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FIRE WHIRLS

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Missoula, Montana

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NATIONAL OCEANIC AND
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NATIONAL WEATHER
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FIRE WHIRLS

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ABSTRACT. Fire whirls are of major concern to wild land fire managers because of their disruptive effect on control and containment efforts. This paper discusses the parameters both geographic and meteorological under which fire whirls form.

I. INTRODUCTION

One of the most interesting phenomenon that can occur in the fire environment is the Fire Whirl. It is also one of the unusual factors that has been responsible for the rapid spread of many wildfires and prescribed fires that were considered safely contained or uncontrolled. When a fire whirl develops inside the fireline, all models for predicting rates of spread or intensity collapse. It is a phenomenon that forms in a fragile environment, but once formed can be a self-perpetuating ogre.

This paper will attempt to describe and define the fire whirl. It will address some of the meteorological conditions that are favorable for the formation of whirls, and some of the related factors that have been observed to be conducive to whirl development.

II. HISTORY

The early history of fire whirls is somewhat vague. However, the dust devil which is closely related, both meteorologically and dynamically, is well documented. Archaeological reports indicate that dust devils are depicted on the Corinthian Pillars of St. Sophia in Thessalonica, Greece. These structures date back to the fifth century B.C. (Geiger 1965.)

Some of the early scholars allude to the whirl winds in both their teachings and writings. Specifically, Aristotle, Pliny, and Fulke made specific comments on the phenomenon they referred to as the "Whyrlewynde". In fact, Pliny provided us with the first actual definition as follows: "A Whyrlewynde sometimes is caused by two contrary winds that meet together" (Heninger 1960). Even though this definition is some 2300 years old, it is still quite valid and is applicable to the fire whirl phenomenon.

In more recent times extremely large fire whirls have been documented. During the bombing raids over Germany in World War II, a huge fire storm was reported. This fire occurred as a result of incendiary bombing of Hamburg (Anderson 1977). The day was characterized by light winds and unstable conditions. With the induced bouyancy from the fire, the

Hamburg Fire Storm was reported to be almost two miles in diameter with winds up to 112 MPH.

III. WHAT IS A FIRE WHIRL?

In defining a fire whirl, I will borrow definitions from two different sources. The first being Cooley (1971) as he talks specifically of dust devils, and the second, Anderson and Goens (1978). This definition is as follows:

> "A fire whirl is a vigorous atmospheric circulation, created when highly unstable, superheated, dry air near the ground breaks through the boundary layer and shoots upward in a swirling motion. This is also the result of an imbalance in the horizontal air flow that creates a positive vorticity cell."

In order to more fully understand this phenomenon, let us look at the more varied members of this atmospheric circulation family. The fire whirl, along with the dust devil, is a member of a larger circulation family. This family includes the following types of systems:

1. <u>Synoptic-scale cyclones</u>, i.e., the "Low-Pressure" system shown on the weather maps. These have a diameter on the order of 600 miles and rotational velocity of 2 MPH.

2. <u>Tropical cyclones</u>, i.e., hurricanes or typhoons. These have diameters of around 60 miles and rotational velocities of up to 220 MPH.

3. <u>Tornadoes and waterspouts</u>. These have an average diameter of about 1000 feet with rotational velocities up to 300 MPH.

Even though the fire whirl can be classified dynamically with these larger scale circulation systems, there is a very significant difference that must be understood. The more general circulations defined above are driven by one basic form of energy. This energy form is the latent heat of condensation. In other words, the formation and maintenance of these systems are controlled directly by available moisture. This can be shown graphically by observing what happens when an extra-tropical hurricane moves onshore. Soon after losing the source of moisture, i.e., the ocean, it collapses. (Of course, frictional changes and other factors are involved.)

In contrast, the fire whirl derives its energy from the release of heat during the combustion process. Looking more specifically at fire whirls, they can be classified as follows:

1. Fire Devils. They are a natural part of fire turbulence with little influence on fire behavior or spread. They are usually on the order of 3 to 33 feet in diameter and have rotational velocities less than 22 MPH.

2. Fire Whirls. A meld of the fire, topograph, and meteorological factors. These play a significant role in fire spread and hazard to control personnel. The average size of this class is usually 33 to 100 feet, with rotational velocities of 22 to 67 MPH.

