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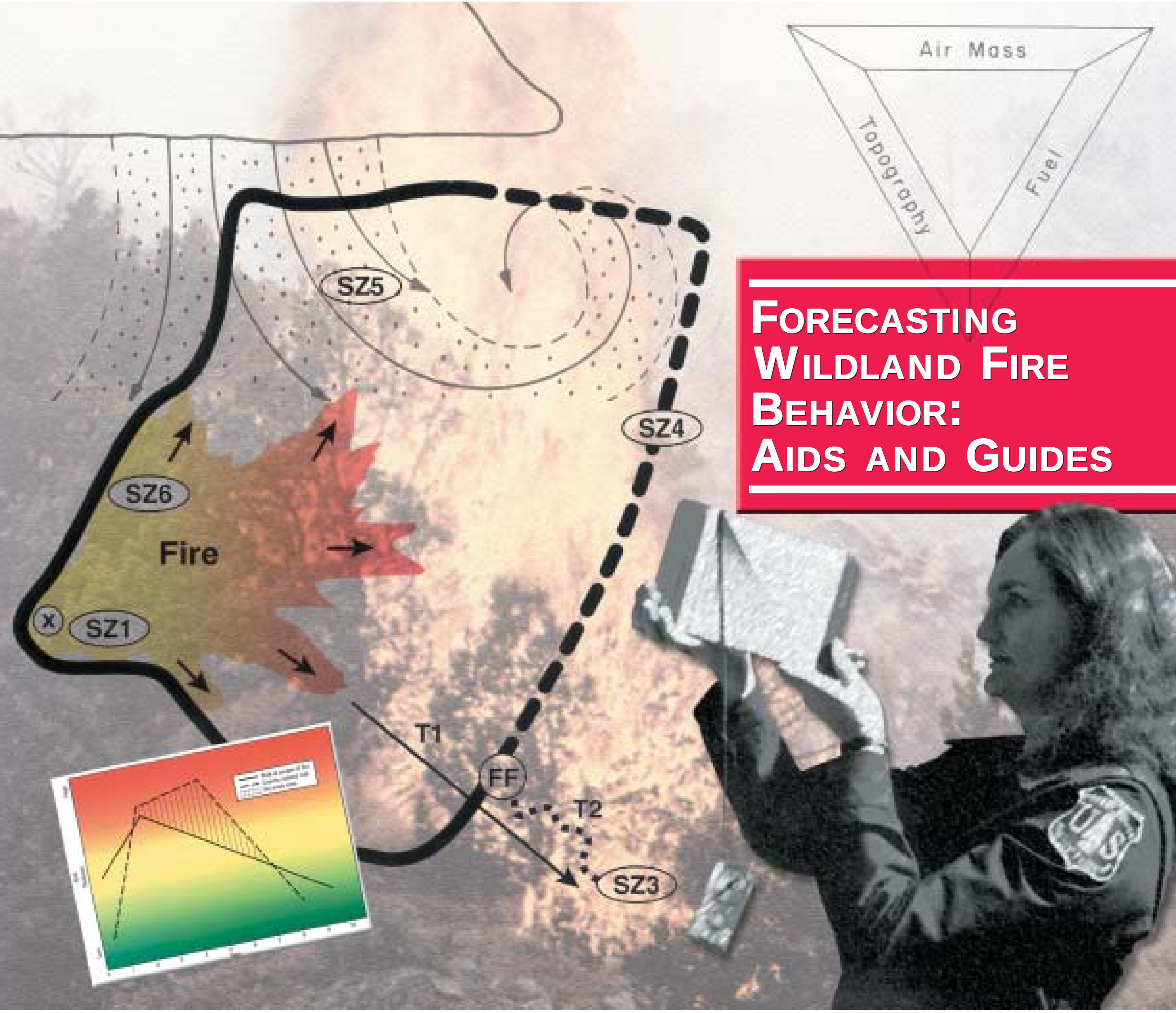

FORECASTING WILDLAND FIRE BEHAVIOR: AIDS AND GUIDES

United States Department of Agriculture
Forest Service

Editor's note: This issue of *Fire Management Today* is the third in a three-part series of reprinted articles related to wildland fire behavior, some of them decades old. Although the articles appear in today's format, the text is reprinted largely verbatim and therefore reflects the style and usage of the time. We made minor wording changes for clarity and added metric conversions where needed. All illustrations are taken from the original articles.

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On the Cover:

Aids and guides from the past, some illustrated here, can help improve the fire behavior forecasting capabilities needed today in both fire use and fire suppression. See the articles in this issue for descriptions.

CONTENTS

The FIRE 21 symbol (shown below and on the cover) stands for the safe and effective use of wildland fire, now and throughout the 21st century. Its shape represents the fire triangle (oxygen, heat, and fuel). The three outer red triangles represent the basic functions of wildland fire organizations (planning, operations, and aviation management), and the three critical aspects of wildland fire management (prevention, suppression, and prescription). The black interior represents land affected by fire; the emerging green points symbolize the growth, restoration, and sustainability associated with fire-adapted ecosystems. The flame represents fire itself as an ever-present force in nature. For more information on FIRE 21 and the science, research, and innovative thinking behind it, contact Mike Apicello, National Interagency Fire Center, 208-387-5460.

Firefighter and public safety is our first priority.

SHORT FEATURES

FORECASTING WILDLAND FIRE BEHAVIOR: AIDS, GUIDES, AND KNOWLEDGE-BASED PROTOCOLS

M.E. Alexander and D.A. Thomas

Can wildland fire behavior really be predicted? That depends on how accurate you expect the prediction to be. The minute-by-minute movement of a fire will probably never be predictable—certainly not from weather conditions forecasted many hours before the fire. Nevertheless, practice and experienced judgment in assessing the fire environment, coupled with a systematic method of calculating fire behavior, yield surprisingly good results (Rothermel 1983).

This is the third and final special issue of *Fire Management Today* in a series of issues devoted to the subject of wildland fire behavior. The first two issues contained 36 articles dealing with wildland fire behavior case studies and analyses published in *Fire Management Today* and its predecessors between 1937 and 2000. These two issues contained lead articles on various aspects of those subjects (Alexander and Thomas 2003a, 2003b). Not included in these two issues are two recent articles on fire behavior published in *Fire Management Today* (Brown 2002; Cornwall 2003).

Marty Alexander is a senior fire behavior research officer with the Canadian Forest Service at the Northern Forestry Centre, Edmonton, Alberta; and Dave Thomas is the regional fuels specialist for the USDA Forest Service, Intermountain Region, Ogden, UT.

> By systematically reflecting upon our fire behavior forecasts and the tools that helped us prepare them, we become the masters of fire behavior models and not their servants.

This issue is devoted to aids, guides, and knowledge-based protocols involved in predicting wildland fire behavior for safe and effective fire suppression (Alexander 2000). It includes 21 articles published from 1947 to 1998. A recent article by Weick (2002) that emphasizes the importance of human factors in the field of fire behavior forecasting could have easily been included.

The Practice of Predicting Wildland Fire Behavior

More than 50 years ago, Barrows (1951) outlined the basic concepts of predicting or forecasting wildland fire behavior that are still very valid today (see the excerpt on pages 6–7). As figure 1 shows, the process of judging fire behavior can be divided into five simple steps:

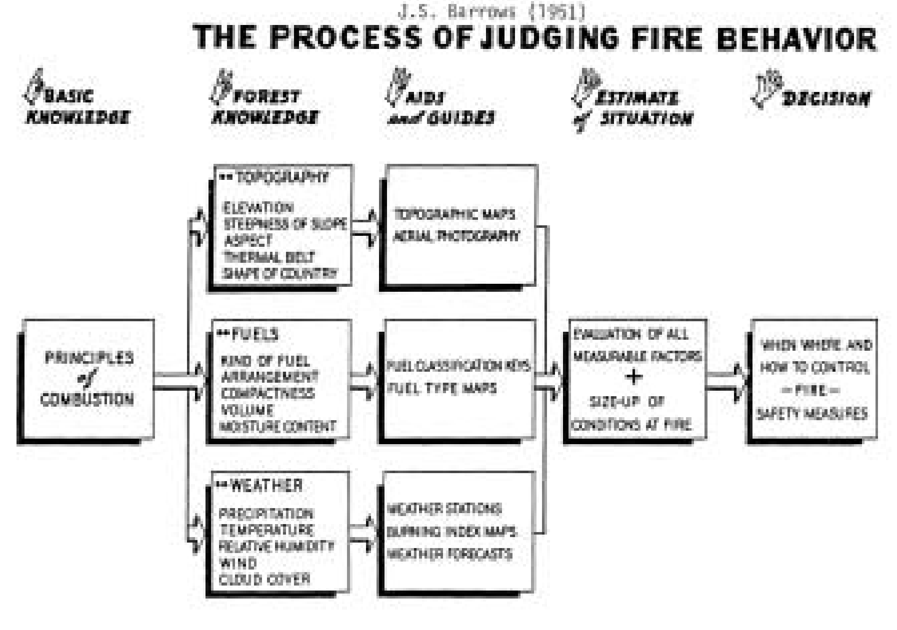

Figure 1—*Judging fire behavior requires systematic analysis of many factors (from Barrows 1951).*

1. *Basic knowledge.* The foundation for judging probable fire behavior must rest on basic knowledge of the principles of combustion: What is necessary for combustion to occur? What causes the rate of combustion to increase or decrease? How may combustion be reduced or stopped?
2. *Forest knowledge.* Three basic factors in a forest area—weather, topography, and fuels—are important indicators of fire behavior.
3. *Aids and guides.* Several aids and guides are available to assist in evaluating weather, topography, and fuels.
4. *Estimate of situation.* The probabilities for various patterns of fire behavior are systematically explored through an estimate of the situation based upon the combined effects of weather, fuels, and topography.
5. *Decision.* The end product of the fire behavior analysis is a decision outlining when, where, and how to control the fire and spelling out any special safety measures required.

For this third and final issue in the series dealing with wildland fire behavior, we chose articles from past issues that reflect the various elements involved in Barrows' (1951) process of judging or predicting wildland fire behavior.

Comparisons of Fire Behavior Predictions and Forecasts Needed

After 50 years, the only item we would add to Barrows' (1951) outline is the need for the fire behavior analyst (FBAN) and others engaged in wildland fire management to pause for a moment to compare, in a rigorous and systematic fashion, the FBAN's or their own fire behavior predictions to actual fire behavior. This is the only way one can truly meet Barrows' (1951) advice to "evaluate the combined effects of all significant factors influencing fire behavior."

We recommend that fire behavior analysts adopt the framework of the After Action Review, as described on the Wildland Fire Lessons Learned Center Website.

Conscious reflection, not as an afterthought but as a normal routine in the day-to-day business of fire behavior forecasting, involves a highly professional method of questioning whether our fire behavior aids, guides, and protocols are working. By systematically reflecting upon our fire behavior forecasts and the tools that helped us prepare them, we become the masters of fire behavior models and not their servants.

To paraphrase Dr. Karl Weick (2003)—coauthor of *Managing the Unexpected: Assuring High Performance in an Age of Complexity* (Weick and Sutcliffe 2001)*—becoming a *mindful* FBAN is a constant struggle for alertness, and to be alert means to "constantly and diligently seek instances where your model didn't work and identify indicators you missed that signaled expectations weren't being filled…."

We recommend that FBANs and others adopt the framework of the After Action Review, as described on the Wildland Fire Lessons Learned Center Website (<http://www.wildfirelessons.net/AftrIncdntRpt.htm>), by putting their fire behavior forecasts through a reflective scrutiny based on four basic questions:

1. What did your fire behavior forecast say would happen?
2. What actually happened?
3. Why did the fire behavior aid, guide, or protocol predict accurately (or inaccurately)?
4. Finally (and most importantly), if you had to make this forecast again, what would you do differently? How would you change the way you used the aid, guide, protocol, or model/system in this different approach?

Judging the quality of a fire behavior prediction or forecast solely on the outcome can be hazardous. By chance, good predictions or forecasts can sometimes have bad outcomes and bad predictions or forecasts can result in good outcomes (fig. 2). From a practical standpoint, overpredictions can be easily readjusted without serious, lasting consequences, whereas underpredictions can be disastrous (table 1) from the standpoint of human safety (i.e., for the public and for fire-

		Outcome	
		Good	Bad
Forecast	Good	*Objective*	*Unlucky*
	Bad	*Lucky*	*Deserving*

Figure 2—*The 2-by-2 fire behavior prediction or forecast matrix (based on Saveland and Wade 1991) shows that even good forecasts can have unlucky outcomes.*

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* See D. Iverson, "Book Review: Managing the Unexpected" *(Fire Management Today* 62(4) [Fall 2002]: 36–37); and J. Williams, "Next Steps in Wildland Fire Management" *(Fire Management Today* 62(4) [Fall 2002]: 31–35).

On the Place of Fire Behavior in Wildland Fire Management*

Although forestry dates back hundreds of years, organized forest fire research has been underway less than 30 years. During much of this time the major efforts have been devoted to studies of fire behavior or closely allied fields. As a result, much has been learned about how fires act, in spite of the relatively short period of organized effort. Knowledge stemming from any research projects, plus the experience gained from the control of thousands of fires, provide a good foundation for a general understanding of the complex subject.

The main purpose of this publication is to summarize the most important aspects of fire behavior as we now know them. The author recognizes that there are still many unknowns in the behavior of forest and range fires. These unknowns will be the targets of future research. In the meantime it is important that the best available information on fire behavior be placed in the hands of the men who must carry on the vital task of fire control …

Knowledge of fire behavior is an essential requirement for firefighters. Successful fire control operations depend, first of all, upon the ability of the protection forces to judge where and when fires will start and how they will behave once ignition takes place. Every member of the firefighting team from ranger to smokechaser must be able to make reliable estimates of the behavior of fires burning under a wide variety of conditions. These estimates must be good enough to provide the basis for decisions which will lead to fast, efficient, and safe firefighting.

Fire Behavior and Suppression Methods

The character and difficulty of the suppression job on every fire depends largely upon the behavior of the fire. The speed, strength, and type of attack are governed by the location of the fire and its reaction to the surrounding environment. Each change in environment may change fire behavior and in turn call for some adjustment in firefighting strategy and techniques. The ability of the man handling the suppression job to evaluate the behavior pattern largely determines the efficiency and economy of the entire firefighting operation.

A primary purpose of evaluating the behavior of every fire is to reduce or prevent unexpected “blowups and runs.” A careful check on everything that will affect the behavior of a fire reduces the chances for the “unexpected.” When a skilled size-up has been made in advance, the unexpected may become expected and a potential blow or run may often be anticipated soon enough to be prevented. Effective fire control requires that suppression plans and action be carried out in accordance with continuing estimates and forecasts of what the fire is going to do. Analysis of fire behavior is a basic requirement in firefighting applicable equally to the one-man smokechaser or the big fire where hundreds of men are in action.

Fire Behavior and Safety

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.

The most dangerous individual in a suppression organization is usually the man who is afraid of fire. Fear is largely a result of ignorance. 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

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*From Barrows (1951) handbook *Fire Behavior in Northern Rocky Mountain Forests.*

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.

Fire Behavior and the Forest Manager

In the northern Rocky Mountains fires influence many phases of the forest management job. The behavior of fires is an important factor in the growth, harvesting, and regeneration of forest crops. How often fires occur and how hot they burn affect both the quality and quantity of products harvested from the forest. The forest manager may influence fire behavior by the nature of his operations, especially in timber cutting. When a forest is opened up by thinning or harvesting operations, lower humidities, high temperatures, and higher wind velocities are created within the stands. Fire behavior is thereby affected. Sometimes the debris remaining after logging constitutes a fuel condition which greatly increases the chance for fires to ignite and burn intensely. For these reasons it is important for forest managers to know fire behavior and to be able to evaluate the influence of forest management operations on it.

Judging Fire Behavior

Many complex factors influence the ignition, rate of spread, and general behavior of fires. Some of these factors can be measured more or less precisely with instruments. Others do not lend themselves to exact measurements and therefore must be evaluated in general terms. The combined effects of all factors, whether measured precisely or not, determine the behavior of a fire. No single factor, such as wind, steepness of slope, or kind of fuel, will provide the answer to questions of when and where fires will start and how fast they will spread. Likewise, no single instrument or meter will answer these fundamental questions. Therefore it is necessary for the fire control man to develop a system aided by instruments and other guides where available, which will help him evaluate the combined effects of all significant factors influencing fire behavior.

Keen observation is a fundamental requirement for judging fire behavior. Many visible signs are present in the forest to assist the fire control man in arriving at reliable decisions. These include such things as the color of the grass and other annual vegetation, the position of a fire on a slope, the time of day, and the amount of sunshine filtering through the forest canopy. One of the purposes of this handbook is to analyze the importance and the meaning of the most significant of the many factors that may be observed and to present a method of evaluating their combined effects.

Fire Safety Measures

A thorough understanding of fire behavior is essential to the promotion of safety in firefighting operations. Accidents often occur when so-called "unexpected fire behavior" develops. To avoid these "unexpected events," the first and most important safety measure on every fire, regardless of size, is to make the estimate of the fire behavior situation.… Fires behave according to certain laws. Runaway fires do not just happen. When keen observations and evaluations are made of weather, topography, and fuels, there are very slim chances for firefighters to be surprised suddenly by an unexpected blowup.

Every fire behavior situation calls for special safety measures. In most cases the best safety measure is aggressive and intelligent firefighting aimed at abating the danger spot.

Keen observation and interpretation of weather, topography, and fuels lead to a good understanding of fire behavior and to safe, efficient firefighting.

fighters). Underpredictions can also render chosen operational strategy and tactics useless (Cheney 1981).

In addition to evaluating the outcome of a forecast, it is wise to look at the fire behavior prediction process itself. Russo and Schoemaker (1989) examine common pitfalls for decisionmakers that are equally valid for FBANs and others making fire behavior predictions or forecasts. Decision trap 10 (see the sidebar) is a failure to audit the decisionmaking process—a failure to understand that one's decisionmaking leaves one constantly open to the other nine decision traps.

Other Related Articles and Information

It's worth noting that *Fire Management Today* and its predecessors have also published a variety of other fire behavior and fire behavior-related articles in the past 67 years (Bunton 2000a, 2000b). Many are shown in the list of additional references beginning on page 10.

Because copies of many of these articles are difficult to obtain, even through library sources, they are being scanned and will be made available through the World Wide Web. Many are now available for downloading from the *Fire Management Today* Website (<http://www.fs.fed.us/fire/fmt/index.html>). The same Website has an author index posted for volumes 1–59 of *Fire Management Today* and its predecessors.

Acknowledgments

The authors offer their sincerest heartfelt appreciation to Hutch Brown, Madelyn Dillon, and Carol LoSapio, editors of *Fire Management Today,* for their significant contributions to this special issue, and to April Baily, the journal's general manager, for supporting the concept of these special issues on wildland fire behavior. Their dedication and outstanding editorial abilities have brought "life" to many of the articles contained in this issue that have long been forgotten.

Judging the quality of a fire behavior prediction or forecast solely on the outcome can be hazardous.

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Table 1—*The scope of quantitative wildland fire behavior prediction (adapted from Rothermel 1974, 1980).*

Fire situation	***Intended use***	***Resolution***		***Relative usefulness/ value***	***Ease of prediction accuracy***	***Impact of inaccurate prediction***
		Timeframe	***Area***			
Possible	Training	Long-term	Not applicable	Moderate	Extremely to very easy	Minor or minimal
	Long-range planning (e.g., preparedness system development)	Yearly/ seasonal	State/ province/ territory	Good	Easy to moderately Easy	Significant
Potential	Short-term planning (e.g., daily fire assessment)	Daily/ weekly	Forest/ district	Very good	Moderately difficult to difficult	Serious
Actual	Near real-time (e.g., automated dispatch, project fires, escaped fire situation analysis)	Minutes to hours	Stand- or site-specific	Excellent	Very to extremely difficult	Critical

The Ten Most Dangerous Decision Traps*

1. *Plunging in:* Beginning to gather information and reach conclusions without first taking a few minutes to think about the crux of the issue you're facing or to think through how you believe decisions like this one should be made.
2. *Frame blindness:* Setting out to solve the wrong problem because, with little thought, you have created a mental framework for your decision that causes you to overlook the best options or lose sight of important objectives.
3. *Lack of frame control:* Failing to consciously define the problem in more ways than one or being unduly influenced by the frames of others.
4. *Overconfidence in your judgment:* Failing to collect key factual information because you are too sure of your assumptions and opinions.
5. *Shortsighted shortcuts:* Relying inappropriately on "rules of thumb," such as implicitly trusting the most readily available information or anchoring too much on convenient facts.
6. *Shooting from the hip:* Believing you can keep straight in your head all the information you've discovered, and therefore "winging it" rather than following a systematic procedure when making the final choice.
7. *Group failure:* Assuming that with many smart people involved, good choices will follow automatically, and therefore failing to manage the group decisionmaking process.
8. *Fooling yourself about feedback:* Failing to interpret the evidence from past outcomes for what it really says, either because you are protecting your ego or because you are tricked by hindsight.
9. *Not keeping track:* Assuming that experience will make its lessons available automatically, and therefore failing to keep systematic records to track the results of your decisions and failing to analyze these results in ways that reveal their key lessons.
10. *Failure to audit your decision process:* Failing to create an organized approach to understanding your own decisionmaking, so that you remain constantly exposed to all the above mistakes.

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* Based on Russo and Schoemaker (1989).

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FOREST FIRES AND SEA BREEZES*

G.L. Hayes

Spot fires which started upwind from going forest fires have been reported by I.S. Stivers, Forest Ranger for the New York Conservation Department, whose district covers eastern Long Island. They had been observed on a number of occasions, and from a number of different fires.

Suspecting at first that incendiaries were setting fires behind him, Stivers sent patrols upwind from going fires. The patrols found no incendiaries but they did find new fires starting. They, and he, also observed that the smoke column, after rising high in the air, turned and moved back in a direction opposite to the surface winds. The spots were starting from embers which fell from this smoke column.

On other occasions, Stivers wrote, surface winds changed abruptly in mid-afternoon from a northerly or westerly to a southerly or easterly direction, carrying going fires in an unexpected direction and upsetting suppression plans. A typical case was a fire on Sunday, April 1, 1945, at 2:30 p. m., that started with a northwest wind and began to spread to the southeast. Fifteen minutes later the wind shifted fast to the southwest and sent the fire over the Radio Corporation Communications plant at Riverhead.

When this article was originally published, G. L. Hayes was a forester for the USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Coastal surface winds can change direction abruptly in mid-afternoon, carrying going fires in an unexpected direction and upsetting suppression plans.

The conditions described and the location, on Long Island, indicate that the type of local winds known as sea breezes was responsible for both the upwind spot fires and for the rapid changes in direction of the surface wind. Much has been learned about sea breezes in recent years that should be of very material help in planning fire suppression in such coastal areas as Long Island. Obviously, fire suppression is most difficult when rapid and unexpected changes in wind conditions occur. If the wind shifts can be anticipated, defensive action can be planned in advance.

There is an excellent discussion of sea breezes in the June 1946 issue of the bulletin of the American Meteorological Society under the title “Theory and Observation of Land and Sea Breezes,” by Raymond Wexler. As many fire control men in coastal areas may not have access to the Bulletin, the following digest of Mr. Wexler’s article has been prepared. The land breeze is not mentioned as it occurs mainly at night and is felt primarily over the water.

Definition and Characteristics of Sea Breezes

A sea breeze is a local circulation in which the wind near the surface blows from the water onto the land and returns at a higher elevation from land to water. During the daylight hours the air is heated more over the land than over the water. This sets up a local pressure system that induces the warmer, lighter land air to rise and flow seaward and the colder, heavier air over the water to settle and flow landward.

The sea breezes occur on warm days near the shores of large bodies of water. They are strongest and best developed along the seacoasts but occur also along the shores of bays and large lakes. In the temperate zone the landward flowing wind current may be from 200 to 2,000 feet (60–600 m) thick and may reach inland for 20 to 25 miles (32–40 km). Above this is the return current. Under the same conditions it may extend offshore as far as 60 miles (97 km) over the ocean. In hotter climates or in combination with topographic winds the inland range is extended. The winds from lakes extend shorter distances.

Two distinct types of sea breezes are recognized. The first type develops when there is little or no gradient wind;** the second type develops when there is a light offland gradient wind. The first type develops as

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** The gradient wind is the air movement caused by the prevailing pressure differences in the atmosphere. It is the wind that is usually predicted in the Weather Bureau forecasts.

a small circulation near the shore early in the day, soon after the air over the land has become warmer than the air over the water. With continued heating of the land, the circulation extends progressively farther landward and seaward and grows stronger and deeper.

The second type, which is the more common in temperate latitudes, develops over the water and usually comes onto the land suddenly, later in the day. The offland gradient wind holds the colder and heavier sea air back and heats it up until the force of the wind can no longer hold it. Then the sea air rushes ashore where it is heated until it rises and joins the gradient wind which is blowing out to sea overhead. The typical sea breeze circulation is then established.

The most dangerous part of the sea breeze circulation, from the fire control standpoint, is the front or surface separating the landward blowing sea air from the seaward flowing land air. The reasons are:

1. The winds blow in opposing directions on either side of the front and rise at the front.
2. The front moves. The rate of its advance is less than the velocity of the sea breeze behind it and it decreases as it moves farther inland. When a front moves across a fire, the rear or a flank suddenly becomes the head of the fire.
3. The winds along the front are the strongest and gustiest part of the sea breeze circulation. Initial gusts of the sea breeze as strong as 34 miles per hour (55 km/h) have been recorded, whereas the average behind the front is only about 11 miles per hour (18 km/h).

> The most dangerous part of the sea breeze circulation is the front or surface separating the landward blowing sea air from the seaward flowing land air.

After about a half hour from the time the front has passed, the velocity is usually very constant, with little gustiness. As the higher winds are then flowing opposite to the surface winds, the danger of upwind spot fires is present.

Although the sea breeze blows from water to land, it does not always blow perpendicular to the coast line. It tends to blow perpendicular at first then shift to the right as the day grows older. Thus, along the east coast where the shore is directly north and south it would tend to start as an easterly wind, shifting to southerly. Along the west coast it would tend to start as a westerly wind, shifting to northerly.

External Factors Influencing Sea Breezes

Several conditions affect sea breeze formation and behavior.

1. *Character of day*. As sea breezes occur only when the air over the land becomes warmer than over the sea, clear, hot days are most favorable to their formation. They can and do occur on overcast days but they form later, are milder, and extend inland for shorter distances. In general, the clearer and hotter the day, the earlier the sea breeze will form, the stronger it will get, and the farther inland it will penetrate. With light gradient winds and clear skies, it usually starts about 2 to 3 hours after sunrise and ends within 2 hours before sunset.
2. *Gradient wind.* Calm conditions, or a light offland gradient wind are favorable for sea breeze formation. If the gradient wind is blowing parallel to the shore or off the water, the sea breeze will not develop.

   The velocity of the offland gradient wind affects the time of arrival of the sea breeze and the distance inland that it will move. Under calm conditions, the sea breeze may develop near the shore soon after sunup and move progressively farther inland until the maximum temperature for the day is reached, after which is subsides. The stronger the offland gradient wind, the later in the day the sea breeze comes ashore, and it may never penetrate far inland. In fact, if the wind is strong enough, the sea air cannot leave the water. At Danzig a gradient wind of 22 miles per hour (35 km/h) was observed just to balance the force of the sea breeze. The front moved intermittently back and forth across the shore line.

   To have a front stall over a fire would create a very bad situation. The winds could be strong, and would certainly be gusty and fluctuate wildly in direction, as the front moved back and forth.
3. *Topography*. Where there are mountains along a shore line, the sea breeze may combine with an upvalley or upslope wind. Such a combination wind is stronger than a straight sea

breeze and may extend much farther inland. If the mountains lie several miles back from the coast, separate circulations may be set up in the morning which will merge after noon. Such a combination in California is reported to establish a continuous flow of wind for as much as 40 miles (64 km) inland. A similar but less extensive flow takes place between Great Salt Lake and the Wasatch Mountains in Utah.

Along the shores of a bay there may be two components of the sea breeze, one from the bay and the second from the sea beyond. The bay circulation will usually be the first to affect the land but may be replaced later by the ocean breeze, accompanied by a change in wind direction.

4. *Vegetation.* A heavy vegetative cover retards heating of the land surface. Hence, the sea breeze starts earlier and becomes stronger along desert or semidesert coasts than along heavily forested ones. Likewise, with other things equal, conditions along our coast are more favorable to sea breezes when the vegetation is dead and the leaves are off the deciduous trees than after the fields and woods "green up."

5. *Atmospheric stability.* An unstable lower atmosphere is more favorable for sea breezes than a stable one. In an unsaturated atmosphere, stability depends on the rate of temperature drop with increasing elevation. If the temperature decreases more than 5-1/2 ºF in 1,000 feet of elevation (or 1 ºF in 182 feet), the air is unstable and ascending convection currents develop easily. If it decreases less than this, it is stable and convectional movement cannot take place. Air over the land that is very stable in the morning may, through surface heating, become unstable later in the day, hence the hottest part of the day is most favorable for sea breezes.

6. *Distance from the shore.* The sea breeze is felt first and has greatest velocity right at the shore. As distance from shore is increased the sea breeze arrives later in the day, has less velocity, and the front moves more slowly.

With so many factors affecting the time of arrival and characteristics of the sea breeze, it is impossible to set up definite rules which will tell when it may arrive or how it will behave for any particular place or day. Where the sea breeze is observed to have important effects on fires, fire control men would profit by observing its characteristics as related to the factors already discussed. Or the local weather forecaster of the U.S. Weather Bureau might be induced to predict the time of arrival, its range inland, and probable velocity at and behind the front. ■

Where the sea breeze is observed to have important effects on fires, fire control men would profit by observing its characteristics.

Russo and Schoemaker (1989) Decision Trap 1—Plunging In:
Beginning to gather information and reach conclusions without first taking a few minutes to think about the crux of the issue you're facing or to think through how you believe decisions like this one should be made.*

* See page 9.

FUNDAMENTALS OF FIRE BEHAVIOR*

H.T. Gisborne

Our job of fire control can be done, in fact has been done, in several ways: By brute strength and little attention to the conditions we are attempting to control; by observation of what is happening but with little or no understanding of why the fire is behaving as it does; or by practical application of knowledge of the basic laws of chemistry and physics that are actually determining the rate at which a fire is spreading. Let us look into the most significant factors that affect fire behavior.

Fire is a Chemical Process

Combustion is a chemical process. It is classified that way because combustion, with or without flame, is a molecular reaction in which molecules of oxygen in the air combine with molecules of cellulose and lignin (which make wood) and thereby change most of the solid into gases. These gases are molecules of different substances. They are no longer cellulose and lignin. Such changes of substance are chemical, not physical, processes. When these changes occur at such a rapid rate that heat and flame are produced, the process is called combustion or fire.

When you look into the fundamentals of combustion and find that there are only three basic factors or three essentials to this chemical process, it is obvious that we are overlooking a bet if we fail to consider each of these three things in our calculating.

> There are only three things you can do to stop a fire—rob it of its fuel, keep it from being heated to the ignition point, or shut off the oxygen supply.

When this article was originally published, H.T. Gisborne was in charge of the Division of Forest Protection for the USDA Forest Service, Northern Rocky Mountain Forest and Range Experiment Station.

Three Essentials of Combustion. Completely controlling the chemical reaction called fire are only three essentials. They are:

1. Fuel or something that will combine with oxygen rapidly enough to generate heat;
2. Heat enough to raise that fuel to the ignition point; and
3. Plenty of oxygen in contact with the fuel or with the gases evolved from the wood.

Remove the fuel as we do when we dig a fire trench; keep it from being heated to the ignition point, as we do when we widen the trench or when we use water; or shut off the supply of oxygen as we do when we throw dirt, use water, or bury a burning log, and you can stop the spread of any fire. *Every one of our methods of fighting fire is based on one or more of those three simple essentials.* THERE ARE NO OTHER WAYS.

Fuel. Chemically, all of the fuels that carry our fires are practically alike. From grass and brush to tree needles, tree trunks, and rotten wood on the ground, they are all of the type that the chemist designates as $(C_6H_{10}O_5)_y$. This means that there are 6 atoms of carbon, 10 atoms of hydrogen, and 5 of oxygen in each molecule of cellulose. Starch, which is found in the roots, seeds, and leaves of all plants, is very similar, differing only in the subscript. The chemists designate the various starches as $(C_6H_{10}O_5)_x$.

This point is important to remember because it helps to reduce some errors of judgment based on the belief that the chemical nature of our fuels differs very materially. When $C_6H_{10}O_5$ burns, every molecule of that substance combines with six molecules of oxygen. The resultant products are gases, 6 molecules of carbon dioxide, and 5 molecules of water vapor. Fire makes water out of the hydrogen and oxygen atoms that are in every molecule of wood. The chemist writes it this way: $C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + 5H_2O$. Unfortunately, that water is not of any help to us because it exists as a gas, a superheated gas, which rises straight up and away from our fuels. The water that really counts is the moisture content of the grass, trees, or brush before they burn.

Because of this similarity of chemical composition of our fuels, it is obvious that we should not calculate probabilities on the belief that different kinds of wood or brush or grass burn differently. The leaves of grass, trees, and brush and the bark

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* The article is reprinted from *Fire Control Notes* 9(1) [Winter 1948]: 13–24. It was used at the 40-man Fire Boss School on May 5, 1947.

and wood of trees are all largely cellulose. The big variable which produces really significant differences in fire behavior is not the chemicals, it is the moisture content.

There are, however, two other ingredients in wood in addition to cellulose that are of some, perhaps academic, significance. One of these is lignin, a substance for which the chemists do not know the formula. The significance of lignin lies in the fact that it has a slightly higher heat content than cellulose and that it leaches and decays more slowly. Hence old wood is likely to have lost more cellulose than lignin and therefore will have a slightly higher heat content per pound of material remaining than fresh cut or freshly killed wood. Differences in the pitch content are also known to affect the heat of a fire.

There are also some other minor differences in the chemical nature of plant and tree leaves, but a series of tests of the fat and oil content of the leaves of six different genera of weeds and brush which were made for three consecutive summers failed to reveal anything significant. Instead, this chemical study made at our Priest River laboratory confirmed the finding that moisture content is THE big variable.

Ignition. When there is plenty of fuel, the next essential of combustion is that it must be heated to the ignition point. For dry cellulose, a temperature of only 400 ºF to 600 ºF (204–316 ºC) is required. The average usually used is 540 ºF (282 ºC). The point that is of practical importance is that if your fuels are even moderately dry they do not have to be heated very hot to reach this ignition temperature. In other words the kindling temperature of grass, wood, cotton batten, or cellulose in any natural form is easily produced. It is not an abnormally high temperature. You will build more held line and have to charge up less line lost if you remember that simple fact and then do something about it.

The key to ignition is the ease with which a fuel can be heated to 540 °F (282 ºC). That ease naturally depends upon one obvious difference in fuels, i.e., their size. The fine fuel naturally heats clear through and reaches 540 °F (282 ºC) far quicker than a heavy fuel like a log. Size of fuel is therefore the significant feature to watch, other things such as moisture content being equal. Actually, size and moisture content influence the process of combustion in much the same way. Make a stick wetter and you reduce its ease of ignition. Similarly, the bigger the stick, the harder it is to ignite it. The wet stick and the big stick both require more time or more heat to raise their surface temperature to the ignition point. And that is another good basic fact to keep in mind both in sizing up probable fire behavior and in deciding on tactics to use along the line. Let your fire burn through the heavier fuels where it will burn more slowly. Fight it at those places where it would go into finer fuels and spread faster. Also, fire line construction is easier in the fine fuels. You gain in two ways by using this basic knowledge.

Moderate to large areas of fuel releasing their energy suddenly are creating conditions that breed not only higher wind velocities, but twisters or even big whirlwinds.

Size of fuel is also worth noting from another angle. Take 10 pounds (4.5 kg) of dry grass or dead pine needles, 10 pounds (4.5 kg) of dry branchwood, and 10 pounds (4.5 kg) of log in one chunk and ignite each of them. What happens? The needles will liberate their B.t.u.’s (British thermal units) in a few seconds, the branches will release theirs in a few minutes, while the 10-pound (4.5-kg) log may take half an hour to release its heat. Ease of ignition is, therefore, not the only difference in fire behavior to expect in accordance with different sizes of fuel. The rate of release of the energy is also tremendously different.

This feature, combustion rate, is what a football player would call the triple threat of fire. And this rate of release of energy is the one feature we fail most often to recognize. The three threats involved are:

1. The more sudden the release of all this heat, the farther it will radiate a temperature of more than 540 °F (282 ºC). And that means something to your tactics. It means that if the fuels are even moderately dry, a wider fire line is needed wherever you find an appreciable volume of fine fuels. This applies to both stopping a fire and in backfiring.
2. The faster the release of those B.t.u.’s, the greater the volume of gas suddenly created, hence the faster it will rise overhead. That also means something to tactics employed, because the swifter the rise of hot air the

The most important variable in fire behavior is fuel moisture, and when our fuel moisture indicator sticks are below 5 percent you can expect your fires to blow up and explode.

greater the chance of sucking up blazing embers and carrying them up and over the line, if the smoke is leaning across the line. That means spot fires.

