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Field Procedures for Verification and Adjustment of Fire Behavior Predictions

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RESEARCH SUMMARY

The problems of verifying fire predictions at the operational level are discussed and four fire prediction situations identified: (1) predicting fire spread several hours before it is expected, using a weather forecast; (2) predicting fire spread just before it occurs, using measured weather data; (3) predicting fire spread after the fact, with weather data measured during the fire; (4) predicting fire behavior after the fact, with all of the fire model inputs measured rather than inferred. Opportunities and problems associated with several types of fire, including wildfires, prescribed fires, both planned and unplanned, as well as fires dedicated to verification, are discussed. Procedures for collecting and analyzing data are detailed for accessible fires and inaccessible fires. Analyses for choosing the appropriate fuel model, for evaluating prediction capability, and for improving predictions by the use of simple linear regression techniques are explained and illustrated with examples from the field.

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INTRODUCTION

Methods for predicting fire spread and related intensity values are becoming available in many forms. Albini's nomographs or nomograms introduced in 1976 were followed by the TI-59 calculator (Burgan 1979). Rothermel (1983) has shown how to integrate these tools into a complete predictive system, including methods for obtaining the fuel and environmental conditions needed as inputs, and how to interpret the outputs into useful fire descriptors. These methods were originally developed for the S-590 Fire Behavior Officers' Course.[1] Similar procedures based on the same research are being incorporated into a revised S-390 Fire Behavior Course.[2] The nomenclature and methods used in this paper assume the reader is familiar with the fire prediction procedures and associated fuel and weather procedures described in the above references.

The capability to predict fire spread has created a need to determine how well the methods and procedures work in local fuel and fire situations. The intent of these verification procedures is not to validate the fire spread model (Rothermel 1972), which is only one part of the overall prediction system, but to verify the complete system, including the fire spread model and all associated models and interpretation aids. Testing the fire spread model requires more elaborate procedures, including careful measurement of fuels and continuous monitoring of environmental factors. Such tests have been made by a few well planned research experiments. These include tests by Lawson (1972) in needle litter; by Brown (1972) in fuel arrays assembled from logging slash; by Sneeuwjagt and Frandsen (1976) in grass; by Bevins (1976) in logging slash; and by Hough and Albini (1978) in southern rough. A summary of these tests (except Lawson's) is given by Andrews (1980). A composite illustration of the results is shown in figure 1. These tests demonstrate that the fire behavior model can predict rate of spread with creditable accuracy and do it in fuels as diverse as grass and logging slash. The question remains: How well will the complete prediction system work in your fuels and under your conditions? This manual will answer that question and also tell how to improve your predictions.

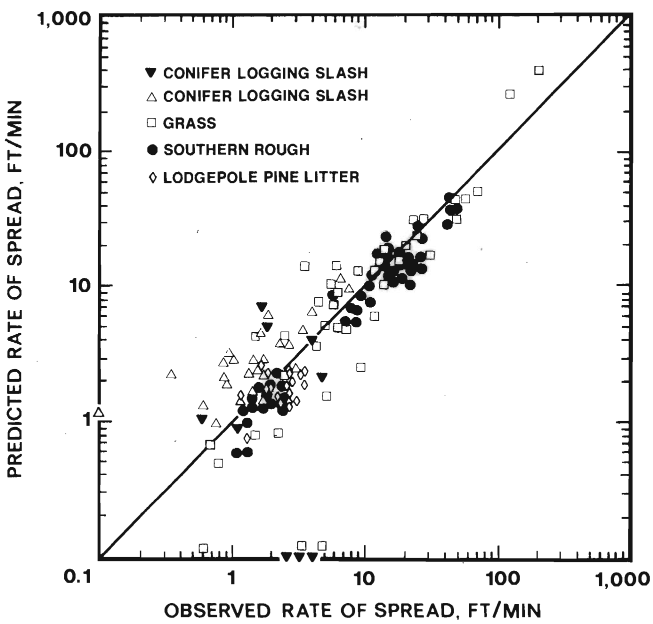

Figure 1.—This logarithmic chart dampens the amplitude of the variation as rate of spread increases, but shows the trend and allows a wide diversity of spread rate to be included on one graph. Data obtained from these sources: conifer logging slash (solid triangles), Bevins (1976); conifer logging slash (open triangles), Brown (1972); grass, Sneeuwjagt and Frandsen (1966); southern rough, Hough and Albini (1978); lodgepole pine litter, Lawson (1972).

[1]Two-week course taught at the National Advanced Resource Technology Center at Marana Air Park, Ariz.

[2]National Wildfire Coordinating Group's S-390 Fire Behavior Course. Produced by Boise Interagency Fire Center; Joe Duft and Jerry Williams, co-chairmen of course development.

The verification concept is simple: obtain data necessary to predict fire behavior and corresponding data on actual fire behavior, then compare the prediction with the actual fire. In practice this is often difficult to do, especially on wildfires. The best example of such data is described by Norum (1982) who analyzed spread rate and flame length data from thousands of acres of fires in Alaska. The results of his analysis of rate of spread are shown in figure 2. Many users do not have access to the large amount of data available to Norum; however, there are many opportunities for collecting data and this paper explains the philosophy of testing, the methods of obtaining data, methods for analysis, and finally, methods for interpreting and calibrating outputs to better match the behavior of fires in unique local fuels.

The verification and calibration methods that are presented do not require sampling of fuel quantity or fuel moisture or impose a requirement for expensive equipment not ordinarily available to operating units.

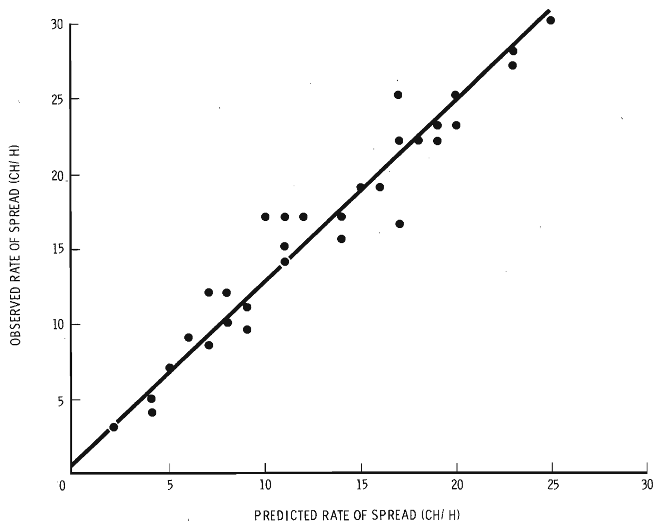

Figure 2.—Verification of the methods for predicting fire behavior applied to Alaska black spruce forests (Norum 1982).

DISCUSSION

The ultimate goal is to improve fire behavior predictions. This will be accomplished by:

—Verifying accuracy of predictions.
—Developing adjustment factors for unique local fuels.
—Correct utilization of the prediction system.

Control efforts on wildfires often become so hectic that it is difficult to verify predictions. Therefore, other fire situations may have to be utilized to obtain verification data.

Before procedures are discussed, it is worth considering both the types of test situations that may be encountered and the types of fires that may be utilized for obtaining verification data. There are many combinations of these and it is not possible to specify a particular data collection procedure for all of them. In fact, the overriding consideration that requires significantly different procedures is access to the fire.

The data collection and analysis procedures that follow later will outline methods that are applicable for either accessible fires or inaccessible fires. The user may adapt the procedures as appropriate for the particular test situation and type of fire available for his/her use.

TEST SITUATIONS

The test situations depend primarily upon how the inputs, particularly weather, will be obtained, and the sequence for obtaining data.

Four test situations are likely to be encountered:

1. Fire predictions with forecasted weather.
2. Fire predictions with weather observed prior to a fire.
3. Fire predictions with weather observed during a fire.
4. Fire predictions with all variables measured.

Situation 1.—Forecasted weather. This test is conducted under the same conditions that a fire behavior officer (FBO) would encounter when fire spread is predicted, utilizing a weather forecast well ahead of the time period of the expected fire growth. The FBO would normally have had a chance to see the fuels and topography of the area where the fire will be. If the forecasted weather does not materialize, verification data will not qualify for situation 1, but may be used to qualify for situation 2.

Situation 2.—Observed weather prior to a fire. In this situation a fire spread prediction is made with observed weather taken on site just prior to the fire. This situation is often encountered on prescribed fires. It does not have the uncertainty of a weather forecast, but the input data are available prior to the fire.

Situation 3.—Observed weather during a fire. For this situation fire spread is calculated with weather, particularly wind, measured periodically during the fire. This does not verify the ability to predict fire behavior prior to the event, but does allow the system accuracy to be verified when weather inputs are as well defined as the situation will allow. This situation will be used to develop calibration factors for different fuel types.

Situation 4.—All input variables measured. This test situation requires careful measurement of fuels, fuel moisture, windspeed, and slope. This would require extensive instrumentation and subsampling, and is in the nature of a research study such as performed by Brown (1972), Lawson (1972), Sneeuwjagt (1974), or Bevins (1976). Such studies are outside the scope of this paper.

The four situations present a paradox about the nature of prediction and verification.

Test situation 1, where all the data are assembled many hours before the expected time of fire spread, will likely have the poorest correlation between predicted and observed behavior, but because it is closest to the real situation, the results are unique and valuable.

Test situation 3 will provide the best test of the prediction ability of the system because conditions are measured and updated periodically during a fire. This provides the best data, but does not simulate real world predictive procedures as is done in situation 1.

From this discussion we can draw three conclusions:

1. All testing is not the same.
2. Data taken from the three situations should be analyzed and evaluated separately as was done by Andrews (1980).
3. Users should choose the type of test situation that meets their objectives.

Types of Fires

It is usually difficult to obtain good data on the behavior and location of fire perimeters on wildfires, especially during the early stages. Therefore it is important that other types of fires be used, including prescribed fires, as well as experimental fires designed for verification. A discussion of the types of fires that may be used to obtain data for the three test situations, along with opportunities and problems that are likely to be encountered, are given below.

UNPLANNED, PRESCRIBED FIRES

Unplanned, prescribed fires come closest to matching a wildfire situation. These fires result from unplanned or natural ignition (lightning) in an area that has been designated for fire treatment in a management plan. Suppression activities on unplanned prescribed fires are usually confined to protecting boundaries or structures. Additional ignitions are usually not made. Because these fires can exist through several burning periods, they offer excellent opportunities for verification in the first situation, i.e., using a weather forecast to predict fire behavior before the event. The second and third situations for verifying and testing with measured data may be more difficult because of inaccessibility or safety considerations, but should not be ruled out. This should be done with a team monitoring the fire without other duties and responsibilities.

PLANNED, PRESCRIBED FIRES

Planned, prescribed fires are conducted for one or more management purposes, such as fuel reduction, wildlife habitat improvement, seedbed preparation, etc. They are almost always conducted within one burning period and therefore do not allow the opportunity for repeating predictions with forecasted weather. Specified weather conditions are normally selected to produce behavior less severe than encountered on escaped wildfires. Results of tests, therefore, will usually not cover the range of fire severity experienced on wildfires.

A more serious problem is the method of ignition. Ignition patterns or sequences are often used to **control** fire behavior. There are presently no modeling methods that will account for the resulting fire interactions. For instance, center ignition to build a strong convection column with strong indrafts followed by perimeter ignitions will result in the line fires on the perimeter being pulled toward the center and consequently do not meet the criteria of a free-burning line fire. These cannot be used for verification. Some prescribed fires, however, are ignited by strip head firing. These fires are not ideal free-burning line fires, and the data may not always be useful, but can be considered if the width between strips is wide and the fire can reach a steady state between strips. Many fire officers use the model as an indication of potential severity of prescribed fires, but this manual deals with verification, not methods of characterizing prescribed fire.

Backing fires may also be compared with a prediction that utilizes zero windspeed and zero slope as inputs. These fires move very slowly, but help to indicate the limits of combustion.

WILDFIRES

Wildfires, even those being suppressed, can provide opportunities for taking data on rate of spread if the fireline is not completely secure and if retardant or water is not being applied to open sections of line. There may also be spot fires beyond the lines that can be observed as they start and grow or the fire may make an unsuppressed run. Access may be limited on wildfires, and smoke and flame or uneven terrain can prevent good observation of the fire's actual location. All these problems are accentuated during the first few hours on a fire until things begin to settle down and the FBO can find vantage points where data can be taken. Aerial infrared imagery provides excellent perimeter data if it is available before the next burning period.

