SUNDANCE FIRE

U.S.D.A. FOREST SERVICE RESEARCH PAPER INT-56,1988
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
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U S. D. A. Forest Service
Research Paper INT-56
1968

SUNDANCE FIRE: AN ANALYSIS OF FIRE PHENOMENA

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PREFACE

Large forest fires are spectacular, usually destructive, frequently dangerous, but always exciting. Fire research organizations, particularly just after a spectacular wildfire, are often eager to organize mobile research teams to study and document fire behavior. Unfortunately, this approach to the study of wildfire is usually not very productive. There are several reasons why not.

It is very difficult for a researcher to be in the right place at the right time when severe fire behavior occurs. Often he is remotely located on the opposite side of a situation, or access to the area of interest is limited or inefficient. There is always the danger that research personnel will interfere with tactical activities at the fire, primarily in the air. There is generally no effective way to properly instrument an area prior to severe fire behavior, simply because there is not enough time and one cannot predict precisely when or where such events will occur.

The Sundance Fire was unique. Early on September 1, there was already a tremendous concentration of fire organization, supplies, equipment, and manpower in the vicinity because of a number of active project fires. An additional force of competent firefighting personnel was gathering to meet the expected need. The Sundance Fire was being fought by State and local forces but was expected to cause increasing difficulty, and preparations were underway to transfer the fire to the U. S. Forest Service. Accumulative weather buildup was extreme, the fire had a 4-mile exposed front, and the current weather was critical. Suddenly the fire made one tremendous run, increasing in size by more than 50,000 acres in one burning period. Since there are communities at each end of the fire run and a road cutting across the center of it, and because firefighting crews were in the Pack River area preparing for a possible run of the fire, many observers saw portions of this spectacular fire run. The mere fact that the event was limited in time and seen by many people permitted the research team to reconstruct some of its characteristics. Interviews with fire control people, local residents, and a variety of other individuals provided firsthand observational knowledge of what happened. Most observations were subjective, but some included measurements.

The Sundance Fire offered a rather unusual situation for analysis and we think the results, as given in this paper, have a great deal of value. Nevertheless, it must be recognized that similar studies might only be redundant. As long as studies are limited by conventional measuring methods, there is no real assurance that an organized effort to chase large fires would produce equal or better analyses. Certainly the development of remote sensing techniques or instrumentation could change the picture considerably, and might allow for improved data collection on wildfires. We believe that fire analyses are best when applied to special case fires.

There is, of course, some value for the scientist to be gained through observation of wildfires. It sharpens his perspective on the real world and on the problems he is facing. We must be cautious, however, not to expect more than is realistic from observing wildfires, while at the same time, we need to consider improved methods for observing them. This is one way that fundamental and theoretical work now underway in laboratories can be related to real-life conditions in the forest.

ARTHUR P. BRACKEBUSCH
Chief of Northern Forest Fire Laboratory

ACKNOWLEDGMENTS

The author acknowledges with deep appreciation the cooperation and assistance provided by the following persons, each in his special field:

DONALD M. FUQUAY for his leadership in organizing the general approach to the analysis and development of a presentation format.

RICHARD C. ROTHERMEL for his leadership in the fieldwork of gathering,data and photographs, and interviewing personnel.

ARTHUR P. BRACKEBUSCH for his background knowledge of the area and experience in fire behavior.

JAMES K. BROWN for his responsible appraisal of the fuel complex and calculations of fuel distribution.

WILLIAM H. FRANDSEN for his capable interpretation of the destruction of the Pack River Bridge and contributions in other parts of the analysis.

DWIGHT S. STOCKSTAD for his consultation on the area and the fire behavior.

ARNOLD I. FINKLIN for his thorough and careful collection and analysis of the meteorological data used in the weather interpretation.

ORVAL W. GASTINEAU, Jr., and ROBERT D. SCHUETTE for their valuable assistance in tabulations, computations, and aerial photo analysis.

BRYAN M. OWEN for his competent graphic rendition of fire phenomena conceptions and preparation of other charts and illustrations.

HERMAN WITTMAN for his assistance in the photographic processing of photographs, graphs, and illustrations.

Personnel of the Priest Lake Timber Protective Association, Kaniksu National Forest, and Division of Fire Control, Northern Region, U.S.D.A. Forest Service for provision of fire logs and maps, interviews and valuable information regarding the area, the timber, and the fire.

CONTENTS

INTRODUCTION

The Sundance Fire in northern Idaho stands as a giant among several big fires in the Northwest during the summer of 1967. The magnitude of this fire resulted from a combination of conditions seldom occurring simultaneously — a prolonged dry period, persistent high temperatures, sustained winds during the fire run, and an uncontrolled 4-mile fire front. These conditions produced a rapidly moving fire that burned over a large area and released an awesome quantity of energy. In a period of only 9 hours this fire traveled 16 miles, engulfed more than 50,000 acres, released millions of heat units, snapped and toppled hundreds of trees, and destroyed much of the storage capacity of the watersheds.

The Sundance Fire started its major run on September 1, 1967, at approximately 2:00 p.m. (1400 P.d.t.) and by 11:00 p.m. (2300 P.d.t.) it had completed the run. Shortly after the major run, personnel from the Northern Forest Fire Laboratory were assigned to the fire staff as fire behavior officers, to predict fire behavior and advise the control teams. At the same time, other NFFL personnel were assigned to a research team responsible for investigating the physical phenomena of this fire and for documenting its nistorical development. Their investigation was actually a detective job, since only evidence remaining on and near the burned area, eyewitness accounts, and records kept by the various agencies were available for interpreting the events. This paper presents the best estimates of fire phenomena that could be made by the research team, using the available information. The progress of the fire, its intensity, the fuel being consumed, the attendant weather events, and other special conditions were analyzed from a multitude of separate observations gathered from both official sources and individuals.

When a forest fire "blows up," the people directly involved are busy moving equipment, materials, and firefighters to new locations, or planning new attack procedures, and their impressions are often confined to a single area or phase of the fire's activity. In reconstructing the fire's movements, any one person's account would have been of limited value. The magnitude of this fire was such that many different people observed it at many different locations. One of the earliest jobs for the research field team was to interview as many people as possible who had observed or participated in the fire activities on, September 1. Interviews from 24 people contributed to the determination of fire front location, rate of spread, type of fire, and energy release rate at specific times.

The investigating team has attempted to sort out the details of a violently eventful period of time and construct from them a coherent account of the phenomena of a particular fire. A general conception of what was happening where and when as the fire progressed is necessary to understanding of the physical phenomena. Therefore this paper begins with a description of the geographical area and a narrative of the movement of the fire. The approach to study of certain major factors in the fire development is then explained, and the values calculated from the data are given in a chronology corresponding to the fire's major run. A more detailed discussion of significant features of the fire then follows, leaving for the appendixes information on methods of calculation and experimental procedures that helped the investigators to draw their conclusions.

THE FIRE AREA

Sundance Mountain, the point of origin for the fire, is on a spur off the Selkirk Divide east of the town of Coolin, Idaho. (Topographic relationships of the fire area are shown in figure 1; see also the foldout map at the back of this paper.) The fire up to September 1 was confined to the lower Soldier Creek (elev. 3,600 ft.) and Lost Creek (4,800 ft.) drainages (fig. 2), which lie west and southwest of Sundance Mountain. On September 1, it progressed northeast up to the Divide, engulfing Jeru Peak (6,394 ft.) and Hunt Peak (more than 7,000 ft.), and skirting south of Gunsight Peak (7,357 ft.). As may be noted in figure 1, the elevation drops from 5,800 ft. at the saddles along the Divide to 3,800 ft. on the Pack River at the north edge of the fire path and to 2,600 ft. at the south edge. Northeast out of Pack River is Apache Ridge, running to the southeast; here the fire path is bounded by Roman Nose Mountain on the north at 7,264 ft. and Dodge Peak on the south at 5,026 ft. Northeast of Apache Ridge the terrain slopes to the southeast and is cut by the major drainages of Falls Creek, Highland Creek, Ruby Creek, and Caribou Creek. The fire ended its run near Snow Peak (more than 4,000 ft.) and worked toward Bonners Ferry, Idaho, down Caribou Creek to an elevation of 2,800 ft.

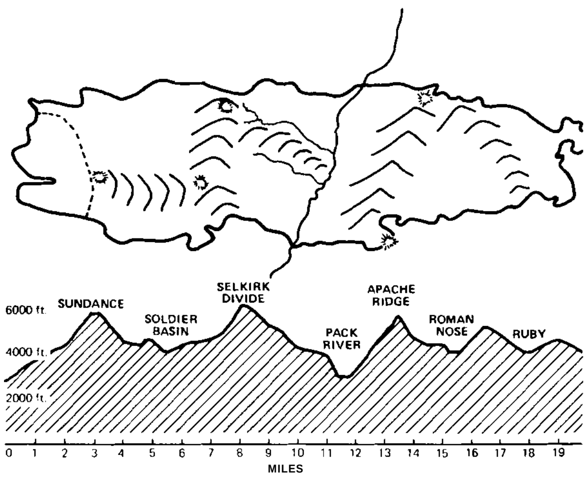


Figure 1. – Topographic diagram of the Sundance Fire area.

Figure 2. – Sundance Mountain, looking to the northeast, with Chase Lake in foreground and Selkirk Dide in near background. Lost Creek is in center and Soldier Creek drainage on left edge.

THE FIRE STORY

THE BUILDUP

The fire story begins in the months before the outbreak itself, in the buildup of fire danger during the summer of 1967. The fire season in northern Idaho developed quite normally, and in the first 3 months showed characteristics of an average fire season. The fire weather records of the Priest River Experimental Forest in northern Idaho, interpreted according to the National Fire-Danger Rating System, illustrate the seasonal buildup of fire danger. The record presented in figure 3 shows the buildup index remaining below the previous record high for the period of 1954 to 1966 until August 11, 1967. The continued buildup in 1967 from late June until mid-September differs from the historical pattern, which has shown one or more breaks in buildup during this period. This year, day by day the situation became more serious, and restrictions were imposed to minimize the hazard of man-caused fires.

Early in August, a high pressure zone had become deeply entrenched over the northwestern United States and was effectively blocking the influx of moist maritime air from the west. No significant amount of precipitation occurred between August 11 and September 1. In the 62 days from July 10 to September 10, only 0.10 inch of rain was measured at Priest River Experimental Forest from four different showers. From August 11 to August 31, the 10-day averages showed the temperatures were the highest, the humidities the lowest, and the fine fuel moisture content the lowest for the season. Relative humidity is estimated to have been below 35 percent continually for at least 72 hours prior to the fire run.

On August 31, all stations in northern Idaho except those at high elevations had buildup indexes rated "extreme." Late on that day, a Pacific weather system was approaching the Washington coast. A warning

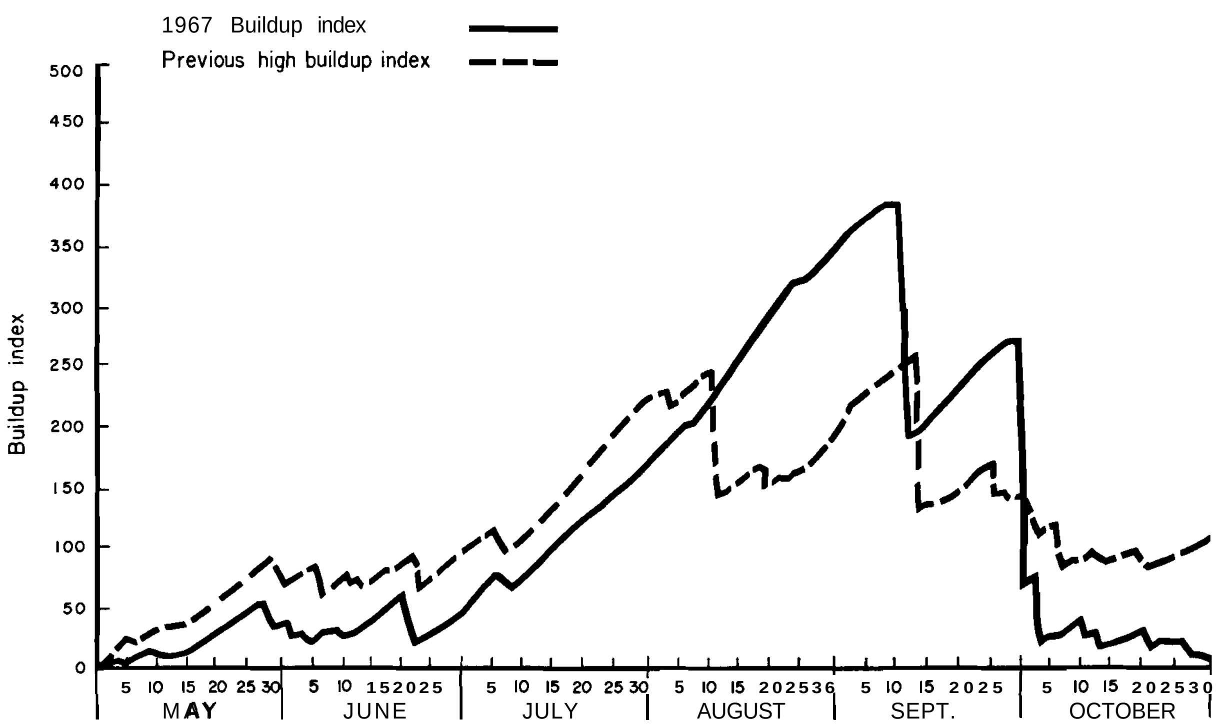


Figure 3. – Buildup index for 1967 compared with previous record high for period of 19541966.

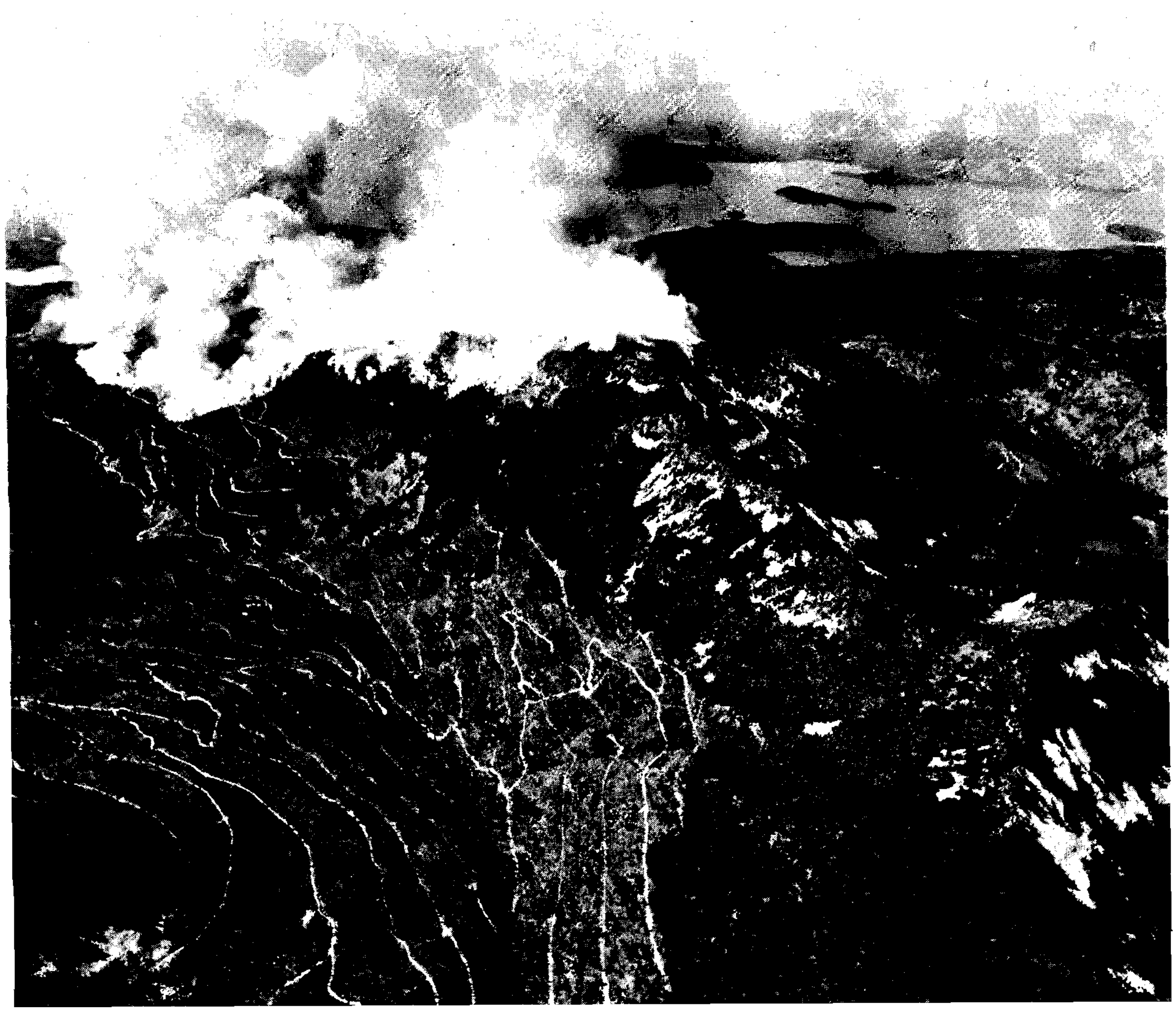
was issued for northern Idaho to expect increasing southwest winds 18-25 m.p.h. on September 1. These winds did increase steadily during the morning of September 1 and continued until late that evening.