3. The faster this release of energy and the faster the uprush created by it, the greater the local wind velocity created by the fire. Moderate to large areas of fuel releasing their energy suddenly are creating conditions that breed not only higher wind velocities, but twisters or even big whirlwinds. I once saw one of the really big ones whirl like a tremendous barrel and move across 2 square miles (5.2 km^2) while I was running 200 yards (180 m) along the top of Desert Mountain, on the Flathead Forest.

Oxygen. This last essential of combustion is one that we can't do very much about. Combustion engineers who design and operate boilers do a lot by controlling this one of the three essentials. But under our conditions there is a1most always plenty of oxygen to facilitate combustion of our fuels. Under free burning conditions such as occur on a forest fire, about 10 pounds (4.5 kg) or 133 cubic feet (3.75 m^3) of air is needed for the complete combustion of only 1 pound (0.45 kg) of dry fuel.

The one time when we do something to reduce the oxygen supply is in throwing dirt. While that dirt does lower the temperature of the fuel it lands on, the principal function of dirt is to shut off or at least reduce the supply of oxygen. Moist dirt is superior to dry dirt primarily because it lowers the temperature more. But when either moist or dry soil covers the surface of the fuel the major benefit is by cutting down the oxygen supply. Water also does the same thing if enough is applied to form a film over the surface of the fuel. But here too the major benefit is in lowering the fuel temperature below the ignition pint.

Combustion—A Molecular Chain Reaction. The public has heard and read a lot recently about atomic fission, so controlled that it becomes a chain reaction and thereby makes possible atomic bombs. More understanding of the fire job and better financial support by the public may follow when we show that the job of fire control is definitely one of stopping a chain reaction which differs from the bombs primarily in that ours is a molecular instead of an atomic chain reaction.

A chain reaction may be compared to a chain letter; you receive one but you send out two or maybe three or four. Each of the recipients of one of these letters similarly sends out two or three or four. The thing spreads like wildfire. The first problem in producing an atomic bomb was along this line. That problem was to obtain certain chemicals which, when assembled in a sufficient quantity and arrangement, known as the "critical mass," would perpetuate the process of splitting atoms of uranium into atoms of two other elements, barium and krypton. It was known as far back as 1939 that in this splitting tremendous energy was released and that the process then split other uranium atoms which in turn released more energy and split more atoms, the process continuing and accelerating as long as there was a supply of a suitable fuel in a proper arrangement and condition.. The job of the atomic physicists was, therefore, to produce this chain reaction yet control it. Our job is simpler. It is merely to control the molecular chain reaction that is fire.

As you can see, fire is a similar process in that if you heat one molecule of a fuel to the ignition point, its process of changing from $C_6H_{10}O_5$ into CO_2 and H_2O may release enough energy to ignite several other adjacent molecules of $C_6H_{10}O_5$. If the fuel is in a critical condition (dry enough), as compared to a critical mass (large enough), that process then becomes a chain reaction and not only spreads like wildfire but it really is wildfire in our case. Whereas the nuclear physicists have to make their fuels, and arrange them carefully in an atomic pile, our fuels are arranged for us and then, periodically, are put into proper condition (dryness) such that the chain reaction starts whenever and wherever the spark is applied.

If this sounds farfetched or academic, let me call your attention to one more fact, which I know you will not dispute. It is this: That when our fuels are in their most critical condition, i.e., their driest, we have some molecular chain reactions which are so violent that we *cannot* stop them, just as there is no stopping an atomic bomb once its chain reaction is started. Furthermore, we have occasions when combustion in the form of a forest fire approaches a rate and even a magnitude rivaling an atomic bomb. Those of you who were on any of our big fires in 1929, 1931, and 1934 probably saw some of these explosions. Many of them covered several square miles in only a minute or two.

If you will keep this chain reaction idea in mind, and if you will size up your fire, either as a whole or on your sector, in the light of the three basic essentials of combustion, you may be able to calculate the probability of one of these explosions. If you can do that, you may be able to save your own life and the lives of your men, as well as improve your fire control tactics.

There is one basic criterion to watch, however, in trying to anticipate a molecular chain reaction at an explosive rate. This is moisture content of the fuel, for it is moisture content, not mass, nor volume, nor size, nor arrangement of fuel which *first* determines whether or not a forest fire can truly explode. And you should remember that this moisture content not only can be, but is being measured. You can get these measurements every day if you want them.

Moisture Content—The Critical Variable

We have not had any true forest fire explosions in Region 1 since 1936. I believe there were a couple of minor ones that year on the Little Rockies Fire on the Lewis and Clark Forest. But we had several really big ones in 1934, 1931, 1929, and one or two in 1926. You have all read about those in 1919 and 1910. The main reason why we have not had any explosions in recent years is this matter of moisture content. Our fuels simply have not dried out to the critical condition that developed in those earlier critical years. Hence, it is evident that the critical variable in fire behavior is moisture content of the fuels. Consequently, I want to call your attention to some of the possibilities available to you for improving your calculation of probabilities by watching fuel moisture above all other elements.

Basis of Fuel Moisture Measurements. You all know about the fuel moisture indicator sticks used at some 175 fire danger stations in Region 1. There are some things those sticks will tell you far better, far more accurately than you can estimate. To make best use of those stick measurements you need to know: Why we use half-inch (13-mm) sticks, how they are made, and how accurate they are.

A burning index rating is essential to calculation of the probabilities in any fuel type.

For four consecutive summers, 1922, 1923, 1924, and 1925, I collected at periodic intervals samples of the five major dead fuels that burn in a forest fire. I took these samples to the laboratory and determined their moisture contents. I found out which fluctuated the most, and which the least. On this basis, I selected the top layer of duff, half-inch (13-mm) sticks, and 2-inch-diameter (5-cm) branch wood as the best representations. We therefore used duff hygrometers, half-inch (13-mm) sticks, and 2-inch (5-cm) sticks at several fire danger stations for the next 5 years to measure fuel moisture. Then, at the suggestion of the rangers in a regional meeting and despite my protest, we discontinued used of the 2-inch (5-cm) ones. Finally, in 1942, with the Model 6 Danger Meter, we dropped duff moisture and began to rely solely on the half-inch (13-mm) sticks.

From a technical viewpoint these half-inch (13-mm) sticks alone fail to represent our fuels in two ways:

1. They do not show the true benefits of light rains as well as duff moisture measurements did; and
2. After heavy rains, they dry out faster than either duff or 2-inch-diameter (5-cm) sticks.

The error is therefore always toward showing more danger than would be revealed if all of the significant *forest* fuels were measured. The half-inch (13-mm) sticks are not too fast, of course, for cheatgrass, but this fuel type does not cover a large percentage of our area. Furthermore, after it has cured, cheatgrass responds so closely to changes of relative humidity that humidity measurements can very well be used as an index of moisture content of that one fuel type. Finally, cheatgrass changes moisture and flammability so rapidly that you might as well always be ready for the worst.

The half-inch (13-mm) sticks which we now use are made from new lumber each year. Any one of several species of wood could be used, because here again we are dealing primarily with cellulose. We use ponderosa pine because it is readily obtainable in clear stock at a reasonable price. We use only sapwood because it is the moisture content of sapwood of twigs, branches, logs, and snags in which we are most interested. We can ignore the moisture content of the heartwood of a log because if the outer sapwood is extremely dry the inner heartwood has got to be dry too. We also ignore the effect that bark has on natural wood, because if we used natural sticks with bark on them some of that bark would soon chip off and then we would no longer know the true oven-dry weight of our sticks.

To be sure that moisture measurements made at different stations do not differ because of differences between the sticks or because of errors by the danger station operator, we go to a lot of work and incur considerable expense. These sticks now cost from $1 to $1.75 per set to manufacture. In making them they are oven-dried and then cut off at the ends until they weigh exactly 100.0 grams *oven dry*. This is done so that all that is needed to determine their moisture content in percent is to weigh them and subtract 100.0 from the total weight.

As you can see, this difference in weight is not only the weight of the water in the wood, picked up from the air and from rain, but it is also the moisture content expressed as a percentage of the oven-dry weight. Consequently, when you call for a fuel moisture content measurement from any of our stations you can bank on its accuracy probably 95 times out of 100. The other 5 times the scales will be out of balance, which is an operator error, or the operator will have read the scales wrong. Eliminating that error is a job for training and supervision.

Application of Stick Moisture. By the present practice we measure stick moistures at only two to four occupied stations per ranger district. That is not enough under some conditions of spotted weather, wet here and dry there, but under widespread and long continued drought it is fully adequate. The sticks are exposed on a flat, in the open, but under a shading layer of screen cloth. The reason for this, preparing to meet "average-bad" conditions, is used in all fire control planning in Region 1. The sticks are therefore always exposed alike at all stations so that the results are truly comparable.

Within the mid-elevation thermal belt, you can expect the least benefit from increased fuel moisture at night.

The intention in such an exposure is to sample average-bad but not the very worst conditions. By sampling average-bad conditions we are using the sound engineering principle of preparing for the worst probable but not the worst possible. Engineers did not build the Golden Gate Bridge at San Francisco to withstand the worst possible earthquake. They built it to withstand the worst probable. Few ditches, storm sewers, or bridges are built to withstand the worst possible flood. To meet worst possible conditions usually costs more than the resource is worth. It is better economics therefore to accept the risk of the worst possible flood, earthquake, or fire weather conditions, and plan to meet only the average-bad or worst probable. We can get adequate fire control at a justifiable cost by using this principle. We do use it, not only in fire danger measurement, but also in all phases of fire control planning in Region 1.

The double layer of 12-mesh screen cloth under which we expose our sticks provides an amount of shade and a fuel-moisture equivalent to what you would get if you operated two danger stations, one in full sun and one under the half shade left after a moderately heavy logging operation. The stick moistures obtained by this method can therefore be accepted as representing average-bad conditions. Open south slopes will have drier half-inch sticks. Densely timbered north slopes will have materially higher fuel moistures. But when the sticks at our stations have high moisture contents, adjacent areas, both open and timbered, also can be expected to be moist to wet. When our sticks are each day showing lower and lower moistures you can depend on it that both the open areas and the timbered slopes will also be getting drier and drier.

Our present sticks and exposures therefore give you one definite and dependable index to watch. They give you something that you can use in calculating, instead of guessing.

The most significant single feature of stick moistures to watch for is just this: Are they below 5 percent and how long have they been there? Your danger of blow-ups and explosions can be really calculated by getting merely that information. If the sticks at both the nearest ranger station and some nearby lookout have been down below 5 percent for several days you can bank on it that every fuel type in that area is in a truly critical condition. Fortunately, this does not happen very often, but it has happened and it will happen again. When it does you will be making the mistake of your life if you fail to know it. You can always find out by consulting the local ranger station fire danger charts or Form 120 R-1. If you are already out on a fire a phone call will bring you the desired information.

If the sticks are reported as at less than 5 percent, you should then ask for two more things: a check of the computations to be sure no errors were made, and a remeasurement of the sticks right then. The dispatcher or his assistant can do both of these in 10 or 15 minutes. If these checks verify the original reports, you can then *calculate* that every fuel type in the area, on both north and south slopes, and at all altitudes, is in its most explosive condition. You can bank on it that fire will spread in all of these types at the fastest rate, that there will be little difference in rate of spread between fuel types, and that the danger of both spotting and of big whirls will be at a maximum. You can expect a chain reaction at its worst.

Those of you who have never seen fires like the Lost Johnny and Half Moon on the Flathead in 1929, the Freeman Lake on the Kaniksu and the McPherson on the Coeur d'Alene in 1931, and the Pete King on the Selway in 1934, simply cannot fully appreciate the significance and the danger under these conditions. It may be enough to point out that the Freeman Lake Fire, starting at 10:30 a.m. on August 3, 1931, exploded almost from the start to cover 20,000 acres (8,100 ha) in the next 12-1/2 hours. This is at the rate of 1,600 acres per hour (650 ha/h), from a standing start! Both duff and 2-inch-diameter (5-cm) sticks were down to 4 percent moisture content that afternoon. Wind was 13 miles per hour (21 km/h) at 10 a. m., and 18 miles per hour (29 km/h) at 7 to 8 p.m. Relative humidity was 10 percent or lower from 2 till after 7 p.m. THAT is explosive fire weather.

Differences in rate of spread between fuel types practically disappear under these explosive conditions. The basic laws of chemistry take charge when nature produces such conditions, and the molecular chain reaction is actually unstoppable until the wind goes down, the humidity goes up, and the fuels absorb a little moisture. If you have to fight such fires, and you should be mentally ready for it, you will probably do it like Kelley and Ryan fought the Freeman Lake explosion. You will not build much fire line that day, but you will calculate where that fire front will be at midnight and you will then have fire camps and men well distributed around it and ready to begin work at the first crack of dawn. Kelley and Ryan had more than 600 men strung around the Freeman Lake Fire front the next morning after that fire started, and those men never let that fire make another major run. That is a record to shoot for; it has seldom if ever been equaled in this region.

The real difficulties and the most frequent need of skill and understanding by fire bosses come, however, in judging gradations between this explosive condition and that easiest of all conditions, when fire will spread, but only so slowly that control is largely a problem of how to do it at the least cost. In between this explosive condition and the easiest condition, other factors than stick moisture become more and more important and all the factors become much more involved. It should be evident, nevertheless, that fuel moisture is THE major variable and that if you are to calculate accurately, your first and best bet is to get the stick moistures and other measurements from the nearest danger stations *before* you even start to order men. After you get to the fire, you can then see to it that you are informed each day, preferably twice a day, as to how fuel moisture and other factors are changing. There are then three other major variables to watch. These are fuel type, the thermal belt, and wind.

Fuel Types

Some men have a misconception about fuel types because they do not understand that our four rates of spread—Extreme, High, Medium, and Low—represent differences only on a class 65 to class 75 day. Obviously, rate of spread will not differ at all in different types when the woods are soaking wet. Also, rate of spread is very nearly the same in all types after several August days with the temperature at 100 °F (38 ºC), humidity at 10 or 15 percent, and the afternoon wind at 15 to 20 miles per hour (24–32 km/h). Hence, we have used the principle of preparing for the average-bad in our fuel type classification, and the rates given on our fuel type maps are those to be expected on an average-bad day. This is about class 70 on our burning index meter. You cannot use those fuel type maps correctly, or dependably, on any other basis.

Although fuel moisture is the critical variable for making fuels explosive, wind velocity is often the straw that breaks the camel's back.

Our fuel type classes are therefore based on differences in rate of spread, not at the explosive point where we can do nothing about it, but at combinations of moisture contents, wind velocity, and vegetative conditions just short of the explosive point. These begin early in August whenever fuel moisture drops to 5 or 6 percent, the humidity falls to less than 15 or 20 percent, and the wind rises above its normal afternoon average of 6 or 8 miles per hour (10–13 km/h). After several days of such weather, especially if the burning index rises to 75, as it will with fuels under 5 percent, humidity under 10 percent, and winds of more than 10 miles per hour (16 km/h), differences in rate of spread become less and less as all fuel types approach the explosive condition.

A burning index rating is therefore essential to calculation of the probabilities in any fuel type. If it shows class 65 to 75, you can count on the differences shown by the fuel type map, insofar as that map is well made. The weaknesses in these maps are well recognized and steps are being taken to correct them.

In applying the burning index to a correct fuel type map, some guides have been worked out, but this is unfortunately a field in which our fire research has been woefully weak. Our best contribution is in U.S.D.A. Circular 591, *Influences of Altitude and Aspect on Daily Variations in Factors of Fire Danger*, by Lloyd Hayes, published in 1941. The outstanding new fact resulting from this research was the discovery and general location of what Hayes called the thermal belt.

> "Calculating the probabilities" means careful consideration of every available source of information concerning each of the basic factors of fire behavior.

Thermal Belt

The major significance of this thermal belt is that inside a certain altitudinal zone burning conditions change less from daytime to nighttime than they do in either the valley bottoms or on the mountain tops. At Priest River this zone begins about 600 feet (180 m) above the valley bottom and continues upward for about 1,000 feet (300 m). Below and above this zone fuels pick up more moisture at night than they do within it. Within the zone the fuels lose a little every afternoon and pick up a few percent between 6 p.m. and 3 a.m., but the change is very slight. Up on the mountain top, however, the same fuels will pick up 4 percent more at night and lose 4 percent more in the daytime. Down in the valley bottom they will pick up and lose 8 to 12 percent more than within the thermal belt. This is true on both north and south aspects. The only places where it may not hold true are in steep-sided, deep, east and west canyons like that of the Salmon River. In that canyon and perhaps in a few other spots like it, the depth of the canyon and its orientation in relation to prevailing winds combine to interfere with normal air drainage. There the thermal belt effect becomes less pronounced or even disappears. Sometimes going fires will also disrupt this belt, if the fires are large enough, but in most places and under most conditions you should calculate your probabilities on the basis of the known difference of burning conditions within this thermal belt.

The next time you have a fire starting in late afternoon or early evening about 1,000 feet (300 m) up from the main valley bottom, I suggest that you note for yourselves whether or not that particular fire does not run faster and for more hours during the night than a similar fire in the valley bottom. Also note whether or not that fire picks up and starts to run earlier in the morning. I think you will find both of these conditions in almost all thermal belt fires. They are essential elements in the equation required to calculate the probabilities.

These facts also should be highly significant to all fire dispatchers. Other things being equal, more men should be sent, and they should be speeded on their way faster to every fire in the thermal belt. Furthermore, on a going fire, if night work can be done on any sector, it should be planned first on those portions of the front from 500 feet to 2,000 feet (152 to 610 m) above the valley bottom, because this is the zone of the thermal belt. Within this zone you can expect the least benefit from increased fuel moisture at night.

Wind

Although fuel moisture is the critical variable that puts all fuel types in an explosive condition, or reduces them to an easy job of fire control, wind velocity is often the straw that breaks the camel's back. In fact, at fuel moistures of 6 or 7 percent up to 20 or 25 percent, wind is often the variable which

Experienced judgment is the final determinant of what you actually do, both in planning to control a fire and out on the fire line where you try to put your plan into effect.

finally determines what a fire will do. Some basic research by Fons at the California station has shown that with fuel moisture at 8 percent, variations of wind velocity are more significant in changing the rate of spread than are variations in fuel temperature, fuel size, compactness, or density.

Whether or not some fire seasons are, as a whole, windier than others I do not know. But we do know that wind is a result of certain meteorological conditions which change periodically at from 3- to 5- or 6-day intervals. If you will watch the wind record portion of any fire danger station chart, particularly for a lookout station, you will see a gradual increase of wind for several days, then a decrease, then another increase. Obviously, by watching this up and down trend you can definitely improve your calculation of the probabilities, even though you cannot forecast precisely.

There are a few general rules of wind behavior which can be used locally in Region 1. First is a discovery, made by Hayes and described in Circular 591, that the places of greatest wind danger at night are, strange as it may seem, the north aspects at high altitudes. To put it another way: While you can usually count on the wind dying down during the night in the valley bottom, you should not count on this if your fire is up on the high divides between major drainages. Instead, at the higher elevations you should expect the highest winds at night, not in the daytime, and more wind on the north aspects than on the south.

Another general law of wind behavior during the ordinary fair weather of June, July, and August, that is quite well known, is that during the day the wind usually blows up the canyon or creek, while during the night it blows down canyon. This reversal of direction in the evening usually takes place just a few minutes after sundown. When both the daytime and the night winds are very light—less than 4 miles per hour (6 km/h)—this reversal may not be of much significance. However, in topography and on areas which are materially heated by the sun's rays, the afternoon wind created by rising hot air may amount to 8 or 10 miles per hour (13–16 km/h). When this is the case, reversals at sundown may produce a significant down-canyon wind. This condition is most pronounced on south aspects and in watersheds draining toward the south into a big canyon running east and west, like that of the Salmon River. But even under these conditions, a large fire may create such an updraft as to upset the normal reversal of wind. Hence, while this generality is worth considering in your calculations there are other factors which also must be recognized before you make your final estimate of rate of spread.

From what has been said it should be clearly evident that "calculating the probabilities" means doing much, very much *more* than just fight a fire with brute strength and numbers of men. It means careful consideration of every available source of information concerning each of the basic factors of fire behavior. But even when that has been done you will still have to use judgment, and perhaps even do some pure guessing. Nevertheless, your batting average is absolutely certain to increase IF you first do the best you can to calculate on the basis of facts and known principles.

Experienced Judgment

Perhaps I should not close on this point; because if by doing that I cause you to discount *any* of the things previously called to your attention then I weaken my point. However, in fire control there are still a lot of basic factors not yet understood or not yet measured. And even when they are measured the basic facts must still be put together, weighted one against another, and a balanced decision then reached. Worse yet, sometimes that decision must then be modified or even seriously compromised on the basis of what you *can* do about it.

Experienced judgment is therefore the final determinant of what you actually do, both in planning to control a fire and out on the fire line where you try to put your plan into effect. But if you will stop to examine just what is meant by experienced judgment, you will come back to the items I have listed above. For what is experienced judgment except opinion based on knowledge acquired by experience? If you have fought forest fires in every different fuel type, under all possible different kinds of weather, and if you have remembered exactly what happened in each of these combinations of conditions, your experienced judgment is probably very good. But if you have *not* fought all sizes of fires in all kinds of fuel types under all kinds of weather then your experience does not include knowledge of all the conditions. In that case, some of the facts and principles described above should be helpful to you.

Summary

There are only three things you can do to stop a fire—rob it of its fuel, keep it from being heated to the ignition point, or shut off the oxygen supply.

When it comes to fire behavior, there are likewise only a few basic variables. The big one is fuel moisture, and when our fuel moisture indicator sticks are below 5 percent you can expect your fires to blow up and explode. As that moisture content rises above 5 percent your fires become less and less explosive and you know that they are then more and more influenced by another major variable, wind.

Both fuel moisture and wind are measured every day of the fire season at numerous stations. Those measurements will show you clearly and accurately what the present moistures and velocities are, and how they are changing, whether getting better or worse. These are facts. They are available to you. They were not available to the rangers and supervisors who fought the fires of 1910 and 1919, nor to many men in 1928 and 1929. You therefore have this accurate knowledge that those men did not have.

Furthermore, you have some knowledge of how both fuel moisture and wind velocity differ according to altitude and aspect. The outstanding general differences are known. Very few if any of the most experienced old-time fire fighters knew these things.

And finally you have not only excellent topographic maps to help you visualize your fire area, but you have the major differences in fuel types shown clearly so that you can calculate what you should expect your fire to do on this particular slope in the next few hours.

Fire control still requires headwork based on knowledge.

It is true that you still have to estimate how much different the fuel moisture will be at your fire from what it is at the fire danger station. You also may still have to guess what the exact wind direction and velocity will be on your fire even after you find out what they are at the nearest ranger and lookout station. And it is true that there may be an acre of High-High fuel right near your fire even though the map shows Medium-Medium or even Low-Low. But if you have been on your district very many years and have gotten around, or if you have someone else there who really knows his fuels, you may be able to pick up that important fact.

Conclusion

Even though there are some holes in our information, we have much more than our predecessors. Those men had to think of EVERYTHING. They even had to go to town to buy their axes and shovels and grub. Then they had to remember out of their own personal experiences what the topography and timber and brush types were like, up there at the fire. Finally, they could only feel the wind and kick the duff to see how dry the fuels were, right where they stood. Finally they could look at the sky and guess at what the weather might be tomorrow. Maybe some of them prayed.

But times have changed. Where those old timers had to guess at most everything, today, we have measurements and maps and many other facilities. While we might like to have more, I doubt that anyone ever will be able to sit down to a machine, punch a key for every factor of the situation, and have the machine tell him what to do. Fire control still requires headwork based on knowledge. If we will make a purposeful attempt to use all of the knowledge and all of the facilities that are availa1ble to us today we can do one thing the old timers could not do: We can come mighty close to getting adequate fire control, and at an operating cost far below what it used to be. ■

Vertical Wind Currents and Fire Behavior*

John S. Crosby

Forest fires are known to behave in a variety of ways, sometimes in quite unexpected ways. Prompt suppression requires that the fire boss, in estimating the probabilities of control within the allowable period, consider factors affecting the behavior of the fire as well as those fixed by the site.

The important variables not determined by the specific location are the weather factors, primarily moisture and wind. Estimates of fuel moisture and winds are made on the basis of weather forecasts, or through a knowledge of normal daily variation and past experience based on observation of weather reactions in the locality. Often the weather forecast must be interpreted in terms of local topography, or proximity to large water bodies, so personal observation may be invaluable.

Although fuel moisture is an important factor, the purpose of this paper is to point out certain wind features, particularly those in which vertical currents are concerned, and to present a few general rules for recognizing the probability of their existence. On the ground, the best information available about wind is its surface velocity and direction, both of which may be constantly changing, whereas little if anything is known of the action of the wind above the immediate surface and which may have considerable effect on the fire.

> Turbulent, gusty winds affect fire behavior by fanning the fire in spurts from varying directions, and by carrying heat and embers to fresh fuels.

General Characteristics of Wind

Wind is air in motion. The direction of motion taken is almost unlimited. Near the ground the wind customarily blows in gusts and lulls, seldom as a steady even flow. Because it cannot be seen, it can only be noted by its effect on various objects, and hence it is difficult to obtain a complete picture of the variations that characterize air flow. Watching the drift of smoke is one way to observe its motion; this is like observing somewhat similar currents in a river. Both water and air are fluid, though water is more limited in its freedom of motion. The water swirls around and over rocks, makes eddies around land projections, and tumbles over falls. It exhibits motion in many directions besides down stream. Likewise, air moves in a turbulent fashion near the ground while still following a general course.

The general flow of air is determined by the air pressure gradient and is modified by the effect of the earth's rotation and the friction caused by the passage of the air over the earth's surface. The direction becomes clockwise around high pressure centers with a slight drift outward, and counterclockwise around low pressure centers with a slight drift towards lowest pressure. At any fixed location the wind direction changes as the pressure systems migrate and take up new positions in respect to that point.

Many reactions are superimposed on the flow of air, particularly near the ground, to modify the pressure flow. Aloft the wind is stronger, and more steady, being changed only by strong reactions.

Up and down air currents may exist in the lower atmosphere in a great variety of intensities and steepness of rise or fall. Small eddies in a light wind may be only a few feet in depth, whereas strong convection currents may extend several miles into the atmosphere, or the gentle lift caused by a warm front may amount to 10 feet in a mile (2 m/km), but extend over 1,000 miles (1,600 km).

At ground level the wind tends to parallel the surface; that is to say, because the wind cannot penetrate or go through the solid earth, its larger up-and-down currents must change to a motion along the surface on reaching the surface, though the direction may be variable, arid small eddies still persist.

When this article was originally published, John Crosby was a forester for the USDA Forest Service, Lake States Forest Experiment Station, St. Paul, MN.

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Sustained vertical motion of the air is more prominent at some distance above the surface, where, of course, it is more difficult to observe. When a vertical motion, such as an eddy or convection current, is superimposed on the existing wind, the result is alternately to speed up and slow down the wind, making it gusty and stronger.

The stronger the horizontal wind, the more turbulent it becomes in its passage over a rough surface, thus creating stronger eddies and more gustiness with frequent changes in direction. Turbulent, gusty winds affect fire behavior by fanning the fire in spurts from varying directions, and by carrying heat and embers to fresh fuels.

Convection Currents

The motion of the air is also strongly affected by the heat it gains from the earth on sunny days. Air in contact with the ground then, because of the additional heat, becomes lighter than air above and tends to rise. The rising warm air sets up convection currents. A forest fire also sets up such currents locally because of the intense heating of the air by the fire.

The earth's surface is not uniformly heated. Water surfaces are cooler than land, and forested land cooler than exposed soil or rocks, so the surface air is not of uniform temperature. Warmed air tends to rise in streams usually localized over the warmer areas, or hills may help to start the warm air upward.

Down-drafts occur as complements to up-drafts. Both currents have their effect on a forest fire. While an up-draft in a favorable atmosphere has the effect of pulling on the rising smoke column, thus increasing the air feeding into the fire, the down-draft increases the surface wind velocity, making it more gusty and turbulent.

Once started, convection currents may be accentuated or depressed by the atmosphere, depending on its condition of stability. If stable conditions exist (where the temperature decrease with elevation in the atmosphere is slight), the convection currents will be damped.

The stability of the air layers both near the surface and aloft greatly influences fire behavior.

However, in relatively unstable air (where decrease of temperature with elevation is great), convection currents are increased in speed and depth. Convection currents sometimes rise to 8 or 10 miles (13–17 km) in the atmosphere and develop great vertical velocities.

With night-time cooling, the air is stabilized at low levels, and the convection currents subside. This change is a part of the daily variation in stability. In flat country the wind then dies down. In mountainous country the wind stops flowing up-slope and begins to flow downslope. Along larger water bodies the daytime landward breeze changes at night to a seaward breeze. These changes are normal only when the pressure gradient is weak.

Influence on Fire Behavior

The stability of the air layers both near the surface and aloft greatly influences fire behavior. Very large fires generate intense heat and may enable the heated air to penetrate moderately stable layers and join or set up vertical currents aloft, thus giving a new impetus to the fire, causing it to flare up unexpectedly. A study of large fires in relation to air stability conditions aloft might throw new light on unexpected fire behavior, and provide a new tool for better forecasting fire behavior.

When there is marked air stability even during the daytime, the height to which convection currents may rise is of little consequence, and the diurnal variation in wind is not important. Thus, a strong daytime wind may not die down much at night because it is driven by the pressure gradient alone, and it will decrease only as the pressure gradient decreases.

These considerations are useful only insofar as one is able to plan for them and hence a few very general rules may be helpful.

While the actual stability of the air and the pressure gradient are basic, they are not subject to convenient observation at a fire. Indirectly, however, the condition of stability shows itself in several ways.

Cloud Formations. Cumulus type clouds are always an indication of rising air currents, and often indirectly of instability. In mountainous country, the rising currents may be due to lift over a ridge, while in level country it is almost always a result of convection if not associated with a front. For these clouds to form there must be sufficient water vapor present in the rising air so that it is cooled to its saturation point before the lift ceases. If the cloud bases are low it is an indication of abundant moisture; if high, water vapor is scarce. This condition is indicated at the ground surface by high or low relative humidi-

Thunderstorms with high bases may be dry storms—the rain evaporates into the air before it reaches the ground, and hence lightning strikes are more dangerous.

ty respectively. The height of the cloud tops indicates the height to which the convection currents extend, and shows also the stability of the air, as the currents do not penetrate stable air layers. Flat-topped cumulus clouds, therefore, indicate stability aloft.

Often, however, vertical currents exist without formation of cumulus clouds as the water vapor content is so low that it cannot be carried high enough to condense. Under such conditions, when the sky is mostly clear, evaporation is speeded, resulting in faster drying of fuels.

When relative humidity is low and temperature high, strong currents may exist to considerable elevations without clouds forming. A further check can be made by watching the rise of temperature during the morning. A sharp rise early that flattens out and remains high substantiates the prospect of deep vertical currents, assuming nearly clear skies. Small whirlwinds or dust devils also indicate unstable conditions, though they may exist only near the surface.

Thunderstorms and very large cumulus clouds indicate instability extending to great heights with strong vertical currents. Thunderstorms with high bases may be dry storms, that is, the rain evaporates into the air before it reaches the ground, and hence lightning strikes are more dangerous.

Stratiform clouds (fog-like clouds or layer clouds) indicate stable conditions at least at the level of the clouds, though stratocumulus may often form in turbulent surface air even though the turbulence is shallow. In general, the lower the stratus clouds, if they persist, the more stable the air, and the less possibility of vertical currents. Low stratus clouds in the morning, however, often are a better indication of good moisture conditions than of continued stability during the day, for they may have formed in a shallow layer of stable air that will rapidly change to an unstable layer during the heat of the day.

Visibility. Good visibility is often a sign of unstable air in which vertical currents may develop. In unstable air the impurities are carried aloft and away, while stable air traps impurities and holds them in a shallow layer of air.

Air Mass. Cool air masses following cold fronts during the fire season east of the Rockies tend to rapidly develop instability in passing over warmer areas. This instability at first is not deep, but increases with time. The cool air is also dry air, and visibility is good. It is usually recognized as coming in with fresh northerly winds.

Winds. Gusty winds with a noticeable decrease in velocity at evening indicate the possibility of strong convection currents during the day. Turbulence and gustiness are more readily started in unstable air. Such gusty winds usually are accompanied by frequent changes in direction. The direction may vary through 45 or more degrees rapidly, back and forth, or more moderately within periods of an hour or so. ■

Russo and Schoemaker (1989) Decision Trap 2—Frame Blindness:
Setting out to solve the wrong problem because, with little thought, you have created a mental framework for your decision that causes you to overlook the best options or lose sight of important objectives.*

* See page 9.

WARNING SIGNS FOR FIRE FIGHTERS*

A.A. Brown

In 1949, 32 men died as a direct result of forest fires on national-forest, State, and private lands. Most of them lost their lives because of extreme fire conditions which resulted in blow-ups. These comments will be confined to these special situations.

Probably it is expecting too much to make fire behavior experts of all fire bosses. Nevertheless, we should go as far as we can in the interest of safety and sound fire strategy.

Large Fire Behavior

We need to study the large fire from the point of view of a local weather phenomenon. As soon as sufficient heat and sufficient area, from which heat is rising, have crossed a particular threshold, the fire takes on new potentials in behavior beyond those to be expected by simply extending the dimensions of a small fire. Sometimes we say "it begins to write its own ticket." This is because of the air turbulence which is set up. Similarly, there is good evidence that local atmospheric conditions, beyond the already known effects of humidity and wind, play a big part. This relates to the stability of the air at the location of a fire. It seems reasonable, when an existing atmospheric inversion or ceiling gives way under pressure of a mass of hot air and gases from below, that there is a sudden acceleration in both the rising and descending air currents and a corresponding acceleration in the surface air circulation with effects similar to those of blowing fresh oxygen on a smoldering fire.

We need to study the large fire from the point of view of a local weather phenomenon.

In other situations unburned gases seem to accumulate, then explode.

Full analysis of such factors will require the help of competent meteorologists and active participation and close cooperation by both research and administrative groups. This will be essential if we are to make significant new progress in foreseeing blow-up behavior. It can be done.

Every fire crew boss needs to have a good knowledge of fire behavior if he is to be left on his own responsibility.

Warning Signs

In the meantime, here are some warning signs to consider when critical situations arise:

Manpower placement and safety—

1. Every fire crew boss needs to have a good knowledge of fire behavior if he is to be left on his own responsibility. The alternative is close supervision and explicit safety instructions by an experienced supervising officer.
2. There is always danger in placing men above a large fire and in fighting it from the head down in steep country. Wherever such strategy is necessary, lines of retreat and places of refuge become a critical part of the responsibility of the fire boss.
3. Closely related to No. 2 is the fact that it is always hazardous to attempt to outrun a fire uphill when there is danger of being trapped. Nearly always there are safer alternatives.
4. Special precautions are needed in assigning men to special duties when they are detached from the main crews or will otherwise be isolated for a time from direct supervision and guidance by an experienced fireman.
5. The danger of being asphyxiated is often overlooked in selecting places of refuge. The bottom of a gulch in the direction of spread may become a chimney flue even though it has no fuel to burn, and most low places directly in the path of the head of the fire have such hazards.

Effects of ground cover—
The fire front moves much more rapidly, through grass and open cover than through heavy timber. All experienced fire fighters realize this, but they often underestimate the contrast in the rate of spread. The fire perimeter can be expected to change from 2 to 10 times as rapidly on the sectors of a fire in

When this article was originally published, A.A. Brown was chief of the Division of Fire Research, USDA Forest Service, Washington Office, Washington, DC.

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* The article is reprinted from *Fire Control Notes* 11(3) [Summer 1950]: 28–29.

that kind of cover. These two—cheatgrass and dry bunchgrass—have extremely high rates of speed in steep country, even if the cover is sparse. It is well to recheck the known ratios between contrasting but intermingled fuel types and to impress them on trainees.

Influence of weather and topography—

1. Prevailing wind direction, particularly if the wind is of low velocity, will be modified a great deal by rugged topography.
2. Extremely rugged country is apt to produce erratic behavior in any fire that has gained momentum because of the conflicting air currents that are set up.
3. The mouth of a canyon in rough country is always affected by conflicting air currents. Any fire in its close vicinity is likely to reflect these air currents in its behavior. The head of the fire in such cases may not be the most threatening.
4. To an experienced fire fighter, dust devils—those local whirlwinds of dust—are an ominous sign. Such whirls account for many blow-ups. ■

> To an experienced fire fighter, dust devils are an ominous sign for blow-ups.