3. Fire Tornadoes. These systems begin to dominate the large-scale fire dynamics. They lead to extreme hazard and control problems. In size, they average 100 to 1,000 feet in diameter and have rotational velocities up to 90 MPH.

4. Fire Storm. Fire behavior is extremely violent. Diameters have been observed to be from 1,000 to 10,000 feet and winds estimated in excess of 110 MPH. This is a rare phenomenon and hopefully one that is so unlikely in the forest environment that it can be disregarded.

While considering these four general classes of fire whirls, there can be three different types of whirls generated. They are:

1. The Thermally Driven Form. This form results from some type of shear in the horizontal airflow coupled with the energy release (convection) from fire activity.

2. The Convection Column Vortex. This form is more poorly understood. It originates high in the convection column (up to 1000 feet) and extends in the ground as much as a fourth (1/4) mile on the leeward side of the fire.

3. The Wake-Type Whirl. This results from the generation of eddies caused by airflow around an obstacle coupled with heat released by the fire.

All three of these types can be a significant problem in the spread or control of fire. The fire whirl in its steady-state form, i.e., after it has formed and before it begins to collapse, has two sharply defined regions of differing airflow (Byron and Martin 1970). The cooler, slowly rotating zone surrounds a central core of hot gases with high horizontal and vertical velocities. This central core can have temperatures from 1800° to 2400°F and burning rates two to seven times normal. Flame height can be 10 to 50 times the core diameter. Fire spread occurs when burning debris is entrained into the column just above the surface boundary layer, is carried aloft and then cast out from the upper portion of the whirl core some time later. The path of the whirl can be quite erratic; therefore, direction and rate of spread are almost impossible to forecast.

There has been considerable speculation and controversy regarding the direction of rotation of fire whirls. Since the whirl is basically a microscale low-pressure system, meteorological theory suggests that it should rotate cyclonically (counter-clockwise) in the Northern Hemisphere. There has been little specific research in this area regarding fire whirls, but much work has been done regarding dust devils. It seems safe to draw from the results of these studies and apply the findings to fire whirls.

Research by Cooley (1971) indicates that on the whole, dust devils showed little preference in direction of rotation (see Table I).

Table I

Direction of Rotation	Flower 1936	CDOP*	McDonald 1960	Sinclaire	Williams 1948	Total
Cyclonic	199	53	9	60	9	330
Anticyclonic	175	35	29	84	12	335
Total	374	88	38	144	21	665

*Cooperative Dust Devil Observation Program

His study shows that the very smallest and very largest dust devils show a preference for cyclonic circulation, while the intermediate size indicated very little preference in rotational direction. From this and other experience, it can be said that fire whirls can rotate in either sense. It appears as if the triggering circulation force will determine the sense of rotation. That is to say, if the horizontal shear is in a cyclonic sense, the whirl will rotate cyclonically, and conversely if the shear happens to be anticyclonic. The direction of rotation actually is not significant since the spread and behavior of the fire are influenced because the whirl is there, not because it is rotating in one direction or another.

IV. HOW ARE FIRE WHIRLS FORMED?

Since our subject is fire whirls, we can say that they are formed in and by the fire environment.

More specifically, in order for a fire whirl to form, two conditions must be present:

1. A buoyant column of heated air.

2. Ambient vorticity. Vorticity is defined by Huschke (1959) simply as a vector measure of local rotation.

The ambient vorticity is the generating circulation that is impressed upon the buoyant heated column to initiate the fire whirl. Once the whirl has been formed, its continued existence depends more on the flow of energy into and out of the whirl than on the available vorticity (Anderson 1977).

In order for the whirl to form, the very thin boundary layer must be highly unstable. Ryan (1972) reports in his research that the lapse rates most conducive to whirl formation are as follows:

Table 2

Lapse Rate Layer Description	Temperature Lapse Rate °F/1,000 Ft.	Temperature Lapse Rate °C/Meter
Surface to 1 foot (0.3 meter)	33	.060
1 foot to 33 feet (10 meters)	137	0.25
33 feet to 3,280 ft. (1 kilometer)	6.6	0.012
Overlying dry to subadiabatic layer	5.5	0.01 or less

He found that the lapse rate in the lower one foot is the basic determinant of whirl frequency and diameter, while the whirl rotational velocity is dependent on the instability of the layer from 33 to 3300 feet.

In conclusion, we can say that as the lapse rate in the 1-foot to 33-foot layer increases, increasingly larger diameter whirls may develop. The existence of a fire in such a localized environment provides additional buoyancy and if ambient vorticity is available, fire whirls can be rapidly generated.

