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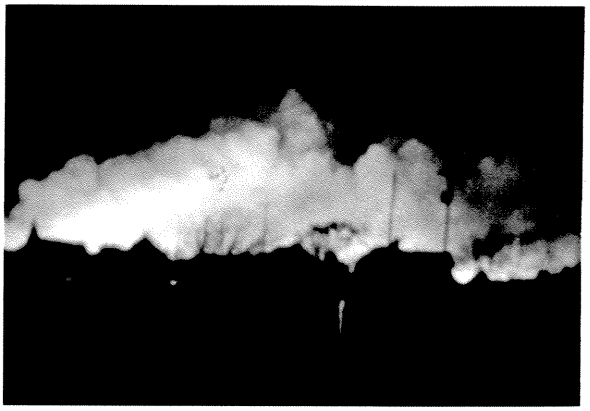
AN ANALYSIS of the Air Force Bomb Range Fire

by

Dale D. Wade

and

Darold E. Ward



U. S. Department of Agriculture-Forest Service
Southeastern Forest Experiment Station
Asheville, North Carolina

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Associate Fire Behavior Scientists

Southern Forest Fire Laboratory

Macon, Georgia

INTRODUCTION

There are few places in the world where wildfire behavior can be studied strictly as it is affected by weather variables, both ambient and fire-induced. Eastern North Carolina offers this opportunity. Large, homogeneous expanses of highly combustible fuel exist on land that has a maximum elevation of 10 ft. (3 m.) above mean sea level.[1] Fine fuel weights of 15 tons/acre (33.6 M.T./ha.) are common, and under extreme drought conditions these fuel weights may more than double as the peat soils, characteristic of this region, dry to depths of 1 to 2 ft. (0.3 to 0.6 m.).

Wildfires occurring in eastern North Carolina frequently become dangerously explosive, blowup fires. The 29,300-acre (11,860-ha.) Air Force Bomb Range Fire of March 22-26, 1971, was such a fire; it was studied by a fire documentation team from the Southern Forest Fire Laboratory. The fire exhibited several blowup features including high-density, short-distance spotting, a well-developed convection column, and rates of spread exceeding 2 m.p.h. (0.9 m./sec.) during a 4-hour period with a maximum of almost 5 m.p.h. (2.2 m./sec.) during one 4-mile (6.4-km.) run. The fire traveled 14 miles (22.5 km.) prior to the passage of a cold front, then changed direction, and ran an additional 6 miles (9.7 km.) as a post cold-frontal fire. A record of fire behavior was imprinted on the area vegetation in the form of concentric bands of unconsumed fuel that outlined the fire during the first 4 hours after ignition. Fire suppression was hampered by the poor trafficability of the soils, the heavy fuels, and the rapid rate of fire spread.

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[1]Metric equivalents appear in parentheses. See Appendix for conversion factors.

BACKGROUND

The inaccessibility of pocosins[2] contributes to the development of tremendously large fires such as the Lake Phelps Fire that burned 250,000 acres (101,175 ha.) during March and April 1955 and the Hyde-Tyrrell Fire that burned 100,000 acres (40,470 ha.) during April 1963. Other blowup fires have occurred during the summer (Bluff Point Fire--July 1952), fall (Hales Lake Fire--October 1952), wet periods (Pungo Lake Fire--April 1959), and drought periods (Dare County Fire--August 1957).

The area burned by the Air Force Bomb Range Fire contained a well-stocked natural stand of 13-year-old pond pine (Pinus serotina Michx.) and a dense pocosin understory, both of which developed after the lightning-caused 1957 Dare County Fire that denuded some 75,000 acres (30,350 ha.).

Dare County itself is a sparsely populated peninsula comprised primarily of pocosins and marshland. Most of the area is managed for forest production. A network of drainage canals and woods roads offers the only interruption in an otherwise unbroken expanse of fuel. Fire can travel in a truly uninhibited fashion.

Two military bomb ranges are located in the heart of the county, and both have a fire history because of the ordnance used. Several presuppression measures are taken to insure that any fires started will be confined to the target areas. A system of roads and canals acts as a fuel break and gives access (fig. 2). Fuel modification involving herbicides and prescribed fire and a suppression force composed of a helicopter and several tracked, cross-country vehicles have resulted in direct control of 137 of the 138 fires that occurred on the Air Force Bomb Range from 1965 through 1970. The average area burned was 0.5 acre (0.2 ha.).[3] The sole exception, prior to 1971, was a 3,600-acre (1,460-ha.) fire in April 1966.

FIRE DEVELOPMENT AND CONTROL

The stage was already set for a conflagration on March 22, 1971. During four of the preceding five days, the dead and cured fine fuels on the Air Force Bomb Range had been subjected to the desiccating effects of low humidities, moderate-to-fresh winds, and full sunshine. The Air Force Bomb Range Fire was ignited by a practice bomb dropped at 1028

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[2]"In general, pocosins may be described as those areas, including swamps and bays, with soils having 20 percent or more organic matter content, fair to poor internal drainage, and supporting stands of pond pine. Also, these areas have a medium to heavy density understory composed principally of woody shrubs and reeds. The pocosins constitute roughly 2 million acres in coastal North Carolina" (12, p. 3). See figure 1 for distribution of the principal areas of organic soil in eastern North Carolina.

[3]Green, H. J., Roten, Dane, and Plotkin, H. S. Air Force Bomb Range Fire. 17 pp. 1971. (Mimeogr. rep. of the Board Rev., N. C. For. Serv., Dep. Conserv. Dev.)

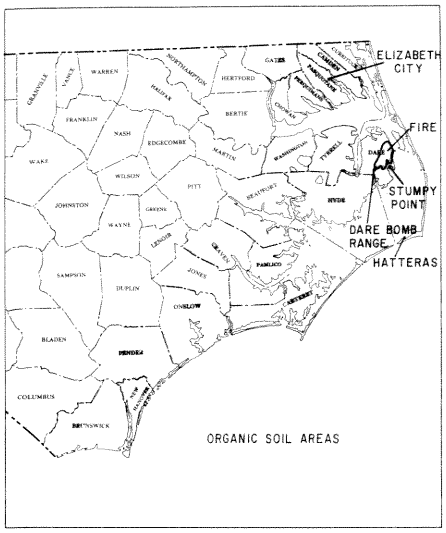

Figure 1.--Principal areas of organic soil in eastern North Carolina. The Air Force Bomb Range Fire and nearby weather stations are shown. [Soil map adapted from Wendel, Storey, and Byram (12).]

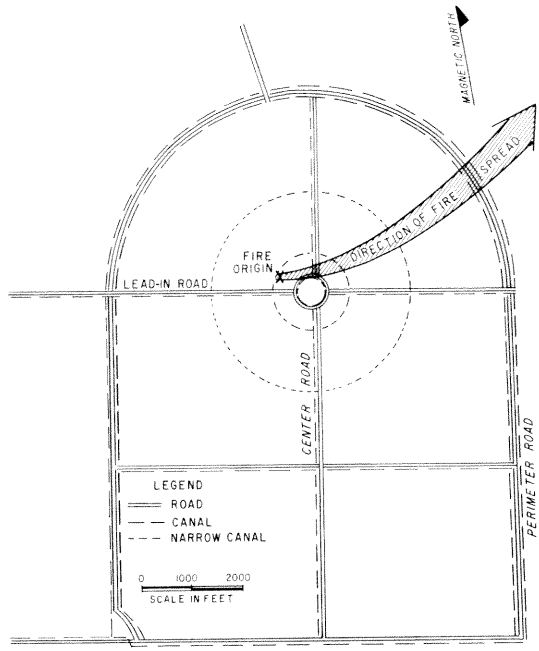

Figure 2.--The system of roads and canals used for access and fire control at the Dare County Air Force Bomb Range. Fire origin is marked by an "x."

e.s.t. and immediately became dominated by surface winds blowing at 20 m.p.h. (9 m./sec.). The fire was beyond control before the standby crew stationed on the range reached it.

The fire crowned through more than 15,000 acres (6,070 ha.) of pond pine during the next 20 hours and eventually burned 29,300 acres (11,860 ha.) of timber and nonforested watershed (fig. 3). The initial 14-mile (22.5-km.) run from the Air Force Bomb Range northeast to Croatan Sound produced a narrow, elongated shape typical of fires pushed by high winds. Rate of spread averaged over 2 m.p.h. (0.9 m./sec.) for 4 hours and nearly reached 5 m.p.h. (2.2 m./sec.) during a 1-hour period. The flanks remained active throughout the night of the 22nd until a cold front passed over the area before dawn on the 23rd. The resulting shift in wind direction from southwest to north created two heads from the southeast flank, one of which was pushed rapidly toward the town of Stumpy Point.

This sequence of events is typical of blowup fires in the South. They must be contained within a comparatively short time after ignition or suppression efforts become ineffectual. The fire will then remain uncontrollable until either fuel or weather conditions ameliorate, with a resultant decrease in fire intensity. In the case of the Air Force Bomb Range Fire, it was a change in fuel conditions that initially checked fire spread. One head lost its momentum in a wet, marshy area about 100

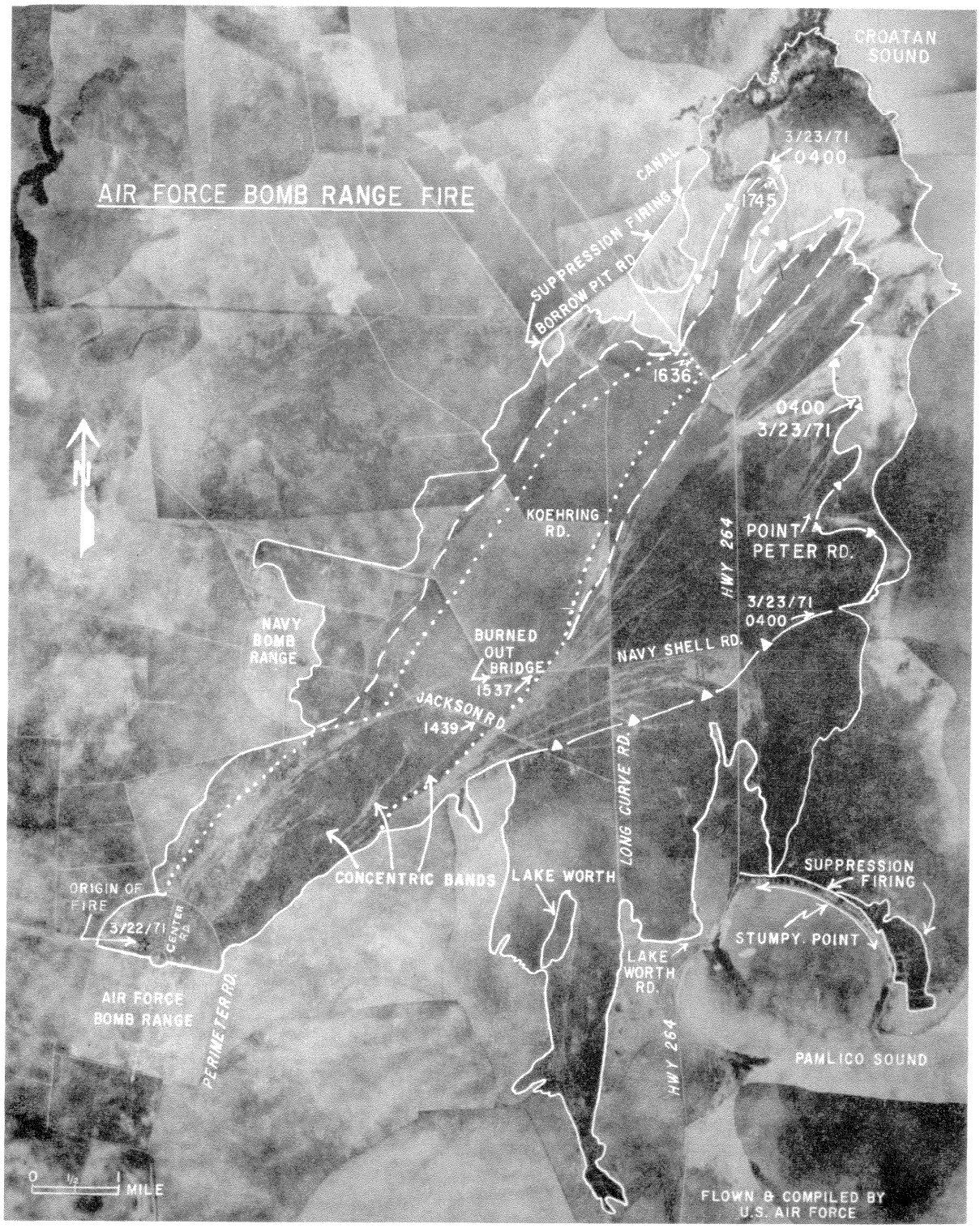

Figure 3.--Photo mosaic of the burned area. Outer solid line shows final perimeter of fire. Inner lines show fire perimeter at various times. The fire was controlled on March 26, 1971, at 29,300 acres (11,860 ha.).

yards (90 m.) north of Stumpy Point. The other also encountered wet conditions and was dissipated. Some flareups occurred along the northwest flank Tuesday and Wednesday, but, in general, the fire remained quiet until Friday, March 26, when a general rain occurred.

