Environmental Conditions as indicators of Potential for Rapid Rate of Spread in Wildland Fires

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Background

On July 10, 2001, fourteen firefighters and two forest visitors became entrapped in the Thirtymile fire on the Methow Valley Ranger District, Okanogan and Wenatchee National Forest, which resulted in four firefighter fatalities. Upon examination of the environmental conditions that existed when the entrapment occurred it became apparent that the conditions were all too familiar. Temperature was 94°F, relative humidity of 9%, slope was 5% or less, and mid flame wind speed was 2-4 mph, with a 17 mph gust at time of entrapment. A review of eleven other fatality fire investigation reports revealed similar environmental conditions (Table 1).

Table 1

Fire (Yr)	Temp	% Relative Humidity	Mid Flame Wind Speed	% Slope	% Fine Fuel Moisture	% Probability of Ignition	Number of Fatalities
#1 Mann Gulch (1949)	97	10	5	40	3	100	13
#2 - Loop (1966)	88	13	5	40-60	3	90	12
#3 - Gibson Creek (1977)	87	28	3	45	5	70	1
#4 - Spanish Ranch (1979)	84	27	5	40-60	5	70	4
#5 - Mack Lake (1980)	83	21	4	0-30	4	80	1
#6 - Golden Gate Estates (1985)	80	31	10	10	7	50	1
#7 - Lauder (1987)	80	20	4	70	7	50	1
#8 - Dude (1990)	90	8	4	10	2	100	6
#9 - South Canyon (1994)	87	9	13	50	2	100	14
#10 - Kates Basin (2000)	86	10	15	25	3	90	1
#11 - Thirtymile (2001)	87	13	3	5	3-6	60-90	4
#12 Cramer (2003)	97	15	20	65	3	90	2

Why is it that firefighters are underestimating these environmental conditions that lead to fatalities and not making the necessary adjustments in fire operations? Findings of the 1957 Task Force established by Forest Service Chief Richard McArdle found that

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"Basic elements of fire behavior are not understood; indicators of change in usual fire behavior not recognized; local fire-weather forecasts not obtained, inaccurate or not understood" (Moore *et al,* 1957). We see similar situations cited in fatality fire investigation reports today. South Canyon Fire: "The potential for extreme fire behavior and reburn in Gambel oak was not recognized on the South Canyon fire" (Rosenkrance et al., 1994). Thirtymile Fire: "Potential fire behavior was consistently underestimated throughout the incident" (Furnish *et al*, 2001).

Curt Braun hypothesizes that "Firefighters are unable to evaluate and combine fire related information to reliably predict fire behavior," and "In the absence of specific prediction methods, firefighters relied on their **experience** to determine the fire's future activity" (Braun 2002). He indicates that the Fire Orders and Watch-out Situations have been developed as the result of investigations of fatality fires. Firefighters are very successful suppressing most wildland fires. The majority of fatalities have occurred during transition from initial and extended actions, to project fires. Since we use the Fire Orders as "Rules of Engagement", we encounter a high frequency of "False Alarms" in our safety system. We may have been aware of extreme environmental conditions that are conducive to rapid fire spread, but this rapid fire spread did not occur. This can leave the firefighter with the perception that it was a "Safe" working environment.

Dan O'Brien states "Every wildland fire fatality is ultimately the result of a decision gone bad." One of the causal factors he focuses on is "Failure to recognize changing conditions and make the necessary adjustments in fire operations." The greatest danger from this causal factor comes from having a favorable outcome. This leads to recognizing, yet normalizing, risk because this is what happened last time and everything turned out fine (O'Brien, 1997). "High frequency events do not cause us problems. It is low frequency, high-risk events that cause us grief" (Graham 2002). This brings us to our reliance on experience in suppression operations and might help us understand why experience does not always serve firefighters well, and may actually give firefighters the confidence to expose themselves to more risk than they intended, or understood.

