribed burn.

Except during the early part of the prescribed fire, I_S always exceeded I_F (Table 2). At first glance, one might expect the smoldering phase of combustion to have a dominating influence at all times on column dynamics. In actuality, the influence of the I_S on column dynamics is small if ignition (flaming combustion) is maintained. This

Table 2. The contribution of flaming and smoldering combustion to the total intensity of the Hill Township prescribed burn based on areas given in Table 1.

Time since ignition(min)	Total intensity (kW) - flaming phase (I_F)*	Total intensity (kW) - smoldering phase (I_S)*	Total intensity (I_T) (Kw)
2.0	6 064 200	0	6 064 200
3.8	16 914 240	0	16 914 240
4.9	23 162 400	1 516 050	24 678 450
6.7	22 831 560	4 228 560	27 060 120
7.8	21 715 560	7 306 650	29 022 210
10.9	31 611 960	12 735 540	44 347 500
14.9	12 490 920	20 638 530	33 129 450
17.9	13 019 040	23 761 260	36 780 300
19.8	25 958 160	24 560 460	50 518 620
23.5	18 000 000	30 371 070	48 371 070
26.5	18 000 000	35 099 970	53 099 970
30.0	7 200 000	33 280 710	40 480 710
33.0	0	33 299 970	33 299 970
36.0	0	28 034 550	28 034 550
39.0	0	24 142 080	24 142 080
42.0	0	19 260 390	19 260 390
45.0	0	15 542 220	15 542 220
48.0	0	11 716 110	11 716 110
52.0	0	5 853 120	5 853 120
55.0	0	3 222 360	3 222 360
60.0	0	600 000	600 000
63.0	0	0	0

*Low heat of combustion (H) used was 18 000 kJ/kg.

is best explained by focusing on smaller specific areas of the prescribed burn, for example a square meter, because flaming combustion produces a larger reaction intensity (kW/m^2) than does smoldering combustion at this scale. This is due to a higher fuel-consumption rate during flaming combustion (Fig. 3). Reaction intensity, the energy release rate per unit area of the prescribed burn, may be written as:

$$I_R = Hw_C \qquad [5]$$

where I_R is reaction intensity (kW/m^2), and w_C is the fuel-consumption rate (kg/m^2 per sec). For the case study in Table 2, I_R for flaming combustion (I_{RF}) is 360 kW/m^2; only 90 kW/m^2 is produced by smoldering combustion (I_{RS}) when both slash and duff are involved. When smoldering combustion involves just the duff, as happens at the end of the burn, I_{RS} would only be 30 kW/m^2. Because of this, the flaming combustion portion of the prescribed burn, with a higher reaction intensity, is important in controlling fire behavior. By producing strong indrafts, it can influence the direction of fire spread. Indrafts are produced as cool air rushes in to replace air that has been heated by the fire and has risen due to increased buoyancy (column development). The active main convection column, therefore, will be positioned over a_F as long as a_F is maintained at a critical size to support column development. Equation 3 may be rewritten as:

$$I_T(t) = I_{RF}a_F(t) + I_{RS}a_S(t) \qquad [6]$$

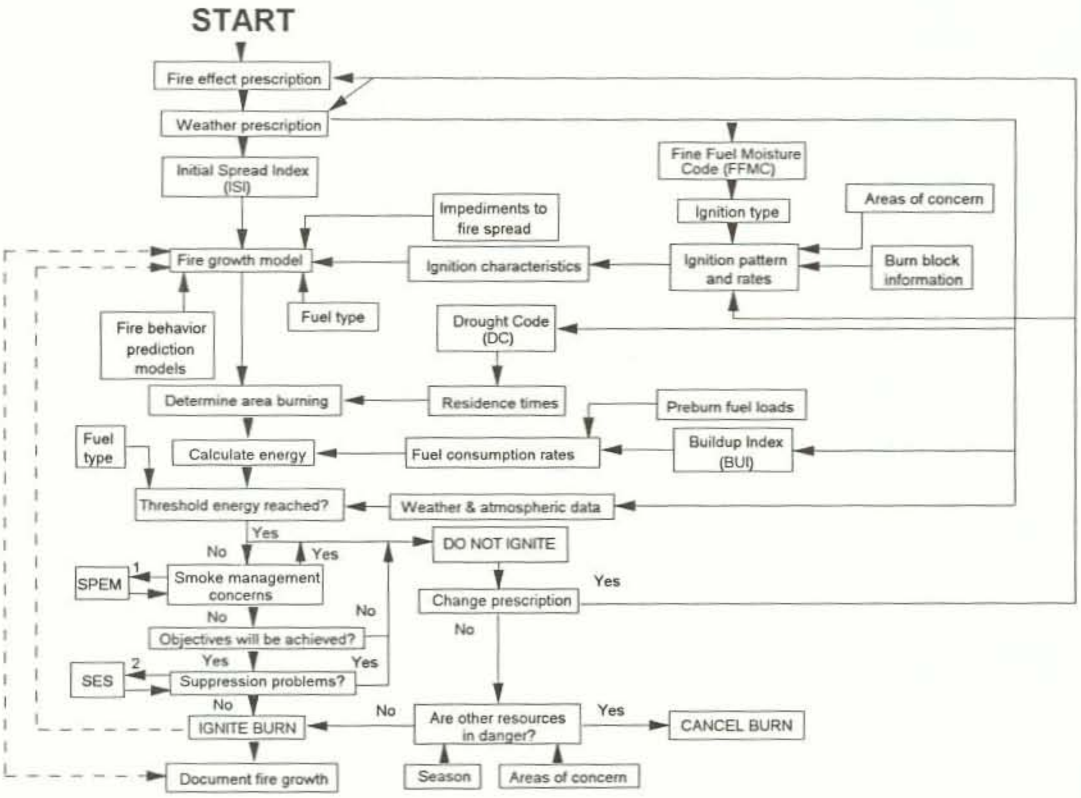
The importance of flaming combustion stresses the need for forethought, especially when using any indrafting process, such as center firing, to control the fire. An adequate area (a_F) and supply of available fuel (w) are required to produce sufficient intensities (I_F) so that adequate indrafts are developed to maintain fire and column control. Uncut forested areas, swampy areas, roads, and log landings from forest harvesting operations (areas devoid of fuel) are sites that will never develop the I_{RF} necessary to produce strong indrafting. However, in the past, they have often been used operationally as starting points to try to develop the indrafting required for ignition techniques like center firing. The results, of course, have produced poor examples of the center fire ignition technique. Obvious lack of forethought in these cases can lead to unexpected control problems with the fire and convection column. An adequate a_F (i.e., high overall I_F) is required to maintain column development, which when strong enough can lift firebrands that extinguish themselves inside the main column. When a_F is small (i.e., I_F is weak), the column is generally not well defined and is often blown over by the ambient wind, thereby allowing a better chance for firebrands to fall out of the column onto fuels outside the burn area. Maintenance of the necessary I_F fails when ignition ceases altogether or is so slow that insufficient a_F is being ignited.

In Table 2, although I_F reaches a level as high as 31 611 690 kW, it appears that it was more practical to maintain a level of 21–26 million kW. This shows that maintaining an area in flaming combustion (a_F) has an upper limit based on the ignition strategy chosen (e.g., number of ignition helicopters used, helicopter speed, ignition system used, fireline characteristics, etc.). Meanwhile, the area in smoldering combustion (a_S), due to a longer smoldering combustion time, continues to increase to a higher level than that of flaming combustion. In the current example (Table 2), I_F gradually decreases after 19.8 minutes into ignition since a_F begins to decrease at this time with the completion of ignition (Table 1). The reason for this gradual decrease is ignition proceeds on only certain portions of the prescribed fire as ignition in other sections have been completed to the burn boundary and no further ignition is needed (Fig. 4). After ignition has ceased, it takes approximately 33 minutes (3 minutes flaming combustion and 30 minutes smoldering combustion) for normal combustion to be completed. Combustion will continue only in a few spots where favorable burning conditions exist (e.g., fire burning where logs crisscross, fire burning in a hollow log, etc.)

In operational practice, I_F must always be sufficiently large to maintain control of the convection column; otherwise, smoldering combustion will be the dominating influence. Through experience, this can be determined by keeping an eye on the convection column. If the main column is not well defined or is being bent over by the ambient wind, control of the column may be lost due to insufficient flaming combustion (i.e., there is insufficient a_F or I_F). The immediate response should be to try to regain control of the convection column by increasing a_F by commencing ignition again (i.e., increasing a_F). If ignition is already underway, a_F may be increased by increasing the ignition rate, or by changing from point-source to line ignition. In addition, I_F may be increased by igniting areas of heavy fuel accumulations near the convection column (i.e., increasing W_F). Even a well maintained convection column must be watched; otherwise, the proper fire-induced indrafting to maintain convection column control could be quickly lost, thereby resulting in fire spotting or escape. This loss of focus is not unusual since the ignition boss can often become distracted by the excitement of burning and may concentrate solely on laying fire on a specific portion of the burn site rather than on viewing the entire prescribed fire and convection column.

On prescribed burns, the "collapse" of the convection column is often cited as a reason for the fire's escape. Most often this occurs when the aerial ignition device has to be refueled or repaired, and significant time elapses before ignition resumes, thereby allowing the convection column to break down. This occurs when the energy of the wind exceeds the kinetic energy of the convection column (Byram 1959, Nelson 1993). The strong indrafting and upright column created by an active fire, as well as the use of the fire as a control mechanism, are lost. At this stage, smoke problems and firebrand spotting become more prevalent because of increased horizontal winds over the prescribed burn. Table 2 can help to illustrate how easily this may happen on an operational prescribed fire. In this case, the helitorch had to be refueled between 11:30 and 18:30 minutes after ignition. As can be seen in Table 2, I_F decreased because of the reduction in a_F during this period. Since I_S is still increasing at this point, regaining control of the convection column depends upon getting the aerial ignition device operational quickly so as to maintain a_F (i.e., a critical level of I_F). Flaming combustion on prescribed burns in Ontario usually lasts only 1–4 minutes at any spot (*see* Fire Residence Times), and is dependent on fuel dryness, as represented by a fuel moisture code such as the Drought Code (DC) of the FWI System. If ignition is stopped for a longer period than the flaming combustion residence time, then the convection column dynamics will become controlled by I_S rather than by I_F. Major delays on center fire-ignited prescribed burns may prevent completely regaining control of the convection column where areas adjacent to the fire get smoked in.

Figure 1. This large-scale, convection-style prescribed burn shows the establishment of a complex multiple-ignition pattern through the use of the Ontario Aerial Ignition Device ("ping-pong ball" machine).