VERIFICATION TEST FIRES

Verification fires are designed specifically for the purpose of collecting data to verify fire spread predictions, and to determine calibration constants for matching fuel models to local fuels. These fires would normally be conducted under test situation 3 where weather is measured during the fire. Because both the time and place of the fire are selected, the test is under better control than in other fires and there is a better chance for obtaining good data.

PROCEDURES

Because of the concern for safety and the severe restrictions that accessibility of the fire can cause, the procedures are divided and explained for either accessible fires or fires with restricted accessibility.

Accessible Fires

The procedures for accessible fires outlined below assume that workers can safely reach and gather data near the fire. The procedures may be used with any of the fire types discussed earlier. These procedures stress the importance of obtaining data when conditions are as uniform as possible to eliminate that uncertainty from obscuring the results. This would normally be done with a series of tests in one kind of fuel. The location of the expected burn area should be well defined and the time of observation will be short compared to the usual procedure of wildfire monitoring. Procedures for verifying predictions over longer periods, say 2 to 4 hours in an afternoon as a fire spreads unconfined, are discussed in the section on inaccessible fires.

Two types of data are required: the data needed to make fire behavior predictions, and data that records what the fire did. Because conditions change as time goes on and as the fire grows, it is necessary to coordinate the data collection so the results can be related. This is accomplished by organizing data collection by time periods. Those things that remain relatively constant, such as slope and fuel type, can be predetermined and those things that change rapidly, such as weather, fire position, and flame length, are recorded by time period. The perimeter of the fire must be known at the beginning and end of each period of time. The descriptors of fuels, weather, and topography during each period are used to predict rate of spread and flame length.During each period the two parameters most likely to change (wind and fire location) should be given the most attention.

A data sheet designed for recording observations of both the fire environment and the fire behavior is shown in figure 3. Each column is for one time period. Data from other sources such as photographs, recorded verbal comments, or measurements of fire spread distance may be entered later. The data sheet should be used in conjunction with a high resolution map on which the best estimate of the location of the fire perimeter

Figure 3
FIRE OBSERVATION DATA SHEET

Observer's Name____________________ Date__________

Fire Identification______________________________

Section of line identification_________________________

INPUTS							
Start time							
Projection point							
Slope							
Aspect							
Elevation							
Fuel model							
Shade percent							
Dry bulb temp.							
Wet bulb temp.							
Relative humidity							
Live fuel moisture							
20' windspeed							
Handheld anemometer windspeed							
Wind direction							
Fire, wind, slope direction							
FIRE OBSERVATIONS							
Average flame length							
Maximum flame length							
Overstory torching							
Overstory crowning							
Firewhirls							
Spotting occurrence							
Spotting distance							
Spread distance							
End time							

Figure 3.—Fire observation data sheet.

can be sketched. Use a portable tape recorder for making quick verbal descriptions of fire behavior and reasons for starting and stopping test periods. The recorder is superior to written notes because it is much faster, and you can talk while watching the fire.

FIRE OBSERVATION DATA SHEET

Heading

Enter the observer's name and the date on which the data are taken.

Identify the fire.

Identify the section of the fire on which the data are taken.

Space is available for other identifying information.

Start Time

Enter the time of day (24-hour time) that an observation is to begin. This is not time of ignition, but the time that a line of fire has developed that is independent of its ignition source and has reached a relatively steady state. Fuel ahead of the fire should be of the same type for a sufficient distance to obtain a reasonable spread measurement. If the wind changes significantly in speed or direction, the time period may have to be terminated (see End Time).

Projection Point

The designation "projection point" is used to identify the position from which the growth of the fire will be projected and monitored. Identify the projection point on a map.

Inputs

Slope.—Measure the slope. This can be done with a handheld instrument. Learn to disregard undulations that are small with respect to the size of the fire or that the fire may cross in a time short compared to the observed run time. It may be more convenient to measure slope after the fire.

Aspect.—Record the aspect as one of the four cardinal directions or a combination of two of them.

Elevation.—Record the elevation in feet.

Fuel model.—Observe the fuel stratum that is carrying the fire. Photograph the fuel, both with and without fire in the scene. Dictate a description of the fuel into the recorder, noting the type of fuel, e.g., grass, shrubs, litter, or slash. Describe both the living and dead material and the relative abundance of each. Describe the stage of growth or the curing of the live fuel and its coloration. If the fuels are nonuniform, one fuel model may not be satisfactory to represent the area. Another option is to use the two-fuel-model concept (see appendix). Enter two fuel models that describe the area, the first that describes the dominant fuel cover and the second that describes significant concentrations within the first. Below the fuel model number enter the estimated percent cover of each fuel.

Shade factor.—Ignition component and 1-hour timelag fuel moisture calculations are affected by the shading of fuels at the fire site. Shading can result from either cloud cover or canopy cover. Estimate the percent shading.

Dry bulb temperature.—Enter dry bulb air temperature (be sure thermometer is shaded and ventilated).

Wet bulb temperature.—Enter wet bulb temperature. Follow prescribed procedures for accurate measurements.

Relative humidity.—Convert dry bulb temperature and wet bulb temperature to RH, using a chart for the appropriate elevation (not needed until ready to estimate dead fuel moisture and fire behavior).

Live fuel moisture.—Estimate the live fuel moisture from the guide provided by Rothermel (1983). If live fuel moisture is measured include only the foliage and fine stems, and do not mix live and dead samples.

20-ft windspeed.—For exposed fuels that are not beneath a timber canopy, such as grass, shrubs, or logging slash, a continuous measurement of windspeed at the standard 20-ft height can be very helpful. Set the anemometer at a location that will be as representative as possible of the wind that will be blowing over the fire. If possible it should be upwind of the fire on the order of 15 to 20 times the expected flame length from the fire. For example, if the flame lengths are expected to be 4 ft, the anemometer should be at least 60 to 80 ft away. Closer locations will be influenced by indrafts to the fire. Since the system is designed to be a predictive system, it must work with forecasted winds that would be present in the absence of fire. The fire model is designed to account for indrafts to unrestricted line fires in surface fuels.

Handheld anemometer windspeed.—Although 20 ft above the vegetation cover is the standard height for taking windspeed observation (Fischer and Hardy 1976), it must be interpreted to determine midflame windspeed needed by the fire model (Rothermel 1983). A good representation of the midflame windspeed can be measured with an anemometer near eye level. A high quality 3-cup handheld anemometer with low starting inertia is recommended. If one is not available, the pith-ball type of wind meter in the belt weather kit can be used.

A two-person team consisting of an observer and a data recorder may be needed for a short time when fire is moving rapidly. Use two clean pith-ball wind meters, one plugged so that it always reads the high scale, and the other open for reading the low scale. Clamp the anemometers together side by side, place them on a rod that can be rotated, and stick it in the ground. Slide the anemometers to the approximate midflame height. Note the height of the anemometers. Rotate the anemometers directly into the wind and call off the position of the ball of the low or high observation; read the low velocity whenever it is on scale. The observations should be repeated at a uniform rate. The recorder should record all the observations made within each time interval. For short fast runs, readings may be needed as often as every 15 seconds; for slow moving, long duration fires, the interval can be much longer. It is important, however, to take the wind data that coincide with a measurement of a fire run; that is, at the same time and in the same body of air.

An alternative to this procedure is to use an averaging anemometer. This instrument records the total travel distance of the air that passes past it from the time it is turned on. This is easily converted into average windspeed by dividing this total distance by the length of time of the observation.

Wind direction.—Record the direction the wind is coming from. If it is light and variable, note that fact. Record the direction as one of the four cardinal directions or a combination of two.

A tassel of colored yarn attached to the rod described above will indicate wind direction; the observer should keep the wind meters facing into the wind. If it is not possible to locate a measuring point upwind of the fire in a position that is representative of the same slope on which the fire is burning, then it can be located to the side; but care should be taken that the wind being measured has not traveled over a burning area before it reaches the measuring point.

Relative directions, fire, wind, and slope.—Record the direction the head of the fire is spreading with respect to the wind direction and the maximum slope. Examples of four conditions are illustrated in figure 4. It is also possible for the wind to be blowing cross-slope, with the fire spreading fastest in the uphill or downhill direction. A code for recording the directions is given in table 1. Explanation of how to calculate fire spread for cross-slope fires is given by Rothermel (1983). Although the fire model was designed to predict behavior at the head of the fire, it can be adapted to work with backing fires and on the flanks. On a large fire these may be the only accessible places and a record of what the fire spread, wind, and slope directions are at each projection point is essential.

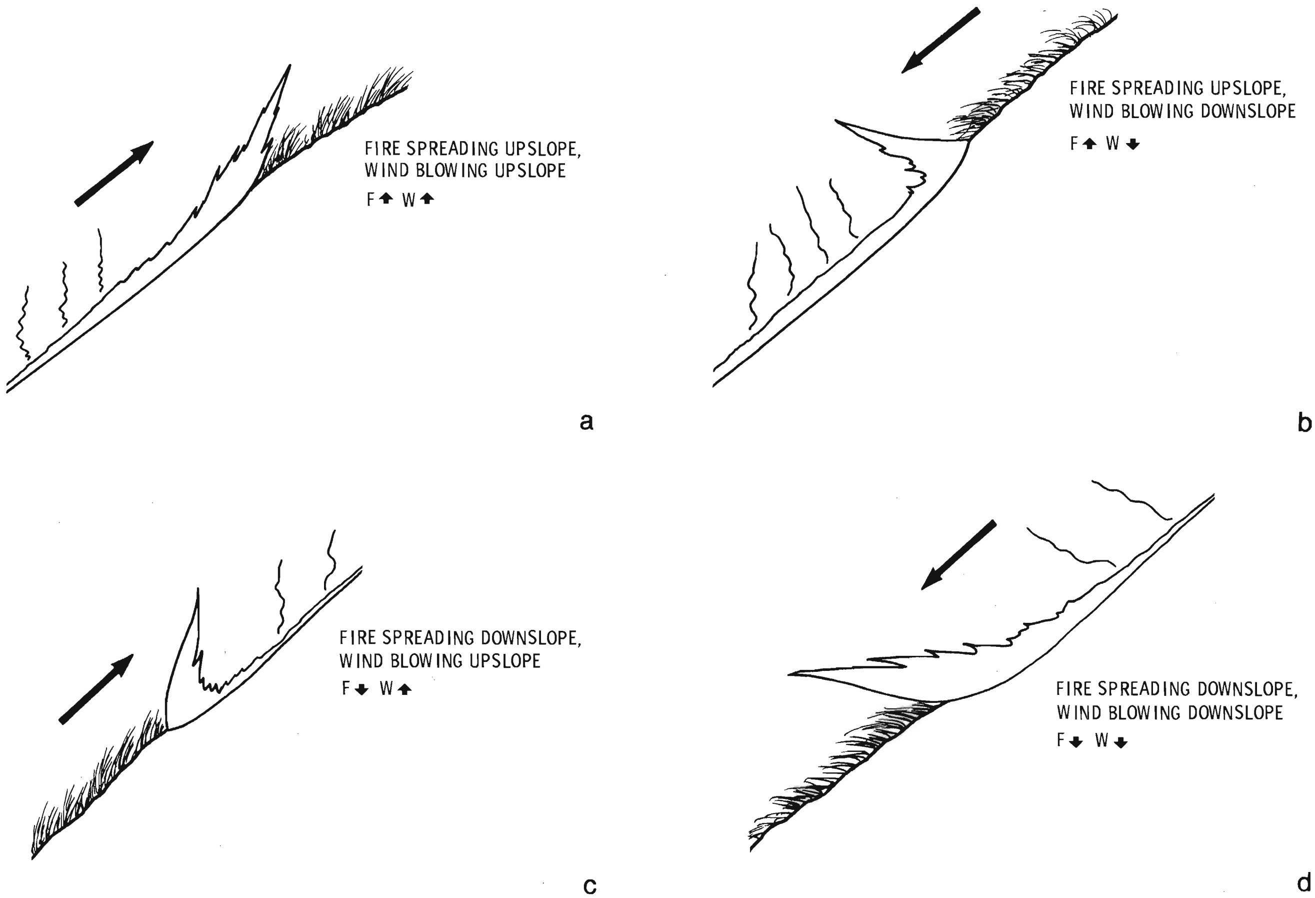

Figure 4.—Flame shapes on slopes as affected by direction of fire spread and direction of wind.