THE EARLY DAYS – August 11 to 31

This, then, was the weather picture. For the fire activity preceding the major run on September 1, we have information from the Priest Lake Timber Protective Association and the Division of Fire Control, Northern Region, U. S. Forest Service. On August 11, a lightning storm moved over the area causing five fires on or near Sundance Mountain. Three of the fires were discovered and attacked on the 11th, and two were declared out that same day; the third was declared out on August 15. A fourth fire was discovered on August 20, and 37 men, including 12 smokejumpers, brought the fire under control that evening – 1830 – with 2 acres burned. The fire was declared out on August 25 but was monitored by air patrol for several days.

At 2240 on August 23, fire number 5 broke out near the Sundance Lookout. The fire was contained by the end of the day, August 24, with an estimated 35 acres burned. Suppression activities continued for the next 5 days. Late in the evening of August 29, at 2220, Priest Lake Timber Protective Association Headquarters near Coolin, Idaho, received word the fire had jumped the line and was out of control. Men and equipment were evacuated to headquarters. The fire was observed rolling down the hill in the Lee Creek drainage. A northeast wind had prevailed throughout the day and it is assumed this wind, coupled with the normal nighttime downslope currents, resulted in a wind-driven fire moving downslope. Information available from observers indicated the winds were

Figure 4. – Looking west at Sundance Mountain after the fire's night run toward Coolin on August 29. Lost Creek in foreground; Soldier Creek on right.



20-25 m.p.h. on the fire, but there was calm at Cavanaugh Bay near Coolin. The ground and crown fires were observed to move as a single front, with spotting up to one-half mile ahead. The main advance took place between 2230, August 29, and 0200, August 30, which would give an average rate of spread of 0.80 m.p.h.

At 0700, August 30, the total acreage burned was reported as over 2,000 acres. Very little enlargement of fire area occurred, and there were only a few minor runs in the afternoon. Both Soldier Creek and Lost Creek drainages were now threatened if the wind shifted to the southwest (fig. 4). On August 31, heavy smoke obscured the fire most of the day, but a spot fire broke out across a dozer line about 1700 and resulted in an intense burnout of lower Lost Creek. The southwest winds were starting to exert some influence judging by ash fallout reported by residents near Naples, Idaho, 18 miles to the northeast. Eight bulldozers were opening roads in the McCormick and Jeru Creek drainages.

From this point, the story is best told in hourly reports of fire progress, which can be followed on the foldout map showing the fire-edge lines. The hourly progress of the fire was determined from the eyewitness accounts obtained through interviews. The approximate time an individual was in an area and where he saw the fire or the fire front were synchronized with the other observations. From this consolidated information, a coherent description of the fire's rate of spread was developed.

THE MAJOR RUN – September 1,1967

0700. The fire area had enlarged to approximately 4,000 acres and the eastern fire edge extended from the ridge between East River and Lost Creek north around Sundance Mountain and down into Soldier Creek (see foldout map). At 1010 on September 1, the U. S. D. A. Forest Service was requested to take over fire suppression activities on the Sundance Fire.

Up to 1300. Fire activity had not increased significantly as reported by the air patrol observer, who had flown close to the perimeter. A run along the ridge between East River and Lost Creek had occurred since 0700 but was not burning intensely.

1400. The fire had started its advance to the northeast (see foldout map), the initial activity being in Lost Creek, which is at a higher elevation than Soldier Creek. In Soldier Creek the fire moved in a northeasterly direction along contours and downslope from Sundance Mountain. At this time the fire was considered to be a ground fire, consuming most of the brush and some crown material.

Bulldozers were continuing to open roads east of the Selkirk Divide. Action was started to pull the equipment back. A fire camp had been established in Pack River south of Jeru Creek near Lindsey Creek.

1500. By now the fire had increased in intensity, crossed Soldier Creek to the northeast side, continued up the south side, and reached the ridgetop in Lost Creek southwest of Jeru Peak. The fire was spotting across the Divide south of Jeru Peak and coming back up the east exposure slopes. The main front was becoming more brush and crown fire, with the brush controlling spread.

1600. Lost Creek had burned out and spreading had been stalled by the Divide. The fires burning upslope on the east side were influenced by indraft winds. In Soldier Creek the entire front had become a crowning fire. Winds were carrying firebrands across the Divide and spot fires were burning upslope. Fire-induced winds were approaching 80 m.p.h., resulting in some timber blowdown. The ground fire was lagging the main front and the brush was providing continuity to sustain the crowning fire.

Dozers working at the head of Jeru Creek prepared to move back to Pack River. At about 1600, a two-man rescue team left Pack River fire camp by pickup truck to bring out men working the head of McCormick Creek.

1700. The Selkirk Divide slowed the fire front; however, firebrands were being cast to the northeast. The ground fire moved up to

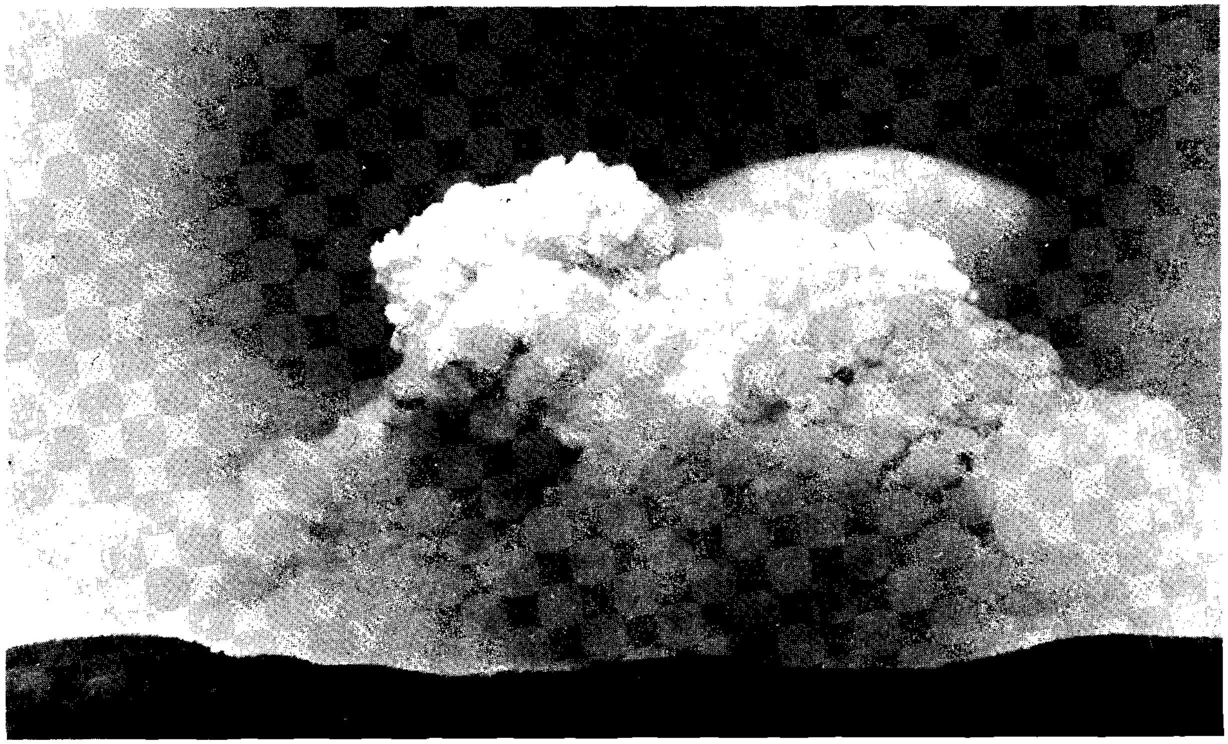
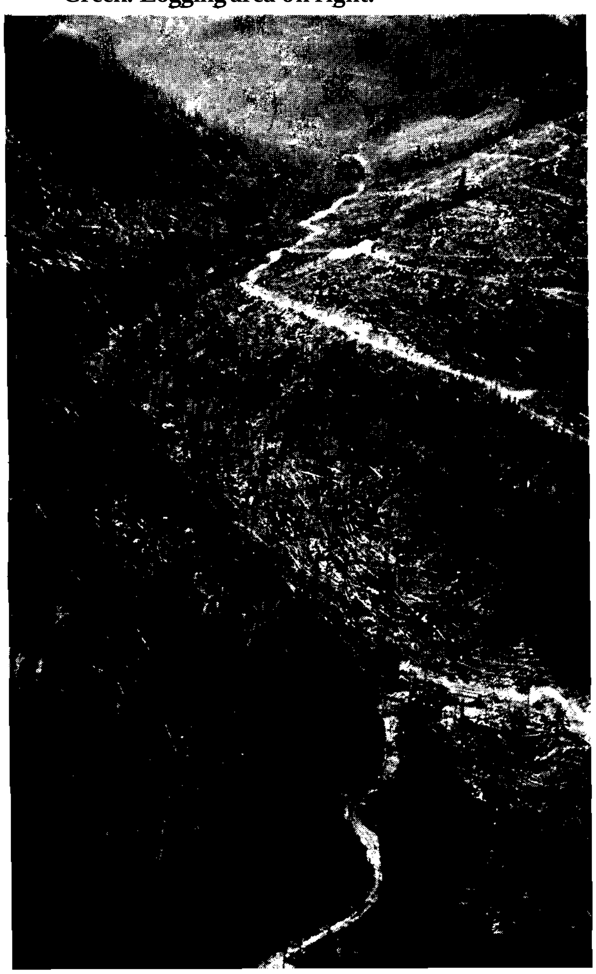


Figure 5. – Convection column above Sundance Fire looking east, at 1700 on September 1,1967.

Figure 6. – Fire destruction at mouth of McCormick Creek. Logging area on right.



the Divide, meeting the spot fires burning up the east slopes between Jeru Peak and Hunt Peak. The cbnvection column (fig. 5) reached a height of 25,000 ft. at this time and was detected as a weak echo by the U. S. Weather Bureau radar at Missoula, Montana.

The rescue team had entered McCormick Creek and reported the smoke column was 4 to 6 miles.wide. The dozers had moved out of the heads of Jeru and Hellroaring Creeks.

1800. During this period the fire intensity decreased as the small fuel sizes were consumed. The spot fires on the east portion of the fire front, being influenced by the prevailing wind, became consolidated and quickly developed into a crowning fire. The large advancement of the fire between 1700 and 1800 may be seen on the foldout map.

The rescue team paced the fire while returning to Pack River after being blocked by the fire in McCormick Creek. As the rescue team reached the mouth of McCormick Creek (fig. 6), they could see flames on the ridge just southwest of them. The Roman Nose lookout could not see any fire because of the

Figure 7. – Blowdown and burnout in Pack River area.

smoke pall. A scout had left the Pack River camp and was at Youngs Creek trying to establish radio contact with the rescue team. Sometime during this period, the fire overran the dozer boss and operator near Fault Lake at the head of McCormick Creek. As the rescue team reached the mouth of McCormick Creek (fig. 6), they could see flames on the ridge just southwest of them.

1900. As the fire front reached the lower reaches of the ridge between McCormick and Homestead Creeks, it was slowed by the steeper slopes, indrafts coming up and down Pack River, and a suppressed wind effect at the lower elevations. The ground fire was probably lagging the main front with the brush controlling spread, but considerable crowning was still occurring.

The rescue team moved down Pack River under the advancing front of the fire and met the scout at Youngs Creek. Winds were breaking boughs and tops out of nearby young timber. Considerable spotting over Pack River was observed by others but the rescue team and scout saw only one large firebrand. While at Youngs Creek they saw fire cross the road about one-fourth mile upriver. They moved out toward the fire camp and estimated they were **3** to 4 minutes ahead of the fire. Upon their return to the fire camp, radio contact was made with the Roman Nose lookout instructing him to meet a pickup truck in Falls Creek. The pickup left Sandpoint, Idaho, near 1900.

2000. Shortly after 1900 the fire swept down Jeru Creek so that the entire 5-mile front was in the Pack River drainage (see foldout map). For the next half hour the fire front was nearly stalled due to the turbulent winds created by indrafts up and down Pack River and down McCormick Creek. Fire whirls were triggered by these winds and moved randomly in the area near the Pack River bridge and the junction of McCormick Creek and Pack River. The indrafts and fire whirls caused extensive blowdown and tree breakage, as may be seen in figures 7 and 8. The fire activity in this area must have been similar to the classical "fire storm" with its intense burnout and associated winds in a fixed area.

Figure 8. – Valley fire storm area.

The Roman Nose lookout had left the area to meet the pickup in Falls Creek. At 1930 he encountered a large spot fire blocking any further advance toward Falls Creek and turned back to the lookout. About 20 minutes later at 1950 the entire west slope of Apache Ridge appeared to ignite simultaneously. Observers at the Pack River fire camp stated no flame was visible one minute and the next the whole slope was aflame. The turbulent winds, convective and radiant preheating, and the firebrands lofted by the whirls evidently contributed to the ignition process. The fire swiftly moved up the slope and developed into a crowning fire. Rate of spread accelerated as the fire approached the ridgeline and firebrands were cast far in advance of the front. The convection column reached an altitude of 31,000 ft. at 2000 (fig. 9).

The pickup sent for the Roman Nose lookout entered Falls Creek about 1930 and was buffeted by extremely strong winds and dust devils as he headed for the Roman Nose Creek crossing. The dust devils occurred rather regularly and were estimated to be between 10 and 25 ft. in diameter.

2100. After sweeping over Apache Ridge and moving into Falls and Roman Nose drainages, the fire slowed. It was still a crowning fire, sometimes with flames moving horizontally through the crowns. Between about 2015 and 2100, the lookout observed spot fires far ahead of the front in Falls Creek; large spot fires were also seen above Roman Nose Lake No. 1. Meanwhile the pickup had reached Roman Nose Creek crossing. The driver saw fire to the west and southwest moving toward him. Upon turning around and leaving the area, he saw firebrands and large embers flying horizontally.

At 2025, a spot fire started at the mouth of Snow Creek and at 2045 another started in Myrtle Creek (see foldout map). These spot fires were at least 10 miles in advance of the main front. In addition, numerous firebrands were falling to the ground at the intermediate distances. The spot fires observed from Black Mountain burned as both heading and backing fires, and one was observed to spread suddenly in all directions, developing a radial pattern of fire spread. At the same time, the convection column rose to 35,000 ft. and the pilot observer felt it was continuing to build. Long-range firebrands were being transported by at least two possible mechanisms:

1. By being carried aloft in the convection column, then entering the influence of the

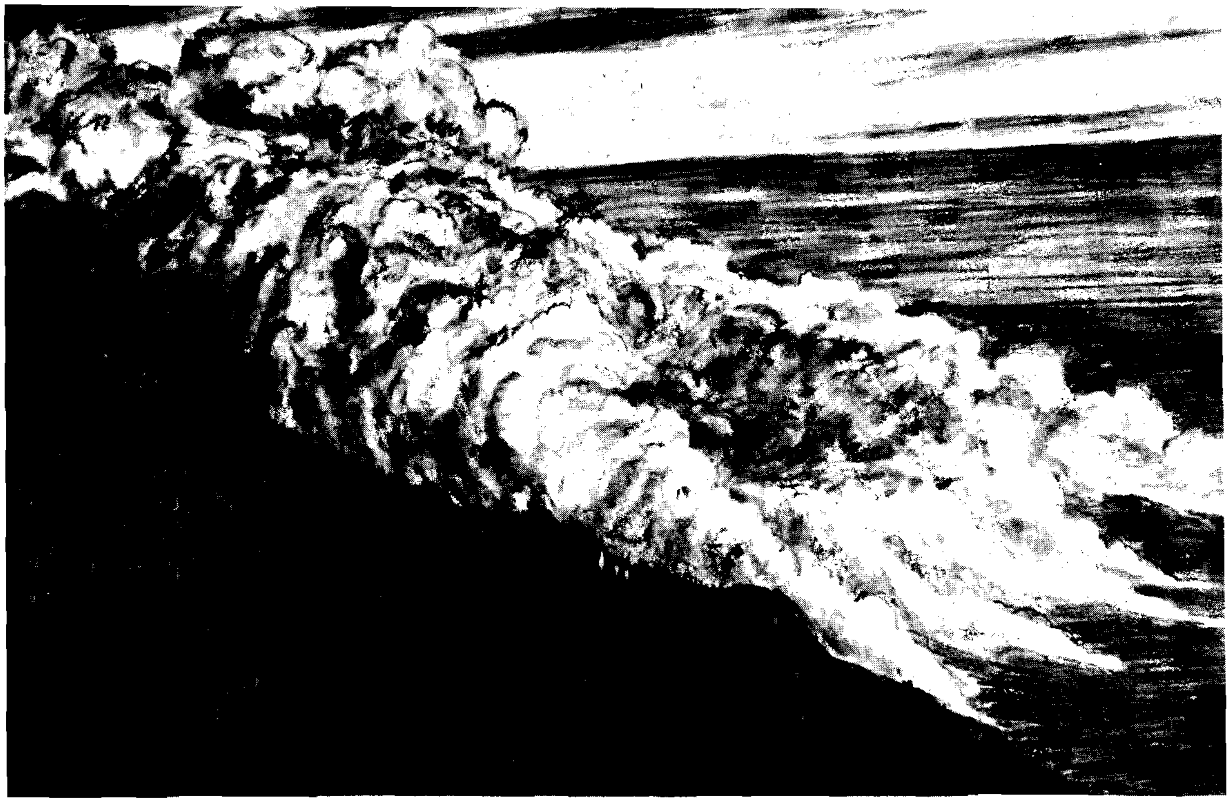


Figure 9. – Artist's conception of convection column, then about 31,000 ft. high, made from slide taken by jet pilot over fire near 2000 hours.

prevailing wind and falling under the gravitational influence (8)[1];

2. By being carried aloft in the convection column, then entering the influence of a vortex street and being stabilized in it. The vortex street moved on downstream of the strong convection column (1). (For a more detailed discussion of this point, see the section below titled "Firebrand Activity.")

