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General Technical Report **NC-83**

The Mack Lake Fire

Albert J. Simard, Donald A. Haines, Richard W. Blank, and John S. Frost

Return to Bill Irvine

Front Cover Photo.—*The Mack Lake Fire shortly before it passed through the village of Mack Lake. Note the spot fire on the edge of the lake. Photo courtesy of the Huron-Manistee National Forest, Mio Ranger District.*

PREFACE

The full story of a major wildfire contains many chapters, such as organization, suppression, and logistics. This report on fire behavior is only one chapter in the story. In limiting our observations to fire related phenomena, our conclusions must also be limited to fire's contribution to the outcome of events. Thus, the report does not address management concerns involving actions taken or not taken. These have been adequately discussed in a previous report (USDA Forest Service 1980) and will not be repeated here.

The reader may note differences between information presented herein and that previously published. Earlier information was based on preliminary analyses of incomplete data. This report reflects a comprehensive analysis of all available data as well as a thorough review. Thus, where differences exist, this report should be considered correct.

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North Central Forest Experiment Station
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St. Paul, Minnesota 55108
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THE MACK LAKE FIRE

Albert J. Simard, *Project Leader,*
Donald A. Haines, *Principal Meteorologist,*
Richard W. Blank, *Forestry Technician,*
and **John S. Frost,** *Meteorological Technician,*
East Lansing, Michigan

On May 5, 1980, at 1030 EDT,[1] a prescribed fire was ignited in jack pine slash near Mio, Michigan (fig. 1). The purpose of the burn was to remove logging debris up to 1 inch in diameter in preparation for replanting jack pine. The ultimate objective was to create habitat favored by the endangered Kirtland's warbler. At 1206, the fire spotted into standing jack pine timber adjacent to the prescribed burn area. At 1215, the fire spotted across Michigan Highway 33 and became a wildfire. In the first 3-½ hours, during which the fire advanced 7-½ miles, no amount of fire line or road width held or slowed the fire. After the fire had advanced 4 miles, the passage of a dry cold front turned the southeast flank into a head fire. In the first 6 hours, the fire took one life, destroyed 44 homes and buildings, and burned 20,000 acres of forest land. Aided by a change in fuels and ameliorating burning conditions, suppression crews contained the fire by constructing 35 miles of fire line just 30 hours after it started, at a final size of 24,000 acres. In consuming 270,000 tons of fuel, the fire released 3 trillion Btu's of energy—as much as 90 thunderstorms, or nine times the energy released by the Hiroshima atomic bomb.

Although the Mack Lake Fire is the largest fire recorded on the Huron National Forest since record keeping began in 1911, it is not comparable to the historically "great" firest in the Lake States. Between 1871 and 1918, fires in Michigan, Wisconsin, and Minnesota burned 1 million or more acres in each of six different years and resulted in 2,500 deaths (Plummer 1912, Guthrie 1936). Simard and Blank (1982) found that within the area burned by the Mack Lake Fire, there have probably been five other fires in excess of 10,000 acres since 1820 (one every 28 years including Mack Lake). In 1946, six fires burned 14,300 acres in 1 day under similar weather conditions. Given that fires will continue to occur, and that critical weater conditions will occasionally prevail, there is every reason to expect that some future jack pine fires will escape initial attack. Thus, a case study documentation of the Mack Lake Fire is important not only as a historical account of events but also as a valuable guide for future fire suppression planning.

Trying to understand the behavior of all large fires with individual case studies is like trying to understand a movie by examining individual frames chosen at random. Each fire is only a single observation of a complex process, and many observations are

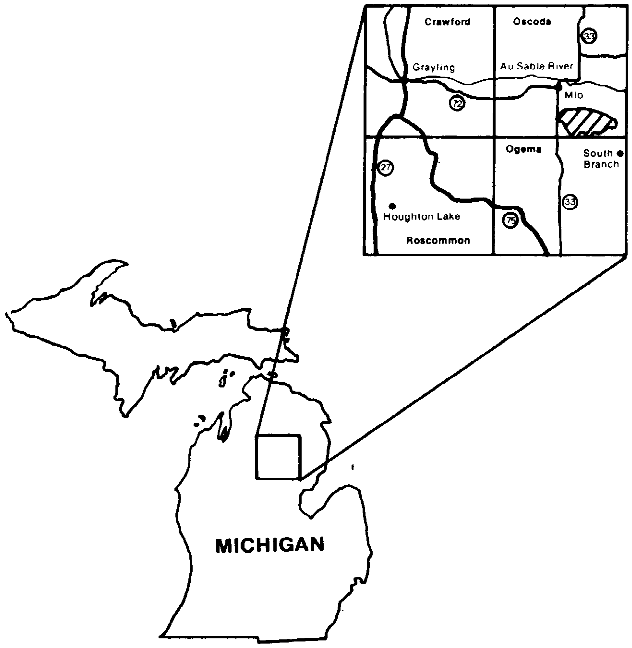

Figure 1.—*Location of the Mack Lake Fire. Cross-hatched area (insert) was burned by the fire.*

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[1] *All times in this paper are Eastern Daylight Savings time, unless otherwise noted.*

needed before patterns begin to emerge. Despite the complexity, however, careful examination of even a single fire can yield insights into the underlying physical processes that control large fire behavior.

METHODS

The authors were assigned to the Mack Lake Fire as a fire behavior analysis team. Because all significant fire activity had stopped 20 hours before we arrived at the fire site (1400 on May 6), the investigation was limited to reconstructing past events. Some important observations could not be obtained (e.g., a light rain precluded meaningful fuel moisture measurement).

Between May 6 and 9, we observed the burned area by aircraft and vehicle. The prescribed fire, escape, and fatality areas were observed in detail. General fuel conditions were assessed and fuel weights sampled to estimate consumption. We took numerous still photographs and examined video tapes and polaroid photographs of the fire along with aerial photos of the burned area. We interviewed members of the burning (and initial attack) crew, the meteorologist-in-charge of the nearby Houghton Lake National Weather Service office, and senior fire management specialists having extensive experience with jack pine crown fires. We examined relevant documents: witness statements (obtained by ourselves and the accident investigation team), local weather records, the Mio Ranger District log, the prescribed burning plan, and documentation of the fire itself.

Although efforts were made to verify all indirect information, portions of this report are based on hearsay evidence. Further, at the time the fire made its major run, personnel were concerned with fire control and not documenting observations. Additionally, the major run occurred while the control organization was reorganizing from initial attack to project fire status (USDA Forest Service 1980). Therefore, few experienced persons observed the fire. Despite these limitations, the authors feel that the following description is a reasonably accurate chronicle of the events that occurred and conditions that preceded the Mack Lake Fire.

During the months that followed the fire, we analyzed additional data. Growth rings from 14 large red pine trees killed by the fire were counted to determine the area's fire history (Simard and Blank 1982). Antecedent meteorological conditions were summarized from district fire weather records and climatological data obtained from the Michigan State Climatologist. We obtained additional fuel loading measurements from burned and adjacent unburned areas. Seed fall and seedling counts were taken to estimate regeneration success. A rain gauge network was installed to monitor postburn precipitation. Finally, we examined unburned tree crown strips in detail to determine possible underlying causes.

THE ENVIRONMENT

Weather

Fire Climate

As a result of the Great Lakes' influence, Lower Michigan has a semimarine climate. The lake influence is lessened at Mio, which is sheltered from Lake Michigan by a higher plateau to the west. Mio has a 1°F higher average maximum temperature, a 2°F cooler average minimum temperature, and an average of 6 inches less annual precipitation than stations 30 to 40 miles to the northwest. The highest temperature in Michigan (112°F) was recorded at Mio on July 13, 1936 (Michigan Weather Service 1974).

Although the average 26.5 inches of precipitation is well distributed throughout the year, twice as much falls in the summer (3 inches per month) as in the winter (1.4 inches per month), with spring and fall in between (2.25 inches per month). Average monthly relative humidity at 1300 is lowest in May (50 percent) and average monthly windspeed peaks at 8.6 mi/h in April. Evaporation during the growing season exceeds precipitation by 45 percent. Although periodic mild droughts occur, extreme severity on the Palmer scale is experienced only 3 percent of the time (Michigan Weather Service 1974).

The most severe fire weather in Michigan normally occurs when the Lake States are on the northwest or back edge of a Hudson Bay, northwest Canadian, or Pacific high pressure area (Schroeder and Buck 1970). Generally, air masses and associated frontal systems move through the region in a southeasterly direction every 3 to 5 days. When a high pressure system persists longer than normal, however, fuels have more time to dry out. The approach of a cold front aggravates the situation by increasing the flow of dry, warm air from the southwest. Consequently, peak fire danger is expected when the Lake States have been under extended high pressure influence just before the passage of a cold front, as happened, for example, prior to the Peshtigo and Great Chicago fires of 1871 (Haines and Kuehnast 1970). Precipitation associated with frontal passage normally ends the period of high fire danger.

The Fire Season

Total precipitation for 1979 recorded at Mio was 27.6 inches—1.2 inches (4 percent) above normal. Precipitation was well distributed throughout the year, with only 2 months (February and September) receiving less than 1.5 inches. Total precipitation from January through April was 5.4 inches—1 inch (16 percent) below normal. The Palmer Drought Index at the time of the fire was −1.17, indicating a slight, but insignificant, soil moisture deficit. We may, therefore, conclude that drought was not an important factor in the Mack Lake Fire.

Winter snowfall was 45.5 inches—15.9 inches (26 percent) below normal. The shortfall was not uniformly distributed throughout the winter. Between October and February, the snowfall was only 49 percent of normal. Because (1) the maximum snow depth was only 11 inches, (2) there were only 14 days with 7 or more inches of snow on the ground, and (3) the maximum single snowfall was only 4 inches, there was minimal fuel bed compaction. Field personnel reported that dead grasses and herbaceous material were standing at the time of the fire rather than lying flat, as is usually the case.

Daily 1300 weather observations and fire-danger ratings for April and the first few days of May at Mio are listed in table 1. Based on the National Fire-Danger Rating System (NFDRS) Burning Index (BI) (Deeming *et al.* 1977), fire danger during the season was either high to extreme (19 days, 53 percent) or low (15 days, 42 percent), with little in between (2 days, 5 percent) (fig. 2). On six occasions, the index jumped from low to high (or vice versa) in a single day. The BI indicates three fire danger peaks in the very high range and one in extreme, with the May 5 peak the third highest during the season.

Synoptic Pattern

The Hudson Bay high pressure area that was to influence Michigan on May 5 first formed over southern Alberta on April 22. On April 29, a cold front on the southeast edge of the high pressure area passed over Michigan, dropping ½ inch of rain at Mio.

By May 1, Michigan was under the influence of the high, which was centered over northern Minnesota. The cold front that was to pass over the Mack Lake Fire appeared off the British Columbia coast. By May 2, the high over Minnesota joined with a second high to the west, placing most of central North America under its influence. Dry air dropped the 1300 relative humidity at Mio to 28 percent and increased the temperature to 75°F. The cold front extended from a low pressure area centered over northern Alberta southward to Los Angeles. It is significant to note that the synoptic pattern over east-central Alberta on May 2 was the same pattern that would move to Michigan on May 5. On May 2, a forest fire in east-central Alberta burned 20,000 acres in the first 5 hours after ignition (Alexander *et al.* 1983).

Table 1.—*1300 fire weather observations and National Fire-Danger Rating System (NFDRS) Burning Index values for Mio, Michigan, for April and May 1980*

Date		Temp.	Relative humidity	Precip.	Windspeed	NFDRS Burning Index
		°F	*Percent*	*Inches*	*mi/h*	*Model Q*
April	1	57	43		7	62
	2	58	21		10	70
	3	43	33		16	54
	4	52	82	0.43	13	0
	5	55	58		15	44
	6	51	71		10	47
	7	55	60	.01	4	37
	8	53	88	.33	4	0
	9	48	80	.52	6	0
	10	38	83	.31	7	0
	11	42	62	.02	4	10
	12	37	91	.31	4	0
	13	37	66		7	31
	14	34	81		9	0
	15	38	91	.53	6	0
	16	37	33	.03	10	52
	17	48	73		8	40
	18	63	30		8	58
	19	69	33		15	80
	20	65	21	.19	5	46
	21	69	19		4	49
	22	78	34		5	54
	23	49	32		15	90
	24	40	68	.03	17	73
	25	57	37		7	58
	26	48	86	.01	7	0
	27	49	87	.01	9	0
	28	47	93		10	0
	29	50	93	.51	4	0
	30	56	82		0	0
May	1	65	57		2	10
	2	75	28		2	32
	3	78	22		7	53
	4	80	19		10	63
	5	80	24		18	79
	6	57	52	.03	2	2

On May 3, the center of the continent was still under the influence of the high. The low moved eastward to northern Saskatchewan and the cold front trailed southwestward to Nevada. On May 4, a flat upper-air pattern persisted over much of the western and north central United States (fig. 3), allowing the

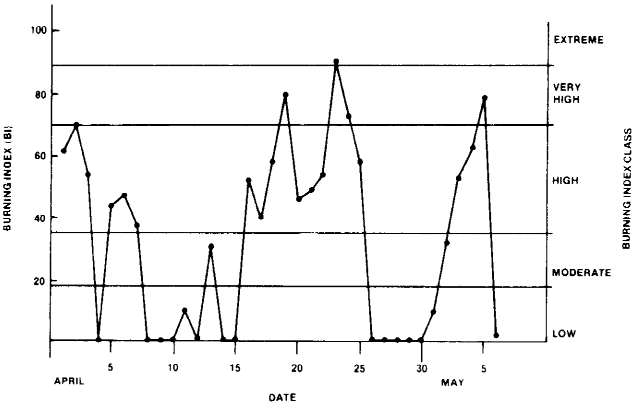

Figure 2.—*National Fire-Danger Rating System Burning Index (fuel model Q) for Mio, Michigan, April and early May 1980.*

Central States to remain under the influence of the weak surface high. It also allowed the slow eastward movement of the cold front, now over the Dakotas. The 1300 relative humidity over Mio dropped to its lowest point (19 percent), temperature rose to 80°F (14° above the average high for May), and winds increased to 10 mi/h.

On the morning of the fire, the 500-millibar chart indicated a high pressure ridge lying over the northern Rockies (fig. 4). A closed low covered eastern Canada with split centers over Newfoundland and Hudson Bay. This produced tightened gradients over the northeastern United States with a northwest flow over the Great Lakes region. The upper air steering caused the surface low pressure area to move southeastward to southern Ontario. Ahead of the weak cold front, relative humidity was low (24 percent) and temperature was unseasonably high (80°F). Windspeed at Mio increased significantly to 15 mi/h, gusting to 25-plus as the front approached. It was during this time that the Mack Lake Fire made its major run. Although the temperature decreased and the humidity increased as the front passed, there was no precipitation. Thus, as the wind direction shifted, the fire continued to burn vigorously and what had been the southeastern flank became a wide front.