Table 1.—Symbols for indicating fire spread direction with respect to wind and slope

Direction of fire spread	Wind direction: Upslope, within ± 30° of maximum	Cross-slope: Upward	Cross-slope: Downward	Downslope, within ± 30° of fall line
Upslope side of fire	F↑ W↑ Wind and fire going upslope as shown in fig. 4-a	F↑ W↗ Upslope side of fire; wind crossing upslope	F↑ W↘ Upslope side of fire; wind crossing downslope	F↑ W↓ Fire spreading upslope; wind blowing downslope; as shown in fig. 4-b
Downslope side	F↓ W↑ Fire backing downslope; wind blowing upslope as shown in fig. 4-c	F↓ W↗ Fire backing downslope; wind crossing upslope	F↓ W↘ Fire spreading downslope; wind crossing downslope	F↓ W↓ Fire spreading downslope; wind blowing downslope as shown in fig. 4-d

Fire Observations

Average flame length.—Estimate the average flame length along the fireline. Flame length (fig. 5) is the distance between the tip of the flame and the ground (or surface of the remaining fuel) midway in the zone of active flaming. Do not confuse flame height with flame length. It is extremely helpful to have an object of known length to provide a reference scale. Stakes set in the burn area with 1-foot sections painted alternate colors, or with metal flags attached at known spacing (the spacing depends on the expected scale of the flames) are very helpful. Small trees or a person standing near the fire may also be used for scaling. Measure the tree height before or after the fire.

It is difficult to measure flame length. The flame tip is a very unsteady reference; your eye must average the length over a time period that is representative of the fire behavior. Flame length can be estimated from photos of narrow fuel beds, but photographs of large fires taken from the rear are of little use. Infrared photographs give good quality flame images even through smoke (Britton and others 1977). Photographs alone may not provide the data needed. Supplement photos with visual estimates.

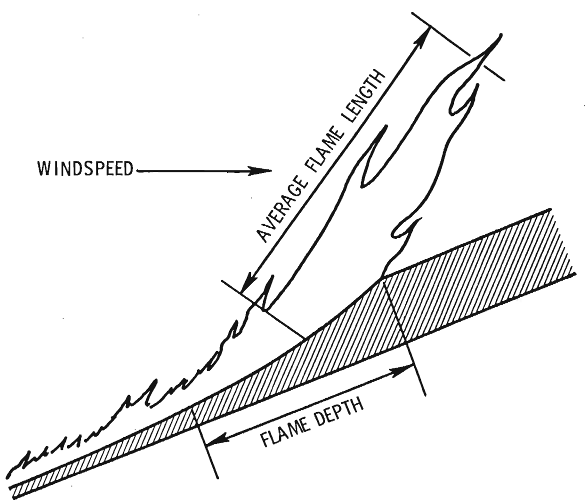

Figure 5.—Flame dimensions for a wind-driven fire on a slope.

Maximum flame length.—Record the maximum flame length observed along the fireline during the time period.

Overstory torching.—Note if torching of overstory trees is occurring.

Overstory crowning.—Note if sustained crowning of the overstory is occurring.

Fire whirls.—Note the presence of firewhirls. Record the conditions under which they develop, such as the direction of the ambient wind, or wind above the fire with respect to slope.

Spotting.—Note if short range spotting is occurring. Note if firebrands landing in front of the fire are starting new fires before the fire front burns over them or if small spot fires are being overrun by the main fire front before significant new fires are started.

If firebrands are being lofted by torching trees or from burning piles, an estimate of the maximum spotting distance can be made using a model developed by Albini (1981). Chase (1981) provides a complete description for predicting the maximum expected spotting distance with Albini's model, using a program developed for the TI-59 calculator. A worksheet is provided and the program can be obtained on a magnetic strip from the Northern Forest Fire Laboratory. We are interested in accurate descriptions of firebrand behavior and spotting distance, and would appreciate receiving this information along with a complete description of the situation as called for by the worksheet in Chase's publication.[3]

Spread distance.—Methods of measuring spread distance depend on the size and rate of spread of the fire, and on the equipment available. It is not necessary to map the entire fire perimeter. Figure 6 indicates the data needed. The following suggested methods have been tried. Choose the one that suits your fire situation.

[3]Send data to: Fire Behavior Project, Northern Forest Fire Laboratory, P.O. Drawer G, Missoula, MT 59806.

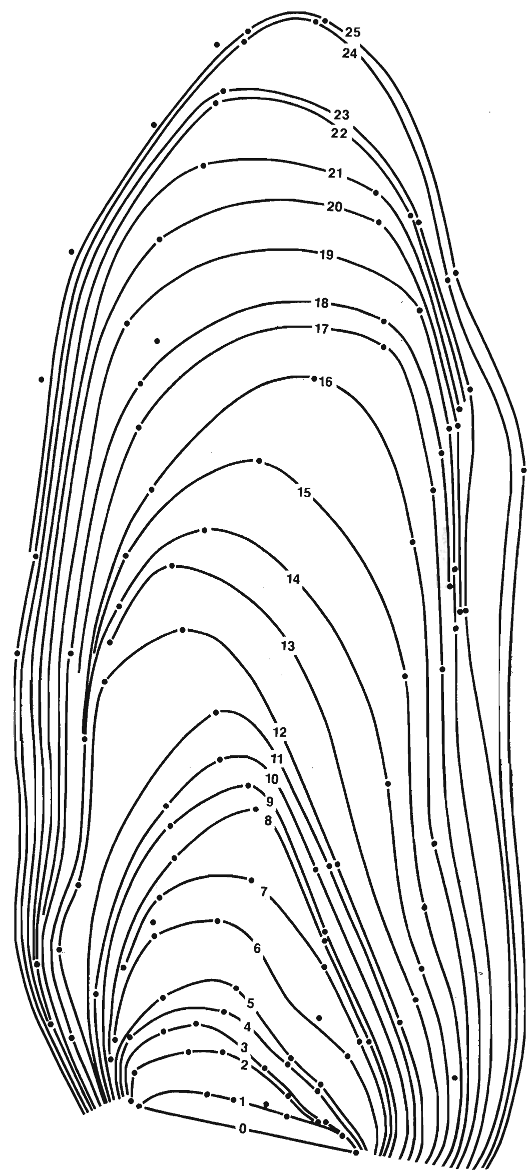

Figure 6.—Fire growth map showing fire position every minute. Data taken and compiled by Phil Cheney in Australia, 1976. Fire burned in grass, primarily sorghum. Original scale was 1 cm = 20 m. Rate of spread for any interval is the distance traveled divided by the time of the interval.

1. On low intensity, slow-spreading fires that are safe to move around, numbered metal tags can be dropped or thrown to mark the fire edge. Recent experience by Phil Range and Paul Veisze of the BLM Nevada Office has shown that short pieces of aluminum tubing work well because they are easily found after the fire. The time each marker is thrown is recorded. After the fire has burned out, the distance between successive tags is measured and recorded.

2. If the fire is too severe to move around, observe the fire front and draw contour lines on a high resolution map noting the time that each line is drawn. A handheld rangefinder may be useful to determine distances to landmarks or the fire front.

3. Record fire front locations by photography. Either aerial photos or surface views or both may be used. The time of each photograph must be known without exception. Fire location can then be mapped by noting the relationship between the fire front and visible landmarks. If visible landmarks are lacking, posts or similar targets may be placed in advance of the fire. Black and white infrared film (Kodak high-speed infrared or equivalent) will produce best results because it does not record the smoke image (Britton and others 1977).

4. A handheld rangefinder is particularly useful because of its portability. It does not require preplacement of poles at known distances ahead of the fire. Some form of marker is needed to focus on, but any tree, bush, or rock will do. Identify a marker distance at the beginning of the time period and one at the end. If you are behind the fire and thus observing it in the direction of spread, the distance and time of spread between the points is readily obtained. Triangulation may also be used with staff compass and rangefinder.

5. In some test situations, fireworks such as whistling rockets can be placed at known intervals in the direction of fire spread. Record the time of discharge as the fire passes. To insure that none are missed by the fire, a long fuse should be attached.

End time.—Record the time at which you wish to terminate the burning period for the data recorded in this column. As stated, this should be based on a significant change of conditions such as when the fire burns into a new fuel type, or the weather conditions alter with a change in wind direction, windspeed, or fuel moisture. Start a new time if the fire burns onto a different slope, or if the fire stops spreading. The next period does not need to start at the same time the preceding one stops. It is often necessary to reorganize observers and equipment.

ANALYSIS

The choice of analysis procedure depends upon what you wish to learn from the data as well as completeness of the data. Examples and explanations of data analyses from a variety of fire studies will be given in this section and in the section on inaccessible fires. The analysis outlined below assumes that data were collected as specified in the preceding instructions. Several results can be obtained from the data.

—A determination of the best fuel model to represent fire in a particular fuel.

—An overall evaluation of how well the actual fire behavior matched that predicted.

—Development of a calibration or adjustment factor for the best fuel model and the fuels that were burned.

—Determination of a better moisture of extinction.

Organize Data

Organize the data from verbal transcripts, photographs, maps, and supplemental rate of spread data sheets by the same time periods used on the fire observation data sheets. Transcribe data from these sources onto the fire observation data sheet.

Study the photos and fuel descriptions and pick the most appropriate fuel model and one or two supplemental fuel models that may be appropriate.

Some data are redundant, and you will have to decide what to use. If you had a well located 20-ft anemometer, convert that data to the midflame height with the wind reduction tables for the appropriate sheltering condition. Otherwise, use the handheld anemometer readings as the midflame windspeed.

If the winds were erratic in direction or speed, or the fire was obviously changing behavior during a time period due to transition of fuels, then the data from that time period may not be useful for developing calibration factors. Analysis of the ability to predict fire growth under any circumstances is given in the section on inaccessible fires.

If the fire was torching, spotting, or crowning, the fire model does not predict the behavior of these events, but the flame length data should indicate the onset of these events as explained in the fire behavior interpretation chart (fig. 7).

Calculating Fire Behavior

When the initial screening of data is complete, transfer the data needed for predicting fire behavior to a fire behavior worksheet (fig. 8). Calculate fire behavior for each time period and for each fuel model selected according to the methods given by Rothermel (1983).

The calculated and observed values should be in the same units of measure. The nomograms and TI-59 fire CROM give spread rate in chains per hour and flame length in feet. It is often convenient to measure spread rates in feet per minute. To convert chains per hour to feet per minute, multiply chains per hour by 1.1. For example, 75 chains per hour equal 82.5 feet per minute.

FIRE SUPPRESSION INTERPRETATIONS
Interpretations drawn from Roussopoulos and Johnson (1975)

CAUTION: These are not guides to personal safety. Fires can be dangerous at any level of intensity. Wilson (1977) has shown that most fatalities occur in light fuels on small fires or isolated sectors of large fires.

Flame length (feet)	Fireline intensity (Btu/ft/s)	Interpretations
< 4	< 100	- Fires can generally be attacked at the head or flanks by persons using hand tools. - Handline should hold the fire.
4-8	100-500	- Fires are too intense for direct attack on the head by persons using hand tools. - Handline cannot be relied on to hold fire. - Equipment such as dozers, pumpers, and retardant aircraft can be effective.
8-11	500-1000	- Fires may present serious control problems--torching out, crowning, and spotting. - Control efforts at the fire head will probably be ineffective.
> 11	> 1000	- Crowning, spotting, and major fire runs are probable. - Control efforts at head of fire are ineffective.

Figure 7.—Fire suppression interpretations of flame length and fireline intensity.

