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FIRE BEHAVIOR CONSIDERATION OF AERIAL IGNITION

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Abstract: Aerial ignition devices are being used which can start fires by a succession of point sources or by a line of fire. Through the use of these devices, the fire manager has considerable control of the fire situation. Control of the ultimate fire behavior depends on the ignition pattern and the indrafts generated by the fires. By understanding the expected fire behavior and the fuel and environment, the manager can burn in marginal situations, thereby extending the available burning period.

INTRODUCTION

Introduction of aerial ignition devices for prescribed fire does not mean that the traditional factors known to affect fire behavior have changed, although it would appear that way sometimes. What has changed is our ability to strongly influence the "fire situation" through use of mobile, rapid, and effective aerial ignition systems. Control of the fire situation is achieved primarily in two ways: placement of fire where needed at the right time and interactions of induced winds between fires. The fire behavior implications of this are understood by the practitioners, but documented explanations cannot be found. Regardless of the ignition method, it is necessary to know how a prescribed fire is expected to behave, both for planning and operational purposes. We are expected to achieve management objectives as explained earlier by Jim Brown, minimize the risk of escape, and keep costs down. Predicting fire behavior is not a simple task when all the uncertainties of fuels and weather, ignition patterns, and fire interactions are considered. We will examine prediction methods after discussing some peculiarities of prescribed fire and the significance of aerial ignition techniques.

POINT SOURCE VS. LINE IGNITION

Aerial ignition hardware is available for producing either point source ignitions or line source ignitions. The mechanics of these are amply described in other papers. The fire behavior resulting from the two techniques can be quite different.

It is assumed that the ignition source is capable of igniting fuel in close proximity to where it landed. The behavior of the fire after ignition in this discussion, therefore, is not related to the ignition device other than whether it was started as a point or as a line.

Fires lit from point source devices tend to be less intense and of longer duration than those lit as a line of fire. This can be explained by the buildup time of the fire. As the fuel begins to burn around a point source, it is drawing its energy from a relatively small area and adjacent fuel will be heated over a relatively small area. If the fuel is sufficiently plentiful and dry, the fire will gradually expand and grow in intensity. This process will continue until the fire reaches an intensity that will just support its flame structure and rate of spread by the rate at which it is consuming fuel in its path. Thereafter, if conditions remain reasonably uniform, the fire will be in a steady state condition. If the fuels are not uniform, the fire will pulsate depending on the fuel and its conditions as the fire grows.

It takes time to reach the steady state condition and during the early stages the fire is less intense. For fires started from a point, this time will be longer than for fires started from a line.

The shape of the fire as viewed from overhead will initially be circular and than become elongated in the direction most favorable to spread as caused by wind or slope (fig. 1).

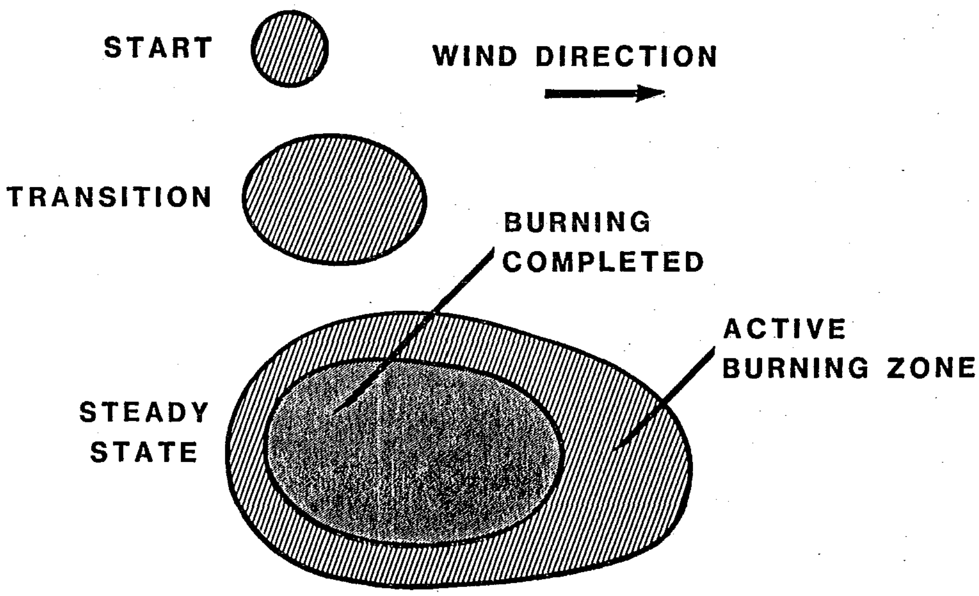

Figure 1. Growth of a point source fire.

In actual use, a succession of incendiary devices are dropped resulting in a large number of point source fires. The pattern spacing is dependent upon the frequency of drops and spacing between lines of drops.