1 SPEM- Smoke Production and Emission Model

2 SES- Suppression Expert System

Figure 2. A flowchart of the PFIES showing the large number of decisions that must be made concerning the ignition of a prescribed burn (from *M^cRae et al. 1991).*

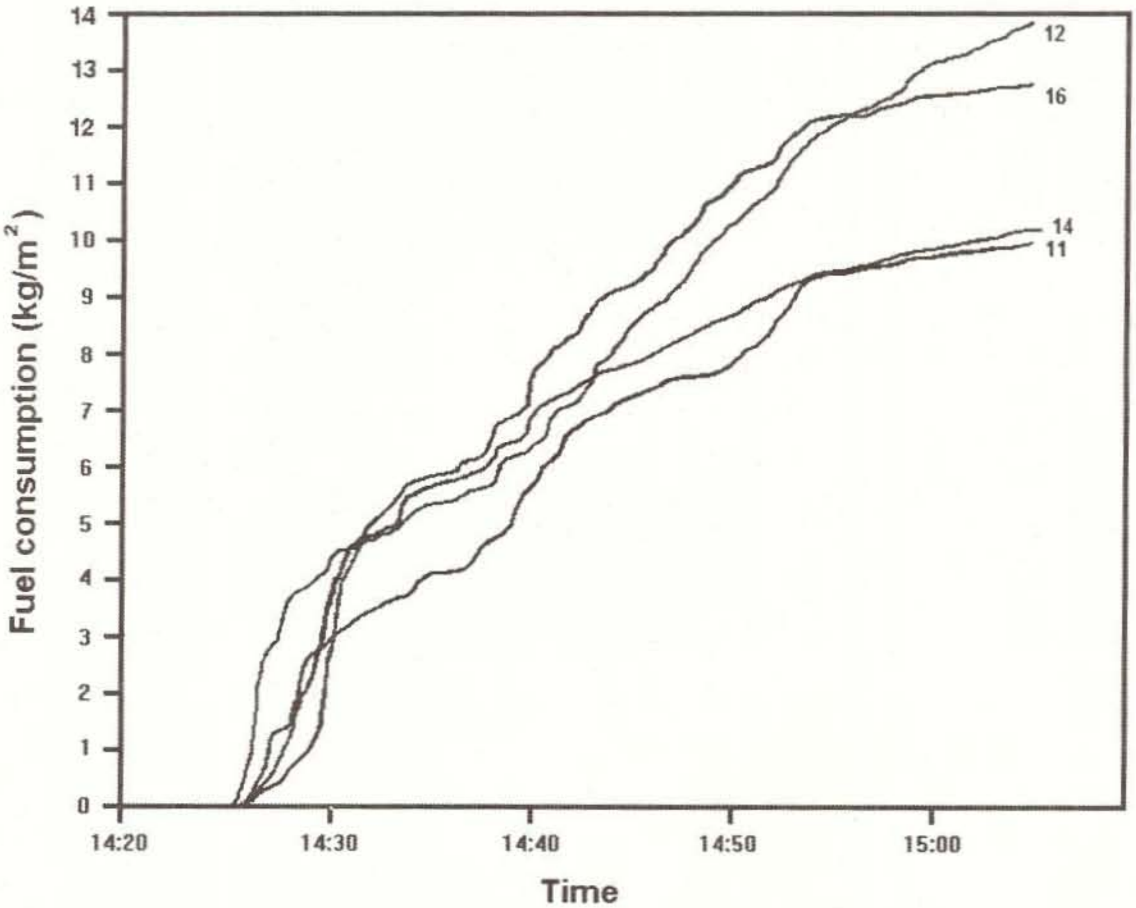


Figure 3. Cumulative fuel consumption for each of the four sets of data (Packages 11, 12, 14, and 16) on the Hill Township prescribed burn (from *Susott et al. 1991*)*. Note the steep slopes, indicating high fuel consumption rates, during the flaming combustion period between 14:26 and 14:30 hours.*

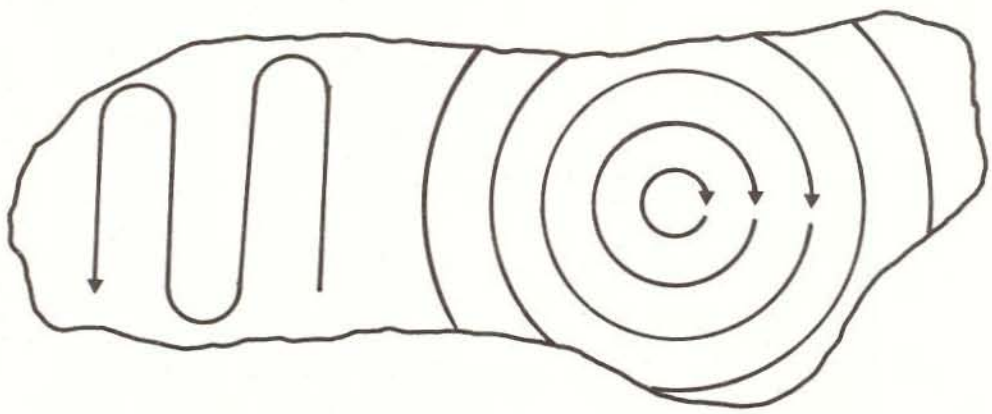


Figure 4. Ignition pattern for the Hill Township prescribed burn.

Figure 5. A sequence of pictures showing: (a) convection column control being maintained early in the prescribed burn with proper ignition procedures to create indraft winds (left to right) into the mainfire located outside of the picture to the right, (b) a wind reversal is experienced (now right to left) as ignition was curtailed for refueling of the helicopter and convective activities ceased, and (c) fire escapes across perimeter firelines (where the anemometer tower is) due to wind-direction reversal where the ambient wind became dominant and allowed the fire to race across unburned fuel.

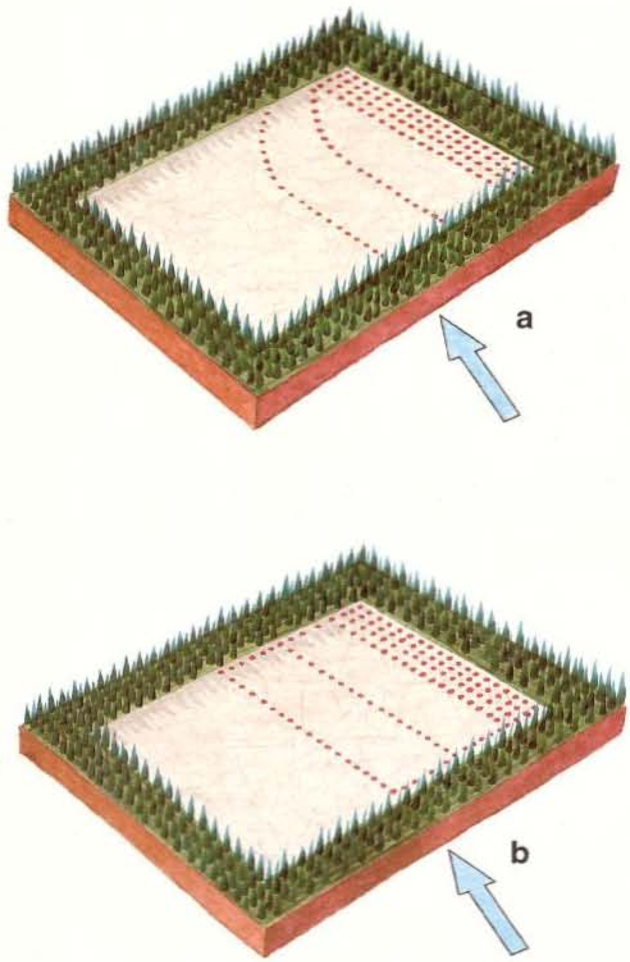


Figure 6. Illustrations of how to: (a) incorrectly, and (b) correctly end the windward edge of an ignition line before the helicopter leaves for refueling. The ignition line in (a) leaves unburned fuel between itself and the burn perimeter. This could lead to a fire run to the burn perimeter and cause an escape if the ambient wind (the solid blue arrow) should dominate the fire.

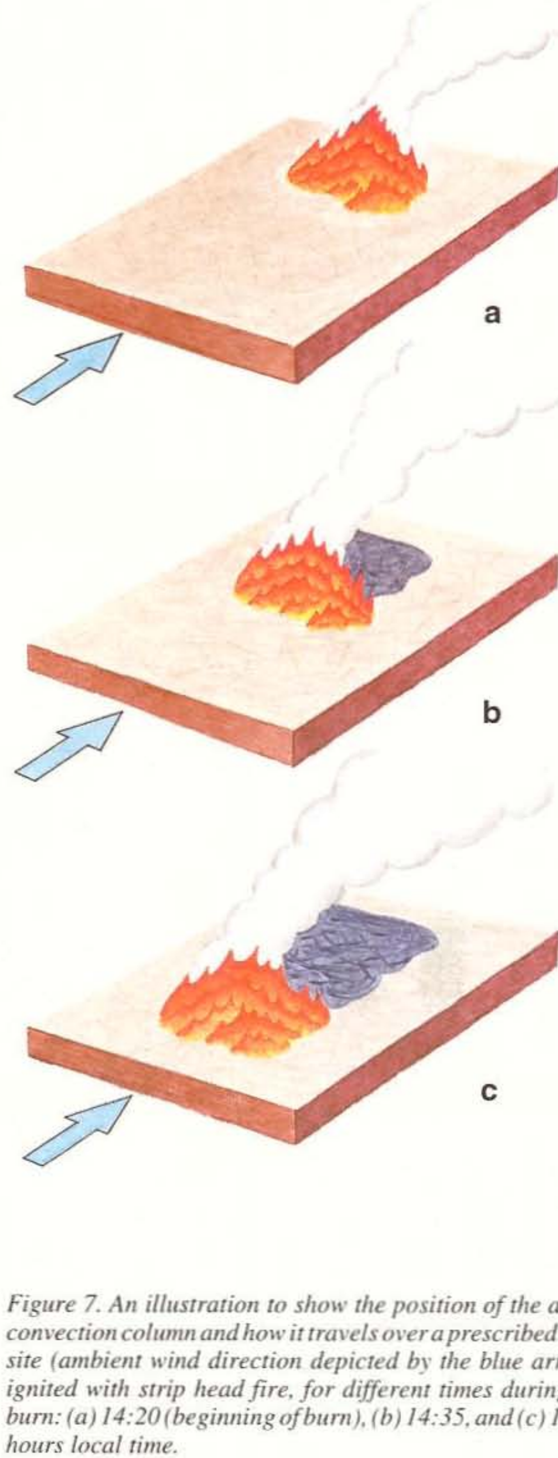


Figure 7. An illustration to show the position of the active convection column and how it travels over a prescribed burn site (ambient wind direction depicted by the blue arrow), ignited with strip head fire, for different times during the burn: (a) 14:20 (beginning of burn), (b) 14:35, and (c) 15:00 hours local time.

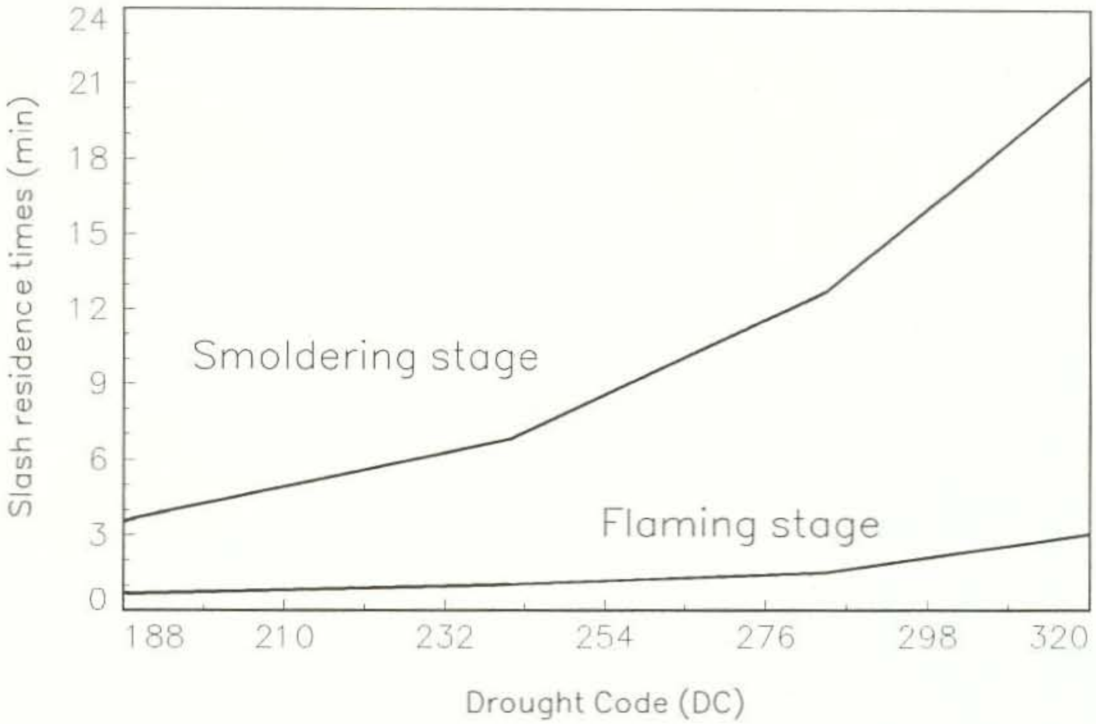


Figure 8. The relationship between residence times and the DC of the FWI System.