FIRE BEHAVIOR WORKSHEET

Sheet ____ of ____

NAME OF FIRE ____________ FIRE BEHAVIOR OFFICER ____________

DATE ____________ TIME ____________

PROJ. PERIOD DATE ____________ PROJ. TIME FROM ________ to ________

INPUT DATA									TI-59 Reg. No.
1	Projection point				____	____	____	____	
2	Fuel model proportion, %				____	____	____	____	
3	Fuel model				____	____	____	____	
4	Shade value	0-10%=0;10-50%=1 50-90%=2;90-100%=3)		SHADE	____	____	____	____	60
5	Dry bulb temperature, °F			DB	____	____	____	____	61
6	Relative humidity, %			RH	____	____	____	____	62
7	1 H TL FM, %			1H	____	____	____	____	28
8	10 H TL FM, %			10H	____	____	____	____	63
9	100 H TL FM, %			100H	____	____	____	____	30
10	Live fuel moisture, %			LIVE	____	____	____	____	33
11	20-foot windspeed, mi/h				(____)	(____)	(____)	(____)	
12	Wind adjustment factor				(____)	(____)	(____)	(____)	
13	Midflame windspeed, mi/h			M WS	____	____	____	____	79
14	Maximum slope, %			PCT S	____	____	____	____	80
15	Projection time, h			PT	____	____	____	____	81
16	Map scale, in/mi			MS	____	____	____	____	82
17	Map conversion factor, in/ch				____	____	____	____	
18	Effective windspeed, mi/h				____	____	____	____	
OUTPUT DATA									
19	Rate of spread, ch/h		[A]	ROS	____	____	____	____	88
20	Heat per unit area, Btu/ft^2		[R/S]	H/A	____	____	____	____	90
21	Fireline intensity, Btu/ft/s		[B]	INT	____	____	____	____	53
22	Flame length, ft		[R/S]	FL	____	____	____	____	54
23	Spread distance, ch		[C]	SD	____	____	____	____	42
24	Map distance, in		[R/S]	MD	____	____	____	____	43
25	Perimeter, ch		[D]	PER	____	____	____	____	40
26	Area, acres		[R/S]	AREA	____	____	____	____	89
27	Ignition component, %		[E]	IC	____	____	____	____	44
28	Reaction intensity, $Btu/ft^2/min$		[R/S]	IR	____	____	____	____	52

page 1

Figure 8.—Fire behavior worksheet.

FINE DEAD FUEL MOISTURE CALCULATIONS

a. Projection point				
b. Day or night (D/N)	D/N	D/N	D/N	D/N
DAY TIME CALCULATIONS				
c. Dry bulb temperature, °F				
d. Relative humidity, %				
e. Reference fuel moisture, % (from table A)				
f. Month				
g. Exposed or shaded (E/S)	E/S	E/S	E/S	E/S
h. Time				
i. Elevation change B = 1000'-2000' below site L = ±1000' of site location A = 1000'-2000' above site	B/L/A	B/L/A	B/L/A	B/L/A
j. Aspect				
k. Slope				
l. Fuel moisture correction, % (from table B, C, or D)				
m. Fine dead fuel moisture, % (line e + line l) (to line 7, other side)				
NIGHT TIME CALCULATIONS				
n. Dry bulb temperature, °F				
o. Relative humidity, %				
p. Reference fuel moisture, % (from table E)				
Use table F only if a strong inversion exists and a correction must be made for elevation or aspect change.				
q. Aspect of projection point				
r. Aspect of site location				
s. Time				
t. Elevation change B = 1000'-2000' below site L = ±1000' of site location A = 1000'-2000' above site	B/L/A	B/L/A	B/L/A	B/L/A
u. Correction for projection point location (from table F)				
v. Correction for site location (L) (from table F)				
w. Fuel moisture correction, % (line u - line v)				
x. Fine dead fuel moisture, % (line p + line w) (to line 7, other side)				

Figure 8.— con.

Plot Data

To assure data validity it helps greatly to visualize the results; take the time to make a graph comparing the calculated and observed values of rate of spread and flame length.

Compile the observed and predicted rate of spread and flame length data in tabular form as shown in tables 2 and 3. Use the first column for identifying the data in each row by time period, plot number, etc. One column of observed values can be compared with several columns of predicted values, one for each fuel model.

Table 2.—Rate of spread data for tall grass fires taken by Paul Hefner in southeastern Oregon

Observation No.	Observed rate of spread	Predicted rate of spread: Fuel model No. 1	Fuel model No. 2	Fuel model No. 3
	------ *Ft/min* ------			
1	88	36	18	76
2	*	4	3	6
3	132	98	41	120
4	374	266	139	292
5	132	66	29	76
6	495	733	279	612
7	**	733	416	816
8	143	110	45	142
9	319	328	125	300
10	495	381	227	482
11	***	327	278	531
12	3	3	2	4
13	126	72	47	128
14	240	381	163	381
15	352	150	150	292
16	****	150	294	474
17	253	304	109	286
18	251	204	76	199
19	29	21	11	47

* trouble with ignition.
** no measurement, everyone too busy.
*** lost control due to fire whirl.
**** rate of spread not measured but flame length was.

Table 3.—Flame length data for tall grass fires taken by Paul Hefner in southeastern Oregon

Observation No.	Observed flame length	Predicted flame length: Fuel model No. 1	Fuel model No. 2	Fuel model No. 3
	------ *Feet* ------			
1	12	3	5	11
2	*	1	2	3
3	12	4	6	13
4	18	7	11	19
5	15	4	6	11
6	25	13	17	31
7	**	13	21	36
8	15	5	7	14
9	20	8	11	20
10	20	9	15	26
11	***	8	16	26
12	3	1	2	3
13	10	3	7	6
14	15	9	13	23
15	28	5	11	19
16	36	5	16	23
17	28	8	11	20
18	18	6	9	16
19	12	2	4	9

* trouble with ignition.
** no measurement, everyone too busy.
*** lost control due to fire whirl.

In tables 2 and 3 we have displayed data taken by Paul Hefner (fire management officer, Burns District, BLM, Oregon) from fires burned in tall grass with some sagebrush during July and August 1980 in southeastern Oregon. The data were taken as a part of a burning program for range improvement. The first 14 observations were made in tall grass; the last 5 observations included 10 to 12 percent sagebrush in the area. Paul used fuel model 3 (Anderson 1982), which represents tall grass, for his predictions. (Fuel models and typical fuels are described in Anderson 1982.) The other two grass models, 1 and 2, have been included in the analysis to illustrate selection of the correct fuel model and to demonstrate the method for improving predictions.

The rate of spread data in table 2 are plotted in figures 9, 10, and 11. Note that the predicted value is indicated on the X axis, which is along the bottom. The observed values are indicated on the Y axis, along the side. Choose a scale (representative length of spaces on graph) that is appropriate for your data. The scales of the X and Y axes should be the same to aid interpretation of the data. Work with the data from one fuel model at a time. Then, for each observation there is a predicted value. Each predicted/observed pair of values will plot as a single point on the graph. To do this move along the X axis until the predicted value is found. Then go vertically from that point until the vertical distance representing the observed value is reached. At this point make a dot. Repeat until all other observations have been plotted for one fuel model. Repeat for the other fuel models. They can be plotted on the same graph if you choose, but the dots must be identified with a symbol so the different fuel models may be distinguished. We have plotted rate of spread on three separate graphs (fig. 9, 10, and 11) and flame lengths on three other graphs (fig. 12, 13, and 14).

Draw a diagonal line across the graph that represents perfect agreement between predicted and observed values. Your data probably will not lie on the line of perfect agreement; to find out how well the prediction matches the observed data, it is necessary to do a regression analysis. The regression analysis can be utilized to produce correction factors for improving future predictions in the same fuel type.

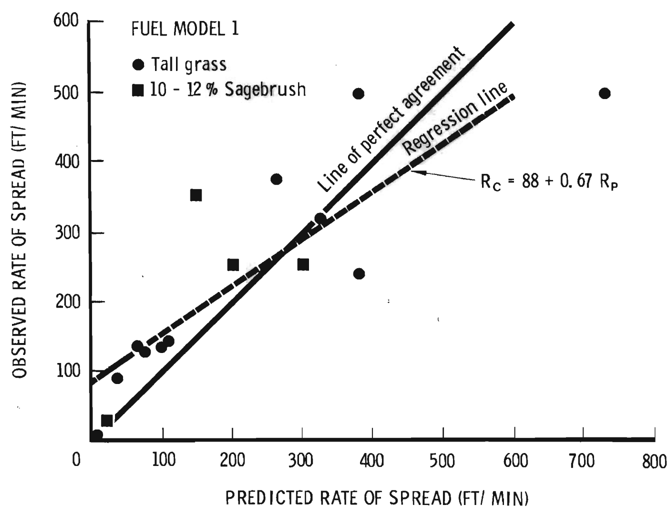

Figure 9.—Comparison of observed rate of spread in tall grass, with predictions made with fuel model 1 (Paul Hefner data).

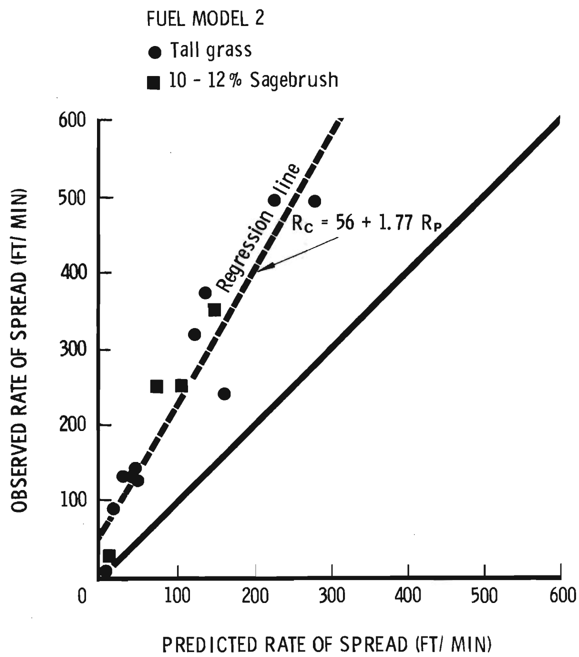

Figure 10.—Observed rate of spread in tall grass compared to predictions made with fuel model 2 (Paul Hefner data).

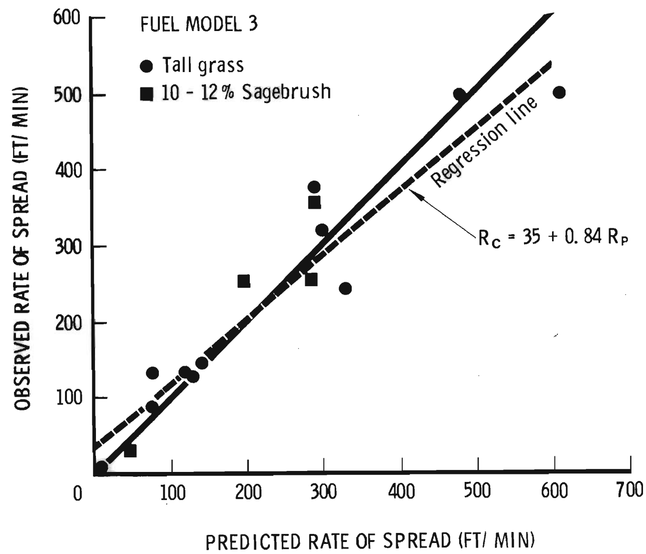

Figure 11.—Observed rate of spread in tall grass compared to predictions made with fuel model 3 (Paul Hefner data).

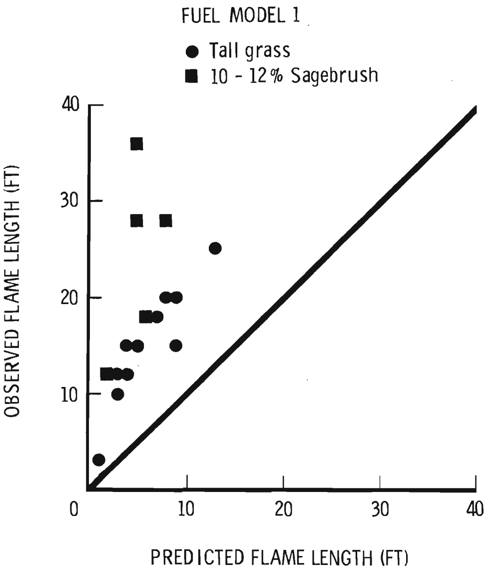

Figure 12.—Observed flame length in tall grass compared to predictions made with fuel model 1 (Paul Hefner data).