Even after the fire calmed down on Tuesday morning, the control force could not take full advantage of the situation. Because the water table was near the surface, the organic soils would not support tractor-plow units, and line building became an exceedingly difficult task. Lightweight, full-tracked, off-road vehicles such as Nodwells[4] equipped with portable pumps were used to trample down the brush along the fire perimeter. Then water was used to extinguish the active fire edge. At points where the vehicles did not proceed directly along the fire perimeter, their path of crushed brush was used as a baseline from which burning-out operations were initiated.

Fire development, behavior, and control, together with information on fuel and weather conditions between March 22 and March 26, are summarized in table 1.

FUELS

Pond pine, a fire-adapted species,[5] was the dominant overstory tree on the burn, averaging 1,250 stems/acre (3,100/ha.). About 64 percent of the forested area was covered with well-stocked, 13-year-old pond pine that came in after the 1957 burn (fig. 4). Another 13 percent contained poorly or medium-stocked, 13-year-old pond pine. The remainder was comprised of reproduction from the 1966 burn and older trees that survived the 1957 burn. In addition, 5,000 acres (2,025 ha.) of marsh, 5,000 acres (2,025 ha.) of low, open pocosin, and 1,200 acres (490 ha.) planted to species other than pond pine also burned.

The 13-year-old pond pine averaged 16 ft. (4.9 m.) in height and 2.9 inches (7.4 cm.) d.b.h. Its principal associates were redbay (Persea borbonia (L.) Spreng.) and sweetbay (Magnolia virginiana (L.)), which, together, averaged 13 ft. (4.0 m.) in height, 1.6 inches (4.1 cm.) d.b.h., and 220 stems/acre (550/ha.).

Species composition of the understory was variable. Wendel et al. (12) categorized pocosin fuels into 16 broad types on the basis of species composition of the understory, density, height, and age of rough. At least five of the types occurred on the burn area (table 2). The weight of fuel samples taken of types R-14, RB-10, and P-14 in the vicinity of the burn compared favorably with those given by Wendel et al. (12).

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[4]Mention of trade names throughout this Paper does not constitute endorsement by the U. S. Department of Agriculture.

[5]Among the fire adaptations of pond pine are its ability to produce viable seed at an early age, its serotinous cones, and its ability to sprout from both the root collar and the bole following defoliation by fire.

Table 1.--The Air Force Bomb Range Fire: Development, behavior, control, fuels, and weather between March 22 and 26, 1971

MONDAY, MARCH 22, 1971

Burning period (e.s.t.)	Fire status and control activities	Fire size, fuel, weather, and fire behavior
1028-1100		
1028	Fire ignited in dead brush and cured grass by practice bomb.	Fire size: 8 acres (3 ha.)
1043	Bomb range closed.	Fuels: Type[1]--GB-7
1047	Two cross-country vehicles manned by 5 men and equipped with portable pumps arrive at fire.	Weight--6.2 tons/acre (13.9 M.T./ha.)
1100	Fire crosses Center Road.	Weather at 1100:[2]
		Wind--W20, gust 30 m.p.h. (W9, gust 13 m./sec.)
		Temp.--70° F. (21° C.), RH--34 percent
		Fire behavior:
		Rate of spread--0.4 m.p.h. (0.5 km./hr.)
		Intensity[3]--835 B.t.u./ft./sec. (6,897 cal./cm./sec.)
		Total intensity[3]--0.03 x 10^7 B.t.u./sec. (7.6 x 10^7 cal./sec.)
1101-1226		
1130-1150	Two tractor-plow units arrive along Center Road and attack flanks. North flank soon becomes too hot for direct attack.	Fire size: 155 acres (63 ha.)
1215	Crew starts suppression fire along Perimeter Road. Air observer arrives over fire.	Fuels: Type[1]--GB-7
1226	Fire crosses Perimeter Road and begins crowning through young pond pine.	Weight--6.2 tons/acre (13.9 M.T./ha.)
		Weather at 1200:[4]
		Wind--WSW20, gust 30 m.p.h. (WSW9, gust 13 m./sec.)
		Temp.--71° F. (22° C.), RH--28 percent
		Fire behavior:
		Rate of spread--0.5 m.p.h. (0.8 km./hr.)
		Intensity[3]--1,042 B.t.u./ft./sec. (8,606 cal./cm./sec.)
		Total intensity[3]--0.18 x 10^7 B.t.u./sec. (45.4 x 10^7 cal./sec.)
1227-1439		
1230	Formation of an intermittent convection column begins.	
1245	Two Snow airtankers arrive and begin dropping retardant along the north flank. Retardant application discontinued because ineffective, and retardant planes placed in a hold pattern to be used for emergency drops.	Fire size: 2,094 acres (847 ha.)
		Fuels: Type[1]--RB-10, R-14, GB-7
		Weight--11.6 tons/acre (25.9 M.T./ha.)
		Weather at 1400:[4]
1439	Suppression firing crew reports from Jackson Road that fire has crossed Road.	Wind--SW15, gust 20 m.p.h. (SW7, gust 9 m./sec.)
		Temp.--72° F. (22° C.), RH--25 percent
		Fire behavior:
		Rate of spread--1.8 m.p.h. (2.9 km./hr.)
		Intensity[3]--7,006 B.t.u./ft./sec. (57,870 cal./cm./sec.)
		Total intensity[3]--2.81 x 10^7 B.t.u./sec. (708 x 10^7 cal./sec.)
1440-1537		
1440	Fire continues to crown through 13-year-old pond pine.	
1500	Fire crosses wet area between Jackson and Navy Shell Roads.	Fire size: 2,975 acres (1,204 ha.)
1537	Suppression firing crew reports from Navy Shell Road that fire has crossed Road.	Fuels: Type[1]--P-14, RB-10, R-14, GB-7
		Weight--10.8 tons/acre (24.3 M.T./ha.)
		Weather at 1500:[4]
		Wind--SW15, gust 20 m.p.h. (SW7, gust 9 m./sec.)
		Temp.--71° F. (22° C.), RH--25 percent
		Fire behavior:
		Rate of spread--0.8 m.p.h. (1.3 km./hr.)
		Intensity[3]--2,918 B.t.u./ft./sec. (24,102 cal./cm./sec.)
		Total intensity[3]--2.74 x 10^7 B.t.u./sec. (690 x 10^7 cal./sec.)

[1]Fuel types are listed in the table by descending amounts of acreage. GB-7 = grass--low brush; RB-10 = medium reeds--brush; R-14 = very high reeds; P-14 = high pocosin; P-5 = low pocosin--open.

[2]On-site reading.

[3]Intensity is defined as the rate of energy release per foot of fire front. Total intensity is defined as the total energy released per second by the fire during a given time period.

[4]Weather parameters estimated from readings at nearby weather stations.

Table 1.--The Air Force Bomb Range Fire: Development, behavior, control, fuels, and weather between March 22 and 26, 1971 (continued)

MONDAY, MARCH 22, 1971

Burning period (e.s.t.)	Fire status and control activities	Fire size, fuel, weather, and fire behavior
1538-1636		
1538	Fire moves into denser fuels. About this time, surface winds back more to the south.	Fire size: 6,518 acres (2,638 ha.) Fuels: Type[1]--P-14, RB-10, R-14, GB-7 Weight--11.4 tons/acre (25.6 M.T./ha.) Weather at 1600:[4] Wind--SSW20, gust 40 m.p.h. (SSW9, gust 18 m./sec.) Temp.--71° F. (22° C.), RH--25 percent Fire behavior: Rate of spread--4.7 m.p.h. (7.6 km./hr.) Intensity[3]--18,116 B.t.u./ft./sec. (149,638 cal./cm./sec.) Total intensity[3]--11.44 x 10^7 B.t.u./sec. (2,883 x 10^7 cal./sec.)
1545	Convection column is maintained and builds to its maximum height of 15,000 ft.	
1630	Suppression fire started along U. S. Highway 264.	
1636	Suppression firing crew reports from Highway 264 that fire is across Highway.	
1637-1745		
1700	Fuel becomes progressively wetter as the fire approaches Croatan Sound.	Fire size: 9,796 acres (3,964 ha.) Fuels: Type[1]--P-14, RB-10, R-14 Weight--11.8 tons/acre (26.4 M.T./ha.) Weather at 1700:[4] Wind--SW20, gust 30 m.p.h. (SW9, gust 13 m./sec.) Temp.--68° F. (20° C.), RH--32 percent Fire behavior: Rate of spread--1.7 m.p.h. (2.7 km./hr.) Intensity[3]--6,747 B.t.u./ft./sec. (55,730 cal./cm./sec.) Total intensity[3]--9.33 x 10^7 B.t.u./sec. (2,351 x 10^7 cal./sec.)
1745	Fire about 2 miles beyond Highway 264 burning toward the Sound.	
1746-0400		
1900	Forward rate of spread stops because of wet fuel.	Fire size: 17,386 acres (7,035 ha.) Fuels: Type[1]--P-14, R-14, Marsh grass Weight--12.1 tons/acre (27.1 M.T./ha.) Weather at 2400 on March 22, 1971:[4] Wind--SW20, gust 30 m.p.h. (SW9, gust 13 m./sec.) Temp.--60° F. (16° C.), RH--50 percent Fire behavior: Rate of spread--0.2 m.p.h. (0.3 km./hr.) Intensity[3]--816 B.t.u./ft./sec. (6,740 cal./cm./sec.) Total intensity[3]--2.46 x 10^7 B.t.u./sec. (620 x 10^7 cal./sec.)
2200	In anticipation of a 90° clockwise change in wind direction, the fire boss has crews burn out along the north side of roads located south of the fire. Very active flanking, particularly along the southeast flank.	

TUESDAY, MARCH 23, 1971

0400	Cold front passes, and anticipated shift in wind direction occurs. The plowline from Perimeter Road to near Jackson Road stops fire from running south along this part of the fire. The remainder of the south flank becomes a head fire.	
0401-0530		
0430	Suppression fires set to save the town of Stumpy Point. Citizens evacuate homes.	Fire size: 23,554 acres (9,532 ha.) Fuels: Type[1]--P-14, P-5, R-14 Weight--10.1 tons/acre (22.7 M.T./ha.) Weather at 0500:[4] Wind--N15 m.p.h. (N7 m./sec.) Temp.--55° F. (13° C.), RH--80 percent Fire behavior: Rate of spread--1.3 m.p.h. (2.1 km./hr.) Intensity[3]--4,427 B.t.u./ft./sec. (36,567 cal./cm./sec.) Total intensity[3]--8.67 x 10^7 B.t.u./sec. (2,184 x 10^7 cal./sec.)
0500	Fire runs into marshy area and stops 100 yards (90 m.) short of Stumpy Point.	
0530	Fire crosses Lake Worth Road, runs out of dry fuel, and dies.	

[1]Fuel types are listed in the table by descending amounts of acreage. GB-7 = grass--low brush; RB-10 = medium reeds--brush; R-14 = very high reeds; P-14 = high pocosin; P-5 = low pocosin--open.

[2]On-site reading.

[3]Intensity is defined as the rate of energy release per foot of fire front. Total intensity is defined as the total energy released per second by the fire during a given time period.

[4]Weather parameters estimated from readings at nearby weather stations.

