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Wildland firefighter safety and fire behavior prediction on the fireline

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Abstract. Using the 2013 Yarnell Hill fatality fire in Arizona as a backdrop, this paper considers whether the global wildland fire community has failed on-the-ground firefighters. To begin answering this question two specific lines of inquiry are addressed: (i) was the fire behavior during the major run beyond what would be predicted by currently available guidelines? and (ii) what fire behavior knowledge and tools are available to allow wildland firefighters to assess their 'margin of safety'? A set of three recommendations are offered in light of our findings.

Additional keywords: fire behavior field guide, fire rate of spread, firefighter travel rate, flame length, Granite Mountain Interagency Hotshot Crew, margin of safety, Yarnell Hill Fire

Introduction

In his seminal work on *Fire Behavior in Northern Rocky Mountain Forests*, Jack Barrows (1951, p. 1), considering the subject of fire behavior and wildland firefighter safety said:

> An important reason for understanding fire behavior is to provide safety for the firefighters. Every fire behavior situation calls for specific safety measures. Experience gained from fighting thousands of fires has shown that the suppression job may be accomplished with a reasonable degree of safety. To achieve safety it is highly important that all firefighters have a general knowledge and the leaders of the firefighting forces have a high degree of knowledge of fire behavior. … Many risks can be eliminated from firefighting if each man knows what to expect the fire to do. The average firefighter need not be an expert on all phases of fire behavior, but he should have a working knowledge of ignition, combustion, and rate of spread of fires burning in forest fuels. Equipped with such basic fire behavior "know-how" the individual firefighter can approach his job without fear and with confidence that he can perform required duties in a safe and efficient manner.

Despite these general recommendations by Barrows, numerous entrapments and burn-overs have occurred that were directly related to an under appreciation or misjudgement of fire behavior potential (e.g. rapid changes in fire spread and intensity) involving both new and experienced firefighters. In an effort to learn from each of the tragedies, the wildland fire community has developed recommendations or lessons learned which have in turn led to a whole host of firefighter safety guidelines starting with the *Ten Standard Fire Fighting Orders* in 1957 (Alexander and Thorburn 2015). Similarly, many advances in fire behavior research and fire behavior training have taken place that have exposed wildland firefighters to a much more rigorous understanding and evaluation of fire behavior potential (Scott *et al.* 2014; Cruz *et al.* 2015). Yet in spite of these advances firefighter fatalities due to entrapments and burn-overs continue to occur. Such incidents are sometimes of disastrous proportions and are not restricted to just North America but are in fact global in nature (Alexander *et al.* 2012).

The circumstances surrounding the Yarnell Hill Fire tragedy of June 30, 2013, in which 19 members of the 20-person Granite Mountain Interagency Hotshot Crew (GMIHC) perished, are documented in Part 1 of the serious accident investigation report of this unfortunate incident (http://www.wildfirelessons.net/yarnellhill). In Part 2 of the report, the investigators raise over 35 questions for ground and air crews, incident and agency managers, and researchers to consider as part of a 'learning discussion'. The wildland firefighter fatalities associated with the Yarnell Hill Fire is one more in a long list of similar tragic incidents from all over the world that prompts us to ask a more general question that should be of concern to the entire wildland fire community: Have decades of wildland fire research, training and administration failed to give firefighters the knowledge, skills and tools to assess potential fire behavior and implications for their safety? The purpose of this paper is to hopefully deepen the learning discussion.

The case of the 2013 Yarnell Hill Fire

According to the Yarnell Hill Fire serious accident investigation report (p. 78), the flame front in the vicinity of the entrapment area/deployment site advanced at a rate of around 270 to 320 m min^{-1} with flame lengths of 18 to 24 m, an extreme level of fire behavior by any account.

Was the fire behavior during the major run beyond what would be predicted by currently available guidelines?