As the man on Roman Nose Lookout retreated to a rockslide, where he stayed until the fire had abated the following day, a crowning fire moved up Zuni Creek out of Pack River and carried over into Ruby Creek.

2200. By this time the fire had moved from Ruby Ridge into Ruby Creek and additional spotting occurred on Caribou Ridge (see foldout map). The fire front had become broken, probably for several reasons, including the facts that more area had been logged over a long period of time, so little slash was present, and that the spot fires had not consolidated into a single front. Hence there was poor fuel continuity and the main fire front was deprived of fuel. Sporadic flareups were occurring, indicating the meeting of heading and backing fires or burnout of pockets of fuel. At this time the fire was primarily a brush fire, with considerable crowning.

[1]*Numbers* in parentheses refer to Literature Cited.

2300 on into September 2, 1967. The fire became more affected by prior burnout and became a ground fire as it moved into Caribou Creek. The rate of spread had decreased although some crowning took place. The main front had become poorly defined because of reduced fuel continuity. Nearly 60 percent of the area could now be considered affected by previous burning.

A spot fire northeast of the main fire zone was reported at 2345. This probably resulted from the spot fire at the mouth of Snow Creek. Various portions of the fire became individual fires that resulted in flank increases and an occasional minor run. This type of behavior continued until the fire was controlled.

Weather conditions continued to improve during the night (see table 2, p. 16). Observations made in Ruby, Highland, and Falls Creeks at 0200 indicated the fire was cooling down.

One of the greatest concerns at this time was the possibility of a wind shift to the northwest or southeast. A fire front 20 miles wide would have resulted; however, the wind held steady and the acreage increased only slightly, 4 percent, before control was achieved.

THE FIRE PHENOMENA

From the fire story told in the preceding section, it is clear that a great deal was happening in a short time on the Sundance Fire. The investigating team has analyzed the fire records to determine conditions such as weather, rate of spread, fuel loading and consumption, and fire intensity. For purposes of comparison, some of these determinations will be presented as an hourly log of the fire's major run.

WEATHER

A detailed analysis of the atmospheric conditions leading up to the fire and through 12 hours after its run was made by the meteorological personnel of the Fire Laboratory. Estimated hourly free-atmosphere conditions — wind, temperature, and humidity — both preceding and during the major run of the fire, were derived for 5,000 ft. m.s.l. (Free-atmosphere conditions are those which would be experienced at some height above the ground, removed from surface influences.)

The account that has been given of the progress of the fire has emphasized the importance of the weather influences and has included a description of the weather preceding the major outbreak of the fire. An illustrated analysis of the general weather pattern associated with the fire is given in Appendix 2. Bi-hourly reports on weather conditions during the major run are given in the log.

With regard to temperature, it should be noted that the quantity of heat released by the fire modified the reported temperatures considerably near the ground, as evidenced by small islands of desiccated foliage. On the other hand, the general winds on the fire were probably always lower than those calculated for free-atmosphere conditions except where accelerated by fire-induced forces.

RATE OF SPREAD

It is evident from the fire story given earlier that the Sundance Fire spread with unusual rapidity during certain periods, slowing somewhat in the intervals. In the Log (p. 13), calculations for rate of spread are given for each hour. These are average values corresponding to the time and distance interval shown on the foldout map.

It is interesting that the fire-spread indices based on the National Fire-Danger Rating System, averaged for the stations in the area, predicted actual conditions quite well. This is evident from the following comparison:

	Predicted (0800)	Actual (1600)
August 31	30	36
September 1	52	64
September 2	60	52

FUEL LOADING AND CONSUMPTION

The forest burned by the Sundance Fire was composed of mixed conifer stands interspersed with logged areas (fig. 10). A variety of stand conditions ranging from young to overmature and poorly to heavily stocked existed before the burn.

To determine fuel loading, measurements were made on nearby areas comparable to those burned, as well as on the burned area itself. The fuel complex was considered to contain three levels: ground litter, brush, and crown material.

Timber inventories for the Kaniksu Working Circle were used to estimate the crown fuel weight, by a method based on research done by Fahnestock (3). Data from the State of Idaho indicated that timber distribution on private and public lands should be similar, so the timber estimates based on Forest Service records were applied to the whole fire area. The average crown fuel load was estimated at 2.04 tons per acre. Field measurements yielded a value of 5.25 tons per acre in a heavily stocked stand.

The brush level was estimated by field sampling at a loading of 2.7 tons per acre. Visual observations throughout the bum area indicated the brush loading could have varied from 1 to 20 tons per acre, but the estimated average should be reasonable.

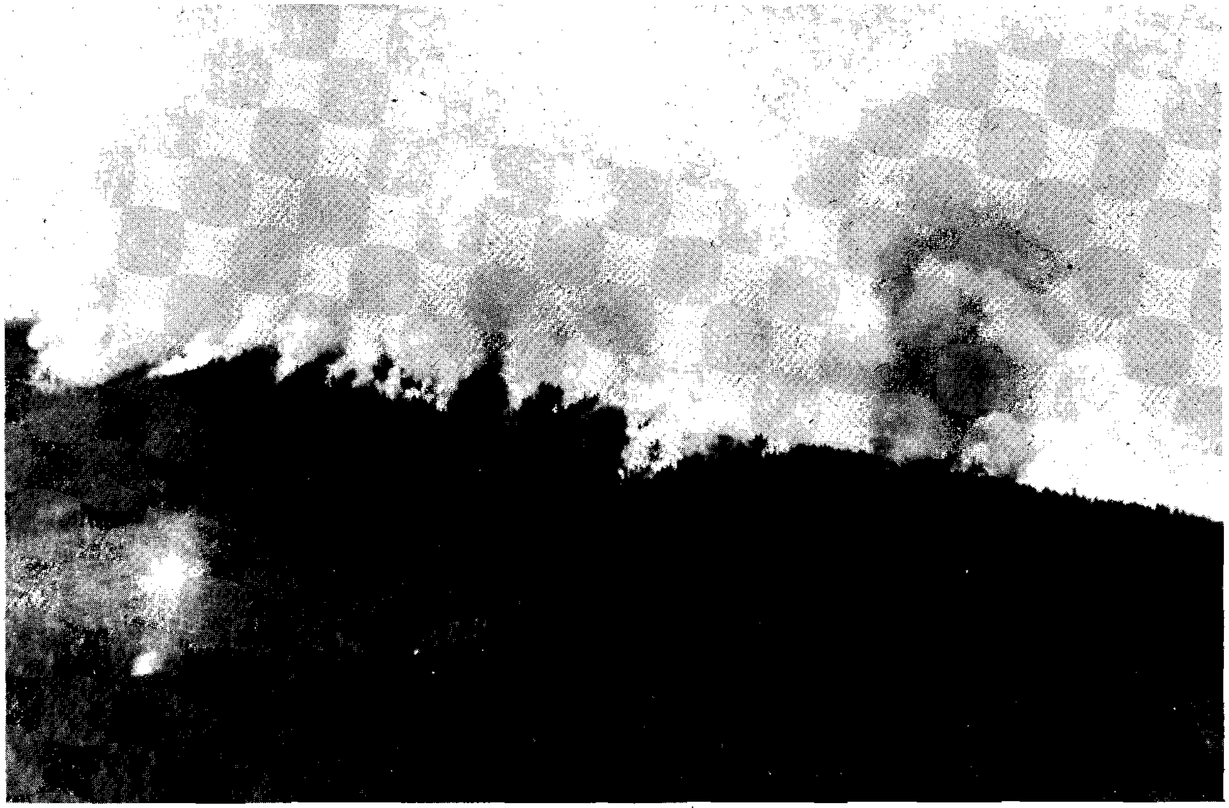


Figure 10. – Clearcut logging area (left foreground) at the site of the Sundance Fire. At this time, on August 30, the fire was backing into Soldier Creek drainage.

Ground litter loadings were obtained from field sampling and found to be near 20 tons per acre. Again, in some areas the loadings could have been as low as 1 ton per acre.

In determinations of fuel loading, crown material was limited to foliage and branches under 1/8-inch diameter, since field inspection of residual stems indicated most of such material was consumed. Areas where larger material in the crowns was burned were evident, but were disregarded in the computations. The maximum size for brush material was set at one-fourth inch, based on field sampling.

Ground litter loadings varied considerably, but the field-obtained values were accepted as representative. The effects of logging slash and its treatment on the fire's intensity are difficult to evaluate. About 50 percent of the untreated logging slash in the area was more than 8 years old. Most of the fresh slash was at the southwest end of the fire area and was burned the day before the major run. Slash areas, therefore, were not considered to be different from the timbered areas in ground-litter determinations.

Details of the calculations of fuel loading are given in Appendix 1, along with a description of the measurements of moisture content. Samples of the fuels were taken to establish moisture content levels in each stratum.

Percentage estimates of fuel consumption are given in the Log, at approximately hourly intervals. These percentages are based on information gathered during the interviews, research data, and the acquired knowledge of experienced firefighters. The amount of fuel from each of the three fuel levels consumed in the fire front was estimated after considering the terrain and wind conditions, the rate of spread, and the observations of eyewitnesses. For example, where the fire front is being carried by the brush level at a low rate of spread with little wind we might consider that 90-percent available ground +95-percent brush +20-percent crown fuel was being consumed in the fire front. The percentages apply to the size classes and loading as previously described.

Laboratory work (7) has shown that the percent of ground fuel burned in the flame front decreases as windspeed increases. We estimated 20-percent ground fuel consumption in our calculations. The difference between this and the field-determined amount consumed is assumed to have been burned by sporadic flaming and glowing combustion following passage of the main fire front.

INTENSITY

Fire intensity values were calculated and are given in the Log at hourly intervals, along with values for maximum energy release from the total front. These, too, are average values corresponding to the time and distance intervals.

As explained earlier, physical constants for loading and moisture content of strata were derived. These constants established the amount of fuel on the site that could contribute energy to the fire. The average energy content of fuel was set at 8,500 B.t.u./lb.; the heat required to remove the moisture and raise the fuel to ignition in each fuel level was then subtracted to arrive at an energy release potential (B.t.u./lb.). Values of the energy potential per unit were calculated by multiplying the loading, corrected to pounds per square foot, by the energy release potential.

For any time interval of interest, the energy per unit area was combined with the percent consumption values to obtain the energy released per unit area. Fire intensity and total energy release rate were calculated by use of the rate-of-spread determinations and application of laboratory findings for residence time (time the flaming zone exists at one point).[2] The physical constants for the three fuel levels are given in table 1.

The values for energy release rate are shown in figure 11, for a 12-hour period that includes the fire's major run. To arrive at our values, the residence time for the fire-controlling fuel level was combined with a rate of spread to establish a flame depth. The active combustion area was calculated by multiplying the fire edge length by the flame depth. The combination of the combustion area and the energy released per unit area divided by the residence time yielded the total energy release rate per unit time (B.t.u./sec.).

Fire intensity in B.t.u. per second per foot of fireline (fire edge) was calculated after Byram (2, chap. 3, p.79). Values were obtained by combining the summed energy per unit area and the rate of spread for a time interval. The fire intensity values (fig. 12) appear reasonable when compared with the limits established by Byram. He gives an

[2] *Anderson, Hal E. Heat transfer and fire spread. U.S.D.A. Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah. (In preparation.)*

Table 1. – Estimated fuel constants for the Sundance Fire area.

Fuel strata	Loading		Moisture content	Residence time	Energy release potential[1]	Energy per unit area
	Ton/acre		Percent	Min.	B.t.u./lb.	B.t.u./sq.ft.
Ground						
litter	20	(max.)	12	1.0	7,675	7,060
	1	(min.)	12	1.0	7,675	384
Brush	2.7	(ave.)	60	2.0	7,718	957
Crown	5.25	(max.)	145	0.33	6,773	1,630
	2.04	(min.)	145	0.33	6,773	636

[1] *Corrected for moisture and heat to ignition.*

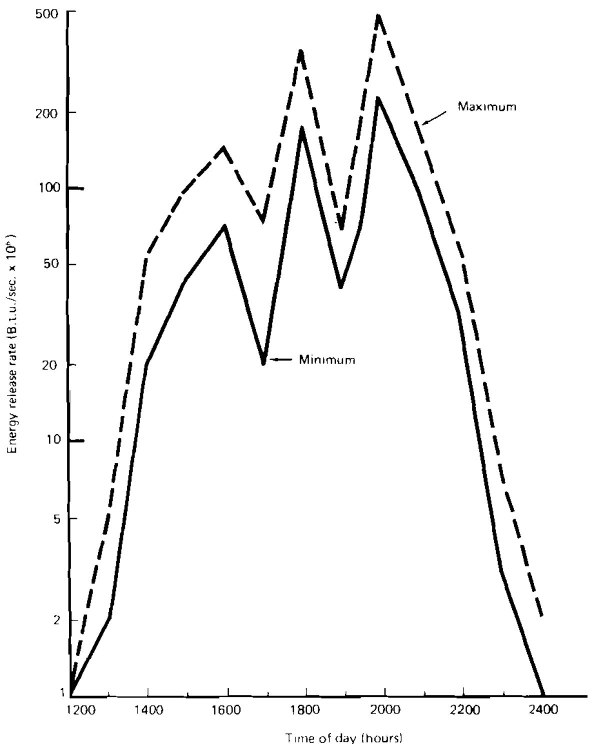


Figure 11. – Rate of energy release at fire front over a 12-hour period on September 1.

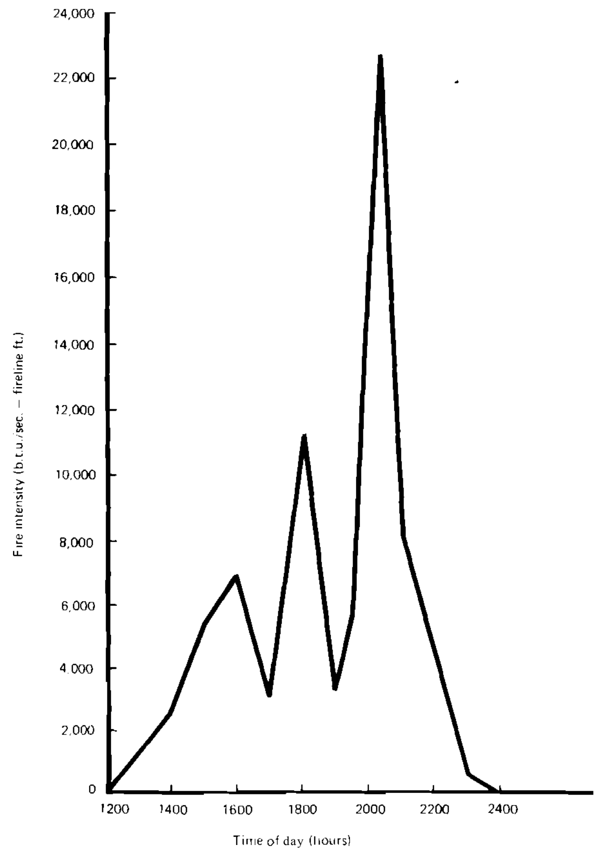


Figure 12. – Fire intensity calculated by Byram's method for a 12-hour period on September 1.

upper limit of 30,000 B.t.u./sec.-ft. for large wildfires, whereas we derived a value of 22,500 B.t.u./sec.-ft. for the Sundance Fire.

The values given here are only approximations, since the derived residence time is an estimate. Each level of fuel and each size of fuel has its own residence time, which may or may not overlap that of the next size. This means residence time may be underestimated because of the sequential ignition and burnout of fuel sizes in increasing order. This probability seems partially verified by the nature of the flame-depth values, which were determined using the assigned residence time and the deduced rate of spread. Flame depth varied from a minimum of 44.0 ft. to a maximum of 264.0 ft., a range that appears narrow for the existing conditions.

FIRE LOG FOR SEPTEMBER 1

0700. Fire area 4,000 acres; fire edge extends from ridge between East River and Lost Creek north around Sundance Mountain and down into Soldier Creek.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 14 m.p.h. SW; relative humidity 25 percent; dry-bulb temperature 71° F.

Up to 1300. No significant increase in fire area. Increased activity in Lost Creek showed the fire front was becoming more active. Weak convection column over burned area meant an increase in windspeed could have a prompt influence on rate of fire spread at the boundaries.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 20 m.p.h. SW; relative humidity 27 percent; dry-bulb temperature 77" F.

1400. Fire advancing to northeast; mainly ground fire.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 21 m.p.h. SW; relative humidity 25 percent; dry-bulb temperature 78" F.

Rate of spread. 0.75 m.p.h.

Fuels. Main fire front: 20-percent ground +75-percent brush +10-percent crown.