V. WHEN AND WHERE ARE WHIRLS FORMED?

Since fire whirls are primarily the result of local processes, favored areas and conditions can be identified. Whirl occurrence is directly related to thermal instability and available vorticity; therefore, those areas in which these conditions exist will be the most likely candidates.

It has been found that maximum whirl activity does not always occur when surface temperature (standard shelter height 4 feet above the ground) is at a maximum. It occurs instead when the low-level (up to 30 feet) lapse rate is at a maximum. This is directly related to aspect, slope, and latitude in respect to incoming solar radiation. Figure 1 shows the difference in the time of day when incoming solar radiation is at its maximum on different major aspects. According to this, earliest evidence of whirl activity should occur on east slopes, followed by south then west. In the Northern Hemisphere, north slopes have a more uncertain potential due to the lower irradiance levels.

Regardless of slope, the following factors can contribute to whirl formation on any slope:

1. Large angle of incidence for solar radiation.

2. Minimum cloudiness.

3. Low humidity.

4. Dry exposed soil or burned-over area.

5. Winds below 5 MPH at 30-ft. level.

As the day progresses, more of these factors become effective and interact with local burning conditions and wind fields to make the likelihood of whirls greater. Interestingly, it has been found that, as in factor 2 above, even though minimum cloudiness is conducive to whirl formation, a slight change from clear to 2/10 to 3/10 cloud cover can decrease whirl activity by as much as 50%.

The duration of a fire whirl is quite variable. The average duration is on the order of a few minutes, but Graham (1957) reports whirls lasting as long as two hours. They tend to move across or up slopes, but as surface winds reach 5 MPH and stronger they tend to move with the surface flow.

The following is a listing of locations and conditions where whirlwind formation is quite likely.

1. Whirls can occur wherever and whenever eddies can be expected. Winds channeled either up canyon or down canyon can generate eddies:

   a. Behind spur ridges.

   b. At sharp bends in the canyon.

   c. Where two or more canyons join.

2. Whirls can occur along the boundary of two different air masses (i.e., fronts) where thermal differences and wind shear (speed and direction) occur.

3. Whirls can occur in the burned-over area after the fire has passed. The blackened surface will heat up rapidly with solar radiation to provide an extremely unstable low-level lapse rate.

4. Hot spots can trigger whirls as they tend to occur at:

   a. Points where there are differences in slope.

   b. Points where fuel quantities increase.

c. Topographic locations conducive to extreme fire behavior such as ravines or box canyons.

5. If the fire has a strong and well developed convection column, fire whirls can occur either up in the column and work downward, or as wake-type whirls on the downwind side of fire.

6. Whirls can occur if the prevailing winds are blowing across the ridge line and the fire is burning upslope on the lee side (see Figure 2). This is the classical case where the fire is promoting instability by heating from below, and the winds across ridge lines are causing cooling from above and providing wind shear for the initiating vorticity field.

VI. CASE STUDY - THE OUTLAW FIRE

Fire whirls have been described and briefly analyzed in the preceding portion of this paper. As was noted, fire whirls can cause the rapid spread of fire. The case of the Outlaw Fire which occurred on the Idaho Panhandle National Forest in mid-September 1974 is an excellent example.

1. Weather Conditions.

Weather conditions over northern Idaho had been fairly consistent for about a week prior to the fire. High pressure on the surface and aloft had been persistent. A fairly strong subsidence inversion existed. This led to very warm and dry surface conditions. Afternoon temperatures were in the low to mid-80s with minimum humidities 15-20%. On the morning of September 15, the surface weather chart (see Figure 3) showed a high-pressure cell along the Montana/Idaho border southwest of Missoula. The low-level flow was southeast to south. This would be an important factor. The morning forecast indicated little change in the weather pattern with poor smoke dispersal nights and mornings. The forecast was for westerly gradient level winds--a forecast error that would prove costly.

2. Topographic Conditions.

The fire area was located on the Avery District of the Idaho Panhandle National Forest, specifically in Section 24, T44N, R4E, and started as a controlled burn. Figure 4 shows the topography and fire size. The initial plan had been to burn a 35-acre area of slash within which were some fairly heavy jackpots. The origin is marked on the map (see Figure 4). It is significant because it is on a northerly aspect near the ridgetop.