WEBSITES ON FIRE*

The Pulaski Project

Developing a fully accessible, world-class hiking trail to the Nicholson mine (also known as the Pulaski Tunnel) and rehabilitating the adit itself are chief goals of the Pulaski Project. Founded in 2002, the project is designed to honor the memory of “Big Ed” Pulaski and other wildland firefighters and to focus attention on issues surrounding wildland fire management and forest health. Now an action element of the Greater Wallace Community Development Corporation, the project has many planned endeavors, including a National Wildfire Education Center and Museum in Wallace or Silverton, ID. The proposed center will link the Pulaski story to the challenges facing forest management and wildfire issues in 21st-century America.

The project’s Website includes news and information on wildland fire history and management, along with a jointly sponsored and moderated listserv discussion group on forest health, conservation, and fire management. The site also provides links to fire season reports, fire-related publications, and an abundance of other resource sites of interest.

Found at **<http:www.Pulaski-project.org>**

Wildland Fire Research

Established in January 2001, the Wildland Fire Operations Research Group (WFORG) in Hinton, Alberta, provides leadership in fire operational research and technology development. The Website describes many areas of research and development, including fire equipment and protective clothing, fire management systems, and current operational issues for fire managers. Research outputs are intended to benefit firefighters, fire managers, equipment manufacturers, and fire service agencies. The site also posts upcoming wildland fire conferences and symposiums in the United States and Canada and links to other research efforts.

Found at **<http://fire.feric.ca>**

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* Occasionally, *Fire Management Today* briefly describes Websites brought to our attention by the wildland fire community. Readers should not construe the description of these sites as in any way exhaustive or as an official endorsement by the USDA Forest Service. To have a Website described, contact the managing editor, Hutch Brown, at USDA Forest Service, Office of Communication, Mail Stop 1111, 1400 Independence Avenue, SW, Washington, DC 20250-1111, 202-205-1028 (tel.), 202-205-0885 (fax), hutchbrown@fs.fed.us (e-mail).

RECOGNIZING WEATHER CONDITIONS THAT AFFECT FOREST FIRE BEHAVIOR*

Owen P. Cramer

Violent or erratic fire behavior often develops as a complete surprise even to the more experienced fire fighters. Such behavior usually is not completely explained and is frequently dismissed with the remark that the fire suddenly "blew up." Unusual fire behavior is often closely related to certain weather conditions that can be recognized by visible characteristics. These weather conditions, some of their characteristics, and their relation to fire behavior are described here.

The descriptions and terminology used in this discussion agree with definitions in the U.S. Weather Bureau *Weather Glossary* of 1946, with two exceptions. These are *fire storm*, which has been used in published accounts of fires started from extensive incendiary bombings, and *fire whirlwind*, which is possibly used here for the first time. Weather conditions described are divided into two major groups: phenomena of stable air, of which only inversion is discussed; and phenomena of unstable air, including turbulent, convective, and whirling.

> In stable air, both the intensity of the fire and the amount of spotting are reduced. Smoke will not rise as high, and much drift smoke will remain in the lower layers.

Stable Air

General Features. Stable air (stability) is air in which vertical motions are suppressed primarily because of the vertical distribution of temperature. In stable air, underlying air is relatively cooler and heavier; overlying air is relatively warmer and lighter. If the temperature decreases no more than 5 °F per 1,000 feet increase in elevation in dry air, the air is stable. In extremely stable air, temperature may actually increase with height.

There are several indicators of stable air. Surface wind is steady or frequently calm and smoke tends to lie in layers. Clouds are the stratus or stratified type showing no vertical motion (fig. 1). Visibility is often poor, particularly in the lower layers. Ground and valley fogs form in stable layers near the ground. Air in the lower layers is usually stable during calm, clear nights, but becomes unstable in midday when heated by the warm ground.

Convective circulation into the base of a fire and in the column of rising hot gases above a fire is weak. Both the intensity of the fire and the amount of spotting is reduced. In stable air, smoke will not rise as high, and much drift smoke will remain in the lower layers. The most common stability phenomenon is the inversion layer.

Inversion. An inversion is a horizontal layer of air through which temperature increases with increasing height. An inversion is the most stable air condition. Inversion layers occur at any height and vary greatly in thickness. As the ground cools at night, a surface layer of air becomes colder than the air above and produces a surface inversion. Surface inversions are most pronounced in valley bottoms to which

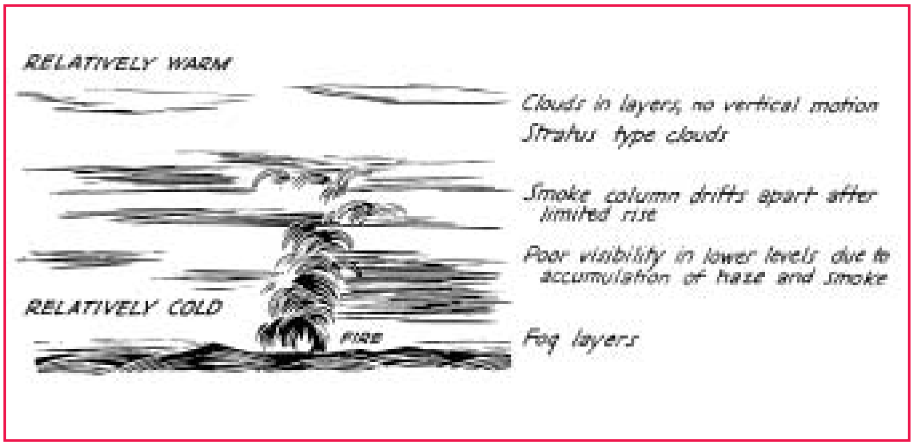

Figure 1—*Stable air.*

When this article was originally published, Owen Cramer was a meteorologist for the USDA Forest Service's Pacific Northwest Forest and Range Experiment Station.

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* The article is reprinted from *Fire Control Notes* 15(2) [Spring 1954]: 1–6.

cold air flows from surrounding slopes. This type of inversion is readily dissipated by ground heating during the day.

Since an inversion tends to suppress any vertical motion, its base is frequently marked by:

- The flat top of a cloud or fog layer,
- The common height at which rising cumulus clouds cease to rise, and
- The height at which a rising smoke column levels off (fig. 2).

There is often greater wind, or a shift in wind direction, above the inversion. An inversion near the ground affects a fire in the same way as stable air but to a greater degree. In the lower layers it tends to weaken drafts into and above a fire, thereby reducing the fire's intensity and spotting potential. It has been suggested that flammable mixtures of gases liberated by a slow-burning fire might accumulate under a surface inversion, and that these might ignite and burn explosively.

Unstable Air

General Features. Unstable air (instability) is air that tends to turn over owing to relatively warm, light air in the lower layers and relatively cooler, heavy air in the upper layers. The decrease in temperature with increasing height is greater than in stable air—5.4 °F or more per 1,000 feet in dry air. Vertical motions are accelerated. Upward and downward currents develop. Indicators are erratic surface winds with gusts and lulls, and a variation in direction and turbulence above the surface layers. Since smoke, dust, and haze are widely dispersed by mixing of high and low layers, visibility is generally good. Clouds in unstable air are the cumulus type with pronounced vertical development and restricted horizontal area (fig. 3). A deep layer of moist, unstable air may be marked by cumulonimbus clouds or thunderstorms. Instability at the cloud level does not necessarily mean that this condition exists all the way to the ground. If it does exist, it may be indicated by dust whirls and erratic winds.

> Spot fires are more likely in unstable air because of the more intense drafts in the fire and the greater vertical speed in the smoke column.

Unstable air affects fires in several ways. Spread of fires may be accelerated by gusty wind. The column of smoke over the fire will rise faster and to greater heights than in stable air, resulting in a stronger indraft at the base of the fire and a hotter burning fire. Spot fires are more likely because of the more intense drafts in the fire and the greater vertical speed in the smoke column. Unstable air is favorable for the formation of fire whirlwinds. These effects are discussed in more detail under the several instability phenomena described below.

Turbulence. Turbulence is irregularity in air motion, shown by bumpy air for the pilot and gusty wind for the ground observer. Any obstacle to the wind sets up

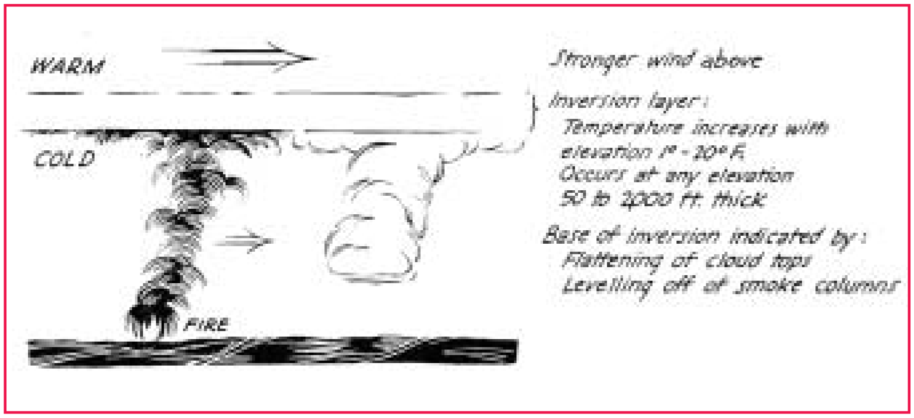

Figure 2—*Inversion.*

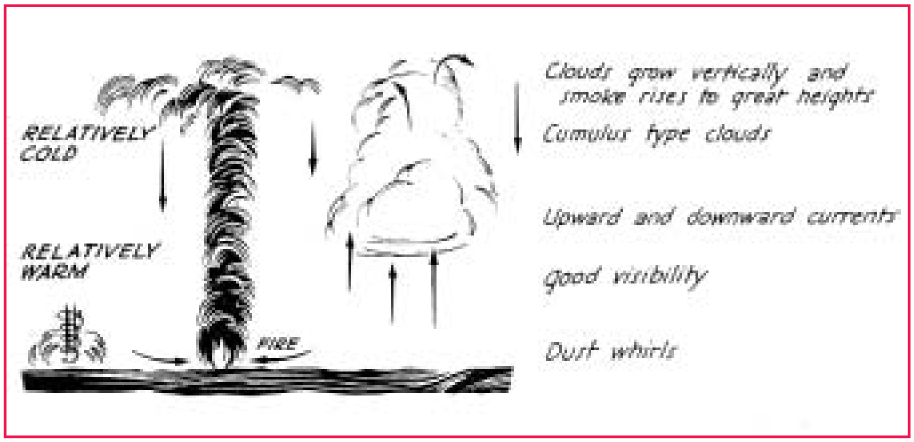

Figure 3—*Unstable air.*

mechanical turbulence on the leeward side (fig. 4). Intermingled currents of rising warm and descending cool air cause thermal turbulence, which is characteristic of unstable air. Turbulence may be accentuated by an uneven surface heating that varies with color of soil, amount of shade, and type of ground cover.

Gustiness. Gustiness is a characteristic of wind in unstable or turbulent air. Gustiness refers to surface winds that vary rapidly in vertical and horizontal speed and direction. Increasing instability and increasing turbulence caused by surface obstacles result in corresponding increases in gustiness. Since a fire greatly increases surface instability, the intensity of gusts is likely to be greater in the immediate vicinity of a fire. Gusts usually cause a fire to spread spasmodically in unpredictable directions. They also cause rapid fluctuation in fire intensity and rate of spread.

> The more intense the convective circulation, the hotter and faster the fire will burn and the higher embers will be carried.

Convection. A convection is motion in the air resulting from temperature differences in adjacent bodies of air. Convective currents are characteristic of unstable air. They consist of rising warm air and descending cool air currents (fig. 5). Heating at the ground either by the sun or by fire may initiate the upward current. Surrounding air descends and flows toward the base of the column of rising air. The rising warm air above a continuing heat source is known as the convective column. Above a fire this is seen as the smoke column. Cumulus clouds are convective columns that have become visible because of moisture condensation. The greater the instability of the air or the greater the source of heat, the more intense becomes the convective circulation caused by a fire, including both indraft at the base and updraft in the smoke column. The more intense the convective circulation, the hotter and faster the fire will burn and the higher embers will be carried.

Thundersquall. A thundersquall is the sudden wind that blows outward from beneath a thunderstorm.

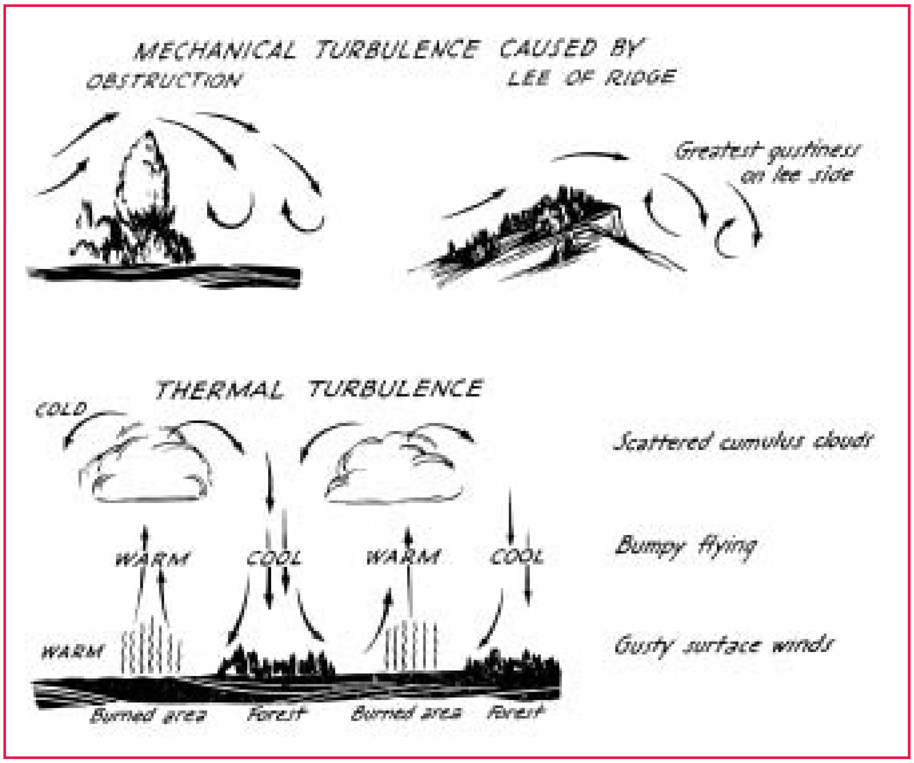

Figure 4—*Turbulence.*

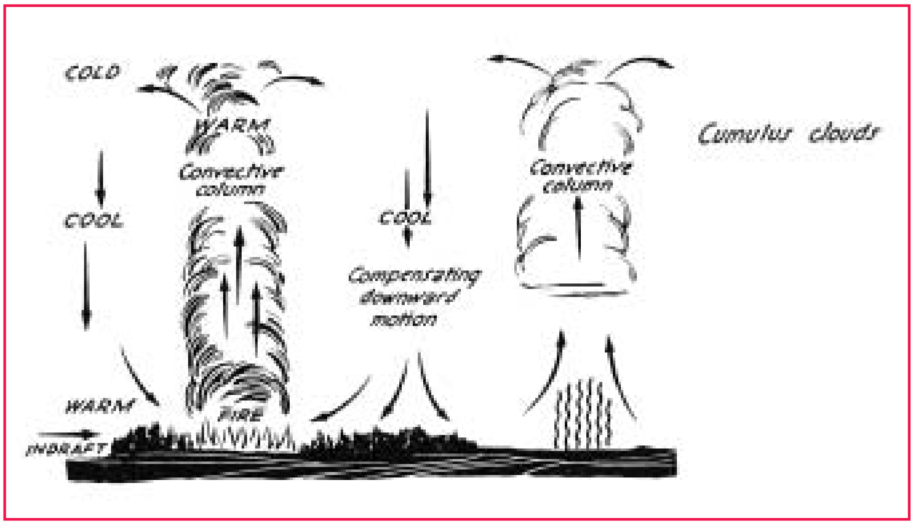

Figure 5—*Convection.*

Such a wind originates in the area of heaviest precipitation in a cumulonimbus cloud, a convective cloud type that occurs in unstable, moist air. Air, cooled by precipitation, descends from the cloud and fans out at the surface (fig. 6). The thundersquall usually occurs with a well-developed thunderstorm and hits suddenly with speeds averaging 30 to 50 miles per hour (48–80 km/h) for a period of several minutes. The thundersquall may occur beneath a thunderstorm from which no precipitation reaches the ground, and may extend outward a mile (1.6 km) or more ahead of the storm edge.

These sudden, strong winds may sweep a fire far beyond its confines before the rainy section of the thunderstorm arrives. If the rain evaporates before reaching the ground, the fire may continue to burn unchecked.

Whirlwind. A whirlwind is any revolving mass of air, from the dust whirl to the hurricane. The tornado, a whirlwind associated with thunderstorms, is the most severe, though not the largest type. Whirlwinds are usually associated with extremely unstable air. Fires frequently make the nearby atmosphere unstable and produce fire whirlwinds. Two types of whirlwind will be described, the dust whirl and the fire whirlwind.

Dust whirl. The dust whirl is the smallest type of whirlwind, frequently known as a dust devil. Dust whirls indicate unstable air. They occur on sunny days with light surface wind when the layers of air next to the ground become much hotter than the air immediately above. These whirls are usually 5 to 25 feet (1.5–8 m) in diameter and may extend upward several hundred feet. Though usually not of destructive force, dust whirls can throw small debris several yards. The greatest speed is near the center, where a strong upward current occurs. Dust whirls occasionally form in the vicinity of fires and move into the fire area, throwing sparks and embers in all directions and temporarily intensifying the fire as they pass.

Even a small fire whirlwind may produce considerable spotting and local intensification of the fire.

Fire Whirlwind. A fire whirlwind is any whirlwind caused by a fire. The fire whirlwind may vary in intensity, from a small dust whirl to a whirlwind that easily snaps off large trees. The diameter of its circulation may vary from 3 to 50 yards (2–45 m) or more. Fire whirlwinds encompassing whole fires 1,000 yards (910 m) or more across have been reported. Besides the rotating horizontal winds, there is a strong vertical current at the center, which may raise burning debris to great heights. Even a small fire whirlwind may produce considerable spotting and local intensification of the fire. A central spout or tube may sometimes be present (fig. 7). Because of the wind and

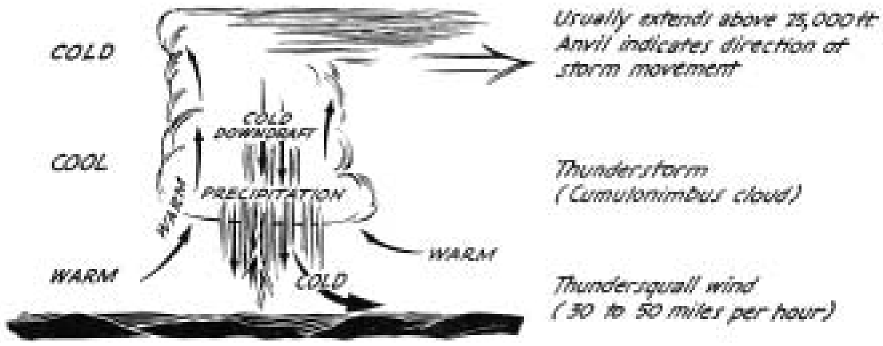

Figure 6—*Thundersquall.*

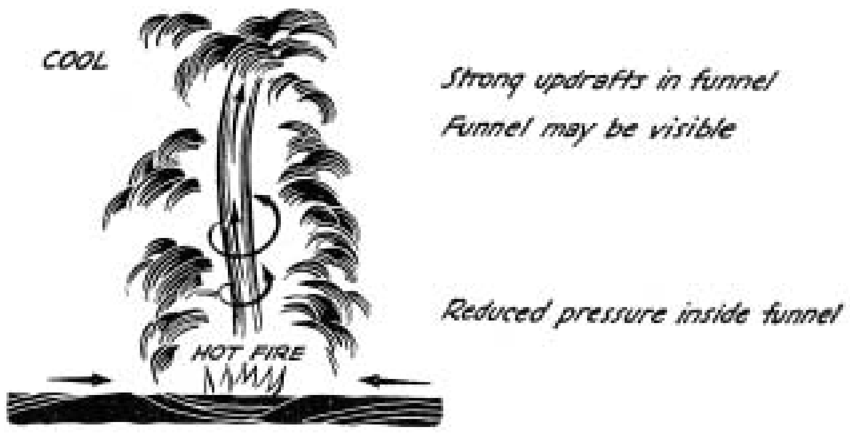

Figure 7—*Fire whirlwind.*

the resulting accelerated combustion, fire whirlwinds are sometimes accompanied by a roaring noise similar to that produced by a rapidly burning fire. Duration and behavior are variable. Fire whirls may occur and recur where the combination of fire-produced instability, topography, and wind are favorable. It is sometimes possible to dissipate a small, recurring fire whirlwind by cooling the part of the fire over which it forms.

In a fire storm, the surface draft into the base of the fire may be of destructive violence several hundred yards outside the fire.

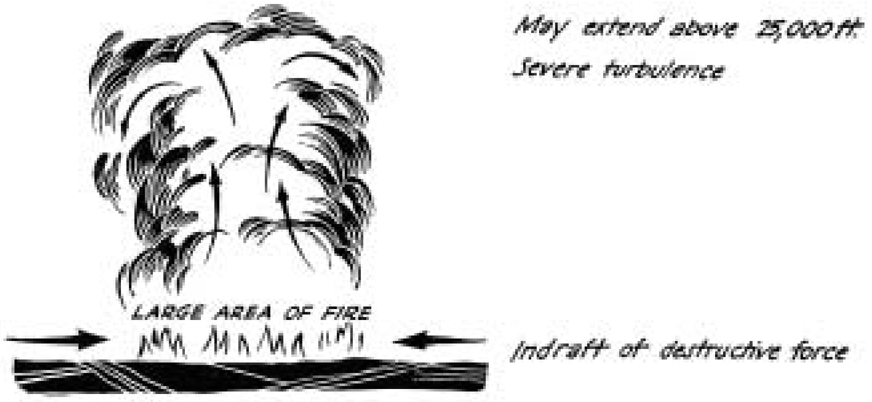

Figure 8—*Fire storm.*

Fire Storm. A fire storm is a violent convection caused by a large, continuous area of intense fire. This phenomenon was frequently observed after extensive firebomb raids in Europe and Japan. The convective system usually encompasses the entire fire (fig. 8). The surface draft into the base of the fire may be of destructive violence several hundred yards outside the fire. The fire storm, like other convective phenomena, increases in intensity with greater atmospheric instability. Burning material may be lifted several miles high. A fire storm is not likely in the usual wildfire, where only the periphery is actively burning. ■

The Blowup Fire and Firefighter Safety*

A review of fire fatalities through the years focuses our attention on four major problems.

The greatest man-killer, of course, is the blow-up fire which almost yearly takes its toll. Hundreds have died from this source, if one considers the historic fires of the past, such as Peshtigo. Losses of life are becoming fewer because of organized fire-suppression efforts. Fast initial action with machine-age equipment such as planes, trucks, and tractors, a better understanding of fire behavior, more thorough planning of control strategy, more foremen trained in handling men on fires, has had much to do with the reduction in the number of fire fatalities in recent years. But blow-up fires still constitute the worst potential killer. Much remains to be done before the problem is solved.

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* From Seth Jackson, “Death on the Fire Line (*Fire Control Notes* 11[3] [July 1950]: 26–27).

METEOROLOGICAL PROBLEMS ASSOCIATED WITH MASS FIRES*

DeVer Colson

Weather plays an important role in the behavior of mass fires. The knowledge and understanding of the meteorological conditions existing prior to and during these fires are essential for efficient fire fighting and control in both urban and rural situations. Ordinary fires or even large fires which are burning and spreading in a regular manner do not present the major control problems. Serious situations often develop when what seems to be a routine fire suddenly intensifies or begins to spread at a greatly increased rate or changes its direction of spread abruptly. In forestry parlance, the term "blow-up" or "explosive" has been applied to such forest fires, since these fires often seem to explode. However, many fires have been designated as "blow-ups" simply because of a lack of understanding of the factors controlling the behavior of these fires.

> Many fires have been designated as "blow-ups" simply because of a lack of understanding of the factors controlling the behavior of these fires.

There is much to be learned both in identifying these factors and in forecasting the occurrence of these factors. Some of the possible meteorological factors will be discussed briefly in this paper.

General Burning Conditions

Most serious fires occur with extremely low fuel moisture caused by severe or extended drought conditions. These conditions are usually combined with high surface temperatures and low relative humidities and often with strong surface winds.

When this article was originally published, DeVer Colson worked for the U.S. Weather Bureau.

One notable example involved the famous Chicago fire on October 8, 1871; and the associated fires in Wisconsin and Michigan on the same day, which burned over 1 million acres (400,000 ha), including the entire town of Peshtigo, where over 600 lives were lost. Weather data indicate extreme dryness and strong winds on that date. On days with less hazardous burning conditions, these fires might well have been controlled before they had reached such disastrous proportions.

In the preparation and planning for the fire bombing raids over the Tokyo area, weather conditions were studied in connection with brush fires in North Carolina, a region climatically similar to the Tokyo area. The following factors were used: precipitation, relative humidity, and maximum wind speed. The maximum wind speed on the day of the fire was used, while the precipitation and relative humidity were weighted over the day of the fire and the three previous days. These same factors are used directly or indirectly in most current fire danger rating systems.

Surface Wind Patterns

The details of the surface wind patterns are necessary for efficient fire fighting operations. These details would include:

- The actual local surface wind patterns;
- the diurnal variations in these patterns; and
- the dependence of these local patterns and their diurnal variations on the surface pressure patterns, as well as frontal and storm passages, the upper level weather patterns, atmospheric stability, wind and temperature profiles, and topography.

A knowledge of the local wind patterns and their variations is even more essential in areas of rugged terrain. In these areas, there are the additional effects of general drainage patterns (mountain and valley winds) and the diurnal up- and downslope winds due to the differential heating of the slopes. The relative influences of all these factors vary greatly with the ruggedness of the terrain.

Two local wind surveys have been conducted, one by the U.S. Weather Bureau in 1949–52 at Oak Ridge, TN, and the other by Operation Firestop in 1954 at Camp Pendleton, CA. Unfortunately, much of the data from these sur-

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* The article is reprinted from *Fire Control Notes* 17(1) [Winter 1956]: 9–11.

In the Mann Gulch fire, the unusual currents may have been due to the strong surface winds resulting from descending currents from the high-level thunderstorms in that area.

veys cannot be applied to other areas because of the influences of the local terrain and weather conditions. However, as data from additional surveys are accumulated, more and more generalizations can be made that can be applied to other areas. Such wind studies are important in air pollution and smog control.

It is the unusual cases that cause the most trouble. Some recent cases are the 1949 Mann Gulch fire in Montana and the 1953 Rattlesnake and 1954 Sierra City fires in California. At each of these fires, fire fighters lost their lives when the fire spread rapidly in an unusual and unexpected manner. In the Mann Gulch fire, the unusual currents may have been due to the strong surface winds resulting from descending currents from the high-level thunderstorms in that area. In the other two cases, the rapid spread of the fire may have been due to a combination of the normal night downslope air drainage acting simultaneously with a pressure gradient across and through the passes. As more is learned about these wind patterns, more of these unusual fires and their behavior patterns can be anticipated.

Topography

With the proper pressure gradient across mountain ridges and through passes, strong local winds will be set up as the air flows down the lee side. Examples of such strong local winds are the Santa Ana winds in southern California, the east winds in western Oregon and Washington, and the chinook winds on the east slopes of the Rocky Mountains. These winds have a tremendous effect on fires, since they are associated with high temperatures and low relative humidities.

Upper Level Winds

As fires spread into the crowns of high trees, a different rate of spread can be expected since the wind speed and direction at this level may be quite different from that near the ground. Also, with burning buildings, the surface winds may have little connection with the fire spread at higher levels. With convection currents carrying burning embers up into even higher levels, the rate and direction of the spread of the fire due to spotting may be entirely different from that which would be expected from just a knowledge of the surface winds alone.

Turbulence

In addition to the actual local wind patterns, the turbulence or the fluctuations in both the wind speed and the direction must be considered. The magnitude and frequency of these fluctuations have been found to be closely associated with the degree of atmospheric instability. Also, the magnitude and frequency of these fluctuations will be greater at well-exposed sites than at well-sheltered locations. Mechanical eddies and turbulence can be generated as air flows across and around sharp features of terrain and buildings.

As fires spread into the crowns of high trees, a different rate of spread can be expected since the wind speed and direction at this level may be quite different from that near the ground.

Convection

Under certain atmospheric conditions, better convection can be sustained which will promote more efficient burning. These conditions are usually associated with atmospheric instability, that is, with near or superadiabatic temperature lapse rates. However, the convection column will not attain great heights if the wind speed increases too rapidly with height. Too strong a wind speed may cause the column to be broken away from its energy source.

Temperature inversions tend to act as a lid on free convection. However, under these conditions, as the free air temperature reaches a certain value or as the energy of the fire becomes great enough, the convection can break through the inversion and can suddenly extend to much greater heights, especially if the atmosphere is unstable above the inversion. When this breakthrough occurs, sudden changes will take place in the fire behavior and the spread.

Much experimental and theoretical work is now in progress on the general problems of turbulence, dif-

When a temperature inversion breaks, sudden changes will take place in the fire behavior and the spread.

fusion, convection, and allied problems at many air pollution and micrometeorological projects.

Thunderstorm and Lightning

The high-level and often dry thunderstorms present a great hazard in the Rocky Mountain area because of lightning fires. Project Skyfire has been set up in the Northern Rocky Mountain area to study the origin, development, structure and intensity, movement, distribution of these storms, and the possibility of modification of these storms to reduce the lightning hazards.

Meteorological Phenomena induced by a Large Fire

Once a fire develops, the original wind and temperature distribution around and over the fire will be changed. A complete study of this problem requires accurate and detailed data on temperature, humidity, wind speed and direction, and the composition of the gases in the convection column. From these results, it will be possible to determine the rate of transfer of heat, momentum, and the distribution of energy about the fire. In addition to experimental studies at actual fires, much information has been gained from model studies.

Strong indrafts, usually referred to as the firestorm, have been observed in the vicinity of some large fires and may become quite appreciable at times.

Conclusion

As more is learned about the meteorological factors as well as a better knowledge of the fuel distribution and efficiency of combustion, fewer fires will be designated as “blowups.” These fires can be anticipated and their behavior patterns expected. However, a vast amount of difficult experimental and theoretical work will be necessary to accomplish this goal. ■

Russo and Schoemaker (1989) Decision Trap 3—Lack of Frame Control: Failing to consciously define the problem in more ways than one or being unduly influenced by the frames of others.*

* See page 9.

SOME PRINCIPLES OF COMBUSTION AND THEIR SIGNIFICANCE IN FOREST FIRE BEHAVIOR*

George M. Byram

Although a large fire is essentially a physical or meteorological phenomenon, combustion itself is a chemical chain reaction process, which takes place at high temperatures. In all forest fires, large or small, materials such as leaves, grass, and wood combine with oxygen in the air to form combustion products plus large quantities of heat. Heat, as we shall see, is the most important combustion product in fire behavior.

Phases of Combustion

There are three rather definite phases of combustion, although they overlap somewhat and all exist simultaneously in a moving fire. First comes the preheating phase, in which fuels ahead of the fire are heated, dried, partially distilled, and ignited. In the second phase, the distillation of gaseous substances continues but is now accompanied by their burning or "oxidation." Ignition might be regarded as the link between the first, or preheating, phase and the second, or gaseous, combustion phase. Ignition may also be regarded as the beginning of that part of the combustion process in which heat is given off. The flames seen over a forest fire or in a fireplace are the burning of distilled gases; combustion products are principally invisible water vapor and carbon dioxide. If combustion is not complete, some of the distilled substances will condense without being burned and remain suspended as very small droplets of liquid or solid over the fire. These condensed substances are the familiar smoke that accompanies most fires. Under certain conditions, some of the water vapor may also condense and give the smoke a whitish appearance.

Heat makes combustion a chain reaction by letting gases distilled from the fuel react with oxygen in the atmosphere to give off more heat, raising the temperature of adjacent fuel.

In the third or final phase the charcoal left from the second phase is burned and leaves a small amount of residual ash, which is not a combustion product. If combustion is complete and if the charcoal** is mostly carbon, the primary combustion product in this phase will be carbon dioxide because the initial water is driven off in the first two phases. Some carbon monoxide is formed as an intermediate product, which in turn burns as a gas to form carbon dioxide. The small blue flames appearing over the coals in a fireplace are carbon monoxide burning. However, if combustion is not complete, small amounts of carbon monoxide remain. In this phase the fuel is burned as a solid, with oxidation taking place on the surface of the charcoal.

Even though the three combustion phases tend to overlap, they can be plainly seen in a moving fire. First is the zone in which leaves and grass blades curl and scorch as they are preheated by the oncoming flames. Next is the flame zone of burning gases.

Following the flames is the third but less conspicuous zone of burning charcoal. Unless fuels dry to a considerable depth (that is, unless the Build-up Index is high), this last zone may be almost absent. If this happens the burned-over area will appear black instead of gray, which means that much of the remaining charcoal, as well as some of the underlying fuel, has not completely burned. With the exception of such years as 1947, 1952, and 1955, a blackened burned-over area has been more common than a gray ash-covered area in the Eastern and Southern States.

When this article was originally published, George Byram was a physicist for the USDA Forest Service, Southeastern Forest Experiment Station.

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* The article is reprinted from *Fire Control Notes* 18(2) [Spring 1957]: 47–57.

** The composition of charcoal varies, depending on the conditions under which it is formed. If the distillation temperature is low, 400 to 500 °F (204 to 260 °C), the charcoal will contain considerable tar coke. However, in the rapid heating and resultant high temperatures existing in a forest fire, the deposits of secondary products in the charcoal are probably low.

Heat of Combustion

The heat of combustion is heat that makes combustion a chain reaction. Heat supplied to unburned fuel raises its temperature to the point where the fuel, or the gases distilled from the fuel, can react with the oxygen in the atmosphere and in so doing give off more heat. This in turn raises the temperature of adjacent fuel, and thus the chainlike nature of combustion becomes established.

The heat energy released by burning forest fuels is high and does not vary widely between different types of fuels. Table 1 gives the heats of combustion for a number of substances. These materials and heats were selected from tables in *Kent's Mechanical Engineers Handbook,* 12th edition. Their average is probably a good approximation for forest fuels. Fuels do not ordinarily burn with maximum efficiency, so the actual amount of heat released per pound of fuel in a forest fire will be somewhat less than shown in the tabulation. For a small fire burning in dry fuels with very little smoke, the combustion efficiency might be as high as 80 percent. Large fires burning with dense smoke would be less efficient. Combustion efficiency probably drops somewhat with increasing moisture content.

Table 1—*Heat produced by various fuel types.*

Substance	***Heat of combustion***	
	Per pound, dry (B.t.u.)	***Per kg, dry (kJ)***
Wood (oak)	8,316	19,330
Wood (beech)	8,591	19,969
Wood (pine)	9,153	21,275
Wood (poplar)	7,834	18,209
Pine sawdust	9,347	21,726
Spruce sawdust	8,449	19,639
Wood shavings	8,248	19,172
Pecan shells	8,893	20,671
Hemlock bark	8,753	20,345
Pitch	15,120	35,145
Average (excluding pitch)	8,620	20,036

Convection, with some help from radiation, is the principle means of heat transfer from a ground fire to the crowns of a conifer stand.

Heats of combustion are given in British thermal units per pound of dry fuel. A B.t.u. is the quantity of heat needed to raise the temperature of 1 pound of water 1 ºF. For example, the above tabulation shows with the help of a little arithmetic that the burning of 1 pound (0.45 kg) of an average woody fuel gives off enough heat to raise the temperature of 100 pounds (4.5 kg) of water about 86 ºF. To raise the temperature of 100 pounds (4.5 kg) of water (about 12 gallons [45 L]) from a temperature of 62 ºF (17 ºC) to the boiling temperature of 212 ºF (100 ºC) would require about 1.7 pounds (0.76 kg) of an average woody fuel if it burned with maximum efficiency. About 1 pound (0.45 kg) of pitch would accomplish the same result.

The rate of heat release in a forest fire can be visualized by comparing it with a familiar rate, such as that required for house heating. For example, consider a hot, rapidly spreading fire burning with a 20-chain (1,320-foot [400-m]) front and with a forward rate of spread of 50 chains (3,300 feet [1,000 m]) per hour. If the fire burns 6 tons of fuel per acre (13.4 t/ha), in 1 hour's time enough fuel would be consumed to heat 30 houses for a year if each house yearly required the equivalent of 10 cords (25.5 m^3) of wood weighing approximately 2 tons per cord (0.7 t/m^3).

Occasionally there is a fire in the Eastern States with a rate of spread exceeding 5,000 acres per hour (2,000 ha/h). If it burns in a dense, continuous stand of conifers, which might have 12 tons (10.9 t) or more of available fuel per acre, such a fire could consume enough fuel in an hour to heat 3,000 houses for a year.