Table 1.--The Air Force Bomb Range Fire: Development, behavior, control, fuels, and weather between March 22 and 26, 1971 (continued)

Burning period (e.s.t.)	Fire status and control activities	Fire size, fuel, weather, and fire behavior
TUESDAY, MARCH 23, 1971		
0531-1800 0900	Mobile fire camp set up at Stumpy Point. Acreage lost during remainder of day because of flanking along northern perimeter. Fire control efforts directed toward line construction along the north flank. A canal running due east from Highway 264 is reinforced with retardants. Line construction is exceedingly difficult, with as many as 5 tractor-plow units bogged down at one time.	Fire size: 24,600 acres (9,955 ha.) Fuels: Type[1]--P-14 Weight--11.8 tons/acre (26.4 M.T./ha.) Weather at 1300:[2] Wind--N12 m.p.h. (N5 m./sec.) Temp.--49° F. (9° C.), RH--50 percent Fire behavior: See fire status opposite
WEDNESDAY, MARCH 24, 1971		
0001-2400	Control activities directed toward burning out along the north side of the fire. A boat is sent down the canal to the Sound with orders to burn out south of the canal. The burnout operation is not completely successful as a result of higher humidities and the high water table. Several areas are partially burned out, as shown on the photo mosaic (fig. 3).	Fire size: 29,300 acres (11,857 ha.) Fuels: Type[1]--Marsh grass, GB-7, P-14 Weight--7.3 tons/acre (16.3 M.T./ha.) Weather at 1300:[2] Wind--N16 m.p.h. (N7 m./sec.) Temp.--45° F. (7° C.), RH--51 percent Fire behavior: See fire status opposite
THURSDAY, MARCH 25, 1971		
0001-2400	Activities concentrated on strengthening and holding the fire perimeter. Anticipated change in wind direction to the east does not occur. (Orientation of the flanks is the same with a NE wind as with a SW wind.)	Fire size: 29,300 acres (11,857 ha.) Weather at 1300:[2] Wind--NE8 m.p.h. (NE4 m./sec.) Temp.--44° F. (7° C.), RH--30 percent
FRIDAY, MARCH 26, 1971		
0001-1000	With the occurrence of 0.75 inch of precipitation in the form of rain and snow, the fire is declared controlled. (Another 1.28 inches fell the next day.) However, a number of ground fires are still burning, and an additional week of mopup is required before the fire is officially out.	Fire size: 29,300 acres (11,857 ha.) Weather at 1300:[2] Wind--NE18 m.p.h. (NE8 m./sec.) Temp.--50° F. (10° C.), RH--100 percent Precipitation--0.75 inch

[1] Fuel types are listed in the table by descending amounts of acreage. GB-7 = grass--low brush; RB-10 = medium reeds--brush; R-14 = very high reeds; P-14 = high pocosin; P-5 = low pocosin--open.

[2] On-site reading.

[3] Intensity is defined as the rate of energy release per foot of fire front. Total intensity is defined as the total energy released per second by the fire during a given time period.

[4] Weather parameters estimated from readings at nearby weather stations.

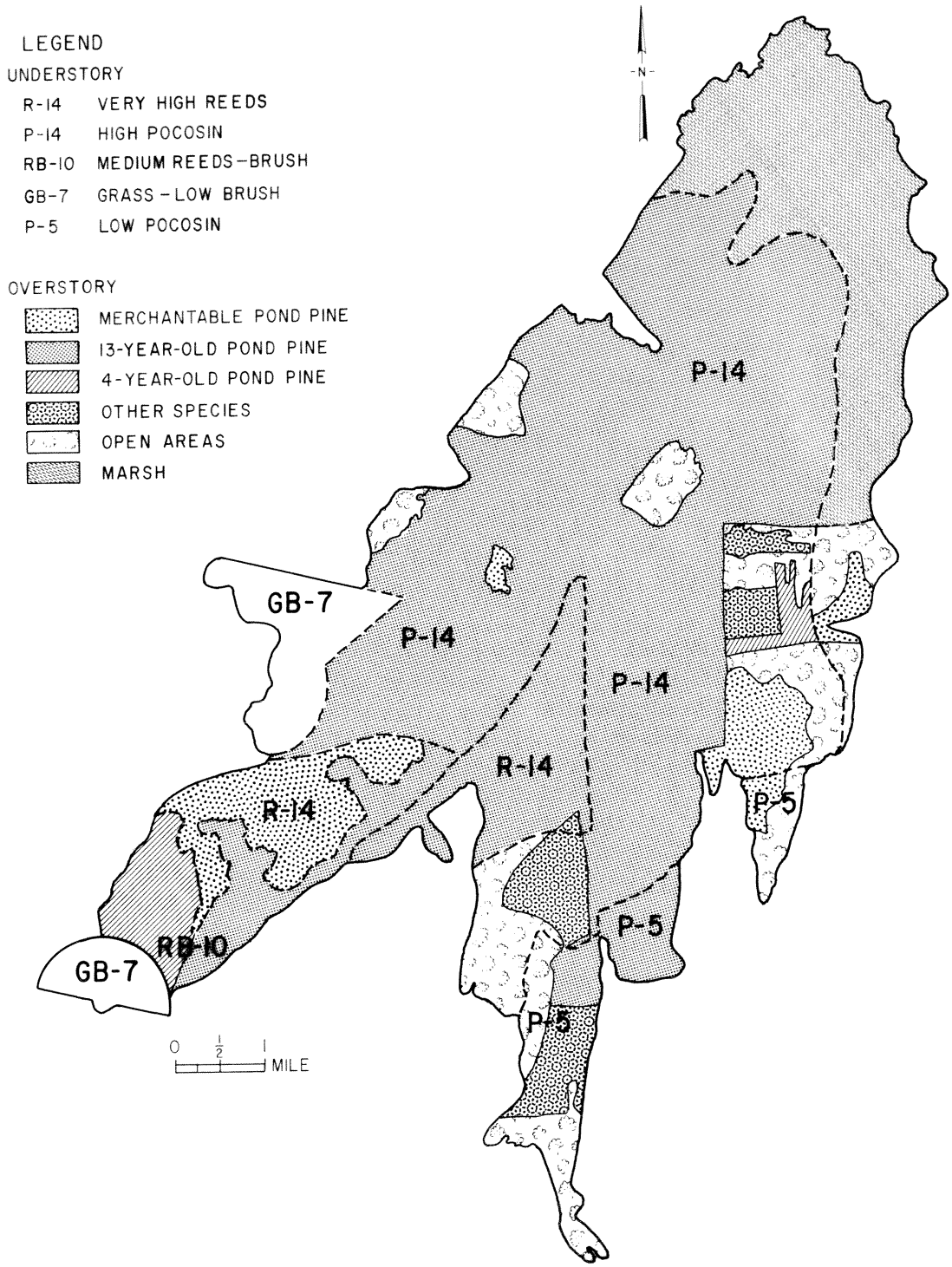

Figure 4.--Understory fuels and timber types on the burned area. [Understory map adapted from Wendel et al. (12). Overstory map adapted from: Honnold, Clark D. Damage appraisal, Westvaco Corporation lands, Dare County, North Carolina. 27 pp. 1971. (Appraisal rep., Appraisal contract DACA21-71-C-0071.)]

Table 2.--Weight, height, and blowup potential for five of the more common fuel types burned

Fuel type[1]	Fuel weight before burn[1,2]	Fuel weight after burn[3]	Blowup potential[1,4]	Average height of understory fuel
	lb./acre (kg./ha.)	lb./acre (kg./ha.)		ft. (m.)
P-14, high pocosin	25,600 (28,700)	2,000 (2,250)	3.4 (med. high)	14 (4.3)
R-14, very high reeds	30,900 (34,650)	2,100 (2,350)	5.8 (med. high)	10 (3.0)
RB-10, medium reeds--brush	21,900 (24,550)	2,100 (2,350)	2.8 (med.)	5 (1.5)
GB-7, grass--low brush	12,900 (14,450)	[5]500 (550)	1.1 (med. low)	3 (.9)
P-5, low pocosin--open	12,800 (14,350)	[5]2,000 (2,250)	1.1 (med. low)	2-3 (.6-.9)

[1]After Wendel et al. (12).
[2]Includes all understory vegetation, aerial and ground litter, and overstory needles.
[3]Estimated from a dozen $\frac{1}{4}$-milacre (1.01-m.^{2}) samples collected after the burn.
[4]Blowup potential for a given type of firebrand is the quotient of the ember lifting power of a fire in a fuel type of known weight per unit area and the ember lifting power of another fire burning in the same fuel type with the same heat yield and rate of spread but having a fuel weight of 6 tons/acre (13.5 M.T./ha.).
[5]Visual estimate.

Most pocosin shrubs are evergreen; their foliage and stems reach a minimum annual moisture content between 70 and 100 percent immediately prior to the initiation of new growth, which usually takes place in early April (2). The flammability of pocosin understory fuels was aptly summed up by Blackmarr and Flanner (2, p. 1), who stated that they form "... a dense, relatively homogeneous mixture of finely divided fuel particles suspended just above the litter." One of the striking features of the area was the large amount of needle drape providing vertical continuity of the fine fuel to the top of the overstory.

Fuels on the Air Force Bomb Range target area were classed as type GB-7 (grass--low brush) and weighed about 6 tons/acre (13.9 M.T./ha.). No overstory was present. Both NE and NW quadrants of the target area had been sprayed with herbicides during the summer of 1969. A prescribed burn was conducted on the area during the following winter, but the fire was of very low intensity and did not cover much of the area. Thus, most of the desiccated shrubs on these quadrants were still standing. Grass on the area was also very flammable because it was still in the cured stage.

WEATHER

Weather parameters for Dare County during March 1971 showed wide fluctuations. This is a typical situation and is due, in part, to the frequent passage of cold fronts over the area during this time of the year.

Precipitation was above the 30-year norm for March, and temperatures were a few degrees below the 30-year mean.[6] Four cold fronts

[6]Data taken from charts compiled by Environmental Data Service, NOAA, and published in Weatherwise 24(1-3), 1971.

moved across the area between March 7 and 25, but only 0.5 inch (1.3 cm.) of the 4.74 inches (12 cm.) of total rainfall during March at Elizabeth City--about 30 miles (48 km.) northwest of the fire site--fell during this period. The Drought Index (7) climbed from 0 in early March to 56 on the 25th, before again returning to 0 on the 29th. The Buildup Index (9) also reached its March maximum of 30 on the 25th.

A cold front moved rapidly across Dare County on March 19, bringing cold, dry air with it. Relative humidities, which were already low, continued to decline and remained below 60 percent for the next 72 hours, with daytime minima near 25 percent. Temperatures increased on the 22nd, reaching 70° F. (21° C.) on the bomb range by 1100 e.s.t.

The low relative humidities, high temperatures, and daytime windspeeds of 15 to 20 m.p.h. (7 to 9 m./sec.) all combined to create excellent drying conditions. On the day the fire began, the Buildup Index was 28, the Spread Index (9) was 36, and the Drought Index was 54. Periodic estimates of temperatures, relative humidities (RH), and wind velocities between March 22 and 26 are given in table 1.

Upper-air windspeed profiles at dawn and dusk on March 22 at Cape Hatteras--about 30 miles (48 km.) southeast of the fire site--both showed low-level windspeed maxima with decreasing windspeeds aloft for the next several thousand feet (900 to 1,200 m.) (fig. 5). These soundings were both classified according to Byram (3) as type 2-b. They were considered adverse from the standpoint of fire control because of the decrease in windspeed above the low-level maxima and the proximity of the maxima to the surface.

The data on temperature and relative humidity from the sounding taken at Cape Hatteras at 0615 e.s.t. are plotted in figure 6. If surface air on the bomb range at 1100 e.s.t. was displaced vertically, it would cool at the dry adiabatic lapse rate and rise to an altitude of about 7,400 ft. (2,200 m.) before coming to equilibrium with the surrounding air. The surface temperature of 70° F.(21° C.) at 1100 e.s.t. is marked by Point A on figure 6, and the line through this point depicts the temperature profile that would exist. The evening temperature profile (not shown) indicates that the afternoon mixing depth extended to nearly 9,000 ft. (2,740 m.).