3. Fire Situation.

The burning crew planned ignition of this small broadcast burn around 2:00 p.m., PDT. The inversion was just lifting at this time. As the ignition began, a fresh supply of oxygen from the lifting inversion aided active fire spread and the fire pushed into the heavier fuel concentrations. The fire flared and began burning upslope. As it neared the ridgetop, it came under the influences of the shearing wind from the south-southeast. A fire whirl was formed and it grew to almost 200 feet in height. As the whirl grew in height, it was tipped by the upper flow and burning embers were spread over approximately 350 acres. An innocent-looking 35-acre slash burn became a 350-acre wildfire. This happened because conditions for a fire whirl were not anticipated. The wind forecast was in error, the burning crew that was not aware of microscale weather conditions, and total situation was not recognized as hazardous.

VII. SUMMARY AND CONCLUSIONS

As noted in the Introduction, fire whirls are one of the most interesting and hazardous phenomenon that occur in the fire environment. As with many natural phenomenon, their occurrence can be easily explained in retrospect. To forecast their occurrence is a much more difficult problem. At this point, the best we can do is learn to recognize some of the situations wherein all factors favorable for fire-whirl formation are present. Upon recognizing these situations, we can hopefully be somewhat prepared if they do occur.

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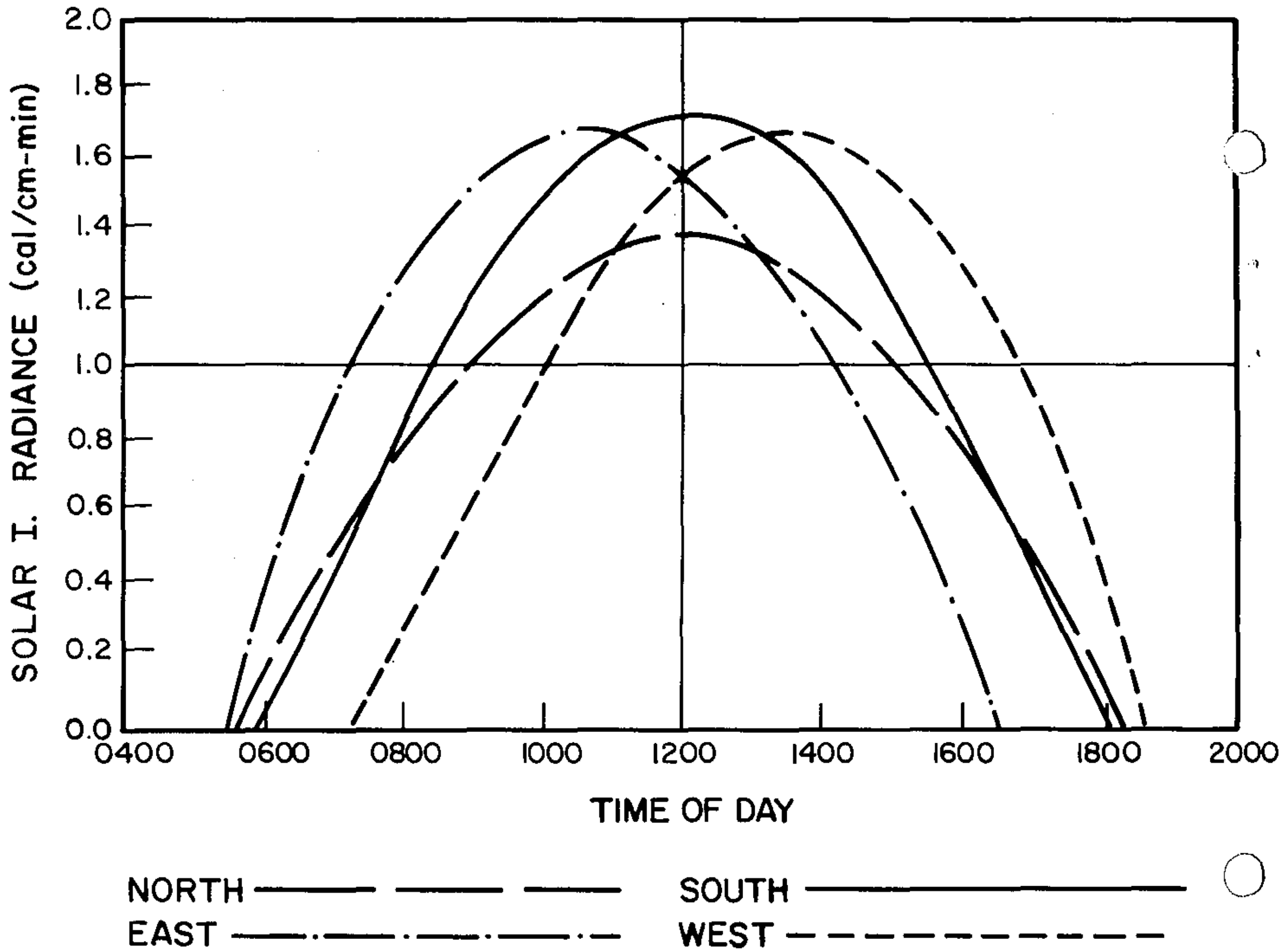