By May 6, the 500-millibar chart showed that the Hudson Bay low-pressure center was north of Lake Superior (fig. 5). A shallow trough originating from it lay over Lower Michigan, producing cloudy skies and occasional light showers (0.03 inches). A weak pressure gradient behind the cold front (now over southern Ohio) resulted in light afternoon winds (2 mi/h) which, along with increased humidity (52 percent), moderated burning conditions, allowing the fire to be easily controlled.

The Day of the Fire

Hourly relative humidity and temperature readings were obtained from a hygrothermograph[2] located at Mio (table 2). Hourly windspeed and wind direction for Houghton Lake (35 miles away) on May 5 are also given in table 2. By 1000, the temperature had reached 75°F and relative humidity had dropped below 30 percent, where they remained for the next 5 hours. The maximum temperature (83°F) was 17°F higher than the average maximum for May at Mio (Michigan Weather Service 1974). Minimum relative humidity (21 percent) was well below the May average (51 percent) for Houghton Lake. Climatological data indicate that in the Lake States, relative humidity is lower than 25 percent on fewer than 3 percent of all days.

Between 1000 and 1900, the front moved at an average of 23 mi/h (Falkowski 1981). Until 1400, winds were southwesterly, varying from 5 to 12 mi/h. By 1400, the leading edge of the front passed (fig. 6) and windspeed increased to 15 to 18 mi/h with gusts of 25 to 30 mi/h. Although the wind direction shifted 40° to west-northwest, there was no appreciable change in either temperature or humidity. By 1700, the wind shifted another 40° to north-northwest, accompanied by a slight temperature decrease and humidity increase. The peak gust for the day (30 mi/h from the northwest) occurred at 1728 EDT. After the front passed, the temperature and wind gradually decreased and humidity increased. Although the fire continued to burn during the night, its forward rate of spread gradually decreased to nil by morning.

Schroeder and Buck (1970) state that "Atmospheric stability may either encourage or suppress vertical air motion." The strength of the convective activity above a fire will affect the indraft at the surface and consequent fire intensity. The indraft may also reduce the rate of spread of a fire with a well-developed convection column. Brotak (1976) measured the atmospheric stability associated with 62 major wildfires in the eastern United States. He employed a simple indicator of stability by calculating the temperature difference between the 950- and 850-millibar pressure levels. Most of the fires studied (92 percent) occurred when the lapse rate between these levels was steeper than the dry adiabatic lapse rate (5.5°F per 1,000 feet). He concluded that a temperature difference of at least 11°F between the 950- and 850-millibar levels appears to be associated with major fires.

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[2] *Hygrothermograph readings normally differ slightly from psychrometer readings used to measure weather inputs to the NFDRS (table 1).*

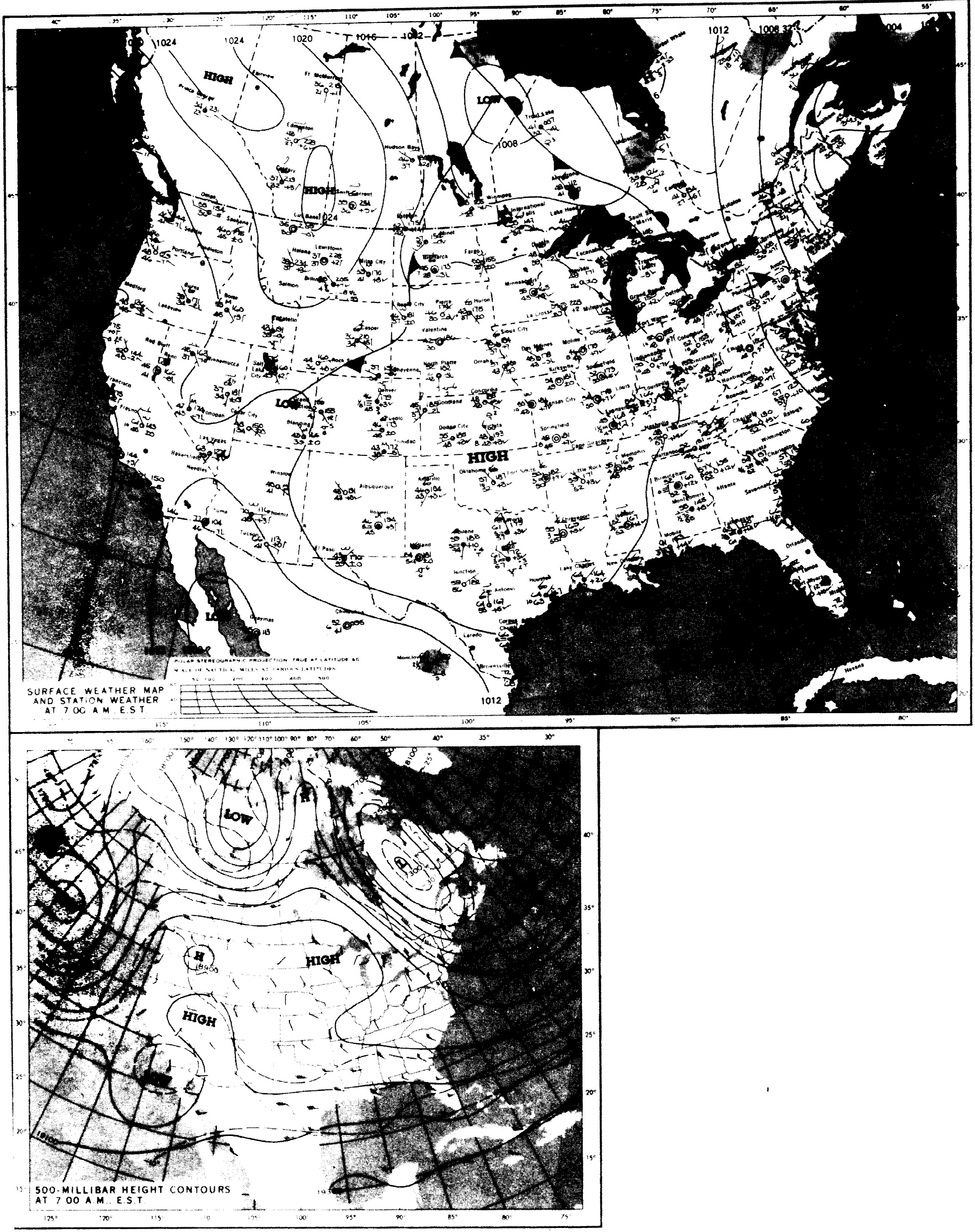


Figure 3.—*Surface weather map and 500-millibar chart for May 4, 1980 (from U.S. Department of Commerce 1980).*

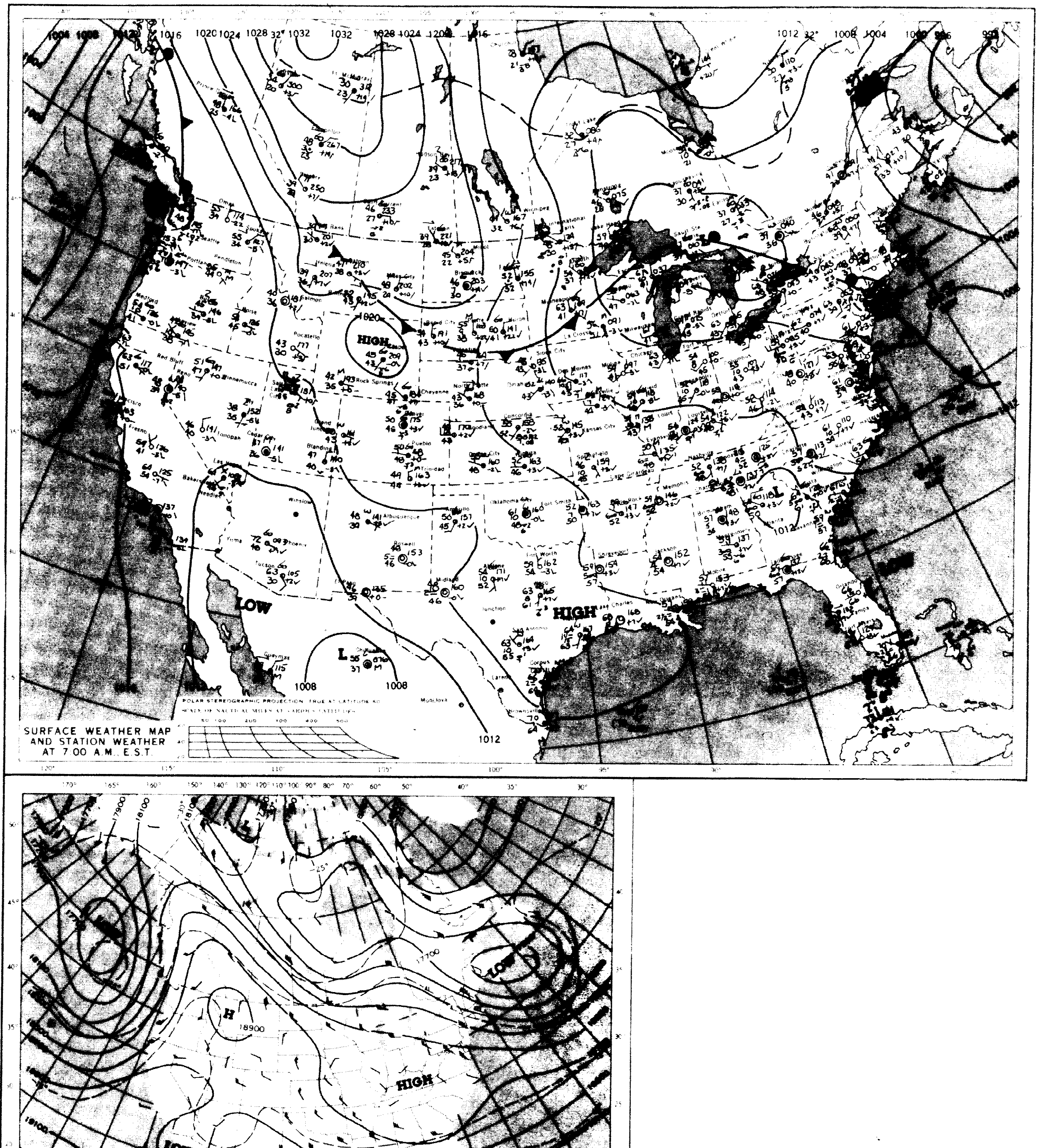
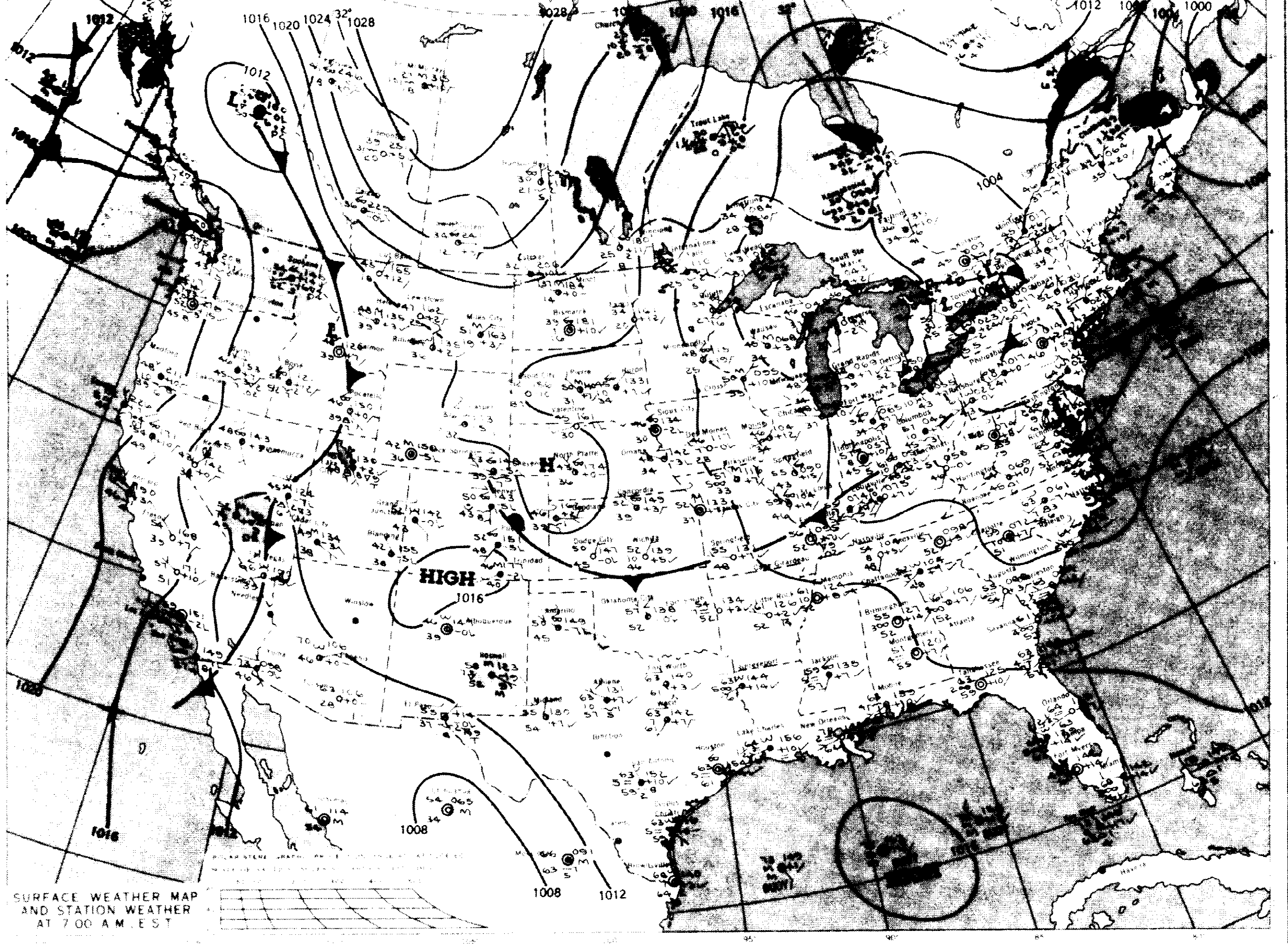
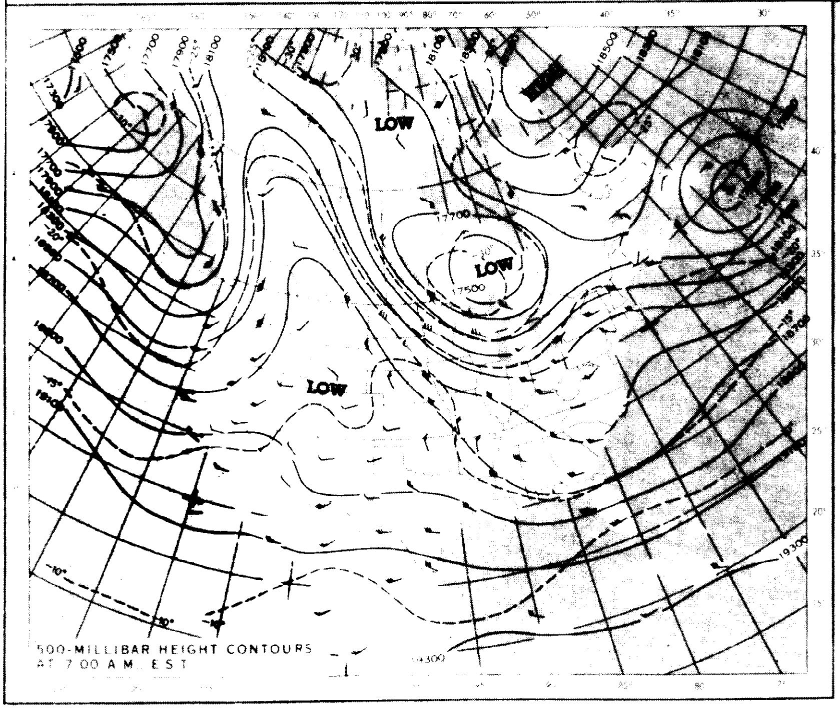


Figure 4.—*Surface weather map and 500-millibar chart for May 5, 1980 (from U.S. Department of Commerce 1980).*



SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.