Figure 9. This area, recently ignited using a helitorch, shows the large number of possible incendiary fires (photograph courtesy of OMNR).

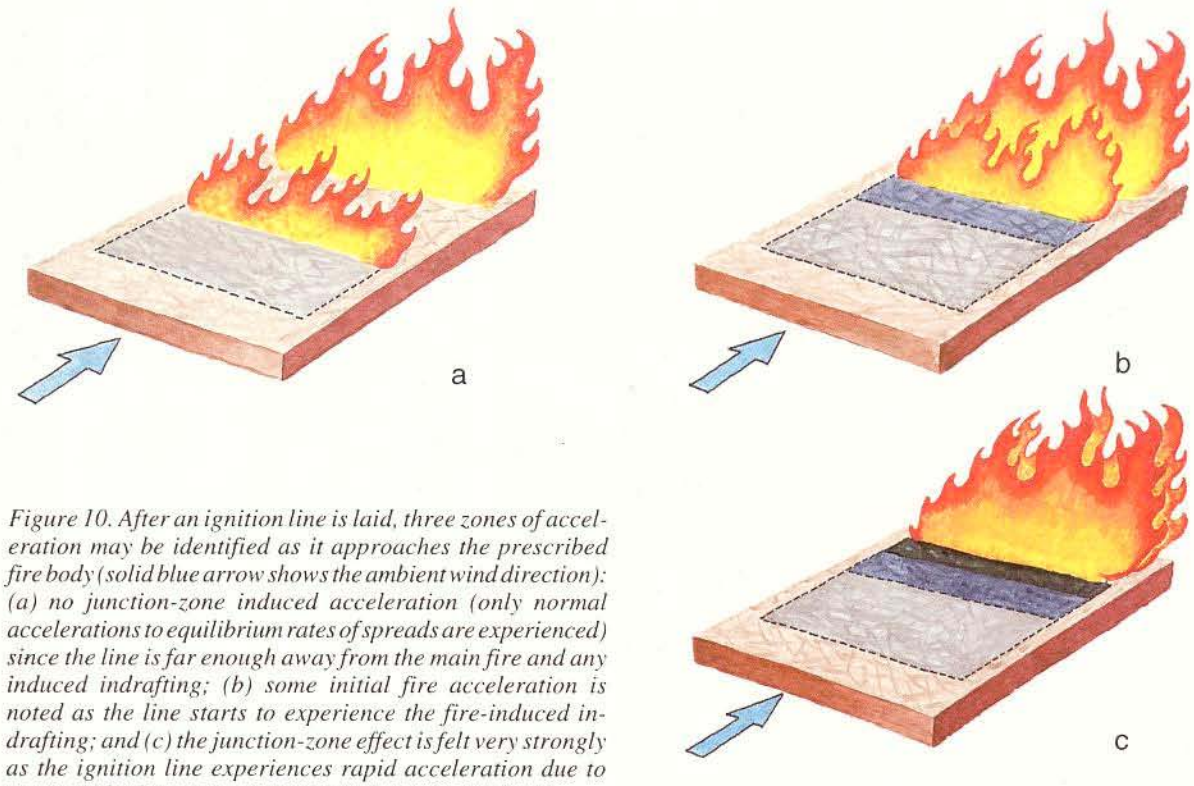


Figure 10. After an ignition line is laid, three zones of acceleration may be identified as it approaches the prescribed fire body (solid blue arrow shows the ambient wind direction): (a) no junction-zone induced acceleration (only normal accelerations to equilibrium rates of spreads are experienced) since the line is far enough away from the main fire and any induced indrafting; (b) some initial fire acceleration is noted as the line starts to experience the fire-induced indrafting; and (c) the junction-zone effect is felt very strongly as the ignition line experiences rapid acceleration due to strong indrafting as it approaches the main fire body.

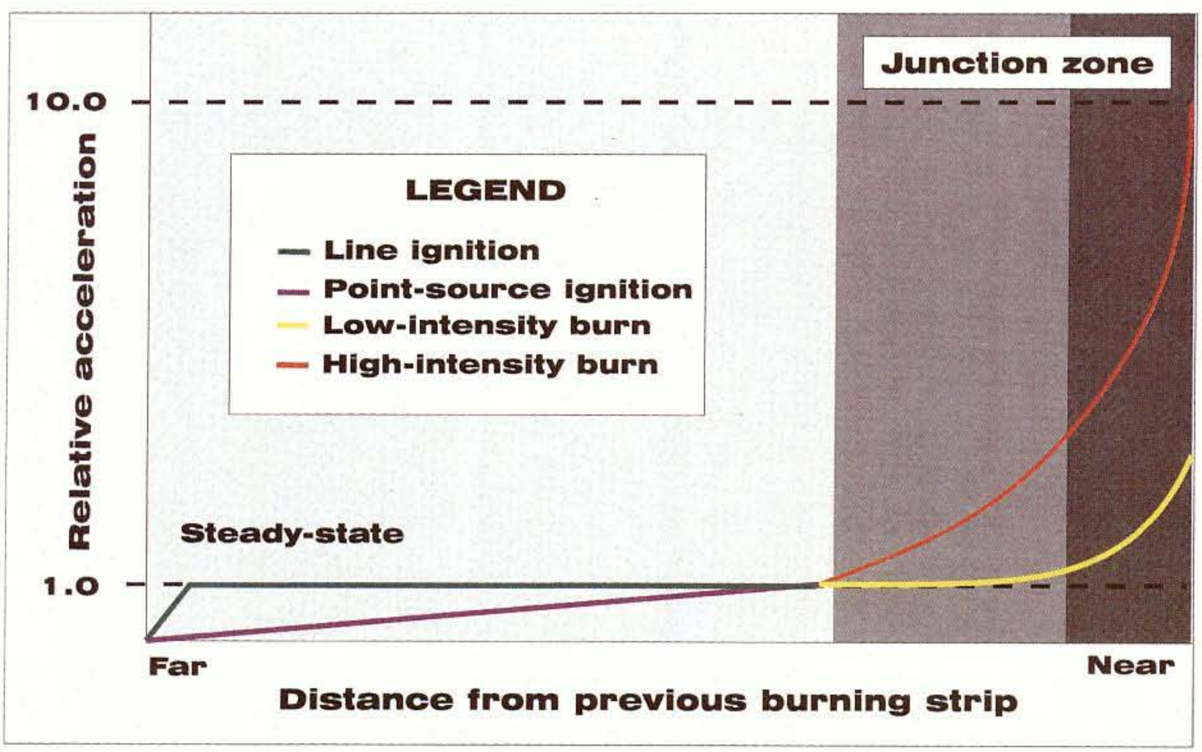


Figure 11. A graph showing relative acceleration of the same ignition line shown in Figure 10, based on whether a point or solid-line ignition was used, and the prescribed fire intensity of the main body.

Normally, aerial ignition stoppage may occur if the helicopter itself is getting low in fuel, if the helitorch runs out of fuel, or if the OAID runs out of incendiary devices ("ping-pong balls"). In rarer cases, ignition may stop if personnel on the ignition helicopter become curious and wish to observe what they have accomplished, or if a suppression problem has occurred due to a fire escape. Such stoppages of ignition can quickly cause a previously strong convective column to break down and firebrands to drop onto adjacent areas outside the prescribed burn because of column tilt over these areas. This, of course, aggravates the suppression problem. Figure 5 presents a sequence of pictures of a prescribed burn perimeter, which is on the left side of the photograph. The main fire is just to the right. In Figure 5a, the prescribed fire ignition has developed nicely and proper ignition has produced indrafting from the perimeter edge (the anemometer is on the perimeter fireline) into the main fire (left to right as seen in smoke movement across the picture). In Figure 5b, a reversal of wind flow may be seen shortly after the ignition helicopter departs for refueling (now seen as smoke movement from right to left across the picture). This results in a loss of I_F, which causes a loss in indrafting winds, thereby allowing the ambient wind direction to reestablish over the prescribed burn. Because the ignition stoppage was unplanned and unburned fuel was left between the fire and the perimeter, this allowed the fire to make a run to the perimeter when the wind switched direction (fire-induced to ambient). In turn, this leads to numerous fire escapes (Fig. 5c).

The previous two examples on ignition curtailment show that it is imperative to always maintain a functional ignition device. It may be advantageous to have a spare aerial ignition device ready in case the one in use malfunctions and can not be quickly repaired. Ignition teams should be encouraged to locate as close as possible to the actual burn site so as to reduce the turnaround time when additional fuel is required. Extra helitorch fuel barrels or OAID canisters need to be full and ready to keep turnaround times small. When an ignition helicopter is used, it should be full of fuel at the start of the prescribed burn so as to reduce the need to stop for refueling during the burn. Refueling a helicopter can take a lengthy time in Ontario as regulations require that the helicopter be shut down. On large prescribed burns, where refueling is inevitable, fuel for the helicopter should be stored close by rather than at some distant location. In the case of strip ignition, the ideal departure of the helicopter should be planned by burning out the complete burn block to safe boundaries. In most cases, it would be better to refuel prior to starting ignition on a block even if it is earlier than planned, rather than start and have to leave a block half ignited. If this is not possible on strip head fire ignition, the fuel should be burned out to the perimeter in such a manner that if the helicopter is delayed it will not cause a problem (*see* Fig. 6). The inclination of an inexperienced fire pilot is often to round the corner (Fig. 6a). This allows for the possibility that the fire may run to the perimeter and escape if fire-induced winds are replaced by ambient winds. This could happen when ambient winds reappear and dominate the fire by blowing in a direction receptive to cause such a fire run (as was shown in Fig. 5). Figure 6b shows the correct method of completing an ignition line perpendicular to the burn edge. It is a good policy to follow this procedure for each ignition line in case there is a reason to stop the ignition (e.g., an equipment malfunction). This procedure is impossible, of course, when using center fire ignition. In this situation, once ignition is started the prescribed fire team is committed to continue. Otherwise, any ignition stoppage could eventually allow the downward fire edge to run toward the planned prescribed burn perimeter when the indrafting process is lost and ambient winds resume over the site. Possibly, this could cause suppression problems.

These examples help to explain why ignition on a prescribed burn should never be curtailed. Maintaining control of the convection column to prevent escalation of any suppression problems is essential. Ignition can only be concluded when the entire area has been burned; otherwise, the fire may make an uncontrolled run through unburned fuels left on the site. This area may constitute only one block of a multiblock prescribed burn, but it will need to be burned out to proper containable fire boundaries. Inexperienced bosses may curtail ignition when problems occur and thereby create a dangerous situation by losing control over the fire and convection column.

At the end of any prescribed burn, when ignition ceases (a_F or I_F decrease), the convection column will eventually break down. During the burn, this situation is avoided. At the end of the burn, this may be considered a planned breakdown as all fuels should have been burned out to the site perimeter (i.e., all fuel is ignited to prevent any unplanned fire runs within the burn site). Spotting should be reduced using this approach. Hazardous areas outside the perimeter should be identified prior to burning and carefully monitored.

So far, this discussion has shown how dynamic prescribed fire behavior works; it has also detailed some of the ways in which it can be influenced. The highest energy-release rate (I_{RF}) occurs where ignition is taking place. Energy release on a specific area of the prescribed burn decays with time as it progresses from flaming to smoldering combustion. However, as ignition (strip head fire) proceeds there is a continual addition of a_F, which allows the active convection column to travel across the prescribed burn site (Fig. 7). The rate of this travel is dependent principally upon the rate of burning. The depth or diameter of the active convection column correlates well with the size of a_F.