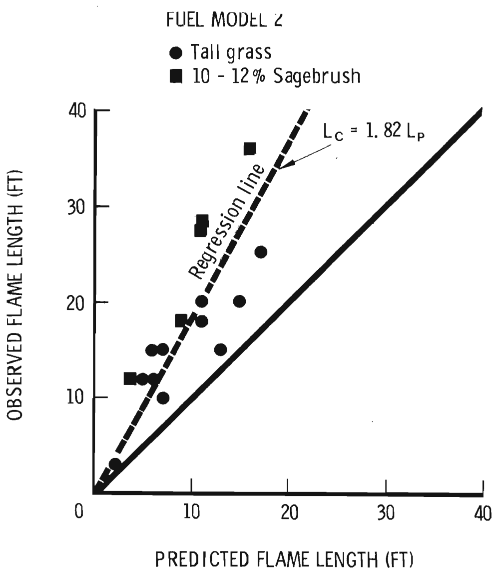

Figure 13.—Observed flame length in tall grass compared to predictions made with fuel model 2 (Paul Hefner data).

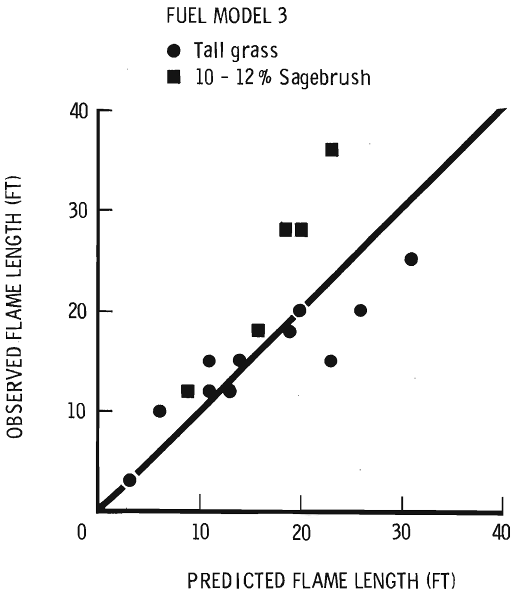

Figure 14.—Observed flame length in tall grass compared to predictions made with fuel model 3 (Paul Hefner data).

Regression Analysis

The theory behind the technique of regression analysis can be found in any statistics textbook so will not be dealt with here. Many small calculators, including the TI-59, provide a means of computing regression analysis; but you must use the Master Library Module rather than the NFDR/fire behavior module. Instructions are in the owner's manual.

The purpose of the regression analysis is to find the best correlation between the observed data and the predicted data. When this is done, the results can be used in the future to correct the predicted fire behavior to better represent the actual fire behavior. One of the results of the regression analysis will be a line on the graph that provides a visual display of the results. Another result is an equation of the following form:

$R_c = a + b\,R_p$

This equation contains two values of rate of spread, the predicted value, R_p, and what will become the corrected value, R_c. The coefficients a and b are constants that are determined by the regression analysis. With this equation a corrected rate of spread, R_c, can be determined from a predicted value and the constants a and b.

a is the Y intercept. a may be positive (+) or negative (−). It indicates where the line that is the best representation of your data will cross the Y axis.

b is the slope of the line. It should be positive and can be smaller or larger than 1. The closer it is to 1, the closer the regression line will parallel the line of perfect agreement.

When performing the regression analysis, be sure to enter the predicted values as the X values and the observed values as the Y values.

The data in table 2 produced these regression equations for fuel models 1, 2, and 3, with Paul Hefner's data:

Fuel model 1	$R_c = 88 + 0.67\,R_p$
Fuel model 2	$R_c = 56 + 1.77\,R_p$
Fuel model 3	$R_c = 35 + 0.84\,R_p$

These equations are represented by dashed lines in figures 9, 10, and 11. To plot a line it is necessary to know two points along the line. One is given as the Y intercept. Note in figure 9 that the dashed line crosses the Y axis at a value of 88. To find another point, choose a convenient number along the X axis. For example:

let $R_p = 500$
then $R_c = 88 + (0.67)(500) = 88 + 335 = 423$

In other words, at $R_p = 500$, $R_c = 423$. Plot that point and draw a straight dashed line from it to the Y intercept (in this case 88). Extend the line across the graph.

Continue following the instructions of the regression analysis to determine the correlation coefficient (which is sometimes called the "r^2 value"). The correlation coefficient is a measure of how well your data groups around the regression line which you have just drawn. It will have a value between 0 and 1. The closer it is to 1, the nearer the points are to the regression line. Further explanation of regression analysis can be obtained from a statistics book.

Ideally, your data will produce a regression analysis with the Y intercept value near zero, the slope near 1, and the correlation coefficient near 1.

To select the most appropriate fuel model, arrange the coefficients in a table similar to that for Hefner's data for the three grass fuel models in table 4. (More elaborate statistics are unnecessary.) Primary consideration should be given to the correlation coefficient, (r^2). It is difficult to set firm rules on this, but r^2 values greater than 0.9 are excellent for this type of data, and values above 0.75 are acceptable. Data for fuel models that produce r^2 values less than 0.75 are probably not worth the development of correction factors.

Table 4.—Summary of results of regression analysis with Paul Hefner's rate of spread data

Fuel model	Correlation coefficient r^2	Y intercept a	Slope b
1	0.84	88	0.67
2	.94	56	1.77
3	.94	35	.84

If the r^2 is suitable, look for a low Y intercept. Y intercept values that are a small fraction of the mean of the expected range can be ignored, as done by Norum (1982). The slope coefficient then becomes a simple multiplicative correction such as reduction of all predicted values by 80 percent. Repeat the analysis with flame length data. Although you can use different fuel models to predict rate of spread and flame length as Norum (1982) indicates, it is much less troublesome if you can find one model for both.

A summary of the results of the regression analysis with Paul Hefner's data is shown in table 4. Inspection of figures 9, 10, and 11, and table 4 leads to the choice of fuel model 3. It has the highest correlation coefficient, the same as model 2. It has the smallest Y intercept and a slope closest to 1.0. The dashed line in figure 11 can be seen to lie much closer to the solid line than for the other fuel models in figures 9 and 10. In fact, model 3 fits well enough that no correction to the rate of spread prediction is justified.

The flame length data as shown in figures 12, 13, and 14 also support the selection of fuel model 3 (fig. 14) as the best choice.

Based on all criteria then, fuel model 3 best represents the fuel and fire situations observed by Paul Hefner in tall grass in eastern Oregon.

Calibration

Suppose that you cannot find a model that produces accurate predictions. That is, predicted values are consistently high or consistently low. Such a case is exemplified by the data from fuel model 2 in figure 10. The model consistently underpredicts the observed values, but they are tightly grouped all along the regression line with a correlation coefficient of 0.94, the same that model 3 gave. This indicates that fuel model 2 is consistent, even though it is not accurate. In such a case the regression equation can be utilized to correct the prediction. The regression equation for Hefner's data with fuel model 2 is:

$$R_c = 56 + 1.77\, R_p$$

Let us examine the process. Norum showed that if the Y intercept was near zero, it was only necessary to multiply the predicted value by the slope value to get a better estimate of the observed or actual value. This may not always be the case and it may be necessary to include the correction for the Y intercept. Plot the corrected predictions versus the observations to see if this is necessary.

First multiply all predicted values by the slope correction, 1.77, and replot the data. The calculations are shown in table 5. A plot of the data is shown in figure 15.

The corrected predictions in figure 15 are better; the data points parallel, but still do not straddle the line of perfect agreement. The adjustment with the regression equation is completed by adding the Y intercept value. The complete correction, R_c, is shown in table 5 and plotted in figure 16. This figure shows that the predictions are now as accurate as these data will allow. For comparison, the regression equation for fuel model 3 was utilized to correct the data and the corrected data for both models are shown in figure 16. Visually it would be hard to say which set of data points lies closest to the line of perfect agreement. Fuel model 2 with calibration would be acceptable if fuel model 3 did not exist.

Table 5.—Tabulated calculations of corrections to rate of spread predictions utilizing fuel model 2 with Paul Hefner's data

Observation No.	R_{ob}	R_p	$1.77R_p$	$R_c = 56 + 1.77R_p$
1	88	18	32	88
2	*	3	5	61
3	132	41	72	128
4	374	139	246	302
5	132	29	51	107
6	495	279	494	550
7	**	416	736	792
8	143	45	80	136
9	319	125	221	277
10	495	227	402	458
11	***	278	492	548
12	3	2	4	60
13	126	47	83	139
14	240	163	288	344
15	352	150	266	322
16	****	294	520	576
17	253	109	193	249
18	251	76	134	190
19	29	11	20	76

* trouble with ignition.
** no measurement, everyone too busy.
*** lost control due to fire whirl.
**** rate of spread not measured but flame length was.

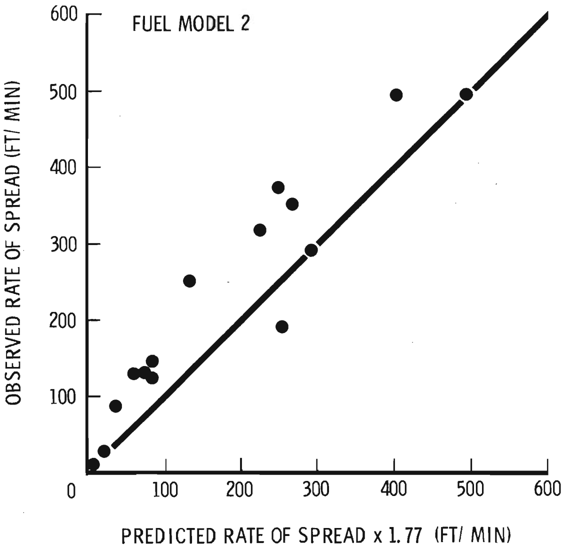

Figure 15.—Rate of spread predictions for fuel model 2 corrected by only the slope of the regression equation (Paul Hefner data).

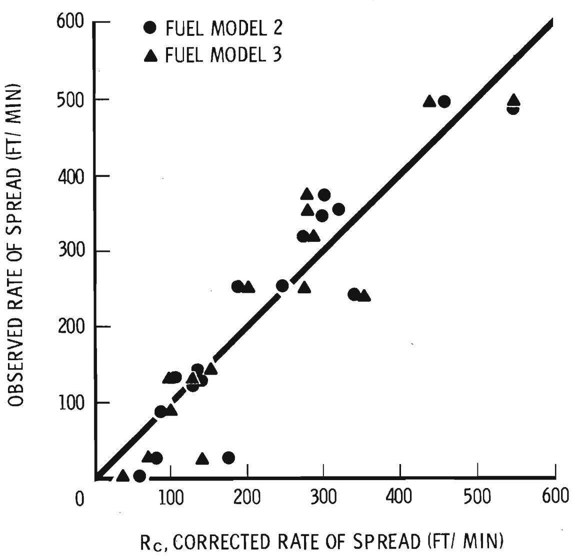

Figure 16.—Observed rate of spread compared to predictions corrected by both the slope and the Y intercept of the regression equations for fuel models 2 and 3 (Paul Hefner data).

If desired, the same process can be used on the flame length data; however, the desire for better accuracy must be balanced with the practicality of keeping the prediction methods simple enough to be useful.

Before we leave Hefner's data there are some significant points that should be discussed. There was trouble with ignition for data that plotted near the origin, indicating that burning conditions were marginal. By contrast, when the predicted flame lengths were 36 ft (observation 7) with rate of spread predicted to be 816 ft/min, no observations were taken because everyone was too busy controlling the fire. Also, when the flame length was 26 ft and the predicted rate of spread 531 ft/min (observation 11), control of the fire was lost due to a fire whirl. These observations are consistent with interpretations of fire behavior expressed in figure 7 and it is gratifying that the prediction methods are capable of matching the data throughout this range of fire behavior.

Another interesting interpretation is that the data taken with 10 to 12 percent sagebrush in the area seemed to show no effect upon rate of spread. This is concluded from the intermingling of data points with or without sagebrush. This is what would be expected; with that small amount of sage, the grass can carry the fire around it. The flame length data, however, produce a different interpretation. In figure 14, the data points representing the fires with 10 to 12 percent sagebrush have significantly higher observed flame lengths than the pure grass. Again, this would be expected as the fires flare up when burning through the brush concentrations.

Calibration Without Regression Analysis

It is possible to obtain a correction factor for rate of spread or flame length without a regression analysis if the data points do not have too much scatter. The importance of having data over the entire range of conditions, from barely burning to barely controllable, cannot be stressed too strongly if the analysis is to be meaningful.

To illustrate the method we will use the flame lengths calculated with fuel model 2 from Paul Hefner's data shown in figure 13. (All points will be considered the same type fuel.) Instead of using regression analysis to determine the regression equation, we will draw a line through the points by eye and develop a calibration factor from that. In this case the data seem to trend through zero so there is no need for a Y intercept constant.