Gusty surface winds were reported at the bomb range during the day, and pilots in the area experienced very bumpy flying--two strong indicators that vertical mixing was occurring in a layer near the ground. Because the atmospheric moisture represented by the tracing for relative humidity in figure 6 decreased rapidly through the first 2,600 ft. (800 m.) above the surface, vertical mixing would result in lower relative humidities near the surface. The sounding taken at Cape Hatteras at 1815 e.s.t. showed uniform relative humidities near 38 percent from 1,200 to 6,600 ft. (400 to 2,000 m.). This value is close to the average value of 36 percent for the 0615 sounding, indicating that vertical mixing in this layer did indeed occur during the day.

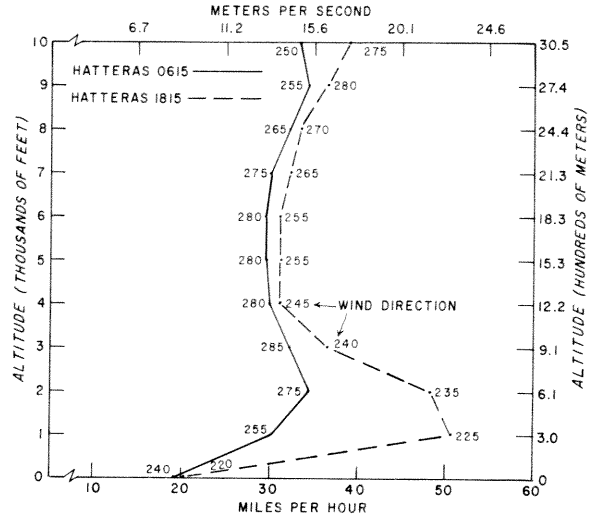

Figure 5.--Upper-air windspeed profiles at dawn and dusk of March 22, 1971, at Cape Hatteras. Wind direction is indicated by azimuth readings.

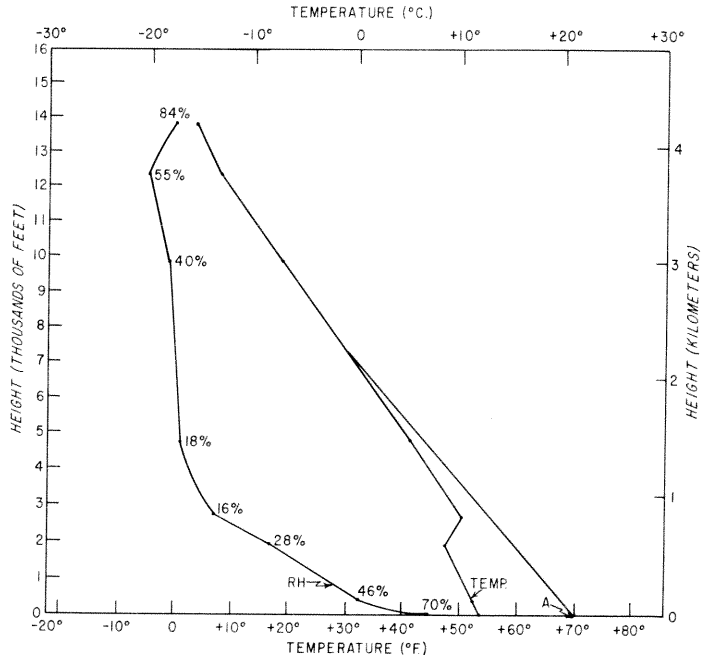

Figure 6.--Upper-air sounding taken at Cape Hatteras on March 22, 1971, at 0615 e.s.t. Point A indicates the surface temperature of 70° F. at 1100 e.s.t., and the line through this point depicts the temperature profile that would exist if the surface air was displaced vertically.

Surface winds backed from west to southwest during the day in response to changes in the surface pressure field associated with an approaching cold-frontal system. With the passage of the cold front at 0400 on the 23rd, the winds shifted to the north and drove the exposed flank of the fire south as a head fire. Scattered showers occurred ahead of the front, but rainfall was estimated to be less than 0.05 inch (0.1 cm.) and had little effect on the fire.

Winds remained northerly until the next cold front arrived over the fire 3 days later. This frontal system dumped over 1 inch (2.5 cm.) of rain and snow on the area, finally allowing fire control.

FIRE BEHAVIOR

Fire intensity (I) is defined as the rate of energy release per unit length of fire front. This rate depends upon such things as how fast the fire moves into new fuel, how much of the total fuel burns, how much energy is released when the fuel burns, and how fast the fuel is consumed (4).[7]

According to Wendel et al. (12), virtually all pocosin understory fuels are under 1 inch (2.5 cm.) in diameter. Field experience and laboratory tests indicate that most fuels under 1 inch (2.5 cm.) in diameter will be consumed within 4 minutes. Because of the short burnout time, all available fuel energy (heat yield) was considered released into the convection column. The amount of energy stored in pocosin fuels averages about 8,500 B.t.u./lb. (4,725 cal./g.) of fuel. An average moisture content of 70 percent was assumed for the fuel complex. The heat needed to vaporize the water in the fuel, the heat lost because of radiation, and the energy not freed because of incomplete combustion were all subtracted, resulting in an approximate heat yield of 5,000 B.t.u./lb. (2,780 cal./g.) of fuel consumed.

Calculated fire intensities per foot (cm.) of fire front, as well as rates of spread, fuel weights, and total fire intensities can be found in table 1. Rate of fuel consumption in tons/sec. can be derived for each time period by multiplying total fire intensity in B.t.u./sec. by 10^{-7}. Areas of major fuel types burned are listed by time period in table 3. These areas were used to calculate the average values for fire behavior during each time period given in table 1.

While the fire was still on the target area, computed fire intensity surpassed the 1,000 B.t.u./sec./ft. (8,260 cal./sec./cm.) value Byram (4) suggested as a maximum for the majority of wildfires. The air observer estimated the smoke plume to be 5,000 ft. (1,525 m.) high and building rapidly when the fire crossed Perimeter Road. Short-distance spotting was already occurring.

Upon entering the 4-year-old pine reproduction across Perimeter Road, the fire moved into the tree crowns. About 1,000 acres (405 ha.) of this dense, 6- to 8-ft.-tall (1.8- to 2.4-m.) reproduction were burned. The crown fire then continued toward Jackson Road through 1,350 acres (545 ha.) of older pond pine that had survived the 1957 fire; these pines were intermixed with 650 acres (260 ha.) of 13-year-old pond pine. Understory fuel type R-14 (very high reeds) was associated with the merchantable pond pine, and type RB-10 (medium reeds--brush) was associated with the remainder. Computed fire intensities ranged from 6,000 B.t.u./sec./ft. (49,560 cal./sec./cm.) in fuel type RB-10 to

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[7] $I = Hwr$

where: I = fire intensity, B.t.u./sec./ft. (cal./sec./cm.)
H = heat yield, B.t.u./lb. (cal./g.)
w = weight of available fuel, lb./ft.^{2} (g./cm.^{2})
r = rate of fire spread, ft./sec. (cm./sec.).

Table 3.--Areas of fuel types burned at specific times

Time (e.s.t.)	Location	Area burned in fuel type[1] --						Total area burned during time period	Cumulative area burned
		GB-7	RB-10	P-14	R-14	P-5	Marsh grass		
		acres (ha.)							
Monday, March 22, 1971									
1028	Fire origin	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
1100	Center Road	8 (3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	8 (3)	8 (3)
1226	Perimeter Road	147 (59)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	147 (59)	155 (62)
1439	Jackson Road	49 (20)	1,139 (461)	0 (0)	751 (304)	0 (0)	0 (0)	1,939 (785)	2,094 (847)
1537	Navy Shell Road	146 (59)	235 (95)	345 (140)	155 (63)	0 (0)	0 (0)	881 (357)	2,975 (1,204)
1636	Highway 264	218 (88)	398 (161)	2,665 (1,079)	262 (106)	0 (0)	0 (0)	3,543 (1,434)	6,518 (2,638)
1745	NE of Highway 264	0 (0)	282 (114)	2,810 (1,137)	186 (75)	0 (0)	0 (0)	3,278 (1,326)	9,796 (3,964)
Tuesday, March 23, 1971									
0400	Flanking south	0 (0)	0 (0)	6,040 (2,445)	1,350 (546)	0 (0)	200 (81)	7,590 (3,072)	17,386 (7,036)
0600	Two heads: south	0 (0)	0 (0)	3,640 (1,473)	648 (262)	1,880 (761)	0 (0)	6,168 (2,496)	23,554 (9,532)
Friday, March 26, 1971									
1000	End of fire	1,205 (488)	0 (0)	2,160 (873)	0 (0)	0 (0)	2,381 (964)	5,746 (2,325)	29,300 (11,857)
	Total	1,773 (717)	2,054 (831)	17,660 (7,147)	3,352 (1,356)	1,880 (761)	2,581 (1,045)		

[1]GB-7 = grass--low brush; RB-10 = medium reeds--brush; P-14 = high pocosin; R-14 = very high reeds; P-5 = low pocosin--open.

8,750 B.t.u./sec./ft. (72,275 cal./sec./cm.) in type R-14. We believe spotting increased in both intensity and distance until it began to exert a major influence on fire behavior and produced pulsations in the rate of energy release as the spot fires burned together. (This theory is discussed in depth in the section on patterns of fuel consumption.) The average rate of fuel consumption jumped from 0.18 ton/sec. (0.16 M.T./sec.) to 2.8 tons/sec. (2.5 M.T./sec.) as the fire burned toward Jackson Road.

The fire crossed Jackson Road at 1439 and moved into understory type P-14 (high pocosin) beneath a well-stocked stand of 13-year-old pond pine. This fuel type had the second highest blowup potential of any understory type on the burned area (table 2). However, the fire encountered a band of more mesic conditions between Jackson Road and Navy Shell Road, resulting in a decrease in fire intensity and a slight reduction in the average rate of fuel consumption to 2.7 tons/sec. (2.4 M.T./sec.). Only active flanking on the north side of the fire prevented a further decrease in the rate during this period.

The fire left this mesic area and ran into a much heavier quantity of fuel as it crossed Navy Shell Road. When the 1957 fire was burning in this same area, it was extinguished by showers southwest of Navy Shell Road, but no rain occurred northeast of the Road. Thus, the organic soil was consumed to depths of 1 ft. (0.3 m.) or more, creating an excellent seedbed northeast of the road. Southwest of the road, many of the existing pond pine rootstocks survived and sprouted, also creating a well-stocked stand, but it was less than one-half the density of the one northeast of the road. The understory was type P-14 (high pocosin) on both sides of Navy Shell Road, but it was noticeably more vigorous on the northeast side.

As the Air Force Bomb Range Fire crossed Navy Shell Road, the southwesterly surface winds pushed the exposed north flank into the heavier fuels. Thus, total fire intensity increased because of the greater amount of available fuel per unit area and the larger area of fire front. The convection column was rapidly pushed higher, and fuels such as pine cones and dead branches that had been acting as firebrands were ejected from the column at such heights that most of them burned out before landing.

Spotting density and patterns were difficult to observe because of the heavy smoke ahead of the fire. The air observers did report a multitude of firebrands in the convection column and a number of spot fires, but all were within one-half mile (0.8 km.) of the head. This spotting was partially responsible for the fire traveling the $4\frac{1}{2}$ miles (7.2 km.) to U. S. Highway 264 in less than 1 hour. Neither ground nor aerial observers noted any fire whirls on the fire.

An average intensity of over 18,000 B.t.u./sec./ft. (1.49×10^5 cal./sec./cm.) of fireline and a total energy release rate of 1.144×10^8 B.t.u./sec. (2.883×10^{10} cal./sec.) were calculated for this time

period.[8] The rate of fuel consumption reached 11.4 tons/sec. (10.3 M.T./sec.), its maximum value, and the fire more than doubled in size during this hour. The convection column extended to about 15,000 ft. (4,570 m.), where it was topped with a characteristic cap cloud.

After crossing Highway 264 at about 1635, the fire continued its run northeast, reaching Croatan Sound later that evening. The southwest winds driving the fire did not diminish that evening, and the fire flanked and crowned through more than 10,000 acres of pond pine, plantations of other coniferous species, and low, open pocosin during the night.