Fire Residence Times

The residence time of the two phases of combustion will increase as drought conditions increase. Unpublished results from the Canada/United States Cooperative Mass Fire Behavior and Atmospheric Environmental Impact Study (Stocks and M^cRae 1991) suggest that a fuel moisture code, such as the Drought Code (DC) of the FWI System, may serve as a good indicator of fire residence time (Fig. 8). The greatest rate of increase is in the smoldering phase of combustion. Flaming combustion residence times do increase, but at a much lower rate than that of smoldering combustion. As fuels become drier, the increase in residence times for the fire will mean that fuel consumption will also increase (M^cRae 1980). The ignition boss, in particular, must understand the consequences of the increased residence times (and fuel consumption) associated with smoldering combustion as burning conditions become drier. This data suggests that as conditions become drier, there is a substantially increased residence time for smoldering combustion, and the minimal size of a_F (to provide an adequate I_F) may have to be increased to maintain good control of the column (e.g., a_F at a DC of 280–330 may have to be increased 1.3 to 1.5 times the a_F at a DC of 190). Data also indicates that as conditions become drier it is even more important to prevent any major interruptions with ignition.

Line and Point-source Ignition Differences

Solid-line ignition allows for the quick establishment of equilibrium spread rates (Cheney 1981, Johansen 1987; Weber 1989). Spot ignition on postharvested jack pine (*Pinus banksiana* Lamb.) forest sites, on the other hand, requires approximately 24 minutes for the fire to accelerate to equilibrium rates of spread.[1] It must be appreciated that high intensity fires (I_F) can be produced quickly by line ignition. The reason for this is the large a_F, which is quickly established due to the faster fire acceleration characteristics.

The helitorch drops a large number of individual clumps of ignited gelled fuel (Fig. 9). These individual fires grow together to quickly produce a solid ignition line (line ignition). Development of the solid ignition line is further enhanced because igniters are prone to leaving their hand on the helitorch ignition switch. For each second that fuel is dropped, a line 22 m long is created when the helicopter speed is 80 km/h. Realistically, the helitorch operator, even if the intention is not to create a solid line ignition, will always produce a solid line of fire on the ground. A 3-second burst of the helitorch could produce a solid ignition line 66 m long; use of the OAID may leave only one or two single incendiaries when one chute is being used over this distance. A helitorch application rate of 10 L/ha of gelled fuel is considered normal by the OMNR. Therefore point-source ignition using the helitorch, even when the operators believe they have only momentarily held the switch, is virtually impossible. Even disregarding the length of the ignition line produced, the spray width of the gelled fuel (10–12 m) makes a simple single-spot ignition impossible to achieve using the helitorch (Fig. 9). This may be the source of some control problems as ignition personnel do not appreciate just how much fire is actually being dropped. It must be realized that the helitorch, even when used by experienced personnel, has a much greater potential to produce higher energy-release rates than the OAID. I_F (or a_F) must be carefully controlled when the helitorch is used, especially when burning out at the beginning of a fire.

The OAID is an underrated and underutilized ignition tool that became ignored with the operational introduction of the helitorch in Ontario in 1986. The ability of an ignition boss to better control fire behavior, under ideal prescribed burning conditions, is greatly improved using the OAID. The reason for this is that the ignition boss can place individual incendiaries rather than producing a "mass fire", which occurs when the helitorch is used. Placement of the incendiaries by the OAID can also be made more precisely. However, the OAID should not be used when live vegetation is abundant or the Fine Fuel Moisture Code (FFMC) of the FWI System is low (<85). Under these conditions, fire often needs the physical benefits of the helitorch's line ignition to grow so that it can cover the entire site. The exception to this rule is on sites where continuous, noncompacted beds of feathermoss (*Pleurozium schreberi* [BSG.] Mitt.) or lichens (*Stereocaulin paschale* [L.] Hoffm.) are present. These types of fuel beds dry very quickly after precipitation (M^cRae 1986, Alexander et al. 1991) and may permit fire spread at lower values of the FFMC (78–84) than are normally considered possible by fire personnel. Spot ignition in these fuel types, even at lower FFMC values (80–84), will produce substantial rates of spread that may need to be regulated in controlling fire intensity.

Junction-zone Effects

Interaction between different fire spots or lines will result when junction-zone effects are experienced (i.e., an acceleration of fire lines as they approach previously burned

[1] Unpublished results on file with the Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, Ontario.

strips caused principally by the presence of strong, fire-induced indrafting winds) (Fig. 10). Major accelerations of up to ten times the normal equilibrium spread rates may be experienced (M[c]Rae et al. 1989). The major influence of junction zones is that they can substantially increase the fire's intensity (I_F) due to a rapid increase in a_F. This high intensity can produce erratic fire behavior, such as the creation of large fire whirlwinds (M[c]Rae and Flannigan 1990).

The acceleration effect experienced will be less for lower-intensity fires, where the fire-induced indrafting winds may not be as well developed (Fig. 11). The low- and high-intensity junction-zone effects, as depicted in Figure 11, may be experienced at different times on the same prescribed burn, dependent on I_F. Junction-zone effects can be diminished by using point-source ignitions if the spots are allowed to run only short distances, thereby preventing maximum or equilibrium rates of spread from being achieved before being influenced by the junction zone. Under ideal conditions, line ignitions, which always attain equilibrium rates of spread very quickly, will produce the strongest junction-zone effects.

The ignition boss needs to be conscious of junction-zone effects in order to manage a_F properly if control of the prescribed burn will be jeopardized by any increases in I_F. Often, a major error at the start of a prescribed burn is not waiting long enough to develop a sufficiently wide burn out before increasing the rate of burning for the main body. When major junction zones are allowed to develop near the burn perimeter (Fig. 12), fire spotting and escapes must be anticipated because of an increased I_F. Burning out requires patience; do not rush this initial stage of the burn. It needs to be conducted with a benign fire. At any time during the burn the ignition boss can reduce I_F by reducing the ignition rate, or by altering the ignition line characteristics if there is any concern of increased energy release rates caused by junction-zone effects (i.e., decrease I_F by decreasing a_F).

Influence of the Wind

Many individuals involved with large-scale, aerially ignited prescribed burns view the ambient wind only as a force that will influence the rate of spread and the direction in which the ground-based fire will travel. They are often not aware of the complex wind fields that develop in, over, and around the actual prescribed burn. This problem may be due to the fact that most fire personnel are occupied with various duties while on prescribed burns, and thus are unable to be close enough to observe and gain an appreciation of the wind field changes that can occur. Because of this lack of experience, the effects of the wind field may not be addressed in planning and conducting the burn. Some of these effects are critical for maintaining fire control after, rather than during, ignition.

The ambient wind field has a direct effect on the initiating fire, but as the convection column builds up this effect diminishes. Once developed, the fire's convection column is opaque to the ambient wind (only fire-induced winds will be experienced in the fire area). The ambient wind must go around rather than through the column (Countryman 1971). Under all but calm conditions, eddies will develop on the downwind side of the column (Fig. 13a). These eddies move across the burn site but, because of the ignition sequence, remain downwind of the main convection column as it travels across the site (Fig. 7). Under certain conditions, these eddies can become quite severe and even cause large fire whirlwinds (M[c]Rae and Flannigan 1990). Eddies are not present on center fire ignited prescribed burns (Fig. 13b).

The principles of the energy flow model theory developed by Byram (1959), and later revised by Nelson (1993), should be understood by prescribed burn personnel. Simplified, this model shows that when the energy flow in the wind field (P_w) is greater than the kinetic energy of the fire's convection column (P_f), the fire is completely dominated by the wind field. This condition is usually observed as a bent-over convection column. Shortly after ignition on most large-scale prescribed burns, however, P_f exceeds P_w for a considerable height above the ground, and the energy of the fire dominates the wind field. When this effect is present ($P_f > P_w$) on strip head fire ignited prescribed burns, ambient winds will be absent on the downwind side of the column and eddy effects, as shown in Figure 13a, will be present. Ambient winds will only reappear downwind once the column energy breaks down ($P_w > P_f$). At the end of a prescribed burn, the collapse of the convection column must be considered to ensure control of the burn. To reduce problems, there should be no areas left unburned where fire spread can occur downwind of the main ignition due to the reestablishment of the ambient wind.

Figure 14 shows how wind fields may change on an ongoing large-scale fire as the convection column shifts with time. Ambient winds that are present prior to burning (Fig. 14a) are still felt during the start of the prescribed burn, especially when burning out with a low-intensity fire (Fig. 14b). However, as the convection column builds up, P_f quickly exceeds P_w and wind directions are altered around the opaque convection column (Fig. 14c). Wind direction changes may easily be felt 1–2 km downwind on large burns. The leeward wind direction, often a reverse of that of the ambient wind, is a result of fire-induced and eddy winds. As the convection column travels across the burn site (Fig. 7), the wind changes associated with the column move with it. On very large burns this migration may result in the ambient wind being prevalent again on the extreme leeward side (Fig. 14d). If for some reason the fuels were not completely burned between the initial burn out operation started in Figure 14a and the leeward boundary when the ambient wind reestablishes over this area, the fire could spread over this unburned area. It would travel in the direction of the wind and possibly escape into Area A as shown in Figure 14d. During this period, when the influence on the original burn out area changes from an indrafting fire wind to an ambient wind, a considerable potential exists for the fire to escape, i.e., the fire can race across unburned fuels located close to the perimeter. It is a good policy to make sure that the burn out is completed before proceeding to ignite the main portion of the burn. The question mark in Figure 14d indicates an area of the burn where wind direction may be quite variable as it switches from fire-induced to ambient. In many cases, vortices comparable to dust devils will form. These can lift both ash and firebrands aloft.

Properly burning all fuels to the edge as the prescribed burn proceeds must be stressed. Often this creates a dilemma as to how to lay the ignition line on the perimeter of the burn. The final ignition line should always be laid as close as possible to the burn edge (Line A in Fig. 15). This philosophy should be followed for completing ignition along all burn edges (*see* Fig. 6). This procedure will prevent problems should the ambient wind direction change. In Figure 15, if Line B is laid as the final ignition line far enough inside the burn such that it will not have completely backburned to the perimeter before the wind switches back to the prevailing ambient wind direction, then the back edge of the ignition line will revert into a head fire and move rapidly toward the burn edge. Given this wind change, the back edge of this ignition line will generally always be a line ignition that will reach the burn perimeter at high equilibrium rates of spread, which could result in serious spotting problems.

Sometimes prescribed burns are ignited under calm conditions, but as ignition proceeds the wind speed gradually increases. This may cause fire control concerns. In these cases $P_w > P_f$ can occur at very low heights over the burn, thereby resulting in tilted columns. This is contrary to a safe burn where the upward convection of firebrands allows time for them to burn out before falling out of the convection column. Maintenance of this upright column becomes even more essential when higher winds suddenly materialize. The ignition boss must keep calm and choose those ignition methods that will maintain an erect column. Figure 16a shows an example of a prescribed burn ignited with high wind speed (a low-level jet stream of up to 50 km/h) present at an altitude of only 270 m above the ground. This was only realized once ignition had commenced. Such wind conditions quickly pushed over the column and caused major safety problems. In these high wind speed cases, horizontal roll vortices (Haines and Smith 1987) can develop on either side of the pushed-over column. They are generally more pronounced on one side of the column and serve for bringing stronger winds at higher altitudes closer to the ground. Each inner roll vortex has an outer twin vortex associated with it that counter rotates (Fig. 16a). Wind flow from the twin flows outward away from the fire when it reaches the ground. Such an event would be contrary to what one might expect, where not knowing the presence of roll vortices, the fire spreads away from the main fire body opposite to the expected fire-induced indrafts. The danger in this situation is that if the outer (twin) vortex reaches the ground, it can push an outer ignition line away from the main fire through unburned fuel toward the burn perimeter. Because of the high winds involved, rarely does this uncontrolled fire front stop at the burn perimeter, but continues over most control lines. This is also true when fuels outside the perimeter are considered fireproof, even if spread is only momentary, because of the high-intensity (I_F) fire front preheating the fuels before it.