Barrows (1951) outlined the general process of predicting wildland fire behavior that are as valid today as they were nearly 65 years ago (Fig. 1). Most of the operational fire behavior guidelines and modeling systems presently used in the US are founded on the framework as illustrated in Fig. 2. In addressing the question raised above, let us assume that the following environmental conditions prevailed during the major run of the Yarnell Hill Fire based on data and information contained in the serious accident investigation report and Rothermel's (1983) guidelines:

- Fire Behavior Fuel Model 4 – Chaparral (1.8 m) as per Anderson (1982)
- 0% slope steepness
- Fine dead fuel moisture contents of 3%
- Live woody fuel moisture content of 75% (cf. Davis and Dieterich 1976)
- Mid-flame windspeeds of 32-40 km h^{-1} given forecasted 6.1-m open winds of 64-80 km^{-1}

The BehavePlus fire modeling system (Andrews *et al.* 2008) predicted the head fire rate of spread (ROS) and flame length (FL) to vary from 248 to 340 m min^{-1} and 18 to 21 m, respectively. This is a good match with the reconstructed values for the major run.

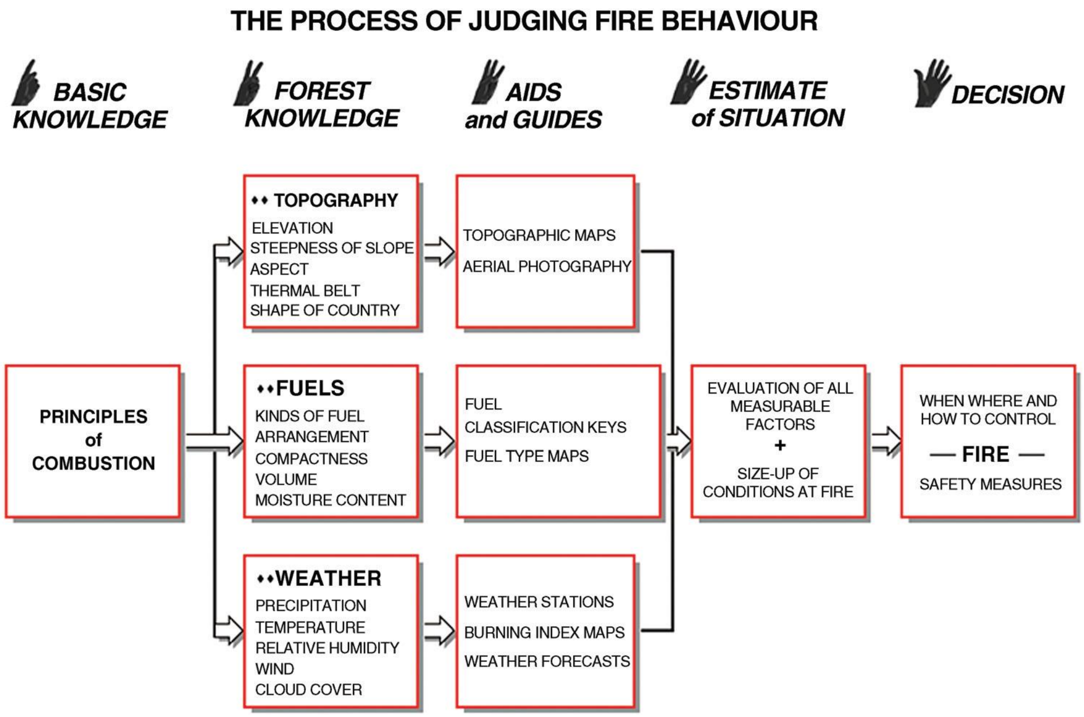

Fig. 1. Judging and interpreting predictions of wildland fire behavior requires the systematic analysis of many factors and considerations (from Barrows 1951).