Mike Johns, Assistant United States Attorney for the District of Arizona reports the following from the litigation following the 1990 Dude Fire fatalities. "Fire managers would shudder at the legal arguments made in the Dude Fire litigation which demonstrates the great amount of discretion which the Standard Fire Orders and Watch outs permit." There is no objective standard against which to measure the risk against the propriety of the action" (Johns 1996). The Orders and Watch outs equate to rules of engagement with only subjective or implied rules for non-engagement or disengagement set in the culture of fire management (Beaver 2001).

Original Fire Order number 3, "Base all actions on Current and Expected fire behavior" does not describe what specific actions firefighters should take. It is likely that firefighters would have difficulty effectively accomplishing the variety of assignments they are given in evolving environmental conditions, if specific instructions were included in this fire order. So firefighters must understand the fire environment based on their training and experience. If firefighters have consistently worked successfully in environmental conditions encountered on fatality fires, and did not experience rapid rates of spread or extreme fire behavior, it is not surprising for firefighters to discount the risk of working in this environment. Firefighters rely on their "Slide carousel" where they have stored their fireline experiences to memory. In any fire task or incident, the brain quickly scans these "slides" and looks for a close match. Without a match (no slide), or with a match that did not see the fire reach its potential, the firefighter is enroute to problems (Graham 2002). This is one reason why firefighters need assistance in identifying the potential for rapid rate of spread before it occurs. They must identify the potential for all situations, which includes a worst-case scenario (Beaver 2001). By doing this the **potential** for rapid rate of spread can be identified, whether it occurs or not, or whether it is in your "slide carousel". Firefighters must be briefed on potential fire behavior, establish specific trigger points and corresponding action plans.

It is difficult for firefighters to process all of the information required to understand all of the relationships in the fire environment. Ted Putnam suggests that due to conscious awareness, our fundamental mental process, we can be conscious of only one object at any moment in time. Our brains process information sequentially (A+B+C) and not interactively (A*B*C). With training, people are good at identifying how much of A, B, or C is present (estimating wind speed), but poor at combining multiple factors (wind speed, fuel moisture, and percent slope). Because of this we tend to favor one of the three factors and base decisions heavily on the level of that single factor (Putnam 2001). Unfortunately fire behavior is influenced by a complex set of variables that do not occur in a simple linear fashion. Personal observations suggest that weather conditions slowly become more severe, day-by-day, and firefighters continue to use the same strategy and tactics that they have been successfully using on previous days. Given this mindset, it may become difficult to recognize when critical environmental thresholds are being reached which encourage rapid rates of spread.

Thirtymile Fire Behavior

The Thirtymile fire displayed extreme fire behavior and rapid rates of spread beginning with the initiation of the entrapment fire. During this period, crews were engaged in suppressing spot fires. Firefighters who were present at the Thirtymile fire when it entrapped firefighters indicated that they experienced an ember shower. The entrapped firefighters experienced another ember shower at the deployment area, as captured by a photo taken by firefighter Mathew Rutman (Figure 2). These ember showers provide an important contribution to the rapid rates of spread that occurred. Surface fire spread has been described by Rothermel's spread model (Rothermel 1972) used in the BEHAVE fire behavior prediction system. Rothermel also developed a model for predicting crown fire rate of spread (Rothermel 1991). The BEHAVE model does not incorporate the contribution of spotting to the rates of spread. Rothermel's 1991 crown fire model is based on a linear regression to relate course-scale observed crown