The development of the pushed-over convection column (Fig. 16a), while mainly attributed to the materialization of the high wind speed conditions, can be perpetuated further by the actual ignition pattern used during the burn (Fig. 16b). In this case, because of disorientation concerning the original center fire ignition location, most of the ignition took place downwind of the original start. Therefore, the main fire intensity (I_F) occurred downwind because of the ignition offset, which naturally pulled over the convection column and accentuated the pushed-over column that already existed because of the strong winds. A pushed-over column provides the conditions necessary for the development of roll vortices. An ignition boss realizing that wind conditions are strong might want to assist the convection column to remain upright (Fig. 17a), thereby reducing the probability of developing any roll vortices that could cause control problems. This can be done by altering the ignition pattern to build up the fire more on the upwind side (Fig. 17b).

Areas of Concern

With continued movement toward a multiuse approach to forest management, more areas of concerns (AoC) are being left uncut on large prescribed burn sites. The main reasons cited for leaving an AoC are for wildlife habitat (e.g., moose habitat in the boreal forest) or as shoreline reserves (e.g., riparian protection to the waterbody). These areas pose an interesting problem to the prescribed burner—burn a large area with substantial fuel loads around an AoC, but at the same time save the AoC from burning. If such areas cannot be preserved, then the future opportunity for using prescribed fire may be curtailed. Without recognizing the ability for manipulating and controlling the prescribed fire to do what is required, this may appear to be a difficult task for many resource managers as well as many prescribed burn planners. Saving an AoC during the summer prescribed burning season (DC<300) in the boreal forest should be very easy since the natural, live understory vegetation can be used to deter any low-energy fires.

Patience and time are required to properly burn around an AoC. Too often in the past, ignition was completed around an AoC without regard for the type of fire behavior that would be produced. An example of this occurs where, using a helitorch, a solid line of fire is ignited 100 m upwind of the AoC. Such an ignition line rapidly spreads before the wind (Fig. 18a). The line ignition allows the fire to attain equilibrium spread rates very quickly, thereby resulting in an intense, fast-spreading fire that reaches the AoC. With a typical Initial Spread Index (ISI) of the FWI System of 7 for an afternoon prescribed burn, the ignition of a fireline should reach the equilibrium spread rates of 12 m/min very quickly (Stocks and Walker 1972). Simple momentum at these speeds (and intensity) can push the fire into a relatively fire proof AoC (due to the preheating of fuels), even if just momentarily. Ignition around these AoC needs to be developed such that spread rates and, therefore, the development of fire intensity is kept low. The use of point ignition would be the best approach in this situation (Fig 18b). Basically, the ignition around the AoC is a burning out operation. The initial ignition line also needs to be laid close to the AoC so as to reduce the probability of any fire running into it (similar to the reasoning used for perimeter ignition line placement in Fig. 15), and thereby controlling intensities that could provide the momentum to carry fire into the AoC. Ignition lines that follow should be closely laid to complete the burning out operation. Only then is it permissible to continue regular head fire ignition.

Ignition Patterns

The most common aerial ignition patterns used by the OMNR are center fire and strip head fire. The decision to use either pattern depends upon many factors.

Center fire ignition

Center fire ignition requires the establishment of an intense central fire with a well-developed convection column. The center fire has to be created quickly after ignition begins since the setting of circular ignition lines around the prescribed fire depends upon fire-induced indrafting to pull ignition lines toward the main fire. The use of center fire ignition is usually carried out when winds are calm or light. This caution is taken to ensure that, if the convective action of the column in drawing the outer ignition line on the lee side is weak, this fire line does not reverse and become a head fire that spreads uncontrolled toward the perimeter. Light fuel loads should be avoided so that sufficient I_F is always produced to ensure the creation and maintenance of a good convection column (indrafting). Narrow burn areas are generally avoided, since it is impossible to allow for the development of the traditional succeeding circles of ignition lines to be indrafted into the main fire. Center fire ignition allows for good smoke dispersal, because the smoke is lifted straight up into the convection column and dispersed with upper-level winds. It must be remembered that once started, the I_F of the center fire must be maintained to ensure that the convection column does not collapse and that the indrafting process stops. Refueling turnaround times of the helicopters need to be as short as possible to ensure that the I_F is maintained. The use of center fire as an ignition technique by the OMNR has decreased, possibly because some bosses fear that they will fail to maintain the proper indrafting. Since calm wind conditions are needed, the evening period, when the major convective activity of the day has ceased, can provide ideal conditions. Even in this short burning period, large prescribed burns can be completed. One example of this is the 455-ha English Township prescribed burn, which was completed in 2 hours (M^cRae 1986).

Center fire ignition often takes place with little reconnaissance prior to the prescribed burn. As such, the initial starting point can be poorly selected, and fail to maintain the necessary I_F. M^cRae et al. (1989), using the Battersby Township prescribed burn as an example, showed how a center fire was an improper choice on an area of poor slash fuel continuity broken up by unmerchantable, uncut forest stands; roads; and log landings (areas devoid of fuels) (Fig. 19). As these features are usually present somewhere on a harvested site, they must be recognized for what they are—fire growth inhibitors. This example illustrates the need to estimate how areas within the burn that have no ability to carry the fire will affect fire growth and column development during ignition. In the case of the Battersby Township prescribed burn, the downwind portion of the fire was poorly developed. Since the intensity of the fire was good upwind, it pulled the column upright and no major control problems were experienced. If the reverse had been true, in that the convection column became more developed downwind, then there could have been a potential for the column to bend over (as in Fig 16a). On many burns, ignition bosses seek out hills to start their center fires in the hope that this will help to develop the high intensities (I_F) needed to initiate indrafting. More important, however, is the need to find sufficient quantities of available fuel to allow for the quick development of an intense fire. Inexperienced ignition bosses may become cautious when they see a large amount of fire on the site, but this is exactly what is needed when using this technique. Hills can help in producing high I_F when slope acceleration is taken advantage of to increase a_F quickly, but adequate dry fuels are still more important.

Strip head fire ignition

The use of strip head fires appears to be the preferred method of ignition on most prescribed burns conducted in Ontario. For personnel lacking ignition experience, this technique is the easiest and safest method to master. It is also best used on areas where fuel loads are low or when fire behavior indices of the FWI are low (i.e., center fire ignition would be a poor choice in these situations because of the lack of available fuels). This technique employs a series of successive parallel ignition lines, which are ignited upwind of each other and allowed to burn into the main fire body. The trick to succeeding is knowing how far apart to space the successive ignition lines and the rate of doing so for controlling I_F. It is this experience that is not well documented. Often, ignition bosses get themselves into trouble because they are unsure as to whether the intensity will be increased or decreased, for example, by moving the ignition lines closer or further apart. On the 1986 Garibaldi Township prescribed burn, the ignition boss had as much as 7 km of line ignition going at any one time with spacings of up to 0.7 km between ignition lines (Fig. 20). This 955-ha prescribed burn was completely ignited in 2 hours. Partly as a result of the high I_F values generated, a firestorm was produced, creating thunderous noise and fire whirlwinds (M^cRae and Stocks 1987, M^cRae and Flannigan 1990).

Operationally, the mystery of ignition line placement (i.e., what actions increase or decrease I_F) may be resolved by thinking of the consequences on intensity as related to a_F. If the distance between ignition lines is decreased and the ignition rate remains the same or is reduced, then a_F will decrease. However, if the ignition rate is increased then there is a potential to increase a_F. The rate at which a_F increases will also depend upon whether point or solid-line ignition is used. When the distance between ignition lines is increased there is a potential for a higher a_F, particularly with line ignition. This is especially true when burning conditions are good. When conditions are marginal (i.e., FFMC $\leq$ 85), the fire spread will be poor and the a_F may remain low. Therefore, when changing ignition line distances one must understand how this will affect a_F (and I_F).

When using the strip head fire ignition technique, the rate of burning (ha/hr) should be considered to ensure that excessive a_F are not allowed. This could result in very erratic fire behavior or firestorms. The rate of burning is a product of fireline characteristics, the distance between ignition lines, ignition rates, and equilibrium rates of spread. A simple chart to relate the burning rate to erratic fire behavior is shown in Table 3. Of course, if the fire has a low I_R or is in a safe spot where erratic fire behavior will not be a problem, then such guidelines may be ignored.

Table 3. A chart showing the hazard of different rates of burning as related to the utilization of the strip head fire ignition technique under ideal burning conditions.

Rate of burning (ha/hr)	Erratic fire behavior hazard rating[1]
> 400	Extreme – fire storms
200 – 400	High
100 – 200	Moderate
< 100	Low

[1] This rating provides only a general evaluation of hazard because, given proper fire and atmospheric conditions, erratic fire behavior may occur even on small burn sizes.

Of the two ignition patterns, strip head fires are more prone to causing the development of large fire whirlwinds (M^cRae and Flannigan 1990). Center fire ignition prevents the formation of eddy wind fields, which are required for the development of whirlwinds, because of the indrafting process that occurs completely around the fire perimeter (Fig. 13b). Whirlwinds may develop only prior to the build up of the center fire convection column or once the column dissipates. Firestorms, where the convection column starts to rotate, are absent on center fired prescribed burns.

When burning conditions are marginal (i.e., FFMC<85 or BUI<30), it may be necessary to decrease the distance between ignition lines and to increase the rate of ignition. Here, the increased application of fire increases a_F and the probability that fire will spread over a good portion of the area even with discontinuous or wet fuels. In this case, an increase in a_F does not necessarily mean a large increase in I_F since I_{RF} is limited due to a reduced fuel consumption rate (w_F). Such a strategy of increasing a_F may also be useful where an increased I_F is required to maintain control of the convection column. With point-source ignition (e.g., OAID), because it takes longer to reach equilibrium spread rates, the resulting energy-release rates will be lower than those attained for line ignition (e.g., helitorch). Therefore, use of the helitorch is always better under marginal conditions. Due to the helitorch characteristics of producing higher intensities, ignition rates should be reduced for line ignition whenever there are safety concerns

Figure 12. An aerial view of a burn out operation shortly after ignition shows the development of a high-intensity fire close to the downwind burn perimeter (note the mass-fire ignition and potential for junction zones). This is an incorrect procedure because extra time should be allowed to burn out a sufficiently large area so as to reduce spotting potential. In the prescribed burn depicted, erratic fire behavior developed and this resulted in spotting, which required major suppression efforts.

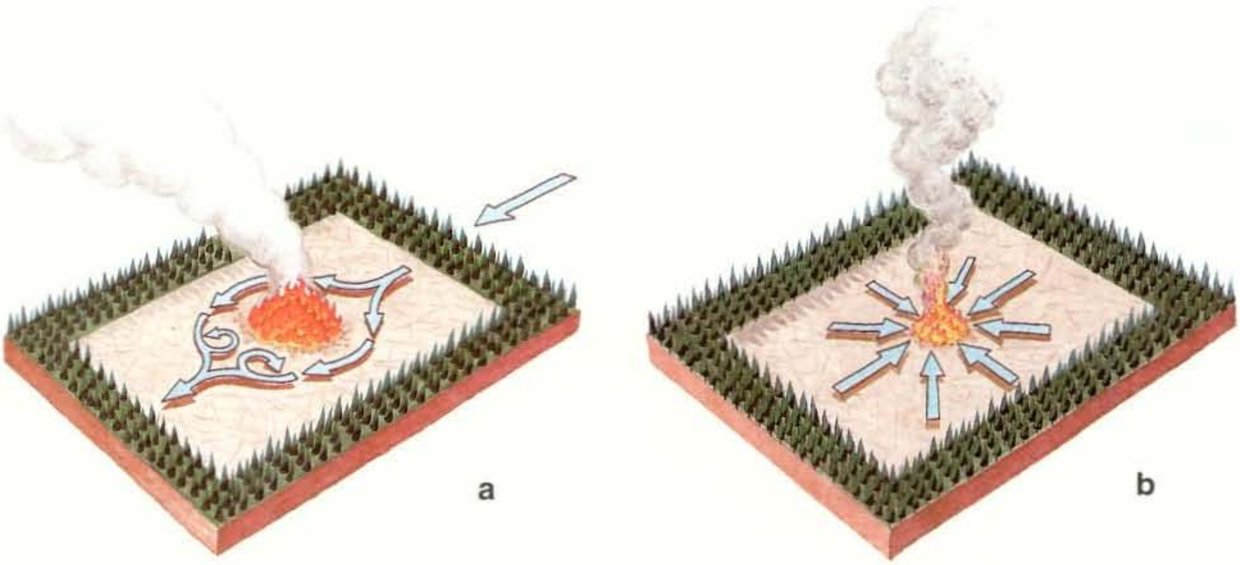


Figure 13. (a) This illustration shows how the ambient wind field (large blue arrow) is blocked and then forced around the convection column. Note the location of eddies downwind of the column, versus (b) where a convection column produced by center fire ignition, under none or low ambient winds, creates indrafts on all sides of the column, but no eddy effects.