Intensity. Maximum energy release rate from total front: 53 X 10^6 B.t.u./sec.; fire intensity: 1,000 B.t.u./sec.-ft.

1500. Fire has advanced to ridge southwest of Jeru Peak; main front brush and crown fire.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 24 m.p.h. SW; relative humidity 22 percent; dry-bulb temperature 78" F.

Rate of spread. 1.25 m.p.h.

Fuels. Main fire front: 20-percent ground +90-percent brush +40-percent crown.

Intensity. Maximum energy release rate: 100 X 10^6 B.t.u./sec.; fire intensity: 5,400 B.t.u./sec.-ft.

1600. Fire at Selkirk Divide; ground fire lagging main front, brush sustaining crowning fire.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 25 m.p.h. SW; relative humidity 20 percent; dry-bulb temperature near 77" F.

Rate of spread. 1.6 m.p.h.

Fuels. Main front: 10-percent ground +95-percent brush +80-percent crown.

Intensity. Maximum energy release rate: 145 X 10^6 B.t.u./sec.; fire intensity: 6,900 B.t.u./sec.-ft.

1700. Fire moving slowly across Divide; convection column 25,000 ft. high.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 29 m.p.h. SW; relative humidity 20 percent; dry-bulb temperature 75" F.

Rate of spread. Less than 1 m.p.h.

Fuels. Main fire front: 30-percent ground +85-percent brush +20-percent crown.

Intensity. Maximum energy release rate: 73 X 10^6 **B.t.u./sec.;** fire intensity: 3,150 **B.t.u./sec.-ft.**

1800. Fire has advanced on east front.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 33 **m.p.h.;** relative humidity 20 percent; dry-bulb temperature 73" F.

Rate of spread. 2.5 **m.p.h.;** could have peaked at more than 5 to 8 **m.p.h.,** as measured by rescue team.

Fuels. In frontal advance: 10-percent ground **+90-percent** brush **+95-percent** crown.

Intensity. Maximum energy release rate: 358 X 10^6 **B.t.u./sec.;** fire intensity: 11,300 **B.t.u./sec.-ft.** — highest level up to this time.

1900. Fire has reached ridge between **McCormick** and Homestead Creeks; ground fire lagging main front, brush controlling spread, considerable crowning.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 37 **m.p.h.** SW; relative humidity 21 percent; dry-bulb temperature 71" F.

Rate of spread. **1 m.p.h.**

Fuels. In frontal advance: **6-percent** ground **+95-percent** brush **+60-percent** crown.

Intensity. Maximum energy release rate: 72 X 10^6 **B.t.u./sec.;** fire intensity: 3,400 **B.t.u./sec.-ft.**

2000. Fire in Pack River drainage; "fire storm"; convection column 31,000 ft.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 44 **m.p.h.** SW; relative humidity 23 percent; dry-bulb temperature 68" F.

Rate of spread. 6 **m.p.h.** approaching Apache Ridge.

Fuels. In frontal advance: **6-percent** ground **+60-percent** brush **+95-percent** crown.

Intensity. Maximum energy release rate: 474 X 10^6 **B.t.u./sec.;** fire intensity: 22,500 **B.t.u./sec.-ft.** These are maximum values for the entire run.

2100. Fire has advanced over Apache Ridge and into Falls and Roman Nose drainages; convection column 35,000 ft.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 45 **m.p.h.** SW; relative humidity 28 percent; dry-bulb temperature 66" F. Windspeed as checked by Roman Nose lookout was steady at 35 to 40 **m.p.h.**

Rate of spread. 2.5 **m.p.h.**

Fuels. In fire front: 4-percent ground +70-percent brush +80-percent crown.

Intensity. Maximum energy release rate: 174 X 10^6 B.t.u./sec.; fire intensity: 8,250 B.t.u./sec.-ft.

2200. Fire at Ruby Ridge and Ruby Creek; spotting on Caribou Ridge; broken front; brush fire with considerable crowning.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 52 m.p.h. SW; relative humidity 31 percent; dry-bulb temperature 65" F.

Rate of ***spread.*** 1.5 m.p.h.

Fuels. Approximately 30 percent of fuel previously affected by spot fires; fuel available to front: 6-percent ground +80-percent brush +70-percent crown.

Intensity. Maximum energy release rate: 60 X 10^6 B.t.u./sec.; fire intensity: 3,800 B.t.u./sec.-ft.

2300 and on into September 2. Fire moving into Caribou Creek; main front poorly defined; fire cooling down.

Weather. Free-atmosphere conditions at 5,000 ft.: Winds 49 m.p.h. SW; relative humidity 36 percent; dry-bulb temperature 63" F. With the winds decreasing and the relative humidity increasing, general conditions on the fire were improving as shown in table 2. Winds on the firewereabout 10 m.p.h. in Ruby, Highland, and Falls Creeks at 0200.

Rate of ***spread.*** 0.5 m.p.h. or less.

Fuels. In fire front: 6-percent ground +60-percent brush +50-percent crown.

Intensity. Maximum energy release rate: 7.8 X 10^6 B.t.u./sec.; fire intensity: 735 B.t.u./sec.-ft.

Table 2. – Estimates of free-atmosphere conditions from 2200, September 1, 1967, to 0600, September 2, 1967.

Time	Wind (SW)	Relative humidity	Dry-bulb temperature
	M.p.h.	Percent	°F.
2200	52	31	65
2400	48	41	61
0200	39	50	58
0400	31	62	54
0600	25	71	52

SOME PROMINENT FIRE FEATURES

The run of the Sundance Fire and its end cannot be attributed to any single factor. The wide front, dry fuels, and winds certainly played major roles in its advance, but firebrand activity was also instrumental. The termination of the run was influenced by the decrease in windspeed and the increase in humidity, and again by the firebrand activity that caused burned-out areas ahead of the main front. In addition the terrain was sloping downhill and prior logging activities had removed part of the fuel continuity. Like any fire, this one was controlled by nature's infinite variety of conditions and their combinations. The best we can do is assess the influence of the obvious variables, estimate their relative importance, and attempt to describe how the fire probably responded to each.

To some extent, this has been done in the preceding pages. However, some additional comments may be helpful with respect to certain outstanding features of the fire.

INFLUENCE OF TERRAIN AND WIND ON FIRE SPREAD

The rate of spread of this fire was strongly influenced by the terrain features and the wind, singly or in combination. If figure 13, showing the changes in rate of spread during the major run, is correlated with the topographic diagram (fig. 1), the windspeeds reported in the Log, and the foldout map, the influence of terrain and wind may be clearly seen.

In Soldier Creek the rate of fire-front advance can be attributed to the slope and wind. The upslope terrain, exposed to southwest airflow from across a broad valley, allowed a crowning fire to become established at a lower windspeed. The fire probably accelerated until it reached the Selkirk Divide where it was slowed by backing fire from the spot fires and its own induced winds.

Down into Pack River along McCormick Creek and Homestead Creek the wind was strong enough to push a crowning fire downslope. However, at the lower elevations the winds had less effect, the slopes became more steep, and indrafts countered the surface wind so the fire moved at a slower rate.

The sharp increase in rate of spread over Apache Ridge can be attributed to preheating of fuel, spotting, upslope, and movement of the front into the wind's influence. Massive spotting and high winds advanced the fire through Falls Creek. The fire moved on to lower elevations where the winds were not so effective and in some areas backing spot fires developed a firebreak that slowed the spread.

In addition the relative humidity rose above 30 percent toward the end of the run and may have prevented some spotting activity. Experience indicates that spotting tends to diminish when relative humidities rise above 30 percent.

BLOWDOWN

The extent of timber blowdown prompted an investigation of the probable indraft maximum in selected areas. Work carried out by Lommasson (5) on mass fires or fire storms

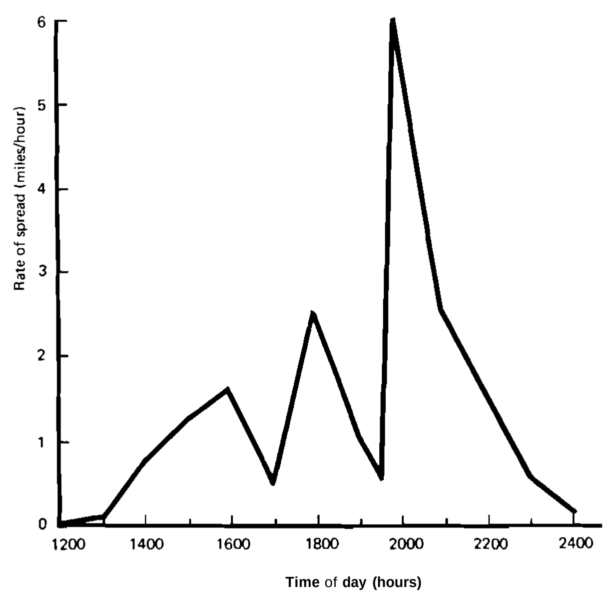


Figure 13. – Rate of fue spread during a 12-hour period on September 1.

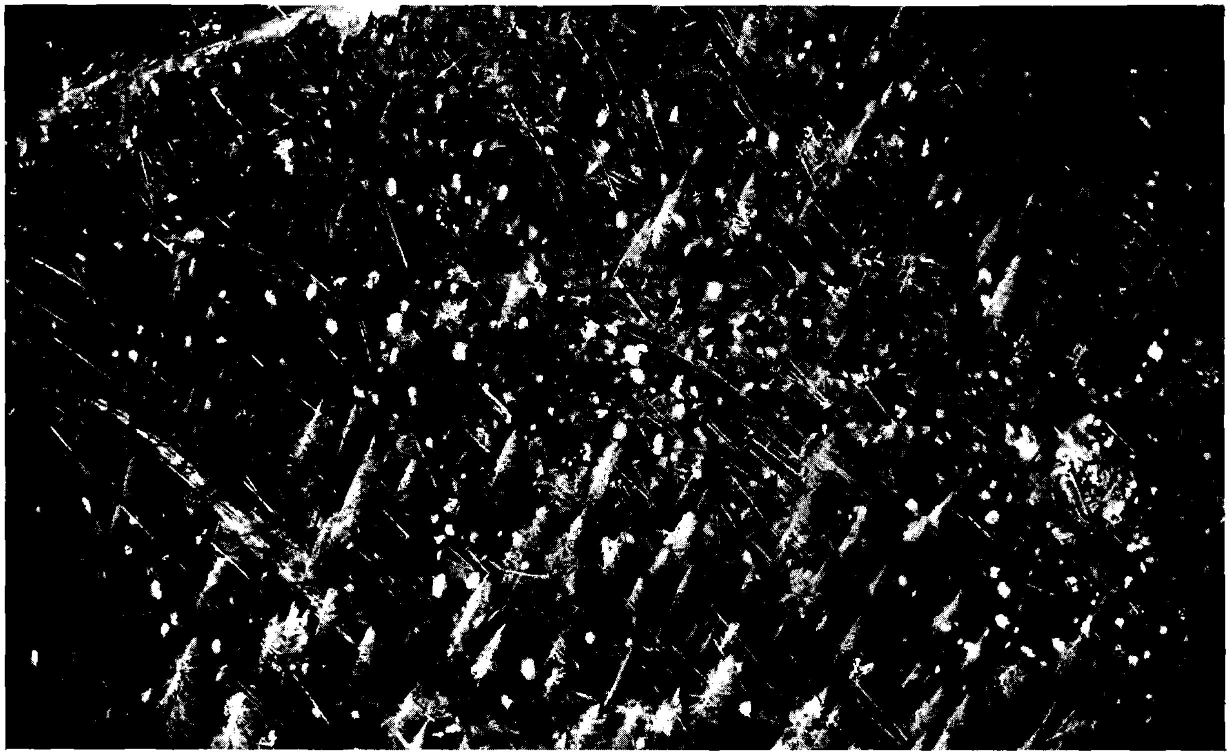


Figure 14. – Blowdown in Falls Creek area.

has provided a means of estimating indraft winds. His equation also provided the means of determining whether our values for flame depth and energy release were reasonable or not. The equation is

$$V_W = \frac{(88 \text{ X} 10^{-3}) \; (\$) \quad {}^{1/3}}{\text{W-}}$$

where

V_W = windspeed, m.p.h.

$\frac{dE_T}{dt}$ = total energy release rate, B.t.u./sec.

A = combustion area, sq. miles.

Values for four areas where blowdown was evident in aerial photographs (fig. 14) were tested with this equation:

Up Soldier Creek	V_W = 80 m.p.h.
Down Upper McCormick Creek	V_W = 95 m.p.h.
Over Apache Ridge	V_W = 96 m.p.h.
Across Falls Creek	V_W = 80 m.p.h.

It has been generally estimated that winds in excess of 80 m.p.h. are needed to cause blowdown. Owen Cramer of the U. S. D. A. Forest Service, Pacific Northwest Station, after viewing slides of the damage, informally estimated the winds to be near 120 m.p.h. The agreement of our values with other estimates, considering the extrapolations we used, encourages continued efforts to develop theories and mathematical descriptions of field-observed phenomena.

FIREBRAND ACTIVITY

Firebrands and spotting were evident throughout the fire run and are believed to have played an important role in the fire's behavior. From the pattern of rate of spread and the record of reported fires, it was apparent that firebrand material had been carried 10 to 12 miles in advance of the main fire front. Much debris was found northeast of the fire area (fig. 15) in the form of moss and lichen strands or wreaths, larch and hemlock cones, needles, cedar fronds, branches the size of a pencil, and pieces of bark up to 4½ inches long and 1½ inches wide. The fallout

Figure 15. – Debris and possible firebrand material found at Bonners Ferry airport, September 1, 1967.

of this debris was widespread over the area northeast of the fire. Much of it was scorched or blackened but the particles had not burned to completion. Neither had they successfully ignited their surroundings. Reports of burning material falling near residences in the Kootenai Valley were received but none of this material was positively identified as burning when it landed.

What kind, size, and shape of burning material could most likely have been carried such distances? Work done in Spain by Tarifa (8) was examined. He investigated the flight paths of spheres, cylinders, and rectangular plates and their burning characteristics to determine the lifetime of firebrands and the probable range. Various species of wood were used and some study was made of pine cones and charcoal elements.

In studying his results, we found that wood elements would have to be large and carried quite high in the convection column to have a 10-mile range. The burning process, according to Tarifa, is glowing combustion, not flaming. Flaming firebrands existed only at low windspeeds. Charcoal brands have much longer burning times than any of the woods or natural firebrands. Pine cones burn much like wood once the scales have burned off.

For our study we had an estimate of the wind and the distance the brands had to travel. We calculated the drag coefficient, terminal velocity, and mean velocity of fall for four types of brands: (a) a charcoal sphere, 1 inch in diameter; (b) a charcoal cylinder, 1.75 inches long and 0.6 inch in diameter; (c) a flat charcoal plate, 1.1 inches square and 0.43 inch thick; and (d) a pine cone about 3.75 inches long and 2.2 inches in diameter. We used the techniques presented by Tarifa to calculate the maximum flight time possible for each brand. This we considered as the time the brand would remain burning; thus the particle would have to reach the ground within this time period to ignite other material. From the mean velocity of fall and time of flight, we could calculate the height at which a particle of the given size must be cast – that is, the ejection altitude. In turn, we could then calculate the vertical velocity in the convection column required to carry

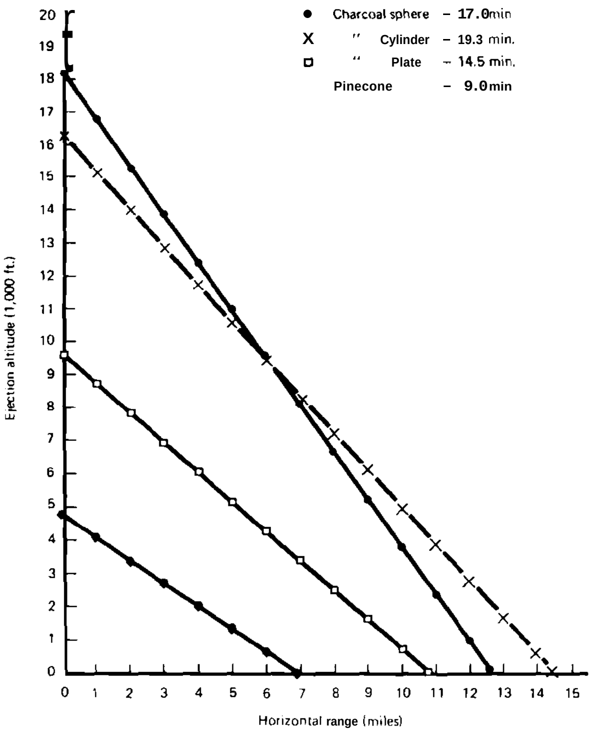


Figure 16. – Range of various types of firebrand material.

the brand to the proper height. The results of these calculations are shown in figure 16.

Any of the charcoal brands could have traveled the 10 to 12 miles in a glowing state, whereas the pine cone could have transported fire up to 7 miles. With a convection column developing to over 31,000 feet, it appears reasonable that vertical velocities of 45 m.p.h. would have existed and material could have been carried to altitudes over 18,000 feet in the convection column. Winds of 44 m.p.h. or greater did exist and could have carried the brand once it tumbled out of the column.