500-MILLIBAR HEIGHT CONTOURS AT 7:00 A.M. E.S.T.

Figure 5.—*Surface weather map and 500-millibar chart for May 6, 1980 (from U.S. Department of Commerce 1980).*

Table 2.—*Hourly weather data for Mio and Houghton Lake,*[1] *Michigan, May 5, 1980*

Time (EDT)	Element				
	Relative[2] humidity	Temp.[2]	Windspeed	Wind gusts	Wind direction
	Percent	*°F*	*---------mi/h------*		*Degrees*
0800	—	57	5	[3]—	230
0900	80	65	8	—	230
1000	28	75	7	—	270
1100	23	80	12	—	230
1200	21	82	8	—	250
1300	22	83	10	—	250
1400	22	82	15	25	290
1500	26	81	18	28	280
1600	37	77	15	25	290
1700	46	71	17	30	330
1800	55	65	17	28	330
1900	56	60	16	24	330
2000	50	57	13	23	320
2100	51	53	12	23	330
2200	54	52	10	—	330
2300	56	50	10	—	330
2400	60	48	8	—	330

[1] Relative humidity and temperature data are from Mio and wind data are from Houghton Lake—a first-order National Weather Service station located 35 miles southwest of the fire.

[2] Hygrothermograph readings which differ slightly from standard 1300 psychrometer data (table 1).

[3] No data available.

The May 5 morning and evening upper air temperature profiles for Flint, Michigan[3] are similar except for a strong morning surface inversion. Therefore, only the evening observation is presented (fig. 7). The sounding shows a conditionally unstable lapse rate from the surface upward, except for a shallow layer (568 to 588 millibars) that approaches isothermal. The air temperature difference between the 950- and 850-millibar levels exceeded 14°F—3°F above the threshold noted by Brotak (1976). Dewpoint values were low, indicating relatively small amounts of moisture throughout the lower atmosphere. The profile suggests that only small amounts of energy were necessary to overcome existing static stability. Consequently, atmospheric conditions favored convective activity, given the initial energy produced by the fire.

Brotak (1976) also found that low-level jet streams were associated with one out of three major wildfires in the eastern United States. The primary mechanism is thought to be downward transport of momentum by turbulent mixing which increases surface windspeed and gustiness. It is reasonable to hypothesize that low-level jets aggravate an already bad situation resulting from the close proximity of a dry cold front.

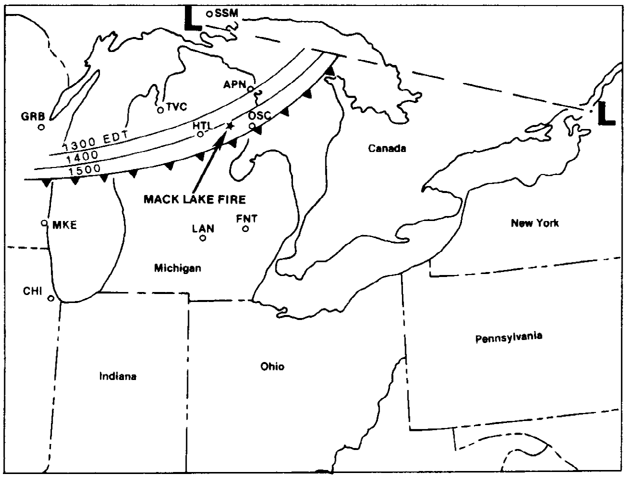


Figure 6.—*Location of the leading edge of the cold front during the afternoon of May 5, 1980.*

Upper level wind information was available from Sault Ste. Marie and Flint, Michigan and Green Bay, Wisconsin. The profiles at 0800 on May 5 show a marked increase in windspeed from the surface to 2,000 feet at Green Bay and Flint, two stations ahead of the cold front (fig. 8). They also show maximum speeds averaging 32 mi/h at 2,000 to 3,000 feet, a decrease to an average of 26 mi/h at 4,000 feet, and little change above 4,000 feet. This is a classic low-level jet profile. The wind profile behind the front

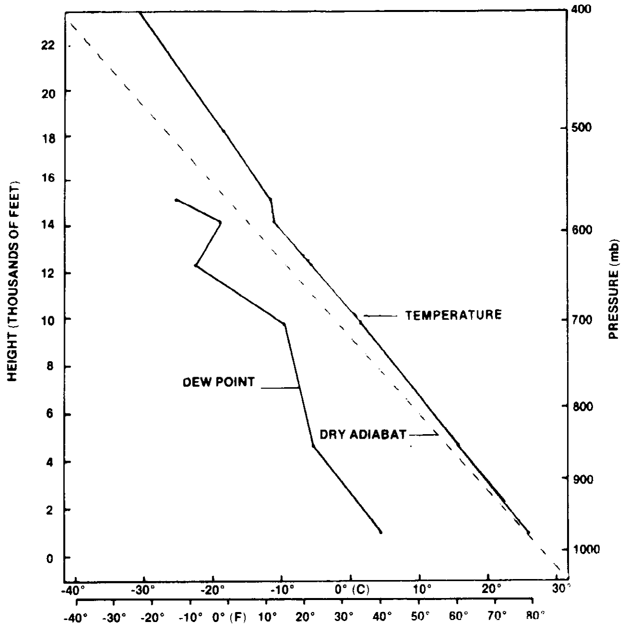


Figure 7.—*Upper air temperature profiles at Flint, Michigan, at 2000 EDT on May 5, 1980.*

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[3] *The closest station to the fire (120 miles away) that reflects air mass conditions over Mio at the time the fire broke out.*

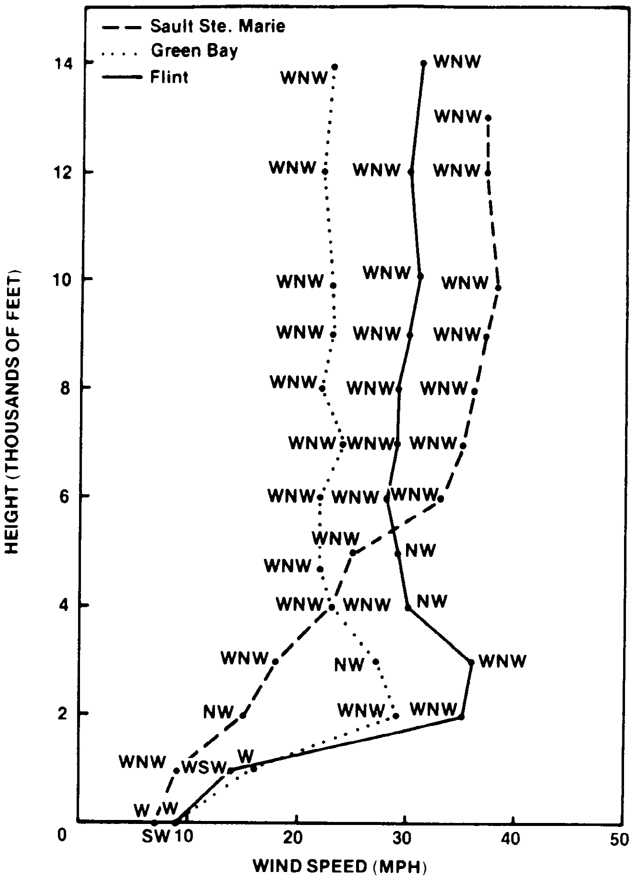

Figure 8.—*Vertical windspeed profiles at Sault Ste. Marie, Michigan; Green Bay, Wisconsin; and Flint, Michigan, at 0800 EDT on May 5, 1980.*

(Sault Ste. Marie) shows generally increasing windspeed with increasing height. This is characteristic of a well-mixed atmosphere which, when coupled with surface cooling after sunset, reduces turbulent mixing and resultant surface winds.

Fuels

General Description

Forty-two percent (10,100 acres) of the total area burned by the Mack Lake Fire had a jack pine (*Pinus banksiana)* overstory (table 3, fig. 9) growing on Grayling sand, which dries rapidly after rain. Part of the area had burned in 1946 and some portions had seeded naturally, while some areas had been planted. The overstory contained mixtures of open areas, reproduction-, sapling-, and pole-sized stands. Much of the latter originated following 1910 to 1913 fires. Part of the area had been prescribed burned in 1964 with subsequent regeneration 5 to 10 feet tall at the time of the Mack Lake Fire. Sixty-two percent of the jack pine was in the pole-size class and 38 percent was in the seedling and sapling class. Overall stand densities ranged from less than 100 stems/acre in open stands to patches of reproduction at densities in excess of 5,000 stems/acre. Pole timber densities generally ranged from 400 to 1,200 stems/acre. Tree heights varied from 20 to 30 feet (4- to 6-inch d.b.h.) to 40 to 60 feet (8- to 10-inch d.b.h.).

Table 3.—*Area burned and fuel consumed on the Mack Lake fire by timber type*

Timber type	Area burned	Percent of total	Fuel consumption
	Acres		*Tons/acre*
Jack pine	10,117	42	9.1[1]
Red pine	3,707	16	10.6[1]
Oak/pine	1,985	8	12.5[2]
Oak/hardwood	2,864	12	14.6
Aspen	3,250	14	14.5
Miscellaneous	320	1	11.2[3]
Private	1,591	7	11.2[3]
Total	23,834	100	11.2[3]

[1] Data from tables 4a and 5a, adjusted downward for 80 percent foliage consumption.

[2] Based on inventory data indicating 50 percent oak, 45 percent red pine, and 5 percent jack pine.

[3] Weighted average of measured fuel types.

Scattered throughout the jack pine area were red pine (*Pinus resinosa*) plantations (3,700 acres) and pine/oak mixtures (2,000 acres). The latter included

Figure 9.—*Typical jack pine stand.*

cutting in the prescribed burn area. From table 4a, an additional 12 tons/acre of litter, duff, and herbaceous material were present, of which 6 tons/acre were consumed. Therefore, the total prefire loading on the prescribed burn site was 32 tons/acre and total consumption was 26 tons/acre.

Total prefire loading for red pine (21 tons/acre) was similar to that for jack pine (table 5a). There was more litter, less duff, and more estimated foliage in the red pine stand. Combined bulk density for red pine litter and duff (2.8 lbs/ft^3), however, was half that for jack pine. Based on three paired plots, total consumption for red pine was 12 tons/acre. Adjusting downward for 80 percent foliage consumption yields an average consumption of 10.6 tons/acre in red pine.

Prefire surface fuel loadings for aspen (22.5 tons/acre) and oak (40 tons/acre) were greater than that for the pines (tables 5b, 5c). The major difference was in the litter and duff layers. Aspen stands contained 60 percent more material (by weight) than the pine stands, and oak stands were three times heavier. Average depth of litter and duff in the aspen stands was 1.9 inches, yielding a bulk density of 5.1 lbs/ft^3. Litter and duff under the oak stand averaged 2.6 inches deep, yielding a bulk density of 7.4 lbs/ft^3. Based on six paired plots, fuel consumption in the aspen and oak stands averaged 14.5 tons/acre.

Table 5a.—*Average fuel loading and consumption for red pine stands (8.0-inch d.b.h., 143 ft^2/acre basal area)*

	Before	After	Consumed
	---------Tons/acre---------		
Shrubs, herbaceous	0.2	0.0	0.2
Litter	5.3	2.7	2.6
Duff	4.7	3.0	1.7
Wood[1]	4.6	3.3	1.3
Foliage[2]	6.0	.0	6.0
Total	20.8	9.0	11.8

[1]Average for all species (12 samples).
[2]Based on Brown's (1965) equation (not including branchwood).

Table 5b.—*Average fuel loading and consumption for quaking aspen (7.3-inch d.b.h., 80 ft^2/acre basal area)*

	Before	After	Consumed
	---------Tons/acre---------		
Shrubs, herbaceous	0.3	0.0	0.3
Litter	3.9	1.0	2.9
Duff	13.7	3.7	10.0
Wood[1]	4.6	3.3	1.3
Total	22.5	8.0	14.5

[1]Average for all species (12 samples).

Fuel loading in a typical sedge area was 3.5 tons/acre, of which 2.6 tons/acre were consumed (table 5d). This was the lowest fuel loading found on the fire site. There is no estimate available of how much of the total area burned was in this fuel type.

Fuel consumption by timber type is summarized in table 3. A weighted average of 11.2 tons/acre of fuel was consumed. Multiplying by the total area burned yields an estimated 267,000 tons of fuel consumed by the Mack Lake Fire.

Fuel Moisture

Surface fuels.—Fuel moisture data were not available for the day of the fire. Two fuel moisture stick observations at 1300 EDT were available from Mio—USDA Forest Service (11 percent) and Michigan Department of Natural Resources (8 percent). Using Simard's (1968) equation and the 1400 observations at Mio (table 2), equilibrium moisture content was determined to be 5 percent. The National Fire-Danger Rating System 1-hour time lag fuel moisture prediction was 6 percent, and the Canadian Fire Weather Index fine fuel moisture code estimate was 7 percent. It is reasonable to assume, therefore, that the primary cured fuels involved in the fire had moisture contents between 5 and 10 percent.

Fuel moisture samples were taken on May 6, 2 hours after a trace of rain had fallen. Lichen and

Table 5c.—*Average fuel loading and consumption for black oak stands (7.5-inch d.b.h., 95 ft^2/acre basal area)*

	Before	After	Consumed
	---------Tons/acre---------		
Shrubs, herbaceous	0.2	0.0	0.2
Litter	8.9	3.5	5.4
Duff	26.6	18.9	7.7
Wood[1]	4.6	3.3	1.3
Total	40.3	25.7	14.6

[1]Average for all species (12 samples).

Table 5d.—*Average fuel loading and consumption for sedge areas*

	Before	After	Consumed
	---------Tons/acre---------		
Shrubs, herbaceous	0.5	0.2	0.3
Litter	.1	.0	.1
Duff	2.3	.7	1.6
Wood	.6	.0	.6
Total	3.5	.9	2.6

bracken fern had moisture contents of 20 and 19 percent, respectively. Clearly they would have been lower on May 5. Blueberry stems had a 67-percent moisture content. Although this is lower than reported minimum values (105 percent) during the growing season in Michigan (Loomis and Blank 1981), our sample included only woody stems, whereas previous data included foliage as well as stems.