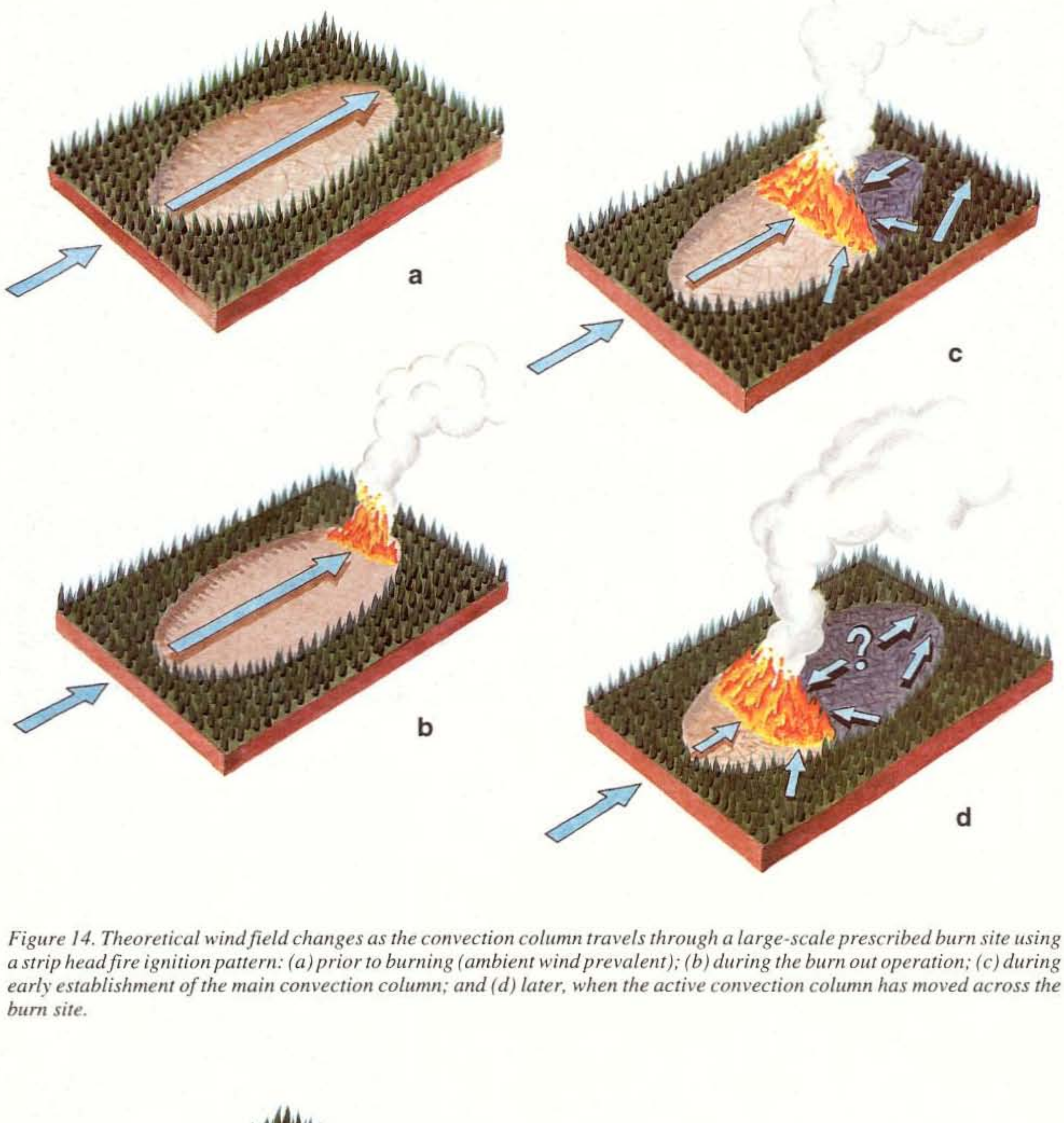


Figure 14. Theoretical wind field changes as the convection column travels through a large-scale prescribed burn site using a strip head fire ignition pattern: (a) prior to burning (ambient wind prevalent); (b) during the burn out operation; (c) during early establishment of the main convection column; and (d) later, when the active convection column has moved across the burn site.

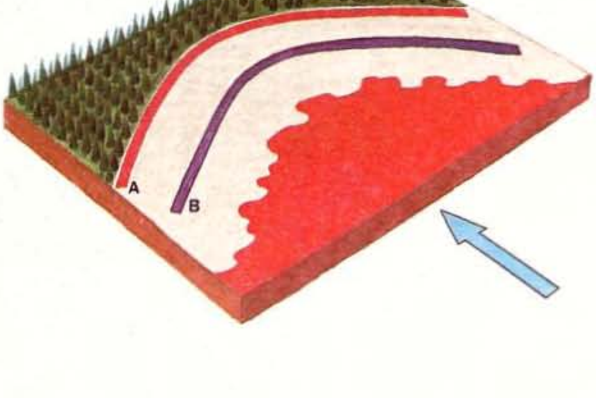


Figure 15. Line A is the proper location for an ignition near the burn edge. The area outlined in red represents the main fire body. If Line B was used as the final ignition line, a loss of control might occur if fire-induced indrafting winds weaken before it burns out completely to the burn edge. The return of ambient winds (blue arrows) could revert the back edge of the fire line to a rapidly moving head fire, which could cause fire control problems at the burn edge.

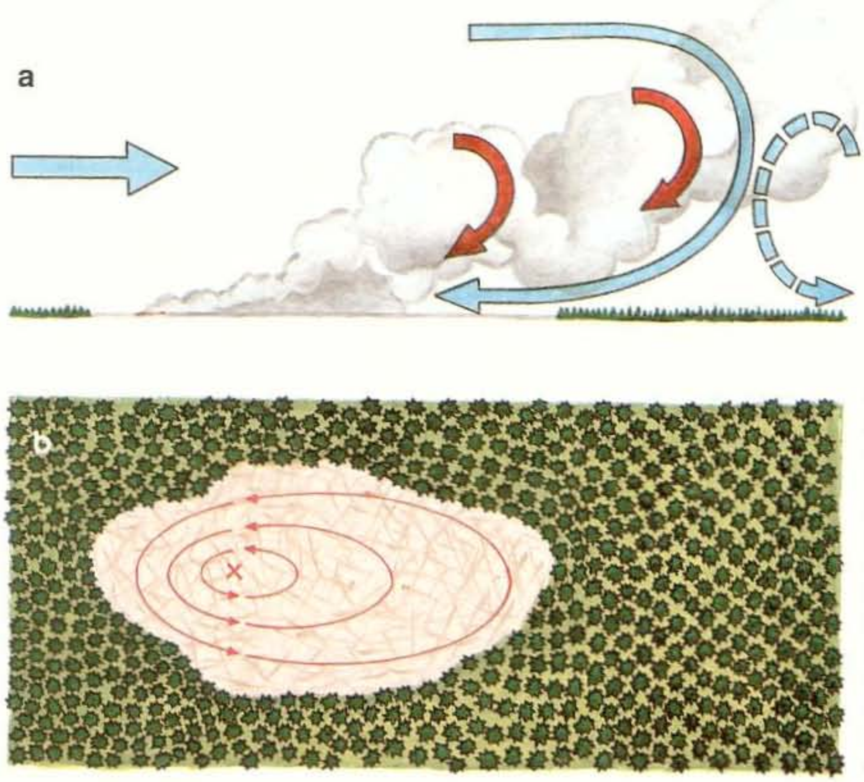


Figure 16. (a) An illustration of an actual convection column of a prescribed burn ignited as a center fire under high-wind conditions (ambient wind direction is left to right). Note the position of horizontal roll vortices (blue arrows) that occur on the flank of the convection column and not on the leeward side of the column as the diagram may suggest (red arrows show convection column movement); and (b) the ignition pattern which, besides the high wind conditions, accentuated the development of the pushed-over convection column.

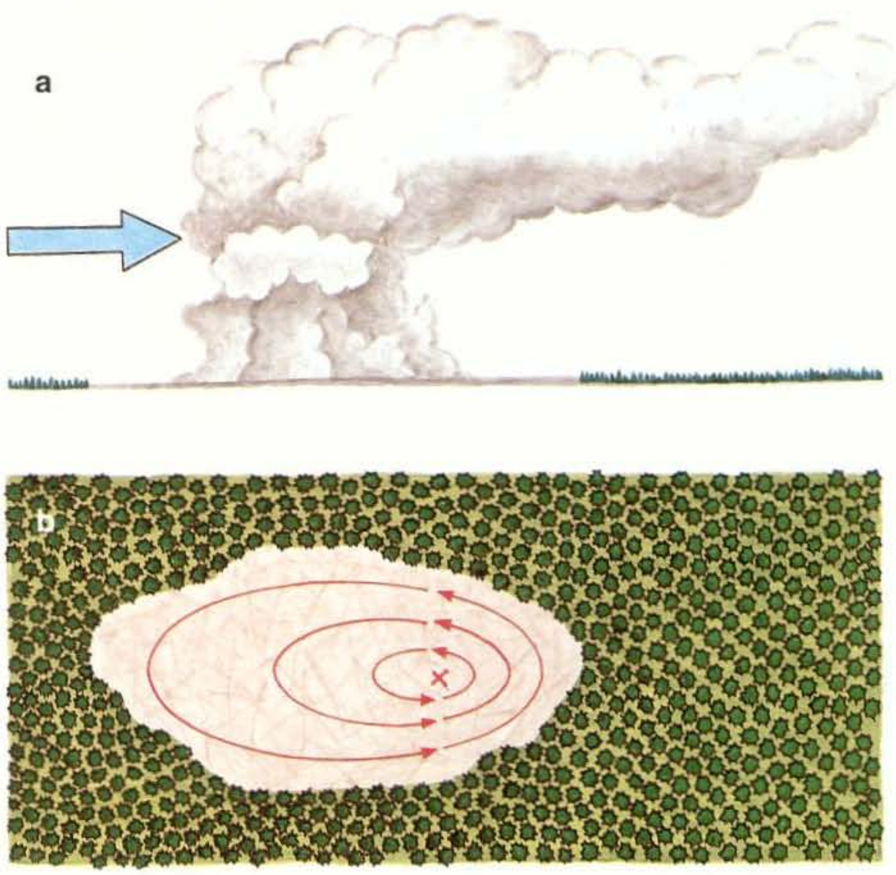


Figure 17. (a) An illustration of the stand-up, center fired convection column of a prescribed burn developed under high ambient wind conditions (ambient wind direction is left to right). When the ignition pattern is built properly, as in (b), it will lead to increased intensity upwind of the burn center.