Heat Transfer

There are three primary ways in which heat travels or is transferred from one location to another. These are conduction, convection, and radiation. Although dependent on convection, there is a fourth or secondary means of heat transfer in forest fires, which might be described as "mass transport." This is the carrying of embers and firebrands ahead of the fire by convective currents and results in the familiar phenomenon of "spotting."

As a heat-transfer mechanism, conduction is of much greater importance in solids than in liquids and gases. It is the only way heat can be transferred within opaque solids. By means of conduction, heat passes through the bottom of a teakettle or up the handle of a spoon in a cup of hot coffee.

Convection is the transfer of heat by the movement of a gas or liquid. For example, heat is transferred from a hot air furnace into the interior of a house by convection, although the air picks up heat from the furnace by conduction.

Radiation is the type of energy one feels when sitting across the room from a stove or fireplace. It travels in straight lines like light, and it travels with the speed of light.

Most of the preheating of fuels ahead of a flame front is done by radiation. For a fire that occupies a small area and can be thought of as a "point" (such as a small bonfire or a spot fire), the intensity of radiation drops as the square of the distance from the fire increases. For example, only one-fourth as much radiation would be received at 10 feet (3 m) as at 5 feet (1.5 m) from the fire. However, when a fire becomes larger, the radiation intensity does not drop off so rapidly. For a long line of fire, the radiation intensity drops as the distance from the fire increases; that is, one-half as much radiation would be received at 10 feet (3 m) as at 5 feet (1.5 m). For an extended wall of flame, radiation intensity drops off even more slowly. This tendency for radiation to maintain its intensity in front of a large fire is an important factor in the rapid growth of a fire's energy output.

Convection, with some help from radiation, is the principle means of heat transfer from a ground fire to the crowns of a conifer stand. Hot gases rising upwards dry out the crown canopy above and raise its temperature to the kindling point. Although convection initiates crowning, both convection and radiation preheat the crown canopy ahead of the flames after a crown fire is well established. Convection is also a factor in the preheating of the ground fuels in a surface fire but to a lesser extent than radiation. The effects of both radiation and convection in preheating are considerably increased when a fire spreads upslope, because the flames and hot gases are nearer the fuels. The opposite is true for downslope spread.

Conduction is one of the main factors limiting the combustion rate in heavy fuels, such as slash and limbs and logs in blowdown areas.

Convection and radiation can transfer heat only to the surface of unburned (or burning) fuel. Actually, radiant heat may penetrate a few thousandths of an inch into woody substances and this penetration may be of some significance in the burning of thin fuels, such as grass blades and leaves. However, radiation, like convection, for the most part transfers heat only to the surface of fuel material, and conduction may be considered the only means of heat transfer inside individual pieces of fuel. For this reason conduction is one of the main factors limiting the combustion rate in heavy fuels, such as slash and limbs and logs in blowdown areas. Materials that are poor conductors of heat, such as most forest fuels, ignite more readily than do good conductors, but they burn more slowly. Although the effects of conduction are far less conspicuous than those of radiation and convection, conduction is a very important factor in the combustion process.

Factors Affecting the Combustion Rate

Many factors affect combustion in such complex ways that they are not yet fully understood even for a simple gas or liquid fuel. Solid fuels are even more complex. Even so, there are two rather simple factors that have obvious and definite effects on the combustion rate of woody substances and are of great importance in forest fire suppression. The first of these is the moisture content of the fuel, and the second is fuel size and arrangement.

It is difficult to overestimate the effect of water on the combustion rate and, hence, on fire behavior. Water in a fuel greatly diminishes the preheating rate in the first phase of combustion. Much of the heat is used in raising the temperature of the water and evaporating it from the fuel. The large quantities of resulting water vapor dilute the oxygen in the air and thus interfere with the second or gaseous combustion phase. If the initial fuel moisture is high enough, water vapor may make the mixture so "lean" that the gases will not burn. This dilution of the oxygen in the air also affects the third or carbon-burning phase of combustion. Although data are lacking, it is probable that moisture reduces considerably the heat yield or combustion efficiency. This heat loss would be in addition to that resulting from the water-heating and evaporation requirements.

It is difficult to overestimate the effect of water on the combustion rate and, hence, on fire behavior.

The effect of size and arrangement of fuel on combustion can be illustrated by the following example. Consider a large pile of dry logs all about 8 inches (20 cm) in diameter. Although somewhat difficult to start, the log pile will burn with a hot fire that may last for 2 or 3 hours. The three primary heat-transfer mechanisms are all at work. Radiation and convection heat the surfaces of the logs, but only conduction can transfer heat inside the individual logs. Since conduction is the slowest of the three heat-transfer mechanisms, it limits the combustion rate in this case. Consider now a similar pile of logs that have been split across their diameter twice, or quartered. Assume that the logs are piled in an overall volume somewhat greater than the first pile, so there will be ample ventilation. This log pile will burn considerably faster than the first one because the combustion rate is less dependent on conduction. The surface area was more than doubled by the splitting, so that convection and radiation are correspondingly increased in the preheating effects. The burning surface is also increased by the same amount.

Assume that the splitting action is continued indefinitely until the logs are in an excelsior state and occupy a volume 30 or 40 times as great as in their original form. Convective and radiative heat transfer will be increased tremendously in the spaces throughout the whole fuel volume, and the combustion rate might be increased to a point where the fuel could be consumed in a few minutes instead of hours.

The effect of fuel arrangement can be visualized if a volume of excelsior like fuel, such as that just described, is compressed until it occupies a volume only 4 or 5 times that of the original volume of logs. The total burning surface and radiative conditions remain the same as before compression, but both convective heat exchange and oxygen supply are greatly reduced. There will be a corresponding decrease in fire intensity.

Fuel size and fuel arrangement have their greatest effect on the lower intensity fires and in the initial stages of the buildup of a major fire. When a fire reaches conflagration proportions, the effect on fire behavior of factors such as ignition probability and quantity of firebrand material available for spotting may be greater than the effect of fuel size and arrangement. This point will be discussed in the section on applications to fire behavior.

The Fire Triangle

The principles of combustion may be summarized in an effective way by means of the fire triangle. This triangle neatly ties together not only the principles of combustion but illustrates their application as well. The three sides of the triangle are FUEL, OXYGEN, and HEAT. In the absence of any one of these three sides, combustion cannot take place. The fire triangle represents the basic link in the chain reaction of combustion (fig. 1). Removing any one or more sides of

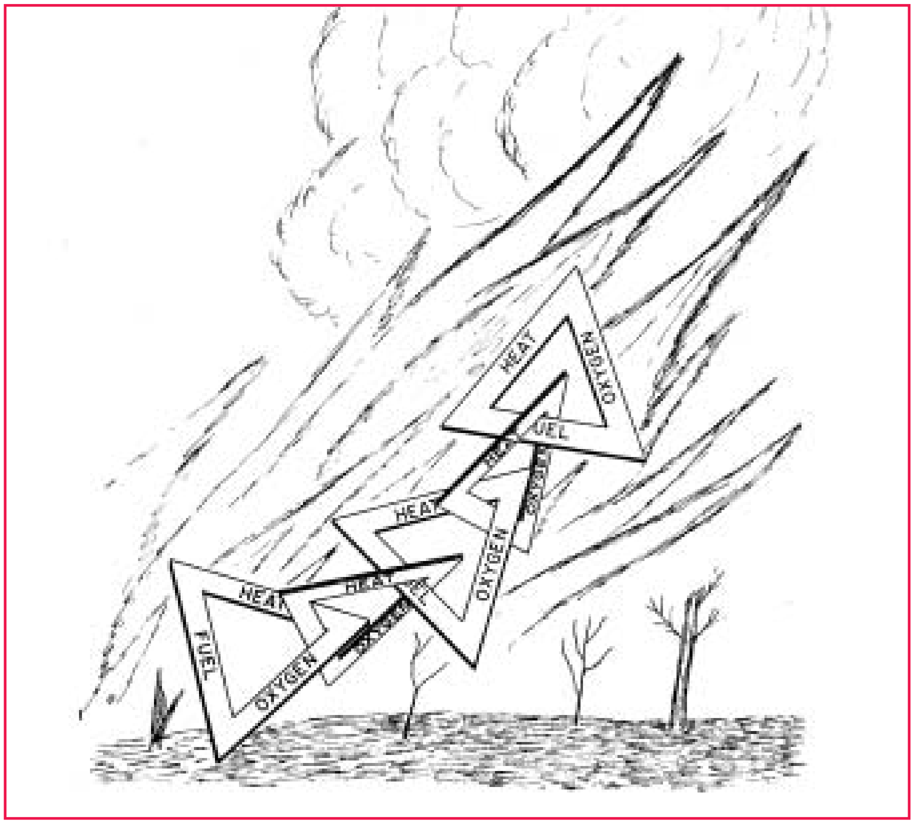

Figure 1—*The fire triangle is the basic link in the chain reaction of combustion.*

Fuel size and fuel arrangement have their greatest effect on the lower intensity fires and in the initial stages of the buildup of a major fire.

the triangle breaks or destroys the chain. Weakening any one or more sides weakens the chain and diminishes fire intensity correspondingly.

The purpose of all fire suppression efforts is to remove or weaken directly or indirectly one or more sides of the fire triangle. Conversely, all conditions that increase fire intensity operate in such a way as to greatly increase or strengthen the sides of the triangle, and hence, the chain reaction of combustion. In a blowup fire the chain becomes so strong that it cannot be broken by the efforts of man. This means that when blowup conditions exist, the only opportunity to break the chain is by early strong initial attack.

Application to Fire Behavior

It is more difficult to apply our knowledge of ignition and combustion to the behavior of very high-intensity fires, sometimes referred to as conflagrations or "blowups," than to the behavior of the more frequent low-intensity fires. The ordinary fire behaves for the most part as one would expect from the principles or combustion. In a conflagration or blowup, however, the sides of the fire triangle are greatly strengthened by factors that are absent, or nearly so, in small fires. Although these factors work through the basic combustion principles, they so greatly modify the expected effects of the basic processes that a high-intensity erratic fire cannot be considered as a large-scale model of a low-intensity fire.

This is best illustrated by considering the spatial structure of the two types of fires. The height of the significant vertical structure of a low-intensity fire can usually be expressed in tens of feet. This distance is usually small compared to the surface dimensions of the burning area, so that in a physical sense the fire is "thin" or two-dimensional as far as volume structure is concerned. On the other hand, the significant vertical structure of a well-developed conflagration may extend thousands of feet into the air, and this dimension may at times exceed the surface dimensions of the burning area.

The height that smoke rises above, or in the neighborhood of, a fire is not always a true indicator of the height of the active convection column above a fire. Smoke from a small fire may reach a height of 1,000 feet or (300 m) more, but active convection may reach only a few percent of this height.*

It is the three-dimensional structure of a large fire that causes it to take on storm characteristics which, in turn, produce behavior phenomena that one could not expect by scaling upwards the behavior of a low-intensity fire. However, this does not mean that scale-model fires, including small fires in the laboratory under controlled conditions, would not be useful in preliminary convection column studies. Probably experimental work on convection column properties should be started first on small-scale fires. Such work might give essential fundamental information on the relation between the variables controlling the convection process.

Certain properties of the atmosphere, such as the vertical wind profile and to a lesser extent the vertical temperature profile, appear to be the controlling factors in extreme fire behavior if an extensive area of plentiful dry fuel exists. A discussion of the atmospheric factors is outside the scope of this paper, but it may be well to examine in some detail those phases of the combustion process that permit the atmospheric factors to exert their maximum effect.

Fire behavior is an energy phenomenon, and its relation to the combustion process can be understood by the use of four basic fuel factors relating to energy:

1. Combustion period,
2. Critical burn-out time,
3. Available fuel energy, and
4. Total fuel energy.

This last factor is constant, or nearly so, for any given quantity of fuel per acre. The first three are variables which, even for any homogeneous component in a given fuel type, depend on factors such as fuel moisture content and fire intensity. A fifth fuel factor, the quantity of firebrand material available for spotting, is more or less independent of the other four and will be treated separately.

The combustion period may be defined as the time required for a fuel to burn up completely, and depends primarily on fuel size, fuel arrangement, fire intensity, and fuel moisture. It may range from a

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* Although it is too involved to discuss in a paper on combustion, the height of the convection zone depends on the rate of heat output of the fire, the wind speed, the vertical wind shear, and the stability of the atmosphere.

few seconds for thin grass blades to several hours or longer for logs and heavy limbs. Critical burn-out time is defined as the maximum length of time that a fuel can burn and still be able to feed its energy into the base of the forward traveling convection column; its magnitude depends primarily on fire intensity or the rate of a fire's energy output. The available fuel energy is that part of the total fuel energy which is fed into the base of the convection column. For fuels with a combustion period equal to or less than the critical burn-out time, the available fuel energy is equal to the total fuel energy. If the combustion period is longer than the critical burn-out time, then the available fuel energy is less than the total fuel energy. Total fuel energy is determined by the quantity of fuel per acre and the combustion efficiency. If the combustion efficiency is assumed to be constant, the terms "available fuel energy" and "total fuel energy" can be replaced by the terms "available fuel" and "total fuel."

An example will illustrate how fire behavior relates to the four preceding quantities. Consider a fire spreading in an area of plentiful heterogeneous fuel, a considerable part of which is in the form of flammable logs and heavy slash and the rest a mixture of smaller material such as twigs, pine needles, and grass. Assume that the critical burn-out time is about 20 minutes. Those fuel components with a combustion period less than 20 minutes will have an available fuel energy equal to their total fuel energy. However, logs and heavy limbs may require several hours to burn out, so their available energy may be comparatively low; they could still be burning after the fire had moved several miles, so would not be affecting the behavior of the fire front.*

From the standpoint of fire behavior, a crown fire in a dense conifer stand could have more available fuel energy than a fire in an area of heavy logging slash. However, unless large portions of a heterogeneous fuel have very long combustion periods, fuel size and fuel arrangement should not have as much influence on the behavior of major fires as on smaller fires. In a major fire a larger proportion of the heavier fuels take on the characteristics of flash fuels. This is a combined result of the shorter combustion periods and longer critical burn-out times for the high-intensity fires. Nevertheless, fuel size and fuel arrangement contribute heavily to the rate of buildup of fire intensity, especially in the early stages, and are therefore an important part of the fire behavior picture.

The purpose of all fire suppression efforts is to remove or weaken directly or indirectly one or more sides of the fire triangle.

Much of the effect of fuel moisture can be interpreted in terms of the four basic fuel factors. Because moisture decreases the combustion rate, it increases the length of the combustion period. This, in turn, means that a smaller fraction of a heterogeneous fuel will have a combustion period less than the critical burn-out time. The available fuel energy and fire intensity will therefore drop as fuel moisture increases. For most fires there are some fuel components which do not burn because of their high moisture content; in other words, these components may be regarded as having infinitely long combustion periods.

An increase in fire intensity can greatly reduce the combustion period for those fuel components with the higher moisture contents. For some components the combustion period might be infinite for a low-intensity fire, but perhaps only a few minutes, or even less, for a high-intensity fire. For example, in the high-intensity Brasstown fire on March 30, 1953, in South Carolina, as well as in other large fires in the Southeast in the last few years, green brush often burned, leaving blunt pointed stubs. In a similar manner a reduction of the combustion period from infinity to a few seconds for green conifer needles takes place when a fire crowns.

The fifth fuel factor, the quantity of firebrand material available for spotting, becomes increasingly important as fire intensity increases. Equally important is the relation between surface fuel moisture and the probability of ignition from embers or firebrands dropped from the air. This relation has not as yet been determined experimentally, but ignition probability increases rapidly with decreasing fuel moisture—hence with decreasing relative humidity. We know that the ignition probability for most firebrands is essentially zero when fuel moisture is 25 or 30 percent (on an oven-dry weight basis). We also know that not only ignition probability but also combustion rate is

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* Heat sources a considerable distance behind the main flame front could possibly have indirect effects on fire behavior by slightly modifying the structure of the wind field.

In a blowup, the sides of the fire triangle are so greatly strengthened that a high-intensity erratic fire cannot be considered as a large-scale model of a low-intensity fire.

greatest for oven-dry material. In addition, both of these phenomena in the lower moisture content range appear to be considerably affected by a change of fuel moisture content of only a few percent.

The importance of the relation between fuel moisture and ignition probability in the behavior of large fires can be illustrated by a hypothetical example. Suppose that from the convection column over a large fire, 10,000 embers per square mile per minute are dropping in front of the fire. Suppose that the surface fuel moisture content is such that only 0.1 percent of these firebrands catch and produce spot fires, thus giving only 0.1 spot fires per square mile. On the other hand, if we assume that the surface fuel moisture is low enough for 5 percent of the embers to catch, then there would be 500 spot fires per square mile. As they burn together, these spot fires would greatly increase the rate of spread and intensity of the main fire.

Thus, relative humidity (working through fuel moisture) has a twofold effect on rate of spread in certain types of extreme fire behavior. First is the effect on fuel combustion rate and rate of spread of the ordinary flame front. This effect would be present on small and large fires alike. Second is the effect in accelerating rate of spread and fire intensity by increasing the probability of ignition from falling embers. This latter effect would be present only on fires where spotting was abundant. Ignition probability will also depend on other factors, such as the nature of the surface fuel in which firebrands fall and the fraction of the ground area covered by the fuels.

Fuel characteristics that make plentiful and efficient firebrands are not definitely known. The material would have to be light enough to be carried aloft in updrafts, yet capable of burning for several minutes while being carried forward by the upper winds. Decayed punky material, charcoal, bark, clumps of dry duff, and dry moss are probably efficient firebrands. Leaves and grass are more likely to be inefficient firebrands except over short distances.

The initial phases of the blowup phenomenon are directly related to the combustion process and the basic fuel factors. A decreasing fuel moisture means higher combustion rates and shorter combustion periods. There will, therefore, be an increase in the available fuel energy, or available fuel, accompanied by an increase in fire intensity. The increase in fire intensity lengthens the critical burn-out time, which means a further increase in available fuel. A cycle of reinforcement is thus established which favors growth of fire intensity. As the intensity increases, the atmospheric factors become increasingly important. It is at this stage that spotting and ignition probability may become dominant fire behavior factors.

By using the basic fuel factors it is possible that a fuel classification method could be developed to classify fuel in terms of expected fire behavior. It would first require a series of burning experiments to measure some of the factors and their response to variables such as moisture content and fire intensity. However, once this was done, the classification system itself might be comparatively simple. Probably its greatest value would be in estimating the conflagration potential of different fuel and cover types for different combinations of weather conditions.

There is an important difference in the energy conversion process for a low-intensity fire and a high-intensity fire. In the “thin” or two-dimensional fire, most of the energy remains in the form of heat. At the most, such a fire cannot convert more than a few hundredths of one percent of its heat energy into the kinetic energy of motion of the updraft gases and the kinetic energy of the convection column eddies.* On the other hand, a major conflagration may convert 5 percent or more of its heat energy into kinetic energy which appears in the form of strong turbulent updrafts, indrafts, convection column eddies, and whirlwinds which can carry burning material aloft. The efficiency of the energy conversion process, and hence the kinetic energy yield, increases rapidly with increasing fire intensity. This is brought about by the mutual reinforcement action in the basic fuel

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* Although a detailed discussion is outside the scope of this paper, energy conversion processes in a fire can be studied by a thermodynamic procedure in which a large fire, like a thunderstorm, can be treated as a heat engine. The efficiency of a heat engine is measured by the fraction of heat or thermal energy that can be converted into the kinetic energy of motion. A two-dimensional fire has an efficiency as a heat engine that is very nearly zero or, at the most, only a few hundredths of one percent. A major high-intensity fire has an efficiency as a heat engine that may reach 5 percent or more.

factors plus favorable atmospheric conditions.

In addition to the difference in the energy conversion processes in the two types of fires, there is an enormous difference in rate of energy yield. For example, there were periods in the Buckhead fire in north Florida in March 1956 when the rate of spread probably exceeded 8,000 acres (3,200 ha) per hour. The rate of energy release from this fire would compare favorably with the rate of energy release from a summer thunderstorm.

Summary

Combustion is basically a chemical chain reaction that can be divided into three separate phases:

1. Preheating and distillation,
2. Distillation and the burning of volatile fractions, and
3. The burning of the residual charcoal.

For a forest fuel, ignition is the link between phase 1 and phase 2 of the combustion process. For most forest fuels the heat of combustion is between 8,000 and 9,000 B.t.u.'s per pound on a dry weight basis.

> The initial phases of the blowup phenomenon are directly related to the combustion process and the basic fuel factors.

> It is the three-dimensional structure of a large fire that causes it to take on storm characteristics.

Heat is transferred by conduction, convection, and radiation. A fourth means of heat transfer might be defined as mass transport and is the familiar phenomenon of spotting, which becomes increasingly important on high-intensity fires.

Fuel moisture has more effect on the ignition and combustion process than any other factor.

Low-intensity fires are essentially two-dimensional phenomena, and major high-intensity fires three-dimensional. The third dimension of a high-intensity fire permits the conversion of part of its heat energy into the kinetic energy of motion, which changes the relative significance of the various combustion factors and greatly modifies their expected effects. For this reason a high-intensity fire cannot be regarded as a magnified version of a low-intensity fire.

The relation of fire behavior to the combustion process can be understood by the use of a group of basic fuel factors, which are (1) combustion period, (2) critical burn-out time, (3) available fuel energy, (4) total fuel energy, and (5) quantity of material available for spotting. Such a group of factors might be used to classify fuels in terms of expected fire behavior.

If atmospheric conditions are such that one or more strong convection columns can form, the following appear to be the main combustion factors that determine the intensity and rate of spread of a major fire:

1. The quantity of available fuel energy, or available fuel, per acre. The magnitude of this quantity depends on a reinforcing relationship between the basic fuel factors. In turn, this relationship is regulated primarily by fuel size and arrangement, fuel moisture, and the intensity of the fire itself.
2. Quantity of firebrand material per acre available for spotting.
3. Probability of ignition from firebrands dropping ahead of the main burning area. This probability depends on several factors, the most important of which is the prevailing relative humidity determining the surface fuel moisture. ■

VORTEX TURBULENCE— ITS EFFECT ON FIRE BEHAVIOR*

James B. Davis and Craig C. Chandler

"The fire wasn't doing much until the air tanker went over, and then it spotted all over the place," complained the fire crew foreman.

Vortex turbulence consists of a pair of miniature whirlwinds trailing from the wingtips of any aircraft in flight.

Such reports have caused fire control officers to ask, "Can air tankers really cause erratic fire behavior?" The answer is yes—under some conditions. The gremlin is "vortex turbulence," a pair of whirlwinds streaming out behind the wingtips.

What is Vortex Turbulence?

Vortex turbulence is a sheet of turbulent air that is left in the wake of all aircraft. It rolls up into two strong vortices, compact fast-spinning funnels of air, and to an observer on the ground appears to trail behind each wingtip (fig. 1). Because it moves out at right angles to the flight path, vortex turbulence can be distinguished from propeller wash, which is largely localized to a narrow stream lying approximately along the flight path. Unfortunately, however, vortex turbulence is usually invisible.

Under certain conditions the two vortices may stay close together, sometimes undulating slightly as they stretch rearward. The interaction between them tends to make them move first downward, then outward along the surface of the ground.

How Important are Vortex Wakes?

The Flight Safety Foundation, Inc., reports: "In recent years, there have

Figure 1—*Low-flying spray plane. Note funneling effect of spray trailing behind each wingtip. This is vortex turbulence.*

When this article was originally published, James Davis was a forester for the USDA Forest Service, Pacific Southwest Forest and Range Experiment Station; and Craig Chandler was a fire behavior specialist for the Forest Service, Forest Fire Research. Washington Office.

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been increasingly frequent reports by pilots encountering severe disturbances of another airplane even when separated from it by distances of several miles. There also are an increasing number of fatal accidents to lighter airplanes, resulting from upsets near the ground or structural failures which are being ascribed to encounters with wakes of large airplanes. It is now generally accepted that the only disturbance which an airplane can produce that is powerful and persistent enough to account for these incidents arises from the vortices which trail from the wingtips of any airplane in flight.”

The vortex in the form of a horizontal whirlwind can cause sudden and violent changes in fire behavior on calm days in patchy fuels.

Ordinarily, vortex turbulence does not pose any difficulties to fire control forces. But under special circumstances vortex wakes may cause a fire to act most unexpectedly. Line personnel should become familiar with the vortex problem and the situations where it is likely to affect fire behavior.

What Causes Vortex Turbulence?

Vortex turbulence is a byproduct of the phenomenon that gives lift to an airplane. Air flowing the longer route over the top of the wing has to travel faster than the air flowing across the bottom in order to reach the trailing edge simultaneously. The difference in speed causes a difference in pressure between the top and bottom of the wing with a resultant upward force, or lift. If you want to demonstrate this effect, hold the back of a spoon in a stream of water from a faucet. The spoon will be pulled into the stream as soon as the water touches it.

However, here is where the trouble starts. Since the air pressure is greater on the under surface of the wing than on top, some air tries to flow around the end of the wing to the lower pressure area. Because of the flow around the tip, the main stream—instead of flowing straight back across the top and bottom of the wing—tends to fly inward toward the fuselage on the top of the wing and outward on the bottom. As a result, the air doesn’t “fit together” at the trailing edge but forms a vortex sheet that rolls up into two large whirlwinds that trail from each wingtip (fig. 2).

Is Turbulence the Same for All Air Tankers?

Vortex severity and persistency vary with several factors. Most important are the type and size of the aircraft and the condition of the air. Vortex turbulence is greatest when produced by a large aircraft with a heavy wingspan loading.

Thus, the heavier the aircraft or payload per unit of wing surface, the more severe the turbulence will be. The B-17 is a heavier airplane than the PBY. Thus, when the vortex wake immediately behind a B-17 is 29 m.p.h. (46 km/h), the lighter PBY’s vortex will be only 16 m.p.h. (26 km/h) under the same flying conditions, since both planes have the same wingspan.

How Does Air Tanker Speed Affect Turbulence?

It may seem surprising, but turbulence is inversely related to airspeed (fig. 3).

Other factors being equal, an aircraft with a high wingspan loading at slow airspeed is the source of the strongest vortices. In terms of air safety, one of the greatest hazards is a heavily loaded aircraft flying at slow speeds before landing or after takeoff. Essentially, this is the condition when an air tanker slows down for an accurate airdrop.

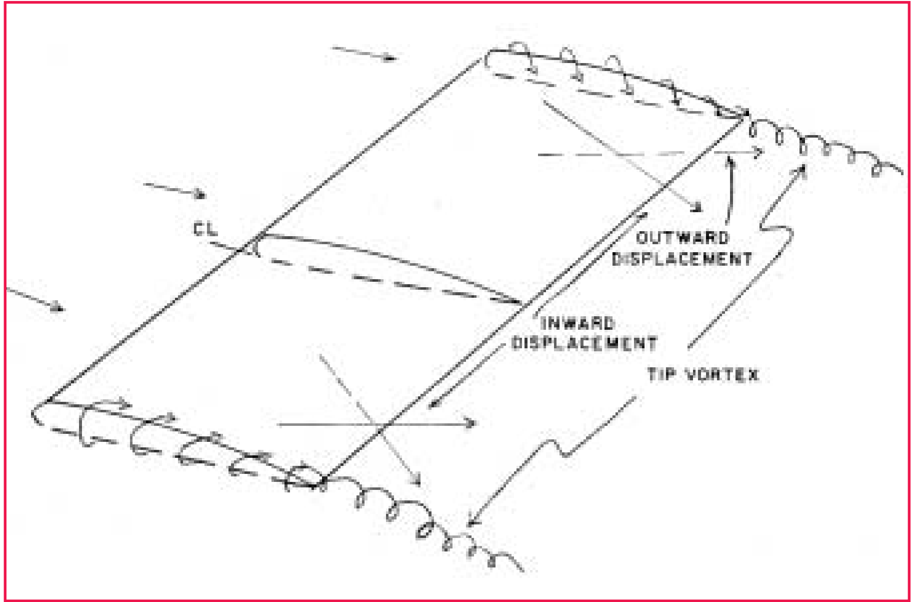

Figure 2—*Airflow over wing with distortion of flow and vortex formation.*

The air tanker pilot should be aware of the problem his aircraft can cause through the effect of vortex wakes on a fire.

How Does Aircraft Height Affect Turbulence?

At high altitude, the two vortices remain separated by a distance slightly less than the aircraft's wingspan. However, the interaction of the two causes them to drop. As they approach within approximately a wingspan of the ground, they begin to move laterally outboard from each wingtip. The lateral motion may be better termed "skidding" than "rolling," for at the ground contact point the direction of rotation is opposite the core's lateral movement (see fig. 2). The downward movement may require only 10 seconds from a TBM flying at 50 feet (15 m), but a minute or more from the same aircraft flying at 150 feet (45 m). The time required for downward movement is important for two reasons:

1. Wind can blow the vortices away from the drop area. For example, a 10-m.p.h. (16-km) wind can blow the vortices more than 800 feet (240 m) in the short time required to drop from 150 feet (45 m).
2. Vortices weaken rapidly with time. Under average air conditions, the turbulence may lose its danger potential in less than a minute. In rough air, the funnels break up and weaken even more rapidly. Calm air is the worst situation because it permits the turbulence to persist for a longer period.

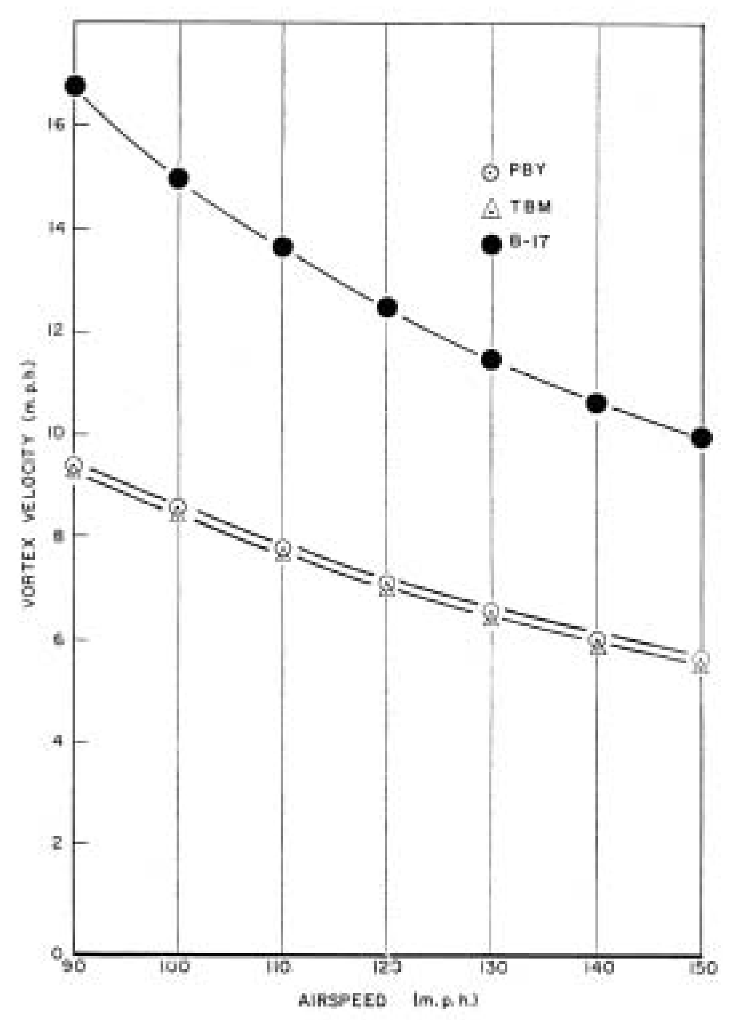

Figure 3—*Relation of vortex velocity to air tanker speed. The tanker's altitude was 75 feet (23 m); vortices took about 15 seconds to reach the ground, where their velocities were obtained.*

How Does Vegetation Affect the Vortex?

Natural surfaces are more or less rough and, therefore, cause frictional resistance to air movement above them. The rougher the surface, the greater the friction. Timber, for example, has a much greater slowing effect on wind than does open grassland. Whereas a vortex turbulence is more like a horizontal whirlwind than what we normally think of as a wind, the same frictional considerations apply. A heavy stand of timber would dissipate most of the force of a vortex; the same vortex would be only slightly weakened in grass or scattered timber.

How Do Vortex Wakes Affect Fire Behavior?

Although there are many observations on the effect of vortex wakes on other aircraft, we have only two or three on forest fires. However, what is known about the vortex and about fire behavior can lead to some pretty good guesses.

Because wind tends to break up the vortex and is normally accompanied by much natural turbulence, the chances are that vortex turbulence will probably be noticeable only on a calm day. Not only will the vortex wake be stronger on quiet days, but because the fire will usually be spreading slowly, the sudden air turbulence will be even more unexpected and potentially serious.

On the ground, the effect of vortex turbulence will be felt as a sudden gust which may last only a few seconds or for up to half a minute. In litter, grass, or light brush the result will be a sudden but brief flareup or increase in local fire intensity and rate of spread. In heavy timber or brush fuels with a continuous overstory, vortex turbulence will usually not reach the ground and so will have no noticeable effect on fire behavior.

In patchy fuels, where timber or brush is interspersed with open grassy areas, the effects of vortex turbulence may be extremely serious. Although the vortex wake will not reach the ground beneath a timber canopy, it may in the openings. Because the core usually remains above ground, the true wind direction at the surface is not parallel to the ground but slightly upward (fig. 4). Thus, both flames and burning embers tend to be swept upward as well as outward. Thus, vortex turbulence, compared with a natural gust of the same velocity, has a greater potential for triggering crowning and spot fires because flames and embers are driven up into the crowns.

The most serious situation is calm air on the ground but a light, steady wind aloft. Under these conditions the vortex may be carried far from the aircraft to strike the ground in an unexpected location, with ember showers being moved over long distances by the upper winds. Only rarely would one encounter a fire in patchy timber and brush under precisely these weather conditions; yet this was apparently the case on one well-documented fire in California in 1962.

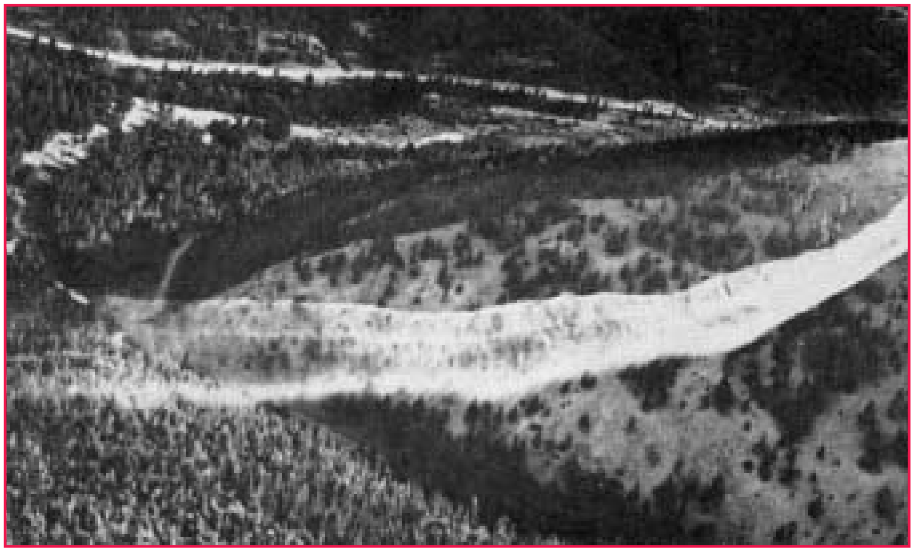

Figure 4—*Wake from a DC-3 and pronounced vertical motion of the vortex.*

Summary

Vortex turbulence consists of a pair of miniature whirlwinds trailing from the wingtips of any aircraft in flight. The more heavily loaded the aircraft, and the lower and slower it flies, the stronger the vortex turbulence will be and the more likely to reach the ground. The vortex will be in the form of a horizontal whirlwind with velocities up to 25 m.p.h. (40 km/h)—sufficient to cause sudden and violent changes in fire behavior on calm days in patchy fuels.

Wind, gustiness, and surrounding high vegetation will tend to break up or diminish vortex intensity.

The fire crew should be alert for trouble when:

1. The air is still and calm.
2. The fire is burning in open brush or scattered timber.
3. The air tanker is large or heavily loaded.
4. The air tanker is flying low and slow.

The air tanker pilot should be aware of the problem his aircraft can cause. He may know the effect of vortex wakes on his or other aircraft, but may not know the effect on a fire. He can abide by the following rules during situations of possible danger from vortex wakes:

1. Don't fly parallel to the fireline more than necessary.
2. Keep high except when making the actual drop.
3. Ensure that ground crews are alert to the presence of the air tanker and the pilot's intentions.

Acknowledgments

The authors have received technical guidance from many sources but are especially grateful to Richard C. Rothermel, Aeronautical Engineer, Northern Forest Fire Laboratory; Herbert J. Shields, Supervisory Engineer, Arcadia Equipment Development Center; and Alan W. McMasters, Operations Analyst, Pacific Southwest Forest and Range Experiment Station. ■

THE CONCEPT OF FIRE ENVIRONMENT*

C.M. Countryman

Webster** defines "environment" as "the surrounding conditions, influences or forces that influence or modify."