Foliage moisture.—Van Wagner (1967) found a spring dip in jack pine foliar moisture starting 4 to 6 weeks prior to flushing (fig. 13). Average jack pine twig and foliage moisture content measured 2 to 5 days after the Mack Lake Fire was 120 percent, with a range of 100 to 135 percent (10 samples). Although this is higher than the minimum noted by Van Wagner (100 percent), it is lower than the average moisture content throughout the rest of the year.

Stashko and McQueen (1974) state that 1 or 2 days of high wind and low relative humidity can reduce foliar moisture content by as much as 20 percent. Data from Grieve and Such (1977) indicate short-term jack pine foliar moisture content variations on the order of 10 to 40 percent, which they attribute to sampling error. It is possible, however, that on porous soils such as Grayling sand, foliar moisture stress can be induced on dry, windy days. Therefore, it is possible that on the day of the fire, foliar moisture could have been 10 to 15 percent lower than our measurements indicate.

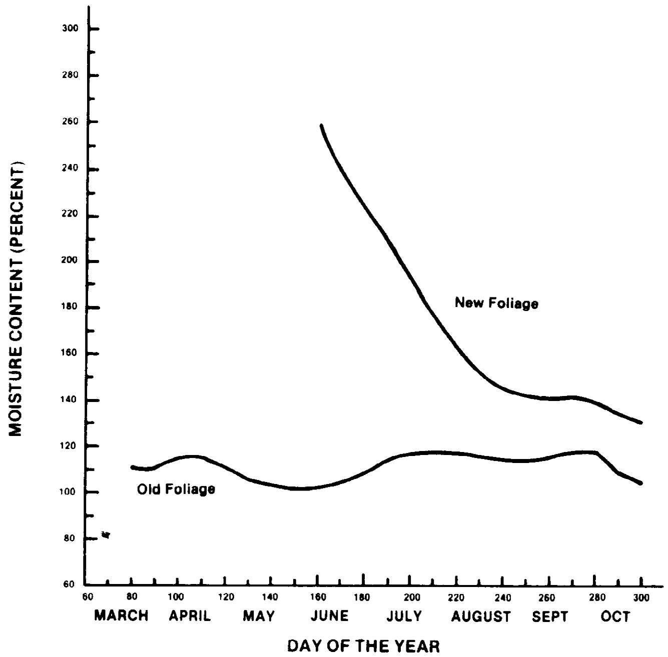

Figure 13.—*Annual trend in jack pine foliar moisture at Petawawa, Ontario (from Van Wagner 1967).*

Van Wagner (1974a) states that the difference between spring and summer foliar moisture can double the rate of crown fire spread. Grieve and Such (1977) indicate that jack pine crown fires are likely at moisture contents below 135 percent. They note, however, that high jack pine foliar moisture coincides with green surface vegetation, and low foliar moisture coincides with cured surface vegetation. They conclude that several factors are involved in crown fire occurrence, and it is not possible to determine the specific role of each.

Topography

The Mack Lake Fire burned on the eastern edge of the Lower Michigan highlands, which are about 75 miles across. Average elevation is 1,250 feet (570 feet above Lake Michigan) and maximum elevations range from 1,500 to 1,700 feet. The fire burned on a plateau approximately 14 miles wide, extending 12 miles beyond the eastern edge of the highlands. The top of the plateau is a very shallow basin approximately 5 miles across, draining into Mack Lake. In a north-south cross section, the valley rises from 1,170 feet at Mack Lake to an average of 1,300 feet (maximum 1,470 feet) along the edges of the plateau. Going from west to east, the basin is nearly flat, rising from 1,150 feet along Big Creek to 1,250 feet.

The fire made its major run in a flat portion of a basin where many areas have elevational differences of less than 10 feet in a mile. The edges of the basin are rolling, with slopes of 20 to 30 percent and elevational differences of 30 to 70 feet. These changes no doubt resulted in local topographic effects, such as increased upslope rates of spread, greater fire intensity on southern exposures, and increased turbulence and spotting. They did not, however, significantly affect the overall behavior of the fire.

The basin has roads along a majority of section lines and secondary roads within many sections, breaking the area into square mile or smaller blocks. As with topographic effects, roads probably influenced local fire behavior. They were ineffective, however, in stopping or significantly slowing the fire (upper-left photo, back cover). The initial escape resulted from spots that jumped more than 200 feet across a two-lane highway (fig. 14). There are no significant wetlands or marshes in the basin which might have impeded the fire's progress. We therefore conclude that there were no topographic barriers to the spread of the fire, once it became established.

Figure 14.—*View from probable point of spotting to point of ignition, east of Highway 33 (50 feet to left of highway sign).*

FIRE PHENOMENA

Fire Chronology

An aerial photomosaic of the Mack Lake Fire (fig. 15) indicates the approximate position of the fire front at each time in the following chronology.

Between 1022 and 1026 (May 5)*[4]

The Crane Lake prescribed burn (fig. 16) was ignited. No unusual fire activity was noted for the first 45 minutes. The piled slash burned vigorously, with flame lengths of 10 to 15 feet, but flame lengths between the piles were only 6 to 12 inches (fig. 17). Although some spot fires crossed the control line, they were easily contained and firing resumed. During the next 45 minutes, three more spot fires occurred, one of which required a double plow line to contain.

*At 1206**

The prescribed fire spotted into standing jack pine timber adjacent to and upslope (26 percent) of the prescribed fire area (fig. 18). Being on the windward edge of a hill (fig. 19), the stand was exposed to the wind; this, coupled with heavier fuel loadings, including bracken fern, resulted in a much faster spread rate than had been experienced in the prescribed burn area. The fire spread eastward toward Highway 33, 675 feet away, with scorch heights ranging from 1 to 6 feet. A tractor/plow attempted to contain the spot between the prescribed burn and the highway (fig. 19).

*Between 1215 and 1230**

The fire spotted across Highway 33. This may have resulted from the burning slash piles or from the spot fire torching a small group of trees at the edge of the highway. The first spot across the highway had scorch heights of 2 to 4 feet and was contained at three-fourths of an acre. A second spot (225 feet from the fire, fig. 14), first noted at 15 feet in diameter, was attacked by a tractor/plow within 4 minutes of detection. At this time, considerable smoke was reported across Highway 33, hampering visibility. The spot torched some trees within 25 feet of the point of origin and then dropped to the ground in a narrow strip of mature jack pine. The fire boss recalled a sudden increase in windspeed at this time. The fire entered an extensive sapling-sized jack pine stand and crowned within 100 feet of the point of origin (fig. 20). Surface fuel at the point of crowning was primarily sedge combined with pine litter and duff (table 5d).

Between 1232 and 1245**

The fire front was ½ mile east of Highway 33, and spotting at least ¼ mile ahead (fig. 21). The tractor/plow was now working the north flank. An armored tanker started following and eventually passed the tractor/plow. The tractor/plow operator was trapped shortly after being passed by the tanker. The tanker crew reported that they never saw the head of the fire, despite traveling at 4 to 6 mi/h while spraying water. Although the fire was on the ground close to where the crew was working (flame heights of 1 to 2 feet), torching and crowning were visible 100 to 200 feet inside the line (flame heights of 30 to 40 feet). The fire was described by the crew as turbulent with "heavy, roiling black smoke." The wind shifted direction several times and the fire frequently fingered in a northerly direction. The fire was reported to be "...very sensitive to wind. A slight change in wind direction and a hot flank immediately turned into a crowning head." The changes were described as instantaneous. In the words of the tanker operator, "I'm sure that the main head of the fire was heading east, but the flanks were acting like the head of many fires I've been on."

Wind data from Houghton Lake and patterns of unburned tree crowns give no indications of short

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[4] *District log book entries are noted by an asterisk. Other times are estimates made by observers.*

Figure 16.—*Aerial view (looking north) of Crane Lake prescribed burning unit. Ignition began at intersection of north-south fire line and east-west skid trail (right-center). Firing proceeded northward (note unburned area east of fire line) and around island of standing timber. Escape (west of Highway 33) was into standing timber just beyond island.*

gure 17.—*Early stage of prescribed fire. Note contrast in fire intensity between piles and open areas. Photo courtesy Huron-Manistee National Forest, Mio Ranger District.*

Figure 18.—*View of standing timber into which initial escape occurred (top of hill in background).*

Figure 19.—*Plow line that failed to hold initial escape. Note openness of stand into which fire spotted.*

duration shifts of the ambient wind, implying local fire-induced turbulence. Subsequent examination of the area strongly indicated that a horizontal roll vortex (see page 24) formed along the flank where the crew was working (fig. 22). The crew was working on the north side of an unburned crown strip. The crew's description of fire conditions (1- to 2-foot flame

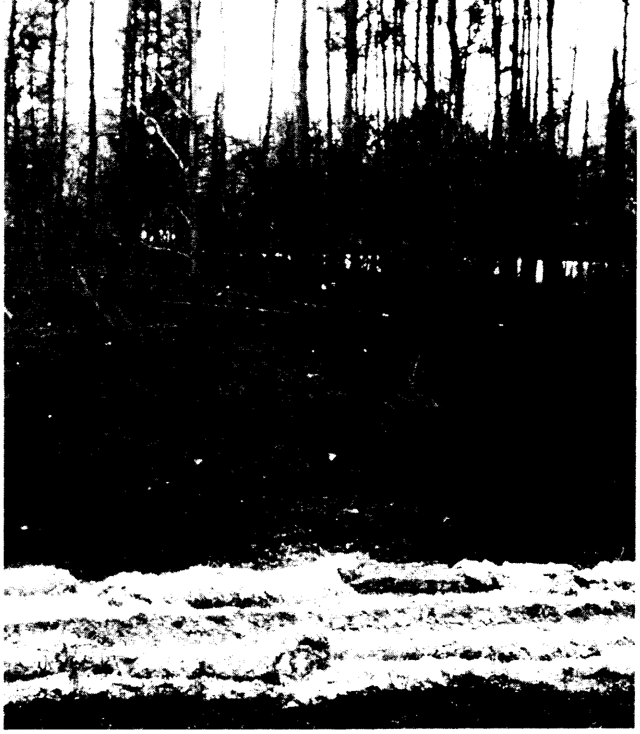

Figure 20.—*View of escape area (east of Highway 33, in background). Fire crowned in sapling-sized timber in foreground. Note plowline in foreground.*

Figure 21.—*Two spot fires along north flank, 1/4 mile ahead of main fire front. (Second spot is behind trees at left.) Photo courtesy of Huron-Manistee National Forest, Mio Ranger District.*

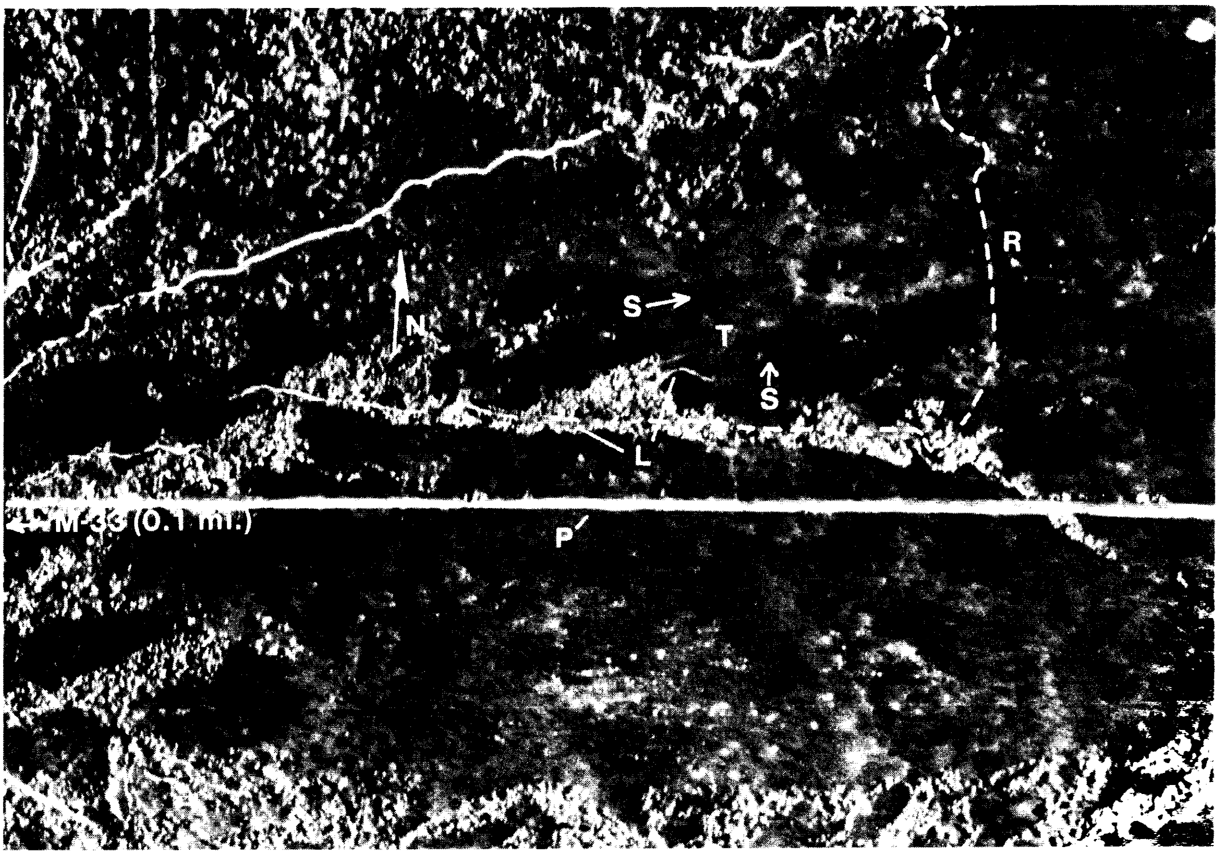

Figure 22.—*Aerial photograph of the fatality area. L = tractor plow line, (three subsequent plow lines can be seen in the northeast quadrant of the photo), N = north, P = power line and gravel road, R = approximate route of leading tanker unit, S = fire spread direction, and T = final location of tractor/plow unit. Photo courtesy Huron-Manistee National Forest.*

heights and extreme turbulence) is consistent with a strong downdraft carrying firebrands and igniting a line of fire, along which they were working (see fig. 26). Their description of 30 to 40 foot flame heights and crowning 100 to 200 feet further inside the burning area is consistent with a vortex updraft. The evidence of a northward moving crown fire approximately 100 feet east of the point where the tractor abruptly turned northward is consistent with a local north wind resulting from the downdraft portion of a vortex. There is also evidence of an eastward moving crown fire (originating from spots which crossed the line behind the tractor) approximately 200 feet north of the tractor's final position. Once established, the latter crown fire was presumably beyond the influence of the vortex and responded to ambient winds. The tractor/plow and operator were trapped between the two fires while the tanker (approximately 100 yards ahead) was able to turn northward and escape.

Because other scenarios could be reasonably consistent with the physical evidence, we cannot prove that our hypothesis is what actually transpired. However, all other possibilities we considered do not appear to agree with the physical evidence as well as that postulated here. Therefore, although we have described what, in our opinion, is the most likely sequence of events, further research on the formation of horizontal roll vortices will be needed to confirm or refute our hypotheses.