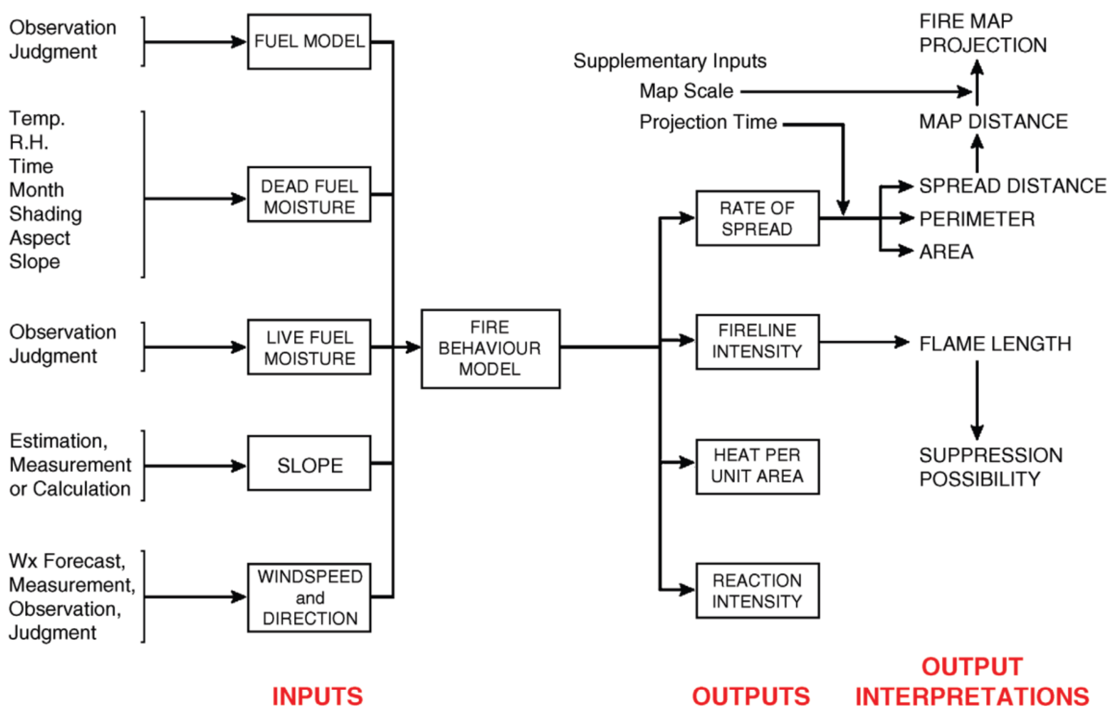

Fig. 2. General information flow involved with the underlying framework of most operational fire behavior guides and modeling systems used in the US (from Rothermel 1983).

For lack of computer access the GMIHC was unable to perform BehavePlus fire modeling system computations on the fireline. The National Wildfire Coordinating Group (2014a) *Incident Response Pocket Guide* (*IRPG*) doesn't include methods to predict or estimate ROS or FL. However, the National Wildfire Coordinating Group (2006) *Fireline Handbook Appendix B: Fire Behavior* supplement does. Table 30 on p. B-74 from that publication is reproduced here as Fig. 3. The tabulation is limited to a maximum mid-flame windspeed (MFW) of 19 km h^{-1} and live woody fuel moisture (LWFM) of 90 to 120%. The maximum predicted ROS and FL are 84-105 m min^{-1} and 11-12 m, respectively, still a very extreme level of fire behavior.

TABLE 30: FUEL MODEL 4—0% SLOPE

Fuel Moisture % (1-Hour)		Midflame Wind, mi/h						
		0.	2.	4.	6.	8.	10.	12.
		Rate of Spread/Chains per Hour						
3.0	120-90	5	24-29	56-70	97-120	143-178	195-243	252-313
6.0	120-90	4	21-25	49-61	85-104	126-155	171-211	221-272
9.0	120-90	4	19-23	46-56	79-96	117-143	160-194	206-250
12.0	120-90	4	18-22	43-53	74-90	110-134	149-183	192-235
15.0	120-90	3	12-19	28-46	47-78	70-116	96-158	124-204
18.0+	120-90	1	6	11-13	19-23	29-34	39-46	51-60
21.0	120-90	0	0	0	0	0	0	0
		Flame Length/Feet						
3.0	120-90	5.7	12-13	18-20	23-25	27-31	32-35	35-40
6.0	120-90	5.1	11-12	16-18	20-23	25-27	28-32	32-35
9.0	120-90	4.8	10-11	15-17	19-21	23-26	27-30	30-33
12.0	120-90	4.6	10-11	14-16	18-20	22-24	25-28	28-32
15.0	120-90	3-4	6-10	10-14	12-18	15-22	17-25	19-28
18.0+	120-90	1	3	4-5	6	7	8	9
21.0	120-90	0	0	0	0	0	0	0

Fig. 3. Tabulation for Fire Behavior Fuel Model 4 – Chaparral (1.8 m) for zero percent slope contained in the National Wildfire Coordinating Group (2006) *Fireline Handbook Appendix B Fire Behavior* supplement. This tabulation is not available in SI units. Conversion factors: mi/h × 1.61 = km h^{-1}; chains per hour × 0.335 = m min^{-1}; feet × 0.305 = m.