This definition applies to "fire environment" very well. For fire environment is the complex of fuel, topographic, and airmass factors that influences or modifies the inception, growth, and behavior of fire.

Fire environment may be represented by a triangle (fig. 1). The two lower sides of the triangle represent the fuel and topographic components of fire environment. The top side represents the airmass component; this is the "weather" part of the fire environment.

Interrelationships of Components

Fire environment is not static, but varies widely in horizontal and vertical space, and in time. The fire environment components and many of their factors are closely interrelated. Thus, the current state of one factor depends on the state of the other factors. Also, a change in one factor can start a chain of reactions that can affect the other factors.

For example, consider the simple topographic factor of slope aspect. The amount of heating of fuel by the sun on a slope depends partly on aspect. A slope facing east begins to warm first, and its maximum temperature occurs early in the day (fig. 2A). A slope facing south reaches its maximum temperature about 2 hours later, and it is higher than the maximum of the east-facing slope (fig. 2B). A slope facing west reaches its maximum temperature still later, and this maximum is higher than those of the east and south slopes (fig. 2C). The north slope also has its distinctive diurnal trend (fig. 2D). The data illustrated in figure 2 were obtained from observations taken on a clear day on 45-degree slopes early in July at 42° N. For a different combination of cloud cover, slope, time of year, and latitude, a different pattern would be observed. This differential heating of different aspects affects the probability of fire starts, and also fire growth and behavior.

Fire environment is the complex of fuel, topographic, and airmass factors that influences or modifies the inception, growth, and behavior of fire.

When this article was originally published, C.M. Countryman was a research forester for the USDA Forest Service, Pacific Southwest Forest and Range Experiment Station.

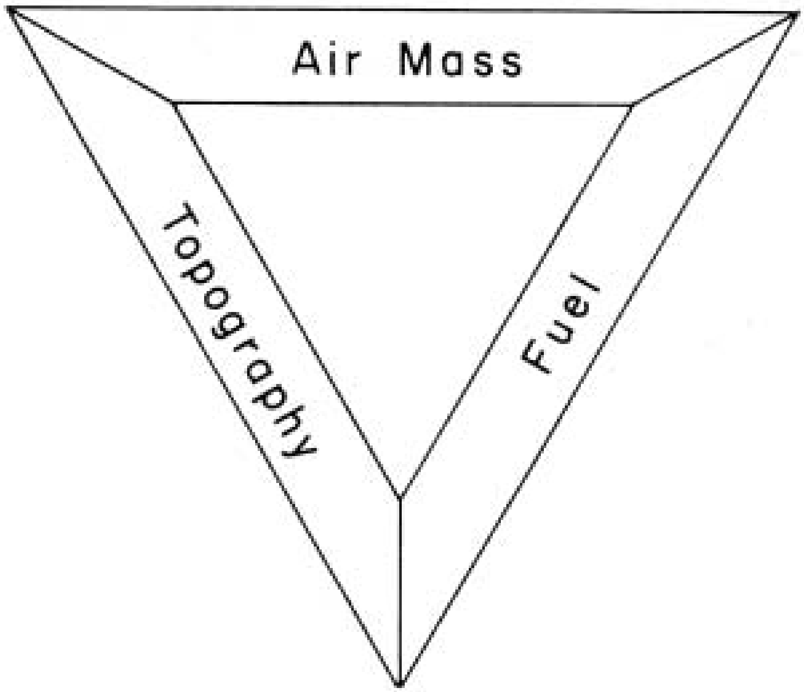

Figure 1—*Fire environment may be represented by a triangle. Each side represents a component of fire environment.*

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* The article is reprinted from *Fire Control Notes* 27(4) [Fall 1966]: 8–10.
** Webster's Third International Unabridged Dictionary (1961: G. & C. Merriam Co.), p. 760.

When the surface of a slope is heated, it transmits this heat to the air above it by conduction, convection, and radiation. The resulting increase in air temperature changes the relative humidity. In addition, local winds also are often strongly affected by the differences in air temperature resulting from the differential heating of slopes of different aspects. These winds are further modified by the configuration of the topography and by the surface fuels. Since the moisture content of fine dead woody fuels depends primarily on the relative humidity of the air, the differences in heating of slopes can affect both fuel moisture content and fuel temperature. The amount of heating of fuels, vegetative or urban, on the surface is affected by airmass conditions such as clouds, moisture content, and windspeed.

> Because fire behavior and fire environment are interdependent, changes in one will cause changes in the other.

Fire and Fire Environment

Where does fire fit into this picture? In an environment without fire, radiant energy from the sun is almost the only source of heat. This energy heats the earth's surface and to a minor extent the air above it. Most of the energy that directly and indirectly modifies the airmass and fuel components of fire environment comes from the heated earth surface. Because of differences in slope, aspect, and ground cover, heating by the sun is not uniform—some areas become much warmer than others. This variation in the local heat sources creates the variability in local weather and fuel conditions.

Perhaps we can most simply consider fire as just another local heat source. As a heat source it reacts with its surroundings in the same

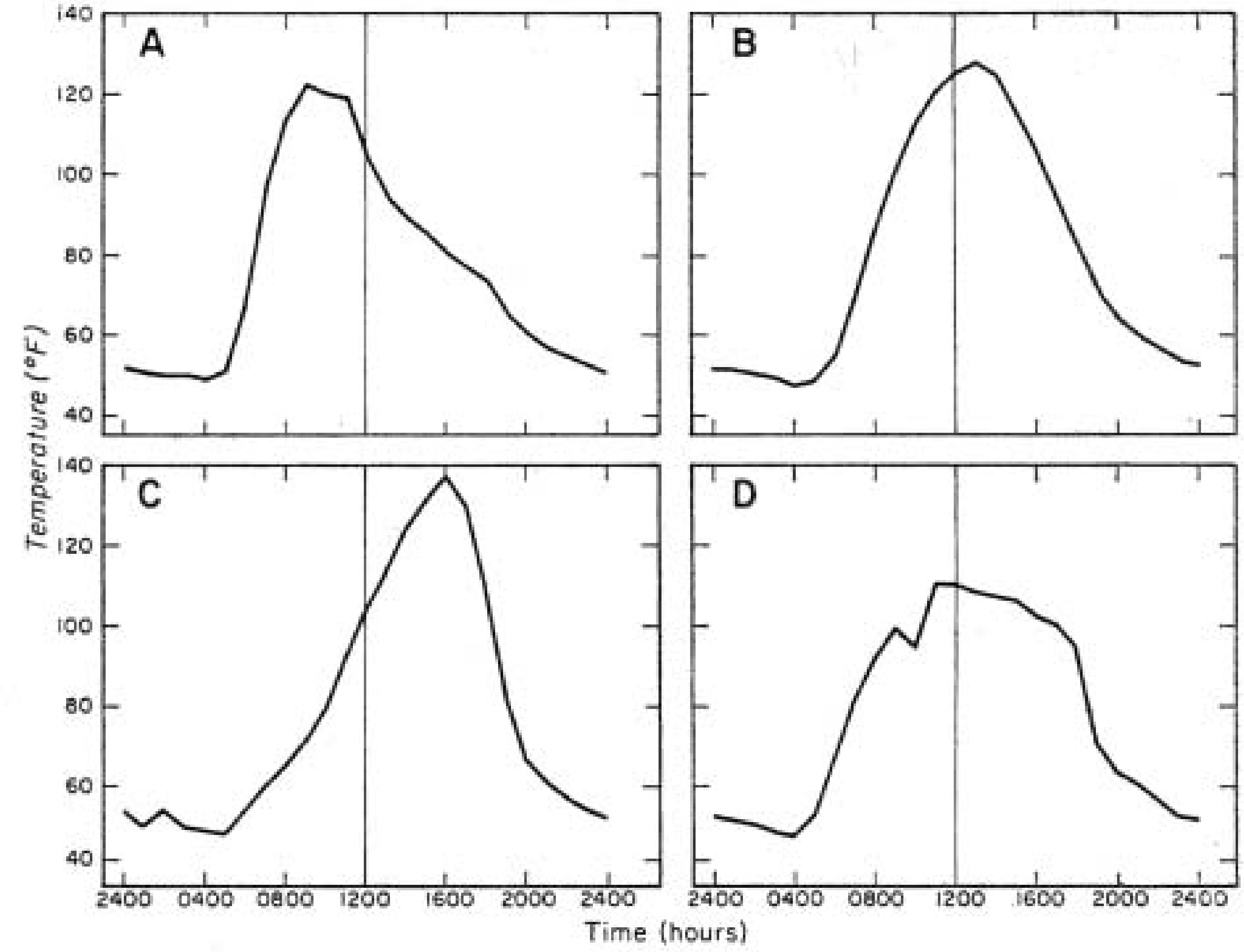

Figure 2—*Relationship of temperature to time of day on 45-degree slopes facing in four directions: A, east; B, south; C, west; and D, north. Data were taken on a clear day in early July at 42° N.*

way as other local heat sources: interacting with the airmass to create changes in local weather, and with the fuel to a modify fuel moisture and temperature. Because of the high temperatures in a fire, however, the reaction can be much more violent. By adding fire to the center of the fire *environment* triangle (fig. 1), this symbol becomes the fire *behavior* triangle. It is the current state of each of the environmental components—topography, fuel, and airmass—and their interactions with each other and with fire that determines the characteristics and behavior of a fire at any given moment.

Fire Environment Patterns

Because fire behavior and fire environment are interdependent, changes in one will cause changes in the other. To understand or predict fire behavior, we must look at the fire behavior and the fire environment at all points of the fire. Thus, both fire behavior and fire environment are pattern phenomena.

The scope of the fire environment depends primarily on the size and characteristics of the fire. For a very small fire, the environment is a few feet horizontally and vertically. For a large fire, it may cover many miles horizontally and extend thousands of feet vertically. An intensely burning fire will involve a larger environmental envelope than one burning at a lower combustion rate.

Open and Closed Fire Environments

From a fire behavior standpoint, fire environment can be separated into two general classes:

A fire burning under a dense timber stand is burning in a closed environment that may be much different than the more open environment above or outside the stand.

1. Closed environment, and
2. Open environment.

Inside a building, for example, the fire environment is nearly independent of outside conditions. Fuel characteristics are determined by the construction of the building and by its contents. The climate and, hence, the moisture content of the hygroscopic fuels are controlled by the heating and cooling systems. Air movement and topographic effects are nearly nonexistent. This is confined or “closed” environment. However, the environment outside buildings is not confined. Current airmass characteristics vary with the synoptic weather patterns and local conditions. Wind movement and topographic effects prevail. This is “open” environment.

Fire burning inside a building is controlled by the fire environment within the building. The outside environment has little effect. As long as the fire remains within the building (fig. 3A), there can be no spread to adjacent fuel elements. The fire is confined.

If the fire breaks out of the building, it is no longer burning in a closed environment. Outside conditions can influence its behavior, and the fire can spread to other fuel and grow in size and intensity (fig. 3B).

Closed and open environments also exist in wildland fuels; however, the boundaries between the two environments are not as clear as they are in urban areas.

For example, a fire burning under a dense timber stand (fig. 3C) is burning in an environment that may be much different than that above or outside the stand. Fuel moisture is often higher, daytime temperature is lower, and windspeed is much slower. In this situation the fire is burning in a closed environment.

If the fire builds in intensity and breaks out through the crowns of the trees (fig. 3D), it is burning in an open environment and can come under an entirely different set of controls. Fire behavior and characteristics can change radically.

Open and closed environments exist in other fuels as well as timber, such as grass and brush. Because of the short vertical extent of these fuels, the probability of fire burning entirely in a closed environment is much less. But the closed fire environment in a fuel bed influences fire behavior, even if only part of the fire is burning in a closed environment.

The most obvious use of the concept of fire environment and fire behavior patterns is probably in understanding and predicting wildfire behavior, but the concept can also be used in prescribed burning. In fires of low or moderate intensity, which are usually desired in prescribed burning, the fire environment pattern largely controls the behavior pattern. Thus, by knowing the fire environment pattern for the area, the fire behavior pattern can be predicted. And by selecting

Figure 3—*These fires are burning in the following fire environments: A, closed urban; B, open urban; C, closed wildland; D, open wildland.*

the proper environment pattern, the desired type of behavior can he obtained and dangerous points can be alleviated.

> For a prescribed fire, by knowing the fire environment pattern for the area, the fire behavior pattern can be predicted.

Summary

Fire environment is the complex of fuel, topographic, and airmass factors that influences or modifies the inception, growth, and behavior of fire. It is the current state of these factors and their inter-relationship with one another and with fire that determines the behavior and characteristics of a fire at any given moment.

Fire environment is not static, but varies widely in space and time. Both fire environment and fire behavior are pattern phenomena, and both patterns for the area of the fire must be considered in order to understand and predict a fire's behavior.

Because of the difference in the fire environment patterns, the behavior of fire burning in a closed environment may be vastly different from one burning in an open environment. The concept of fire environment and fire behavior patterns is useful for the understanding and prediction of fire behavior for both wildfires and prescribed fires. ■

GET THE MOST FROM YOUR WINDSPEED OBSERVATION*

John S. Crosby and Craig C. Chandler

Surface windspeed is often the most critical weather element affecting fire behavior and fire danger. It is also the most variable and, consequently, the hardest to evaluate.

> Peak windspeeds that persist for 1 minute can affect gross fire behavior, including rate of spread and fire intensity.

What Is Gustiness?

Air moving across the surface of land is constantly changing speed and direction. Standing still, one observes a series of gusts and lulls. Because of gusts, trying to measure windspeed is much like trying to measure the speed of a car on a winding mountain road. It slows on the turns, speeds up on the straightaways, and slows to a crawl on bumpy stretches. To obtain a reliable average speed, one must determine the time required to travel at least 2 miles (3.2 km). And the rougher and more crooked the road, the longer is the distance required to obtain a reliable average. This same principle applies to wind measurements. The greater the gustiness (the ratio between the range in momentary windspeeds and the average speed), the longer it takes to determine a reliable windspeed.

Peak windspeeds that persist for 1 minute can affect gross fire behavior, including rate of spread and fire intensity. For example, a surface fire in pine litter spreading at 10 chains (660 feet [201 m]) per hour with the wind averaging 5 miles per hour (8 km/h) would spread 11 feet (3.3 m) farther than expected during a minute when the wind was blowing at 9 miles per hour (14 km/h). During that minute it would burn with twice its average intensity and would be nearly three times as likely to jump a prepared fireline.

Momentary gusts have little effect on the overall rate of fire spread and intensity, but they do produce large fluctuations in flame height and can easily trigger crowning or throw showers of sparks across the fireline when other weather factors are in critical balance. Gusts will usually be close to the average value and will rarely exceed the maximum value.

Gustiness is caused by mechanical and thermal turbulence.

Mechanical turbulence is produced by friction as the air flows over the ground surface. Its magnitude depends on the height above the ground where measurements are made, the roughness of the ground surface, and the windspeed. The maximum mechanical turbulence is found close to the surface in rough topography on windy days.

Thermal turbulence occurs when horizontal wind meets convective currents produced by unequal heating or cooling at the ground. Its magnitude depends mostly on topography, ground cover, solar radiation, and atmospheric stability. The maximum thermal turbulence occurs above rough topography with patchy ground cover during sunny afternoons in unstable air.

Gustiness Problem

Gustiness is a serious problem for both fire researchers and fire-control planners. Because of gustiness, wind measurements at two locations cannot be compared unless they are taken at the same height above the ground and for the same length of time. For maximum comparability, measurements should be taken as high above the ground as possible and for as long as possible. But high towers and long observations are expensive. Therefore, for fire-danger rating we have established a standard anemometer height of 20 feet (6.1 m) and a standard observation time of 10 minutes.

While these standards are fine for fire-danger rating, they often confuse the firefighter on the ground. Rapid changes in fire behavior are determined by rapid changes in the wind blowing on the burning fuel, and not by changes in the long-

When this article was originally published, John Crosby was a research forester for the USDA Forest Service, North Central Forest Experiment Station, Columbia, MO; and Craig Chandler was Forest Service Assistant Chief, Forest Fire Research Branch, Division of Forest Protection Research, Washington, DC.

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term average windspeed 20 feet (6.1 m) above ground. Often the firefighter loses confidence in his meteorologist or his weather station, or both, because he is told to expect a 16-mile-per-hour (26-km/h) wind and found the fire fanned by 35-mile-per-hour (56-km) gusts. He often must estimate the variations in windspeed that may be expected for the average speed that is reported.

Tool for Estimating Gustiness

To help firefighters estimate gustiness, we determined the 10-minute average speed, the probable fastest 1-minute average speeds, and the probable average and highest momentary speed or gust during the fastest 1-minute speed (table 1). The table values were determined from several hundred noon and afternoon observations made at Salem, Missouri, during fire seasons. They were taken when gustiness was likely to be greatest, as it often is on difficult fires. Thus, the estimates are most accurate when they are needed the most.

It is difficult to convert windspeeds taken by firefighters to the standard windspeed. In preparing spot forecasts for project fires, wind measurements are often made with a hand-held anemometer. This instrument indicates gust speed accurately, but it is almost impossible to accurately determine average speed with it. Consequently, the windspeed reported from the fireline almost invariably is the average gust speed rather than the accepted 20-foot (6.1-m), 10- minute standard. Therefore, another table was

Often the firefighter must estimate the variations in windspeed that may be expected for the average speed that is reported.

Table 1—*Wind gust estimating table.*

Standard 10-minute average		***Probable maximum 1-minute speed***		***Probable momentary gust speed***			
				Average		***Maximum***	
mph	***km/h***	***mph***	***km/h***	***mph***	***km/h***	***mph***	***km/h***
1	1.6	3	4.8	6	9.7	9	14.5
2	3.2	5	8.0	8	12.9	12	19.3
3	4.8	6	9.7	11	17.7	15	24.1
4	6.4	8	12.9	13	20.9	17	27.4
5	8.0	9	14.5	15	24.1	18	29.0
6	9.7	10	16.1	16	25.7	20	32.2
7	11.3	11	17.7	17	25.7	21	33.8
8	12.9	12	19.3	19	30.6	23	37.0
9	14.5	13	20.9	20	32.2	24	38.6
10	16.1	14	22.5	22	35.4	26	41.8
11	17.7	15	24.1	23	37.0	27	43.5
12	19.3	17	27.4	25	40.2	29	46.7
13	20.9	18	29.0	26	41.8	30	48.3
14	22.5	19	30.6	28	45.1	32	51.5
15	24.1	20	32.2	29	46.7	33	53.1
16	25.7	21	33.8	30	48.3	35	56.3
17	27.4	22	35.4	32	51.5	36	57.9
18	29.0	23	37.0	33	53.1	38	61.2
19	30.6	24	38.6	34	54.7	39	62.8
20	32.2	25	40.2	35	56.3	40	64.4
21	33.8	26	41.8	37	59.5	42	67.6
22	35.4	27	43.5	38	61.2	43	69.2
23	37.0	28	45.1	39	62.8	44	70.8
24	38.6	29	46.7	40	64.4	46	74.0
25	40.2	30	48.3	41	66.0	47	75.6
26	41.8	31	49.9	43	69.2	49	78.9
27	43.5	32	51.5	44	70.8	50	80.5
28	45.1	33	53.1	45	72.4	51	82.1
29	46.7	34	54.7	46	74.0	53	85.3
30	48.3	35	56.3	47	75.6	54	86.9

Note: All readings were taken in the afternoon 20 feet (6.1 m) above the ground.

developed to convert gust speed 5 feet (1.5 m) above the ground to the standard 20-foot (6.1-m), 10-minute speed for stable, neutral, and unstable conditions (table 2). This conversion should be used when fire-danger indexes are determined from fireline observations or when wind information consists of a mixture of hand-held and tower observations. ■

Gustiness is a serious problem for both fire researchers and fire-control planners.

Table 2—*Standard windspeed estimates based on maximum gusts* [a]

Fastest gust observed on hand-held anemometer [b]		*Standard windspeed when atmospheric condition is:*					
		Stable [c]		*Neutral* [d]		*Unstable* [e]	
mph	*km/h*	*mph*	*km/h*	*mph*	*km/h*	*mph*	*km/h*
0–3	0–4.8	0	0	0	0	0	0
4–6	6.4–9.7	1	1.6	1	1.6	1	1.6
7	11.3	2	3.2	1	1.6	1	1.6
8	12.9	2	3.2	2	3.2	1	1.6
9	14.5	3	4.8	2	3.2	2	3.2
10	16.1	4	6.4	3	4.8	3	4.8
12	19.3	6	9.7	4	6.4	4	6.4
14	22.5	8	12.9	6	9.7	5	8.0
16	25.7	10	16.1	8	12.9	7	11.3
18	29.0	12	19.3	9	14.5	8	12.9
20	32.2	15	24.1	11	17.7	10	16.1
22	35.4	17	27.4	13	20.9	12	19.3
24	38.6	19	30.6	15	24.1	14	22.5
26	41.8	22	35.4	17	27.4	16	25.7
28	45.1	24	38.6	19	30.6	18	29.0
30	48.3	27	43.5	21	33.8	20	32.2
32	51.5	29	46.7	23	37.0	22	35.4
34	54.7	32	51.5	25	40.2	23	37.0
36	57.9	34	54.7	27	43.5	25	40.2
38	61.2	37	59.5	29	46.7	27	43.5
40	64.4	39	62.8	31	49.9	29	46.7

a. Standard windspeed is 10-minute average speed 20 feet (6.1 m) above the ground
b. Readings were taken 5 feet (1.5 m) above ground. For best results observations should be made for several minutes.
c. This column usually should be used for observations between 8 p.m. and 8 a.m.
d. This column usually should be used for observations between 8 a.m. and noon, and between noon and 8 p.m. on overcast days.
e. This column usually should be used between noon and 8 p.m. on clear or partly cloudy days.

Russo and Schoemaker (1989) Decision Trap 4—Overconfidence in Your Judgment:

Failing to collect key factual information because you are too sure of your assumptions and opinions.*

* See page 9.

Atmospheric Stability Forecast and Fire Control[*]

Rollo T. Davis

Unstable air masses increase chances of big fires. Relative humidity seems to play a smaller role than thought before. Atmospheric stability forecasts, projecting stability for 36 to 48 hours, can warn fire control personnel when to expect erratic fire behavior and an increase in blow-up potential.[**]

Have you ever wondered why some forest fires are extremely difficult to control while others, under seemingly like weather and fuel conditions, are relatively easy to curb? Even during dry periods when winds are high and humidities low, some fires show no erratic behavior or blow-up potential and are easily checked. But at other times, under apparently the same conditions, the wildest blow-up develops. Still more puzzling is the fact that some fires are almost impossible to control and become conflagrations even though the soil is wet, humidities are relatively high, and surface winds outside the fire zone are light. Why the difference?

Blow-up characteristics of forest fires have been attributed to low relative humidities and strong surface winds. Papers have been presented about the relationship between relative humidities below 30 percent and large fires. Daniel J. Kreuger, former Georgia Fire Weather Supervisor, made a study of forest fires in Georgia for the years 1950–59. He reported in the Georgia Forest Research Paper #3 that 77 percent of the fires burning 300 acres (121 ha) or more occurred when the relative humidity was 25 percent or less. Ninety-two percent of the large fires occurred when the relative humidity was 30 percent or less. Mr. Kreuger concluded:

> Most large fires occur when the temperature profiles through the lower levels of the atmosphere exhibit some degree of instability.

1. Fires, when promptly and adequately attacked (barring equipment failure), rarely, if ever, become large unless the relative humidity is 30 percent or less at the fire.
2. Potential for large fires increases rapidly as humidities fall below 25 percent. Fire fighters should increase their vigil whenever these low relative humidities exist or are forecast.

Atmospheric Turbulence

The relationship of atmospheric turbulence to erratic fire behavior has also been studied and discussed. As early as 1951, George M. Byram and Ralph M. Nelson presented a paper titled "The Possible Relation of Air Turbulence to Erratic Fire Behavior in the Southeast."[†] In this paper, they pointed out the possibility of a direct relationship existing between unstable low-level air and extreme fire behavior in the Southeast.

A review of the weather conditions at the time of the larger fires occurring in Mississippi during 1967 revealed that large, hard-to-control fires did not necessarily occur on the days with the lowest relative humidities. In fact, the largest fires occurred 24 to 48 hours after a day with desert-like humidities. This pattern seemed to be begun by the passage of a cold front. With cold, dry, continental arctic air overspreading the State behind the front, the relative humidities often dropped below 20 percent. One to 3 days later, relative humidities started climbing, but fire severity and size also increased.

Hoping that this unexpected fire pattern might be explained, the daily surface weather maps and the temperatures from the surface to the 5,000-foot (1,524-m) level were critically examined for all days on which fires of more than 300 acres (121 ha), classed as "E" fires, burned. The examination of the temperature profiles aloft strongly

When this article was originally published, Rollo Davis was a Forestry Meteorologist for the ESSA Weather Bureau, Jackson, MS.

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[*] The article is reprinted from *Fire Control Notes* 30(3) [Summer 1969]: 3–4, 15.

[**] *Editor's note:* Beginning with the Summer 1969 issue of *Fire Control Notes,* most articles in each issue started with a short summary paragraph. In 1972, the practice was largely discontinued.

[†] *Fire Control Notes* 12(3) 1–8.

suggested that the atmospheric instability in the lower atmosphere played a significant role in erratic behavior of fires.

To investigate further, information on all 1967 fires of the class "E" and larger was requested from the Fire Control Directors of the States surrounding Mississippi. The requested information was supplied by Louisiana, Arkansas, Tennessee, and Alabama, and a total of 70 fires were investigated. No attempt was made to investigate weather conditions for fires when fire control personnel were unable to attack the fire shortly after it started.

Atmospheric stability in the layer between the surface and the 5,000-foot (1,524-m) level was categorized for the investigations as follows:

1. *Stable*—Temperatures aloft decreasing with increase in altitude at a rate about 3.5 degrees F or less per 1,000 feet.
2. *Conditionally unstable*—Temperature decrease with increase in altitude at a rate of 3.5 to 5.4 degrees F per 1,000 feet. (Conditionally unstable air tends to become unstable if forced to rise. Additional heat supplied at the surface is sufficient to produce the needed rise.)
3. *Unstable*—Temperature decrease with increase in altitude of 5.5 degrees F per 1,000 feet.
4. *Absolutely unstable*—Temperature decrease with increase in altitude greater than 5.5 degrees F per 1,000 feet.

Only six of the 70 fires studied occurred when the conditions in the low levels of the atmosphere were classified as stable. Fifteen, or 21 percent, occurred when the air mass was classified as conditionally unstable, and fifteen others burned during unstable conditions. The greatest number, by a significant percentage, occurred when the air mass was classified as absolutely unstable. Thirty four of the big fires, nearly one-half of the 70 cases studied, burned when the air mass at the fire site was absolutely unstable.

Relative Humidities

Relative humidities in the area of the fires ranged from 18 percent to 80 percent. A large percent of the fires during periods when the atmosphere was absolutely unstable burned when relative humidities at the surface were above the level normally associated with big or erratic fires. Nearly 60 percent of the large fires studied took place when the relative humidity in the area was above 30 percent. Air mass stability, therefore, appears to be as significant, if not more significant, than low-level moisture in the behavior of forest fires once they got started.

It seems reasonable that air mass stability should play a very important role in the behavior of forest fires. Unstable air, from the meteorological viewpoint, is also convectively unstable. Once the air starts to rise, it will be warmer than its surroundings. The air continues to rise until it reaches a level where the temperature of the surrounding air is the same. When unstable air is displaced upward, it is replaced by air moving laterally, creating an indraft of air, which is also unstable. This air rises. With the heat of the fire being the initiating force to start and maintaining convection, a chain reaction is begun. The convective column increases in size, and the indrafts increase in velocity to fan the flames which then increase the heat to intensify convection, and so on (fig. 1). Fire control personnel are well aware of

Figure l—*Convection currents visibly at work on a forest fire.*

many of the direct and indirect effects of air mass instability on forest fires. Some of the more spectacular effects are rapid crowning, long-distance spotting, erratic movement, and blow-up potential.

Conclusions and Recommendations

Most large fires occur when the temperature profiles through the lower levels of the atmosphere exhibit some degree of instability. Fire control foresters who are furnished daily with an atmospheric stability forecast can plan ahead and use their manpower and equipment better.

The atmospheric stability forecast should be a routine product of all weather offices, and fire control personnel should be trained to use it.

Upper air temperature data are readily available at all ESSA Weather Bureau Offices where forestry meteorologists are stationed. These data enable the forestry meteorologist to determine the degree of atmospheric instability. Using other meteorological information available, such as the computerized lifted index prognostic charts, the forestry meterologist can project the stability into the future and come up with a forecast of the atmospheric stability for the following 36 to 48 hours. Considering the value of such forecasts to the forestry industry, the atmospheric stability forecast should be a routine product of all weather offices, and fire control personnel should be trained to use it. ■

Russo and Schoemaker (1989) Decision Trap 5—
Shortsighted Shortcuts:
Relying inappropriately on “rules of thumb,” such as implicitly trusting the most readily available information or anchoring too much on convenient facts.*

* See page 9.

DOWNBURSTS AND WILDLAND FIRES: A DANGEROUS COMBINATION*

Donald A. Haines

*On June 8, 1981, a wildland fire on Merritt Island, FL, suddenly changed directions, killing two firefighters. On August 2, 1985, Delta Flight 191 crashed and burned while attempting to land at Dallas-Fort Worth Airport. These two events had one common theme, strong thunderstorm downbursts.***

It happens to most firefighters sooner or later if they have been on the job long enough. Everything along the fireline seems fairly well controlled. But then, unexpectedly, the wind shifts and becomes erratic. Wind speed picks up dramatically for 5 to 15 minutes and then decreases.

Another factor is added to the high winds: Precipitation ranging from very light to very heavy. It may fall so hard during a thunderstorm that it puts out the fire, or it may evaporate before it hits the ground.

With a change in weather comes a change in fire behavior—this time for the worse. The fire changes direction, previously controlled lines are lost, and a routine operation becomes life threatening. What happened?

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A downburst is a downdraft associated with a thunderstorm or other well-developed cumulus clouds that induces an outburst of damaging winds on or near the ground.

Definition

The odds are high that the weather event described in the introduction was a downburst. A downburst is a downdraft associated with a thunderstorm or other well-developed cumulus clouds that induces an outburst of damaging winds on or near the ground. When the burst is small (0.4 to 4 km or 0.25 to 2.5 miles in diameter), it is a microburst; larger ones (more than 6.5 km or 2.5 miles in diameter) are macrobursts. Not all downdrafts are downbursts. Fujita (1978) stated that horizontal wind speeds generally exceed 40 miles per hour (64 km/h) on the ground in a true downburst. Although Schroeder and Buck (1970) discussed downdrafts in their handbook *Fire Weather*, recent research has greatly increased our knowledge of downburst occurrence and structure. Because a downburst can cause dramatic and dangerous fire behavior, firefighters should understand this phenomenon.

Downbursts are classed as either dry or wet. Most investigators believe that both types require raindrops as an initial condition because evaporation of these drops cools the air, which then falls as it gets heavier. Humid areas, like the Southeastern United States (where the downdraft is almost always associated with moderate to heavy rain), usually experience wet downbursts. The wet downburst produces a core of rain that is visible, although it may be obscured by associated weather.

Dry downbursts occur in more arid places, like Colorado, when cloud bases are higher and precipitation evaporates before the downdraft reaches the ground (Monastersky 1987). The dry downburst might not be seen easily by either radar or observers in such cases. Both cumulonimbus clouds as well as less fully developed rain clouds can produce them.

During a study of microbursts in the Denver area, Fujita and Wakimoto (1983) found that 81 percent were the dry type. Little or no rain fell to the surface with them. In contrast, during an Oklahoma study, Eilts and Doviak (1987) found that the macrobursts detected on their radar were imbedded in intense convective storms and had large, heavy rain cores. But, these differences in detection may be the result of scanning strategies used with the different radar units Eilts and Doviak (1987). In particular, the Oklahoma radar may have missed lighter rain cores.

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* The article is reprinted from *Fire Management Notes* 49(3) [Summer 1988]: 8–10.

** *Editor's note:* This article, unlike any others in the Summer 1988 issue of *Fire Management Notes*, contains a short summary paragraph. Except for a brief period from 1969 to 1972, this practice was highly unusual in the journal.

Sherman (1987) concluded that with the falling dense air in a downburst, the flow behaves like a toroidal vortex. In other words, as the vortex at the head of a downburst approaches the ground, each element of the falling vortex moves downward and outward along a roughly hyperbolic path. Near the cloud base, winds and rain converge around the descending air, feeding into it. A sharp observer might be able to spot the developing downburst if it is outlined by rain because the precipitation falls rapidly, reaching a downward velocity of 65 miles per hour (105 km/h).

When flying directly beneath a microburst, a pilot in a spotter plane will find that the difference between the headwind and the tailwind is typically 60 miles per hour (97 km/h) as the winds spill out horizontally to either side of the parent cloud. Fujita (1978) showed that in one case this difference exceeded 172 miles per hour (279 km/h).

Several researchers have found a relationship between an observed temperature drop at surface and the increased wind speed. The larger the temperature change, the more severe the wind gusts. The leading edge of the horizontal movement of the wind gusts is called a gust front. As it spreads horizontally, the gust front may develop as an expanding fluid structure many miles long, depending on the strength of the downburst (fig. 1).

A Tragic Example

Although wet downbursts are difficult to forecast, downbursts in a dry environment can be predicted from morning upper-air soundings.

The weather that occurred with the 1981 Florida wildland fire seems to have been a classical downburst (USDA FWS 1981). Two men operating a dozer and plow attempted containment along the eastern flank of the Ransom Road Fire. A thunderstorm developed and winds abruptly changed from south to west. In response, the head of the fire changed from north to east, and the flames overtook the two men. A tower with a recording anemometer to the northeast of the fire area showed wind speeds increasing from an average of 7 to

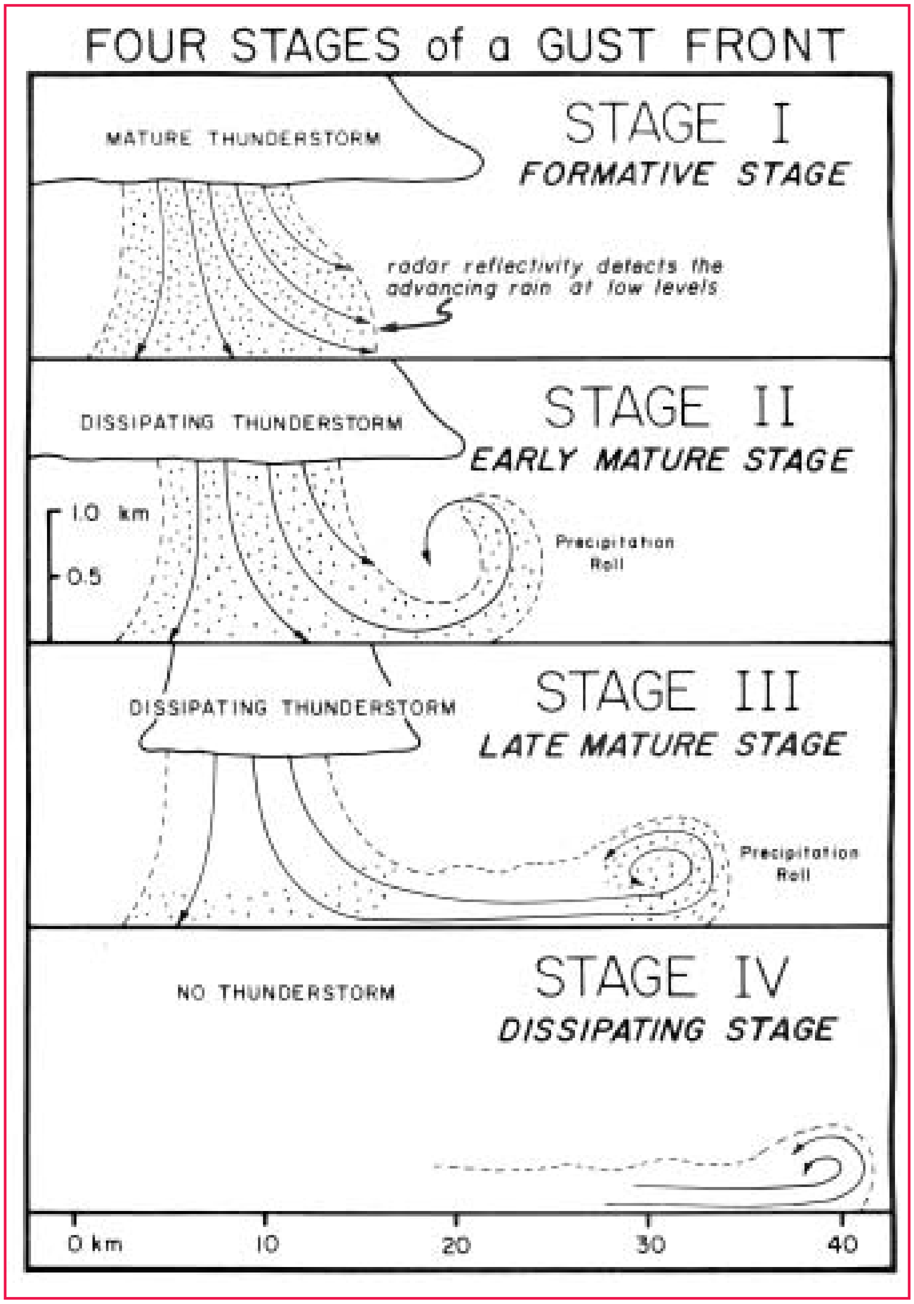

Figure 1—*The four stages of a thunderstorm downburst and gust front. The precipitation roll is a horizontal roll vortex formed by airflow that is deflected upward by the ground. Note the changes in wind direction as the gust front passes a point and moves on (Wakimoto 1982).*

25 miles per hour (11–41 km/h), with gusts to 52 miles per hour (84 km/h). Within 10 minutes, the temperature fell from 82 °F (28 °C) to 60º F (16 °C). The tower readings ended at that point as lightning hit it.