*At 1310**

The fire crossed County Road 489 (1½ miles east of the last reported position). It was approaching the village of Mack Lake, which had been evacuated. Photographs (cover) indicate flame heights of twice the height of the trees (20 to 30 feet). The fire boss reported that "a wall of fire" was approaching the village. He was "impressed with its consistency." He reported flame heights 20 to 30 feet above the trees. These observations suggest flame heights ranging from 40 to 60 feet (back cover—bottom). The fire was still spotting at least ¼ mile ahead (spot on edge of lake—front cover photo).

*At 1325**

The fire had passed through the village of Mack Lake. Forty-four homes and cottages (about one out of three) were destroyed (fig. 23). Although a study was not conducted, a general impression is that homes with mowed lawns and some distance between them and the jack pine forest survived. Those in minimal clearings with natural vegetation and/or with firewood piled adjacent to the house did not. This is consistent with findings after other large wildfires (Fischer and Books 1977).

By this time, the fire was ½ mile east of Forest Service Road 4146 (1½ miles east of the 1310 position). At about this time, a second report indicated that the fire had spread along County Road 604 from Forest Service Road 4458 to 4460 (2 miles) in 15 minutes. These observations indicate spread rates of 6 to 8 mi/h—the fastest reported spread rates during the fire's run. One observer remarked that it was "notably warmer" when the fire was still ½ mile away. The flames were described as similar to movies of the sun, with isolated balls of flame in the air. Another observer noted that, "Following the crown fire, unburned ground fuels ignited and burned in all directions." This could imply that during the major run, the crown fire was independent of the ground fire. This observation could also describe a crown fire which gained momentum from spot fires and raced ahead of the surface fire for some distance before dropping back to the ground. Surface fuels ignite from material that drops from the burning overstory. Such "semi-independent" crown fire behavior was reported on the Gaston Fire in South Carolina.[5] It is in the areas burned during this period that the largest unbroken areas of crown fire are found.

At 1530

The fire was at the junction of County Road 489 and Forest Service Road 4461 (3 miles east of the 1325 position). The wind had shifted to west-northwest and the fire was now spreading east-southeast on a wide front. Although the fire was still spreading rapidly, the rate of advance had slowed slightly. The three back cover photographs were taken during this interval.

At 1600

The fire was ½ mile east of Forest Service Road 4527 along County Road 604 (4 miles east of the 1325 position). This sector of the fire had passed from jack pine to hardwoods and was burning on the ground. The northeast corner of the fire had become a flank, and control actions were becoming effective along this portion of the perimeter. Most of the front, however, was still actively crowning in jack pine.

*At 1825**

The fire was reported to be 4 to 5 miles northwest of the community of South Branch. Since the final perimeter was 5 miles northwest of South Branch, the fire was perhaps 5½ miles away at this time. This is 1½ miles from the 1600 position. The wind had further shifted to north-northwest and the fire was now spreading south-southeast. What had been the southern flank was now the fire front. Although most of the fuel burned during this period was jack pine, the crown fire appears to have weakened. A random sample of an aerial photomosaic (fig. 15) indicates that in the area burned during this period, an average of 30 percent of the crown foliage was not consumed. Since both wind and fuels remained constant, we presume that this change largely reflected increased relative humidity which, by 1800, had risen to 55 percent. During this period, video tapes of the fire taken along Highway 33 (at the rear and flank) show backfire flame heights of 12 to 18 inches in jack pine surface fuels. Flame heights in 2- to 2½-foot-deep fresh slash were 5 to 10 feet, however. Thus, although the fire had slowed, it still presented control problems, particularly where fuel loadings were high. High crown scorch heights of isolated red and jack pine trees in the hardwood areas attest to the fact that even though the fire burned on the ground, it was still moderately intense.

By 2400

The fire spread an additional ½ mile to the east and south, primarily on the ground, through hardwood stands. Mechanized equipment could now work effectively on all sections of the perimeter.

By 0600 (May 6)

The fire had essentially stopped spreading. Suppression forces had constructed 15 miles of control line.

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[5] *Wade, Dale. Research Forester. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Macon, GA; personal communication.*

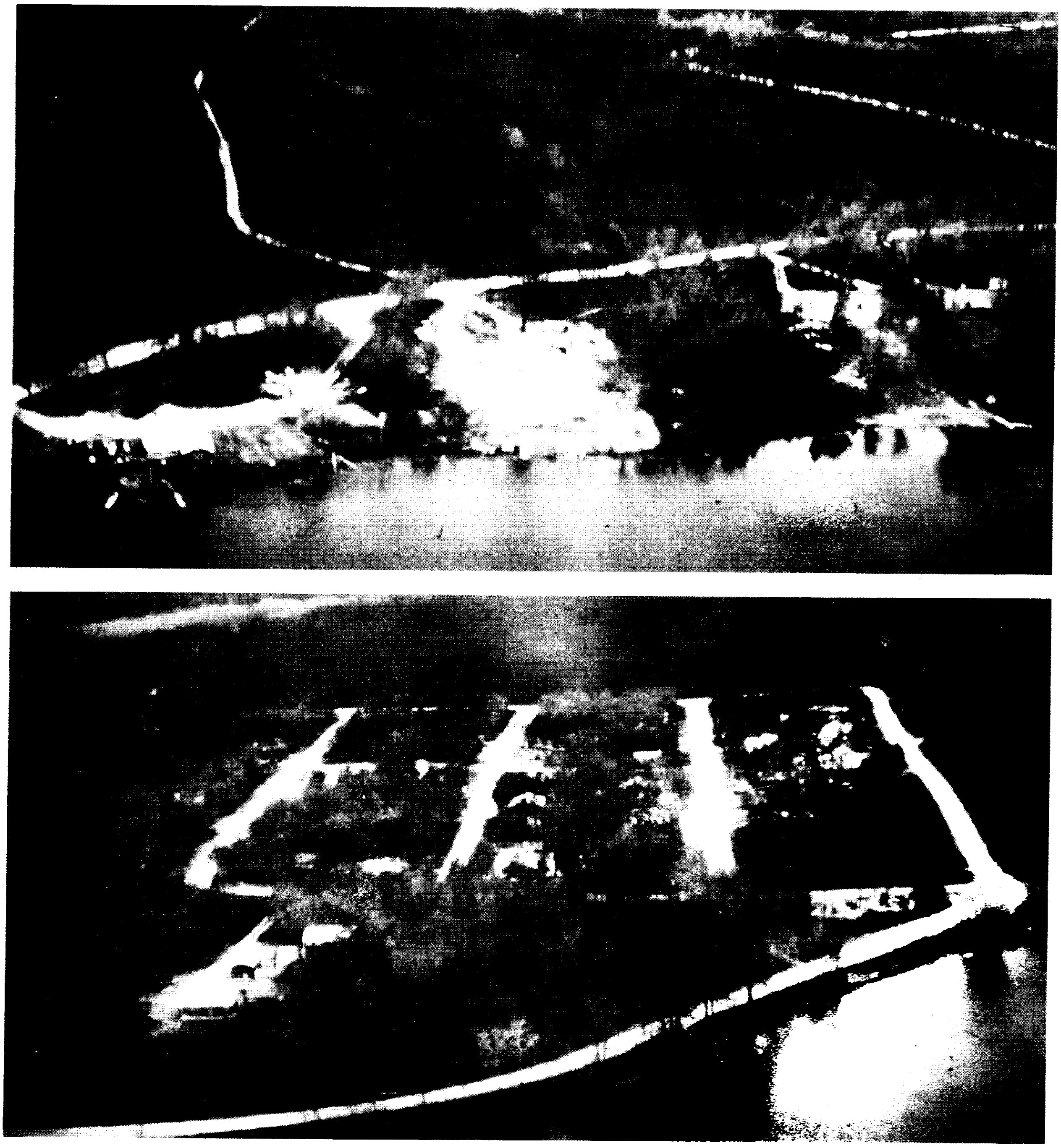

Figure 23.—*Four homes at Mack Lake—two destroyed and two saved. The two homes on the left are shown on the front cover just before the fire passed (top). The village of Mack Lake after the fire. About one structure in three was destroyed (bottom).*

By 1800

The fire was contained at 23,830 acres, with 35 miles of control line. There was no significant increase in acreage burned during the day. Little difficulty was experienced in burning out from plowed control lines.

It is important to note that during the 4 days following passage of the same dry cold front that affected the Mack Lake Fire, a forest fire in Alberta increased from 20,000 to 150,000 acres in size (Alexander *et al.* 1983). Therefore, it is reasonable to assume that if the Mack Lake Fire had not run out of jack pine, the total area burned would have been significantly larger.

Fire Behavior

We calculated or estimated 12 parameters describing the behavior of the Mack Lake Fire. They are divided into two categories: size (table 6a) and energy release (table 6b). The first group includes rate of spread, length of head, length of perimeter, rate of perimeter growth, area, and rate of area growth. The second group includes fireline intensity, frontal energy release rate, total energy release rate, total energy released, fuel consumption, and total fuel consumed. Flame length data for the fire were not available. Although a few flame heights were reported or could be scaled from photographs, the information was too sketchy to include in table 6. Each parameter was determined for eight intervals during the fire's history to coincide with the fire chronology. When the specific endpoints of an interval are no known (e.g., between 1022 and 1026), the averag denotes the beginning or end of the fire behavio interval (e.g., 1024). The two intervals 1325-1530-1600 were combined into one in table 6. Computational techniques are described in Appendix I.

Spread and Intensity

During its major run (1230 to 1600) the Mack Lake Fire spread 7.5 miles at an average rate of 2.1 mi/h. This rate is similar to those of other major fires. The Sundance Fire in Idaho spread 15.5 miles in 9 hours (1.7 mi/h, Anderson 1968), and the Air Force Bomb Range Fire in North Carolina covered 12 miles in 7.25 hours (1.7 mi/h, Wade and Ward 1973). Red Lake 31 in Ontario spread 10 miles in 5 hours (2 mi/h, Stocks 1975), the Badoura Fire in Minnesota spread

Table 6a.—*Mack Lake Fire behavior (size)*

Time	Duration	Rate of spread[1]		Length of head[2]	Length of perimeter[2]	Rate of perimeter growth[1]	Area[2]	Rate of area growth[1]
	h:min	*mi/h*	*ft/sec*	*mi*	*mi*	*mi/h*	*acres*	*acres/hour*
1024–1206	1:42	—	—	—	0.9	—	20	—
1206–1222	0:16	0.45	0.66	0.06	1.3	1.5	23	11
1222–1238	0:16	1.9	2.8	.25	2.2	4.6	80	300
1238–1310	0:32	2.8	4.1	1.0	6.5	7.0	1,000	1,700
1310–1325	0:15	[3]7.0	[3]10.3	1.5	10.0	14.0	3,000	8,000
1325–1600	2:35	1.5	2.2	3.5	20.0	3.9	9,000	2,300
1600–1825	2:25	.6	.8	6.5	24.0	1.4	20,000	4,000
1825–2400	5:35	.09	.13	7.0	[4]34.0	[5].25	[6]23,000	550

[1] Average for the period.
[2] At the end of the period.
[3] Average of two observations.
[4] Based on a final perimeter of 35 miles.
[5] Based on what the calculated perimeter would have been (25.4 miles).
[6] Based on a final size of 23,830 acres.

Table 6b.—*Mack Lake Fire behavior (energy release)*

Time	Fireline intensity	Frontal energy release rate	Total energy release rate	Total energy released	Fuel consumption	Total fuel consumed
	Btu/ft/sec	*Btu/sec*[1]	*Btu/sec*	*Btu*	*Tons/sec*	*Tons*
1024–1206	—	—	1.15×10^6	6.24×10^9	0.09	520
1206–1222	[2]1,350	2.14×10^5	2.74×10^5	2.63×10^8	.02	20
1222–1238	8,100	6.61×10^6	7.56×10^6	7.26×10^9	.63	600
1238–1310	11,800	3.92×10^7	6.10×10^7	1.18×10^{11}	5.1	9,770
1310–1325	[3]29,700	1.98×10^8	2.83×10^8	2.55×10^{11}	23.5	21,230
1325–1600	6,300	8.38×10^7	8.22×10^7	7.64×10^{11}	6.8	63,700
1600–1825	2,300	6.09×10^7	1.62×10^8	1.40×10^{12}	12.6	115,500
1825–2400	[4]530	1.89×10^7	3.39×10^7	6.82×10^{11}	2.8	[5]55,920
Total				3.32×10^{12}		267,260

[1] Based on average head length during period: (final + initial)/2.
[2] Foliage not consumed.
[3] Average of two observations.
[4] Fire burned in hardwoods during this period.
[5] Based on a final size of 23,830 acres.

7.5 miles in 4.75 hours (1.6 mi/h, Minnesota Department of Conservation 1959), and fire DND-4-80 in Alberta spread 11 miles in 5 hours (22 mi/h, Alexander *et al.* 1983). Although 2 mi/h is an impressive sustained run, faster sustained rates, although rare, have occasionally been recorded: the Lesser Slave Lake Fire in Alberta (4 mi/h for 10 hours, Kiil and Grigel 1969), the Mullen Fire in Nebraska (6 mi/h for 5 hours),[6] the Big Scrub Fire in Florida (6 mi/h for 3 hours, Anderson, in press). The peak rates of spread for the Mack Lake Fire (6 to 8 mi/h) equal the peaks for the Sundance Fire and the Badoura Fire. Faster peak rates of spread could not be found in the literature.

The fast spread rate of the Mack Lake Fire resulted from three factors: relative humidity averaging 23 percent, windspeed averaging 15 mi/h and gusting to 30 mi/h, and dense pole-sized jack pine. Between 1600 and 1800, relative humidity rose from 37 to 55 percent. At the same time, the fire moved from jack pine into hardwoods. Both factors contributed to the significant reduction in rate of spread during the evening hours (0.6 mi/h).

During its major run, the Mack Lake Fire had an average fireline intensity of 8,800 Btu/ft/sec. Given the variability associated with estimating fire intensity, this is similar to the averages for Red Lake 31 (8,500 Btu/ft/sec), the Sundance Fire (7,300 Btu/ft/sec), and the Bomb Range Fire (6,000 Btu/ft/sec). Note, however, that intensity at Mack Lake is averaged over only 3.5 hours, compared with 5 to 9 hours for the other fires. Although the Lesser Slave Lake Fire had a reported average intensity of 25,000 Btu/ft/sec, duff burn depths of up to 6 inches were also reported. Because a significant portion of this material would have been consumed after the fire front passed, the Slave Lake intensity is not comparable to that of the Mack Lake Fire. Peak fireline intensity (average of two 15-minute observations) for the Mack Lake Fire was 29,700 Btu/ft/sec. This approximates what some authorities consider an upper intensity limit for a moving crown fire—30,000 Btu/ft/sec (Byram 1959). The maximum 1-hour average fireline intensity (1225 to 1325) for the Mack Lake Fire was 15,500 Btu/ft/sec. This is less than the maximum 1-hour average for the Sundance Fire (22,500 Btu/ft/sec) and the Bomb Range Fire (18,100 Btu/ft/sec).