Fire behavior nomograms (Albini 1976; Rothermel 1983; National Wildfire Coordinating Group 1992) were another potential field tool available in 2013 that do allow for higher windspeed values to be considered (Fig. 4). The nomogram for Fire Behavior Fuel Model 4 – Chaparral (1.8 m) gives a predicted ROS and FL of 251 to 335 m min^{-1} and of 18 to 21 m, respectively. Nomograms and also nomographs (Scott 2007), however, are not commonly employed outdoors in fireline situations by fire suppression crews but they are used by a fire behavior analyst (FBAN) at an incident command post, for example.

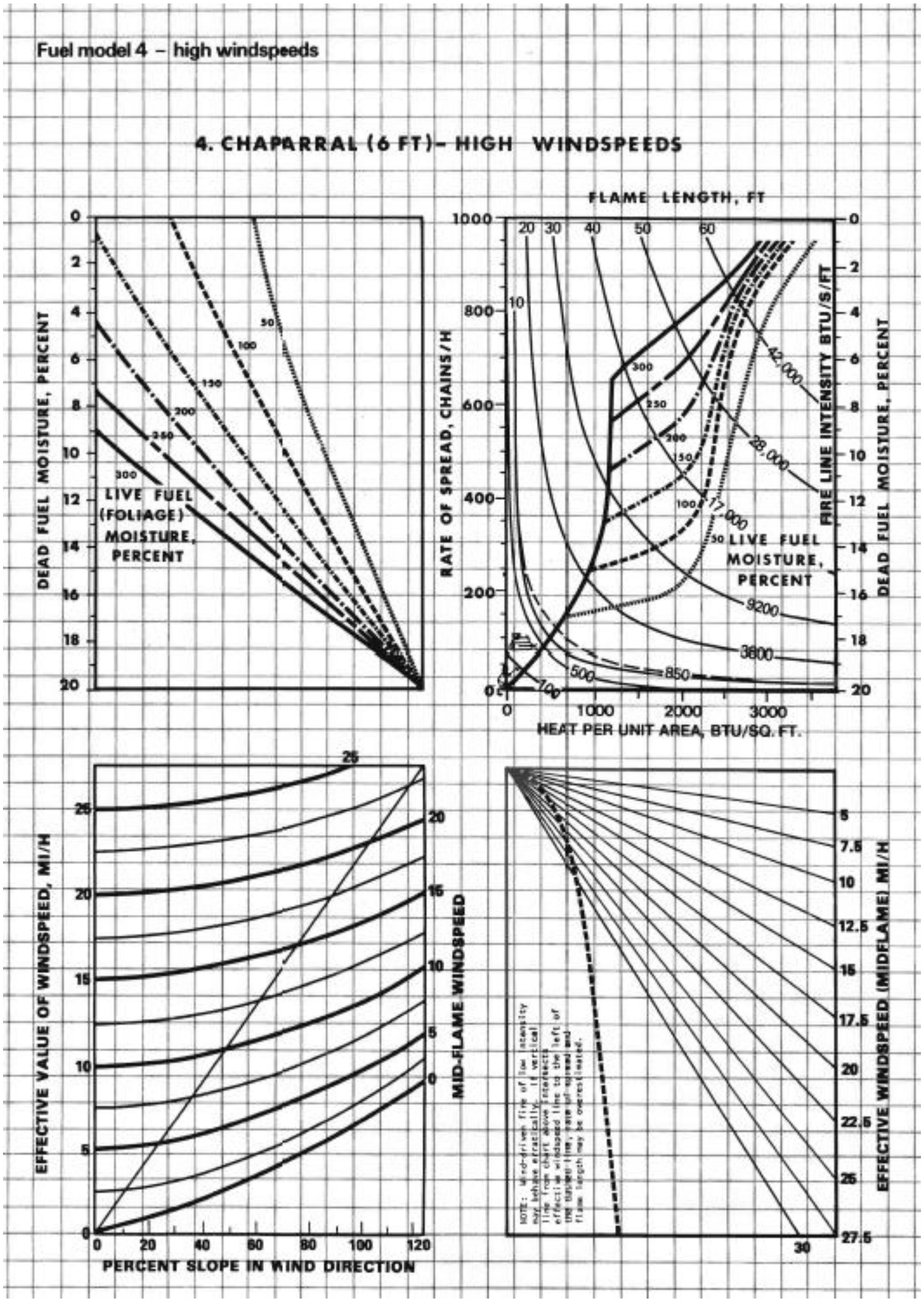

Fig. 4. The National Wildfire Coordinating Group (1992) fire behavior nomogram for Fuel Model 4 – Chaparral (1.8 m) for high windspeeds. This graphic is not available in SI units. Refer to Fig. 3 caption for conversion factors.