This then was a true wet-core downburst as “a heavy rainstorm, accompanied by thunder and lightning, descended on the fire area, lasting for 15 to 20 minutes and just about completely extinguished the wildfire” (USDA FWS 1981).

Forecast Possibilities

Although wet downbursts are difficult to forecast, downbursts in a dry environment can be predicted from morning upper-air soundings. According to Caracena and Maier (1987), “inroads have already been made into the microburst forecast problem in understanding the dry end of the convective spectrum where the concept of severe weather is extended to conditions that favor strong downdrafts from high base cumulonimbi.” They believe that to be able to forecast downbursts in all parts of the United States, meteorologists must first understand how nature generates them over the entire range from wet to dry extremes. Forecasters then could diagnose typical downburst conditions from the daily upper-air data.

Conclusions

Even though research is taking the surprise out of the dry downburst, forecasting the wet downburst will be a difficult problem for some time to come. Predicting the impressive winds that accompany these downbursts remains an elusive goal. Accordingly, the Board of Inquiry for the Ransom Road Fire aimed recommendations at the field level. The Board felt that an observer in a spotter plane in direct contact with the line crews could have anticipated the weather conditions and, hence, fire behavior changes. This could have allowed directions for an escape route. The Board also suggested that crews pull back from the fire during impending thunderstorms in areas with fuels that burn with high intensity and rate of spread, as in the Ransom Road Fire.

> The Board suggested that crews pull back during impending thunderstorms in areas with fuels that burn with high intensity and rate of spread.

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Wakimoto, R.M. 1982. The life cycle of thunderstorm gust fronts as viewed with Doppler radar and radiosonde data. Monthly Weather Review. 112(8): 1060–1082. ■

Russo and Schoemaker (1989) Decision Trap 6—Shooting From the Hip: Believing you can keep straight in your head all the information you’ve discovered, and therefore “winging it” rather than following a systematic procedure when making the final choice.*

* See page 9.

ESTIMATING SLOPE FOR PREDICTING FIRE BEHAVIOR*

Patricia L. Andrews

When predicting fire behavior in the field, it is desirable to be able to obtain the required input information with a minimum of special equipment. This article tells how to estimate slope (percent) using materials in a belt weather kit. This method can be used on wildfires by fire behavior analysts, field observers, and strike team leaders. Those who are monitoring fires that are not receiving full suppression action, such as prescribed fires in wilderness, will find it especially useful.

> Those monitoring fires, such as prescribed fires in wilderness, will find this method especially useful.

Importance of Slope

To predict fire behavior, a fire specialist must supply values for fuel model, fuel moisture, windspeed, and slope. Calculations can be done using tables, nomograms, calculators, or computer programs (Andrews 1986). As described by Rothermel (1983), fuels are classified as a particular fuel model by observation (Anderson 1982); windspeed is measured; live fuel moisture is estimated by the state of curing; dead fuel moisture is determined by an estimate of shade and measurements of temperature and relative humidity; and slope is determined from a topographic map, estimated, or measured with an instrument such as a clinometer. Slope can also be estimated with adequate precision using the method described here.

Figure 1 illustrates the effect of slope on predicted flame length for four fuel models:

- 4 (chaparral);
- 13 (heavy logging slash);
- 2 (timber litter and understory); and
- 9 (hardwood litter).

In this example, there is no wind, dead fuel moisture is 6 percent, and live fuel moisture is 100 percent. Calculations were done using BEHAVE (Andrews 1986). A resolution of less than 5 percent is clearly not necessary, especially when all of the other uncertainties involved in fire behavior prediction are taken into account. On the other hand, the value for percent slope has enough influence that a poor estimate might lead to a significant over- or underprediction.

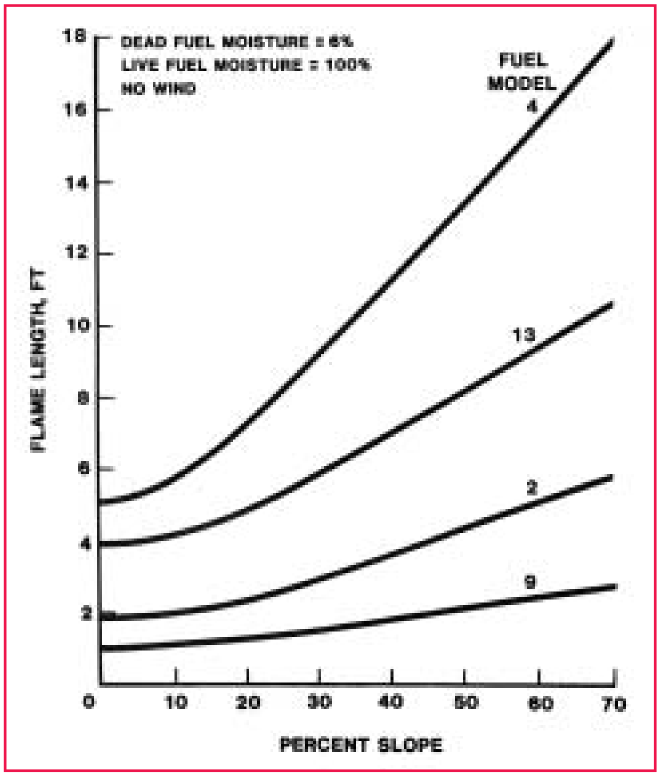

Figure 1—*The influence of slope on calculated flame length is shown for four fuel models under constant wind and fuel moisture conditions.*

Estimating Slope

The lines in figure 2 represent slope percentages from 0 to 100. Using a sheet of adhesive acetate,

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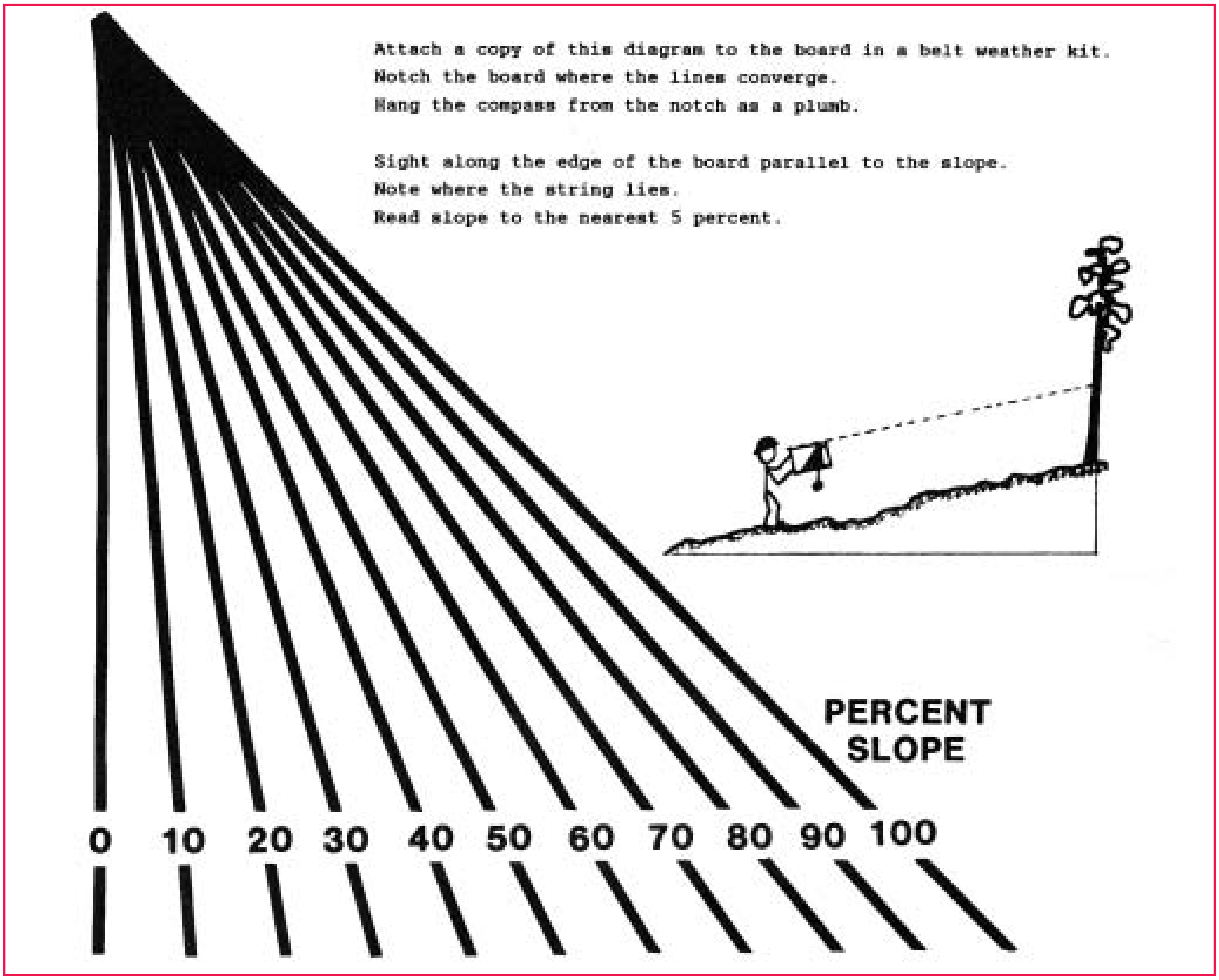

Figure 2—*Diagram for use as directed to estimate slope to within 5 percent. The slight distortion caused by photocopying the diagram is unimportant.*

attach a copy of figure 2 to the board in a belt weather kit. Notch the board where the lines converge. Hang the compass by its neckstring at the notch to serve as a plumb. Sight along the board parallel to the slope, as shown in figure 3. Noting where the string lies, read the slope to the nearest 5 percent.

This method of estimating slope is a simple, no-cost alternative to eyeball estimates, which are notoriously poor, and to instruments such as clinometers, which are expensive and give a level of resolution not required for fire behavior prediction.

Figure 3—*The influence of slope on calculated flame length is shown for four fuel models under constant wind and fuel moisture conditions.*

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AIR TANKER VORTEX TURBULENCE—REVISITED*

Donald A. Haines

Extreme drought had a devastating impact on wildland fire activity over much of the Central and Western United States during the summer and autumn of 1988. State and Federal suppression forces in Michigan's Upper Peninsula confronted fire behavior rarely experienced in early summer, typically a period of low fire occurrence.

The Stockyard Fire

The Stockyard Fire, near Escanaba, MI, proved especially troublesome because of unexpected fire behavior. Among other features, 100-foot-long (30-m) sheets of flame moved horizontally, undulating like waves on a water surface. Fire, brands moving with the sheets caused spot fires that quickly turned into 15- to 30-foot-high (4.5- to 9-m) fire whirlwinds. Even though the Burning Index (National Fire Danger Rating System) was 27 with fuel model E, burning was so intense along some sectors of the fire that escaping gases did not ignite until well above the fire. In those cases, the gases exploded as large bubbles high in the air.

But the most interesting behavior occurred along a 300-foot (90-m) length of the right flank. Here three tractor-plow operators built line within a jack pine plantation. The trees were 3 to 6 inches (8–15 cm) in diameter and 25 to 30 feet (7.5–9 m) high. Compared with other sectors, this was a quiet area. The operators plowed 50 feet (15 m) from a backing fire with 2-foot (0.6-m) flame lengths. Aided by a firing-out crew well behind the tractor operators, the fire burned to the line, leaving a wide black area.

> The crown fire was described as a "waterfall," a "breaking wave," a "curl," and a "wave curl"—in other words, a horizontal roll vortex of some type.

Winds were light and then became calm. The low flames suddenly began to "climb" up a few trees into the crowns. Within a minute or two the flames became a high wall. The wall changed into a crown fire, moving directly toward the tractor crew. Flame tilt had shifted from slightly eastward to vertical and then to westward.

The resultant crown fire was described as a "waterfall," a "breaking wave," a "curl," and a "wave curl." In other words, it was a horizontal roll vortex of some type. Witnesses also stated that this wave (vortex) moved along the fire line at about 15 miles per hour (24 km/h). The vortex rotation threw foot-long (0.3-m) fire brands westward, 100 feet (30 m) away from the flank, into unburned fuels. Flame heights increased to 150 to 250 feet (45–76 m). Luckily no one was killed, although one of the tractor operators was badly injured and spent weeks in a medical bum center. What happened? Of equal interest, why did it happen only along this section of the line?

Possibilities Rejected

None of the more typical causes can explain the unexpected changes in fire behavior. There were no heavy fuel concentrations. Fuels were relatively uniform in a typical jack pine plantation. Also, the area was relatively flat with no unusual topographic features.

There were no apparent immediate weather concerns. The weather charts showed that the region was covered by a large, flat, high-pressure cell. Although the fire occurred near one of the Great Lakes, the land/sea breeze circulation did not change at that time. Also there was no apparent change in the vertical structure of the atmosphere over the fire.

Burnout operations upstream of the site had no effect on downstream activity, nor did anyone see the formation of a large vertical fire whirl or other suspicious fire-initiated features.

Lessons Relearned

However, one interesting incident did occur in this sector only minutes before the sudden, violent increase in fire activity. A DC-4 air

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tanker carrying 2,000 gallons (7,571 L) of retardant flew along the fire line, circled, then came back and dropped the retardant just south of this sector as the fire intensified. The tanker was flying at less than 400 feet (120 m) and at perhaps 140 miles per hour (225 km/h).

Almost a quarter of a century ago, Davis and Chandler (1965) published an article in *Fire Control Notes,* "Vortex turbulence—its effect on fire behavior." In it they warned about aircraft vortex turbulence, a sheet of turbulent air left in the wake of all aircraft. It rolls up into a strong vortex pair—two compact, fast-spinning funnels of air (fig. 1). Unfortunately, this vortex pair is usually invisible. Under certain conditions, the two vortices may stay close together, sometimes undulating slightly as they stretch rearward. The interaction between them tends to make them stay together as they move downward through the air. They usually roll apart as they hit the surface of the ground. This vortex phenomenon was discovered when it caused the crash of several light aircraft caught in the wakes of large airplanes.

Figure 1—*Low-flying spray plane. Note funneling effect on spray trailing each wing.*

Davis and Chandler warned that under special circumstances, vortex wakes may cause fire behavior to change dramatically.

Ordinarily, aircraft vortex turbulence does not endanger fire control forces. But Davis and Chandler warned that under special circumstances, vortex wakes may cause fire behavior to change dramatically.

Vortex severity and persistence vary with several factors. Most important are the type, size, speed, and altitude of the aircraft and the prevailing atmospheric conditions. Other factors being equal, the strongest vortex pair is produced by a large, slow-flying aircraft with a high wingspan loading. The speed is most important before landing or after takeoff. It is also a factor when an air tanker slows down for an accurate airdrop.

Aircraft altitude is important because vortices weaken rapidly with time. Under typical wind speeds, the vortex pair may lose its potential impact in less than a minute. But the pair tends to persist in calm air. At high altitude, the two vortices remain separated by a distance slightly less than the aircraft's wingspan. However, the interaction of the vortices causes them to drop at a rate of 300 to 500 feet per minute (90–150 m/min) depending on various factors.

For a more complete description of the action of these vortices, please read Davis and Chandler (1965)* and also Chandler and others (1983).

Be Aware

Today's fire crews and air tanker pilots would be wise to heed the warnings offered by Davis and Chandler. Fire crews should be alert for trouble in these circumstances:

- The air is still and calm.
- The fire is burning in open land or in scattered or low timber.
- The air tanker is large or heavily loaded.
- The air tanker is flying low and slowly.

Air tanker pilots should be aware of the problem the aircraft can cause and take these precautions:

- Do not fly parallel to the fire line more than necessary.
- Keep high except when making the actual drop.
- Ensure that ground crews are alert to the presence of an air tanker and the intended flight path.

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* *Editor's note:* Reprinted in this issue of *Fire Management Today.*

A TREND ANALYSIS OF FIRELINE "WATCH OUT" SITUATIONS IN SEVEN FIRE-SUPPRESSION FATALITY ACCIDENTS*

Gene A. Morse

Under the auspices of the National Wildfire Coordinating Group's (NWCG's) Fireline Safety Committee, seven events resulting in nine firefighter fatalities were analyzed. Common to all the fatalities was the use of tractor-plow units. The tractor plow is the primary equipment used for forest and wildland fire suppression activities in the South and the East.

The events were well documented with extensive details, photographs, and maps. They provided an adequate background of the events and factors leading to the deaths of the nine firefighters. A careful analysis, it was believed, might reveal a pattern of unsafe actions that could be changed in the future to avoid a recurrence of these tragic events.

A first reading of the fatality reports indicated no common factors in fuels or topography. Some similarities were noted in weather patterns, but it was difficult to draw definitive conclusions based on the weather factor alone.

Approach

The decision was made to apply the process developed in the NWCG Standards for Survival training program as the criteria for analyzing these events. The Standards for Survival focus on the 18 "Watch Out" Situations and the Standard Fire Orders. The "Watch Out" Situations and Fire Orders have gained widespread use as aids to safety among forest and wildland fire suppression agencies.

In each of seven fatality events, a single overlooked "Watch Out" Situation appeared to be the major contributing factor.

Practical application of the Standards for Survival training on an incident centers around identifying a potentially dangerous fireline event, linking it to a "Watch Out" Situation on the Survival Checklist, and then taking a positive action (observing the appropriate Fire Order) to eliminate or minimize the possibility of firefighter injury or death. One response from one of the fatality reports of the seven events illustrates how a "Watch Out" Situation was identified but the Fire Order was not observed:

- *Potentially hazardous event:* "It had been jumping our lines … the thing [fire] had already jumped a 60-foot canal…."
- *"Watch Out" Situation (#16)*: Getting frequent spot fires across line.
- *Fire Order not observed (#1)*: Initiate all action based on current and expected fire behavior.

In analyzing these events, it was apparent that, in each instance, a single overlooked "Watch Out" Situation appeared to be the major contributing factor. Simply following that reasoning process a step further leads to the conclusion that if the dominant positive action—Fire Order—to counteract that negative situation had been immediately observed, then a tragic situation may have been avoided.

Perhaps some readers might say that the method used in this analysis is too simplistic—that overlooking common threats to safety is too basic to be neglected. In this response lies a pitfall: The "Watch Out" Situations—commonly occurring during a fire event—are hazardous situations. It is hard, when a fire seems routine, to believe that it could become threatening. But a fire event has the potential to develop a "Watch Out" Situation quickly. Danger is inherent in a fire event. To develop "scotoma" in regard to these dangers is a major contributing factor to many fireline fatalities.

What is scotoma and how does it apply to fireline fatalities? Scotoma, a medical term, has direct relevance to this analysis. Scotoma is, literally, a blind spot. In a psycho-

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logical sense, it is that condition which occurs when a person tends to block out from his or her consciousness anything considered not important—or critical—to survival.

The significance of scotoma in fireline suppression operations is dramatically emphasized by this statement found in the fatality reports: "Personnel on the fire considered it to be routine … until the fire blew up" (figs. 1 and 2). Although it was phrased differently in several reports, this same type of comment surfaced repeatedly. The meaning is clear: It was "just another fire" to the firefighters.

Scotoma had taken hold and blocked out sensitivity to hazardous events or conditions present in the fire environment.

The prevalence of this attitude or mindset was best expressed by a veteran firefighter recently during a fireline safety training session when he commented, "I know those things ["Watch Out" Situations] are out there on the fire, but I've seen them so many times I'm not really aware of them now."

Trends and Conclusions

This analysis—to identify hazardous conditions or events in the fatality reports and then link them to the NWCG Survival Checklist—aimed at determining significant trends. The findings established that there were 84 separate hazardous conditions or events in the fatality reports. Some specific examples drawn directly from the reports, linked to the Survival Checklist, and the appropriate dominant Standard Fire Order are outlined in table 1.

An analysis of the 84 hazardous conditions or events, when linked

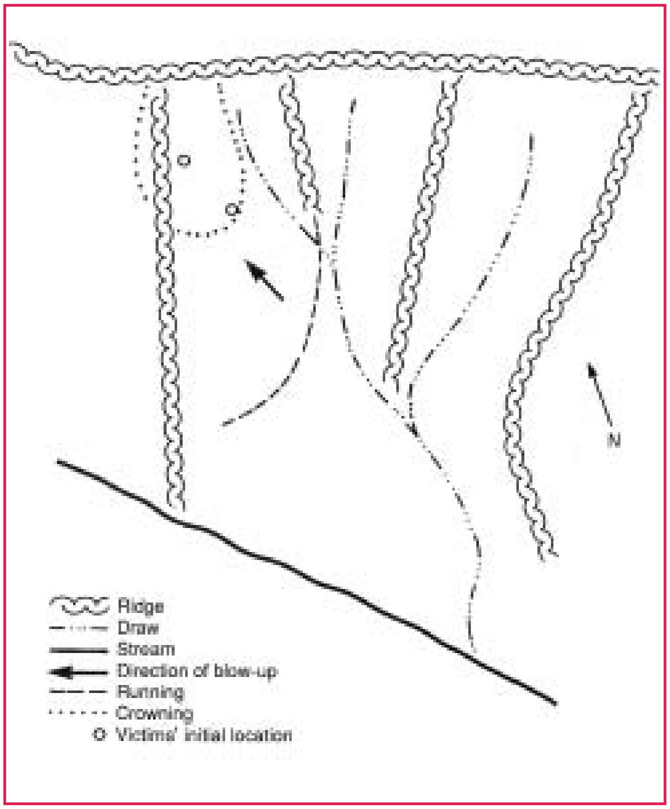

Figure 1—*A number of "Watch out" Situations were present when a fire tragedy occurred in this mountainous region, resulting in two firefighter deaths. The familiar statement, "personnel on the fire considered the situation to be routine until fire blew up," was contained in the fire report. Note victims' location on the windward side of the ridge, adjacent to a draw. Mild drought conditions existed, with 30-mile-per-hour (48-km/h) winds.*

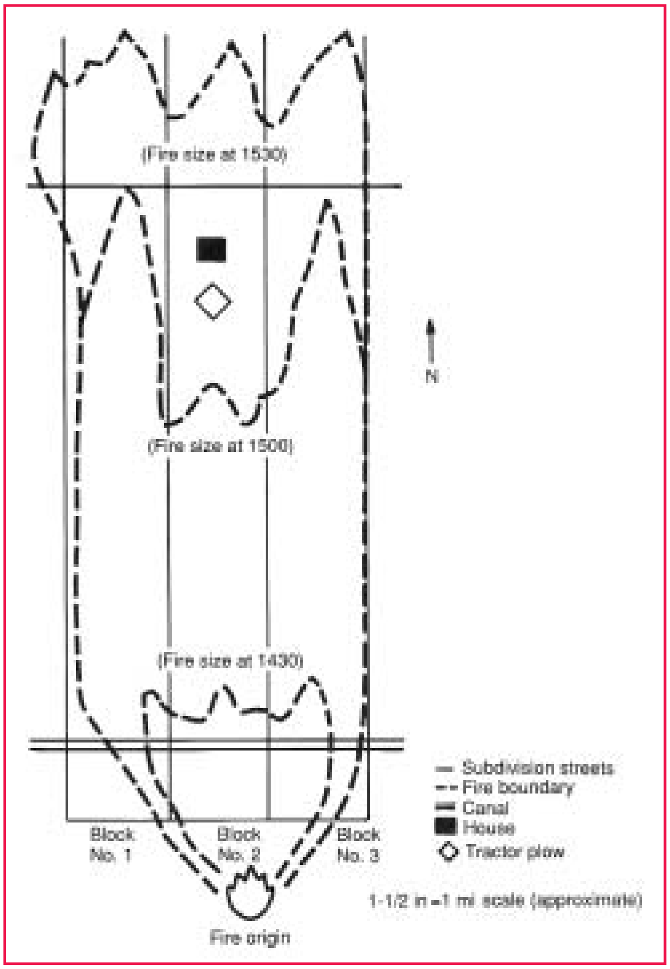

Figure 2—*This sketch of a fatality scene, prepared by a fire behavior analyst, illustrates a dangerous fireline condition. It shows the fire with three separate heads, burning in three subdivision blocks, part of a huge, largely unpopulated subdivision with heavy fuel loading. Mild drought conditions existed. Note that the firefighter's tractor is located in a "pocket," with the fire heads on either side advancing more rapidly than the fire in Block No. 2. Personnel on this fire considered it to be "routine"—until it blew up.*

Table 1—*Nine examples of hazardous conditions listed on the Survival Checklist for which there is a Standard Fire Order.*

Hazardous condition or event	***Survival Checklist***	***Fire Order***
Initial instructions to the firefighter: “Grab the first piece of fire you come to—and do the best you can.”	No. 6: Instructions and assignments not clear.	E: Ensure instructions are given and understood.
“[The fire] looked like one of those waves in Hawaii, like when you shoot the waves on a surfboard. The smoke was going up; it looked like an explosion.”	No. 4: Unfamiliar with weather and local factors influencing fire behavior.	I: Initiate all action based on current and expected fire behavior.
Q: “What radio traffic did you get after XXX offloaded and started plowing?” A: “None … I never heard any.”	No. 7: No communication link with crew members or supervisor.	R: Remain in communication with crew members, your supervisor, and adjoining forces.
Q: “Had there been any briefings? Weather briefings? Fire behavior briefings? Safety briefings? A: “Not to my knowledge “	No. 5: Uninformed on strategy, tactics, and hazards.	R: Retain control at all times.
“There was no apparent briefing with the crew on a plan of attack and escape, if necessary.”	No. 3: Safety zones and escape routes not identified.	D: Determine safety zones and escape routes.
“Heavy palmetto growth prohibited penetration to safety only 60 feet [18 m] away.”	No. 17: Terrain and fuels make escape to safety zones difficult.	D: Determine safety zones and escape routes.
“[He] began initial attack by plowing lines across the head of the fire.”	No. 10: Attempting frontal assault on fire.	F: Fight fire aggressively but provide for safety first.
“[He] noticed a space 50 to 100 feet [15–30 m] long on the line that was not tied together.”	No. 11: Unburned fuel between you and the fire.	O: Obtain current information on fire status.
“It [the wind] blew from the east, southeast, south, southwest, west, and then back again without warning.”	No. 15: Wind increases and/or changes direction.	R: Recognize current weather conditions and obtain forecasts.

to the Survival Checklist, revealed the following trends:

- Twenty-two were tied directly to Survival Checklist Situation No. 4 *(Unfamiliar with weather and local factors influencing fire behavior).*
- Thirteen were linked closely to Survival Checklist Situation No. 7 *(No communication link with crew member or supervisor).*
- Twelve were connected directly to Survival Checklist Situation No. 15 *(Wind increases or changes direction).*
- Eleven were linked to Survival Checklist Situation No. 16 *(Getting frequent spot fires across line).*

Scotoma—blindness to danger perceived as routine—had taken hold and blocked out sensitivity to hazardous events or conditions present in the fire environment.

The relationship is clearly established between fireline fatalities and a lack of awareness or sensitivity to significant changes in fire behavior.

What does this analysis of the deaths of nine firefighters establish? With 13 conditions or events associated with communication, it is obvious that poor or nonexistent communication placed the firefighters in a vulnerable position. No one can question the paramount necessity of maintaining close, effective communication with other personnel in the hostile fire environment.

But it is even more revealing to note that *more than half* of the hazardous conditions or events identified in the analysis relate to some aspect of fire behavior. Specifically, the relationship is clearly established between fireline fatalities and a lack of awareness or sensitivity to significant changes in fire behavior.

Recommendations To Improve Safety

What recommendations can be made on the basis of this trend analysis to reduce scotoma on the fireline and ensure firefighter safety? Listed below are some specific action items that NWCG agencies may wish to consider:

- Besides the established national courses in fire behavior (Introduction to Fire Behavior; Intermediate Fire Behavior; and Advanced Fire Behavior), develop more localized fire behavior training focused on individual State or regional fuel types.
- Teach firefighters about fire science—the relationship between fuels, weather, and topography and fire—and how to transfer fire behavior knowledge into the most prudent application of tactics that will get the fire suppression job done without compromising firefighter safety. Follow up classroom instruction in fire behavior training courses with simulated fire exercises in the field, where firefighters would be required to demonstrate safe, effective firefighting tactics in different fuel, weather, and topography conditions. Evaluate critically to determine if participants had made the right tactical decisions.
- Determine a fuel condition threshold (possibly fuel moisture) for their local area in which going beyond a certain level would signal the mandatory establishment of a safe anchor point, posted lookout, and designated escape routes and safety zones to ensure safe tactical operations in the event of unexpected changes in weather and fire behavior.
- Give high priority to fireline safety training, such as the NWCG Standards for Survival course.

Agencies with few materials available for fireline safety training should obtain a copy of the recently prepared "Fireline Safety and Health Resources." This publication was developed by the NWCG Fireline Safety Committee listing materials available for sharing by all NWCG agencies. ■

Russo and Schoemaker (1989) Decision Trap 7—Group Failure:
Assuming that with many smart people involved, good choices will follow automatically, and therefore failing to manage the group decisionmaking process.*

* See page 9.

LCES—A Key to Safety in the Wildland Fire Environment*

Paul Gleason

LCES—A System for Operational Safety

In the wildland fire environment, where four basic safety hazards confront the firefighter—lightning, fire-weakened timber, rolling rocks, and entrapment by running fires—LCES is key to safe procedure for firefighters. LCES stands for "lookout(s)," "communication(s)," "escape routes," and "safety zone(s)"—an interconnection each firefighter must know. Together, the elements of LCES form a safety system used by firefighters to protect themselves. This safety procedure is put in place before fighting the fire: Select a lookout or lookouts, set up a communication system, choose escape routes, and select safety zone or zones (fig. 1).

In operation, LCES functions sequentially—it's a self-triggering mechanism: Lookouts assess—and reassess—the fire environment and communicate to each firefighter threats to safety; firefighters use escape routes and move to safety zones. Actually, all firefighters should be alert to changes in the fire environment and have the authority to initiate communication.

L—Lookout(s)
C—Communication(s)
E—Escape routes
S—Safety zone(s)

Key Guidelines

LCES is built on two basic guidelines:

- Before safety is threatened, each firefighter must be informed how the LCES system will be used.
- The LCES system must be continuously reevaluated as fire conditions change.

How To Make LCES Work

- Train lookouts to observe the wildland fire environment and to recognize and anticipate fire behavior changes.
- Position lookout or lookouts where both the hazard and the firefighters can be seen. (Each situation—the terrain, cover, and

> The LCES system approach to fireline safety is an outgrowth of my analysis of fatalities and near-misses for over 20 years of active fireline suppression duties.

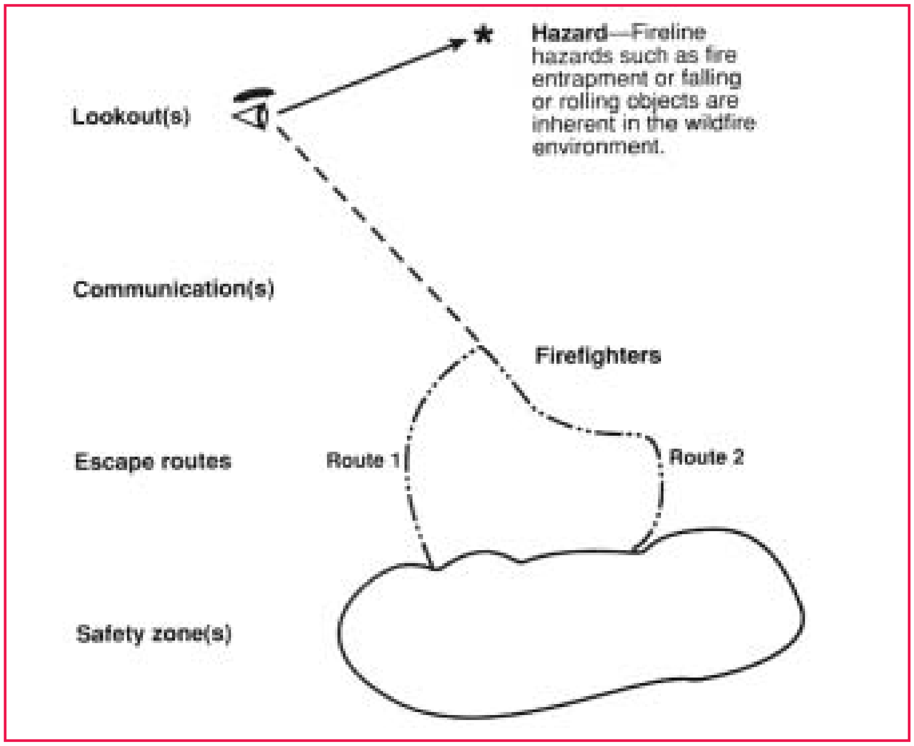

Figure 1—*LCES components.*

When this article was first published, Paul Gleason was the North Roosevelt fire management officer, USDA Forest Service, Arapaho and Roosevelt National Forests, Redfeather Ranger District, Fort Collins, CO.

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* The article is reprinted from *Fire Management Notes* 52(4) [Fall 1991]: 9.

fire size—determines the number of lookouts that are needed. As stated before, every firefighter has both the authority and responsibility to warn others of threats to safety.)
- Set up communication system—radio, voice, or both—by which the lookout or lookouts warn firefighters promptly and clearly of approaching threat. (Most often the lookout initiates a warning that is subsequently passed down to each firefighter by word of mouth. It is paramount that every firefighter receive the correct message in a timely manner.)
- Establish the escape routes (at least two)—the paths the firefighters take from threatened position to area free from danger—and make them known. (In the Battlement Creek 1976 fire, three firefighters lost their lives after retreat along their only escape route was cut off by the advancing fire.)
- Reestablish escape routes as their effectiveness decreases. (As a firefighter works along the fire perimeter, fatigue and distance increase the time required to reach a safety zone.)
- Establish safety zones—locations where the threatened firefighter may find adequate refuge from the danger. (Fireline intensity, air flow, and topographic location determine a safety zone's effectiveness. Shelter deployment sites have sometimes been termed, improperly and unfortunately, "safety zones." Safety zones should be conceptualized and planned as a location where no shelter will be needed. This does not imply that a shelter should not be deployed if needed, only that if there is a deployment, the safety zone location was not truly a safety zone.)

LCES simply refocuses on the essential elements of the standard Fire Orders. Its use should be automatic in fireline operations.

A Final Word

The LCES system approach to fireline safety is an outgrowth of my analysis of fatalities and near-misses for over 20 years of active fireline suppression duties. LCES simply refocuses on the essential elements of the standard Fire Orders. Its use should be automatic in fireline operations. All firefighters should know LCES, the Lookout–Communication–Escape routes–Safety zone interconnection. ■

The author's personalized license plate. Paul Gleason developed the LCES concept while serving as superintendent for the Zigzag Interagency Hotshot Crew. The photo was taken at the request of Gleason's wife Karen after he passed away. Photo: Mike Goodman, Lake Estes, CO, 2003.*

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* For more on Gleason and LCES, see the Summer 2003 issue of *Fire Management Today*, a special issue dedicated to Paul Gleason. In particular, see Paul Keller, "'Gleason Complex' Puts Up Huge 'Plume': A Tribute to Paul Gleason" (*Fire Management Today* 63[3]: 85–90); and Jim Cook and Angela Tom, "Inteview With Paul Gleason" (*Fire Management Today* 63[3]: 91–94).

How IC's Can Get Maximum Use of Weather Information*

Christopher J. Cuoco and James K. Barnett

During initial and extended attack, up-to-date weather information is critical to successful and safe wildland firefighting. Unfortunately, obtaining and evaluating fire weather forecasts can be a challenge. With the few basic weather concepts plus the two user-friendly field aids provided here, Incident Commanders (IC's) can get maximum use of weather information.