Use a transparent plastic ruler or straightedge. Pass one side through the origin and aline the edge so it passes as closely as possible through the remaining points, with approximately as many above the line as below. Draw a line from the origin through the points. Determine the slope of the line by taking the ratio of an observed and a predicted value on the line near its high end. For instance, in figure 13 at $R_p = 20$, $R_{ob} = 37$. The ratio of observed to predicted is then 37/20 or 1.85. For more accurate predictions of flame length in this fuel type, use 1.85 as a correction factor. For example, a predicted flame length of 10 ft will be corrected to 18.5 ft, a much better estimate.

If the points do not trend through the origin, just lay the straightedge along the apparent trend line, so the points group as closely as possible to it. This is what the mathematics of regression analysis does for you—but your eye can do very well also! In this case, measure off the Y intercept and use this value for the number "a" as explained in the section before on spread rate prediction. Subtract this value (which may be negative) from the "observed" value before taking the ratio to determine the slope of the line. Correction of predictions must now use both the slope and the Y intercept as explained in the calibration section.

Adjusting Moisture of Extinction

One of the factors used in the fire model that is not determined from fuel conditions, but only estimated, is the moisture of extinction. This is not a critical value when the fuels are dry, but when the fuel moisture is close to the moisture of extinction the predicted rate of spread can be significantly different from the observed. In fact, in some cases a prediction of no spread will be made when the fire does burn or the reverse may be true. This can be a serious problem for predicting conditions for prescribed burning, which is often done under marginal burning conditions. When a better moisture of extinction is determined, it can be used with the TI-59 fire behavior CROM by inserting it in register 25.

The process will be illustrated with data taken by Collin Bevins in western Washington logging slash during the summer of 1975. Moisture of extinction probably depends most strongly on the fuel loading, size, and arrangement. Bevins inventoried the fuel in size classes 3 inches in diameter and smaller (table 6). The fuel loadings 3 inches and under were similar to those of fuel model 11 (except for Unit S-38L which was not used in the analysis). The moisture content and other observed data are shown in table 7.

The moisture of extinction of fuel model 11 is 15 percent. This means that fuel arrays with fine fuel moisture greater than 15 percent will not be predicted to burn. Note in table 7 that only units S-45L and S-38U were sufficiently dry to be expected to burn on this basis. This is confirmed in figure 17 where all the fires except two were predicted not to burn. The solution to this problem is to increase moisture of extinction. If the model predicts fires to burn when they wouldn't burn, then moisture of extinction should be decreased. But for these data we will increase the moisture of extinction used for predicting fire spread rate and see how the predictions are changed.

Moisture of extinction, or M_x, was increased to 20 percent and to 25 percent, and new predictions were made with fuel model 11. To do this with the TI-59, select fuel model 11 and then enter the new moisture of extinction on the keyboard, which will appear in the display. Press STO 25 and the number being displayed will be stored in register 25. To check if that happened, hit RCL 25 and the moisture of extinction will be displayed. RCL does not erase the stored value. If you wish to evaluate more than one value of moisture of extinction, enter the environmental conditions and make a calculation with the first value of M_x, then change M_x and repeat the calculation with the same environmental conditions. It is not necessary to reenter them.

The results of this process are shown in table 8 for M_x = 15, 20, and 25 percent, and plotted in figures 17, 18, and 19. The results are readily apparent; in figure 18, only two fires were predicted not to burn, but the prediction is still not satisfactory. In figure 19, with M_x = 25 percent, one fire is predicted not to burn, but the others correlate reasonably well with the observed values. Note that the predicted rate of spread for the two fires with drier fuels did not change much when M_x was changed. The prediction for the wettest one did improve somewhat. A regression analysis with M_x = 25 percent gives a correlation coefficient of 0.73. The regression line is plotted in figure 19:

$$R_c = 0.06 + 1.26 R_p$$

Table 6.—Fire model inputs: fuelbed loadings and bulk depths

Plot ID	Location[1]	Needle load	1-h woody load	10-h load	100-h	Net load	Bulk depth
		Lb/ft²					*Ft*
I 14 U	SRD	0.0003	0.0314	0.1389	0.3041	0.4747	0.70
I 14 L	SRD	.0030	.0597	.1283	.4703	.6613	1.01
S 44 U	SRD	.0000	.0216	.2499	.3948	.6663	.12
S 45 U	SRD	.0220	.0396	.1800	.5845	.8261	.50
S 45 L	SRD	.0138	.0605	.2095	.4764	.7602	.93
SO 38 U	SRD	.0150	.0188	.0927	.1846	.3111	.74
SO 38 L	SRD	.0801	.0746	.2685	.3225	.7457	.54
KRD 1 E	KRD	.0018	.0170	.1226	.2493	.3907	.29
KRD 1 W	KRD	.0055	.0207	.1097	.2208	.3567	.43
KRD 4 E	KRD	.0014	.0115	.1465	.1791	.3385	.53
KRD 4 W	KRD	.0023	.0335	.1809	.9128	1.1295	.62

[1]SRD: Soleduck Ranger District, Olympic National Forest, Region 6, western hemlock.
KRD: Klamath Ranger District, Winema National Forest, Region 6, ponderosa pine.

Table 7.—Collin Bevins' rate of spread and environmental data for fires in logging slash in western Washington

Unit	R_{ob}	Fuel moisture 1-h	10-h	100-h	Wind	Slope
	Ft/min	*Percent*			*Mi/h*	*Percent*
I 14 U	3.9	20.9	16.4	9.3	4.9	40
I 14 L	3.2	28.0	21.7	25.2	9.2	44
S 45 U	4.7	20.2	14.0	18.4	5.0	24
S 45 L	14.9	11.2	13.6	36.9	1.6	82
S 38 U	1.8	8.2	11.2	16.2	3.2	32
KRD 1 E	1.1	14.6	18.0	26.2	1.2	0
KRD 1 W	.6	14.6	21.9	26.0	1.2	0
KRD 4 E	3.8	15.5	34.5	24.1	3.0	0
KRD 4 W	2.5	14.6	28.1	32.5	2.5	0

Table 8.—Calculated rate of spread values for Bevins' data using fuel model 11 with moisture of extinction, M_x, values set at 15 percent, 20 percent, and 25 percent

Unit	R_p at M_x = 15%	R_p at M_x = 20%	R_p at M_x = 25%
	(tabulated values are rate of spread, ft/min)		
I 14 U	0	0	4.4
I 14 L	0	0	0
S 45 U	0	1.1	4.4
S 45 L	4.4	7.7	7.7
S 38 U	4.4	5.5	5.5
KRD 1 E	0	1.1	1.1
KRD 1 W	0	1.1	1.1
KRD 4 E	0	1.1	2.2
KRD 4 W	0	1.1	2.2

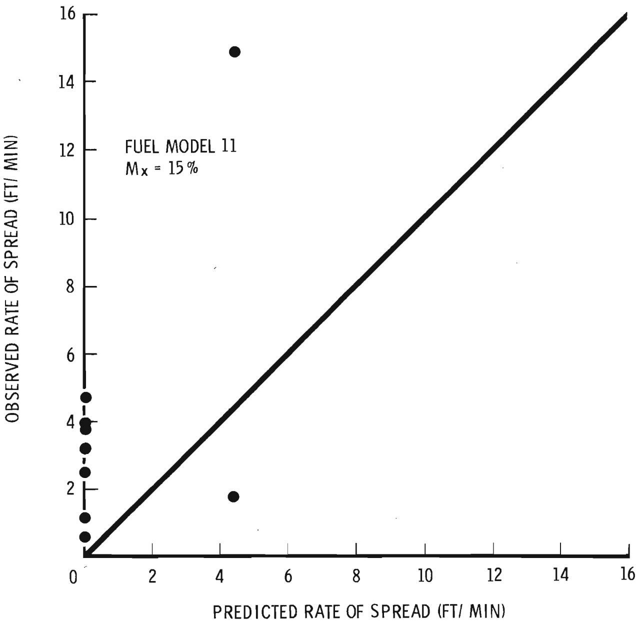

Figure 17.—Observed rate of spread in logging slash compared to predicted rate of spread with fuel model 11, with moisture of extinction set at 15 percent (Collin Bevins data).

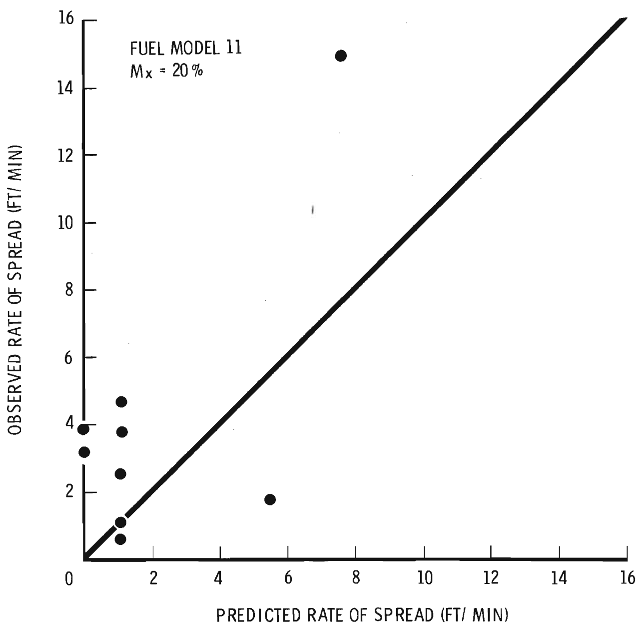

Figure 18.—Observed rate of spread in logging slash compared to predicted rate of spread with fuel model 11, with moisture of extinction set at 20 percent (Collin Bevins data).

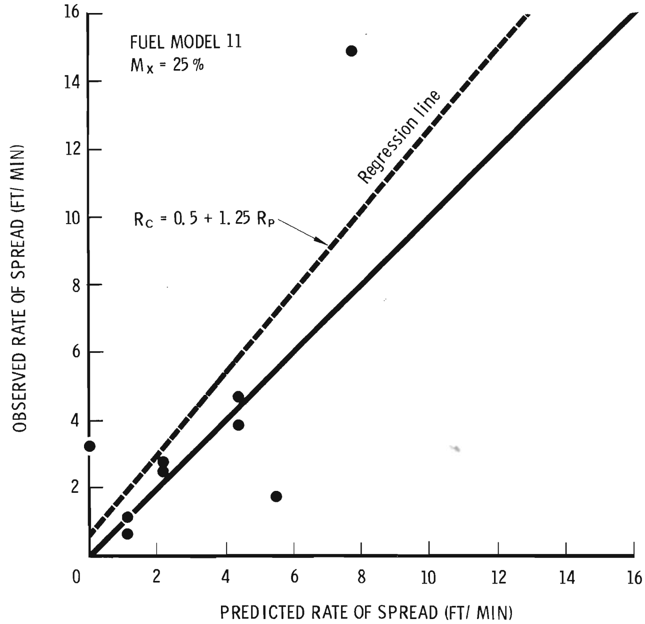

Figure 19.—Observed rate of spread in logging slash compared to predicted rate of spread with fuel model 11, with moisture of extinction set at 25 percent (Collin Bevins data).

For future work in similar logging slash, a better estimate of spread rate can be made with fuel model 11 by changing the moisture of extinction from 15 percent to 25 percent. Why should the moisture of extinction be nearly doubled in these fuels? Our explanation follows.

The logging slash areas of western Washington contain far more material in the large size classes and in the form of broken and scattered debris that do not show up in an inventory of fuel in the 3-inch and smaller diameter size classes. This provides a more continuous cover of organic material than fuel model 11 was designed to represent as a light slash fuel model. Consequently, at higher moisture contents, the fire is able to sustain itself; whereas if it encountered discontinuities at moisture contents above 15 percent, it would probably not spread. The additional amounts of logging slash also provide enough extra organic material to produce larger flame lengths than predicted by fuel model 11 even though spread rate is still controlled by the representation of fine fuels in this model.

Interpreting a Small Quantity of Data
(from test situation 2 or 3)

An example of situation No. 2 (weather observed prior to the fire) is taken from the O'Keefe Creek prescribed fire conducted in western Montana in October 1979. The burn was conducted to study the effect of fire on shrub production in a game management area. The fuels consisted primarily of shrubs with interspersed grass. The shrubs were mostly ninebark and ceanothus. The ninebark leaves had changed color, but were still attached. A test fire was conducted in a small area before general ignition. The test fire confirmed that the shrubs would burn.