The latest edition of the *Fire Behavior Field Reference Guide* allows for a maximum MFW of 32 km h^{-1} for Fire Behavior Fuel Model 4 – Chaparral (1.8 m) (National Wildfire Coordinating Group 2014c, p. 117). Combined with the fuel model, slope steepness, and fuel moistures stated previously, this gives a predicted ROS and FL of 173 to 235 m min^{-1} and 15 to 18 m, respectively. (Note: at some 200 pages in length it is unlikely this guide would be carried on the fireline by an IHC superintendent or assistant superintendent.)

In addressing the question poised at the start of this section, from the perspective of hindsight, one would have to say 'no'. The ROS and FL observed during the major run of the Yarnell Hill Fire on June 30, 2013, was not beyond what could be predicted by the Rothermel (1972) surface fire model in the form of the BehavePlus fire modeling system (Table 1). Some limits imposed on live fuel moisture and windspeed with the three manual methods or tools for fire behavior prediction do restrict the ROS and FL values that are possible (Table 1). However, in real time, decisions can only be made with foresight (Sutton 2011). Whether fire behavior is predictable in practice may also depend on the accuracy and availability of model inputs, appropriate training, whether fire behavior assessment is part of work protocols and operating procedures, and having sufficient time.

Table 1. Summary of after-the-fact predictions of fire rate of spread (ROS) and flame length (FL) by various fire behavior predictive tools for Fire Behavior Fuel Model 4 – Chaparral (1.8 m), including their live fuel moisture and windspeed limits, in comparison to the ROS (270 to 320 m min^{-1}) and FL (18 to 24 m) experienced during the major run of the Yarnell Hill Fire on June 30, 2013

LWFM, live woody fuel moisture; MFW, mid-flame windspeed

Fire behavior predictive tool	ROS (m min^{-1})	FL (m)	LWFM range (%)	MFW maxima (km h^{-1})
BehavePlus fire modelling system (Andrews *et al.* 2008)	248-340	18-21	30-300	64
Fireline Handbook Appendix B: Fire Behavior (National Wildfire Coordinating Group (2006)	84-105	11-12	90-120	19
Fire Behavior Nomograms (National Wildfire Coordinating Group 1992)	251-335	18-21[A]	50-300	38
Fire Behavior Field Reference Guide (National Wildfire Coordinating Group 2014c)	173-235	15-18	80-120	32

[A]The upper FL value was estimated on the basis of the maximum MFW (i.e. 38 km h^{-1}) that could be used given the boundary limitations of the Fire Behavior Fuel Model 4 – Chaparral (1.8 m) nomogram for high windspeeds (Fig. 4).

We do not know, even with the benefit of hindsight, whether a prediction of potential fire behavior was made prior to the crew leaving the safety of the "black" sometime after 1604 h on June 30. However, we do see in several digital images sent out by members of the GMIHC from their cell phones that they did take time to observe the Yarnell Hill Fire's behavior prior to the major run and their relocation. Furthermore, the US Department of Interior and US Department of Agriculture Forest Service (2011) require IHC superintendents and assistant superintendents are required to have taken the course *S-390 Introduction to Wildland Fire Behavior Calculations* which includes instruction in both the *Fireline Handbook Appendix B: Fire Behavior* supplement and the *Fire Behavior Nomograms* (National Wildfire Coordinating Group 2015).

On the basis of an interview (http://www.youtube.com/watch?v=-4hR5annS_Y) conducted by Dave Thomas with Steve Little (Superintendent, Asheville IHC) during the Fire Management Deep Smarts Project (Thomas *et al.* 2012, 2015), it is apparent that some firefighters do in fact utilize the *Fireline Handbook Appendix B: Fire Behavior* supplement to make estimates or predictions of wildland fire behavior in relation to escape routes and safety zones considerations, although it is unknown how widespread and rigorous this practice is at present.