FIGURE 1. DIURNAL RELATIONSHIP OF SLOPE EXPOSURE AND INCOMING SOLAR RADIATION.

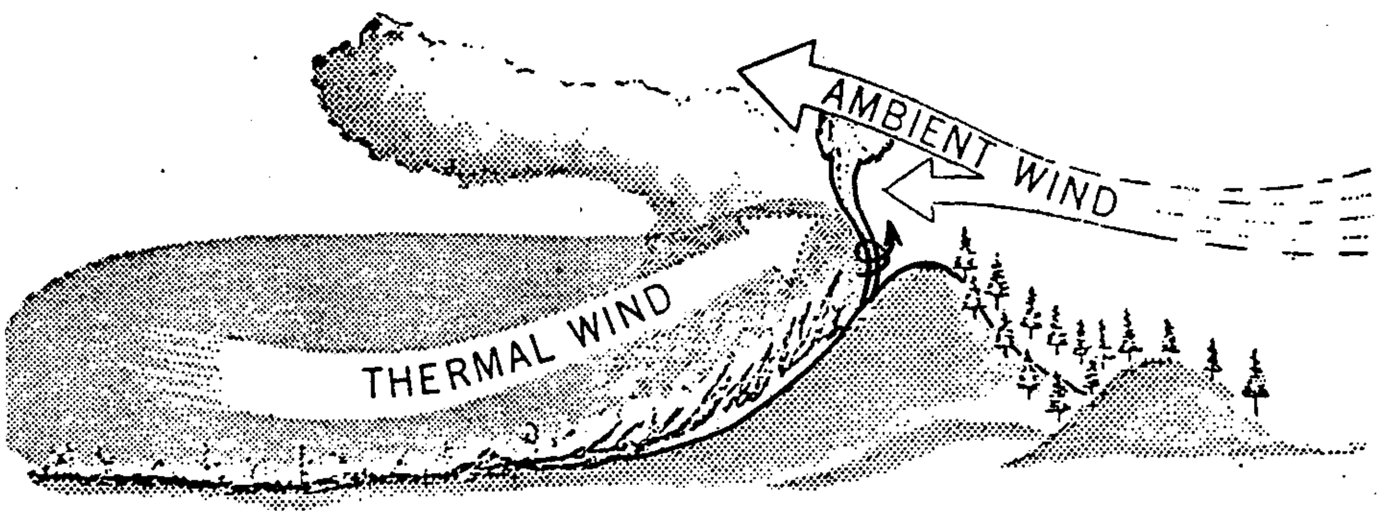
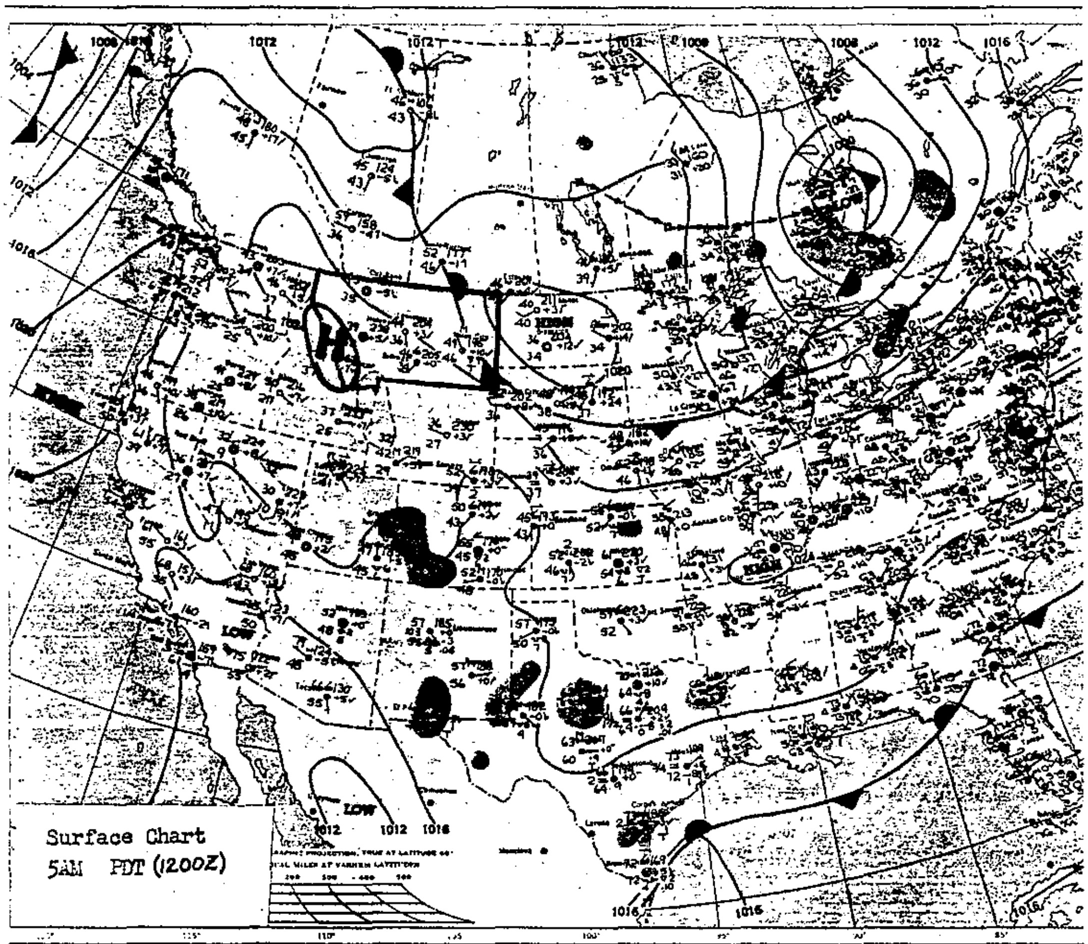