This method of firebrand transport appears quite reasonable but other possibilities do exist. Currently under investigation is the possibility that moving vortices are generated by the fire and prevailing wind. The swirling air or vortices would move on downstream carrying firebrands and debris with them. The intensity and range of these vortices would depend on the amount of heat "pumped" into them by the fire and strength of the wind. Particles carried aloft would tend to either stabilize within the vortex or centrifuge out. Particles with low drag configurations (fig. 15) would tend to stabilize, and as the vortex street dissipated far downstream of the convection column, the suspended debris would "touch down" (1).

Several behavior characteristics noted by the people interviewed support this possibility. It has been stated earlier that the pickup man for the Roman Nose lookout encountered very intense winds and what he described as "dust devils" in Falls Creek ahead of the fire. The occurrence of these dust devils was periodic. The same man encountered similar winds later in the Snow Creek area. The lookout on Black Mountain observed a spot fire which fanned out in all directions in a circular manner. The tree-fall pattern in Falls Creek suggests the trees fell toward the centerline of the fie path from each side. These pieces of evidence have encouraged the investigation of the potential effectiveness of this phenomena (1).

FIRE ACTIVITIES IN PACK RIVER

The Pack River area has received the greatest attention by the news media because of its accessibility, the obvious destructive forces associated with the fire, and the dramatic burning of the Pack River bridge. This area was surveyed by the research team in an attempt to localize the forces the fie exerted; however, these forces appear to have been so dynamic and fluctuating that the evidence remaining is not coherent.

Shortly before the fire entered this area we know men near the river felt very little wind but could hear it overhead. Yet trees that had toppled into the river had green unscorched boughs underwater and burned limbs above water. This indicated that strong winds were present in the valley bottom very shortly before the fire arrived, or before the fire ignited the crown material. Some downed trees showed no signs of burning on the underside, although the upper side was charred.

Winds of different magnitudes and directions may be inferred from the pattern of blowdown and breakage. The tops of many trees were snapped out either by a sudden sharp rush of air or from whipping back and forth, while a great many trees fell under the force of a strong, sustained high wind. The trees with snapped tops were generally less than 2 ft. d.b.h., whereas those that fell were somewhat larger. Tops were snapped off at a nearly uniform height of 60 to 75 feet at a diameter of approximately 1.0 foot. Across open reaches along Pack River below the bridge the trees fell to the north or northeast, but at the mouth of McCormick Creek trees were blown to the east and southeast. Above McCormick Creek some blowdown was to the south and southwest.

All of these clues suggest strong erratic winds just before the fire and the presence of strong fire whirls building and collapsing randomly in the area surrounding the Pack River bridge (fig. 17).

The sequence of events leading to the destruction of the bridge was also examined. The fire burned out both approaches and left the center span intact with some of its paint hardly scorched. The metal plate treads on the approaches were found draped from the concrete piers to the ground, indicating that as the wooden stringers and decking collapsed, temperatures had reached 1,200" F. This temperature level is not unusual in a fire.

Laboratory tests showed the design of the approaches provided sustained combustion in the space between stringers, and the approaches could have continued burning after the main fire had passed. The burning period probably extended over many hours until the decking broke up and the stringers collapsed. Then an increase in heat occurred as the material piled up on the ground, resulting in a period of flaming combustion followed by a long period of glowing combustion. Both types of burningcontributed to the spalling of the concrete piers. Additional information on the Pack River bridge is provided in Appendix 3.

Figure 17. – Fire destructionat Pack River Bridge.

CONCLUSIONS

The spectacular run of the Sundance Fire on September 1,1967, appears to have been a result of the combination of dry fuels from a sustained drought, low humidities for over 72 hours, increasing winds sustained for a period of 9 hours, and a 4-mile active fire front existing on the morning of September 1. The fire advanced 16 miles in 9 hours and created spot fires 10 to 12 miles northeast of the place of origin. Spotting activity increased during the day, reaching a maximum intensity during the period of highest winds in the late afternoon. Whereas spot fires early in the day contributed to the fire spread, late in the day a multitude of firebrands created fuel voids leading to the breakdown of the main front and contributing to the fire's termination. Other factors influencing the decreasing rate of spread were the increasing humidity after 2200, the decreasing wind after 2200, the downslope direction of burning, and to some degree the disruption of fuel continuity due to prior logging activities in the area.

The average rate of spread ranged from 1 to 6 m.p.h. with brief periods of spread rates having higher or lower values. The fire intensity built up to 22,500 B.t.u./sec.-ft. of fire front and was releasing nearly 500 million B.t.u./sec. A convection column rose to 35,000 ft. Extensive firebrand activity and debris were transported from the fire. These brands were either lifted as high as 18,000 feet and transported by the wind or carried in vortices produced by the wind blowing around the convection column. Fire-induced winds could have been greater than 95 m.p.h., and caused the extensive tree blowdown.

Fire buildup indices rated the conditions as "extreme" and spread indices forecast agreed reasonably with actual conditions. The averaged spread index for September 1 was "very high" and when combined with a buildup index of "extreme" produced a rating of "extreme fire danger." The National Fire-Danger Rating System Handbook describes it as:

> **EXTREME.** – *Fires under extreme conditions start quickly, spread furiously, and burn intensely. All fires are potentially serious. Development into high intensity burning will usually be faster and occur from smaller fires than in the very high danger class. Direct attack is rarely possible, and may be dangerous, except immediately after ignition. Fires that develop headway in heavy slash or in conifer stands may be unmanageable while the extreme burning condition lasts. Under these conditions the only effective and safe control action is on the flanks until the weather changes or the fuel supply lessens.*

This very aptly described the Sundance Fire. The present rating system estimated the conditions properly and provided warnings of what could be expected.

This analysis of the Sundance Fire did not reveal any phenomena incompatible with existing knowledge and principles. The extension of laboratory findings and theoretical developments to a field situation resulted in estimates of burning rates, fire intensities, firebrand ranges, and induced windspeeds which are realistic. Evidence of various phenomena gathered during this study has heightened interest in additional research that will provide fuller explanations of such items as vortex generation, firebrand propagation, and spot fire ignition characteristics. The research people assigned to this study have gained valuable experience and we hope our interpretations will be useful and informative to other research and fire control personnel.

APPENDIX 1:

FUEL DETERMINATIONS USED IN THE ANALYSIS

As stated in the text, the fuel complex on the 55,910 acres burned by the Sundance Fire was divided into three levels: ground litter, brush, and crown material. The crown material consumed was composed of foliage and branches under 118-inch diameter based on observations made in the field, The brush level quantity was field sampled and the maximum size involved in the fire front was set at one-fourth inch. The ground litter was sampled in the field at two locations and visual estimates were made throughout the area. Because of findings in laboratory work on fuel consumption, the quantity of the total litter fuel involved in the front was set at 20 percent.

The crown weights were calculated on the basis of timber inventories made by the U, S. D. A. Forest Service. An assumption that State and private lands contain about the same variety of timber types was made after information received from agencies in Idaho had been reviewed. The number of acres occupied by each cover type on Forest Service land, based on the. 1961 forest inventory, is as follows:

Cover type	Trees 5 inches d.b.h. and above	All Forest lands
	Acres	Acres
Larch	4,924	5,849
Alpine fir	3,636	3,636
Spruce	1,892	3,508
Hemlock	1,077	1,238
Douglas-fir	798	883
White pine	694	726
Cedar	670	710
Lodgepole pine	395	395
Ponderosa pine	170	170
Total	14,256	17,115

A study by Fahnestock (3), relating timber volume to slash weight, provided estimates of the crown fuel. First, average timber volumes for the Kaniksu Working Circle were determined by the following d.b.h. classes: 5 to 9 inches, 9 to 11 inches, 11 to 15 inches, 15 to 19 inches, and over 19 inches. Crown weight per acre was then determined from Fahnestock's study for each d.b.h. class using trees of average d.b.h. to represent each class. The weight of needles was calculated assuming 24 percent of the crown weight is foliage. Branches less than one-eighth inch in diameter were assumed to make up 6 percent of the crown foliage. The weight of crown fuel less than one-eighth inch in diameter was calculated as 30 percent of the crown weight. (These percentages were derived by weighting averages by volume for each species present in the Sundance Fire area.)

Crown weights (ovendry basis) for all species in the area are as follows:

Timber size class	Crowns	Foliage	Foliage plus branches <1/8"
Inches	(lbs./acre)	(lbs./acre)	(lbs./acre)
5-9	4,320	1,037	1,296
9-11	3,870	929	1,161
11+	4,830	1,333	1,630
Total	13,020	3,299	4,087

A field sample was taken on a 1110-acre plot near the confluence of Young's Creek and Pack River in a stand of white pine and Douglas-fir appearing typical of timber in that area. All trees were tallied by species and 1-inch d.b.h. classes. Crown weights were calculated from relationships between tree d.b.h. and crown weight (4). Dry-weight estimates per acre are as follows:

Species	Foliage	Foliage plus branches <1/8"
	(lbs./acre)	(lbs./acre)
White pine	3,620	3,700
Douglas-fir	5,360	6,800
Total	8,980	10,500

This plot contained a heavier loading than determined for the fire area as a whole and was used to represent near maximum conditions. The figure used for average loading did not contain crown fuel for trees under 5 inches d.b.h. and probably should be somewhat higher.

A 1/4-milacre plot near Brown's Mill at the northeast end of the fire provided an estimate of the brush level. The ovendry weight was 5,400 lbs./acre of subordinate vegetation. Brush conditions were probably quite variable over the entire area but this plot, appearing typical of the area, was used as an average.

Ground litter was sampled at two locations; one near Brown's Mill and the other at the southwest end of the fire area near Coolin. These 1/4-milacre plots yielded the following loadings (ovendry basis):

	Brown's Mill (lbs./acre)	Coolin (lbs./acre)
Branches		10,040
Duff	17,000	23,880
Buried wood	23,040	
Humus		7,680
Total	40,040	41,600

These forest floor plots should be representative of much of the Sundance area although considerably lower loadings existed in some areas. Moisture content was determined by ovendrying as follows:

Fuel	Moisture content (Percent)
Green foliage	
White pine	144
Hemlock	148
Brush	
Green and some dead brush	67
Snowberry*	54
Forest Floor	
Entire floor (Coolin area)	20
Ponderosa pine litter layer*	8
Surface duff under spruce*	10
Dead branches on spruce*	12

****Samples collected and handled on the Priest River Experimental Forest by C. Carpenter.***

The moisture content of logs in the Hellroaring Creek area was sampled. Logs 3, 6, 12, and 18 inches in diameter were sampled for center and outer moisture contents. These measurements provided some indication of the effect of the moisture depletion for the season.

Species	Log diameter (Inches)	Outer moisture content (Percent)	Center moisture content (Percent)
White pine	3	8.6	8.6
Douglas-fir	6	32.4	37.4
White pine	6	15.2	14.9
Douglas-fir	12	12.7	29.7
Cedar	12	12.2	26.0
Cedar	18	11.6	27.3

APPENDIX 2:

METEOROLOGICAL FACTORS IN THE FIRE RUN

The account of the Sundance Fire in the text of this paper has emphasized the influence of the weather conditions, particularly those that produced the unusually strong winds that were a determining factor in the fire's phenomenal run. In this section we will first look at the general weather situation that existed over North America and the eastern Pacific Ocean, and then pay special attention to the relation of upper-air and surface winds in the vicinity of the fire. Comments on the relative humidity are also included.

The Largescale Weather Situation

For the general weather picture, we will refer to a series of maps depicting atmospheric conditions at about 10,000 ft. m.s.l. (figs. 18 through 22). Maps at this level represent the general airflow and temperature pattern in the lower troposphere, largely free of irregularities induced by local terrain effects in this area.

The solid lines on these maps are height contours; these connect points of equal height (m.s.l.) at which an atmospheric pressure of 700 millibars (mb.) is reached, in analogy to contours on topographic maps (which give heights of the ground surface). The patterns shown by this form of depiction are nearly identical to the isobaric (equal-pressure line) patterns that would be found at a fixed height of 10,000 ft. m.s.l. The contours are drawn for 30-meter intervals and are labeled in tens of meters. The dashed lines are isotherms, drawn at intervals of 5 degrees Celsius. In addition, the winds observed at several individual stations are plotted in conventional symbolic form. That is, the windspeed is proportional to the number of barbs on the tail of an arrow (head not shown). Each full barb represents 10 knots (or 11.5 m.p.h.); a half barb indicates 5 knots. The tail of the arrow points in the direction from which the wind is blowing.

From the wind arrows in these maps, the airflow at 700 mb. is seen to be approximately parallel to the adjacent height contours. The windspeed, at a given latitude, is approximately inversely proportional to the contour spacing. Thus, the steeper the height gradient, the greater the windspeed in that area. In the present discussion, we will substitute the term "pressure gradient," which may be more dynamically descriptive.

The first map (fig. 18) depicts conditions on the morning of August 30 and illustrates a rather abnormal pattern, characteristic of much of the summer of 1967. The dominant pressure features seen here are (a) a strong, extensive warm ridge over the Western United States and Canada and (b) a deep trough and low center in the eastern Pacific area. This trough has been stationary for 3 days. Between the ridge and trough there is a strong pressure gradient. Over the interior Northwestern United States, winds are very light; the map shows a tendency for slow northward movement of warmer air.

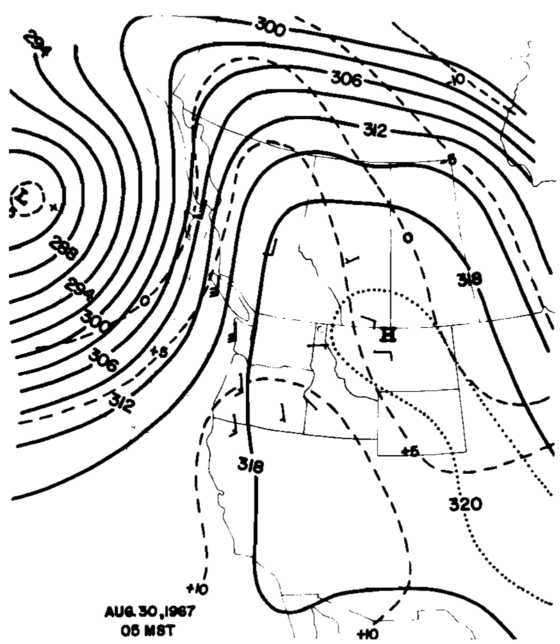


Figure 18. – Analysis of 700-mb. conditions at 0500 m.s.t. August 30, 1967. For explanation of symbols in figures 18-22, see text. Small circle in northern Idaho is approximate location of Sundance Fire.

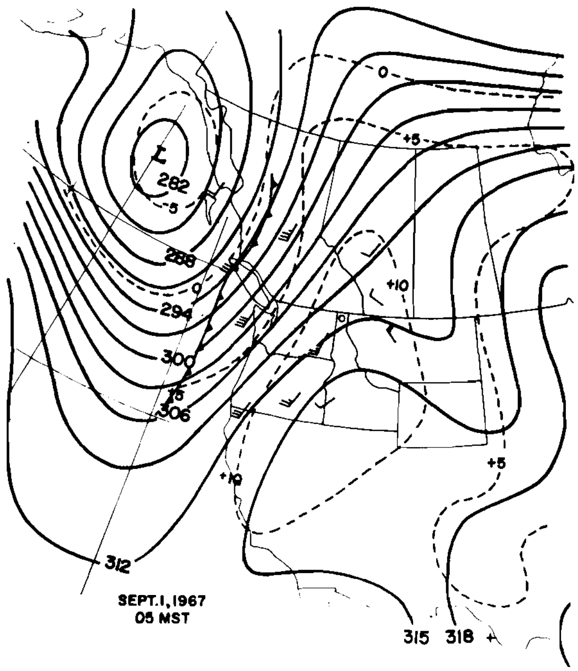


Figure 19. – **Analysis of conditions at 0500 m.s.t. September** 1, **with concurrent surface position of cold front shown by sharp-toothed line.**

In comparison, the "normal" 700-mb. flow over the Pacific Northwest at this time of year is rather zonal (west-to-east), with a slight trough along the Washington-Oregon coast and only a slight ridge over the Canadian Yukon. The "normal" refers to conditions averaged, and thus smoothed, over the period of a month. Nevertheless, the anomaly in the pattern on August 30, 1967, is outstanding.

Twenty-four hours later (map not shown), eastward movement of both the upper pressure trough and ridge had resumed but the area of highest temperature remained stationary over the West. The pressure gradient and observed winds near the British Columbia-Alaskan coast weakened somewhat, while a slight increase appeared over the Washington-Oregon area. A tendency for slow northward movement of warmer air continued over the interior Northwest. Resumption of the trough's movement was in response to a sequence of larger scale, Northern Hemispheric circulation features, whose complexity is beyond the scope of this paper.

The second map (fig. 19), an additional 24 hours later at 0500 m.s.t. (P.d.t.) September 1, shows continued eastward movement of the upper trough. At this time, a portion of the western ridge persisted over the Great Basin area. These two factors brought an increased pressure gradient in the Washington-Oregon area; there were southwesterly winds of about 40 knots near the coast. The speeds approached 25 knots in northern Idaho. Warm air persisted over the interior Northwest, but colder air associated with the trough had increased the temperature gradient across western Washington and Oregon.

Superimposed on this map as the standard sharp-toothed line, is the current (0500) surface map position of a cold front (or possibly an occluded front) that had been moving slowly eastward toward the Pacific Coast. This front is weak, and no pronounced temperature contrast corresponding to it can be found at the 700-mb. level.