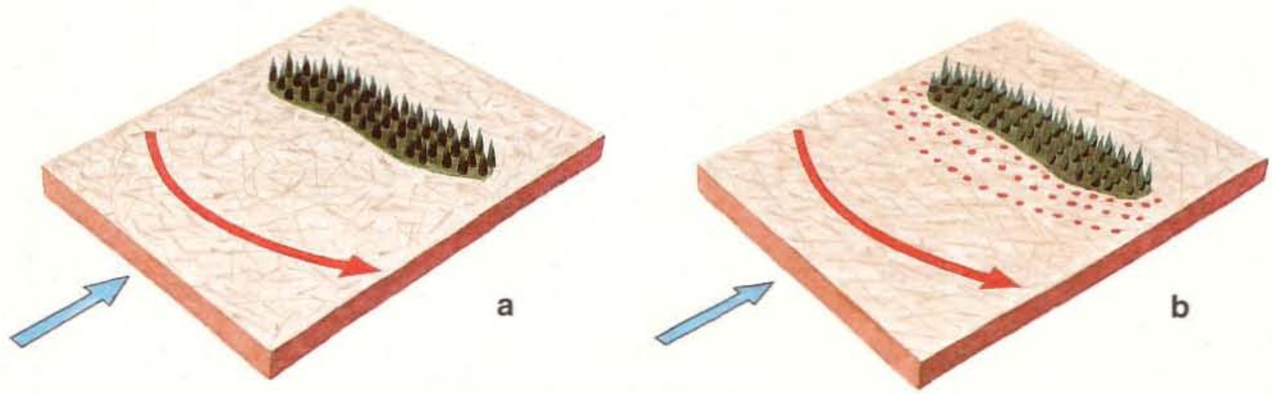


Figure 18. (a) An example of poor ignition, using line ignition, upwind from an AOC (the blue arrow shows the ambient wind direction); versus (b) the correct way to ignite around an AoC using point ignition to burn out first before proceeding with line ignition.

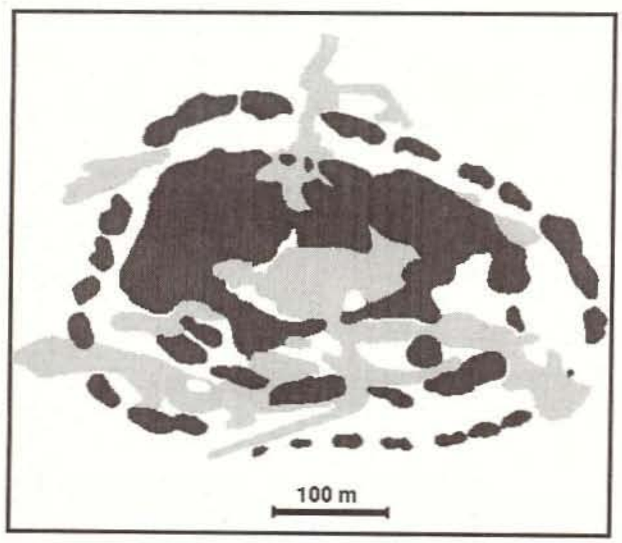


Figure 19. An example of a poor candidate site that was actually used for center fire ignition (ignited area indicated by the darker shaded area). Poor slash continuity (indicated by the lighter shaded area), including unmerchantable forest stands, roads, and landing areas, prevented the development of needed reaction intensities. Ambient wind was from the north.

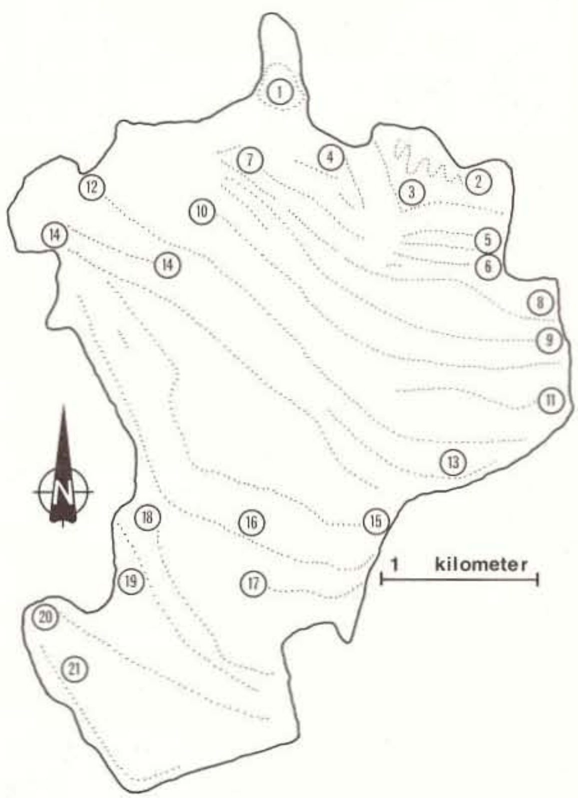


Figure 20. Strip head fire ignition sequence on the Garibaldi Township prescribed burn (955 ha). This was completed in 2 hours (ambient wind direction was from the southwest).

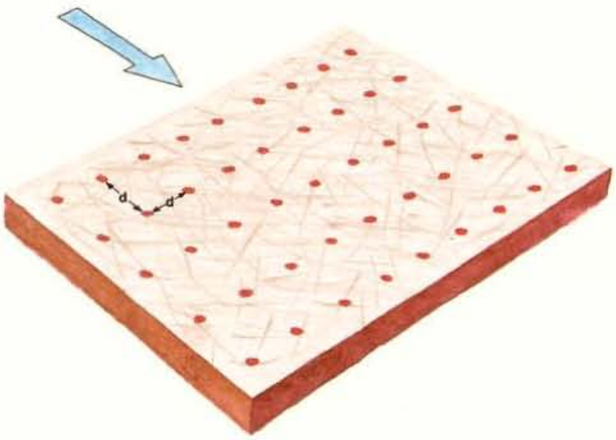


Figure 21. Closely spaced ignition spots prevent major fire accelerations and can control fire intensities (I_F). This strategy is used in burning out at the beginning of a prescribed burn (the blue arrow shows the ambient wind direction).

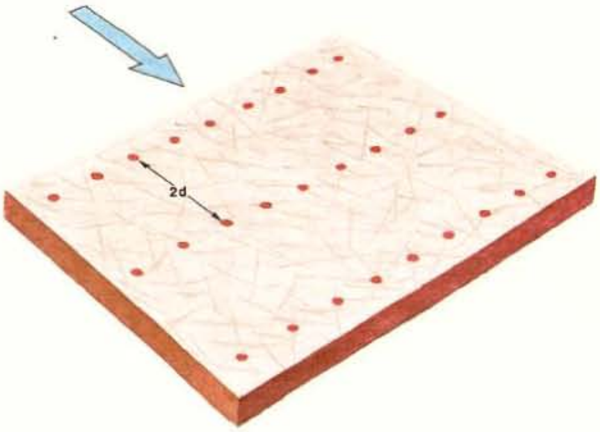


Figure 22. Fire intensities (I_F), when spot ignition is used, will be increased when the spacing between ignition lines is increased due to the increased ability of the fire to accelerate (the blue arrow shows the ambient wind direction).

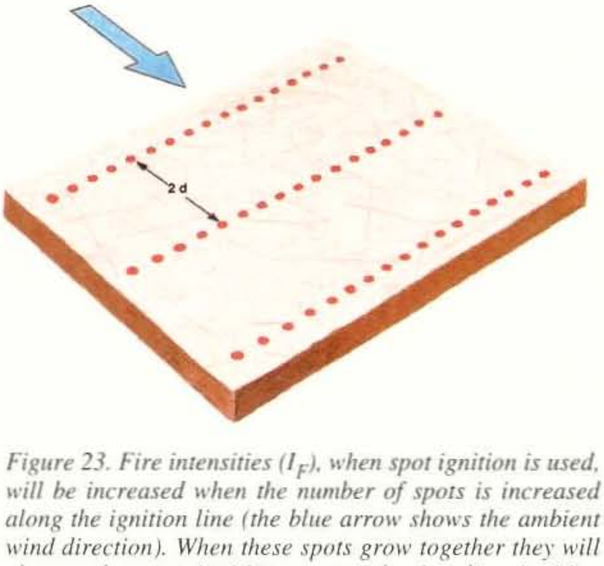


Figure 23. Fire intensities (I_F), when spot ignition is used, will be increased when the number of spots is increased along the ignition line (the blue arrow shows the ambient wind direction). When these spots grow together they will change the spot ignition on one having line ignition characteristics.

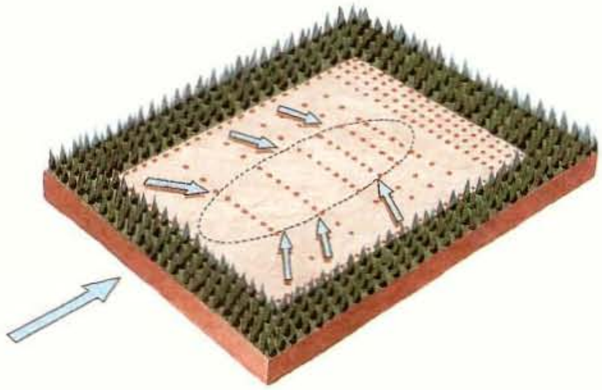


Figure 24. A simple point-ignition pattern to be used with the strip head fire ignition technique (the large blue arrow shows the ambient wind direction) to produce an indraft (small blue arrows on the burn area) from the burn edge into the center of the burn, and thereby reduce suppression problems.

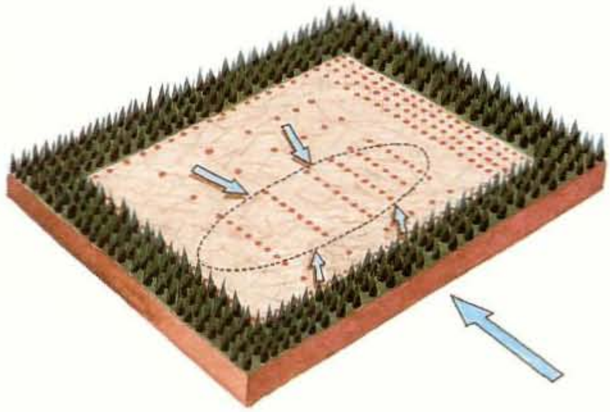


Figure 25. A spot ignition pattern where, due to a change of ambient wind (the large blue arrow) from the situation observed in Figure 24, ignition spacing is concentrated upwind to ensure that the convection column remains upright.

over fire spotting (e.g., time for burning out). While equilibrium rates of spread will not be altered by changing distances between solid line ignition, decreasing the distances and reducing the ignition rate will reduce a_F (I_F).

Ignition Spacing

Point-source ignition spacing, such as that obtained from the OAID, gives the ignition boss a greater ability to control the fire intensity that develops on a prescribed burn. Closely spaced ignition spots with low rates of burning will have the least fire intensity potential of all the spacing methods (Fig. 21). With limited space to accelerate, intensity is kept low since the rate of spread (r) of Equation [2] is kept low (this keeps a_F low). When the spacing is retained perpendicular to the wind direction but the distance between ignition lines is increased (Fig. 22), intensity buildup will be greater than in the first case (provided the rate of application is not changed). Here, the spacing gives the fire an ability to accelerate, and this will increase a_F. A more intense fire develops where the spacing perpendicular to the wind is close together and the distance between ignition lines is large (Fig. 23). As spacing characteristics change (Figs. 21–23), the fire accelerates faster than the point ignitions and becomes more like a line ignition. With increased intensities (I_F), junction zones have a greater effect, thereby boosting intensity levels.

The use of point-source ignition to control I_F (Figs. 21–23) is difficult using a helitorch ignition system. Some procedures for the helitorch can be used to control fire intensity, but it will be more limited than using point-source ignition. Line ignition will always be created because of the physical characteristics of the helitorch system (Fig. 9). The best opportunity to control I_F is by manipulating the distance between ignition lines and the ignition rate used. I_F will be reduced when the rate of burning is reduced.

By manipulating I_F, different portions of the prescribed fire can be drawn away, through fire-induced indrafting processes, from areas where safety concerns exist. This is an important factor—one that is often not addressed in the planning process of the burn. Because of this, rarely is there a conscious change in ignition spacing during the burn to manipulate fire behavior.