Timing and spacing are under control of the ignition boss and give ample opportunity to influence how large and intense each fire will become and whether it reaches a steady state before the fires merge.

The most interesting fire behavior occurs at the time of merging. As the fires become close, heat will be concentrated by two fires on the fuel between them. Accelerated heating will cause a flareup with larger flame lengths as shown in figure 2. These flareups can cause higher scorch heights or periodic torching of an overstory if present.

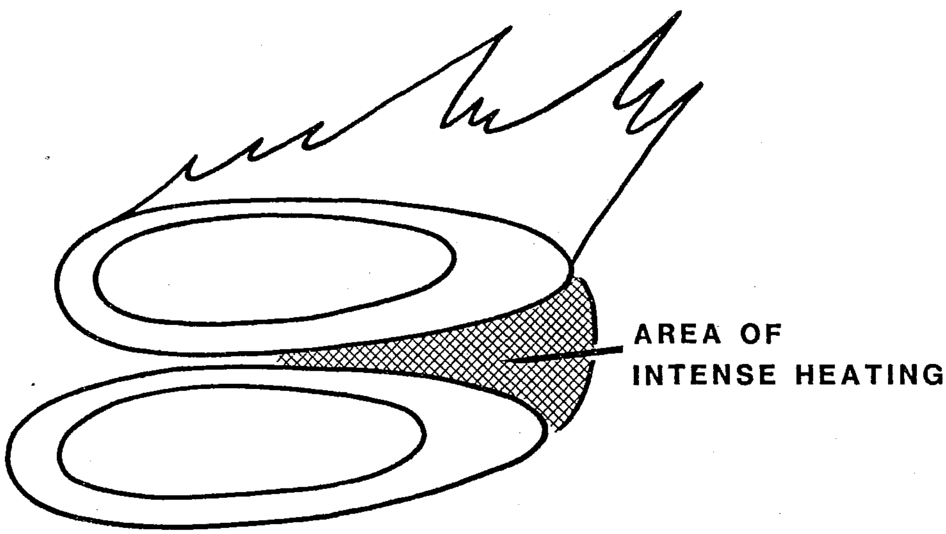

Figure 2. Source of flame flareups between point source fires.

Line source fires are also subject to a buildup period; however, since the line of fire concentrates more heat energy on nearby fuels, the transition to steady state is much faster than from point source ignition. Consequently, fires lit by line source tend to be more intense than those from point source ignition.

INDRAFTS

Prescribed fire practitioners have used the drawing power of fires for controlling burns for many years. Establishment of indraft is demonstrated most dramatically in large clearcuts where the buildup of a strong central convection column with its associated indrafts is used to assure that fires lit at the edges will be drawn into the center column. This method is often done with a combination of ignition methods; aerial ignition used in the center to establish the column, and hand ignition on the edges where the crew is in a safe position and out of the smoke. The strong central convection column produced by center firing of logging slash could be depended upon to last for some time; 10's of minutes or even hours as the large fuels in the center burned out.

Center firing is no longer as common as it was when large clearcuts were more prevalent. Although I understand it is making a comeback as an ignition method. Alternatively, in the West, strip firing is being used extensively, especially with the flying drip torch. Indrafts are generated by strip fires just as they are in center ignition (fig. 3). Besides the obvious difference between center firing, due to arrangement, strip firing with an aerial torch is usually done more rapidly. Consequently, the fuels producing the indrafts are the fine and intermediate-sized fuels. This has important implications on fuel consumption related to how the torch is used and the condition of the fuel.

Fine fuel

Regardless of the mode of ignition, if fine fuels are present they will be the first to ignite. Fine fuels only burn for a short time, however; and if an advantage is to be made of the indrafts at this stage of the fire, the next strip has to be lit quickly. This can be done safely and over large areas with a flying torch. Consequently, better control can be maintained in fuels that consist primarily of fine fuels and successful burns can be conducted in marginally poor burning conditions. For example, grasses or shrubs (or mixtures of them) that are too discontinuous to carry fire without a steady wind can now be burned by strip firing. Without a means of rapid ignition, these fine fuels would burn out before a second strip could be ignited (fig. 4).

With good burning conditions with continuous dry, fine fuel, fires will quickly pull together across the intervening fuel. The sudden ignition of such a large area will result in a very intense but short duration fire.

If only fine fuels are present, the fire will quickly die down and subsequent behavior will depend upon the timing of the next line of fire.