Observed fire behavior was compared with predictions from the Albini (1976) fire behavior models. Model inputs were: effective windspeed, 15 mph; slope, 0 percent; dead fuel moisture, 7 percent; and live fuel moisture, 100 percent. During the initial escape west of Highway 33 (1206 to 1222) the fire burned on the ground, under a closed jack pine canopy. This group of trees was about 3 acres in size and exposed to the wind on three sides. Model 2 (open timber, grass understory) yielded a 0.9-mi/h rate of spread, an 8-foot flame length, and a 500-Btu/ft/sec intensity. Model 10 (closed timber, litter, understory) yielded a 0.2-mi/h rate of spread, a 6-foot flame length, and a 300 Btu/ft/sec intensity. Because the stand might best be described as partially open, the fact that the observed rate of spread (0.45 mi/h) lies between the two predictions seems reasonable.

That the models underpredicted calculated intensity (1,350 Btu/ft/sec) is not as significant as it might appear. First, predictions are well beyond the limit of manual control (100 Btu/ft/sec) and, in the case of model 2, approaching the limit where spotting would be expected to present serious control problems for mechanical equipment (600 Btu/ft/sec, Albini 1976). Second, we determined that 7.3 tons of surface fuel per acre were consumed, and we assumed that it was all consumed by the fire front. Although this assumption is reasonable for the Mack Lake Fire, some undeterminable portion of the material was no doubt consumed after the flaming front passed. Thus, actual fireline intensity was somewhat less than indicated in table 6b. Finally, fuel model 2 incorporates only 2.5 tons/acre of material likely to be consumed by the fire front, and fuel model 10 includes 3.3 tons/acre. Clearly, doubling or tripling fuel loading significantly increases intensity.

Once a fire crowns, the timber understory models no longer apply. The closest approximation to a jack pine crown fire is obtained with model 4 (chaparral, 6 feet). This model predicted a spread rate of 1.6 mi/h, 24-foot flame lengths, and a fireline intensity of 6,000 Btu/ft/sec. Considering the apparent differences between jack pine and chaparral, this is a surprisingly good prediction of what happened. The higher loading of 1- and 10-hour and live fuels in the chaparral model (14 tons/acre) relative to jack pine is offset by a tenfold increase in foliage bulk density (0.04 lbs/ft^3, Albini 1976). Based on the relative magnitude of the differences, it is reasonable to assume that the much lower bulk density of jack pine foliage will predominate, resulting in faster spread rates and higher intensities for jack pine crown fires than are predicted by the chaparral model. Note,

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[6] *Anderson, Hal. Research Forester. U.S. Department of Agriculture, Forest Service, Northern Forest Fire Laboratory, Missoula, MT; personal communication.*

Table 7.—*Wind field and convection column energy balance for the Mack Lake Fire*

		P_w[1]					Altitude where $P_f = P_w$
		Altitude above surface (ft)					
Interval	P_f[1]	0	1,000	2,000	3,000	4,000	
1206–1222	12	2	9	147	156	86	1,100
1222–1238	57	1	6	129	138	74	1,500
1238–1310	85	1	5	119	127	67	1,800
1310–1325	208	0	1	79	85	41	—
1325–1600	45	[2]9	[2]48	134	143	78	[2]900
1600–1825	16	[2]11	[2]54	146	155	86	[2]200

[1] ft-lb/sec/ft^2.

[2] Based on a surface windspeed of 15 mi/h after 1400 (table 2) and assuming a linear increase to 2,000 feet.

Although even a ¼-mile-wide fuel break might not be an effective fire barrier under such conditions, it could yield several fire suppression benefits, particularly if composed of less flammable hardwood species. It could reduce rate of spread and intensity to suppressible levels and provide a relatively safe area from which to make a stand. In some areas, the effective width of a break could be increased by backfiring. Given typical spotting distances, however, even wide fuel breaks would have to be coupled with extensive downwind patrolling to insure a reasonable chance of holding a crown fire.

Horizontal Roll Vortices

An important characteristic of the Mack Lake Fire is the numerous strips of unburned (but generally scorched) tree crowns (fig. 15). Wade and Ward (1973) noted similar unburned crown patterns on the Air Force Bomb Range Fire and the Exotic Dancer Fire in South Carolina. They summarized existing hypotheses about possible causes of the patterns:

1. A fluctuating wind direction could result in decreased intensity along one flank and increased intensity along the other. This could result in alternate backing and flanking behavior. (On the Mack Lake Fire, repeated shifts of 160° would have been needed to account for the physical evidence. No such shifts in ambient wind direction were observed.)
2. Windspeed could periodically decrease to less than that necessary to sustain a crown fire. (There is no evidence of significant ambient windspeed lulls during the fire's run, nor would this account for opposite spreading fires.)
3. A two-dimensional, wind-driven fire ($P_w > P_f$) could advance rapidly into new fuels, increase in intensity, and become three dimensional ($P_f > P_w$). As the fuel burns out, P_f is reduced and the wind again drives the fire. This requires that the fire act as a unit. (We do not believe that this process could account for several continuous 4- to 7-mile-long unburned crown strips noted on the Mack Lake Fire.)
4. Spotting ahead of the fire would result in secondary fires which, as they backed into the main fire, would increase in intensity. (Although this could account for random pockets of unburned fuels, it could not account for the regular banding pattern.)

Because existing hypotheses could not completely account for the physical evidence found on the Mack Lake Fire, we propose an alternate hypothesis. The evidence is strong that unburned crown strips result from downward-moving streams of air (fig. 25). The latter are likely the result of horizontal roll vortices (HRV), a form of Bénard cell (fig. 26). Such cells are well documented in the atmosphere. They produce cloud "streets" in the atmosphere (Kuettner 1959) and long parallel systems of sand dunes in deserts (Bagnold 1952). The cell has been described as helical in the atmosphere, but it is believed that the same air or entrained particles will make repeated rotations.

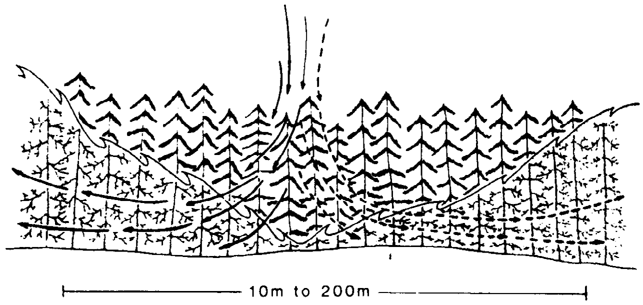

Figure 25.—*Hypothesized action of strong downdraft of air resulting from horizontal roll vortex. The downward moving stream of air could contain firebrands that would start a line of spot fires that would be blown in opposite directions.*

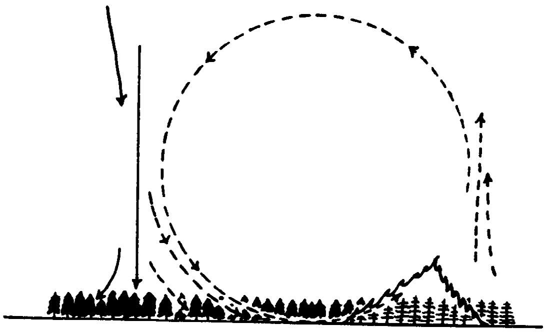

Figure 26.—*Simplified hypothetical cross section of a single horizontal roll vortex, suggesting possible entrainment of outside air. There is also an upward flow due to buoyant forces, which may mask the vortex circulation. The exact location of the vortex relative to the fire perimeter is not known.*

In a crown fire, the vortex should form in the shear zone between the ambient wind and the convective updraft along the edge of the fire (fig. 27). Although the vortex should appear as a horizontal smoke roll along the fire's flanks, the exact location of the vortex relative to the fire perimeter is not known. We examined video tapes of the Mack Lake Fire smoke column[8] and found what appeared to be two horizontal roll vortices. We estimated one on the northern flank to be 2 miles long and ¼ mile wide, but poor viewing angle and lack of ground definition precluded estimates of the dimensions of the second vortex on the southern flank.

Countryman (1968) found downward air motion over a fire, although the pattern of vertical flow was not well organized. Chandler *et al.* (1963) noted that several observations have been recorded of wind blowing outward from large fires. Schaefer (1957) described a large counterclockwise-rotating (looking downstream) Bénard cell 1 mile in diameter that acted as a lateral spread mechanism on the 1956 Dudley Lake Fire in Arizona. The smoke-outlined cell was reported to have remained as a coherent mass 300 miles downwind from the fire. We examined film from the Dudley Lake Fire which clearly showed a circulating air flow, including downward movement. Recently, Luti (1980) demonstrated that the *k-e* 2-equation turbulence model yields a horizontal circulating air pattern as a dominant feature along the forward and rear perimeters of a mass fire.

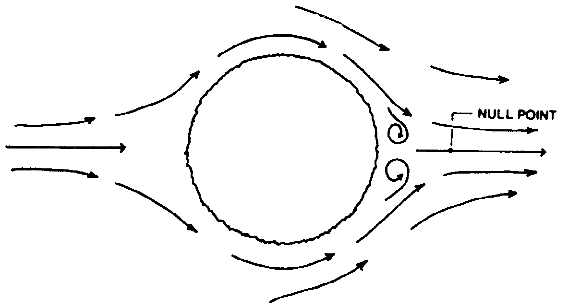

Figure 27.—*View (looking down) of a fire acting as a single unit, indicating location of shear zone along perimeter (from Countryman 1968).*

All postfire observations and evidence support the HRV hypothesis. Some strips are isolated and narrow (fig. 28 (top), foreground) and some are broad and grouped (fig. 28 (top), background), with green crown foliage visible in the center. The width of individual strips varies from 30 to 650 feet. Most strips were reasonably straight but a few curved inward toward the direction of major fire activity (fig. 28 (bottom)). When viewed from the air, one side of many strips was irregular, implying a fire in the early stages of crowning, while the opposite side appeared smooth, suggesting a well-developed crown fire (figs. 22, 28 (top)).

The unburned crown strips were most often parallel, although clusters of strips diverged (usually near the fire's origin) or converged (usually near the fire's termination—fig. 15). Distance between parallel strips ranged from 150 to 2,800 feet. The unburned tree-crown strips crossed roads and gently rolling terrain, while essentially maintaining their identity, often for 2 to 4 miles, and in one case, over 7 miles.

Tree trunk scorch height resulting from wildland fires is highest on the downwind side. Ground examination of the understory in the unburned crown strips invariably disclosed the low-charred sides of tree trunks facing each other. The char pattern was generally less evident in the direction toward which the fire was spreading (fig. 29 (top)) than in the direction from which the fire had come (fig. 29 (bottom)). Char height was generally 1 to 3 feet high on the inside of the tree trunks and 5 to 10 feet on the opposite side (160° apart). This implies that the fire spread in opposite directions with some forward

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[8] *Provided by television station WBKB-TV, Alpena, MI.*

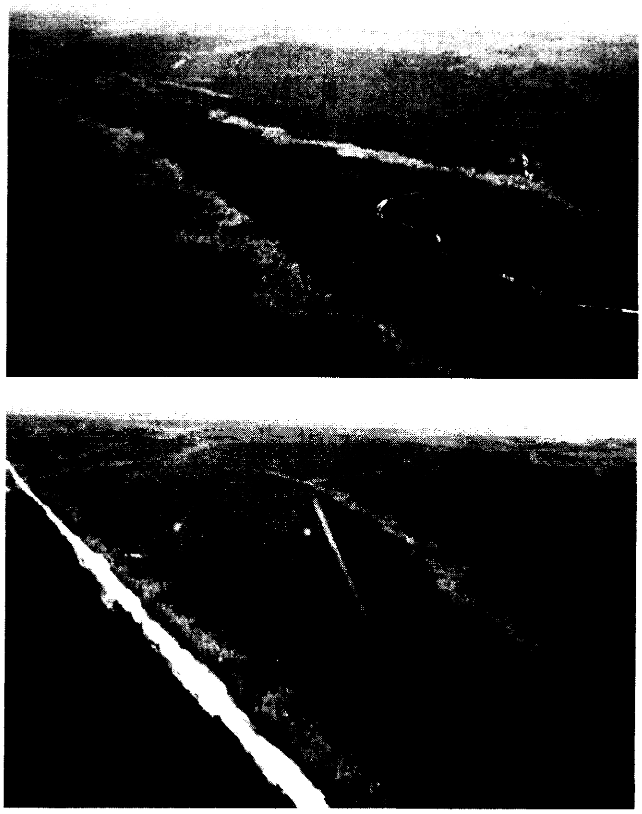

Figure 28.—*Unburned narrow, isolated crown strips showing smooth and ragged edge (foreground). Broad, grouped strips can also be seen (background) (top). Unburned tree crown strip with inward curve (bottom).*

movement. This would be consistent with a downward moving stream of air carrying embers from the main fire and igniting a secondary fire that spread in both directions, pushed by winds spreading outward from the air stream as it reached the ground. In one narrow strip, trees with scorch on opposite sides were only 2 feet apart. More typically, they were 5 to 10 feet apart. The line of opposing spread was generally located from one-fourth to one-third the width of the strip from the apparently more intense (smooth) side. In wide strips, there was often no charring along the center line; even needles a few inches above the ground were unscorched. These understory patterns were found along the entire length of all strips examined.

When the strip and understory pattern became disorganized, we invariably found that it had re-formed within a short distance and concluded that it had changed for one of two reasons:

1. A single strip had re-formed into two or more strips, or multiple strips had re-formed into single strips. This was always accompanied by a change in the overhead tree-crown pattern in conformance with ground evidence.
2. The strip stopped 200 to 300 feet upwind of an intersecting road. We usually found the re-formed strip and understory pattern 50 to 80 feet on the other side of the road.

Figure 29.—*View of line of opposite spread in an unburned tree crown strip (looking in the direction of fire spread) (top). Note less charring visible on opposite side of tree stems than in bottom view. View of line of opposite spread in an unburned tree crown strip (looking in the direction from which the fire is coming) (bottom). Note more charring visible on opposite side of tree stems than in top view.*

In one instance, a strip moved from conifers to hardwoods. Even though there was no crowning in the latter, the uncharred center line continued along a sidehill 200 feet long, with a 25° slope, about 150 feet from the bottom. The pattern indicated that along the length of this hill, the fire burned downslope below the strip and upslope above the strip. In another instance, when a strip crossed a small depression 20 feet deep by 100 feet across, the ground surface pattern was "lost" in the depression, but "found" again on the other side.

We examined the unburned crown strip that formed along the tractor/plow line where the fatality occurred. The edge was smooth on the fire side and ragged on the opposite side (fig. 22). The center line was offset about ⅓ of the distance from the fire side of the strip. The strip extended 1,000 feet beyond the point where the control line was abandoned and curved inward toward the fire. These features indicate that this strip was formed by the same process as the others. In this strip, we found a 2- to 3-foot-wide irregular line of unburned material resulting from the tanker spray pattern. This unburned line was 20 to 30 feet outside the unburned center line of the strip.