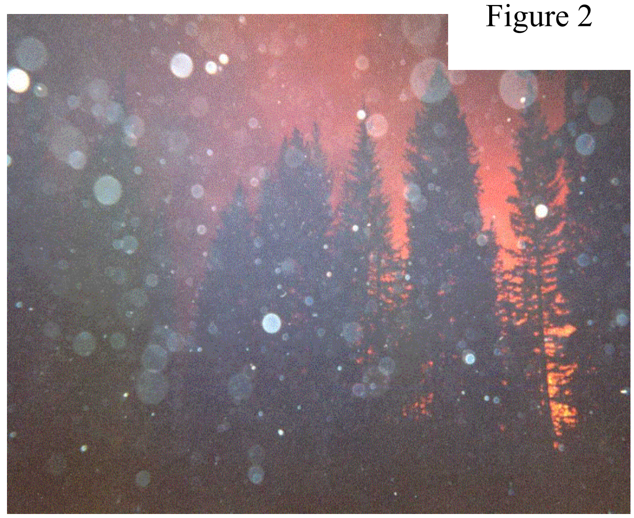


Figure 2

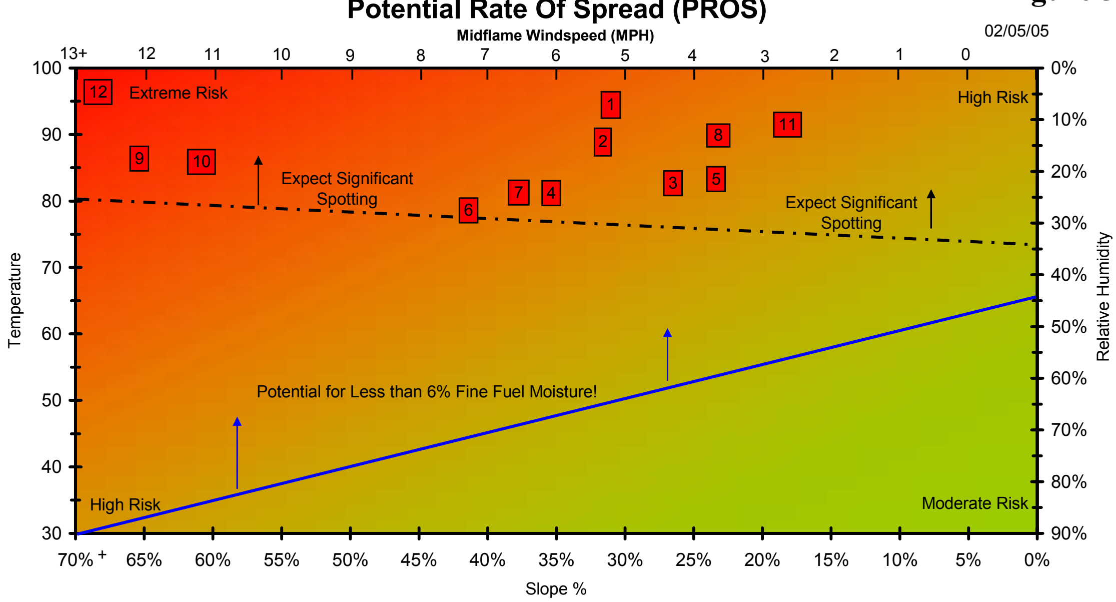
fire spread rates to predictions made with his surface fire model using fuel parameters from Fire Behavior Fuel Model 10. It therefore may indirectly include spotting when it occurred on the fires that he utilized, but specific attention was not given to spotting.

The Thirtymile fire behavior exhibited characteristics, due primarily to spotting, `that we seldom focus enough attention on in fire behavior training. From the time the Thirtymile fire was discovered it spread by torching and spotting. During the majority of suppression activities the Thirtymile fire did not spread rapidly in the Chewuch Canyon floor. The firefighters struggled to contain the fire as it generated four to six foot flame lengths and persistently torched trees with passive crown fire. Whenever trees torched the smoke drifted up canyon and deposited embers. These embers then ignited spot fires and the process continued. Firefighters did not experience rapid rates of spread until the fire burned out of the canyon bottom and made an upslope run which accelerated the rate of spread. Winds in the canyon bottom continued to be two to four miles per hour and did not promote rapid spread. Crown fire was increasing on the flat area immediately across the Chewuch River from the firefighters at the entrapment point. The wind was at their backs as they looked across the river at the crown fire. Then they encountered a 180-degree wind change, depositing an ember shower on the firefighters in the area. They immediately observed new spot fires increasing all around them and began a rapid evacuation of the area. Those who were standing on the road, next to their vehicles, escaped the entrapment fire by driving down the road, while shielding themselves from the heat as they exited the area. Those firefighters who were farther up the valley also exited as quickly as they could, but encountered fire across the road, blocking their escape. The Probability of Ignition of 80% - 100% is what enabled the entrapment fire to ignite and spread so rapidly. Hundreds of embers deposited by the wind change set up the opportunity for hundreds of spot fires to ignite at the same time and coalesce, creating, in affect, a "mass ignition". About this time the up canyon winds became more prominent, enhanced by the in drafts of the main fire as it continued to burn upslope and up canyon. As the mass ignition (Entrapment fire) began to spread it immediately involved the crowns of more trees in the canyon bottom, emitting more embers. The process not only continued to repeat itself, but also became an integral part of the flaming front and the catalyst for the rapid spread that occurred. We know that an ember shower, a blast of heat, and then the flames impacted the firefighters at the deployment site. This activity continued up the canyon for the rest of the burning period. The key to the entire process is fine fuel moisture and Probability of Ignition. Review of other fatality fires (Figure 1), and interviews with firefighters who were present on some of those fires, indicate that ember showers were present. Ember showers by themselves will not create the type of fire advance witnessed on the Thirtymile fire. A high Probability of Ignition is necessary to enable spot fires to start and spread rapidly.