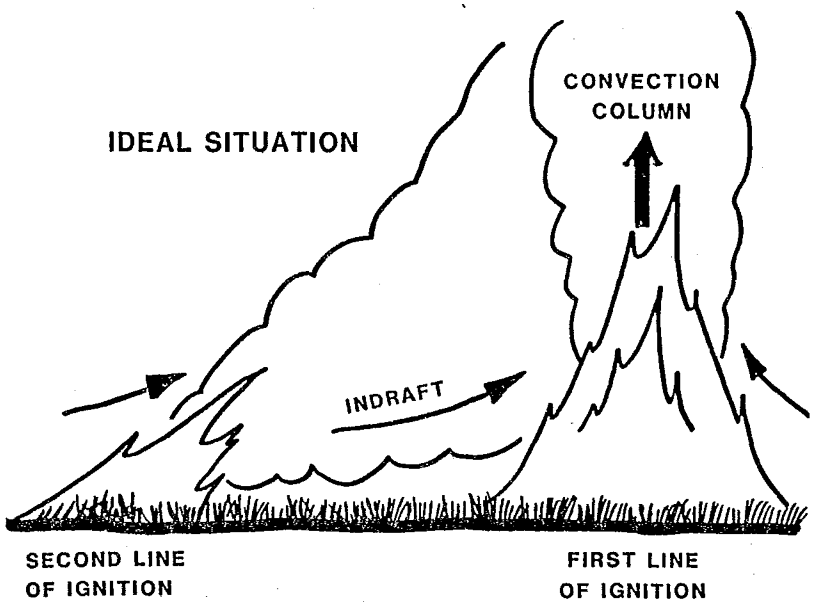

Figure 3. Indrafts between strip fires.

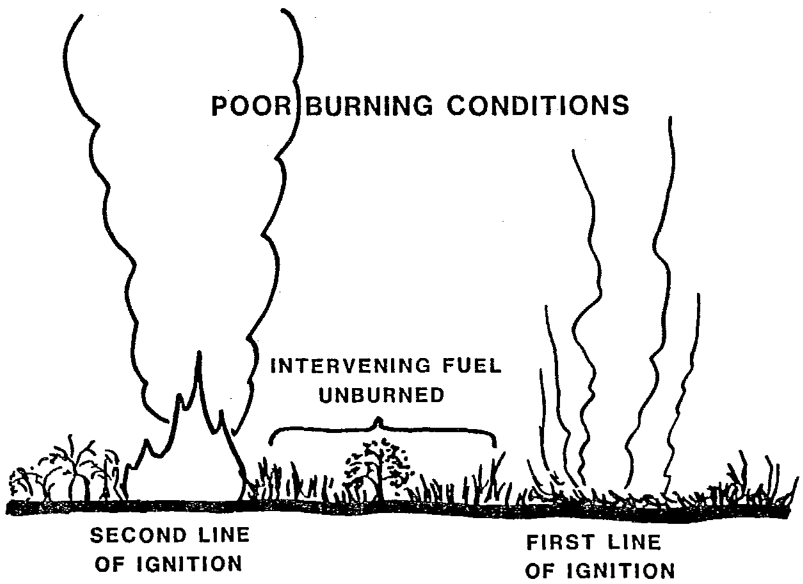

Figure 4. Strip firing results under poor burning conditions.

Large Fuels

If large fuels are present, subsequent behavior depends upon the moisture content and state of decay of the larger fuels. Under marginal burning conditions, the fine fuels will usually be the driest. They can be ignited and, if continuous, fires can be induced to spread between strips. This will not guarantee consumption of the large fuels. Preliminary data from experiments in Washington indicate that there is actually less consumption of large fuels when aerial ignition is used than from a comparable area ignited by handheld drip torches. The burnout of large fuels apparently is not enhanced by an intense fire with large flames and high convective activity. That type of fire develops from burning an area in a short time period. Whether this is good or bad depends upon the objectives of the burn. For silvicultural purposes, it may be desirable to leave large logs on the site for better moisture retention and shade for seedlings. For better understanding of this phenomenon, we must await the complete results of the Washington study. 1/ Under really poor burning conditions, wet or scattered large fuels are not likely to burn even if the fines are dry and continuous.

Severe Fire

Under very good burning conditions, the fire will spread quickly between ignition strips. The intermediate and large fuels will be ignited by the fines and will continue to burn if stacked closely. If successive strips are ignited without waiting for early strips to burn out, very severe fire can result. If the entire block is lit, the control that was being maintained by indrafts will vanish. Air movement will be violent, but highly erratic, because there is no longer any order to the process. If fire whirls occur, they can be very intense.

To prevent violent fire behavior, the ignition of successive strips must be delayed until fire in strips already ignited has diminished.

If severe fire is needed to meet objectives, center firing as described earlier should be considered as an alternative to strip firing.