By 1700 on September 1 (fig. 20), we see that the strongest pressure gradient has shifted further southeastward. This has been

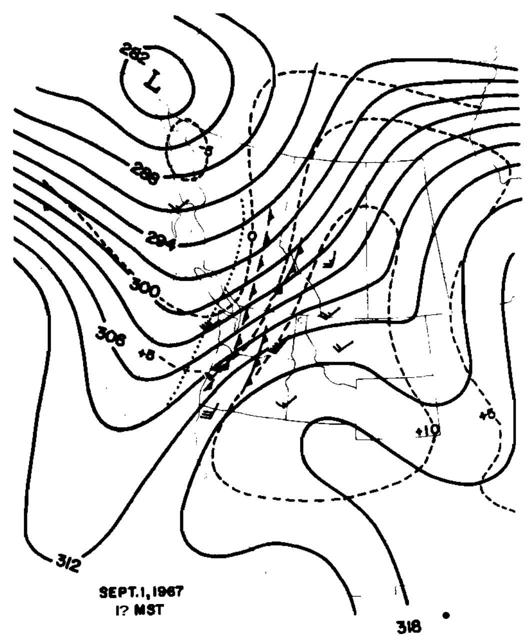


Figure 20. – Analysis of conditions at 1700 m.s.t. September 1, **with surface cold fronts shown as in figure** 19, **except that dissipating Pacifii front is shown in dashed form. The frontal position 6 hours earlier is shown by dotted line.**

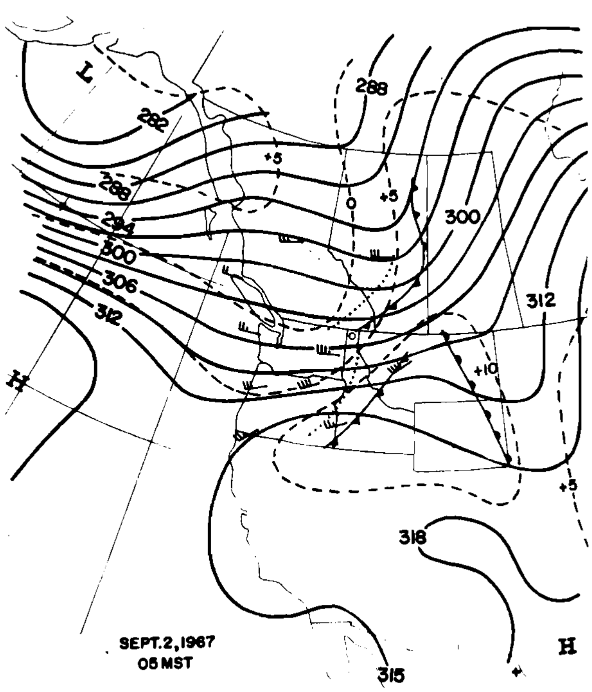


Figure 21. – Analysis of conditions at 0500 m.s.t. September 2, with surface fronts shown. Warm front is shown by round-toothed line.

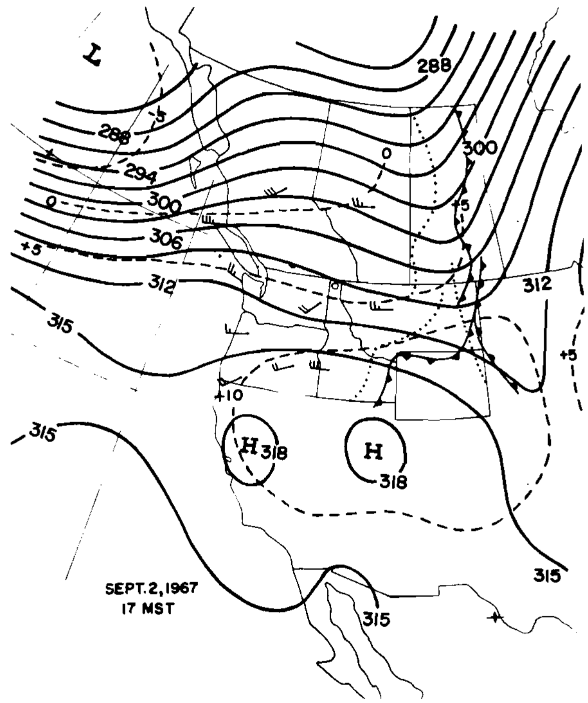


Figure 22. – Analysis of conditions at 1700 m.s.t. September 2, with surface fronts – cold, warm, and occluded – shown.

brought about by (a) further erosion of the ridge over western Canada as the trough pushed inland, and (b) a slight diurnal increase in the strength of the ridge in the Great Basin area. Southwesterly winds of about 35 knots are now indicated in northern Idaho, while 45 to 50 knots are observed upwind in northwestern Oregon.

At the surface, the weak Pacific front has moved inland across British Columbia and western Washington. (Position 6 hours earlier is given by dotted line.) However, by this time, a new cold front has apparently developed east of the Cascades in Washington-Oregon; this is related to increased juxtaposition of the cool and warm air masses (as indicated by the increased temperature gradient in figure 20). Also, a separate, more pronounced, cold front has apparently developed in the southeastern British Columbia area.

Twelve hours later, at 0500 on September 2 (fig. 21), we find the trough has progressed further eastward across western Canada and has dug into the northern portion of the western United States ridge. The offshore portion of the trough has flattened. Airflow over the northwest has thus become more westerly, and the zone of strongest pressure gradient and related wind has moved southward of the northern Idaho area. At the surface, the original Pacific front has dissipated, while the two newly defined cold fronts in Canada and the United States continue to move eastward, generally steered by the upper flow, retaining separate identities. The southern portion of the Canadian front has lagged behind that in the United States. Some light showers and thunderstorms have occurred with the Canadian front, but there have been none thus far with the United States front. Part of northern Idaho appears to be in a region between these fronts. Such frontal detail, possibly induced by topography, is not reflected in the upper air analysis, which is based on observations at stations about 250 to 300 miles apart.

The final map in this 700-mb. series (fig. 22) shows conditions 12 hours later at 1700 on September 2. The pressure gradient over the northwestern United States has decreased further, and flow is now westerly. Little re-

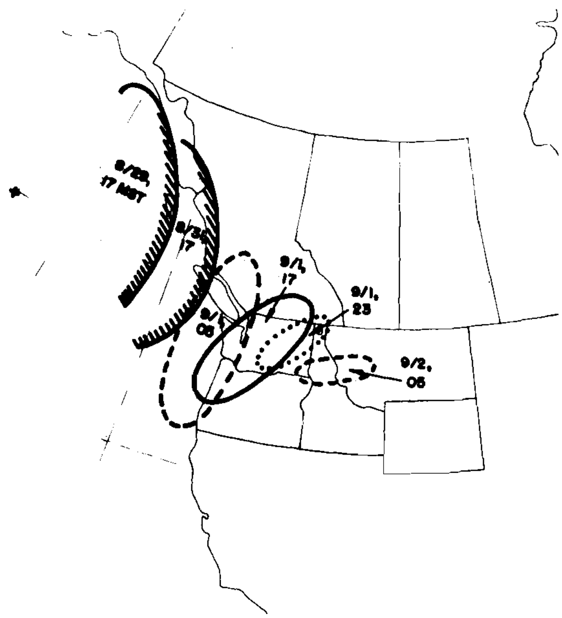


Figure 23. – Areas of strongest winds (40 knots or greater) at 700 mb., August 29 to September 2, 1967.

mains of the trough in the west, while a tendency for ridging appears again. The surface fronts, distorted by topographic barriers and perhaps other factors, have moved well to the east. Light thundershowers occurred during the late morning or afternoon of September 2 in eastern Montana, with only showers to the north in Canada.

Using the indications of the preceding charts (and several not shown here), the areas of strongest wind aloft, preceding and during the fire run, are summarized in figure 23. A speed of 40 knots (46 m.p.h.) has been chosen as the lower limit for inclusion. The outlined areas were defined on the basis of the observed winds and the analyzed pressure gradients. A gradual southeastward to east-southeastward progression of strongest wind is evident. The zone of such wind passes through the northern Idaho area at the time of the 2300 P.d.t. observations on September 1.

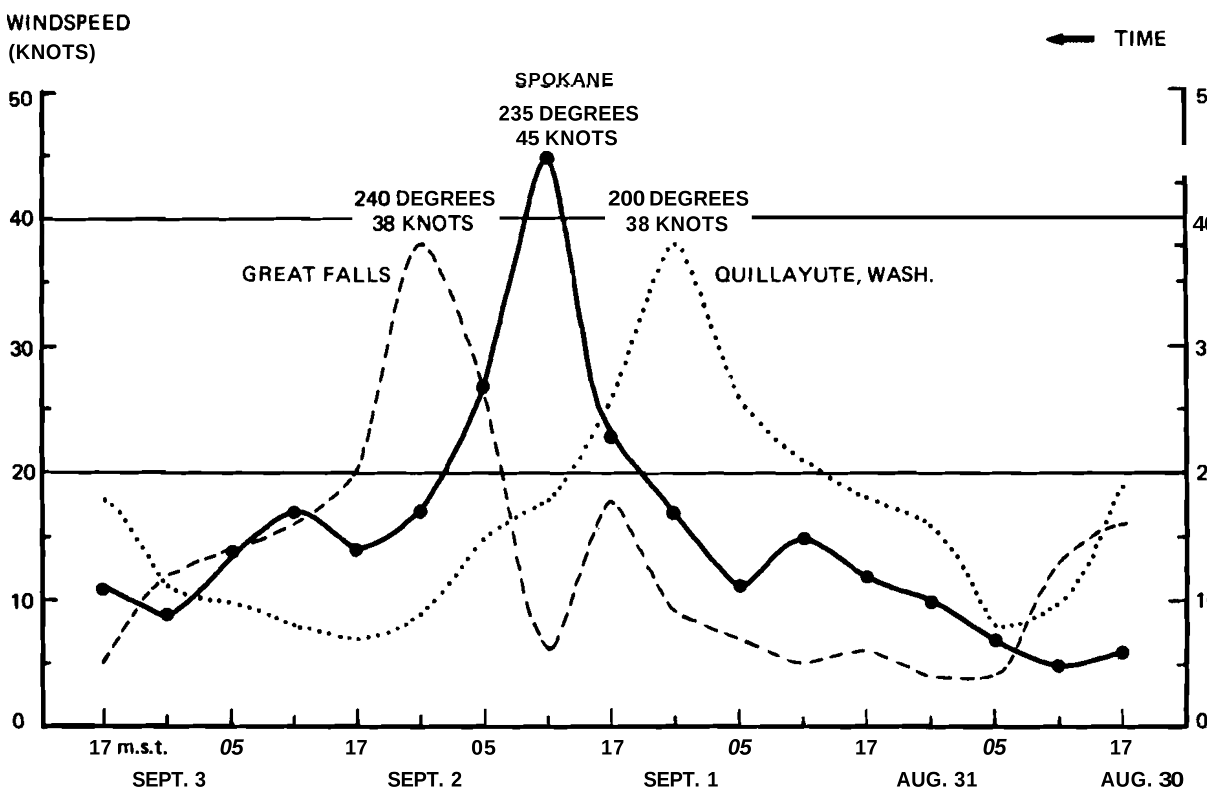


Figure 24. – T i e graph of mean windspeed in the 5,000 to 7,000-ft. m.s.l. layer at Spokane and two adjacent stations, August 30 to September 3, 1967. (Note that time proceeds from right to left in this and the following three figures.) Wind direction in degrees is also shown for the maximum speed for each station.

Upper-Air and Surface Winds in Northern Idaho Vicinity

We may view the winds aloft from another standpoint, in the form of a time graph for an individual station. Figure 24 shows such a graph of the mean windspeed in the 5,000 to 7,000-ft. m.s.l. layer for Spokane, 70 statute miles southwest of Sundance Mountain. For comparison, the corresponding windspeeds are given for two adjacent upper-air stations (to the west and east). These stations are Quillayute, on the northern Washington coast, and Great Falls, Montana. A pronounced peak in speed in the 5,000- to 7,000-ft. layer is seen to have occurred at all three stations. The peak at the coastal station occurred approximately 12 hours before that at Spokane, whereas the peak at Great Falls occurred about 12 hours after that at Spokane. The peak speed in this layer, 45 knots (from the southwest), is highest at Spokane; however, nearly as high a speed, 43 knots, was observed in a lower layer (2,000-4,000 ft. m.s.l.) at the coastal station. This diagram gives further evidence that the strong lower level winds in the Sundance Fire vicinity were a more or less sustained, broad-scale, moving feature which, at least in retrospect, was trackable.

Sustained windspeeds of 40 to 45 knots at 5,000 to 7,000 ft. m.s.l. appear to be exceptional in the northern Idaho area during the fire season. This is the impression gained from an examination of Spokane winds-aloft reports for the period June 15 to September 15 of the years 1957 through 1967. Speeds of 38 knots or greater at 5,000 feet appear to occur on an average of only 2 days per season (based on four wind soundings per day). In all but one of 12 actually observed cases in this 11-year period (wind soundings were made only three times per day during five of the years), the days with such windspeeds occurred in June or September. The wind direc-

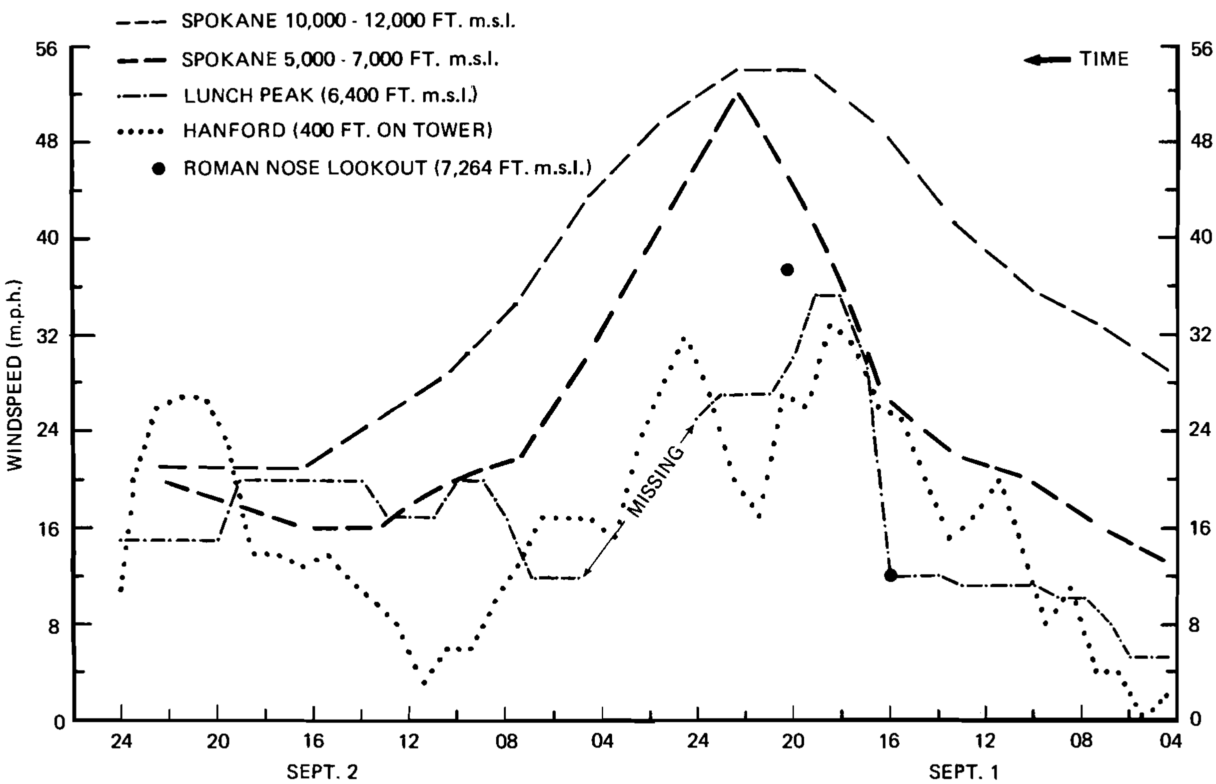


Figure 25. – **Time graph comparing free-atmosphere windspeeds at Spokane and surface or tower windspeeds at several observation points, September** 1-2,1967.

tion in all but one case was southwesterly or west-southwesterly, with some sort of upper trough located near the Washington coast.

We have thus far looked at wind indications from upper-air observations. An obvious question is how do these winds aloft relate to those actually observed or expected at ground- or tree-level locations. Winds in mountain areas may, of course, vary considerably according to exposure to the general airflow. In addition, surface friction acts to reduce the windspeed near the ground, but terrain-induced turbulence (proportional to gradient windspeed) may bring strong gusts. Locally, winds may be increased by terrain-enforced convergence of airflow. Figure 25 compares the free-atmosphere winds observed above Spokane with the winds at several surface stations.

In the Sundance Fire vicinity, hourly wind data were available, except for several nighttime hours, from Lunch Peak, at 6,400 ft. m.s.l. 20 miles to the southeast. A mobile fire-weather station, sent from Boise, was in operation here for the Plume Creek Fire. A rather abrupt rise in the Lunch Peak windspeed is noted between 1600 and 1700 P.d.t. on September 1. Winds from the southwest soon reached an average of approximately 35 m.p.h. at 1800 and 1900 P.d.t.; gusts (not plotted in the diagram) were up to 50 to 55 m.p.h. for several hours.