How does a firefighter quickly recognize when the combination of environmental conditions presents an elevated risk to them? Many in the Fire Behavior Analyst arena have relied on tools such as the "Hauling Chart" (Andrews and Rothermel, 1982) to warn firefighters of the likelihood of fighting fire successfully. These are useful when observing the flame lengths and considering the 4', 8', and 11' thresholds, but they require BEHAVE (Andrews 1986) predictions to anticipate or predict when these thresholds may be reached. The "Pocket Card" is good for determining fire danger based on historic weather and fire history, but does not deal specifically with hourly fire behavior. Fine Fuel Moisture and Probability of Ignition **are** good indicators of hourly potential for extreme fire behavior and rapid rates of spread, and are relatively easy to calculate. Firefighters must have proper training, and use these tools consistently to become proficient in understanding the significance of the values and conditions. Unfortunately, although fireline supervisors are trained in determining fine fuel moisture and Probability of Ignition, they are not always determined by firefighters on the fireline and less frequently shared with all fireline personnel when the weather is recorded.

PROS Chart

Figure 3



A "Potential Rate of Spread Chart" (PROS) has been developed in an effort to assist firefighters in better understanding the significance of the interactive (A*B*C) environmental conditions they are working in (Figure 3). PROS is designed to help firefighters identify when they are approaching or working in environmental conditions where there is little room for error, and minutes and seconds may be the difference between life and death when things go wrong. To use the PROS chart, first record weather observations. This should be done at least hourly. Locate the temperature on the left side of the chart, and the relative humidity on the right side of the chart. Then draw a line between the two. Next, determine the slope percent at your location, and the current average mid flame wind speed. Then draw a line between the two points. The point where the two lines intersect is the Relative PROS Value. It is recommended that when the value is above the Expect Significant Spotting line the weather be taken at least every half hour.

Butler and others present a method for evaluating escape route and safety zone effectiveness using firefighter travel rate data and fire spread information (Butler et al 2000). They summarize "Many cases could be found that illustrate, often with tragic consequences, instances wherein firefighter safety margins were inadequate. Often the failure can be attributed to unexpected and rapid changes in fire behavior." They also conclude that the method demonstrated never provides an objective vehicle for assessing firefighter risk. Their analysis shows the relationship between firefighter travel rate versus fire spread rate for different fuel moisture conditions and fuels (Figure 4). It is interesting to note that under severe conditions the negative safety margins highlighted (rate of spread exceeds firefighter travel rate) correlate well with the Extreme Risk area on the PROS chart.