Firewhirls

Firewhirls depend upon the occurrence of vorticity for their initiation. Vorticity is not rare; Nature sends air into a swirl whenever its flow is interrupted. The major air flow patterns over a site are primarily dependent upon the wind direction in relation to the topography. Probably the most common cause of firewhirls is the location of a burn site on the leeward side of a ridge. Countryman (1971) gives the best summary of conditions leading to

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1/ Sandberg, Dave. Pacific Northwest Station the occurrence of firewhirls. Fire whirls can also be initiated by the ignition pattern. The ignition device is less important except as it facilitates the pattern and timing of ignitions. A strong convection column can act as an obstruction to air flow and whirls will form on the downwind side.

The strength of a firewhirl is dependent upon the power generated by the fire supporting it; i.e., the rate at which energy is released. We see again that rapid ignition of a site affects the resultant fire behavior and can lead to more intense firewhirls.

Firewhirls can be extremely dangerous to the ignition crew or anyone else near the fire as the whirls can wander out of the fire area in an unpredictable fashion. They still contain considerable heat even though they are no longer directly supported by the fire. As the gases and embers within the whirl burn out, they can continue to drift in the windward direction and still contain high rotational velocities. They can also deposit firebrands as they move, posing a threat for spot fires.

Firewhirls can be several hundred feet in height. Even though flames may not be apparent at the higher altitudes, they still contain very high rotational velocities in the outer perimeter and high vertical velocities in their central core. These pose a threat to light aircraft. Helicopter operators doing ignition work should be on the lookout for them. On the ground, their presence is announced by the rushing sound they generate. This could probably not be heard in a helicopter and operators should watch for a very tall slender concentration of smoke in the convection column. There will also be strong indrafts at the base which are identifiable by strong horizontal smoke flow near the ground like the spokes of a wheel with the firewhirl at the hub.

Effect of Slope

Much of the prescribed burning done in this country, especially in the West, is done on slopes, some of them very steep. This can cause special problems in regard to fire behavior, fire effects, and fire control.

The crux of the problem is whether or not the flame will attach itself to the slope. When this happens, the hot convective gases and smoke flow up the slope close to the surface rather than rising vertically.

On a shallow slope the indraft on the upper side will be less than from the downhill side (fig. 5). Fires ignited on the downhill side can be expected to have more indraft than for equivalent conditions on a level surface. The second line of ignition will spread quickly into the first without much movement of the first down to join the second.

On a steep slope there will be no indraft flowing down the slope into the fire. The convection plume will lie against the slope and travel up the slope without breaking away until it reaches a bench or the top (fig. 6).

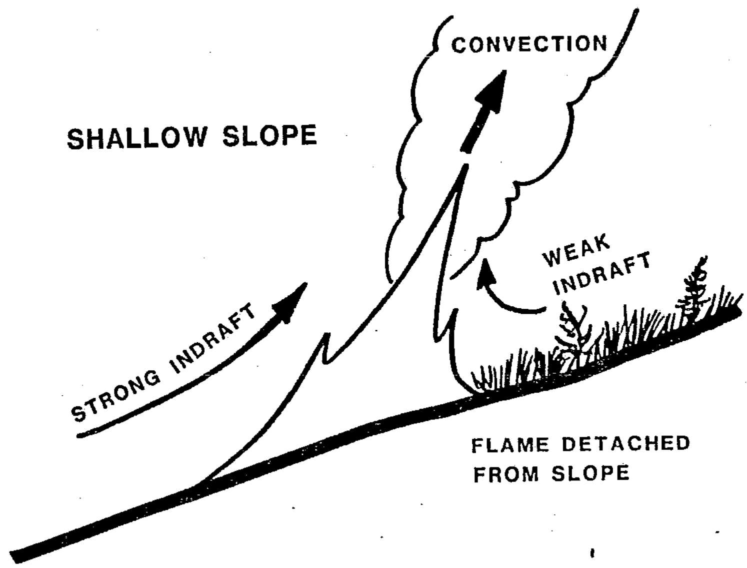

Figure 5. Indrafts on a shallow slope.

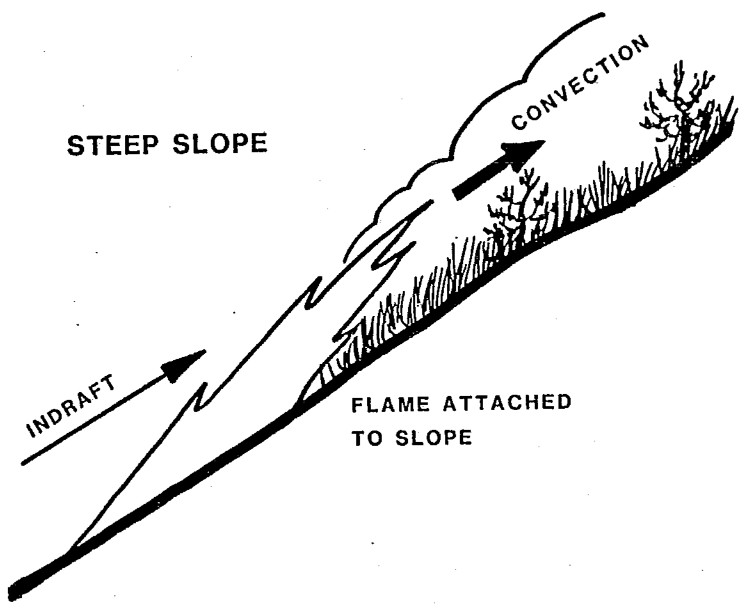

Figure 6. Indrafts on a steep slope.