Roman Nose Lookout, at 7,264 ft. m.s.l. on the northern edge of the fire, had a 12 m.p.h. southerly wind at the regular 1600 P.d.t. fire-weather observation time; a steady speed of 35 to 40 m.p.h. from the southwest was reported at 2015 P.d.t. (note point plotted in figure 25). A lookout atop Mt. Henry (7,235 ft. m.s.l.), in extreme northwestern Montana, reported winds averaging 40 m.p.h. and gusting to 60 m.p.h. (time not given).

Among the mountaintop fire-weather stations reporting once daily, four of the seven in northeastern Washington (at elevations ranging between 3,800 and 5,900 ft. m.s.l.) had windspeeds between 27 and 33 m.p.h. at 1600 P.d.t. Speeds at five such stations in the Idaho panhandle (at elevations between 5,200 and 6,400 ft. m.s.l.) were as yet only between 12 and 16 m.p.h. To illustrate possible terrain-exposure effects, Squaw Peak, Montana (at 6,200 feet), nearby to the southeast, had 29 m.p.h. winds at this time.

The Lunch Peak (and Roman Nose Lookout) windspeeds fit in reasonably well with the 5,000- to 7,000-ft. wind trend at Spokane during the late afternoon and early evening of September 1. The same can be said for the winds atop a 400-ft. tower at the Hanford A.E.C. Works, ground elevation 700 ft. m.s.l., about 120 miles southwest of Spokane. The available Lunch Peak and Hanford speeds differ considerably, however, from those of the free-atmosphere winds at Spokane later in the evening. This difference is probably associated with variations in the vertical, turbulent transfer of momentum through the "friction layer." This layer would extend mainly to near 5,000 ft. m.s.l. at Spokane and to correspondingly higher altitudes above the mountainous area in northern Idaho. Although reference is made in this paper to free-atmosphere winds at 5,000 ft. m.s.l. in the Sundance area, such winds are largely hypothetical.

It may be well to clarify here the relationship between the strong winds in the Sundance area and the movement of a cold front. The strong, or relatively strong, and gusty surface winds observed in eastern Washington and northern Idaho on September 1 began by middle or late afternoon. This onset took place, at high and low elevations, approximately 100 to 150 miles in advance of the cold front that had developed east of the Cascades. Cooler-air movement, representing a gradual change of airmass, was, however, already accompanying these prefrontal winds. The front in this case thus appears to represent a secondary steepening of horizontal temperature gradient imbedded within a broader gradient. The peak in 5,000-ft. m.s.l. free-atmosphere windspeed, which was reached in the late evening, occurred near or slightly behind the surface map projection of this eastward-moving front. But, as indicated earlier, the front was rather diffuse or undetectable in northern Idaho and extreme eastern Washington.

In the absence of more detailed data coverage, the actual effect of this diffuse front (or frontal zone) on the Sundance surface winds remains a matter for speculation. It is, however, apparent that the front alone could not have accounted for the unusually strong, gusty winds which persisted for several hours. These winds were ultimately dependent upon the exceptional summertime pressure gradient that existed in the lower levels of the troposphere. The extent to which winds of gradient strength or greater were experienced near the surface would, of course, vary, as previously discussed. Turbulence commonly attending a cold front may or may not have been an important triggering factor in this case.

The strong pressure gradient and the cold front, both associated with the approaching trough, may be regarded as individual but related parts of a weather system. Basic to such a system is the juxtaposition of two different (warm and cool) airmasses. The upper tropospheric jet stream, whose core in this case was at only 25,000 to 30,000 ft. m.s.l., would also be part of this system. Moving eastward, its axis at 2300 P.d.t. September 1 was about 100 miles northwest of Spokane and the Sundance area. The windspeed over Spokane was approximately 80 knots (interpolated), having increased from 60 knots at 1700 P.d.t. Such a jet could, through dynamic processes, possibly effect a vertical transfer of momentum (and other properties) to the lower troposphere. This would occur within a frontal zone sloping below the jet's core, in the form of a dry-adiabatic sinking of air from the upper tropospheric portion of the zone (located many miles upwind of its lower portion) (6). Some evidence was found supporting the presence of such an effect in the Sundance case, but was regarded as inconclusive.

The estimated hourly free-atmosphere (gradient) windspeeds at 5,000 ft. m.s.l. in the Sundance area, used in this fire report, are given in figure 26. These speeds are based upon the 6-hourly upperwind observations at Spokane. Observed surface winds, referred to earlier, were used as a guide in allowing for a slight timelag in adapting a vertical cross-section analysis of Spokane upper winds (not shown) to the Sundance area. The lag, adjudged also according to spatial differences in pressure gradient on the 700-mb. maps, did not exceed 1 hour and was adjudged to be zero after the time of maximum wind.

Humidity

Also plotted in figure 26 is a curve of estimated "modified" free-atmosphere relative humidity at 5,000 ft. These humidity values are a compromise between those in the free atmosphere and those observed near ground

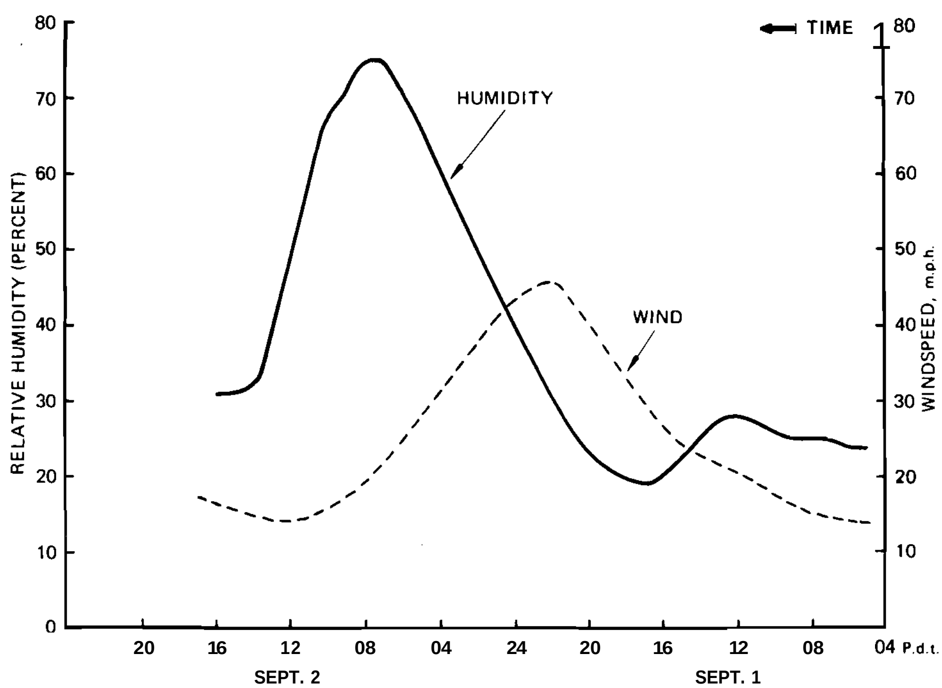


Figure 26. – Time graph of estimated free-atmosphere windspeed and "modified" free-atmosphere relative humidity at 5,000 ft. m.s.l., Sundance Fire area, September 1-2, 1967.

level on a ridge or mountaintop. Relative humidity is, of course, a function of both temperature and actual water-vapor content of the air. The values given here were derived by use of Spokane surface and upper-air observations and the hygrothermograph charts from both Gisbome Mountain Lookout (about 10 miles south of the Sundance Fire area) and Big Spot mobile weather station (about 25 miles north of Sundance). Good consistency was found among the temperature and vapor pressure tendencies from these data sources. The Lunch Peak data, however, were not used here; the observed temperature values and behavior showed discrepancy with those at the above stations and at 6,424-ft. Sunset Peak, Idaho (70 miles SSE of the Sundance Fire), and were considered unrepresentative of the general area.

A relative humidity threshold of about 30 percent has been found empirically by some researchers to be critical in the preconditioning of fine fuels. The estimated relative humidity for the Sundance Fire environment is seen to have remained below 30 percent on September 1 until after 2200 P.d.t., about the time of maximum estimated gradient wind. A steady increase then occurred, raising the humidity to 75 percent the following morning. For comparison, the low relative humidity that persisted for several preceding days and nights is shown in figure 27. The relative humidity increase (September 1-2) was related primarily to the decrease in "modified" free-atmosphere temperature (to 51° F. at 5,000 ft. m.s.l.), rather than to any large increase in vapor content of the air as compared with preceding nights.

Concluding Remarks

In summary, we have described the general weather situation associated with the Sundance Fire run and have examined more specifically the related wind and relative humidity. Additional research, not reported here, examined other considerations stated in the literature to be possibly important in rapid or "explosive" fire spread. Primarily these are (a) vertical wind profile (change of speed and direction with height); (b) airmass instability; (c) subsidence; and (d) downdrafts from adjacent thunderstorms. The last-named factor may be safely regarded as absent in the Sundance Fire case. Findings with respect to the first three, not particularly crucial, will appear in a forthcoming separate, more complete meteorological paper.

The above-presented weather factors must be considered together with other factors, such as fuels and topography, in accounting for the fire behavior. With this in mind, it is nevertheless quite apparent that unusually strong winds occurred in the Sundance vicinity at a most unfortunate time.

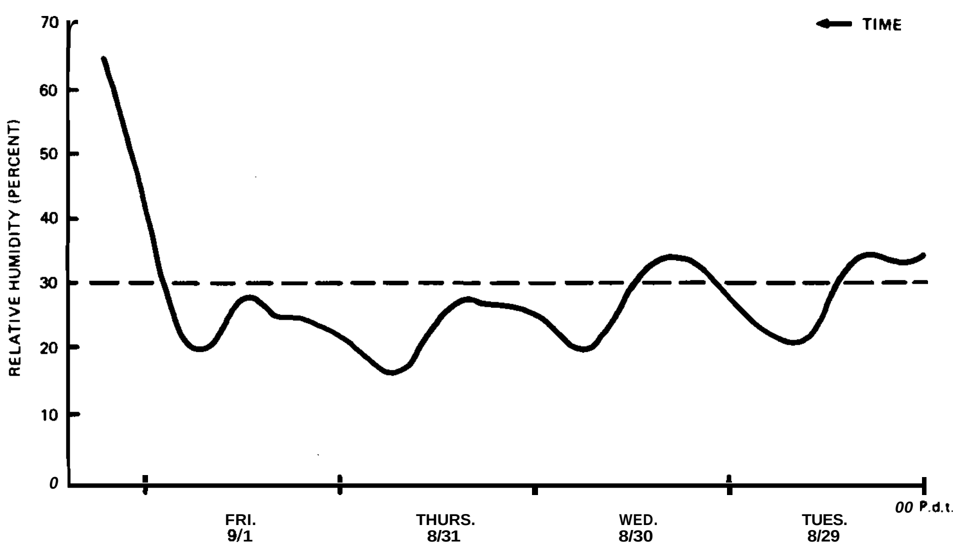


Figure 27. – **Time** graph of estimated "m ed" free-atmosphere relative humidity at **5,000 ft. m.s.l., Sundance Fire area,** for **several** days prior to and including September 1, 1967.

APPENDIX 3:

THE PACK RIVER BRIDGE AS AN AREA FIRE INTENSITY INDICATOR

The Sundance Fire burned with extreme intensity in many areas, as exhibited by rock spalling and complete burnout of ground fuels. The area where the fire crossed the Pack River is a notable example. Here, the visitor is awed by the coupled effects of high winds and intense fire activity. Nearly all the large trees — cedars and hemlocks — have been uprooted or broken and are lying charred among the grey ash remains of ground fuels. Also, the remains of the Pack River Bridge are mute evidence of the fire's passing. There has been much speculation about the intensity necessary to result in the complete burnout of the approach spans and distortion of the carbon steel plates covering the deck runway. This short study is intended to establish the relationship, if any, between fire intensity at the bridge and in the surrounding area.

Extent of Fire Damage to the Bridge

The bridge spans the Pack River in a nearly north-south direction near the McCormick Creek inlet as 'shown on the foldout map. Three connected segments make up the bridge: the center span resting on two concrete piers in the stream bed and two approach spans resting on concrete footing on the streambank. The design is shown in figure 28. The center span is 65 ft. long by 14 ft. wide. Each approach span is approximately 24 ft. long by 14 ft. wide. The decks of the approach spans are 6 inches thick, and are made up of laminated 2- by 6-inch boards. Strength is given to the deck by nine traverse beams 8- by 20 inches by 24 feet, spaced along the length of the span. Carbon steel plates 5116-inch thick were also placed on the deck runways to provide traction and reduce wear. The primary structural material used was creosote-treated Douglas-fir.

Fire damage to the bridge was confined essentially to the approach spans; although there was evidence of burning at each end of the central span, the major portion of it was unscorched by the surrounding fire activity. Figure 17 (main text) shows the burnout of the north approach span. Figures 29 and 30 show other views of the bridge. Notice the unburned paint on the central span shown in figure 29. Figure 30 shows the complete burn-

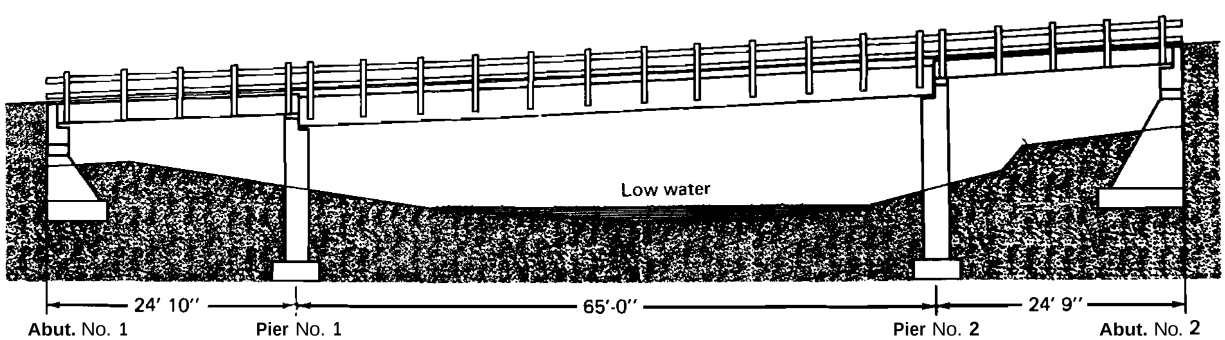


Figure 28. – Side elevation of Pack River Bridge.

Figure 29. – View of Pack River Bridge looking southeast.

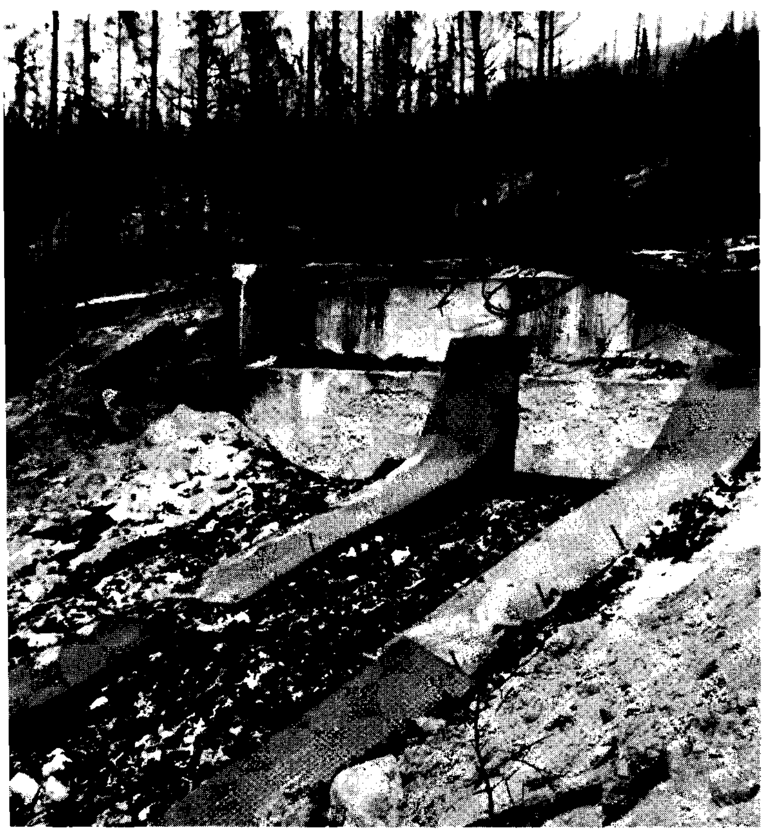


Figure 30. – Burnout of north approach span, Pack River Bridge, showing distortion of steel surface plates.

out of one of the approach spans and the deformed steel plates. The other span is identical in appearance. It is apparent from the photograph that the steel plates had been sufficiently softened by the heat to conform to the shape of the surface they fell upon when the span gave way.

Hypotheses of Ignition and Burning

The probability of ignition of the bridge is of course dependent on the residence time of the fire in the surrounding area. Anderson[3] gives us a relationship between 8, the residence time in minutes, and D, the particle diameter in inches.

$$\theta = 8D$$

From evidence of burned limb stumps, 2 inches in diameter, we estimate a residence time in the surrounding fuels area of 16 minutes. Limbs of larger diameter would help sustain the residence time past 16 minutes; this would certainly be enough time to ignite the brush near the approach spans (the remains of this brush may be seen in figure 17). The burning brush would then act as an ignition source for the bridge.