The burn was conducted by firing successive strips from the top of the ridge to the base. Weather observations were made prior to ignition and are shown in table 9. Rate of spread was determined by measuring the widths of the strips (from a distant point) with a rangefinder and dividing this distance by the time it took fire to cross the strip. Six strips were measured this way. Flame lengths were not measured in these observations. The results are shown in table 10 marked group A.[4]

Table 9.—O'Keefe Creek fire environmental conditions

Item	Value
Shade factor	0
Temperature	60°F
Relative humidity	29%
1-hr fuel moisture	5.5%
10-hr fuel moisture	10%
100-hr fuel moisture	10%
Live fuel moisture	60%
Midflame windspeed	7 mi/h
Slope	17%[1]

[1]Most fires burned on steeper slopes. Constant 17-percent value contributed to underprediction of spread rate for group A.

Table 10.—Results of O'Keefe Creek fire

	Group A		
	Predicted values		Observed values
Fuel model	5	2	
Proportion, %	80	20	
Rate of spread, ft/min	66	85	30, 180, 50, 60, 142, 75
Flame length, ft	10	9	
Composite R utilizing two-fuel-model concept 70 ft/min			Average observed 90 ft/min
			Standard deviation 58

	Group B	
	Predicted values	Observed values
Upper slope		
Rate of spread * ft/min	56	62
Flame length, ft	8 - 9	10
Midslope		
Rate of spread* ft/min	77	56
Flame length, ft	9 - 10	9
Lower slope		
Rate of spread* ft/min	69	44
Flame length, ft	9 - 10	8

*Weighted for two fuels.

A second group[5] marked three transects 1 chain in length using 6-ft stakes inserted prior to the burn. These data are also shown in table 10.

Both groups elected to use the two-fuel-model concept to characterize the fuels and spread rate.

The analysis consists simply of comparing the predicted rate of spread with the observed to see if reasonable estimates could be made. The predicted values of group A for fuel models 5 and 2 ranged from 66 to 85 ft/min. The weighted average by the two-fuel-model concept was 70 ft/min. Observed values in these areas averaged from 30 to 180 ft/min, with a mean of 90 ft/min and a standard deviation of 58 ft/min. These predictions tended to underestimate the observed rate of spread. Group B, working with measured transects on gentler slopes, measured slower spread rates, ranging from 44 ft/min to 62 ft/min. The predictions were closer, ranging from 56 ft/min to 77 ft/min. This amount of scatter in data between the two groups and within the same fire is not unusual. In both cases, the results are sufficiently accurate to characterize rate of spread for this type of prescribed burning.

The flame length data taken by group B show remarkably good agreement between predicted and observed. This is as important to prescribed burn planning as rate of spread. (It should be remembered that the data were taken from strip fires with wide spacing. You cannot expect these results with center firing and edge burning.)

Restricted Accessibility

Restricted accessibility will probably take place on a wildfire or an unplanned, prescribed fire. It is assumed that the fire behavior is rather severe, or the fire is located in rough terrain or a remote location. Because of the difficulty of access, detailed data collection as described for accessible fires may not be possible. The procedures described in this section are designed to test predictions rather than to develop correction factors.

PREDICTIONS

Fire behavior should be predicted by the means of S-590 Fire Behavior Officer techniques described by Rothermel (1983). Output should include a map of the expected location of the fire by time and a fire characteristics chart (Andrews and Rothermel 1982) that shows the probable intensity of the fire. On a large fire, it will probably not be possible to verify or even predict growth along the entire perimeter. In fact, some of the line may be secure. For verification purposes, determine the section of line that can be expected to be most active, and where suppression action has not started.

Predictions made several hours in advance from forecasted weather should anticipate the time of day when the fire will begin to make a significant run and when it will probably stop spreading. The methods cited are designed to predict the rate of spread of the active part of the fire, and since wildfires often spread by a series of runs with rather dormant periods between, verification over long periods of time must account for this variable behavior. For instance, many fires spread faster in the afternoon, but normally the fire position is only updated once a day. Because 90 percent of the growth during the 24-hour period may have occurred in 2 or 3 hours, the rate of spread calculated for the peak burning period must be limited to those hours, or fire growth will be severely overpredicted.

[4]Report by R. C. Rothermel, titled, "Calculations of fire behavior on the O'Keefe Creek prescribed fire," on file at the Northern Forest Fire Laboratory, Missoula, Mont.

[5]Report by Ron Prichard, titled, "Observations of fire behavior on the O'Keefe Creek prescribed fire," on file at the Northern Forest Fire Laboratory, Missoula, Mont.

OBJECTIVES

It is not likely that you will be able to take all the data shown on the fire observation data sheet although the sheet may still be useful for organizing data. Because fire growth has already been predicted and recorded, the primary purpose of the observations is to locate the position of the fire at times that coincide with the forecast and to take sufficient weather and fuels observations to compare the actual conditions with the predicted. If circumstances are favorable, and you are able to gather all of the data needed on the fire observation worksheet, then verify predictions as described in situation 3 for accessible fires.

CAUTION

Observations of fire behavior under severe conditions in remote areas can be very difficult. Under no circumstances should safety be compromised for the purpose of collecting data. Wilson (1977) describes dangerous conditions on wildfires that have trapped firefighters.

Equipment

Do not burden yourself with excessive equipment; carry a small pack that will not encumber your movement in rough terrain. Carry a belt weather kit and a small 35-mm camera. A small handheld dictation recorder with an extra battery and tapes is far superior to written notes because you can observe the fire and be much more descriptive. A reliable watch is also needed. Stopwatches are usually not needed on a wildfire; it is better to record the time of day so that your observations can be coordinated with weather events and the observations of others. A rangefinder and an instrument for measuring slope should also be considered.

Observing Fire Growth

On fires expected to spread on a slope in rough terrain, the best vantage point may be a ridgetop on the opposing slope. Record the position of the fire by sketching lines on a map or on a transparent overlay covering a map. If the fire begins a significant move, note the time and position when it began. Estimate fire position at periodic time intervals. If the weather changes, or the fire moves into a different slope or into a new fuel type, make note of this; to the extent possible note the new windspeed and direction and fuel type. Note the direction of fire spread with respect to slope. Note the flame lengths. A photograph can help in recording flame length. Do not choose to record only the longest flames, or the shortest, but an average maximum along the line.

Occasionally take pictures of significant behavior—not only the severe events, but also the general patterns. Record the picture number and verbally describe what is being photographed. Pictures without a corresponding description of time, place, and fire situation are not good sources of data. If there are fire control forces working in the area, make note of their effectiveness.

From a good vantage point it may be possible to photograph the growth of a section of the fire at periodic intervals. A 35-mm camera mounted on a tripod is recommended. Depending on the fire spread rate, take pictures at 5-, 10-, or 15-minute intervals (Britton and others 1977).

Weather

Someone should be monitoring the general weather, either at a mobile weather station, at a lookout, or with portable weather stations set up at peripheral locations. Periodic observations should be made as needed to determine whether or not the forecasted weather materializes. Near the fire itself on the same slope, aspect, and shade conditions as the fire, use the belt weather kit to monitor the temperature, humidity, windspeed, and wind direction. Indicate which wind readings are taken with a handheld anemometer, to avoid confusing them with anemometer readings taken at 20 ft. Take wet bulb and dry bulb temperatures at least once an hour, or when there is a noticeable change in fire activity. Determine relative humidity and record all values.

Fuels

Observe the general vegetative cover and identify the most appropriate fuel model. The key to choosing a fuel model is identifying the stratum that is carrying the fire. Is it burning primarily in the needle litter, or in the dead and downed material, or the grasses, or the shrubs? If the fire is moving through nonuniform fuels, periodically flaring when encountering fuel concentrations, note the types of fuels that are carrying the fire in general and the types of fuels that are causing the flareups. As the fire proceeds, try to determine the influence of the green fuels. Are they inhibiting the spread? Or are they burning vigorously and helping the fire spread?

A change in the weather, such as higher temperature or lower humidity, can dry the fine fuels and cause the fire to move into a more flammable stratum. Fire will move fastest in the most porous fuels if it can sustain itself there. Wind is especially important for causing change; it can move the fire from a litter stratum into the more porous grass stratum. A change from a litter fuel model to a grass model would then be required.

Slope

Decide ahead of time how you will determine slope. If good contour maps are available, your field observations may be limited to sketching where the fire is and confirming that the maps are not seriously in error. If you choose to use a handheld instrument it may be easier to determine the slope after the fire has passed over the area and things have cooled down. Follow the guides for determining slope given in the section on accessible fires.

Severe Fire

Make note of the time that torching of trees begins, or when actual sustained crowning begins and ends. If this is happening, there is a good chance that spotting may be occurring. Watch for firebrands and spotting. If the fire is crowning, the belt weather kit may not be much help for recording windspeed. In this case the revised Beaufort scale (Jemison 1934) shown in figure 20 may be helpful. Record spotting events as described in the section on accessible fires.

Termination of Spread

If the fire slows down and stops, try to determine why. Did it burn into different fuel? Did the wind stop? Did it encounter a natural barrier? Did higher humidities and lower temperatures of evening seem to affect it?

MODIFIED BEAUFORT SCALE
FOR ESTIMATING 20-FOOT WINDSPEED

Wind class	Range of speeds mi/h	Nomenclature
1	≤ 3	Very light - smoke rises nearly vertically. Leaves of quaking aspen in constant motion; small branches of bushes sway; slender branchlets and twigs of trees move gently; tall grasses and weeds sway and bend with wind; wind vane barely moves.
2	4 - 7	Light - trees of pole size in the open sway gently; wind felt distinctly on face; loose scraps of paper move; wind flutters small flag.
3	8 - 12	Gentle breeze - trees of pole size in the open sway very noticeably; large branches of pole-size trees in the open toss; tops of trees in dense stands sway; wind extends small flag; a few crested waves form on lakes.
4	13 - 18	Moderate breeze - trees of pole size in the open sway violently; whole trees in dense stands sway noticeably; dust is raised in the road.
5	19 - 24	Fresh - branchlets are broken from trees; inconvenience is felt in walking against wind.
6	25 - 31	Strong - tree damage increases with occasional breaking of exposed tops and branches; progress impeded when walking against wind; light structural damage to buildings.
7	32 - 38	Moderate gale - severe damage to tree tops; very difficult to walk into wind; significant structural damage occurs.
8	≥ 39	Fresh gale - surfaced strong Santa Ana; intense stress on all exposed objects, vegetation, buildings; canopy offers virtually no protection; wind flow is systematic in disturbing everything in its path.

Figure 20.—Modified Beaufort scale of wind force (Jemison 1934).

Identify Data

Carefully identify your data with the date, time, fire name, your name, division, sector, etc. Be very careful with photographs. Do not leave partially exposed rolls in the camera. Send all film to be processed promptly. When it returns, label it immediately.

ANALYSIS OF DATA

This type of testing does not lend itself to rigorous statistical analysis. It can, however, indicate whether your fire behavior prediction techniques are working, and if not, what the problem might be. For situation 2 use the map to compare predicted and actual positions over the time that the prediction was made. Compare the fire severity with that indicated on the fire characteristics chart. An example of comparison of predicted and actual fire growth as done by Larry Keown on the Independence Fire in 1979 was reported by Andrews (1980) and is shown in figure 21. The flame length is the clue for predicting severity, and it should be compared with both the observed flame lengths and the propensity for torching, crowning, and spotting. An example of such a comparison prepared by Ed Mathews for the Montana Department of Natural Resources on the Barker Fire in 1979 was reported by Andrews (1980) and is repeated below:

Barker Fire

An FBO was assigned to the Barker Fire in Montana in August 1979. The situation was quite different from that encountered on the Independence Fire. The FBO arrived with a Class I overhead team when the fire was 800 acres and behaving erratically. Hot dry weather through the month of July had dried fuels to well below normal levels. Winds were blowing at 20 to 30 mi/h, with gusts measured to 50 mi/h. It didn't take a fire behavior model to tell the FBO that there was a problem. This example is included to illustrate that, although the fire model is designed for surface fires and does not quantitatively predict the behavior of a fire that is crowning and spotting, it does indicate the potential of severe fire behavior.