If an overstory of trees is present, the scorch height of trees on a steep slope will be affected. Attachment of the flame to the slope will reduce the scorch height in trees above the flames from what would be expected on the level where the flames stand vertically. However, further up the slope at a ridge line where the convection column breaks from the surface and rises, the concentration of hot gases will scorch higher than expected on the flat (fig. 7).

A further consequence of this situation is fire control problems above the burn. Concentrated heating as well as spotting from firebrands occurs on areas above the fire when the flame is attached to the slope. The problem is compounded because the dense concentration of smoke makes it very difficult and even dangerous for fire fighters to work in this area (fig. 8).

There is no definitive research on the problem of flame attachment. It appears from both lab work and discussions with users that the flame becomes attached near 50 percent slope with no prevailing wind. It is not known, but it may not be possible to produce a fire of enough intensity to cause flame detachment on steep slopes regardless of the method of ignition.

FIRE PREDICTION METHODS

Many of you are using methods developed for predicting wildfire behavior for your prescribed fire purposes. This includes the use of nomograms, TI-59 fire behavior CROM, S-390 and S-590 course material and, more recently, the BEHAVE computer system. The fire behavior prediction methods listed above are described in several publications. The basis for these systems is described by Rothermel (1983).

Hopefully, you have successfully adapted these methods to your burning situations; you should be aware, however, that these methods were not specifically designed for predicting prescribed fire behavior and there can be some pitfalls. Completeness and consistency are the system's strengths; its weakness is assumption of uniform conditions, and with respect to prescribed fire assessment, the inability to account for interactions between fires. Because aerial ignition firing techniques often depend on interaction between fires, you must be especially careful that your prediction method is applicable.

The firespread methods were designed for predicting the behavior of a line of fire in uniform fine fuel contiguous to the ground. The method is complete in the sense that it offers methods for estimating fuel conditions, estimating live and dead fuel moisture, slope, wind, and standard procedures for integrating these factors into the calculation of fire behavior. Because the procedures are complete, it is often referred to as the Fire Behavior Prediction System (FBPS). The system predicts the rate of spread, intensity,

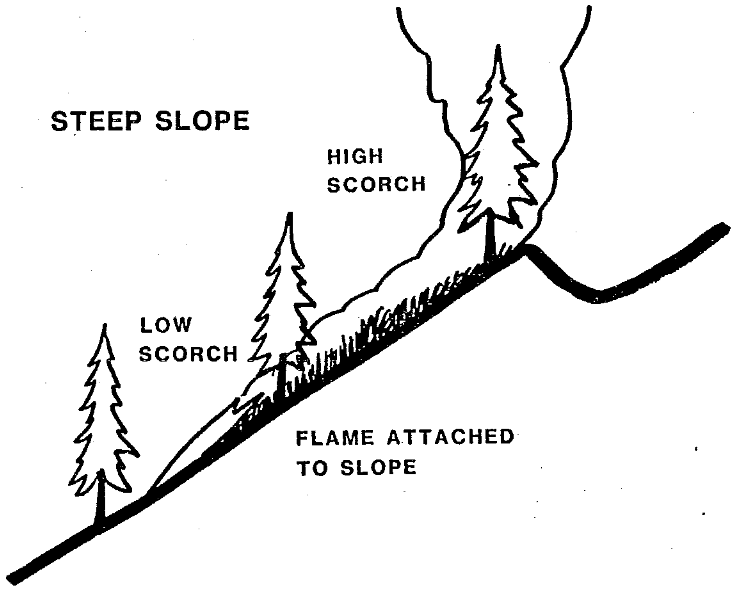

Figure 7. Scorching conditions on steep slope.