Figure 4

Slope (%)	FF Rate of Travel	Wind speed (mi/h) 20'	Fire spread rate, Flame length, Safety Zone minimum size											
			Grass (1)			Shrubs (2)			Crown Fire (3)			Surface Fire Beneath Tree Canopies (4)		
			R/S (ft/s)	FL (ft)	SZ (ft)	R/S (ft/s)	FL (ft)	SZ (ft)	R/S (ft/s)	FL (ft)	SZ (ft)	R/S (ft/s)	FL (ft)	SZ (ft)
Flat (0)	4	0	0.1	3	12	0.1	7	28	0.1	10	40	0.04	5	20
		10	2	14	56	3	31	124	1.3	70	280	0.4	12	48
		20	5	20	80	8	48	192	3	145	580	0.7	17	84
		30	8	26	104	14	62	248	5	220	880	1	21	84
Low (10-20)	3	0	0.2	5	20	0.3	10	40	0.2	20	80	0.1	6	24
		10	2	14	56	3	31	124	1.5	75	300	0.4	13	52
		20	5	21	84	8	48	192	4	150	600	0.8	17	68
		30	8	26	104	15	62	248	5	225	900	1	21	84
Moderate (20-40)	2	0	0.7	8	32	0.7	16	64	0.2	25	100	0.2	8	32
		10	3	15	60	4	33	132	2	80	320	0.5	14	56
		20	5	21	84	9	49	196	4	160	640	0.8	18	72
		30	9	27	108	15	63	252	6	235	540	1	22	88
Steep (40-60)	1	0	1.4	12	48	1.5	22	88	1.1	55	220	3	11	44
		10	3	17	68	4	36	144	2	100	400	0.6	15	60
		20	6	23	92	9	51	204	5	175	700	1	19	76
		30	9	28	112	16	65	260	6	250	1000	1	23	92

SAFETY MARGIN = (FIREFIGHTER TRAVEL RATE) - (FIRE RATE OF SPREAD)

Shaded areas represent a negative safety margin. Conditions are as follows: 1, 10, and 100 hour dead fuel moisture content = 4, 5, 6%. Live fuel moisture content - 50%. For the crown fire modeling late summer sever drought characteristics were used. R-S is fire rate of spread, F-L is calculated flame length, SZ is minimum safety zone separation distance. (1) Fuel Model 3; (2) Fuel Model 4; (3) Fuel Model 12 and maximum rate of spread; (4) Slash and Timber Fuel Models.

Fire spread rates can change dramatically as the fire moves from one fuel model to another. When environmental conditions where most firefighter fatalities occur are entered into BEHAVE all fuel models show rapid rates of spread. Since it is important to keep this tool easy to use, understand, and apply for all levels of firefighters, separate charts were not developed for each fuel model. Instead, risk thresholds are developed on the PROS chart based on fine fuel moistures and ignition probabilities. There are no new requirements for data or information that should not already be available to the firefighters on the fire line. Firefighters need to remember that the PROS Chart does not address fuel changes and they can also significantly affect rate of spread.

It is important to remember that when the environmental conditions are above the “Expect Significant Spotting” line it takes very little wind or slope to dramatically increase the rate of spread of the fire. By leaving all the other conditions the same and using just a three mph wind speed, the rating moves dramatically towards Extreme Risk.

- Firefighters should be carefully reassessing their situation when they experience a rating above the "Expect Significant Spotting" line.
- It is not necessary to wait until the environment reaches historic fatality conditions to consider the need to stand down in a safe area and reassess the situation.

This is advised whenever conditions move above the "Expect Significant Spotting" line. The Risk Management Process on page 1 of the "Incident Response Pocket Guide" PMS #461, NFES# 1077, should be revisited when this occurs. Re-evaluate the situation, identify the hazards, check the controls, and plan operations accordingly!

By using the PROS chart every time the weather is taken a pattern of the environmental conditions throughout the day can be observed. Consistently taking these observations can lead to anticipating when Trigger Points may be reached so that everyone is prepared to act at the appropriate time. This also provides good documentation of the environmental conditions that the firefighters were exposed to and can be helpful during after action reviews. Noting the actual fire behavior that occurred at each weather observation will build a better understanding of fire behavior that can be expected in the future when similar environmental conditions are encountered. In addition to using the PROS chart the firefighter should determine the fine fuel moisture and Probability of Ignition.

Development of the "Potential for less than 6% fine fuel moisture" line was accomplished by referring to the Fire Behavior Appendix B of the Fireline Handbook, Table 2 to determine the reference fuel moisture. Fine fuel moisture of six percent is commonly considered a good indicator of potential for rapid fire spread. To establish the line to represent potential for six percent fine fuel moisture or less, the maximum relative humidity that will yield a fine fuel moisture of six was located. This value is forty-four percent. In a similar way the minimum temperature that will yield fine fuel moisture of six was located. This value is thirty degrees. A relative humidity of forty-four percent and temperature of thirty degrees was located on the chart and a line drawn between the two values. When values occur above this line there is potential to have six percent fine fuel moisture or less. Finding the appropriate correction value in tables 3 through 5 in Fire Behavior Appendix B and adding them to the Reference Fuel Moisture can determine the actual fine fuel moisture.