An additional field tool also available in 2013 was the *FireLine Assessment Method FLAME Field Guide* (National Wildfire Coordinating Group 2007). The *FLAME Field Guide* is not used to predict ROS and FL directly, rather it is used to assess dramatic changes in fire behavior (Bishop 2007), particularly in ROS based on changes in windspeed, fuel type, topography, and other fire environment characteristics. All senior firefighters on an interagency hotshot crew (IHC) are required to have taken the course *S-290 Intermediate Wildland Fire Behavior* (US Department of Interior and US Department of Agriculture Forest Service 2011) where instruction in the use of the *FLAME Field Guide* is given (National Wildfire Coordinating Group 2015).

Using the *FLAME Field Guide* for the Yarnell Hill Fire and assuming an increase in windspeed and a change from a backing fire to a head fire with an effective windspeed-ratio of 56 to 64X, the ROS-ratio was on the order of 110 to 140X. That is, a 100 to 140X increase in ROS was predicted given the increase in windspeed and change in wind direction, a value well above the threshold of 60X noted in the *FLAME Field Guide* where past firefighter fatalities have occurred.

What fire behavior knowledge and tools are available to allow wildland firefighters to assess their 'margin of safety'?

FL values of 18 to 24 m suggests that separation distances of 72 to 96 m are needed (Cohen and Butler 1998), assuming that FL is equivalent to height of the flames. This represents a sizeable area (i.e. 1.6 to 2.9 ha). In any event, a good safety zone is of no use to firefighters if they cannot reach it in time.

The motivation for firefighters to evaluate fire behavior potential is to assess risks to their safety posed by rapid fire spread and (or) intense heat. In his landmark textbook on forest fire control and use, Davis (1959, p. 404) pointed out that:

> Good scouting, communication, knowledge of fire behavior, fire weather forecasting, training, and leadership are the best insurance of safety. If these things are well handled, there is little reason for fire suppression to be more dangerous than any other kind of woods work … There have been instances where there was underappreciation of the danger of a situation and of allowing too narrow a margin of safety.

While Davis's statement regarding working in the woods may hold in many cases, it is clearly not the case under extreme burning conditions, particularly in open wildland environments.

The margin of safety with respect to wildland fire behavior and firefighter safety was first enunciated in print by Beighely (1995). The concept is graphically illustrated in Fig. 5.

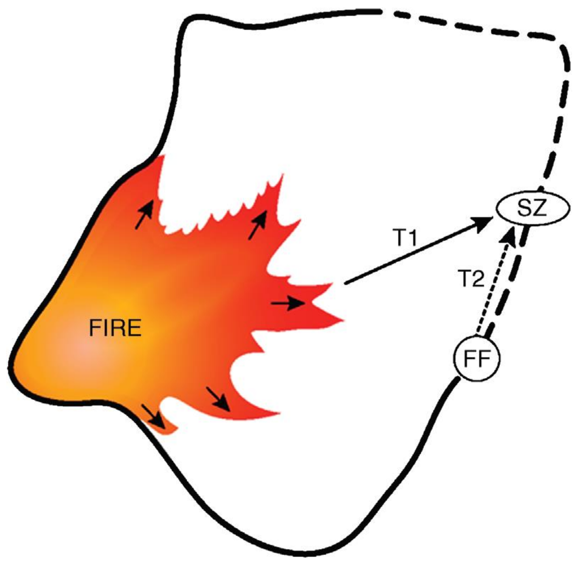

Fig. 5. Illustration of the 'margin of safety' concept involved during indirect and parallel attack wildland fire suppression situations (adapted from Beighely 1995). FF = firefighter(s); SZ = safety zone; T1 = the time taken for the fire to reach the safety zone; and T2 = the total time taken for firefighter(s) to reach the reach the safety zone.

Mathematically, the margin of safety is defined as follows (from Beighely 1995):

$$\text{Safety Margin } (\pm) = T1 - T2 \quad (1)$$

where T1 is the time for a fire to reach a safety zone and T2 is the time for a firefighter(s) to reach the safety zone (Fig. 5). T1 is dictated by the distance involved and the fire's ROS. T2 depends not only on the fire crew's rate of travel (ROT) but other factors such as the delay in recognizing the need to use an escape route as a result of a change or anticipated change in fire behavior, and the time required to communicate this decision to the other crew members (Baxter *et al.* 2004). Equation (1) can also be expressed as:

$$\text{Safety Margin } (\pm) = D1/ROS - (D2/ROT + T) \quad (2)$$

where D1 and D2 are the distances between the fire front and firefighter(s) and the safety zone, respectively, and T is the time taken for the firefighters to initiate travel along the escape route to the safety zone.