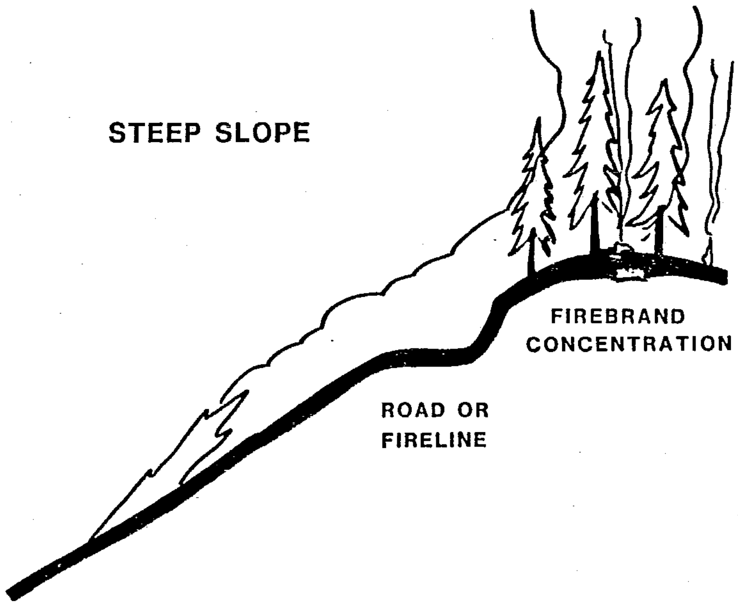

Figure 8. Fire control problems on steep slopes.

and flame length of the flaming region of the fire as it advances. For prescribed fire, the most useful prediction is the flame length. Some parts of the system do not rely upon assumptions of uniformity or steady state. These include spotting distance predictions, the probability of ignition, and fine fuel moisture content.

Spotting distance can now be calculated for two conditions--firebrands from torching trees and firebrands from pile burning. These methods are described by Albini (1979) and Chase (1981). A new method will describe predictions from a spreading surface fire, but it will depend on the ability to predict fireline intensity, a difficult task when multiple fires are interacting.

The tables for ignition probability apply to firebrands and are useful for setting limits on minimum allowable fine fuel moisture outside of the firelines. The ignition probability tables were not designed for incendiary devices.

Fuel moisture remains a key factor in setting prescription window limits. Direct measurement is important and all fire practitioners should have experience measuring fuel moisture, but as burn time draws close, the time it takes to sample and process the fuel limits the usefulness of direct measurements. To aid users, several models have been developed for predicting fuel moisture of various size fuel components.

Limited space prevents a full discussion of fuel moisture prediction and measurement methods, but three are noteworthy as being readily adaptable to prescribed fire needs. The BEHAVE fire prediction system (Andrews, in press) (Burgan and Rothermel 1984) has a new fine fuel moisture model that is highly site-specific. It includes a diurnal adjustment so that fuel moisture can be estimated at any time of the day or night while taking into account the location and condition of the site. For slower responding large fuels, the 1,000-hour fuel moisture estimate from a nearby NFDR station can be helpful in predicting burnout of large fuels. Remote automatic weather stations, RAWS, now have a capability for reporting 10-hour moisture on a real time basis. Fine fuel moisture can be calculated from RAWS data, but the information will not be available until the next morning.

Prescribed fire practitioners have used the fire behavior prediction system to good advantage for planning their fires and setting prescription windows. The ability to do this evolves from experience, both with the system and in the field. Experienced practitioners can set limits on intensity, scorch height, duff removal, spotting distance, probability of ignition, time to burn, and smoke dispersion.

Introduction of the BEHAVE computer system simplifies and speeds the prediction process and provides a printout for displaying the burning window (fig. 9). In addition, BEHAVE allows the user to construct fuel models tailored to match specific fuels on a site. This permits better assessment of expected fire behavior as well as comparisons between the effects of proposed fuel treatments and assessment of before and after fire treatments.

For fire control contingency plans, the fire behavior prediction system is used to assess expected fire behavior outside the burn block. The potential for fire escape can thereby be judged right along with plans for burning.

FLAME LENGTH, FT

1-HR MOISTURE (%)	MIDFLAME WIND, MI/H						
	0	1	2	3	4	5	6
3	5.0	6.1	7.2	8.2	9.1	9.9	10.7
6	4.3	5.3	6.2	7.1	7.9	8.6	9.2
9	4.0	4.9	5.7	6.5	7.2	7.9	8.5
12	3.7	4.6	5.4	6.1	6.8	7.4	8.0
15	3.4	4.1	4.9	5.5	6.2	6.7	7.2
18	2.8	3.4	4.0	4.5	5.0	5.5	5.9

Figure 9. BEHAVE output for selecting a burning window.

Illustrating Fire Behavior

The effect of indrafts upon fire behavior can be illustrated by use of the fire characteristics chart (Andrews and Rothermel 1982). The fire characteristics chart (fig. 10) conveniently displays rate of spread and fire intensity on the same chart. In fact, a point on the graph represents four important fire characteristics: rate of spread, heat per unit area, fireline intensity, and flame length. For example, light loaded fine fuels such as grass can have high rate of spread, but low heat per unit area as shown in figure 10. Old compacted slash would have a lower spread rate, but high heat output as shown in figure 10.