Figure 24 illustrates a proper point-source ignition. First, to ensure that a good control line exists between the main fire and the downwind boundary, burning out, using point-source ignition with closely spaced firelines, is conducted. The close spacing of firelines speeds up the burning out process by allowing some forward rates of spread, but prevents any major spread acceleration because the short distances prevent the point-source ignitions from attaining equilibrium rates of spread. In turn, this keeps the I_F low. The ignition rate is also low during this period. Once a sufficiently large area is burned, ignition spacing and the ignition rate can be increased. Increased spacing will increase I_F (a_F is increased) since rates of spread will pick up due to greater acceleration. To encourage indrafting from the edges into the middle of the burn, and thus reduce spotting outside of the perimeter, the spacing of the incendiaries should be less (more concentrated) in the middle of the burn. This allows the fire to be indrafted into the burn center away from the edge. The final ignition line is placed close to the perimeter so as to properly finish the burn (Figure 15). Note that in Figure 24 an ignition line is laid concurrently, as the main ignition proceeds, along each side (flank) so as to burn the fuel present in this area and prevent any possible run of the fire to the perimeter in the case of a wind shift (Fig. 6).

Because the wind sometimes changes direction or because the fuel is not homogeneous, ignition strategies must be flexible. For example, ignition changes may be necessary to keep the convection column upright (Fig. 25). Here, recognizing a wind direction change, the ignition boss concentrates the ignition (a_F) to one side of the burn to pull and maintain the column upright.

THE IGNITION BOSS

The ignition boss should be divorced from the actual physical ignition of the prescribed burn; often they have been in the ignition helicopter. Here the boss is more apt to be preoccupied with dropping "fire", rather than with concentrating on fire behavior and column dynamics. The ignition boss must have the ability to step back and observe the entire prescribed burn rather than only one small portion of it. Being at a distance, the boss can better direct and control the ignition by observing fire development, and by issuing orders necessary to ensure proper fire and convection column control.

FINAL REMARKS

This publication is a first attempt to bridge the knowledge gap between simple ignition pattern definitions and futuristic computerized expert systems on ignition. It is hoped that this information will stimulate the manner in which ignition bosses plan and conduct their prescribed burns. This ignition information permits, for the first time, the documentation of some rules that will be required to operate the Canadian PFIES.

ACKNOWLEDGMENTS

The author gratefully acknowledges the many fire personnel who, by providing their time and support, have helped this handbook become a reality. Special thanks are extended to the following individuals for their critical review of the handbook: T.W. Blake, R. Burke, D. Curran, B.C. Hawkes, and B.J. Stocks. Funding for publishing of this handbook was provided by the Northern Ontario Development Agreement, Northern Forestry Program.

LITERATURE CITED

Alberta Forest Service. 1990. Alberta Forest Service prescribed burn manual for the forest protection area of the province. Alta. For., Lands and Wildlife, For. Serv., Edmonton, AB. 43 p.

Alexander, M.E.; Stocks, B.J.; Lawson, B.D. 1991. Fire behavior in black spruce-lichen woodland: The Porter Lake Project. For. Can., Northwest Reg., Edmonton, AB. Inf. Rep. NOR-X-310. 44 p.

Byram, G.M. 1959. Forest fire behavior. p. 183–216 *in* A.A. Brown and K.P. Davis, eds. Forest Fire: Control and Use. McGraw-Hill Book Co., New York, NY. 584 p.

Canadian Forestry Service. 1987. Tables for the Canadian Forest Fire Weather Index System. 4th ed. Can. For. Serv., Ottawa, ON. For. Tech. Rep. No. 25. 48 p.

Cheney, N.P. 1981. Fire behavior. p. 151–157 *in* A.M. Gill, R.H. Groves and I.R. Noble, eds. Fire and the Australian Biota. Australian Academy of Science, Canberra, Australia. 582 p.

Countryman, C. M. 1971. Firewhirls–why, when and where. USDA For. Serv., Pacific Southwest Forest and Range Experiment Station, Berkley, CA. 11 p.

Fischer, W.C. 1978. Planning and evaluating prescribed fires - a standard procedure. USDA For. Serv., Ogden, UT. Gen. Tech. Rep. INT-43. 19 p.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. For. Can., Ottawa, ON. Inf. Rep. ST-X-3. 63 p.

Haines, D.A.; Smith, M.C. 1987. Three types of horizontal vortices observed in wildland mass and crown fires. J. Clim. Appl. Meteorol. 26:1624–1637.

Hirsch, K.G. 1988. Ignition patterns used in prescribed burning. Can. For. Serv., Edmonton, AB. Tech. Transfer Note M-004. 4 p.

Johansen, R.W. 1987. Ignition patterns and prescribed fire behavior in southern pine stands. Georgia For. Res. Pap. 72. 6 p.

Laframboise, P. 1991. Guide de brûlage dirigé à des fins sylvicoles. Québec Ministère des Forêts, Sainte Foy, QC. 59 p.

Merrill, D.F.; Alexander, M.E., eds. 1987. Glossary of forest fire management terms. Fourth ed. Nat. Res. Counc. Can., Can. Comm. For. Fire Manage., Ottawa, ON. Pub. NRCC No. 26516. 91 p.

McRae, D.J. 1980. Preliminary fuel consumption guidelines for prescribed burning in Ontario slash fuel complexes. Environ. Can., Can. For. Serv., Sault Ste. Marie, ON. Inf. Rep. O-X-316. 25 p.

McRae, D.J. 1986. Prescribed burning for stand conversion in budworm-killed balsam fir: An Ontario case history. For. Chron. 62(2):96–100.

McRae, D.J.; Flannigan, M.D. 1990. Development of large vortices on prescribed fires. Can. J. For. Res. 20(12):1878–1887.

McRae, D.J.; Lynham, T.J.; Frech, R.J. 1994. Implementing a successful understory red pine and white pine prescribed burn. For. Chron. 70:395–401.

McRae, D.J.; Stocks, B.J. 1987. Large-scale convection burning in Ontario. p. 23–30 *in* Proc. Ninth Conference on Fire and Forest Meteorology. 21–24 April 1987, San Diego, California. Amer. Meteorol. Soc., Boston, MA. 281 p.

McRae, D.J.; Stocks, B.J.; Ogilvie, C.J. 1989. Fire acceleration rates on large-scale convection burns. p. 101–107 *in* D.C. MacIver, H. Auld and R. Whitewood, eds. Proc. Tenth Conference on Fire and Forest Meteorology. 17–21 April 1989, Ottawa, Ontario. 471 p.

McRae, D.J.; Todd, B.; Ogilvie, C.J. 1991. A prescribed fire ignition expert system for Canada. p. 234–241 *in* P.L. Andrews and D.F. Potts, eds. Proc. Eleventh Conference on Fire and Forest Meteorology. 16–19 April 1991, Missoula, Montana. Society of American Foresters, Bethesda, MD. 616 p.

Muraro, S.J. 1975. Prescribed fire predictor. Environ. Can., Can. For. Serv., Victoria, BC. 2 p

Mutch, R.W., tech. coordinator. 1984. Proceedings prescribed fire by aerial ignition. Intermountain Fire Counc., Missoula, MT. 217 p.

Nelson, R.M., Jr. 1993. Byram's energy criterion for wildland fires: Units and equations. USDA For. Serv., Intermountain Res. Stn., Ogden, UT. Res. Note INT-415. 5 p.

Ontario Ministry of Natural Resources. 1987. Prescribed burn planning manual. Aviation and Fire Manage. Centre, Sault Ste. Marie, ON.

Stocks, B.J.; McRae, D.J. 1991. The Canada/United States cooperative mass fire behavior and atmospheric environment impact study. p. 478–487 *in* P.L. Andrews and D.F. Potts, eds. Proc. Eleventh Conference on Fire and Forest Meteorology. 16–19 April 1991, Missoula, Montana. Society of American Foresters, Bethesda, MD. 616 p.

Stocks, B.J.; Walker, J.D. 1972. Fire behavior and fuel consumption in jack pine slash in Ontario. Can. For. Serv., Sault Ste. Marie, ON. Inf. Rep. O-X-169. 19 p.

Susott, R.A.; Ward, D.E.; Babbitt, R.E.; Latham, D.J. 1991. The measurement of trace emissions and combustion characteristics for a mass fire. p. 245–257 *in* J.S. Levine, ed. Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications. MIT Press, Cambridge, MA. 569 p.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index. Government of Can., Can. For. Serv., Ottawa, ON. For. Tech. Rep. No. 35. 37 p.

Wade, D.D.; Lungsford, J.D. 1989. A guide for prescribed fire in southern forests. USDA For. Serv., Southern Reg., Atlanta, GA. Pub. R8-TP11. 56 p.

Weber, M.G.; Taylor, S.W. 1992. The use of prescribed fire in the management of Canada's forested land. For. Chron. 68(3):324–334.

Weber, R.O. 1989. Analytical models for fire spread due to radiation. Combustion and Flame 78:398–408.

GLOSSARY OF TERMS

Burning out: The setting of fire so that it will burn against the wind and thus reduce fire intensity. Burning out of fuels is often conducted adjacent to a control line prior to igniting the main prescribed burn so as to increase the width of the downwind perimeter control line.

Drip torch: An incendiary device (aerial or handheld) that releases slow-burning, flaming fuel at a predetermined rate (Merrill and Alexander 1987).

Frontal fire intensity (FFI): The rate of heat release per unit time per unit length of fire front, expressed in kW/m (Merrill and Alexander 1987).

Helitorch: A specialized drip torch that uses gelled fuel, and is slung and activated from a helicopter (Merrill and Alexander 1987).

Ignition: The application of fire to a prescribed burn site, often in set patterns based on weather, fuel, topography, and ignition system, to safely achieve specific objectives.

Ignition line: A general term used to describe any application of fire, whether it is line ignition or individual spot ignition.

Ignition rate: The rate at which the ignition system travels and drops ignited fuel, expressed as km/min for aerial ignition or m/min for hand ignition.

Ignition pattern: The manner in which the prescribed burn is ignited (e.g., back fire, center fire, strip head fire, etc.). This is determined by weather, fuel, ignition system, and topographic or other factors that will have an influence on fire behavior and the objective of the burn (*adapted from* Merrill and Alexander 1987).

Ignition system: Generally, a specialized piece of equipment used to ignite the fuels found on the prescribed burn (e.g., hand drip torch, helitorch, OAID, etc.).

Junction-zone effect: This occurs when the fire accelerates as it approaches the preceding ignition line or main fire body due to the development of a strong convection column with strong fire-induced surface indrafts.

Line ignition: A specific method of applying fire based on setting a solid line of fire as opposed to individual spots (*adapted from* Wade and Lunsford 1989).

Mass ignition (area ignition): The setting of a number of individual fires throughout an area either simultaneously or in quick succession and so spaced that they soon coalesce, influence, and support each other to produce a hot, fast-spreading fire (Merrill and Alexander 1987).

Ontario Aerial Ignition Device (OAID): A helicopter-mounted, delayed aerial ignition device that drops plastic spherical incendiaries ("ping-pong balls") containing potassium permanganate. The incendiaries are injected with an ethylene glycol/water mixture (usually 50/50) and immediately jettisoned unto the prescribed burn site. A chemical reaction that causes the incendiary to burst into flame occurs approximately 25 seconds after injection.

Point-source ignition: A specific method of applying fire based on setting a number of individual (spot) fires at predetermined spaces and times throughout the area to be burned.

Prescribed burning: The knowledgeable application of fire to a specific land area so as to accomplish predetermined forest management or other resource management objectives (*adapted from* Merrill and Alexander 1987)

Prescribed fire: Any fire deliberately utilized for prescribed burning; usually set by qualified fire management personnel according to a predetermined burning prescription (Merrill and Alexander 1987).

Rate of burning: The rate of area being ignited per unit time, expressed as ha/hr.

Reaction intensity (I_R): The energy-release rate per unit area of the prescribed fire (kW/m^2).

Total intensity (I_T): The total intensity, expressed as kW, for the entire prescribed fire.