The first of the reproducible field aids, the Supplemental Observation Sheet (see sample on page 73), can assist in using the "Mobile Fire-Weather Observer's Record" provided in every field belt weather kit. The Supplemental Observation Sheet can prompt a fire weather observer to take notice of important weather phenomena that may affect fire behavior. This information can be recorded in the "Characteristics and Comments" section of the observation form and passed on to the IC and the fire weather forecaster.

The second field aid—the Weather Evaluation Sheet (see sample on page 73)—will lead an IC through a series of questions designed to increase understanding of current weather conditions. With it, the IC will be able to evaluate the accuracy of a fire weather forecast and determine the effect of current and forecasted weather conditions on fire behavior and firefighting operations.

The two most critical factors in acquiring weather forecasts during an incident are communications and time.

Planning for Efficient Communications

The two most critical factors in acquiring weather forecasts during an incident are communications and time. Typically, dispatchers and IC's communicate via radio. However, radio frequencies often become overloaded and subsequently slow down or eliminate requests for updated weather information. In addition, taking a weather observation, relaying the data, and preparing and transmitting a fire weather forecast all take valuable time.

To make communications more efficient and effective, we suggest the designated individuals below assume the responsibilities following their job titles:

IC's:

- Develop fire weather and fire behavior interpretation skills.
- Practice taking observations using techniques recommended in the Intermediate Wildland Fire Behavior course (S–290).
- Become familiar with Remote Automated Weather Stations (RAWS) and other real-time weather information sources in their area and become proficient in the means to obtain the data. They should seek out this information when fighting fire outside their home territory.**

Dispatchers:

- Become sufficiently trained to understand and communicate

Original editor's note: Chris Cuoco was the National Weather Service (NWS) Colorado Fire Weather program manager throughout the severe fire season of 1994. The U.S. Department of Commerce recently presented him the Silver Medal Award for the fire weather forecasts and Red Flag Warnings he issued before, during, and after the tragic South Canyon Fire on July 6, 1994. He accepted the award in the names and memory of the 14 firefighters who died while fighting the South Canyon Fire. It is his hope that the information presented here will in some way help prevent such a tragedy from ever happening again.

When this article was originally published, Chris Cuoco was a warning coordination meteorologist for the U.S. Department of Commerce, National Weather Service, Flagstaff, AZ; and Jim Barnett was the regional dispatcher for the USDA Forest Service, Rocky Mountain Area Interagency Fire Coordination Center; Broomfield, CO.

** The local NWS Fire Weather Operating Plan (OPLAN) is a good resource for weather observations. The OPLAN will list RAWS sites, locations, elevations, and ID numbers.

* The article is reprinted from *Fire Management Notes* 56(1) [Winter 1996]: 20–24.

Supplemental Observation Sheet

In addition to the items specifically requested on the Spot Weather Observation Form found in the belt weather kit, the following should be observed. Circle or fill in appropriate items and communicate this information to the weather forecaster.

Cloud Observations

Cloud cover percentage	*Cumulus development*	*Key cloud indicators*	*Possible consequences*
Clear (0-10% cover)	Small cumulus	Towering cumulus*	Erratic winds
Scattered (11-50% cover)	Towering cumulus*	Cumulonimbus*	Erratic winds/thunderstorms
Broken (51-90% cover)	Cumulonimbus (anvil)*	Horsetail cirrus	Frontal approach (24-72 h)
Overcast (91-100% cover)	Direction(s)_________	Milky sky	Frontal approach (24-72 h)
Fog	Distance__________	Lenticular clouds	Increasing winds

Other Important Weather Observations		
Inversion break	Time__________	
General wind shift	Time__________	New direction__________
Upslope/downslope wind shift	Time__________	New direction__________
Upvalley/downvalley wind shift	Time__________	New direction__________
Smoke dispersal: Rapid* Moderate Slow		Direction______________
Dust devils*		
Additional comments		

Local Terrain Factors

Fuel types________________________

Canyons (chimneys, chutes)

Steep slopes

Large body of water nearby or snowpack

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*May indicate instability which may cause erratic fire behavior.

Weather Evaluation Sheet

1. Do you have the current **Fire Weather Zone Forecast** for your area?

NO > Call dispatch. Request a forecast.
YES > Evaluate forecast for your area and current weather conditions.

Call for Spot Forecast > If information is incomplete or if the zone forecast is not representative of conditions on the incident.

2. **Evaluating the Spot Forecast:** Answer the questions in the first two columns. Use the third column to relate fire weather and fire behavior to firefighting strategy and tactics. Note that one weather parameter out of criteria may not require an updated forecast; it could be offset by other weather measurements or fuel conditions.

Instability	**Winds, temps, RH**	**Relating weather to fire behavior**
1. Cumulus cloud development ____ **More** development than forecasted (more unstable)? ____ **Less** development than forecasted (more stable)? 2. Smoke column characteristics ____ **Higher** column than expected (more unstable)? ____ **Lower** column than expected? (more stable)? 3. Conditions appear more **unstable** than forecasted? ____ NO ____ **YES > Consider new forecast.**	Cloud cover compared to forecast. ____More ____Same ____Less Wind speed within 5 mph of forecast? ____ YES ____ **NO > Consider new forecast.** Does observed wind direction fit the terrain? ____ YES ____ **NO > Consider new forecast.** Is the wind direction as forecast? ____ YES ____ **NO > Consider new forecast.** Temp within 5 degrees of forecast? ____ YES ____ **NO > Consider new forecast.** RH within 5% of forecast? ____ YES ____ **NO > Consider new forecast.**	1. How will the observed and forecasted weather affect fire behavior? 2. Are current strategy and tactics appropriate for observed and predicted fire behavior? 3. Do we need to change **strategy** and **tactics** to fight this fire **safely**? **Request a new Spot Forecast if you believe fire weather and fire behavior conditions require a change in tactics.**

weather information as rapidly as possible.

Fire Management Officers (FMO's):

- Develop coaching and prompting techniques to assist less experienced field personnel.

FMO's and Dispatchers:

- Establish primary and backup radio frequencies early each fire season.
- Establish a rapid process for passing weather information between the field and the forecaster (e.g., with radio, phone, cellular phone,* fax, computer).
- Develop guidelines for broadcasting fire weather forecasts, Fire Weather Watches, Red Flag Warnings, pertinent special weather announcements, and key National Fire-Danger Rating System (NFDRS) data.
- Develop a "confirmation of receipt" process for routine fire weather forecasts and for critical fire weather information.
- Establish a fire-danger tracking system for each dominant fuel type in the area. (Such a system will aid in determining trends and danger levels.)

Evaluating the Fire Weather Zone Forecast

NWS fire weather offices produce fire weather zone forecasts twice a day and update as needed. The zone forecast provides weather information for relatively large areas. While the most important purpose of the zone forecast is to issue and explain Fire Weather Watches and Red Flag Warnings, it also:

- Discusses the weather situation and general forecasts for geographic and topographic zones in the issuing office's area.
- Includes predictions of upper level winds and smoke dispersal, and provides extended weather outlooks.
- Provides an overall understanding of forecasted weather and the meteorological features causing the weather.

Note: The zone forecast may be too general to apply to some initial and extended attack scenarios.

Warning and Watch Headlines

Red Flag Warnings and Fire Weather Watches are "highlighted" with headlines preceding the forecast discussion and each applicable zone forecast. (The conditions warranting a Red Flag Warning or Fire Weather Watch are explained in detail within the weather discussion.) These headlines:

- Announce critical fire weather conditions that need to be communicated to the field completely and accurately in all wildland firefighting situations.
- Highlight significant weather conditions that do not meet the warning or watch criteria but may require the IC's heightened awareness.

IC's should try to obtain a copy of the entire fire weather zone forecast package or have the dispatcher read the applicable zone forecast over the radio. If receiving the information by radio, IC's should ask the dispatcher to read all headlines in their zone and in the discussion section of the forecast package. After reading or hearing the zone forecast, the IC should ask these questions:

IC's should try to obtain a copy of the entire fire weather zone forecast package or have the dispatcher read the applicable zone forecast over the radio.

- Do I have a complete picture of the weather situation?
- Do I feel comfortable with my knowledge about the general weather pattern (i.e., pressure systems, cold fronts, general wind patterns)?
- Do I understand the predicted fire weather for my area?
- Do the predicted conditions make sense for my incident?

If the IC discovers that the information is incomplete or if the zone forecast is not representative of conditions on the incident, the IC should consider requesting a Spot Forecast.

Information To Provide the Forecaster

During initial or extended attack, detailed site-specific weather observations can greatly improve weather forecast accuracy. To enhance the information provided to the weather forecaster, we recommend observations be taken:

- At the same times each day. (These will reveal trends of temperature, humidity, and winds on the incident.)
- Across the range of elevations and aspects of the incident, if possible.

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* Cellular phones can be especially useful because they allow direct communication from the field to the weather forecaster.

- At key (local) times of day:
  - 0600–0800 for lowest temperature and highest relative humidity (RH).
  - 1500–1700 for high temperature, low humidity, and strongest diurnal winds.

The IC should also provide the forecaster with observations at various times of day to report such other data as:

- The time the morning inversion broke.
- Diurnal wind shifts and the time they occurred.
- Cumulus cloud growth and thunderstorm development.
- Precipitation.
- Cloud cover.

During an extended attack, appointing a dedicated weather lookout or field observer to take observations each hour is ideal. Observations from one well-trained individual will be consistent and will ensure that quality weather observations are provided to the IC and the weather forecaster throughout the course of the incident.

What Should Be Done With Weather Observations?

The IC should pass all fire weather observations to the fire weather forecaster. An observation from the fire site should be included with every Spot Forecast request. If the firefighting effort continues into a second or third burning period, we recommend all observations taken during the previous burning period be included with the next Spot Forecast request.

A quality weather observation program will also provide the IC with critical information for input into tactical firefighting decisions. With this onsite information, the IC can compare the observed weather to the weather forecast and then develop a fire behavior prediction. The key consideration for the IC: always make the connection between observed and forecasted weather and observed and forecasted fire behavior.

Optimizing the Spot Forecast

The requestor has plenty of input into the Spot Forecast provided by the fire weather forecaster. IC's should attempt to anticipate the kinds of information they will need and request that information. The typical Spot Forecast includes:

> During an extended attack, appointing a dedicated weather lookout or field observer to take observations each hour is ideal.

- A weather discussion,
- Forecasts of sky condition,
- The chance of precipitation,
- High and low temperature and RH,
- Winds at eye level or 20 feet (6.1 m) above ground, and
- Smoke dispersal.

IC's can request more detailed information when needed such as:

- A forecast of temperature, humidity, and wind at 2- to 3-hour intervals.
- A forecast for a single element, such as the 20-foot (6.1-m) wind, at 2- to 3-hour intervals.
- A prediction of the time of highest temperature and lowest RH.

The forecaster will let the IC know if more information is being requested than the forecaster's workload will allow or if the request is beyond the limits of the science of weather forecasting.

Monitoring the Weather and Evaluating a Forecast

IC's can evaluate a forecast and decide when a new forecast is needed by monitoring—through measurement and visual indicators—the atmospheric instability, winds, temperature, and RH.

Monitoring Instability. A highly unstable atmosphere is a primary cause of radical fire behavior. Strong instability can create erratic winds and can greatly enhance fire growth. Cumulus cloud development and smoke column characteristics can be used as visual indicators of atmospheric instability. The fire weather forecast should provide IC's with the predicted cumulus development and instability conditions from which smoke column behavior can be estimated.

Atmospheric conditions are more unstable than predicted when:

1. Cumulus clouds develop sooner and to greater heights than expected.*
2. The smoke column rises faster and to greater heights than expected.

Conditions are more stable than predicted when:

1. Cumulus clouds develop later and/or to lesser heights than expected.

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* Cumulus clouds may be more developed or cover a larger area if there is more moisture available in the atmosphere, but the instability may not differ from the forecast. Fewer cumulus clouds or less vertical development may mean drier conditions than expected.

2. The smoke column does not rise as rapidly or as high as expected, or it does not develop at all.

When evaluating atmospheric instability, the IC should ask these questions:

- Does the atmosphere appear more unstable than expected?
- If so, do we need to relay this information to the weather forecaster and ask for a new Spot Forecast?
- How will greater instability affect fire behavior?

When IC's believe the observed instability conditions may significantly increase fire behavior, they should strongly consider requesting a new Spot Forecast.

Monitoring the Winds. Wind observations taken every hour will yield important information about daily wind shifts and the strength of valley breezes at differing elevations. Accurate wind observations will record the true character of local slope and valley breezes. Many factors can influence the development of local winds, but cloudiness is one of the most important and easiest to evaluate. Cloudiness over a site will affect surface heating and the shift in slope and valley breezes. When examining the cloudiness at the fire site, the IC should ask this question: Is there more or less cloud cover than forecasted? Based on the answer, the IC can draw some general conclusions:

- More clouds than predicted will delay the shift to upslope and upvalley winds and often result in lower wind speeds.
- Less cloud cover than predicted will cause an earlier shift to upslope and upvalley winds, with stronger wind speeds and gustier conditions possible.

The IC should consider requesting a new Spot Forecast if the shift to upslope and upvalley winds is delayed by more than 1 hour or if the wind speed varies from the forecast by 5 mph (8 km/h) or more.

When considering the wind direction, the IC should always be suspicious of any wind from a different direction than the terrain would be expected to produce. The question to ask: Does the wind direction fit this terrain? If winds run counter to the normal slope and valley breezes and these winds were not predicted, there may have been a drastic change in weather conditions. The IC should consider requesting a new Spot Forecast.

> The key consideration for the IC: always make the connection between observed and forecasted weather and observed and forecasted fire behavior.

Monitoring Temperature and RH. If an observer is available, we recommend monitoring the temperature and RH by plotting the forecast temperatures and RH on graph paper every 2 to.3 hours, then comparing these plots to the observed data. (This procedure assumes the IC requested predictions of temperature and RH every 2 to 3 hours.) An alternative would be to request a temperature and humidity forecast for a key decisionmaking time, i.e., 1200 or 1300. The IC would determine how accurate the forecast is by comparing the forecasted and observed data for that hour.

Temperature and RH are strongly influenced by cloud cover. Often, small differences between observed and forecasted temperature and RH can be accounted for by observing cloudiness. A 30-percent difference in cloud cover may lead to a 1- to 3-degree Fahrenheit (about 1 degree Celsius) difference in temperature and a 2- to 4-percent difference in RH. The questions to ask:

- Is the observed temperature within 5 degrees of the forecasted temperature?
- Is the observed RH within 5 percent of the forecasted RH?

The IC should consider requesting a new Spot Forecast if the actual temperature differs from the forecast by 5 degrees or more and/or the actual RH differs from the forecast by more than 5 percent.

Note: When comparing observed and forecasted temperature and humidity, be certain to take into account the effect that aspect, cloud cover, sheltering, and elevation will have on the observed values. The ideal for comparative purposes would be to take observations from the same location exactly throughout the course of the incident.

Conclusion

As we have stressed, throughout the incident, the IC should communicate as much information as possible to the fire weather forecaster. As time permits, the IC should give the forecaster quality feedback on forecast accuracy, observed weather conditions, and fire behavior.

We have summarized the recommendations presented here in the Supplemental Observation Sheet and the Weather Evaluation Sheet. We recommend these two field aids be reproduced and carried to the field to be used with the “Mobile Fire-Weather Observer’s Record.”

When using the evaluation sheet, please keep in mind that a single weather element determined to be outside the criteria mentioned above may not require a request for a new Spot Forecast. A weather element outside the stated criteria may be offset by fuel conditions or other weather measurements. The IC needs to consider what effect the overall weather conditions will have on fire behavior and firefighting tactics.

When IC’s believe the observed instability conditions may significantly increase fire behavior, they should strongly consider requesting a new Spot Forecast.

Acknowledgments

The authors want to thank the following for their editorial and technical recommendations: Dave Aldrich, national safety officer, Forest Service; Paul Broyles, chief, Fire Training and Safety, National Park Service; Rick Ochoa, NIFC staff meteorologist; Paul Gleason, fire ecologist, Arapaho-Roosevelt National Forest; Bill Pies, initial attack dispatcher, Deschutes National Forest; Mark Rogers, superintendent, Wyoming Hot Shots; Alan Farnsworth, prescribed fire manager, Peaks Ranger District, Coconino National Forest; Steve Keighton, science and operations officer, NWS.

Dedication: This article is dedicated to the Storm King 14. ■

Russo and Schoemaker (1989) Decision Trap 8—
Fooling Yourself About Feedback: Failing to interpret the evidence from past outcomes for what it really says, either because you are protecting your ego or because you are tricked by hindsight.*

* See page 9.

BEYOND THE SAFETY ZONE: CREATING A MARGIN OF SAFETY*

Mark Beighley

The safety zone and escape route network must be an integral part of tactical fireline operations, not added as an afterthought or after a fireline is constructed.

Wildland firefighting is fraught with hazards. When firefighters encounter those hazards, they are at risk—risk of injury, risk of death. To guarantee safety while wildfires are suppressed, humans would have to stop being involved in firefighting. In most cases, this is not an option. We need firefighters to save lives, protect communities, and reduce damage to natural resources. Yet the question remains—how can firefighters suppress wildfires efficiently without jeopardizing their own lives?

Firefighters Have Alternatives

Firefighters must consider current and future weather and burning conditions and the effect they have on how, what, and where the fire is expected to burn before making decisions about the best suppression strategy to use. For any given suppression operation, firefighters can choose from a variety of strategic and tactical alternatives. Some alternatives maximize the effectiveness of the suppression effort, and some maximize firefighter safety. Sometimes the most effective suppression action is also the safest, but generally there is a tradeoff between the two. Firefighters must always evaluate the risks before selecting a course of action. They may have as little as a few minutes to conduct this risk analysis on fast-spreading fires. On fires that have not developed to their full, explosive fury, firefighters may have as much as several hours to analyze their risk and decide what to do to maximize suppression effectiveness.

No matter what course of action firefighters choose, their decisions are not usually final because they must base their decisions on information that is incomplete. In addition, information deteriorates quickly with time.

Safety Zones

A basic element of fire suppression safety is a safety zone, a place where firefighters are free from danger, risk, or injury. It is vital that firefighters know where and how to get to areas that provide a safe refuge when they analyze risk. In any given tactical operation, firefighters must identify or create safety zones and "escape routes" that provide access to them. For operational assignments that require extensive and lengthy fireline construction, firefighters must develop a network of safety zones and escape routes. How is this network designed? What factors should be considered?

The safety zone and escape route network must be an integral part of tactical fireline operations, not added as an afterthought or after a fireline is constructed. All fireline construction should start from a safe anchor point. As fireline construction proceeds from that safe point, safety zones are identified or constructed along the way. Any time firefighters venture beyond the safety zones, they are at risk. As the distance between the firefighter and the safety zone increases, so does the risk of entrapment or burnover.

Risk Threshold

At some distance from the safety zone, firefighters begin to feel uncomfortable about their position. This discomfort may result from increased fire activity or the threat of increased fire activity. They realize that there may be insufficient time to successfully retreat to the safety zone should the need arise. They have reached their risk threshold—that point at which the level of risk is too high. To reduce the level of risk, firefighters must then reduce the distance to a previous safety zone or locate or create a new safety zone.

The risk threshold for all firefighters is different. Every firefighter possesses a different combination of

When this article was originally published, Mark Beighley was a team leader for Resource Operations, USDA Forest Service, Deschutes National Forest, Bend and Fort Rock Ranger Districts, Bend, OR.

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knowledge and experience with which to evaluate the relative safety of the current situation. Firefighters may also have different information regarding local factors that might affect fire behavior.

There is an assumption that veteran firefighters have well-defined, accurate risk thresholds. Also, it is assumed that these risk thresholds can be depended upon to provide a consistent and appropriate assessment of safety for any given tactical fireline operation. But even if firefighters have developed accurate risk thresholds, they always have a degree of uncertainty because of inadequate or deteriorating information. Because conditions on a fire seldom stay constant for more than a few hours and can change quite rapidly, a constant supply of information is an important facet of the risk assessment process.

When Safe Becomes Unsafe

Risk threshold applications are, fortunately, rarely tested. Even when firefighters are uncomfortable with their position, the fire does not always test the situation. Feedback on risk threshold is infrequent; therefore the accuracy of a firefighter's risk threshold is often unknown. Even under the best of circumstances, the most experienced and knowledgeable firefighters are plagued with imperfections inherent in the human condition. Inattention, distraction, fatigue, attitude, boredom, information overload, mind set, and carbon monoxide poisoning can all work to erode the judgment of the most vigilant of firefighters.

Safe becomes unsafe when the fire has the potential to get to the firefighter before the firefighter can get to a safety zone. That philosophical break-even point is the line between safe and unsafe fireline operations. The firefighter must constantly evaluate where that line is and how close he or she is to it, given the current situation. Uncertainty is always present. Risk threshold is not measurable, therefore not quantifiable. Firefighters cannot measure how close they are to an unsafe situation. Only the fire can provide feedback to the accuracy of their risk threshold.

Even if firefighters have developed accurate risk thresholds, they always have a degree of uncertainty because of inadequate or deteriorating information.

Quantifying Fireline Safety

Without the ability to measure the safety of their position, firefighters will not consistently know when a safe situation becomes unsafe. What is safe in the morning could become unsafe in the afternoon. What is safe about their current position could become unsafe as they continue to build fireline.

In order to assure safe fireline operations, firefighters need processes to evaluate fireline safety that are measurable, consistent, and transferable. When they can measure how safe they are, firefighters can repeat that safety measurement and communicate it to others. They will be able to describe what is safe and unsafe and evaluate the safety of their current and planned actions.

Two distance and time relationships must be evaluated by firefighters before they can determine how safe they are. The first is the distance between the fire and the safety zone and the time (T1) it would take the fire to spread to the safety zone. The second is the distance between the firefighter and the closest safety zone and the time (T2) it would take for the firefighter to retreat to it. Knowing these two times will allow the firefighter to determine where the line between a safe and unsafe operation exists. For example, in figure 1, the firefighters estimate that it will take 18 minutes (T1) for the fire to reach the safety zone and 12 minutes (T2) for them to reach the zone.

Creating a Margin of Safety

A margin of safety can be described as a cushion of time in excess of the time needed by the firefighters to get to the safety zone before the fire gets to them. It is the positive difference of T1 – T2. In figure 1, the difference is 6 minutes (18 minutes – 12 minutes), so the firefighters are in a safe position. If T1 = T2 as in figure 2, the difference is 0 and the fire and firefighters arrive at the safety zone at approximately the same time. Obviously, this situation would not benefit the firefighters; the fire may block their planned escape route. At best, they would experience a very close call, so they need to evaluate their margin of safety for escape or build a new safety zone.

If the difference is less than 0 as in figure 3 (T1 is 12 minutes and T2 is 15 minutes equaling –3 minutes), then it is likely that the fire will reach the firefighters before they get to the safety zone. While we would hope that firefighters would deploy fire shelters and survive the

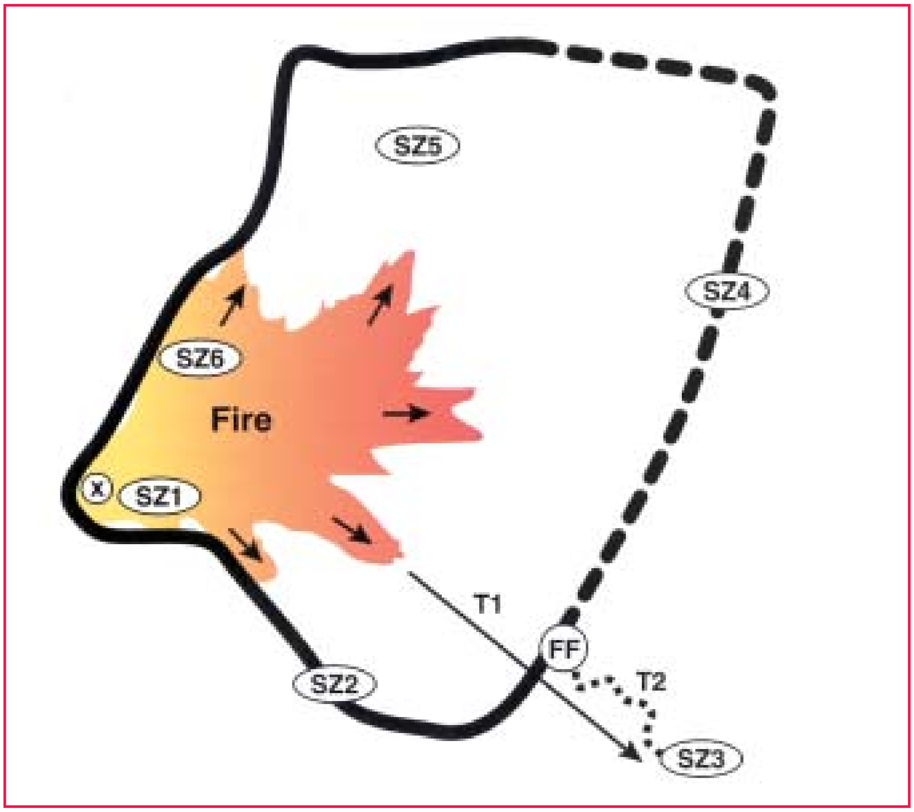

Figure 1—*T1 is estimated at 18 minutes—the time it would take a fire to reach safety zone 3 (SZ3). T2—the time it would take a firefighter to reach SZ3—is tested at 12 minutes. A 6-minute margin of safety exists, and firefighters are in a safe position.*

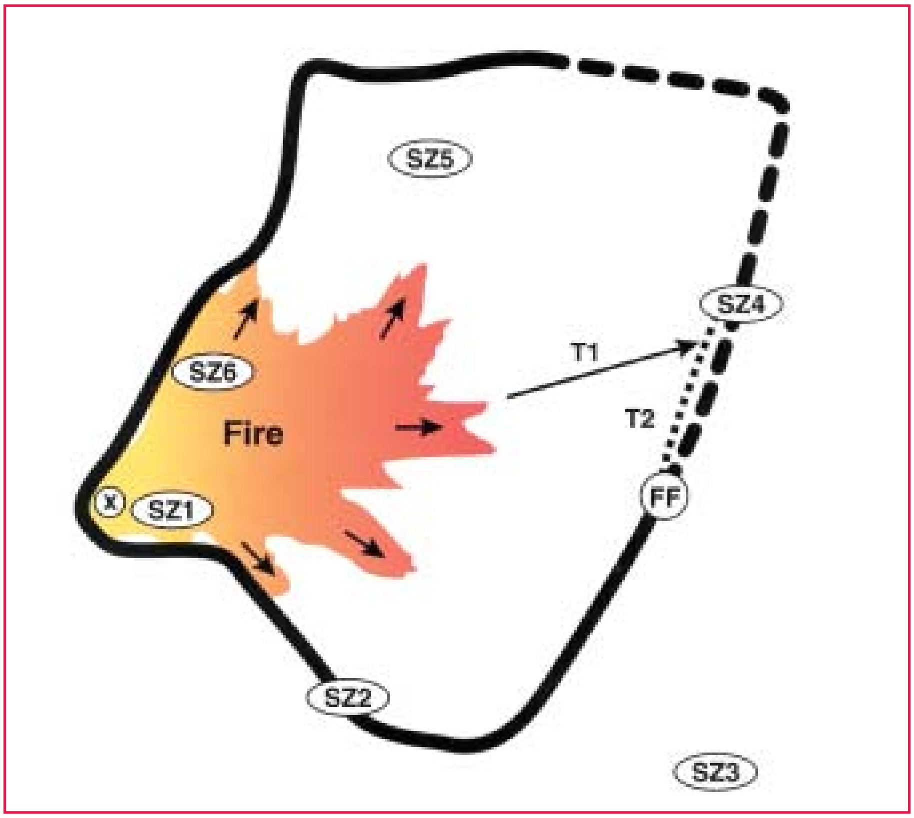

Figure 2—*It is estimated that the fire will reach safety zone 4 (SZ4) 20 minutes after it begins to run—T1 on the map. The time it would take a firefighter to reach SZ4 is the same (T2 = 20 minutes). There is no margin of safety.*

> In order to assure safe fireline operations, firefighters need processes to evaluate fireline safety that are measurable, consistent, and transferable.

fire, for a margin of safety, firefighters must arrive at the safety zone before the fire. T2 must be less than T1. In this example, the firefighters need to locate or construct a closer safety zone, abandon their suppression effort, or the fire behavior characteristics need to change. In short, the greater the positive difference between T1 and T2, the greater the margin of safety.

Firefighters should increase their margin of safety when there is an increase in uncertainty. Uncertainty can come from many situations. Firefighters can be uncertain about future weather conditions, a specific fire location, expected fire behavior in local fuel types, their own and others' physical ability, and the effectiveness of control actions on adjacent divisions or other fires in the immediate area. Firefighters must consider these variables when managing a margin of safety. There should never be any uncertainty about the location of safety zones and escape routes, the adequacy of communications, or the posting of lookouts.

Knowing When "Safe" Becomes "Unsafe"

Firefighters can use the T1 and T2 concept to provide a measurable, consistent, and transferable process to assess their margin of safety. This will enhance the value of L.C.E.S. applications—Lookouts, Communications, Escape Routes, and Safety Zones. Firefighters will

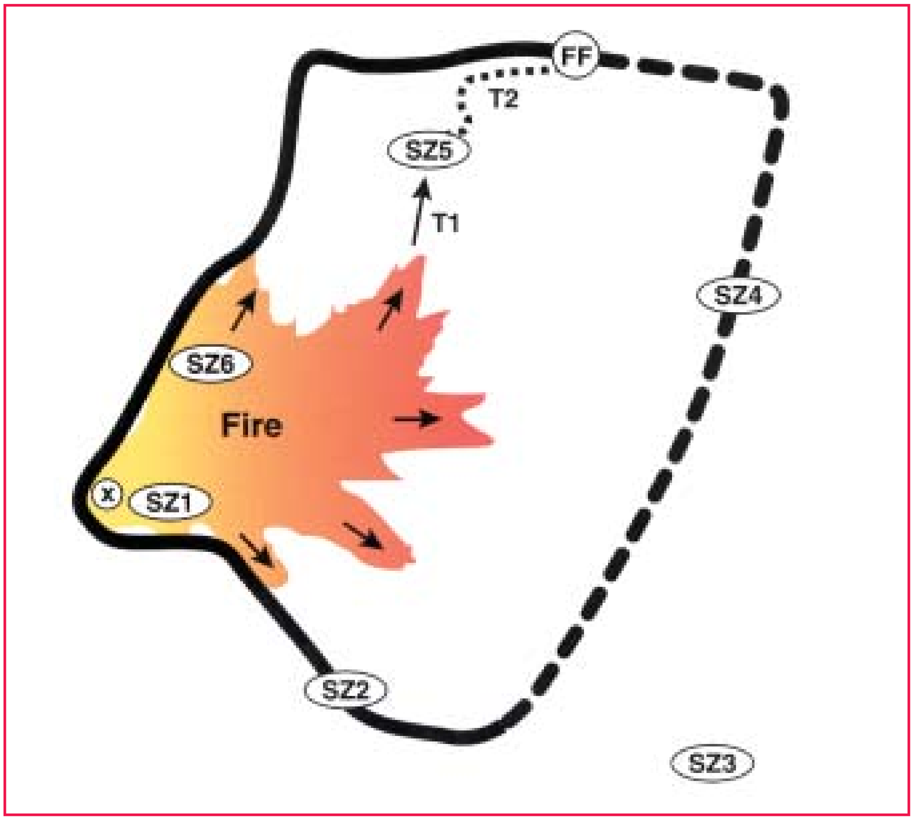

Figure 3—*T1—the time for the fire to reach safety zone 5 (SZ5)—is estimated at 12 minutes after the fire run begins. T2—the time it would take a firefighter to reach SZ5—is tested at 15 minutes, an unsafe situation.*

There should never be any uncertainty about the location of safety zones and escape routes, the adequacy of communications, or the posting of lookouts.

be able to identify when "safe" will become "unsafe" and communicate that to all affected personnel. They will know when to look for new safety zones and when escape route travel times are too long.

For large fire operational planning, this assessment can be conducted prior to committing firefighters to a fireline assignment. Safety zone and escape route requirements can be identified in the Incident Action Plan. A network of safety zones and escape routes can then be developed in conjunction with fireline construction. Firefighters will be able to create and maintain a margin of safety when they are beyond the safety zone. ■

Russo and Schoemaker (1989) Decision Trap 9—Not Keeping Track: Assuming that experience will make its lessons available automatically, and therefore failing to keep systematic records to track the results of your decisions and failing to analyze these results in ways that reveal their key lessons.*

* See page 9.

Firefighter Safety Zones: How Big is Big Enough?*

Bret W. Butler and Jack D. Cohen

All wildland firefighters working on or near the fireline must be able to identify a safety zone. Furthermore, they need to know how "big" is "big enough."

Beighley (1995) defined a safety zone as "an area distinguished by characteristics that provide freedom from danger, risk, or injury." The National Wildfire Coordinating Group proposed that a safety zone be defined as "a preplanned area of sufficient size and suitable location that is expected to prevent injury to fire personnel from known hazards without using fire shelters" (USDA/USDI 1995).

In our study of wildland firefighter safety zones, we focused on radiant heating only. In "real" wildland fires, convective energy transport in the form of gusts, fire whirls, or turbulence could contribute significantly to the total energy received by a firefighter. However, convection is subject to buoyant forces and turbulent mixing, both of which suggest that convective heating is important only when a firefighter is relatively close to the fire. One reason that firefighters in potential entrapment situations are told to lie face down on the ground is to minimize their exposure to convective heating. We hope to define more clearly the relationship between convective heating and safety zone size in future work.

> How much heat can humans endure before injury occurs?

What Do We Know?

Two questions are important when specifying safety zone size:

1. What is the radiant energy distribution in front of a flame? and
2. How much heat can humans endure before injury occurs?

Concerning the first question, Fogarty (1996) and Tassios and Packham (1984) related the energy received by a firefighter to fireline intensity and distance from the flame front. Green and Schimke (1971) presented very specific information about fuel break construction on slopes and ridges in the Sierra Nevada mixed-conifer forest type. Others have discussed the performance of fire shelters under different heating regimes (for example, King and Walker 1964; Jukkala and Putnam 1986; Knight 1988). As one would expect, there is not much information related to the second question. The available information suggests that 0.2 Btu/ft^2/s (2.3 kW/m^2) is the upper limit that can be sustained without injury for a short time (Stoll and Greene 1959; Behnke 1982). Studies by Braun and others (1980) suggest that when a single layer of 6.3 oz/yd^2 (210 g/m^2) Nomex cloth is worn, second degree burns will occur after 90 seconds when a firefighter is subjected to radiant fluxes greater than 0.6 Btu/ft^2/s (7 kW/m^2).

The Nomex shirts and trousers currently used by wildland firefighters have fabric weights of 5.7 and 8.5 oz/yd^2 (190 and 280 g/m^2), respectively. Few studies, however, have explored relationships between flame height and the safety zone size necessary to prevent burn injury.

Theory Versus Reality

We formulated a theoretical model to predict the net radiant energy arriving at the firefighter wearing Nomex clothing as a function of flame height and distance from the flame (Butler and Cohen 1998). Figure 1 displays the results.

The amount of radiant energy arriving at the firefighter depends both on the distance between the firefighter and the flame and on the flame height. The information shown suggests that in most cases safety zones must be relatively large to prevent burn injury.

We compared safety zone sizes predicted by our model against those reported on four wildfires: the Mann Gulch Fire, the Battlement Creek Fire, the Butte Fire, and the South Canyon Fire.

The Mann Gulch Fire overran 16 firefighters on August 5, 1949. Wag Dodge, one of only three survivors, lit a fire and then lay face down in the burned-out area as the main

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When this article was originally published, Bret Butler and Jack Cohen were research scientists for the USDA Forest Service, Fire Behavior Research Unit, Rocky Mountain Research Station, Intermountain Fire Sciences Laboratory, Missoula, MT.

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* The article is reprinted from *Fire Management Notes* 58(1) [Winter 1998]: 13–16.

fire burned around him. The Mann Gulch Fire occurred in an open stand of scattered, mature ponderosa pine (60 to 100+ years old) with a grass understory. Flame heights of 10 to 40 feet (3–12 m) were estimated to have occurred at the time of entrapment. Rothermel (1993) indicates that Dodge's fire burned about 300 feet (92 m) before the main fire overran it. Assuming an elliptical shape for the burned area, with its width approximately half the length, the safety zone created by Dodge's escaped fire would have been about 150 feet (46 m) wide. Figure 1 indicates that the safety zone needed to be large enough to separate the firefighters and flames by 90 to 150 feet (27 to 46 m) or approximately the same width as the area created by Dodge's fire.

The amount of radiant energy arriving at the firefighter depends both on the distance between the firefighter and the flame and on the flame height.

The Battlement Creek Fire occurred in western Colorado during July of 1976 (USDI 1976). The fire burned on steep slopes covered with 6- to 12-foot- (2- to 4-m-) high Gambel oak. Flames were estimated at 20 to 30 feet (6–9 m) above the canopy. Four firefighters were cut off from their designated safety zone. When the fire overran them, they were lying face down on the ground without fire shelters in a 25-foot- (8-m-) wide clearing near the top of a ridge. Tragically, only one of the four survived, and he suffered severe burns over most of his body. Figure 1 suggests that for this fire, the safety zone should have been large enough to separate firefighters from flames by 150 feet (46 m). Clearly, the 25-foot- (8-m-) wide clearing did not qualify as a safety zone.