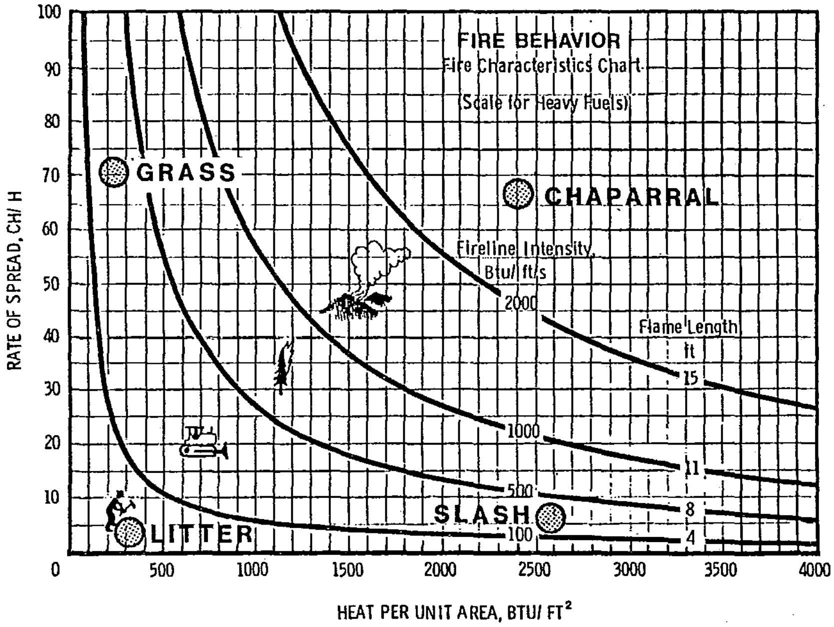

Figure 10. Fire characteristics chart.

Flame length and fireline intensity are represented by the curved lines. Note that both the grass fire and the slash fire would have the same flame length, about 6 ft, but the character of the fire would be completely different.

Another example, forest litter, that neither spreads fast nor has high heat output, would plot low and to the left on figure 10. A severe fire in chaparral would plot high and to the right, indicating both fast spread and high heat output.

The fire characteristics chart can be very useful for illustrating expected behavior of prescribed fires. For example, suppose we have a sagebrush area to burn. A high pressure situation is stagnant over the area, with warm weather but no wind. From experience and/or test fires in these fuels, it is known that the fuel is too sparse to burn without an 8 to 10 mi/h wind. The calculated no-wind behavior is plotted on figure 11. Even though the heat output is considerable, 650 Btu/ft^2, the rate of spread is very low and, as said earlier, the fire won't spread. By use of rapid ignition through aerial drip torch, if induced winds of 8 to 10 mi/h can be generated, the fire would plot as shown at the upper area on figure 11. The fireline intensity would increase significantly and the flame lengths would range between 8 and 10 feet.

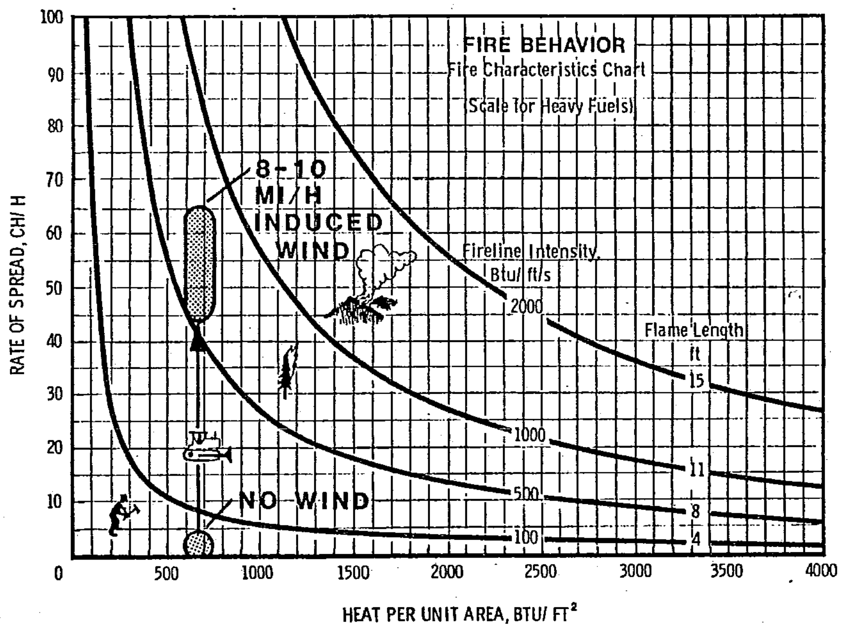

Figure 11. Indraft effect upon sage brush fire characteristics.