The cold front finally passed over the fire area about 0400 e.s.t., and the winds shifted to the north at 10 to 15 m.p.h. (4 to 7 m./sec.). Roughly 6 miles (9.7 km.) of flank became a head fire. Two main heads formed and ran parallel to each other, separated by Highway 264 which also runs in a north-south direction. The head east of Highway 264 tapered into a narrow prong and eventually stopped within 100 yards (90 m.) of the town of Stumpy Point. The fuel type changed from high pocosin under a pond pine overstory to a low pocosin with scattered pond pine about 2 miles (3.2 km.) north of Stumpy Point, and the area became progressively wetter until combustion could no longer be sustained.

The other head was bounded on the west by the band of very wet terrain that had slowed the fire the preceding afternoon and on the east by Highway 264. Intensity was calculated to be 4,427 B.t.u./sec./ft. (36,567 cal./sec./cm.) of fireline, and rate of fuel consumption was 8.7 tons/sec. (7.9 M.T./sec.). This head also ran into an open, marshy area the morning of the 23rd--bringing the period of major fire spread to a finish.

CONVECTION NUMBERS

High temperatures of the gases in and just above the flames make these gases lighter than the surrounding air. Because of their buoyancy, these gases rise and entrain cool air, which reacts with vaporized fuel to form additional combustion products. Thus, buoyancy is the driving force through which thermal energy of the fire is converted to kinetic energy of motion in the convection column.

Byram (4) has developed a theory for predicting the behavior of blowup fires on the basis of the ratio of the rate of conversion of thermal energy into kinetic energy in the smoke plume to the rate of flow of

[8]For comparison, the Sundance Fire, which burned over 50,000 acres (20,230 ha.) in northern Idaho in 9 hours, had a maximum calculated intensity of 22,500 B.t.u./sec./ft. (1.86×10^5 cal./sec./cm.) (1).

kinetic energy in the wind field. This ratio is called the convection number and is depicted by the symbol N_C.[9]

When N_C is greater than unity for a considerable height above the fire, the rate of energy conversion in the convection column surpasses the energy flow in the wind field. The fire will change from a forced convection system to a free convection system and may exhibit violent, unpredictable behavior. When the ratio falls well below unity, a smoke plume rather than a convection column exists and the energy flow in the wind field will dictate fire behavior. Analysis of numerous case histories of wildfires has led Byram (4) to the following observations:

1. N_C is usually greater than unity for a vertical distance of at least 1,000 ft. (300 m.) before a blowup fire can occur.

2. The condition most favorable to the sudden growth of the convection column occurs when N_C is greater than unity high above the fire. This condition is usually associated with a low-level windspeed maximum within 1,500 ft. (450 m.) of the surface.

3. Erratic fire behavior may occur in the transition zone as N_C approaches unity.

4. The vertical structure of the column is determined by the values of N_C rather than by the actual fire intensity and windspeed.

Several underlying assumptions must be made when using the convection number concept. The atmosphere should be neutrally stable, long-distance spotting should not affect rate of spread, released fuel energy should flow into a single convection column, and adequate data on fuels, weather, and fire behavior must be available. The absence of data concerning the vertical wind profile during the fire's run on Monday afternoon is the only major problem in using the N_C ratio on the Air Force Bomb Range Fire. Using morning and evening soundings from off-site stations to obtain results representative of afternoon conditions involves several risks. Recognizing the shortcomings of this procedure, we performed a straight-line interpolation of the dawn and dusk soundings on March 22 at Cape Hatteras to obtain a noontime windspeed profile.

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[9] $N_C = P_f / P_w$ where $P_f = I/C_p(T_o + 459)$ and $P_w = p(v-r)^3/2g$

where:
- N_C = convection number
- P_f = rate at which the buoyant gases of the convection column do work at any height $\mathcal{Z}$ as they ascend above the fire, ft.-lb./sec./ft.^{2} (kg.-m./sec./m.^{2})
- P_w = rate of flow of kinetic energy in the wind field at height $\mathcal{Z}$ above the fire, ft.-lb./sec./ft.^{2} (kg.-m./sec./m.^{2})
- I = fire intensity, B.t.u./sec./ft. (cal./sec./cm.)
- C_p = specific heat of air at constant pressure, B.t.u./lb./°F. (cal./kg./°C.)
- T_o = free-air temperature at the elevation of the fire, °F. (°C.)
- p = density of air at height $\mathcal{Z}$, lb./ft.^{3} (kg./m.^{3})
- v = windspeed at height $\mathcal{Z}$, ft./sec. (m./sec.)
- r = forward rate of spread of the fire, ft./sec. (m./sec.)
- g = gravitational acceleration, ft./sec./sec. (m./sec./sec.).

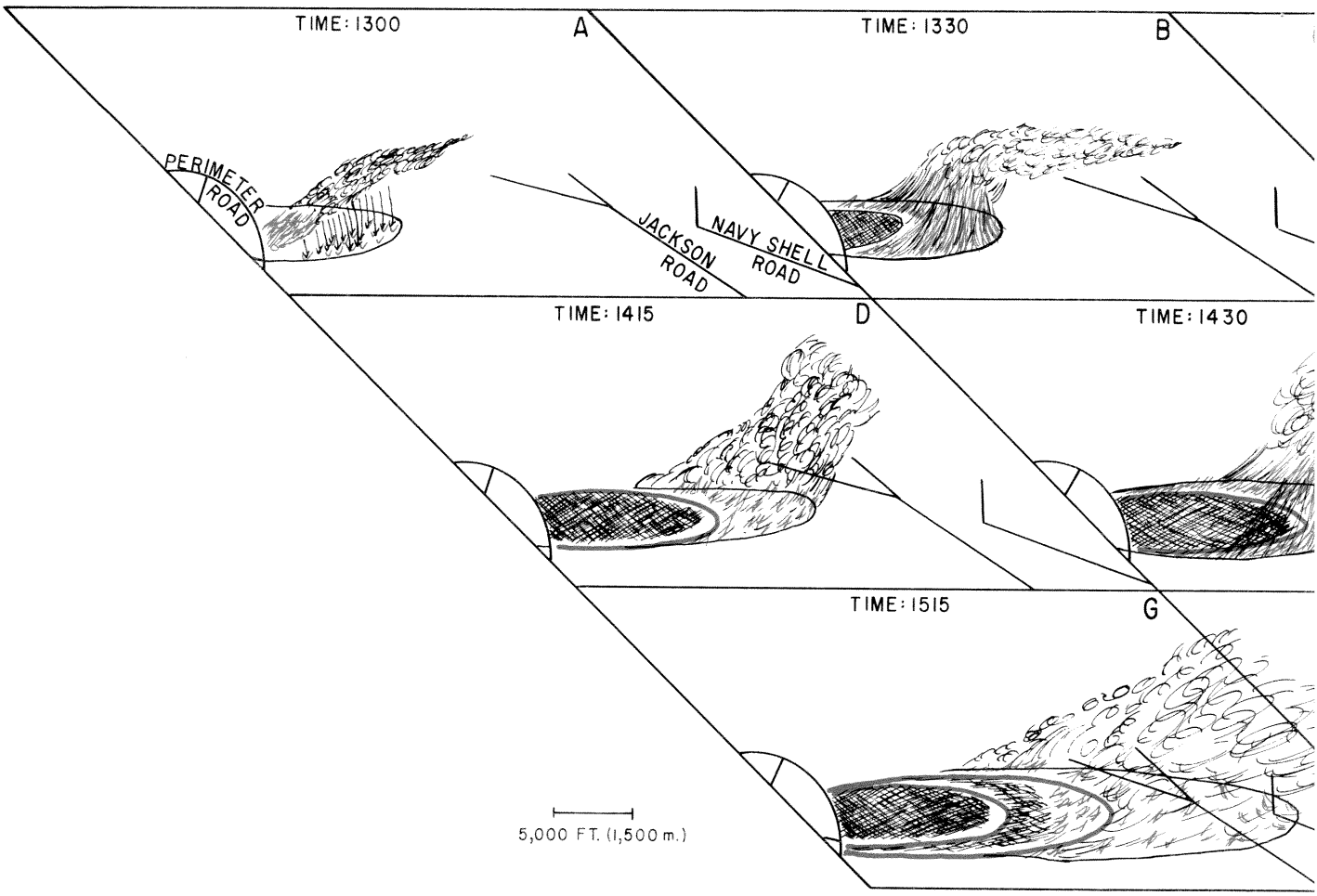
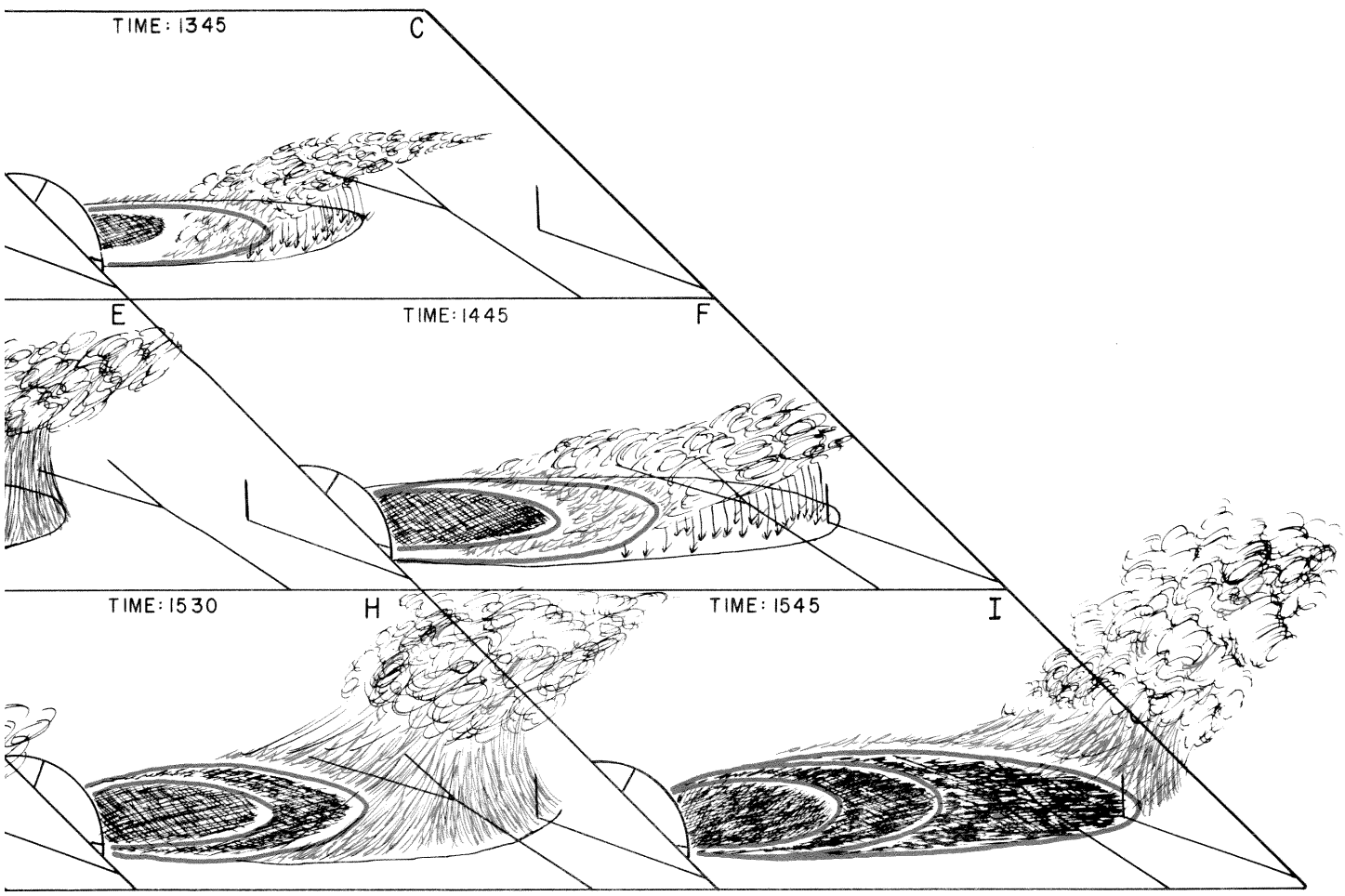

TIME: 1300
A
PERIMETER ROAD
TIME: 1330
B
NAVY SHELL ROAD
JACKSON ROAD
TIME: 1415
D
TIME: 1430
TIME: 1515
G
5,000 FT. (1,500 m.)