A correlation between predicted flame length and fire suppression interpretations is given in figure 7. In this case the calculations that the FBO did when he arrived on the fire resulted in a flame length prediction of 21 ft. This falls well into the fourth category of interpretations: "Crowning, spotting, and major fire runs are probable. Control efforts at the head of the fire are ineffective." This was certainly the case.

The predicted flame length for Monday was 9 ft. According to figure 7, this indicates that "Fires may present serious control problems, i.e., torching out, crowning, and spotting. Control efforts at the fire head will probably be ineffective." Compare this prediction to what was reported in a fire behavior summary, "Fire intensity was significantly less than on Sunday. Spotting and crowning still occurred and extremely hot areas kept forces out of areas in front of the fire." By Monday evening the fire size was estimated to be 2,460 acres.

Only about 30 acres burned on Tuesday. According to the Fire Behavior Summary, "Fireline mopup and line construction are proceeding well on Divisions I and II. Occasional flareups are occurring on these divisions, but are being handled OK by crews on the line." The predicted flame length for this day was 3 ft. The actual situation compared favorably with the interpretation given in figure 7. "Fires can generally be attacked at the head or flanks by persons using hand tools. Handlines should hold the fire."

If the forecasted weather did not occur, the data can still be used for analysis as described for situation 2 or situation 3.

Situation 2.—Forecasted weather did not occur. Use the weather that was observed at the time of each run to make a new prediction. In some cases, the change in weather may mean that a different fuel stratum would carry the fire and a different fuel model should be used. Compare this new prediction with the actual fire behavior, both as to spread on a map and intensity as described above.

Situation 3.—If things went so well that you could fill out a fire observation sheet and know the precise location of the fire, proceed with the analysis described for accessible fires.

If all assumptions of weather, fuels, and initial fire position are felt to be reasonable, and the prediction did not match the actual as closely as expected, the observations can be reviewed to try to locate the problem.

Was the slope properly accounted for? Did the fire move on the slope in the way it was expected? In other words, did it go upslope, downslope, cross-slope, contrary to what was anticipated?

Were the fuels properly identified? Did the chosen fuel models match the stratum in which the fire was burning? Did the fire stay in the litter until the wind picked up or the humidity dropped, causing it to burn in a more flammable fuel stratum? Was the green fuel inhibiting the fire? If so, it might have been at a higher moisture content than was estimated, or a model with more green fuel might be required. Was there so little dead fuel and so much green fuel that the fire just would not spread?

Was fuel nonuniformity a problem? Was it primarily spreading in one stratum and flaring up when it encountered fuel accumulations? Or was it flaring up along the line as it moved from stratum to stratum. If this was the case, then the two-fuel-model concept is appropriate.

Was there short-range spotting that caused the fire to move faster than was predicted? Was there long-range spotting that was causing new starts well ahead of the fire, causing a ragged line and preventing a line of fire spread as anticipated?

Was crowning occurring and causing the fire to spread faster than was predicted for the surface fire? If so, try to determine the ratio of crown fire spread rate to that predicted for the surface fire.

Was the midflame windspeed correctly predicted? This cannot be exactly known, but the handheld anemometer can give a good indication of midflame windspeed if the fire is moving through surface fuels. Compare measurements to the prediction, and see what would happen if the predicted windspeed had been equal to the observed midflame windspeed. Was the wind direction correctly predicted for the observed section of the line?

To help answer these questions, use data collected on the fire to see what the fire prediction system predicts with observed data rather than forecast data.

Inaccessible fires are hard to deal with and you will often be frustrated in your attempts at verification. Nevertheless, worthwhile experience in fire behavior analysis will be gained as you attempt to identify the elements of the problem.

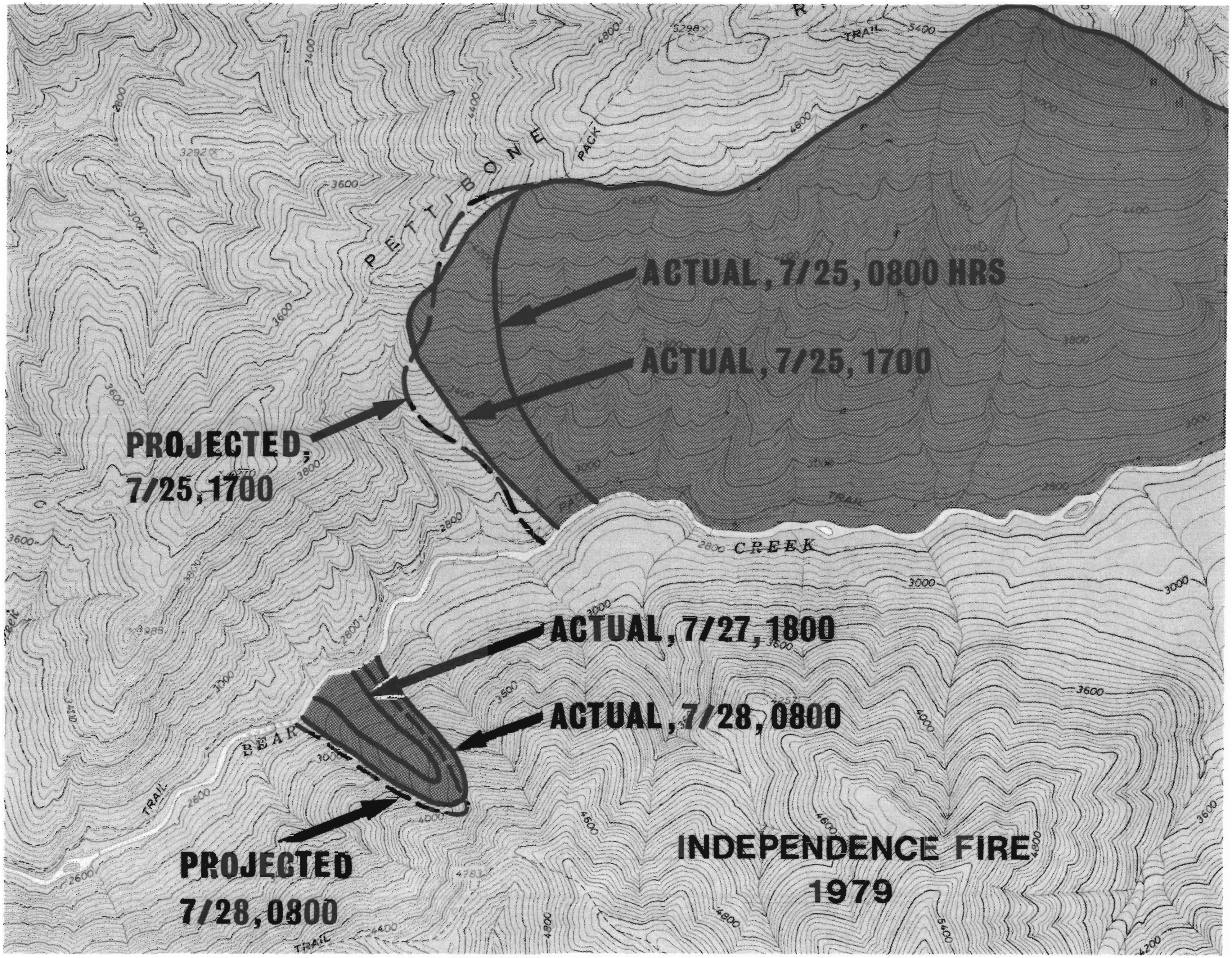

Figure 21.—Examples of actual fire perimeter locations compared to the projected locations made by Larry Keown, Fire Management Officer, on the 1979 Independence Fire in the Idaho Selway-Bitterroot Wilderness.

SUMMARY

This paper shows how a person skilled in predicting fire behavior can verify and improve fire predictions. Four situations for verification are described:

1. Verification with forecasted weather.
2. Verification with weather measured at the time fire spread begins.
3. Verification with weather and other data observed during the fire.
4. Verification with all variables measured.

Possibilities for testing on wildfires, planned and unplanned prescribed fires, and test or experimental fires are discussed.

The most detailed data collection can be made only on easily accessible fires. A data sheet format and procedures for collecting data are given in detail. Analysis procedures indicate how to compare predicted and observed data and how to improve predictions. On severe fires or fires that are inaccessible, data will usually not be complete. In these cases the most important thing to determine is the fire position versus time. This can then be compared to predicted position made with either forecasted weather or observed weather.

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APPENDIX

The Two-Fuel-Model Concept

If nonuniformity of the fuel makes it impossible to select a single representative fuel model, then the two-fuel-model concept should be applied.

The two-fuel-model concept is designed to account for changes in fuels in the horizontal direction, i.e., as the fire spreads, it will encounter significantly different fuels. It is not designed to account for variability in the vertical direction, i.e., growth from one stratum to the next on the same spot is not modeled. It is still necessary to identify the stratum that will carry the fire.

The concept is very simple. It assumes horizontally nonuniform fuels can be described by two fuel models, in which one represents the dominant vegetative cover over the area and the second represents fuel concentrations that interrupt the first. For example, in a forest stand the dominant fuel stratum over most of the area may be short needle litter (fuel model 8) with concentrations of dead and down limbwood and treetops. Depending on the nature of these jackpots, they could be described by model 10 or one of the slash models, 12 or 13. An important feature of the concept is that it is not necessary to try to integrate the effect of both the needle litter and limbwood accumulation into one model. Two distinct choices can be made.

Another example is rangeland, where grass may be the dominant vegetation over the area, with brush concentrations interspersed within the grass. Of course the system will work vice versa, where brush is dominant with interruptions caused by concentrations of grass.

The additional requirements for using the two-fuel-model concept is that it is necessary to make an estimate of the percent cover of the two fuels.

The concept is implemented in a six-step process:

1. Select a fuel model that represents the dominant cover, i.e., 50 percent or more of the area.
2. Select a fuel model that represents fuel concentrations within the dominant cover.
3. Estimate the percentage cover of the two fuels. The sum of the two must equal 100 percent.
4. Using fire behavior models for uniform fuels, calculate rate of spread and fireline intensity in each fuel separately. Select the most appropriate midflame windspeed and use the same value in the rate of spread and fireline intensity calculations.
5. Calculate the most probable rate of spread as the sum of the two spread rates weighted by the percent cover of the two fuels.

Example: Fuel model A covers 75% with R = 10 ch/h
Fuel model B covers 25% with R = 80 ch/h
Most probable $R = 0.75 \times 10 + 0.25 \times 80$
$= 7.5 + 20$
$= 27.5$ ch/h

6. Do not try to combine fireline intensities. As a first approximation, simply estimate that the intensity values calculated separately will occur with the same frequency as the estimated cover fraction of each fuel model.

This can provide important information about the character of the fire. In the case of the needle litter and limbwood jackpots beneath a timber stand: if the litter covered 80 percent of the area with an expected fireline intensity of 75 and the limbwood and treetop accumulation occupied the remaining 20 percent with an expected fireline intensity of 800, then the overstory should be examined for its potential for crowning and producing firebrands. Fire control personnel should be aware that fire in the litter could probably be controlled by hand crews, but the jackpots could cause severe problems.

Utilizing two fuel models to characterize an area greatly increases the flexibility of the 13 stylized fuel models to match conditions in the field. It does require that the fuel and fire behavior specialist become more adept at identifying fuels and that more attention be paid to the interpretation of the variable nature of fire behavior.

Rothermel, Richard C.; Rinehart, George C . Field procedures for verification and adjustment of fire behavior predictions. Gen. Tech. Rep. INT-142. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 25 p.

The problem of verifying predictions of fire behavior, primarily rate of spread, is discussed in terms of the fire situation for which predictions are made, and the type of fire where data are to be collected. Procedures for collecting data and performing analysis are presented for both readily accessible fires where data should be complete, and for inaccessible fires where data are likely to be incomplete. The material is prepared for use by field units, with no requirements for special equipment or computers. Procedures for selecting the most representative fuel model, for overall evaluation of prediction capability, and for developing calibration coefficients to improve future predictions are presented. Illustrated examples from several fires are included. The material is a companion publication to the fire prediction manual titled, "How to predict the spread and intensity of forest and range fire," by R. C. Rothermel.

KEYWORDS: fire prediction verification, rate of spread, flame length

The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

The Intermountain Station includes the States of Montana, Idaho, Utah, Nevada, and western Wyoming. About 231 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

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