A positive (+) safety margin from either equation (1) or (2) implies that the firefighter can reach the safety zone before being overtaken by the fire, whereas a negative (-) safety margin implies that the fire can overtake a firefighter before the firefighter can reach the safety zone. The greater the positive difference between T1 and T2, the greater the margin of safety.

While the margin of safety concept is regarded as useful, application can be difficult in practice. Information on the four key variables shown in equation (2) can be challenging to assess, especially ROS and ROT, partly because they require direct observation, which may be difficult under extreme burning conditions and because they are constantly changing over time and space. ROS and D1 are likely often under-estimated (McLennan 2009). The fire's movement across the landscape requires a constant re-evaluation of both the fire's ROS and position relative to firefighters and safety zones as well as the fire crew's ROT and position relative to an escape route and safety zone. To cope with some of these challenges, firefighters often identify 'trigger point' locations on the fire that will give them, if the fire reaches that location, adequate amount of time to move to an identified safety zone. (Greenlee and Greenlee 2003; Campbell 2005). Although we believe the margin of safety concept to be quite useful in fire suppression operations, we know of no practical guides or tools to assist firefighters with such assessments as documented in the global wildland firefighter safety and fire behavior literature.

Hard data on firefighter travel rates is limited to a few published studies (Rothermel 1993; Butler *et al.* 1998; Ruby *et al.* 2003; Alexander *et al.* 2013). While some existing research is being applied (e.g. Fryer *et al.* 2013), much more observational data needs to be collected in order to cover a wider range of conditions.

While the Lookout(s) – Communication(s) – Escape route(s) – Safety zone(s) *(*LCES) wildland firefighter safety system checklist on p. 6 of the *IPRG* does indicate the need to 'evaluate escape time vs. rate of spread', no mention is specifically made of the need to undertake a margin of safety calculation in the new *Wildland Fire Incident Management Field Guide* (National Wildfire Coordinating Group 2014b).

Wildland fire behavior prediction: slow or fast?

While there have been advances made in fire behavior prediction since Barrows (1951) observations, advances have also been made in the understanding of decision making and human error. Considerable research has been done on decision making under time pressure. Klein (1999) found that many experts rely on intuition informed by experience or 'recognition primed decision-making' (RPD). Rule-based approaches are also used (McLennan *et al.* 2003). While these approaches are effective in many situations, they are not infallible; RPD relies on extensive experience which may not encompass extreme events. What fire behavior prediction provides is access to information that is beyond one's personal experience.

While no fire behavior prediction is perfect (there is inherent uncertainty related to weather forecasts and model error), accuracy can be in the order of 60 to 80% (Cruz and Alexander 2013). However, assessments of fire behavior and margins of safety require the explicit, systematic analysis of many factors. This kind of rational thought process (sometimes called 'System 2') is inherently hard and slow, as opposed to the quick, intuitive judgements of 'System 1' (Kahneman 2011). Even the most basic fire behavior prediction takes some time, perhaps a few minutes. Klein *et al.* (2010) estimated that urban fire department commanders made 78% of their decisions in less than one minute. Just as we often require structured processes and external aids for many rational thought processes, such as a pencil and paper to do mathematics (Heath 2014), work processes, decision aids and training are as essential to operational fire behavior prediction and as deserving of attention as the science itself.

In a general sense one has to wonder just how often, if at all, are current fire behavior guides utilized by field going personnel, and if they are not being used, why not? Is there a lack of confidence in the models upon which they are based? Is it a case that the existing field tools are not convenient to use on the fireline? Could the margin of safety implications be simplified (e.g. Cheney *et al.* 2001)? Is too much reliance placed upon experienced judgement (Burrows 1984) over systematic, model based assessments? Is the main obstacle to full use of fire behavior models and guides under fireline conditions the fact that there appears to be no standard operating procedure on how to use them? Is there not enough time in the day to undertake the calculations of ROS and the margin of safety (Fig. 6) to aid anticipatory thinking (McLennan *et al.* 2009) ?