Figure 10.--Fire phenomena associated at various times with the formation of bands of unconsumed tree crowns as the fire progressed from Perimeter Road to Navy Shell Road. (See the text, page 23, for explanation of the drawings.)



Values of N_C at four time intervals on Monday afternoon were computed from the interpolated data on the wind profile (fig. 7). Actual N_C values fluctuated widely from the plotted averages because of pulsations in the rate of energy release. The times indicated in figure 7 are the approximate midpoints of the selected burning periods indicated in table 1. Reference to figure 7 and table 1 shows that the rise in surface N_C values paralleled the rise in fire intensity. Interpretation of figure 7 in conjunction with table 1 suggests the fire blew up when the N_C ratio increased to near unity. At 1610, N_C was greater than unity throughout an 8,000-ft. (2,400-m.) layer over the fire except at the low-level wind maximum. The fire had become 3-dimensional, as evidenced by the well-formed convection column that extended to about 15,000 ft. (4,500 m.) and a fuel consumption rate that exceeded 11 tons/sec. (10 M.T./sec.).

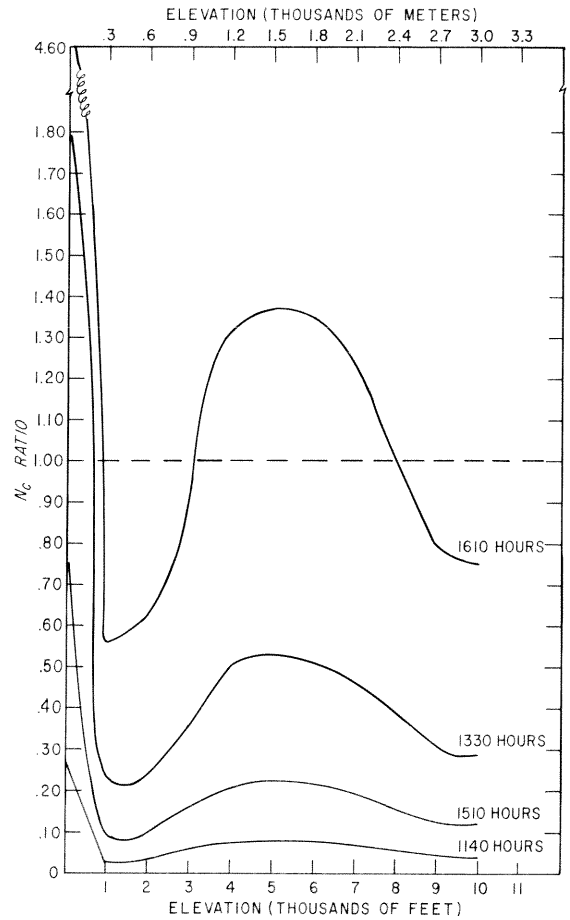


Figure 7.--Average N_C values at various heights and at four time intervals on Monday afternoon, March 22, 1971. Times indicated are the midpoints of selected periods from table 1.

PATTERNS OF FUEL CONSUMPTION

Fifty-ft.-wide (15-m.) bands of unconsumed tree crowns were formed about 1 hour apart. These are clearly shown in figure 3. The shape, spacing, and orientation of these bands are related to the fire's behavior, which, in turn, is a function of fuel, weather, and topographic

variables. The Exotic Dancer Fire[10] and the Air Force Bomb Range Fire are two fires in which consumption patterns were preserved in pocosin fuels (figures 3 and 8). Both fires were noted to burn cyclically. Surges in fire intensity were accompanied by changes in the physical appearance of the convection columns. The columns alternately leaned over and then stood more erect. Smoke color also alternated between yellow when the columns were tilted to black when they straightened.

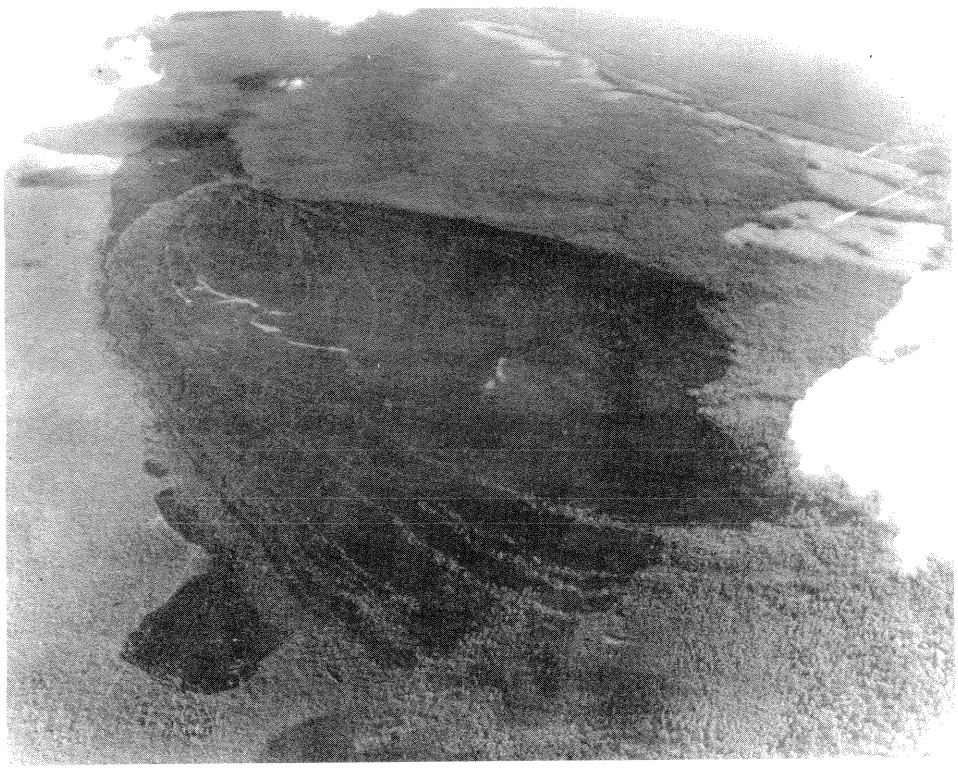


Figure 8.--Fuel patterns preserved on the Exotic Dancer Fire, which burned 2,000 acres (800 ha.) in eastern North Carolina on May 23, 1970. (Photograph by the North Carolina Forest Service.)

On the Air Force Bomb Range Fire, several types of consumption patterns occurred, including pockets of unburned fuels and concentric rings of unconsumed tree crowns outlining various portions of the fire perimeter. Several theories have been proposed for the formation of such patterns. The following five hypotheses are listed because of their probable relevance to the observed patterns, especially to the three major bands outlining the fire perimeter at different times as the fire progressed from Perimeter Road to Navy Shell Road (figures 3 and 9):

[10]Roten, Dane. Fire behavior study, Exotic Dancer Fire, Croatan National Forest. 38 pp. 1970. (Mimeogr. rep., N. C. For. Serv., Dep. Conserv. Dev.)

1. A fluctuation in wind direction for a few minutes could result in a decrease of fire intensity along one flank, with a probable increase in intensity along the opposite flank. This condition would result in the fire's backing under the tree crowns; then, as the wind resumed its original direction, active flanking and crowning would also resume. The lines of unburned fuel crossing Long Curve Road near its intersection with Navy Shell Road were probably caused by this sequence of events.

2. Windspeed could decrease below a level at which it would sustain a crown fire. If this period lasted for more than a few minutes before pre-lull windspeeds returned, the complete fire perimeter might be outlined as a result of fire spread through the surface fuels. Winds influencing the Air Force Bomb Range Fire were gusty, but winds remained above 10 m.p.h. (4 m./sec.) even between gusts.

3. The cyclic pulsations of several large fires in Japanese cities were analyzed by Yoshino (13). He found that (A) the first major run produced the greatest forward rate of spread; (B) after the initial run, lateral spread increased; (C) the accompanying decrease in forward velocity was inversely related to the initial rate of spread; (D) as burnout approached, the fires again became wind driven, achieving a second maximum rate of spread; (E) succeeding maxima in forward rate of spread were less than the initial maxima. The burnout time for wooden structures is much longer than the estimated 4 minutes for the fuels consumed in the Air Force Bomb Range Fire. Although the behavior of the latter was similar to that of the Japanese fires, the same self-regulating behavior cannot be applied to it because of this difference in burnout time.

4. Muraro speculated that pockets of unburned fuel might result from long-range spotting.[11] Ignition points in advance of the main front would tend to back toward the main fire front, as well as run with the wind--thereby forming pseudo-heads. As the main head approached the backfire, the intensity of the backfire and head would increase and the convection column would straighten as they joined. Burning embers would thus be raised faster and higher in the column, again producing long-range spotting. This mechanism could form pockets of unburned crown fuel, but the theory, although related to the behavior of the Air Force Bomb Range Fire, does not explain the observed formation of bands.

5. The unburned tree crowns outlining the entire fire perimeters of the Air Force Bomb Range and the Exotic Dancer Fires appear to be the result of the regulating mechanism that many high-intensity fires exhibit. The explanation we propose is based on the distribution of a large number of firebrands in a given pattern. The shape, spacing, and orientation of the drop pattern are functions of the height of the convection column and of the direction of the winds throughout the vertical distance through which firebrands must descend.

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[11]S. J. Muraro, Research Scientist, Can. For. Serv., Victoria, British Columbia. Personal communication, November 8, 1971.

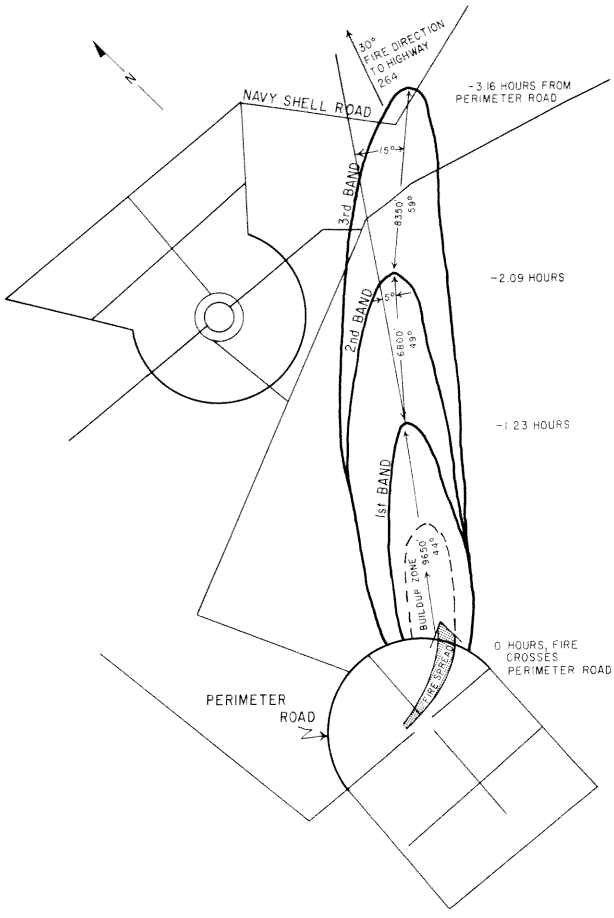

Figure 9.--Geometry of the three major bands of unconsumed fuel preserved as the fire progressed from Perimeter Road to Navy Shell Road.

Our hypothesis is supported by the cyclic, pulsating convection column that was observed to lean over and then stand erect. The spacing of the bands supports the idea that each succeeding pulsation was stronger than the last because of the larger area ignited. The orientation of the bands was to the right of the direction one would expect the fire to burn without long-distance spotting. Even young pond pines have large numbers of serotinous cones which make ideal firebrands. There was little other firebrand material available for long-distance spotting. If the concepts developed by Tarifa (10) are applied, it is reasonable to expect pond pine cones, when supported by the 35 m.p.h. (16 m./sec.) upper winds that existed over the fire, to carry fire as far as 7,000 ft. (2,100 m.) ahead of the main fire front. Greater distances would not be expected because the pine cones would probably burn out before landing.

The concept proposed here is that the Air Force Bomb Range Fire pulsated in a definite manner, as described and illustrated by the time drawings in figure 10 (see centerfold). According to the hypothesis, the first phase (fig. 10A) is marked by an increase in fire momentum, with an accompanying increase in spotting frequency and distance. Convective activity increases further, with a greater amount of spotting. No pronounced pattern of fuel consumption develops during this phase.