On the 1977 Bass River Fire in New Jersey, an abandoned vehicle, near which four firefighters were trapped, was on the southwest side of an unburned tree crown strip (fig. 30). The main fire was spreading southeastward and the strip was along the southwestern flank of the fire. Although in documenting the fire, Brotak (1976) concentrates on "blowup" conditions, his description of specific conditions associated with the fatality are identical to those of Mack Lake. He states:

> ...it appears as if the wind shifted from the northwest to the northeast during a part of the fire's run. This is believed to be responsible for trapping the men...this would have turned the flank of the fire to the north of the truck into a head fire quickly spreading to the southwest.

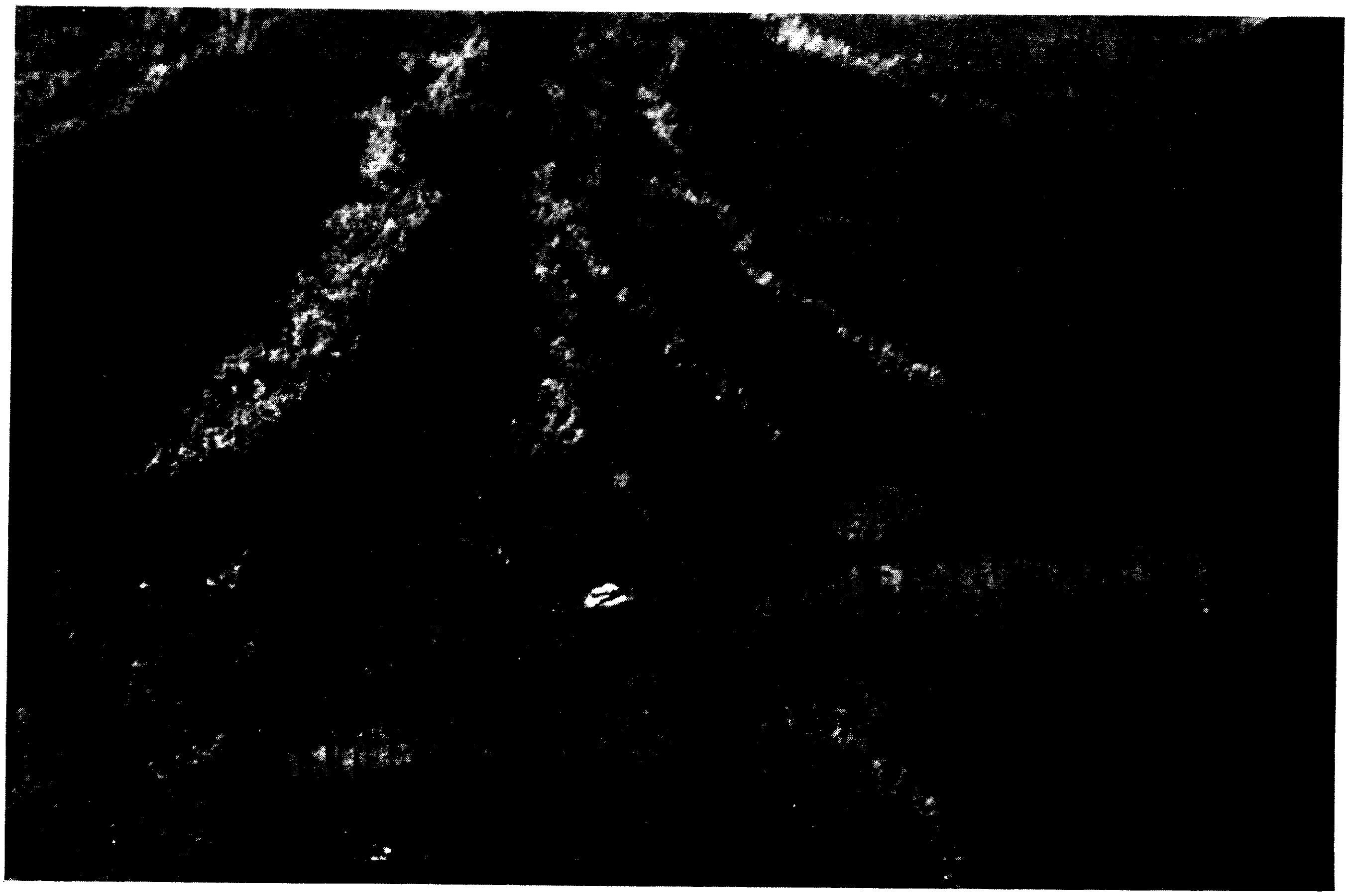

Figure 30.—*Aerial view of part of 1977 Bass River Fire in New Jersey—looking northwest. Abandoned vehicle can be seen in center. Photo courtesy of New Jersey Department of Environmental Protection.*

Figure 30 clearly indicates that the 90° wind shift must have been localized, because the pattern of unburned tree crowns does not change before or after the reported shift. Thus, the evidence, although not conclusive, points toward horizontal roll vortices as the cause of the four men being trapped on the Bass River Fire.

The upper-left photograph on the back cover is a view of the southwest flank of the Mack Lake Fire, looking north along Forest Service Road 4457 (just north of 4461). Although the fire was spreading southeastward at the time that the photograph was taken, the flames are clearly tilting toward the southwest—an identical situation to that described by Brotak (1976). This would be consistent with flames being driven by the outdraft of a horizontal roll vortex along the flank.

Haines (1982) compiled information from a dozen fires across the United States, Canada, and Australia, in fuel types ranging from sawgrass to mature timber, where unburned strips of fuels were reported. Several fires (Fletcher Road in Michigan, Bomb Range in North Carolina, and Bass River in New Jersey) revealed not only unburned crown strips similar to those at Mack Lake but also concentric ellipsoidal bands around the entire fire perimeter in the early stages. Haines (1982) also demonstrated that the existence of horizontal roll vortices in conjunction with crown fires is consistent with existing theories of heat transfer and fluid dynamics.

Additional research is needed to confirm or refute the hypotheses stated here. Several questions must be answered.

- How does a vortex form?
- What combinations of wind, fire size, and intensity result in horizontal roll vortices?
- What combinations of wind, fire size, and intensity permit patterns to curve around the head of a fire?
- Is there a maximum topographic irregularity above which a horizontal roll vortex will not form?
- Do multiple adjoining vortices form as they do in the atmosphere, or is this a single vortex phenomenon?
- Is the mechanism that forms a single large vortex the same as that which forms bands in conifer crown fires or bands in grass fires?

Necessary field observations include:

- Photographic documentation of horizontal roll vortices, including ground reference for scaling.
- Aerial photographs of burned areas before scorched foliage drops to the ground.
- Observations and documentation of the line of opposite spread in crown strips, particularly along the forward perimeter of a fire.
- Meteorological and topographic features related to the fire.

FIRE EFFECTS

The Mack Lake Fire took a heavy toll. One firefighter lost his life. Losses from the destruction of private property will probably exceed 2 million dollars when all claims are settled. Timber losses were estimated at 2 million dollars and watershed and recreation losses at $166,000. On the positive side, range and wildlife values increased by $125,000.[9]

Site Effects

The depth of burn was very shallow (¼ to ½ inch). In all areas except under the slash piles, ½ to 1 inch of duff remained after the fire. Due to the excellent insulating properties of duff, it is unlikely that any significant temperature increase occurred in the soil. Therefore, soil micro-organisms were likely not significantly affected by the fire. The remaining duff, coupled with essentially flat topography, should effectively prevent soil erosion, and the only effect on the soil should be an increase in nutrients for 2 to 3 years.

One season after the fire, the hardwood species (primarily oak and aspen) had resprouted vigorously, indicating little root damage. In the first year, aspen sprouts were 2 to 7 feet high and oak sprouts often equaled the height of the plants prior to the fire (1 to 4 feet). Thus, wherever understory oak was present in the jack pine stands, the fire acted as a releasing agent. Similarly, most of the herbs and woody shrubs present prior to the fire had resprouted vigorously. Finally, the usual assortment of pioneer species, such as fireweed (*Erechtites hieracifolia)* and pin cherry (*Prunus pensylvanica),* were relatively abundant. In general, plant cover was quickly reestablished on virtually all of the burned area. Additional research is currently underway to document the response of the plant communities to the fire.

In the hardwood stands, effects on the overstory ranged from 100 percent mortality adjacent to areas where the fire was crowning in jack pine to virtually no effect where the fire gradually died out during the night. Many of the trees that were top-killed have resprouted. Consequently, the new stand will likely contain a high percentage of coppice growth.

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[9] *Data obtained from the Mack Lake Individual Forest Fire Report, Form 5100-29.*

Jack Pine Reproduction

One week after the fire, 10 seed count samples were taken in the burned area. Seeds were found on nine plots and the exception had no trees of seed-bearing age within a reasonable distance. On the nine plots with seeds, the counts averaged 300,000/acre, with a range of 90,000 to 1,000,000. Riley (1975) states that 20,000 viable seeds per acre are necessary for adequate stocking. Data summarized by McRae (1979) indicate that jack pine seed viability averages 50 percent. Thus, 40,000 seeds/acre should provide adequate stocking. Wherever seeds fell following the fire, the number appears to be more than adequate to regenerate the stand. Chrosciewicz (1974) rates a postburn duff depth of less than 1 inch as high quality in terms of seedling survival. Because most of the fire area fits this class, there is every reason to expect good reproduction wherever a seed source is available.

Because initial conditions for reproduction were ideal, the primary limiting factor is postburn rainfall. Five rain gauges were located across the burned area and rainfall data obtained for the growing season (May to September). Rainfall for the 5-month period averaged 16.3 inches (normal = 14.4 inches), with a range of 15.1 to 17.8 inches between the five rain gauges. Thus, all areas of the fire received between 5 and 19 percent above average rainfall for the first growing season. Only 1 month (August) was significantly below average (-2.2 inches), but even then, no more than 2 weeks elapsed between significant precipitation. Therefore, immediate postfire conditions were favorable for survival of jack pine seedlings.

Casual observation at the end of the first growing season indicated that optimistic expectations might be realized and that a dense stand of jack pine seedlings was likely to become established over much of the burned area. Three plots had an average of 9,000 seedlings/acre, with a range of 2,000 to 17,000. On the assumption that reforestation will occur, the Mack Lake Fire may have created what in 10 years will be 10,000 to 15,000 acres of prime habitat for the endangered Kirtland's warbler.

CONCLUSIONS

1. The Mack Lake Fire was not unique. Five other fires in excess of 10,000 acres have occurred in the Mack Lake area since 1820. The average interval between major jack pine crown fires is 28 years. Large crown fires will continue to be an intermittent fact of life in jack pine forests.
2. In northern Lower Michigan, the spring fire season appears to be typified by wide fluctuations in fire danger. Ninety percent of the days are either low or high, with less than 10 percent in between. Periods of moderate fire weather appropriate for prescribed burning rarely last more than 1 day. This complicates the prescribed burning planning process.
3. The Mack Lake Fire occurred just 6 days after ½ inch of rain fell. Only a slight precipitation deficit was recorded during the 4 months preceding the fire. It is clear that drought is not necessary for a major spring crown fire in jack pine. During the last 4 days of the drying period, relative humidity at 1300 ranged from 19 to 28 percent.
4. Horizontal roll vortices may be a common mechanism of lateral crown fire spread. If they form, they are a safety hazard for crews working on the flanks of crown fires. Further research into this phenomenon will be needed before the processes involved are understood and procedures for predicting the occurrence of horizontal roll vortices can be developed.
5. There are many large, relatively flat areas where jack pine predominates. Once a crown fire begins to run in this timber type, large-scale fire suppression efforts are needed. Fuel breaks, composed of less flammable hardwood species or widely spaced trees, could yield important fire suppression benefits such as reducing rate of spread and intensity, increasing firefighter safety, and providing an opportunity to make a stand.
6. The moisture content of old jack pine foliage is at a minimum during the onset of new growth in the spring. This increases crowning potential and may result in crown fire spread rates twice those encountered in the fall. These changes should be incorporated into fire management planning.
7. Several conditions contributed to the escape of the prescribed fire:
   - Spotting from slash piles.
   - Irregular groups of uncut trees adjacent to the prescribed fire area.
   - Locating the control line near the top of a 25-percent slope.
   - High windspeed (15-plus mi/h).
   - Low relative humidity (21 percent).
   - Low fine-fuel moisture (7 percent).
8. The transition from prescribed burning to wildfire control is critical. Subsequent spot fires can threaten initial attack crews. Since confusion is possible when an escape is attacked, it is important that the transition be planned in advance.

9. In jack pine, a fire can develop from an initial spot to a running crown fire in as little as 10 minutes and to project size in 20 minutes. This requires a rapid change in perspective by fire management personnel at all levels. Firefighters may have to shift from building line to escaping; dispatchers from moving crews to ordering overhead teams and fire camps; and the fire boss from control to community evacuation. Every member of an organization must immediately recognize the changed situation and take appropriate action.
10. The average rate of spread of the Mack Lake Fire (2 mi/h) was similar to that of other fast-moving crown fires. The maximum rate of spread (6 to 8 mi/h) equals the fastest recorded rate for which we had data.
11. During the fire's major run, average fireline intensity (8,800 Btu/ft/sec) was similar to that for other major crown fires. The 1-hour maximum fireline intensity (15,500 Btu/ft/sec) was less than that for three major fires for which we had data. The 15-minute peak intensity (29,500 Btu/ft/sec) may have approximated an upper limit for moving crown fires.
12. The number of permanent and seasonal residences in and adjacent to wild land areas is increasing. Noting that two out of three homes in Mack Lake did not burn, an expanded program should be developed to explain to homeowners the potential for wildfire damage and how to locate and landscape their homes to prevent loss.

Fire is an important and in some cases essential land management tool. It can also be terribly unforgiving of human error. Considerable skill and knowledge is required to successfully walk what is often a narrow, winding path between accomplishing land management objectives and reducing the risk of adverse consequences. A potentially explosive fuel type such as jack pine only serves to exacerbate the situation.

Fire is, however, controlled by fixed physical laws. Careful analysis generally reveals that what often appears as erratic behavior is related to known (though often incompletely understood) physical processes. We hope that this analysis has contributed to an increased understanding of these processes. It is important that we not only learn from experience, but that we also maintain a public and private awareness of fire's potential in jack pine so that we can avoid a repetition of the Mack Lake Fire of 1980.

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APPENDIX I. MEASURING THE FIRE

Fire Geometry

For the spot fire west of Highway 33, perimeter and area were scaled from a map. The final area was also scaled from a map and the final perimeter was obtained from the fire analysis report (USDA Forest Service 1980). For intermediate areas, the perimeter and area were calculated by assuming an elliptical shape with the major axis equal to the distance between the fire's forward position and the rear of the fire. The minor axis was equated with the estimated width of the fire at each observation. Before the wind shift, the length of head was assumed to equal the minor axis. After the wind shift, the head length was estimated from a map. Greater precision in calculating perimeter and length of head was not warranted, given the available data. Because this procedure does not incorporate irregularities, it underestimates the actual perimeter.