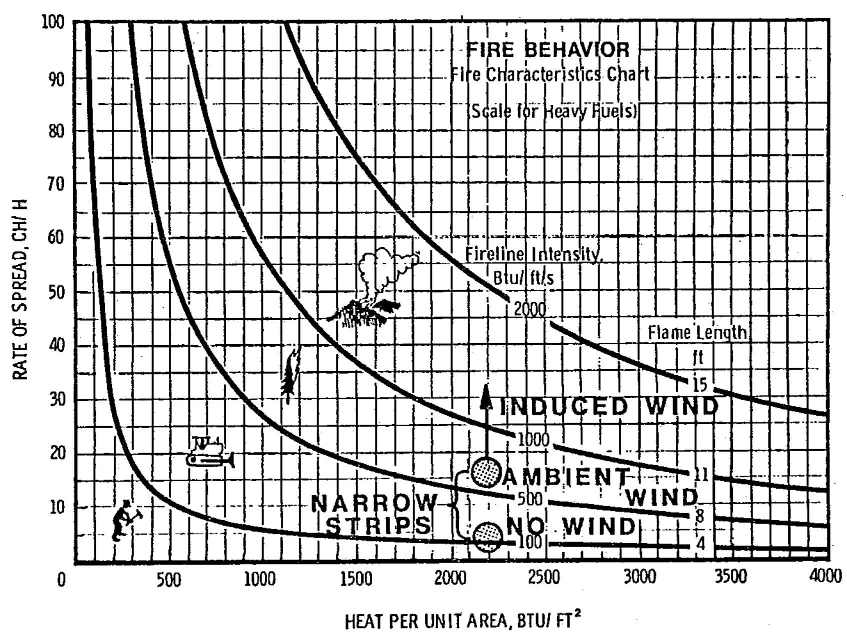

Figure 12. Indraft effect upon logging slash fire characteristics.

This illustrates one advantage of the aerial drip torch for burning under marginal conditions. The capability for igniting successive strips rapidly will take advantage of the induced winds generated before the fine fuels burn out.

Let's look at another example, this time in slash fuels. Suppose we have a logged area on a 30 percent slope with fuels equivalent to fuel model 12, medium slash. The burn will be in the afternoon, with fine fuel moisture near 7 percent, 10-hour 10 percent, and 100-hour 15 percent. Upslope winds will be about 5 mi/h at eye level. We plan to use a helitorch for strip ignition and would like to assess the expected fire behavior.

The following procedures are suggested for illustrating the effect of induced wind on the fire characteristics chart. Calculate the fire behavior for a no-wind condition and for the 5 mi/h wind blowing directly upslope. Both of these conditions are plotted on figure 12. The ambient wind condition indicates the expected behavior, if there are no induced winds on the fire. The no-wind condition indicates the behavior, if the fire were backing down the slope.

If the strips are kept narrow and ignition of successive strips delayed until the fines have burned out, the expected rate of spread and flame length should lie between the two points in the bracketed area marked "narrow strips".

If faster spread rates and larger flames are desired, this can be achieved by more rapid ignition of strips and spreading them wide enough to allow the flames to fully develop, but not so wide as to get beyond the indraft influence. This will plot above the other two points on the chart as shown by the arrow indicating induced wind. The upper limit is unknown and will be determined by the amount of induced wind that can be generated by your use of the ignition system and the heat generation of the fire.

SUMMARY

In summary, we see that aerial ignition systems exert their primary effect through control of the fire situation. They can promote burning in marginal situations, thus broadening the prescription window. Once the fire is lighted, however, the factors controlling fire behavior are still valid. Prediction of fire behavior is difficult, but careful and selected use of available methods can aid planning and execution of prescribed fire by aerial or other ignition methods.

LITERATURE CITED

Albini, Frank A. 1979. Spot fire distance from burning trees--a predictive model. Gen. Tech. Rep. INT-56. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 73 pp.

Andrews, Patricia L. and Richard C. Rothermel. 1982. Charts for interpreting wildland fire behavior characteristics. Gen. Tech. Rep. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 21 pp.

Andrews, Patricia L. BEHAVE: fire behavior predictions and fuel modeling system--BURN subsystem. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; in press.

Burgan, Robert E. and Richard C. Rothermel. 1984. BEHAVE: fire behavior prediction and fuel modeling systems--FUEL subsystem. Gen. Tech. Rep. INT-167. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 126 pp.

Chase, Carolyn H. 1981. Spot fire distance equations for pocket calculators. Research Note INT-310. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 21 pp.

Countryman, Clive M. 1971. Fire whirls--why, when, and where. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station. Forest Service, U.S. Department of Agriculture. 11 pp.

Rothermel, R.C. 1983. How to predict the spread and intensity of forest and range fires. Gen. Tech. Rep. INT-143. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 161 pp.