In the second phase (fig. 10B), the spot fires coalesce, with a higher rate of energy release. The convection column becomes well-developed, reaching an altitude of about 5,000 ft. (1,500 m.), and is loaded with pine cones which serve as potential firebrands. This strong convection column is maintained for 10 minutes at most because of the rapid burnout in the area. While the convection column is strong, the fire draws inward from all sides and the perimeter fire backs for a short time. Then, as the convection column dies down, the periphery of the fire picks up momentum as it burns under the crowns for a short distance, thereby leaving a nearly continuous band of unconsumed tree crowns.

In the third phase (fig. 10C), burnout occurs rapidly. The convection column loses its identity, and the firebrands are transported by the strong gradient winds. Those firebrands highest in the convection column are carried the greatest distance downwind and displaced the farthest to the right.

In the fourth phase (fig. 10D), the ignition points established during the previous phase begin to coalesce. The spot fires gradually increase in intensity as they become larger. As time progresses and individual spots act on one another, the rate of the rise in intensity accelerates.

In the fifth phase (fig. 10E), the second phase is repeated, with the convection column becoming stronger and reaching a greater height.

In the sixth phase (fig. 10F), the intensity decreases rapidly as available fuels are consumed. The column dissipates, emitting a shower of debris and firebrands downwind and to the right of the direction of the surface winds. As a result of the greater height of the column, the firebrands are distributed over a more extensive area lying farther to the right and stretching a greater distance downwind.

The seventh phase (fig. 10G) is a repetition of the fourth phase.

In the eighth phase (fig. 10H), a very strong convection column develops to a height of 8,000 to 10,000 ft. (2,400 to 3,000 m.). The band of unconsumed fuel created is oriented 10° south of the second band, 15° south of the first band, and may be as much as 30° from the direction of the surface winds (fig. 5).

In the ninth phase (fig. 10I), the convection column at first becomes weaker. However, it rapidly regains its structure as the open left flank is carried forward into the more abundant fuels on the north side of Navy Shell Road. The column is now sustained and reaches an estimated height of 15,000 ft. (4,600 m.) during the run to Highway 264.

The spacing and orientation of the bands of unconsumed tree crowns support the proposed hypothesis. The first band was created about 4,500 ft. (1,350 m.) in front of the head and had little, if any, displacement. The second band occurred 6,800 ft. (2,000 m.) from the first and

was displaced 5° to the right. The third band was some 8,300 ft. (2,500 m.) from the second and was displaced more than 15° from the first and more than 10° from the second (fig. 9). These displacements indicate that each surge of intensity resulted in the development of a stronger convection column that showered the area farther downwind and that each succeeding area was offset more to the right than was the area created during the previous pulse. Figure 5 shows how wind direction veered with height, causing the clockwise shift in the placement of the firebrands.

McArthur (8) has also observed fire pulsations resulting from mass spotting, but he does not mention consumption patterns. He suggests that pulsations in fire intensity occur as fuel moistures decrease toward the critical level during the day. During these pulsations, he suggests, the fire changes from a 2-dimensional to a 3-dimensional phenomenon for brief periods of time. Once this critical moisture level is passed, the fire remains 3-dimensional and no longer pulsates.

It is of interest at this point to return to the concept of the convection number (N_c), which is a method of comparing the rate the fire is doing work by thermal convection (P_f) with the work the winds are performing to overcome the thrust of the convection column (P_w). The intensity of the Air Force Bomb Range Fire conceivably fluctuated from 3,600 B.t.u./ft./sec. to over 18,900 B.t.u./ft./sec. (29,700 to 156,100 cal./cm./sec.) during the period when it progressed from Perimeter Road to Navy Shell Road (fig. 11). This hypothesis is based on the premise that the spot fires which were created after the convection column died down during any one cycle at first burned together slowly and that, during the last 10 minutes of the cycle, the fuels on 50 percent of the area were then consumed--thereby creating another strong convection column.

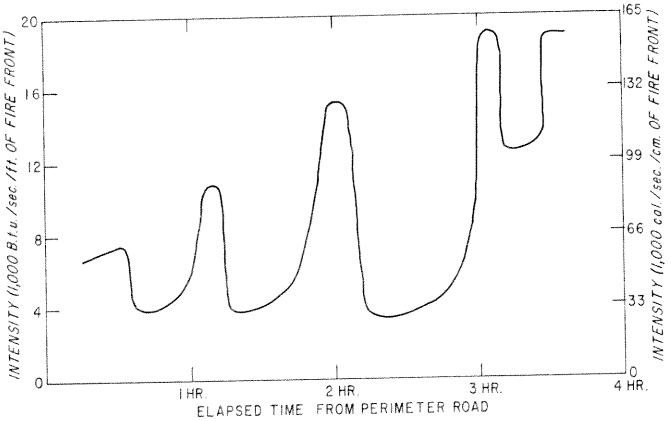

Figure 11.--Oscillations in fire intensity during the period when fuel bands were formed on Monday, March 22, after the fire crossed Perimeter Road.

In figure 12, the changes in N_c resulting from changes in intensity are plotted by height and isopleth lines are used to connect equal N_c values. This method illustrates the chance for growth of the convection

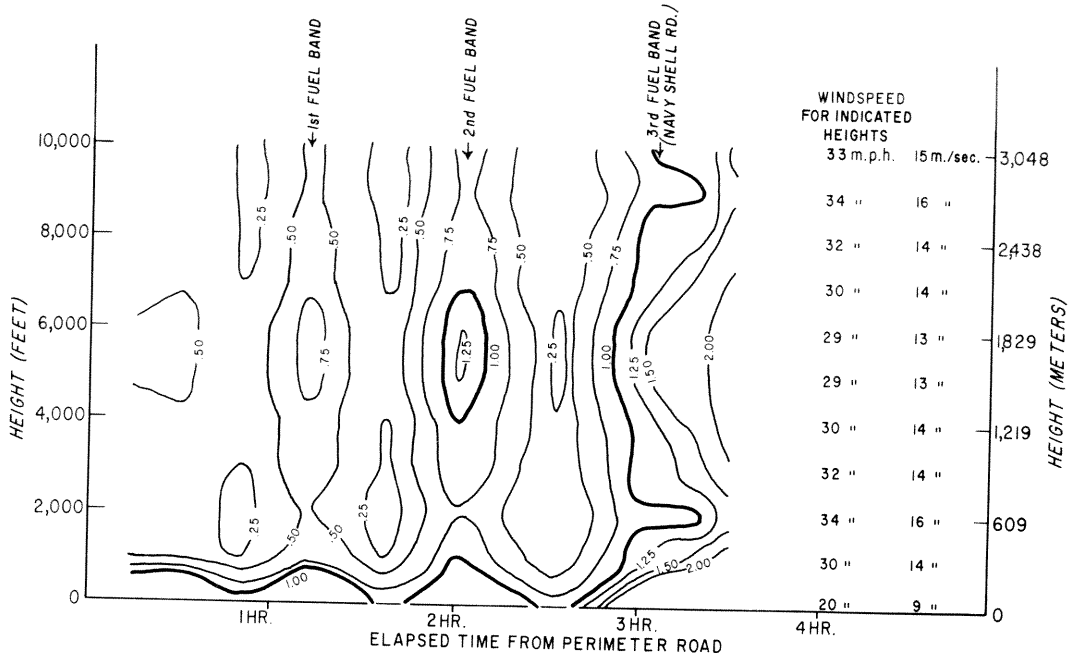

Figure 12. --Time-height cross section with isopleths connecting points of equal N_C value. These correspond to changes in fire intensity during the period when bands of unconsumed fuel were formed after the fire crossed Perimeter Road. An N_C value of 1 is depicted by the heavy isopleth lines.

column during the periods of surges in intensity. The convection column becomes most fully developed when N_C exceeds 1, which occurs when $P_f > P_w$. According to observations made at the fire site, P_f should have been greater than P_w for short periods prior to the time when the fire crossed Navy Shell Road and during the long run from Navy Shell Road to Highway 264. The 0615 sounding at Cape Hatteras (fig. 5) was used to calculate the values of N_C. It can be seen that, if the low-level windspeed maximum is reduced or the intensity of the fire is increased, N_C values will be increased. If, as might be expected, the lapse rate above the fire was actually super adiabatic because of neutral stability of the air, a parcel of rising air would pick up energy and the N_C ratio would increase. The windspeed profile Monday afternoon may have been different from the 0615 profile, but N_C values based on the 0615 profile serve to illustrate that band formation took place during peaks in fire intensity as expressed by the N_C values.

The patterns of fuel consumption exhibited by the Air Force Bomb Range Fire might occur in other areas as the result of changes in either fuels or topography. For example, a change in the vertical distribution of the fuel could obscure or destroy the patterns of fuel consumption resulting from changes in fire momentum. Homogeneous fuels, a large amount of fine fuel, a low fine fuel moisture content, and persistent weather appeared to be the critical factors associated with pulsations in both the Air Force Bomb Range and Exotic Dancer Fires.

Understanding the process of this band formation may make fire suppression more effective. Control techniques might be developed to take advantage of the time between peaks in fire intensity. There is a real danger, however, that a pulsating fire's development may be accelerated because of incorrect or poorly timed techniques of suppression firing. The effectiveness of the operation would depend on such things as the ability to accurately forecast periods of lower fire intensity as well as their durations and the areas where they would occur.

PARTICULATES AND VISIBILITY

The effect large wildfires such as the Air Force Bomb Range Fire have on visibility has not been adequately assessed. Increases in the background level of particulates on a global scale have been noted after large acreage losses during periods when numerous wildfires were burning. The effect large fires have on the reduction of visibility on a local scale can be pronounced. The effort here is to estimate the average concentration of particulates contained in a vertical cross section of the plume.

Because accurate emission factors are not available for wildfires burning in pocosin fuels, it was necessary to extrapolate laboratory findings from loblolly pine needles. In the laboratory, it was found that a slow-moving backfire produces about one-third as many particulates as a head fire. These data indicate that head fires produce about 60 lb. of particulates/ton (30 g./kg.) of fuel burned. A blowup wildfire, consuming immense quantities of fuel while producing strong indrafts and updrafts, probably entrains many times more particulates than the normal prescribed fire of low intensity. Those particulates larger than about 20 μ fall back to earth. Certainly, the larger particles in the form of limbs, pine cones, leaves, and needles fall rather quickly--probably within the first mile (1.6 km.). This fallout was documented by one of the North Carolina Forest Service pilots flying under the column at an elevation of 500 ft. (150 m.) about three-fourths mile (1.2 km.) in front of the fire. Extreme turbulence and peppering by miscellaneous debris were encountered as the plane flew under the column.

The efficiency of burning usually decreases as the rate of fuel consumption and resulting intensity increase. Laboratory studies of emission have substantiated this hypothesis. On the basis of this information, the factor of 60 lb. of particulates produced/ton (30 g./kg.) of fuel consumed was increased to 120 lb./ton (60 g./kg.) in order to more nearly conform with the fire situation at hand. During the time of the major run, the rate of fuel consumption increased abruptly to 11.5 tons/sec. (10.4 M.T./sec.). Under these conditions, the plume height about 3 miles (4.8 km.) downwind from the head was noted to be 15,000 ft.

(4,570 m.), with a lower limit of 1,000 ft. (305 m.). The plume was probably less than 7,000 ft. (2,133 m.) wide at this point. These inputs were used to calculate the average concentration of the smoke plume:

Area of plume cross section = (4,572 m. - 305 m.) x 2,133 m.

$$= 9.1 \times 10^6 \text{ m.}^2$$

Average windspeed of the vertical profile as based on the 1815 sounding at Cape Hatteras = 16.1 m./sec.