The importance of closely positioned kindling fuels is demonstrated by the fact that fire damage to the central span was limited, owing to the absence of a nearby source of ignition. Except for occasional hot flames the region just above the creek bottom would be relatively cool compared to the surrounding area. We conclude that fire activity in the central span near the concrete piers was simply an extension of the fire in the approach spans. During the period of burning, winds near the bridge were predominantly upstream or downstream, that is, normal to the bridge, as evidenced by the creosote smoke deposited on the steel beams on either side of the central span. Consequently, we believe the fire traveled crosswise to the wind and simply burned out near the concrete piers. If there had been ignition on the windward side of the central span, more extensive damage would have occurred in that section.

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[3] *Anderson, Hal E. Heat transfer and fire spread. U.S.D.A. Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah. (In preparation.)*

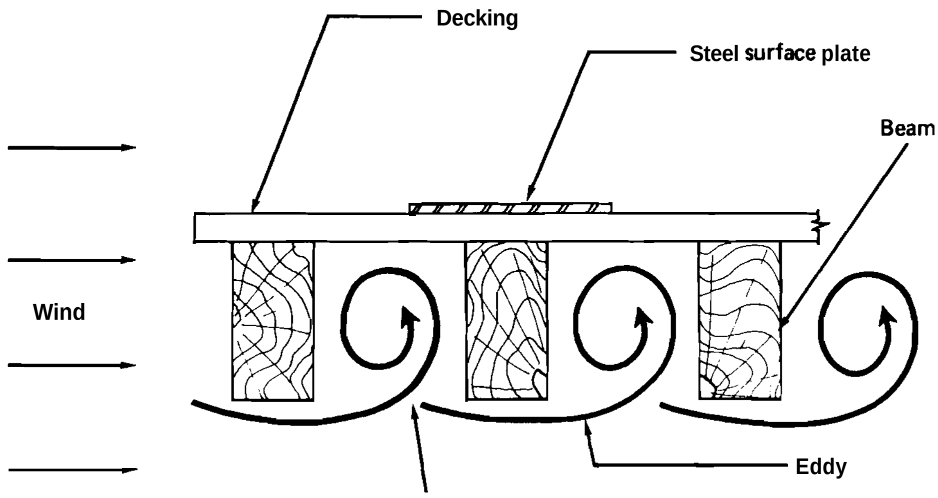

Figure 31. – Cross section of approach span of bridge, showing supposed pattern of wind eddy formation within cavities.

Once the bridge had been ignited, enhancement of the burning can also be attributed to the long rectangular cavities between the beams located below the bridge. It is hypothesized that wind blowing over these cavities perpendicularly to the beam axis or bridge direction produces eddies on the leeward side of the beams within each cavity, as illustrated in figure 31. As the windward side burns, flames are entrained into the eddies on the leeward side. Thus, combustion is propagated into the adjacent cavity. In this situation, only a limited amount of air is entrained into the cavity with the flames so that combustion of only a portion of the volatilized gases from the inside surface can be completed within the cavity. As the heat builds up, an overabundance of the volatilized gases is produced within the cavity. Thus, the proper fuel air mixture is not attained until the gases are swept out of the cavity into the outside air. However, just as these gases leave the cavity and begin flaming combustion they are entrained into the next cavity and so the cycle is repeated until all the cavities are burning. Notice also, in figure 31, that the two walls formed by the beams are advantageously located for enhancement of burning by reradiation between the walls.

There is no direct evidence to support the hypothesis that eddies were formed in the cavities below the deck. However, a reconstruction of the bridge fire under laboratory conditions gives us a qualitative examination of eddy production that could lead to support or rejection of the hypothesis. For our purpose a cross-sectional slice of the beam axis of the bridge-approach span is sufficient. Since a qualitative examination is all that is possible, there is no strict adherence to scaling. The deck is made up of 1½- by ½-inch white pine lumber and the beams are replaced by 2- by 4-inch Douglas-fir. Two coats of diesel oil were applied to the model to simulate the creosote treatment.

The simulated bridge section was placed in the wind tunnel with the wind flowing at right angles to the beam axis. To eliminate burning on the exposed cross-sectional faces it is necessary to cover both faces with sheet metal. Two bridge sizes were burned in the wind tunnel under identical conditions, the only difference being in the width. In the first test the bridge was 42 inches wide and in the second 17 inches. In both cases ignition by simulated ground fuels (excelsior) was on the windward side. Because of the size difference ignition was confined to the first few cavities in case 1 and extended over the entire bridge section in case 2.

Figure 32. – Model of bridge approach span (42-inch size) burning in wind tunnel.

These two cases simulated two possible levels of ignition. Although the ignition was different, the circulation patterns in the cavities are identical. In the photograph, figure 32, a similarity to the expected eddy patterns shown in figure 31 is evident. There is great likelihood then that eddy patterns were created in the cavities below the deck, enhancing the fire activity at the bridge.

Creosote preservative on the wood structures of the bridge and vegetation near the bridge approaches certainly contributed to the ignition process; however, the wind and the associated eddies produced within the cavities under the bridge are of greater importance. If there had been no cavities, it is likely that burning would have been greatly reduced except at the edges, resulting in much slower burning and possibly more unburned residue, rather than the complete burnout of the approach spans that actually occurred.

Winds at the bridge site were primarily fire induced and generated in the drainage in an area remote from the bridge. They were "indraft" winds resulting from strong convective upward flow at the generating source. These winds were sustained as other areas in the drainage burned, creating additional generators. Furthermore, there were enough other areas to sustain winds for the equivalent of at least four residence times, thus accounting for 1 hour of intense fire activity at the bridge site. This was certainly enough time for the bridge to have achieved sustained combustion without the necessity of continued sources of wind and heat. It is very likely that these indraft winds were present at the bridge because the creekbed acted as a relatively unobstructed trough for the flow of air.

Damage to Steel Runways

Heat transfer to the steel runways was sufficient to cause a large reduction in the tensile strength as evidenced by the distortion of the plates shown in figure 30. Considering the density of steel we may assume that it would deform appreciably under its own weight if it lost three-fourths of its peak strength. Examination of the variation in steel strength with temperature indicates that a reduction of strength of that extent would be achieved at 1200" F. This is in no way indicative of the temperature outside the immediate bridge area. Contrary to news reports, there is no evidence that the steel had reached the melting point, 2,800" F.

Conclusions

An examination of the bridge and the simulated bridge fire suggests that:

1. The bridge approaches were ignited by ground fuels.

2. Once ignited, the bridge continued to burn independent of the heat supplied by surrounding forest fire.

3. The bridge design contributed to the fire damage, since eddies formed by the wind normal to the bridge produced and captured pockets of burning gas on the underside of the bridge.

4. The distortion of the steel plates merely indicates that a fire was present long enough to heat the plates to 1,200" F. or more (but not up to the melting point, 2,800" F.)

5. The bridge fire is not an indicator of the intensity of the surrounding forest fire.

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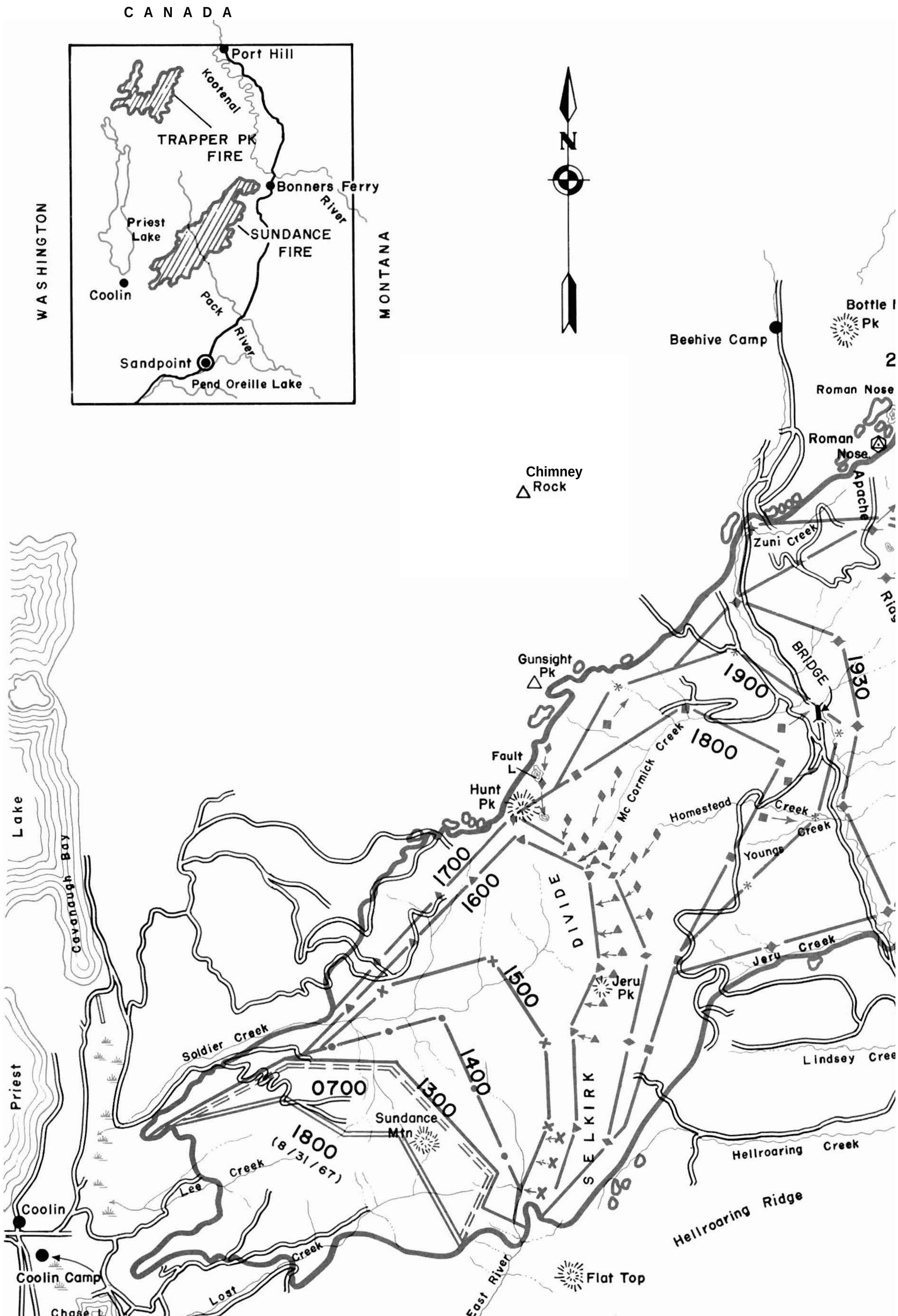
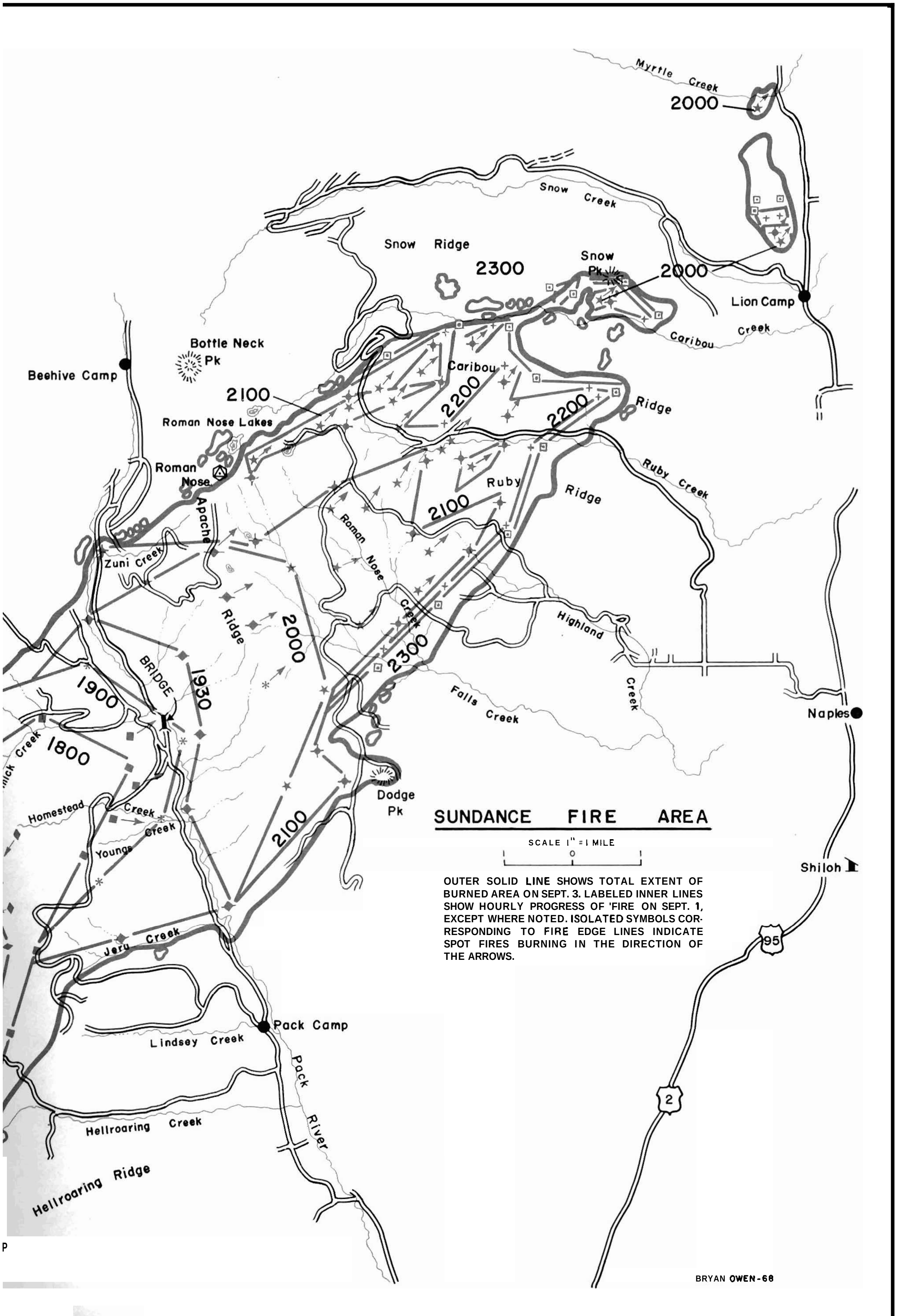


CANADA
Port Hill
Kootenai
TRAPPER PK FIRE
Bonners Ferry
River
Priest Lake
SUNDANCE FIRE
WASHINGTON
MONTANA
Coolin
Pack River
Sandpoint
Pend Oreille Lake
N
Beehive Camp
Bottle Pk
Roman Nose
Chimney Rock
Zuni Creek
Apache
BRIDGE
1900
1930
Gunsight Pk
1800
Fault L.
Hunt Pk
Mc Cormick Creek
Homestead Creek
Youngs Creek
Priest Lake
Cavanaugh Bay
1700
1600
DIVIDE
1500
Jeru Pk
Jeru Creek
Soldier Creek
1400
Lindsey Creek
0700
1300
Sundance Mtn
1800 (8/31/67)
SELKIRK
Hellroaring Creek
Lee Creek
Coolin
Coolin Camp
Chase L.
Lost Creek
East River
Flat Top
Hellroaring Ridge


Myrtle Creek
2000
Snow Creek
Snow Ridge
2300
Snow Pk.
2000
Lion Camp
Caribou Creek
Bottle Neck Pk
Beehive Camp
2100
Caribou
2200
Ridge
2200
Roman Nose Lakes
Roman Nose
Apache
Ruby
Ruby Creek
Ridge
2100
Zuni Creek
Roman Nose Creek
Ridge
2000
Highland
BRIDGE
1930
1900
2300
Falls Creek
Creek
Naples
1800
Dodge Pk
Homestead
Creek
Youngs Creek
2100
Shiloh
95
Jeru Creek
Pack Camp
Lindsey Creek
Pack River
2
Hellroaring Creek
Hellroaring Ridge
SUNDANCE FIRE AREA
SCALE 1" = 1 MILE
OUTER SOLID LINE SHOWS TOTAL EXTENT OF BURNED AREA ON SEPT. 3. LABELED INNER LINES SHOW HOURLY PROGRESS OF FIRE ON SEPT. 1, EXCEPT WHERE NOTED. ISOLATED SYMBOLS CORRESPONDING TO FIRE EDGE LINES INDICATE SPOT FIRES BURNING IN THE DIRECTION OF THE ARROWS.
BRYAN OWEN-68

Anderson, Hal E.
1968. **Sundance** Fire: an analysis of fire phenomena. U. S. Dep. Agr., Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah 84401. 39 pp., **illus.** (U. S. Forest Serv. Res. Pap. INT-56)

The **Sundance** Fire on September 1, 1967, made a spectacular run of 16 miles in 9 hours and destroyed more than 50,000 acres. This run became the subject of a detailed research analysis of the environmental, topographic, and vegetation variables aimed at reconstructing and describing fire phenomena. This report details the fire's progress; discusses the fire's buildup in intensity, the fuel complex through which it traveled, the wind and other atmospheric variables affecting the fire's behavior; and describes the processes that probably account for the tree breakage and blowdown, the long-range spotting, and the subsidence of the fire's run.

The Forest Service of the U. S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives – as directed by Congress – to provide increasingly greater service to a growing nation.