FIGURE 2. SCHEMATIC PICTURE OF FIRE WHIRL DEVELOPMENT WHEN AMBIENT WIND BLOWING ACROSS RIDGE LINE.



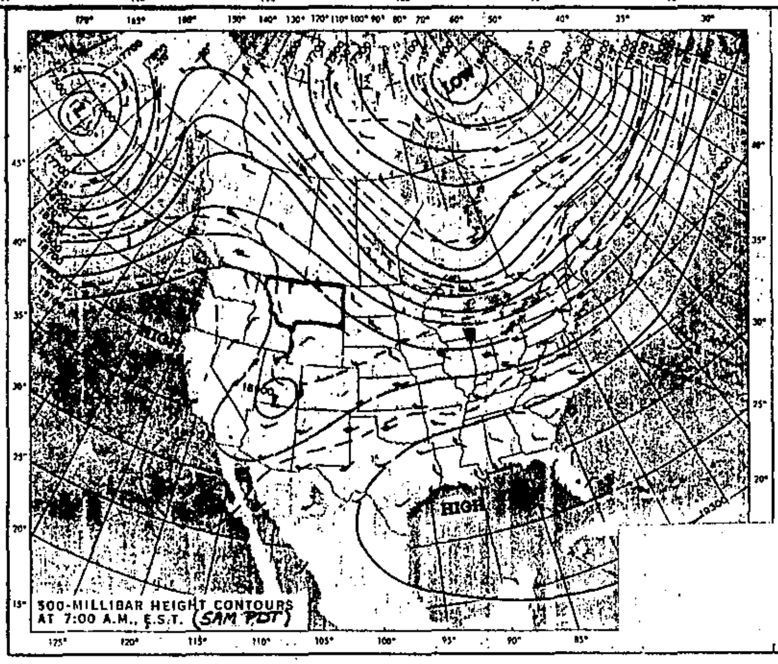


FIGURE 3. SURFACE AND 500-MB ANALYSES FOR 1200Z (5 AM PDT), SEPTEMBER 15, 1974 (EXTRACTED FROM DAILY WEATHER MAPS).