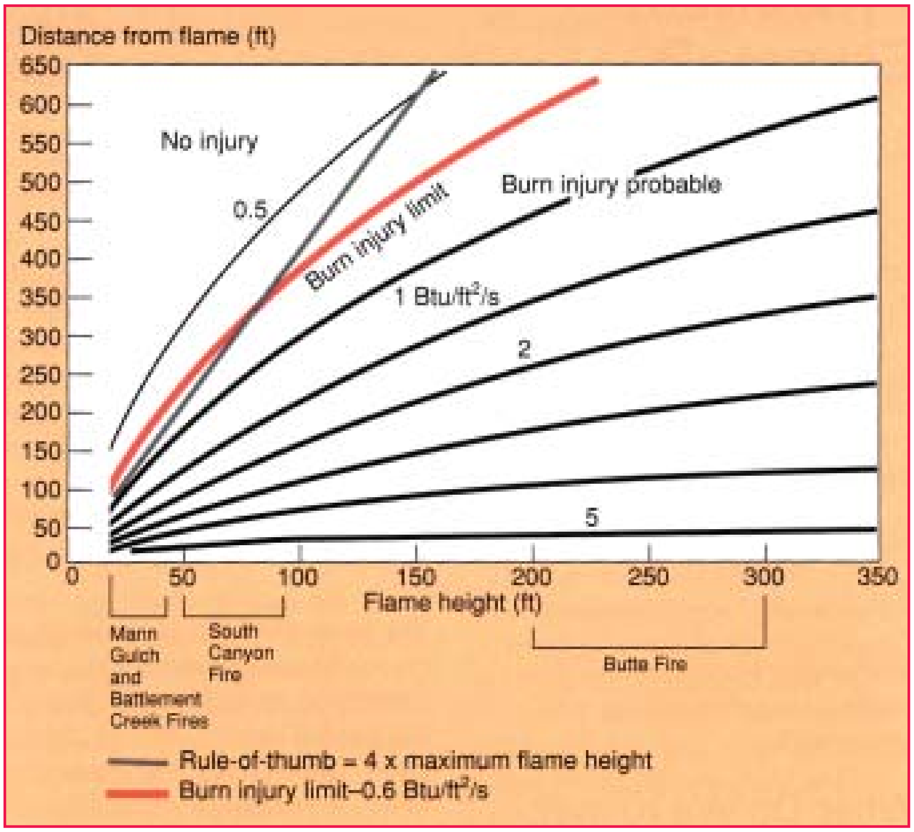

Figure 1—*Lines represent predicted radiant energy arriving at the firefighter as a function of flame height and distance from the flame. It is assumed that the firefighter is wearing fire-retardant clothing and protective head and neck equipment. The heavy shaded line represents the burn injury threshold of 0.6 Btu/ft²/s (7 kW/m²). The heavy solid black line indicates the rule of thumb for the size of the safety zone.*

Flame heights were reported to be 200 to 300 feet (62 to 92 m) high on the Butte Fire that burned on steep slopes covered with mature lodgepole pine and Douglas-fir during August of 1985 (Mutch and Rothermel 1986). Figure 1 indicates that a cleared area greater than 1,200 feet (370 m) across would have been needed to prevent injury to the firefighters standing in its center. In fact, safety zones 300 to 400 feet (92 to 123 m) in diameter were prepared (Mutch and Rothermel 1986). This diameter was not sufficiently large enough to meet the definition of a safety zone, as indicated by the fact that 73 firefighters had to deploy in fire shelters to escape the radiant heat. As the fire burned around the edges of the deployment zone, the intense heat forced the firefighters to crawl while inside their shelters to the opposite side of the clearing.

On July 2, 1994, the South Canyon Fire was ignited by a lightning strike to a ridgetop in western Colorado. During the afternoon of July 6, the South Canyon Fire "blew up," burning across the predominately Gambel-oak-covered slopes with 50- to 90-foot- (15- to 28-m-) tall flames (South Canyon Fire Accident Investigation Team 1994). Tragically, 14 firefighters were overrun by the fire and died while attempting to deploy their fire shelters. Twelve of the firefighters died along a 10- to 12-foot- (3- to 4-m-) wide fireline on a 55-percent slope, the other two in a steep narrow gully. Eight other firefighters deployed their fire shelters in a burned out area approximately 150 feet (46 m) wide. They remained in their shelters during three separate crown fire runs that occurred 450 feet (138 m) away from them; none of these eight firefighters was injured (Petrilli 1996). One firefighter estimates that air temperatures inside the shelters reached 115 °F (46 °C) and remembers smoke and glowing embers entering the fire shelters during the crown fire runs. Survivors felt they were far enough from the flames that survival with minor injuries would have been possible without the protection of a fire shelter (Petrilli 1996). A firefighter who did not deploy in a shelter but remained on a narrow ridge below the eight firefighters during the "blowup" experienced no injuries (South Canyon Fire Accident Investigation Team 1994). Figure 1 suggests that in this situation, the safety zone must be large enough to separate the firefighters and flames by 250 to 350 feet (77–115 m).

A general rule of thumb can be derived from figure 1 by approximating the injury limit with a straight line. After doing so, it appears that a safety zone should be large enough that the distance between the firefighters and flames is at least four times the maximum flame height. In some instances such as the Mann Gulch, Battlement Creek, and Butte Fires, the fire may burn completely around the safety zone. In such fires, the separation distance suggested in figure 1 is the radius of the safety zone, meaning the safety zone diameter should be twice the value indicated.

A safety zone should be large enough that the distance between the firefighters and flames is at least four times the maximum flame height.

What About Fire Shelters?

We calculated the net radiant energy transferred through a fire shelter like those used by firefighters in the USDA Forest Service. The fire shelter is based on the concept that the surface will reflect the majority of the incoming radiant energy. An average emissivity for the aluminum-foil exterior of a fire shelter is 0.07, indicating that approximately 93 percent of the energy incident on a fire shelter is reflected away (Putnam 1991). Model predictions shown in figure 2 suggest that heat levels remain below the injury limits for deployment zones wider than 50 feet (15 m), even with 300-foot- (92-m-) tall flames. However, this model does not. account for convective heating that could significantly increase the total energy transfer to shelters deployed within a few flame lengths of the fire.

Conclusions

Radiant energy travels in the same form as visible light, that is, in the line of sight. Therefore, locating safety zones in areas that minimize firefighters' exposure to flames will reduce the required safety zone size. For example, topographical features that act as radiative shields are the lee side of rocky outcroppings, ridges and the tops of ridges, or peaks containing little or no flammable vegetation. Safety zone size is proportional to flame height. Therefore, any feature or action that reduces flame height will have a corresponding effect on the required safety zone size. Some

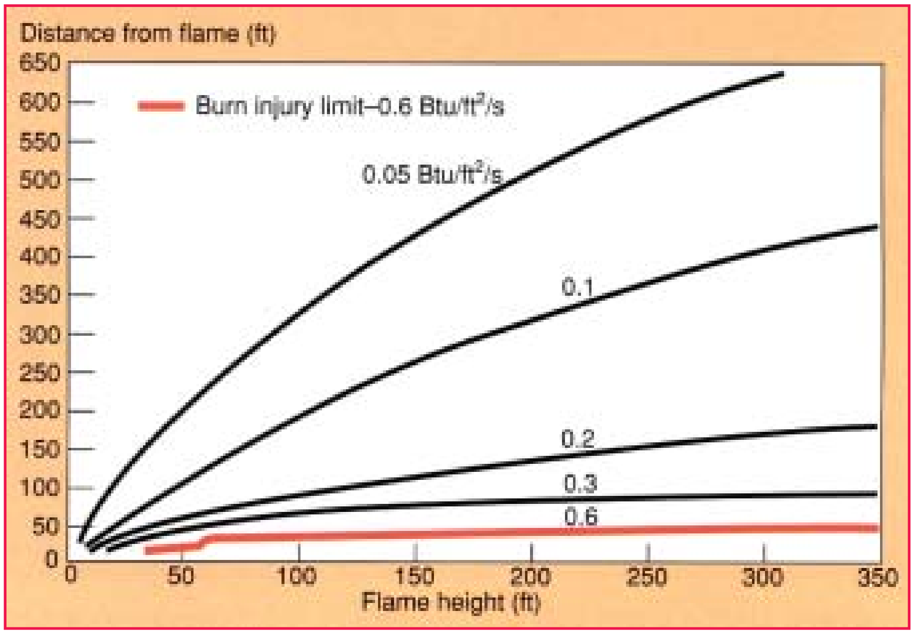

Figure 2—*Predicted radiant energy on a fire shelter as a function of distance between the fire shelter and flames, and flame height. The heavy shaded line represents the burn injury threshold for a firefighter inside a deployed fire shelter.*

examples are burnout operations that leave large “black” areas, thinning operations that reduce fuel load, and retardant drops that decrease flame temperatures.

Locating safety zones in areas that minimize firefighters’ exposure to flames will reduce the required safety zone size.

We emphasize that while this study addresses the effects of radiant energy transfer, convection is not addressed. Convective energy transfer from gusts, fire whirls, or turbulence could significantly increase the total heat transfer to the firefighter and thus the required safety zone size. Further work in this area is needed.

Acknowledgments

The United States Department of the Interior’s Fire Coordinating Committee, Boise, ID, provided financial assistance for a portion of this study. Ted Putnam of the Forest Service’s Missoula Technology and Development Center, Missoula, MT, provided valuable information and advice on the effects of heat on human tissue.

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Russo and Schoemaker (1989) Decision Trap 10—
Failure to Audit Your Decision Process: Failing to create an organized approach to understanding your own decisionmaking, so that you remain constantly exposed to all the above mistakes.*

* See page 9.

SAFETY ALERT: WATCH OUT FOR AIRCRAFT TURBULENCE!*

Billy Bennett

Aircraft play a vital role in today's fire control operations, carrying out such crucial missions as water and fire retardant drops. Yet turbulence from aircraft can sometimes contribute to erratic fire behavior, potentially endangering firefighters. As the National Wildfire Coordinating Group notes in a training publication for firefighters, "The blasts of air from low flying helicopters and air tankers have been known to cause flare-ups" (NWCG 1992). Those on the fireline should keep this potential hazard in mind, mentally adding it to their list of 18 Watch Out Situations.

Incident Within an Incident

A case in point occurred on July 11, 1996, on the Broad Canyon Fire in central Utah. At about 3 p.m., a wind shift caused the fire to jump containment lines during a burnout operation. A Cat D–7 dozer and dozer boss began constructing line around the slopover, which was burning in brush and 15-foot (4.6-m) juniper.

A type 2 helicopter using a bucket with a 35-foot (10.7-m) line began making drops along the fire edge. When the helicopter approached the area near the dozer, the rotor downwash caused the fire to behave erratically, encircling the immediate area around the dozer and dozer boss with fire. The only escape was to push through the active fire into the safety zone of the black. As the dozer operator bladed through the fire, the dozer boss followed close behind, using the dozer as a heat shield. They managed to escape unharmed.

Aircraft turbulence should be one of the unwritten Watch Out Situations for firefighters to keep in mind on the fireline.

Contributing Factors

Several factors contributed to this near-tragic incident, including circumstances clearly identifiable as Watch Out Situations:

- Available fuels were very dry and extremely volatile.
- A sudden wind shift had already caused the fire to jump containment lines.

  Watch Out Situations:

  #15 Wind increases and/or changes direction.

  #16 Getting frequent spot fires across line.
- The incident occurred in a somewhat narrow part of the canyon, where topography might have influenced fire behavior.
- When the helicopter pilot approached the slopover, he could not make radio contact with firefighters on the ground. This caused a delay, because the pilot did not know specifically where to make the drop.

  Watch Out Situations:

  #5 Uninformed on strategy, tactics, and hazards.

Resources assembling for the initial attack on the Broad Canyon Fire in central Utah, July 1996. Photo: Billy Bennett, South Carolina Forestry Commission, Spartanburg, SC, 1996.

When this article was first published, Billy Bennett was a law enforcement officer and fire management officer for the South Carolina Forestry Commission, Piedmont Region, Spartanburg, SC. In July 1996, he was the Staging/Initial Attack Safety Officer for the USDA Forest Service and USDI Bureau of Land Management in central Utah.

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* The article is reprinted from *Fire Management Notes* 58(4) [Fall 1998]: 20–21.

#6 *Instructions and assignments not clear.*
#7 *No communication link with crew members/supervisor.*

- The airspeed of the helicopter as it approached the scene was about 46 miles per hour (74 km/h), and altitude was less than 200 feet (61 m) above ground level. Firefighters on the ground believe that this was too low under the conditions, and the pilot now concurs.
- The helicopter was large enough to cause substantial rotor downwash (the larger the helicopter, the more rotor downwash to expect).

If any of these contributing factors had been removed, the incident likely would not have occurred. However, rotor downwash was probably the final contributing factor to the erratic fire behavior and resulting entrapment. The firefighters were operating within acceptable risk limits before the helicopter arrived, having to some extent compromised only a minimum number of Watch Out Situations. Not until the helicopter arrived did acceptable risk escalate into unacceptable risk within just a matter of seconds.

Fire behavior in brush–juniper fuels on the Broad Canyon Fire in central Utah, July 11, 1996. Fuels were extremely dry and volatile. Photo: Billy Bennett, South Carolina Forestry Commission, Spartanburg, SC, 1996.

Unwritten Watch Out Situation

One of the most important functions of fire managers on the fireline is to recognize when Watch Out Situations and Standard Fire Orders are excessively compromised, and to take immediate corrective action to ensure firefighter safety. Pilots will most likely not know how close firefighters on the ground are to this point of unacceptable risk. When air operations are in progress, pilots and firefighters alike must remember that no Watch Out Situation or Standard Fire Order specifically addresses how aircraft turbulence affects fire behavior. Pilots and firefighters should keep in mind that low or moderate hazards, under certain conditions, can quickly become high or extreme hazards due to unexpected aircraft turbulence.

This incident in no way suggests that turbulence from aircraft will always cause erratic fire behavior. However, it does suggest that aircraft turbulence should be one of the unwritten Watch Out Situations for firefighters to keep in mind on the fireline.

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THE CONSUMPTION STRATEGY: INCREASING SAFETY DURING MOPUP*

Tom Leuschen and Ken Frederick

For many years, the wildland fire community has known that mopping up a fire can be just as dangerous as containing and controlling it. Unfortunately, we have not always done the best job in mitigating the hazards that firefighters are exposed to during this important phase of fire suppression.

A new approach is now available for assessing the need for, and accomplishing, mopup on wildland fires. Known as the consumption strategy, the new approach departs from traditional thinking by using the natural tendency of a fire to burn itself out by consuming its fuel. The consumption strategy realistically compares the risks and consequences associated with an escaped fire to the risks and consequences associated with the hazards firefighters typically face during mopup, which tend to be related to gravity (falling snags, rolling materials, and tripping and falling). The strategy is designed to improve firefighter safety while still suppressing a fire.

> The consumption strategy for mopup exploits a fire's natural tendency to consume its fuels and burn itself out.

The consumption strategy is planned during containment and implemented during control or mopup. It includes these steps (fig. 1):

1. Mopup strategy and standards flow from a determination made about the fire's potential to escape across firelines after it is declared contained.
2. Sections of the fire that show a high potential for escape receive the normal mopup treatment.
3. Sections of the fire that do not show a high potential for escape and that contain significant gravity-related hazards are not considered for lengthy operational assignments that could place crews in harm's way.
4. Sections of the fire avoided due to gravity-related hazards are still patrolled or otherwise monitored. "Patrolling" means that crews or scouts hike along firelines in the avoided areas (staying alert for falling or rolling material) to check for escapes of the fire across firelines but not

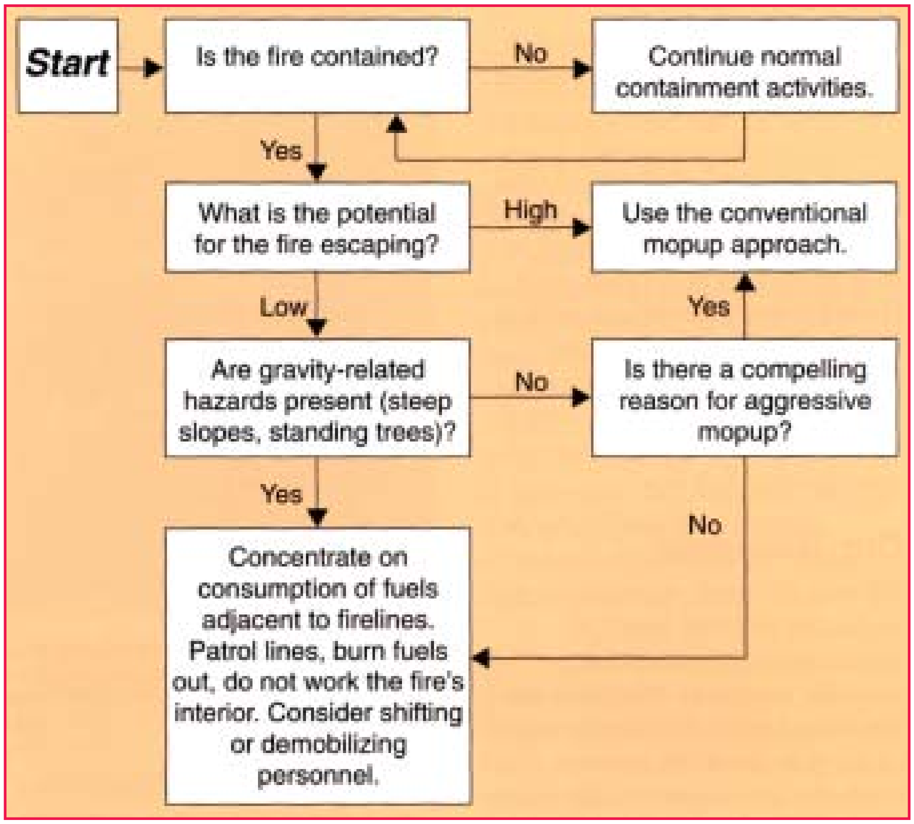

Figure 1—*Consumption strategy decision tree, for application separately to each section of the fire.*

When this article was first published, Tom Leuschen was a fire and fuels specialist for the USDA Forest Service, Okanogan National Forest, Okanogan, WA; and Ken Frederick was an information assistant for the Forest Service, Wenatchee National Forest, Chelan Ranger District, Chelan, WA.

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The consumption strategy reduces gravity-related risks to firefighters during mopup, such as falling trees, slippery slopes, and rolling rocks, logs, and stumps.

to extinguish flames or embers within the firelines.

5. Operational assignments in avoided areas can include, in addition to patrolling, tasks such as blacklining (burning fuels adjacent to firelines), flush-cutting stobs, trimming tree branches immediately inside the lines, and gridding (searching systematically along gridlines) for spot fires well outside of the lines. Firelines can be strengthened, as long as crews maintain good lookouts and do not linger in dangerous spots.

Origins of the Consumption Strategy

The consumption strategy originated in response to a near tragedy during the 1997 fire season. The season was relatively quiet in eastern Washington. In fact, the only project fire on the Wenatchee National Forest was the Gold Creek Fire on the Naches Ranger District in August 1997, which burned about 480 acres (190 ha) of ponderosa pine and Douglas-fir near Cliffdell, WA. During mopup on the incident, a Washington Department of Natural Resources crewmember was struck and seriously injured by a snag being felled by a sawyer. Ironically, the accident occurred when areas inside the fireline were being “snagged” for firefighter safety.

Tom Leuschen, the fire and fuels specialist for Washington’s Okanogan National Forest, was on the Gold Creek Fire as a fire behavior analyst. “It occurred to me,” Leuschen recalled, “that we were asking the firefighters to work in hazardous areas to do mopup when there was minimal risk of the fire escaping.” By the third day of the Gold Creek Fire, Leuschen had hiked the perimeter of the fire and determined that the blaze posed little threat of escaping. However, the operations and plans sections of the type 2 team managing the fire were still trying to control the fire according to standards agreed to by the local line officer and the incident management team—and that included risky mopup work inside the black.

After the accident, Leuschen and the district ranger walked out to the lines with the incident commander, safety officer, and operations section chief to take a sober look at the work. Although discussion continued to focus on how firefighters could work safely inside the lines, Leuschen questioned whether firefighters needed to work inside the black at all. Areas where firefighters had completed several shifts of mopup showed little difference in the kinds and amounts of smoldering debris from similar areas where no mopup had occurred. Residual interior smokes were not a threat to the lines. Furthermore, a large percentage of the fire perimeter consisted of sections where the fire had backed downhill; in order to escape in these areas, the fire would have to jump the lines and aggressively spread downhill, a highly unlikely eventuality. “As a result of our observations,” Leuschen said, “we recommended a change in mopup standards to the line officer.” The group had learned a lesson: Performing mopup where it wasn’t really needed had nearly cost a life.

The Gold Creek incident made it increasingly obvious that we need a strategy for assessing risk to reduce firefighters’ exposure to hazards during mopup. Since the South Canyon tragedy in 1994, risk assessment has focused primarily on avoiding fire entrapments. In recent years, the wildland fire community has paid more attention to mitigating risk during containment and control (constructing and securing firelines) than during mopup. We need to rethink what mopup is. Are we out there trying to physically put out every flame and ember, or are we trying to prevent the fire from escaping control lines while those flames and embers burn out? Depending on the situation, we currently do both; but we should remember to distinguish between the two and to choose the approach that best protects our crews.

Managers’ perceptions of the risks to firefighters must change with changes in a given fire. At a certain point in a fire, the primary danger facing firefighters is no longer the fire itself, but rather falling or rolling objects (fig. 2). As the fire nears containment, entrapment risk decreases but gravity-related risk increases. Trees, both live and dead, with fire in their bases become increasingly unstable; stumps roll as they lose the old, dry roots that have held them on the slope; and firefighter fatigue accumulates, reducing energy and alertness and causing more tripping and falling on steep terrain.

Entrapment during mopup obviously remains a serious risk that overhead and crews must never forget. However, we must elevate our awareness of the risks to firefighters from gravity-related hazards during mopup.

Operational Success

In August 1998, the 8,500-acre (3,400-ha) North 25 Fire on the Wenatchee National Forest's Chelan Ranger District in Washington provided the first opportunity to implement the consumption strategy. A number of factors coincided to make testing possible under actual field conditions. First, Tom Leuschen was detailed to the district as the fire management officer for the summer. Second, the Central Washington Area Incident Command Team, the same team that had handled the Gold Creek Fire, was assigned to manage the North 25 Fire when it escaped initial attack. With the Gold Creek experience still fresh in their minds, the team's leaders were willing to consider a new approach. Third, District Ranger Al Murphy and Forest Supervisor Sonny O'Neal were both willing to accept the possibility of a longer lasting or larger fire if the consumption strategy were implemented. Finally, the North 25 Fire had the topographical and fuel conditions necessary for applying the new approach (fig. 3).

Implementing the consumption strategy on the North 25 Fire offered several immediate benefits:

1. Reduced risk of firefighter injury due to falling and rolling materials on steep, rocky slopes.
2. Reduced need for resources and labor. Because much of the North 25 Fire's perimeter was inaccessible by road, conventional mopup was likely to involve lots of crews, long hoselays, and significant helicopter use.
3. Reduced cost. Assisted by the consumption of available fuels, mopup would cost less than traditional, labor-intensive mopup.

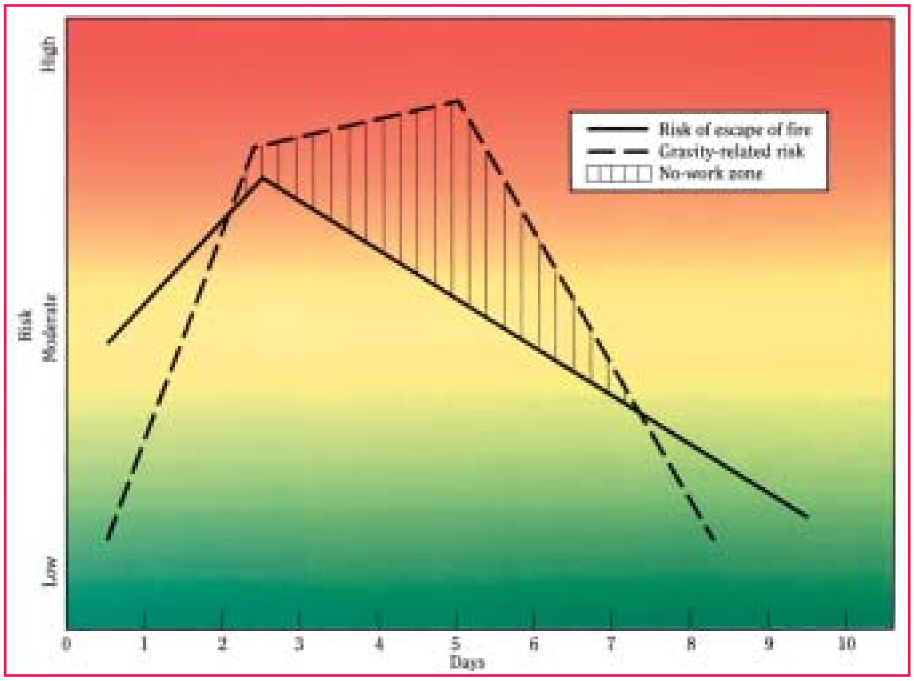

Figure 2—*Consumption strategy risk assessment on a fire in coniferous forest that is contained after 3 days. As the fire nears containment, gravity-related risks (such as falling trees, slippery slopes, and rolling rocks and stumps) exceed risks from an escaped fire. In sections of the fire where gravity-related risks exceed the risk of fire escape (the no-work zone), mopup should be avoided.*

Figure 3—*An Erickson S–64 helicopter drops water on an inaccessible spot fire, part of the North 25 Fire, Chelan Ranger District, Wenatchee National Forest, WA, in August 1998. The steep terrain and poor accessibility of the site called for applying the consumption strategy, which succeeded in controlling the fire while minimizing the risks to firefighters from gravity-related hazards such as falling snags and rolling logs. Photo: Paige Houston, USDA Forest Service, Okanogan National Forest, Tonasket Ranger District, Tonasket, WA, 1998.*

The consumption strategy saves labor and reduces costs, freeing resources for use on other incidents.

4. Reduced spread of noxious weeds, particularly the diffuse knapweed *(Centaurea diffusa).* Ranger Murphy saw that tilling less soil would reduce the amount of prepared seedbed for weed propagation. "The North 25 Fire burned on both sides of one of the busiest roads on this district," he said. "The less ground we dig up, the more we prevent weeds from spreading outside of the road corridor."

The incident management team carefully briefed all operational personnel on why and how the new mopup standards were to be implemented on the fire. Even after several briefings, however, some crews still had trouble accepting the idea of merely patrolling firelines for 3 to 5 days while allowing the fire to consume fuels just inside the lines. "This approach is a cultural shift in how we manage fires," said Incident Commander Jim Furlong. "We are used to being aggressive in extinguishing fires, so being patient like this feels a little unnatural." Some crews modified their line patrol assignments by scavenging a 20-foot (6.2-meter) strip of ground just inside the lines for fuel and then constructing and burning numerous small handpiles. The result was a cleanly burned and very secure blackline.

According to Furlong, many crews understood that the incident management team was looking out for firefighter safety in using the consumption strategy. "The crews that picked up on what we were doing were the hotshot crews," Furlong noted. "I had a number of superintendents come up to me and thank us for using this approach." Twenty-two interagency hotshot crews from the Pacific Northwest and California were on the North 25 Fire.

The consumption strategy succeeded. About a quarter of the fire perimeter was never considered for direct attack, let alone mopup, because it was on an extremely steep, rock-strewn slope overlooking Lake Chelan (fig. 4). Around the remainder of the fire, the operations section chiefs opted for intensive mopup on only 22 percent of the firelines, based on the prevalence of unburned fuels next to the lines. For 3 to 5 days, more than 7 miles (11.2 km) of the 9.5 miles (15.2 km) of accessible perimeter were allowed to smolder under the watchful eyes of daily patrols. There were no accidents during mopup and no significant escapes. Because almost no hose was laid and operations were much less labor intensive than under the conventional mopup approach, seven crews could be freed right away for fire assignments elsewhere.

Lessons Learned

Several lessons can be learned from our experience with the consumption strategy on the North 25 Fire:

- Firefighters should mop up in areas of high gravity-related hazard only when necessary. Too often we approach mopup based on tradition and habit. Especially in an age of increasingly large fires across the West, the same

Figure 4—*The North 25 Fire burns deep in Box Canyon on the south shore of Lake Chelan, Chelan Ranger District, Wenatchee National Forest, WA, in August 1998. About a quarter of the fire perimeter was never considered for direct attack, let alone mopup, because it was on an extremely steep, rock-strewn slope overlooking the lake. The consumption strategy is well suited for consideration on such sites. Photo: Paige Houston, USDA Forest Service, Okanogan National Forest, Tonasket Ranger District, Tonasket, WA, 1998.*

safety mindset should prevail for mopup as for line construction. Sometimes it might be safer and more sensible to be vigilantly patient for a few days while a fire consumes its fuels than to aggressively put it out.

- Line officers and fire managers on project fires should reflect upon what might be a false sense of insecurity regarding how thoroughly a fire should be extinguished before the local administrative unit reassumes responsibility for the fire. Line officers should consider accepting more risk of fire escape in exchange for less risk to firefighter safety. The risk of escape is often only marginally higher under the consumption strategy.
- Fire behavior analysts should measure the potential for escape on each section of line as it is completed. Each section must also be evaluated for gravity-related hazards. These data must then be presented to the line officer for determining mopup standards.
- Although perceiving mopup as putting out the fire is often appropriate, sometimes a more reasonable interpretation of mopup is making sure the fire does not cross control lines. Making this subtle distinction will help fire managers and firefighters avoid the potentially high costs of doing what the fire will likely do by itself—given just a little time.

Safety must always be our first priority in suppressing wildland fires. Applied correctly, the consumption strategy offers a safer, more cost-effective means of achieving the same objective—wildland fire suppression. ■

Wildland Fire Research's Raison D'etre*

One basic presupposition seems to be essential, and to demand full agreement and understanding…. This is the premise that all of our experiment station divisions of fire research have just one justification for existence, just one function, just one objective. That is: To aid the present and future administrators of fire control, Federal, State, and private. We are not doing research for research's sake. We have a definite, decidedly practical goal, and it is still the basic, over-all goal that Graves stated in 1910: "The first measure necessary for the successful practice of forestry is protection from forest fires." Fire research is therefore intended to serve as directly as possible the fire-control men who must first be successful before any of the other arts or artists of forestry can function with safety.

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* From H.T. Gisborne "Review of Problems and Accomplishments in Fire Control and Fire Research (*Fire Control Notes* 6[2] [April 1942]: 47–63).

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Fire Management Today (*FMT*) is an international quarterly magazine for the wildland fire community. *FMT* welcomes unsolicited manuscripts from readers on any subject related to fire management. Because space is a consideration, long manuscripts might be abridged by the editor, subject to approval by the author; *FMT* does print short pieces of interest to readers.

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PHOTO CONTEST ANNOUNCEMENT

Fire Management Today invites you to submit your best fire-related photos to be judged in our annual competition. Judging begins after the first Friday in March of each year.

Awards

All contestants will receive a CD–ROM with all photos not eliminated from competition. Winning photos will appear in a future issue of *Fire Management Today*. In addition, winners in each category will receive:

- 1st place—Camera equipment worth $300 and a 16- by 20-inch framed copy of your photo.
- 2nd place—An 11- by 14-inch framed copy of your photo.
- 3rd place—An 8- by 10-inch framed copy of your photo.

Categories

- Wildland fire
- Prescribed fire
- Wildland/urban interface fire
- Aerial resources
- Ground resources
- Miscellaneous (fire effects; fire weather; fire-dependent communities or species; etc.)

Rules

- The contest is open to everyone. You may submit an unlimited number of entries from any place or time; but for each photo, you must indicate only one competition category. To ensure fair evaluation, we reserve the right to change the competition category for your photo.
- An original color slide is preferred; however, we will accept high-quality color prints, as long as they are accompanied by negatives. Digitally shot slides (preferred) or prints will be accepted if they are scanned at 300 lines per inch or equivalent. Digital images will be accepted if you used a camera with at least 2.5 megapixels and the image is shot at the highest resolution or in a TIFF format.
- You must have the right to grant the Forest Service unlimited use of the image, and you must agree that the image will become public domain. Moreover, the image must not have been previously published.
- For every photo you submit, you must give a detailed caption (including, for example, name, location, and date of the fire; names of any people and/or their job descriptions; and descriptions of any vegetation and/or wildlife).
- You must complete and sign a statement granting rights to use your photo(s) to the USDA Forest Service (see sample statement below). Include your full name, agency or institutional affiliation (if any), address, and telephone number.
- Photos are eliminated from competition if they have date stamps; show unsafe firefighting practices (unless that is their express purpose); or are of low technical quality (for example, have soft focus or show camera movement). (Duplicates—including most overlays and other composites—have soft focus and will be eliminated.)
- Photos are judged by a photography professional whose decision is final.

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Enclosed is/are __________ (*number*) slide(s) for publication by the USDA Forest Service. For each slide submitted, the contest category is indicated and a detailed caption is enclosed. I have the right to grant the Forest Service unlimited use of the image, and I agree that the image will become public domain. Moreover, the image has not been previously published.

Signature ____ Date ______________________

First of Its Kind: A Historical Perspective on Wildland Fire Behavior Training

M.E. Alexander and D.A. Thomas

In 1957, the Chief of the USDA Forest Service appointed a task force to study ways of preventing firefighter fatalities in the future. A review of 16 fatality fires found that the associated fire behavior in all but one case was unexpected by those entrapped or overrun. One of the task force's major recommendations was an intensified program of fire behavior training.*

The recommendation led to the first National Fire Behavior Training School. Trainees assembled at the Smokejumper Center in Missoula, MT, for a course that lasted from March 31 to May 1, 1958. Bacon (1958) has written a good account of the 5-week course.

The 28 trainees came from all regions of the Forest Service, various forestry schools, the U.S. Department of the Interior, and the National Association of State Foresters. The instructors came from the Forest Service, the U.S. Weather Bureau, Yale University, and the Munitalp Foundation. Trainees and some instructors are shown in the group photo below (from Bacon 1958).

Students and instructors at the first National Fire Behavior Training School, held in spring 1958. Front row (left to right): *A. Brackebusch (INT), E. DeSilvia (R-1), J. Philbrick (R-6), E. Marshall (R-6), M. Lowden (WO), E. Williams (R-8), J. Coleman (R-9), E. Bacon (WO), and W. Moore (R-1).* Middle row (left to right): *F. Brauer (R-1), K. Knutson (R-2), K. Wilson (R-2), J. Koen (R-8), J. Kilodragovich (R-1), C. Phillips (CDF), D. Pomerening (R-8), B. Emerson (R-9), H. Reinecker (CDF), and J. Dieterich (INT).* Back row (left to right): *L. Biddson (R-5), C. Fox (R-4), S. Moore (R-6), K. Scholz (R-2), J. Davis (RMF), K. Thompson (R-2), B. Rasmussen (R-4), J. Keetch (R-7), T. Schlapfer (R-5), L. Kelley (R-7), T. Koskella (R-4), W. Murray (R-4), K. Weiesenbam (R-3), F. Mass (R-1), J. Franks (BLM), C. Hardy (INT), W. Krumm (WB), and J. Barrows (INT).* Abbreviations: *BLM = U.S. Department of the Interior, Bureau of Land Management; CDF = California Division of Forestry; INT = USDA Forest Service, Intermountain Forest and Range Experiment Station; R-1 = Forest Service, Northern Region; R-2 = Forest Service, Rocky Moutain Region; R-3 = Forest Service, Southwestern Region; R-4 = Forest Service, Intermountain Region; R-5 = Forest Service, Pacific Southwest Region; R-6 = Forest Service, Pacific Northwest Region; R-8 = Forest Service, Southern Region; R-9 = Forest Service, Eastern Region; RMF = Forest Service, Rocky Mountain Forest and Range Experiment Station; WB = U.S. Weather Bureau; and WO = Forest Service, Washington Office.*

Acknowledgment

The authors wish to thank Mike Hardy and Colin Hardy for their help with naming the individuals shown in the photo.

Reference

Bacon, E.M. 1958. Training in forest fire behavior. American Forests. 64(7): 24-25, 47-49.

Marty Alexander is a senior fire behavior research officer with the Canadian Forest Service at the Northern Forestry Centre, Edmonton, Alberta; and Dave Thomas is regional fuels specialist for the USDA Forest Service, Intermountain Region, Ogden, UT.

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* The task force's full report is on the World Wide Web at <http://wildfirelessons.net/Libr_History.html>.

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