Element	**Daily fire behavior prediction**	**Fire behavior concern**	**Imminent threat**
Fire personnel	Fire Behavior Analyst	Fire crew leaders –	Crew
Decision time	Days to hours	Hours to minutes	Minutes to seconds
Thought process	Rational	Intuitive/Rational	Intuitive
Tools	Fire behavior models, training, experience	Fire behavior guides, training, experience	Training, experience, mental models
Decision/Plan	Daily incident action plan	Re-evaluate strategy & tactics or disengage tactics	Disengage or seek out survival zone

Time wedge

Fig. 6. Illustration of fire behavior assessment and decision making- during a critical day. As fire behavior and the tempo and urgency of events escalates, the 'wedge of time' available to evaluate fire behavior decreases.

The time available for fire behavior assessment during a firefighter's work day may be seen as an arrow or wedge of time (Fig. 6); the broad end often begins with a morning briefing on the daily plan and on a large incident may include discussion of fire behavior potential with a FBAN. During the day the time available for decision making may narrow with increasing fire behavior and the tempo and urgency of events; on a critical day the sharp end may narrow to mere seconds if firefighters are confronted with an imminent threat. The sharp end of the time wedge is clearly too late for fire behavior prediction, but the question arises as to what point(s) should updated fire behavior predictions be used to reassess or 'replan' current tactics? In part this requires overcoming the tendency to continue with an existing plan (Sutton 2011; Frye et al. 2014).

Current approaches to understanding the human contribution to accidents emphasize that, while safety is not inherent to systems, human error is connected to the tools, tasks and operating environment we regularly utilize. Progress in safety will be made by understanding and influencing these connections (Dekker 2002, 2014). The issue is undoubtedly multi-faceted. There is an overriding need for wildland fire and human factors researchers to work together with firefighters and managers to better understand decision processes, tasks and the operating environment in order to improve the connections between decision aids, training, communications and protocols – to better connect human behavior and fire behavior. Nevertheless, the creation of a 'fire behavior pocket guide' with the on-the-ground firefighter in mind would appear to be in order, not just in the US or Canada but globally using as a starting point ideas from existing field guide formats (Taylor *et al.* 1997; Sneeuwjagt and Peet 1998; National Wildfire Coordinating Group 2006; Gould *et al.* 2007; Pearce *et al.* 2012). and interpretive guidelines and threshold values that aim to reduce risk by managing exposure to extreme fire behavior (i.e. risk = hazard x exposure x vulnerability); see, for example, the Operational Safe Work Standard 5 discussed by Beck *et al.* (2002). Perhaps it is now time to consider the application of a mobile device for use on the fireline (Broyles and Verania 2006; Anderson *et al.* 2008) as part and parcel of one's personal protection equipment.

Implications for wildland fire science and management

In light of the Yarnell Hill Fire and similar tragedies on other continents in the past, we believe the following steps should be undertaken:

(1) Undertake a comprehensive literature review/annotated bibliography related to the subject of fire behavior and firefighter safety (e.g. firefighter travel rates on escape routes, safety and survival zones, fire behavior guides, thinking under uncertainty, decision making, organizational safety, risk management) including how such information is incorporated in wildland fire training and standard operating programs.
(2) Undertake interviews with selected individuals in the wildland fire community along the lines of the Fire Management Deep Smarts Project as to: (i) how they are currently using fire behavior information in the field in regards to firefighter safety and what they think should be done to improve field applications of it, including knowledge gaps, and (ii) how and why responders successfully withdrew from incidents that resulted in entrapment of others.
(3) Convene a working group to analyze the information gleamed from steps 1 and 2 to make recommendations regarding management actions and address research needs in the form of an international workshop and symposium, complete with compendium.

Potential organizations that should be involved in such an undertaking include the Australasian Fire and Emergency Service Authorities Council, Bushfire & Natural Hazards Cooperative Research Centre, Canadian Interagency Forest Fire Centre, Fire Management Study Group of the North American Forestry Commission, Food and Agriculture Organization of the United Nations, Forest and Rural Fire Association of New Zealand, International Association of

Wildland Fire, Joint Fire Science Program, National Interagency Hotshot Crew Steering Committee, National Wildfire Coordinating Group, Pau Costa Foundation, and Wildland Fire Lessons Learned Center, just to name a few.

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