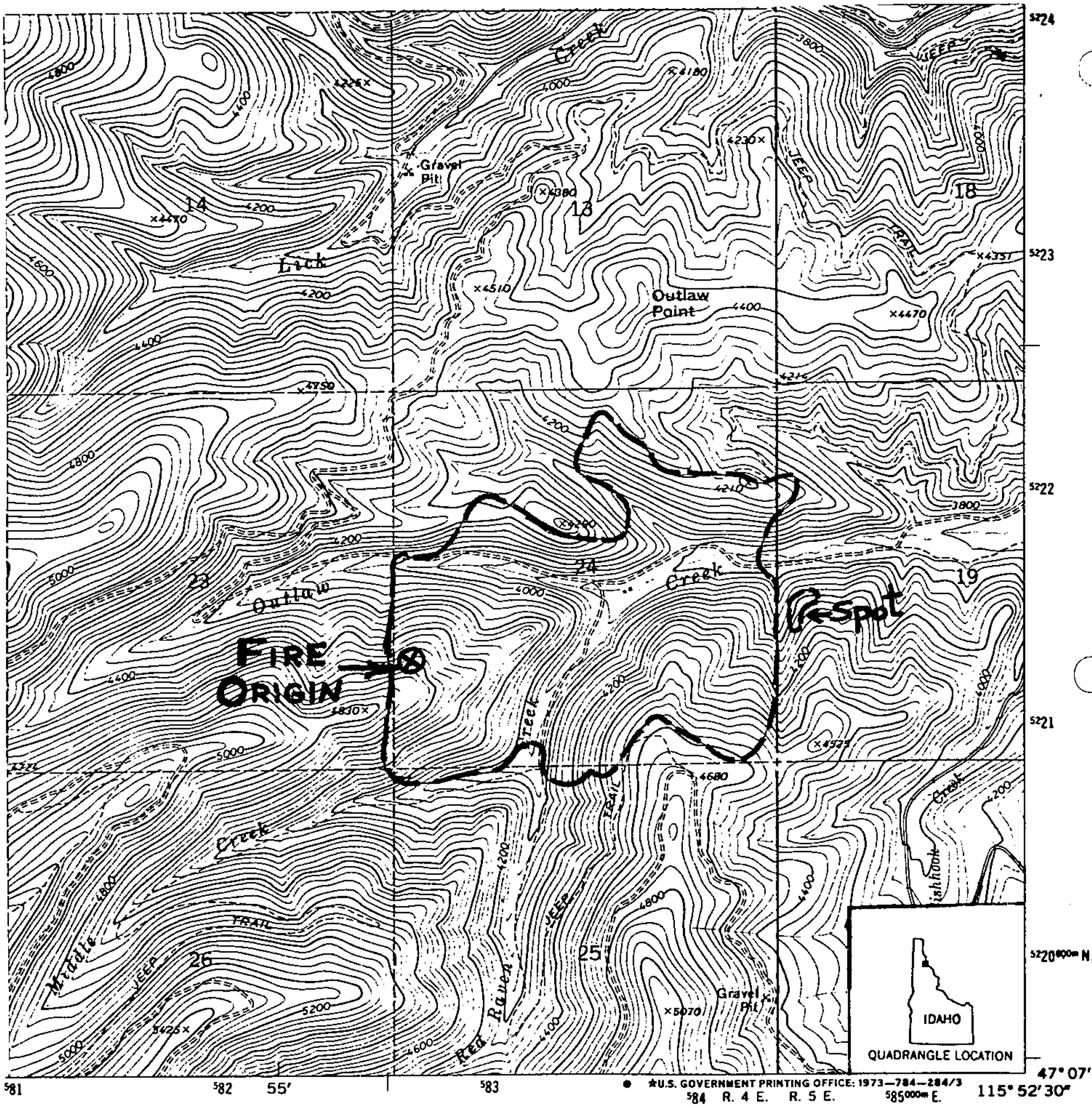


FIGURE 4. TOPOGRAPHIC MAP AND AREA OF THE "OUTLAW FIRE", SEPTEMBER 1974. HEAVY DASHED LINES ENCLOSE BURNED AREAS. HEAVY CONTOURS AT 200-FOOT INTERVALS. LIGHT CONTOURS AT 40-FOOT INTERVALS.

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