Spotting potential was determined using Probability of Ignition values. A Probability of Ignition of 70% appears to be significant and should be cause for concern. Fire behavior observed on the Thirtymile fire offers insight into the significance of this value.

The Ignition Probabilities of the twelve fires in this study were determined and all but two of them had Ignition Probabilities of 70% or higher. Most were 80% - 100%. Two were 50%, but they also had very steep slopes or high winds contributing to the spread. It appears as though approximately 70% and higher Probability of Ignition presents the opportunity for this rapid spread process to occur. More research should be done to validate this subjective observation. This process of ember production, ember showers, and mass ignition, has not received enough attention in fire behavior training sessions or research. It is something that we need to begin focusing our training on, especially since we are capable of identifying and predicting when these environmental conditions occur.

The following descriptions provide an explanation of risk areas on the Pros chart:

The **Moderate Risk** area was established at below the potential for less than six percent fine fuel moisture line, which is relatively slow rate of spread conditions. Firefighters should be cautioned that rapid rate of spread is likely to occur above the potential for less than six percent fine fuel moisture line, but given steep slopes and high winds rapid rates of spread can occur anywhere on the chart. Aggressive firefighting, and indirect fireline construction, has the greatest chance for success along with reduced risk to firefighter safety when the environmental conditions fall into the Moderate Risk area of the chart.

High Risk values occur above the potential for less than six percent fine fuel moisture line. If values occur in this area the firefighter needs to remember that it takes very little wind to move into the Extreme Risk area. Remember that rapid fire spread frequently does not occur, even though the environmental conditions exist to promote it. Firefighters may avoid entrapment because the rapid spread never developed. The few times that it does occur, often surprises firefighters and, unfortunately, consequences may be tragic.

The **Extreme Risk** area encompasses the fatality fires. Other fatality fires may occur outside of the Extreme Risk area, but the PROS chart is attempting to capture the environmental conditions that we can expect rapid rates of spread frequently. Rapid rates of spread can occur anyplace on the chart, but will normally develop more slowly outside the Extreme Risk area, and requires strong winds and/or steep slopes.

The **Expect Significant Spotting** line (Figure 3) was established based on Probability of Ignition values. To determine probability of ignition, refer to the Fire Behavior Appendix B of the Fireline Handbook, Table 12. Approximately 80% Probability of Ignition was used as the "Expect Significant Spotting" threshold for the PROS Chart. This is not an exact value because the Reference Fuel Moisture is used to determine the fine fuel moisture needed to yield an 80% Probability of Ignition without the use of correction tables. To get an accurate Probability of Ignition, correction tables must be applied when the fine fuel moistures are determined. To yield a Probability of Ignition of eighty percent requires fine fuel moisture of four percent or less and a temperature of eighty degrees or more. A relative humidity of thirty-four percent is the highest relative humidity that will yield four percent fine fuel moisture. Thirty-four percent relative humidity is used for this line, along with eighty-degree temperature. These values were then plotted and the Expect Significant Spotting line drawn. This does not necessarily yield an exact eighty percent Probability of Ignition, but does provide a good reference value for the PROS chart.

Summary

This tool is designed to help the firefighter identify the Potential for Rapid rates of spread early enough to be able to safely respond. When this risk can be identified, the firefighter should consider the worst-case scenario that can occur under the environmental conditions and act accordingly. When working above the Expect Spotting line, rate of spread can change so quickly that special precautions should be taken.

- There should not be any unburned fuels between the fire and the firefighter. Spotting from below would be catastrophic!
- Avoid situations where that can occur, such as under slung line.
- Downhill fireline construction should not be attempted under these conditions.

Be an intelligent firefighter and go back to basics: One foot in the black, anchor and flank. There is no room for error under these environmental conditions.

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