We estimate that at 1325 the fire was 4 miles long and 1.5 miles wide, yielding a length to width ratio of 2.7:1. Equations developed by Anderson (in press) predict a 5.4:1 ratio with a 15 mi/h mid-flame windspeed. Wind direction variability (not incorporated in Anderson's model) would decrease the forward:flank spread ratio. Horizontal roll vortices would increase observed lateral spread beyond what would normally be expected (thereby further decreasing the ratio). A simpler model developed by Simard and Young (1978) predicts a 1.9:1 ratio under the same conditions.

Rate of Spread

Rate of spread was determined by dividing the distance traveled between successive reports of the fire's forward position by the time interval between the reports. Some reports were obtained from the district log book and some were based on estimates made by observers.

Fireline Intensity

Byram (1959) gives a formula for fireline intensity:

$$I = hwr \qquad (1)$$

where I = fireline intensity (Btu/ft/sec),
h = heat value of the fuel (Btu/lb),
w = weight of fuel consumed (lbs/ft^2), and
r = rate of spread (ft/sec).

In using (1) we assumed that all of the fuel was consumed in the flaming front. Although this overestimates intensity to some extent, there is no reliable method for separating fuel consumed by the fire front from that consumed afterward. We felt that for the Mack Lake Fire, the resulting error would be relatively small.

Energy Release

The total energy released by the fire front per unit of time is:

$$E_f = I_f L_f \qquad (2)$$

where E_f = frontal energy release rate (Btu/sec),
I_f = fireline intensity at the front (Btu/ft/sec), and
L_f = length of the fire front (ft).

Although the fire front is generally less than one-fourth of the total perimeter, most of the fire's energy will be released at the front due to its high fireline intensity relative to the remainder of the perimeter.

The total energy released by the fire can be determined by:

$$E_t = 43{,}560 \text{ hwa} \qquad (3)$$

where E_t = total energy released by the fire (Btu) and
a = fire area (acres).

Dividing E_t by the time interval over which it is measured yields the total energy release rate per unit time.

Residence Time

The length of time that a fuel particle will continue to burn was given by Anderson (1969):

$$T_r = 8d \qquad (4)$$

where T_r = flaming residence time (minutes), and
d = fuel particle diameter (inches).

For the Mack Lake Fire, little woody material in excess of ¼ inch was consumed. Thus, typical residence time was 2 minutes.

Heat Value

Hough (1969) gives low heat of combustion values of various components of jack pine and aspen fuel complexes (table 8). These were adjusted for heat losses due to vaporization of fuel moisture. Weighted average heat of combustion for jack pine (7,900 Btu/lb) and hardwood (7,370 Btu/lb) fuel complexes were obtained. The dense, black smoke emitted by the Mack Lake Fire (front and back cover photos) indicates incomplete combustion, as is typical of large fires. Therefore, using data from Byram (1959), an incomplete combustion heat value reduction was estimated for jack pine surface fuels (12 percent) and foliage (28 percent). The weighted average reduction (14 percent) gave a heat of combustion of 6,820 Btu/lb for the jack pine fuel complex. For aspen, with a less intense surface fire, a reduction of 6 percent yielded a value of 6,930 Btu/lb of fuel. Finally, an average radiation loss of 800 Btu/lb (Byram 1959) gives a heat yield (h) of approximately 6,000 Btu/lb for jack pine and 6,100 Btu/lb for the hardwood fuel complex. The latter values were used for all intensity calculations.

Table 8.—*Heat of combustion value of fuels consumed by the Mack Lake Fire*

	Low heat value	Average moisture content[2]	Heat loss to vaporization	Fuel consumed[3]	Weighted average heat value
	Btu/lb[1]	*Percent*		*Percent*	*Btu/lb*
Jack pine needles	8,575	120	1,165	0.28	
Jack pine twigs	8,707	15	145	.13	
Jack pine litter[4]	8,657	10	97	.24	
Jack pine duff	7,857	25	242	.35	7,908
				1.00	
Aspen, oak litter	7,952	10	97	.30[4]	
Aspen duff[5]	7,280	25	242	.61	
Aspen twigs	8,150	15	145	.09	7,371
				1.00	

[1] Data from Hough (1969). Corrected for ash content and vaporizing water of reaction.
[2] Estimated average for all material consumed.
[3] From tables 4 and 5.
[4] Includes shrubs and herbs.
[5] Estimate based on average increase in ash content for other species.

Fuel Consumption

We distinguished four fuel consumption rates. In the prescribed burn area (1024-1206) fuel consumption was 26 tons/acre ($w = 1.2$ lbs/ft^2). Between 1206 and 1222 the fire burned on the ground in a jack pine stand. From table 4a, fuel consumption without crown foliage was 7.3 tons/acre ($w = 0.34$ lbs/ft^2). Between 1222 and 1825, 20,000 acres were burned. We assumed that all the non-hardwood stands (17,720 acres—table 3) were burned during this period. Thus, 2,280 acres of hardwood were also burned during the same period. Based on that assumption and data from table 3, the weighted average fuel consumption between 1222 and 1825 was 10.5 tons/acre ($w = 0.48$ lbs/ft^2). We assumed that the fire burned only in hardwood stands after 1825 consuming 14.6 tons/acre ($w = 0.67$ lbs/ft^2).

Energy Balance

Byram (1959) gives equations for comparing the energy flow rate of the wind with the rate at which thermal energy is converted to kinetic energy. For a neutrally stable atmosphere:

$$P_w = \frac{\rho\,(v - r)^3}{2g} \qquad (5)$$

where P_w = the rate of flow of kinetic energy in the wind field at height z above the fire (ft-lb/sec/ft^2),

ρ = air density at height z (lb/ft^3),

v = windspeed at height z (ft/sec),

r = forward rate of spread of the fire (ft/sec), and

g = acceleration of gravity (ft/sec^2).

$$P_f = \frac{I}{C_p\,(T_o + 459)} \qquad (6)$$

where P_f = the rate at which thermal energy is converted to kinetic energy in the convection column of a fire (ft-lb/sec/ft^2),

I = fireline intensity (Btu/sec/ft),

C_p = specific heat of air at constant pressure (Btu/lb/°F), and

T_o = air temperature at the surface (°F).

The following values were used to calculate P_w and P_f in table 7.

Altitude (ft)	ρ	v	
surface	0.0765	13	r – table 6a
1,000	.0743	20	$g = 32$
2,000	.0721	51	I – table 6b
3,000	.0706	53	$C_p = 0.24$
4,000	.0679	44	$T_o = 80$

APPENDIX II. COMPARING FIRE-DANGER RATING SYSTEMS

Fire danger can be defined as an assessment of the expected occurrence, rate of spread, and intensity of wildland fires resulting from an observed state of the weather, fuels, and topography. The transformation from a weather observation to expected fire behavior is strongly dependent on microclimate and fuel characteristics. Thus, to evaluate the worst fire danger, the National Fire-Danger Rating System (NFDRS) estimates the moisture content of roundwood, without bark, off the ground, and in the open (Deeming *et al.* 1977). In contrast, to evaluate average fire danger, the Canadian Fire Weather Index (FWI) estimates the moisture content of surface litter and duff under a canopy (Van Wagner 1974b). It is instructive to compare how the two contrasting systems portrayed fire danger during the 1980 spring season at Mack Lake.

FWI class boundaries were established on the same basis as the NFDRS Burning Index (BI), using climatological data from Gore Bay, Ontario, the closest comparable Canadian station (Simard and Valenzuela 1972). FWI values were calculated using Mio weather data for April and May 1980 (table 9, fig. 31). We normalized the two data sets by dividing each FWI and BI value by the maximum value, thereby permitting a direct comparison of the two indices (fig. 32). The FWI indicates similarities to the BI in that the times of peak fire danger are the same. The FWI also suggests that the fire season was bimodal, but the relative percentages are different (fig. 33). Only 9 days (25 percent) were high to extreme, 23 days (64 percent) were low, and 4 days (11 percent) were moderate. There were four occasions when the index jumped from low to high (or vice versa) in a single day.

There is a difference in the response of the two systems immediately after a rainfall of 0.1 inch or more. On three out of six occasions[10], 1 day after significant rain, the BI jumped to the high class (table 1, fig. 2). It remained at zero only once. In contrast, the FWI remained at zero 1 day after significant rain on four of the six occasions and did not rise higher than the moderate class on the remaining two. The lag in the FWI eliminated three apparent lesser fire danger peaks implied by the BI. The FWI indicates that most of the fire season had had low fire danger, except for four distinct peaks.

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[10] *Omitting two occasions when more than 0.1 inch of rain was recorded on the subsequent day.*

Table 9.—*National Fire-Danger Rating System (NFDRS), Burning Index (BI), and Canadian Fire Weather Index (FWI) values for April and early May 1980 at Mio, Michigan*

Date	NFDRS (BI)[1]	BI / BImax	FWI	FWI / FWImax
April 1	62	0.69	7	0.17
2	70	.78	12	.29
3	54	.60	16	.39
4	0	.00	0	.00
5	44	.49	1	.02
6	47	.52	2	.05
7	37	.41	2	.05
8	0	.00	0	.00
9	0	.00	0	.00
10	0	.00	0	.00
11	10	.11	0	.00
12	0	.00	0	.00
13	31	.34	0	.00
14	0	.00	0	.00
15	0	.00	0	.00
16	52	.58	0	.00
17	40	.44	1	.02
18	58	.64	5	.12
19	80	.89	14	.34
20	46	.51	1	.02
21	49	.54	7	.17
22	54	.60	11	.27
23	90	1.00	19	.46
24	73	.81	10	.24
25	58	.64	2	.05
26	0	.00	2	.05
27	0	.00	2	.05
28	0	.00	1	.02
29	0	.00	0	.00
30	0	.00	0	.00
May 1	10	.11	0	.00
2	32	.36	1	.02
3	53	.59	14	.34
4	63	.70	25	.61
5	79	.88	41	1.00
6	2	.02	8	.20

[1] Fuel model Q.

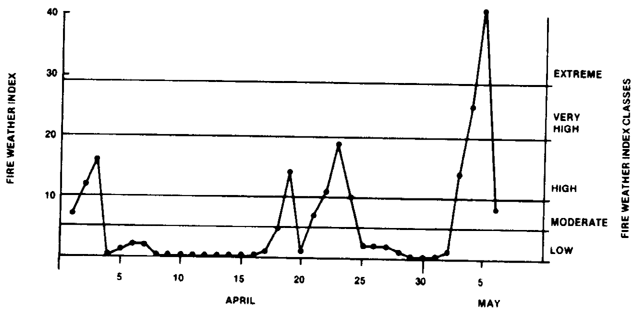

Figure 31.—*Canadian Forest Fire Weather Index (FWI) for Mio, Michigan, April and early May 1980.*

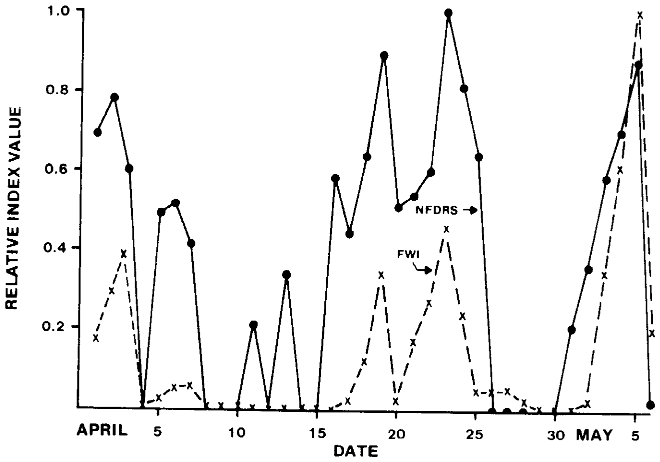

Figure 32.—*Relative values of the National Fire-Danger Rating System (NFDRS) Burning Index and the Canadian Fire Weather Index (FWI) for Mio, Michigan, April and early May 1980.*

Perhaps most important, the fire danger peaks indicated by the FWI are of different magnitudes. While the first three peaks were similar and in the high range, the fourth (on the day of the Mack Lake Fire) was well into the extreme range—more than twice as high as the next highest peak. Thus, the FWI implied that fire danger on May 5 was considerably more severe than it had been during the previous three peaks.

Each system reflects the aspect of fire danger it was designed to measure. Because it predicts fire danger in the open, the NFDRS reaches peak values quickly and remains relatively high under continued drying. In so doing, however, the system may lose some ability to distinguish between varying degrees of high to extreme danger under a closed forest canopy. Because the FWI predicts fire danger under a

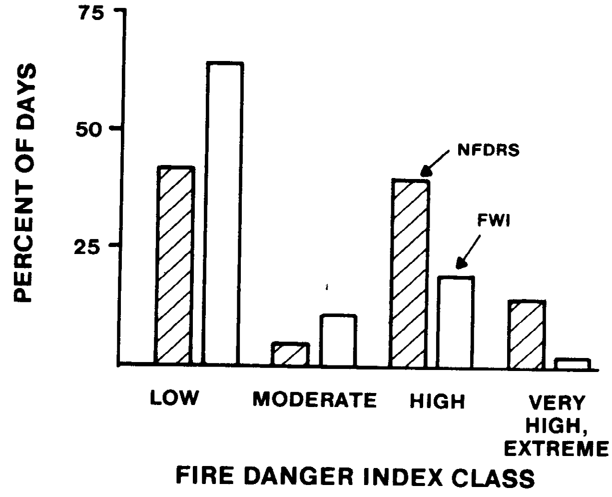

Figure 33.—*Percent of days by fire-danger rating index class.*

canopy, it responds more slowly than the NFDRS and may, therefore, be better able to distinguish fire danger peaks in forest stands. Assuming that fire managers would respond differently to two portrayals of the same fire season is sufficient justification for further study of these differences.

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Upper Right Photo.—*As with many natural processes, a fully developed crown fire dwarfs suppression efforts. Photo courtesy of the Huron-Manistee National Forest, Mio Ranger District.*

Upper Left Photo.—*Looking north along the southwest flank of the fire. Although the fire is spreading southeastward (left to right), the flames are being driven to the southwest (right to left). The action of a horizontal roll vortex could account for this apparent anomaly. Photo courtesy of the Huron-Manistee National Forest, Mio Ranger District.*

Bottom Photo.—*The Mack Lake Fire as it burned through the Kirtland Warbler Management Area, shortly after passing through the village of Mack Lake. Photo courtesy of the Huron-Manistee National Forest, Mio Ranger District.*

Simard, Albert J.; Haines, Donald A.; Blank, Richard W.; Frost, John S. The Mack Lake Fire. Gen. Tech. Rep. NC-83. St. Paul, MN: U,S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1983. 36 p.

Describes the Mack Lake Fire near Mio, Michigan. Few documented wildfires have exceeded its average spread rate (2 mi/h) and energy release rate (8,800 Btu/ft/sec). The extreme behavior resulted from high winds, low humidity, low fuel moisture, and jack pine fuels. Horizontal roll vortices may have contributed to the death of one firefighter.

KEY WORDS: fire behavior, crown fires, jack pine, weather, fuels, horizontal roll vortices.