Ventilation factor = $(9.1 \times 10^6 \text{ m.}^2)$ (16.1 m./sec.)

$$= 1.46 \times 10^8 \text{ m.}^3/\text{sec.}$$

Particulate emission rate = (10,432 kg./sec.) (60 g./kg.)

$$= 626 \text{ kg./sec.}$$

$$= 6.26 \times 10^{11} \mu\text{g./sec.}$$

$$\text{Particulate concentration} = \frac{6.26 \times 10^{11} \mu\text{g./sec.}}{1.46 \times 10^8 \text{ m.}^3/\text{sec.}} = 4{,}260 \mu\text{g./m.}^3$$

Meteorological range may be a useful way of describing the net effect this concentration of particulates would have on visibility. Fritschen et al. (5, p. 21) define meteorological range as "... the visual range which would be observed if the air were perfectly homogeneous ...," that is, if the particulate size and shape were continuous throughout the plume. They used the following equation for computing meteorological range in smoke plumes:

$$\text{Meteorological range} = \frac{11.7 \times 10^5 \text{ km.}}{\text{Particulate concentration, } \mu\text{g./m.}^3}$$

If their equation is used, the meteorological range through a smoke plume with a particulate concentration of 4,260 μg./m.^{3} would be 275 m. or 900 ft. It is quite likely that the condensed water vapor and other products of combustion resulted in an even more limited visual range.

In a burn conducted to dispose of logging slash in the Pacific Northwest, Fritschen et al. (5) determined the maximum concentration of particulates 3.9 km. downwind and 0.9 to 1.6 km. in altitude to be 1,980 μg./m.^{3}. The rate of maximum energy release for their burn was about one-third the rate for the Air Force Bomb Range Fire. The average concentration of particulates 3 miles (4.8 km.) downwind from the Air Force Bomb Range Fire was at least twice the maximum concentration measured on the slash burn.

Visibility during the first 36 hours of the Air Force Bomb Range Fire was not reported to be a problem at ground level except for a 6-hour period at Cape Hatteras (fig. 1). Observers at the Cape noted a reduction in visibility to 3 miles (4.8 km.) Tuesday morning. On Tuesday, Wednesday, and Thursday nights, visibility became a severe problem along Highway 264. The problem stemmed from the combination of a low-level temperature inversion coupled with ground fires burning on the spill banks adjacent to the drainage ditches and canals. On Wednesday night, this inversion had trapped the smoke and fog in a layer roughly 5 ft. (1.5 m.) thick on the highway. Travelers driving cars through this layer of smoke and fog reported they could look out the side window and see stars above but not the roadway below. Persons walking more than 4 or 5 ft. (1 to 2 m.) ahead of these cars were completely obscured.

FIRE EFFECTS

The effect a high-intensity wildfire has on the vegetation, soils, and wildlife may appear much more severe immediately after the fire than at a later date. This generalization applies to the Air Force Bomb Range Fire. A survey of the burned area was conducted the week after the fire. In general, one would have thought a new barren had been created (fig. 13). There were carcasses of deer overrun by the fire and an obvious absence of small mammals. One wooden bridge spanning a 30-ft.-wide (9-m.) canal was destroyed along Navy Shell Road (fig. 14), and several others were saved only because of prompt action by control forces. Traffic along Highway 264 was snarled, and one accident resulted from the smoke. Luckily, ground conditions were wet and the fire stopped short of Stumpy Point.

Figure 13.--A dense stand of 13-year-old pond pine after the fire. Note the complete defoliation of the trees, consumption of the understory, and the high water table.

Figure 14.--Remains of a wooden bridge spanning a 30-ft.-wide (9-m.) canal along Navy Shell Road.

In general, pond pine and pocosin fuels have adapted well to a fire environment and usually return rapidly to pre-fire conditions after the occurrence of a wet-season fire. According to Garren's (6) classification of successional responses based on site conditions and fire frequency, one would expect little regeneration of pond pine and the creation of open areas after a dry-season fire. Neither the dry-season Dare County Fire in 1957 nor the wet-season Air Force Bomb Range Fire in 1971 followed Garren's fire successional patterns.

The Dare County Fire climaxed an extended period of drought. The fire burned for 2 weeks, consuming the organic soil to depths of 12 to 18 inches (30 to 46 cm.), thereby exposing, if not outright killing, many root systems of pond pine. Stumps remaining after the deep burning of the 1957 fire and the subsequent fire in 1971, which, in contrast, consumed little organic soil, are shown in figure 15. Comparison of the Drought Index at the time of each of these fires explains the differences in the consumption of organic soil (fig. 16). No sprouting occurred after the 1957 fire because the root systems were killed, but an excellent seedbed was created. Considerable rain also followed the fire and undoubtedly helped establish abundant regeneration of pond pine.

Pond pine sprouts readily from both the root collar and bole, and such sprouting was expected to occur after the Air Force Bomb Range Fire. Defoliation by wet-season fires generally has little effect on the survival of pond pine and causes only a temporary reduction in height and diameter growth. Dr. Maki[12] has noted that pond pine sprouts and

[12]Dr. T. E. Maki, Professor of Forestry, N. C. State Univ. at Raleigh. Personal communication, February 18, 1972.

Figure 15.--Stumps remaining after both the 1957 fire, which consumed the organic soil to depths of 12 to 18 inches (30 to 46 cm.) and exposed the root systems of the pond pine, and the Air Force Bomb Range Fire, which reburned the area but consumed little organic soil.

develops new boles from stumps less than 5 inches (13 cm.) in diameter and matures into commercial-sized trees of equal quality to those regenerated by seed. However, he has noted that, when stem diameter is larger, cambial strands from the root and bole seldom reunite.

Although no survival studies have been made for the Air Force Bomb Range Fire, the general impression upon viewing the area a year later was that a much lower percentage of trees sprouted from the bole than had been expected (fig. 17). The lack of bole sprouts is one more indicator of the high intensities associated with this fire. However, a high proportion of trees sprouted profusely from the root collar. The degree of basal sprouting suggests that a well-stocked stand of pond pine will again occupy the burned area, but the loss of 13 years' growth must be considered more than a temporary setback in a 50-year rotation.

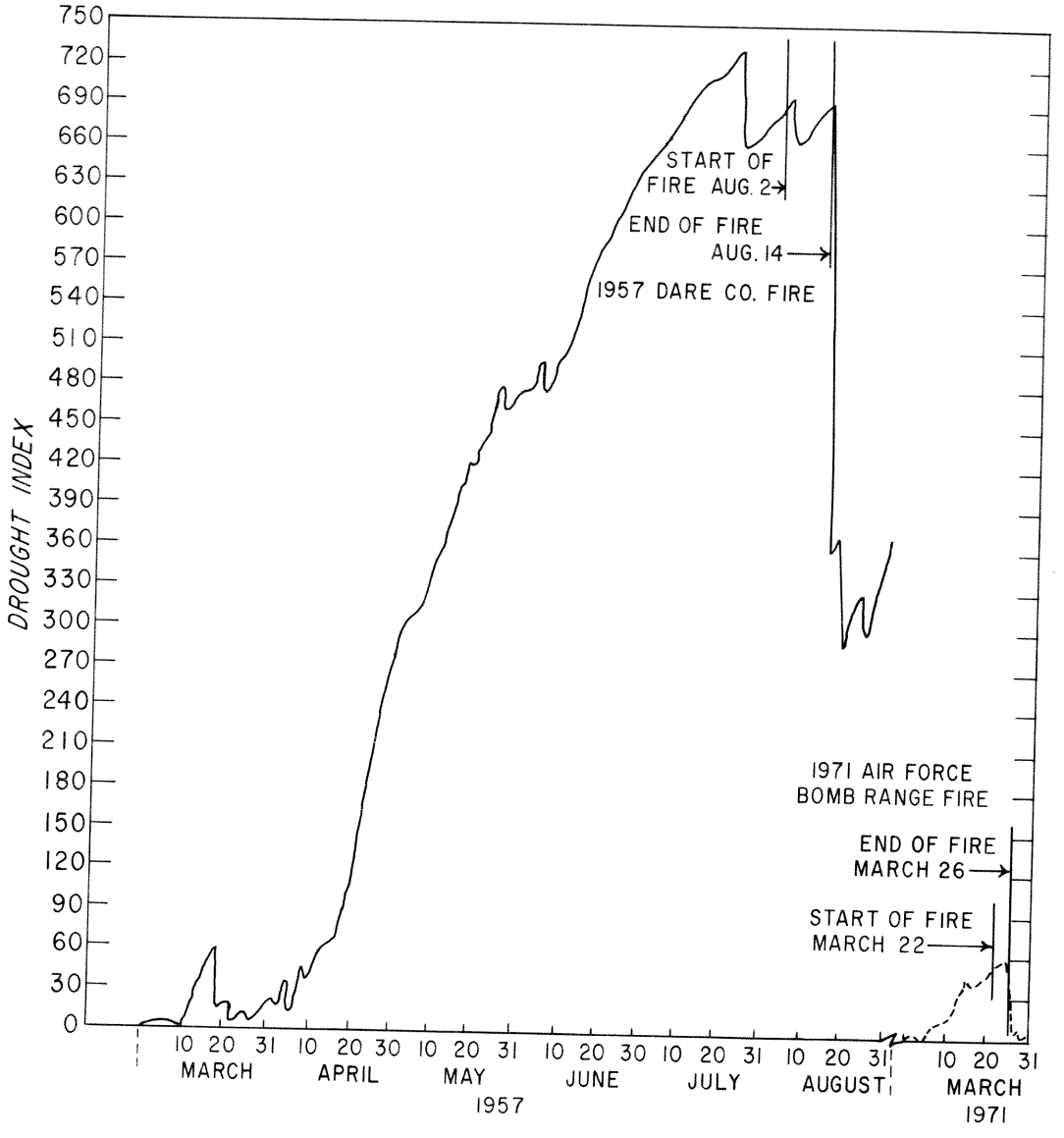

Figure 16.--Comparison of the 1957 and 1971 Drought Indices compiled from records at Elizabeth City, North Carolina.

The Army Corps of Engineers appraised the fire damage because of government liability. Clark D. Honnold,[13] the consulting appraiser, summed up the general condition of the burned area as follows: "From evidence on the ground throughout the entire fire-damaged area and including those plantations of pond pine which were hand planted or seeded, it is believed a stand at least similar to what was there before the fire will regenerate from sprouting or from seed from past seasons."

[13]Honnold, Clark D. Damage appraisal, Westvaco Corporation lands, Dare County, North Carolina, p. 4. 1971. (Appraisal rep., Appraisal contract DACA21-71-C-0071.)

Figure 17.--The burned area 1 year after the fire. Note the lack of bole sprouts, the prolific sprouting from the root collar, and the regrowth of the understory.

FIRE MANAGEMENT IN THE POCOSINS--RESEARCH NEEDS

In many respects, fire behavior in pocosin fuels remains a mystery. Facts have been slow to accumulate. Examples of unusual fire behavior are numerous. The Exotic Dancer Fire is one such example; it occurred on the Croatan National Forest some 75 miles southwest of the Air Force Bomb Range Fire. Another example of unpredictable fire behavior is described in the "Southern Region 1971 Annual Fire Report" (11, p. 15):

> "The Croatan had another high-intensity Pocosin fire on a low class day. BUI [Buildup Index] was 15 [and] SI [Site Index]-5, yet the fire burned 180 acres and ran three-quarters of a mile before being stopped. Had the fire started earlier in the day, or not met a road, it would have been much larger. We have

such limited knowledge of the Pocosin that we can offer no explanation. We can only guess that:

The actual fire conditions in the Pocosin are quite different from other areas.

Ratio of dead-to-live green fuels is deceptively high.

The pocosin fuels are always cured or in transition, never really green."

Our current fire danger rating system is not responsive to the fire potential of the pocosins. Research and development to adapt the national system to this area should have prime consideration. Beyond that, we need more information on the effects of fuel physics and chemistry on rate of burning.

The North Carolina Forest Service has made tremendous strides toward developing an effective capability of fire suppression. There is a need for continued research to determine the economics of fire suppression in the pocosins, to develop and apply advanced systems for delivering fire retardants during the day and at night, to improve methods of fire reconnaissance, to improve methods of suppression firing, to improve the accuracy of fire-weather forecasting, and to investigate the economics of fuel modification and the construction of fuel breaks.

Prescribed burning may be a solution to managing fuel buildups in the pocosins. Conditions and techniques under which accumulations of understory fuel can be reduced without damaging the pond pine overstory will need investigation. Finding the optimal approach to fire management in the pocosins will require looking into the periodicity of burning, alternatives to burning, fire protection, fire detection, and initial attack.

Case histories and documentations of fires have usually relied on human observations. In compiling such reports, these observations are checked one against another, compared with past observations, accepted or rejected, and modified where appropriate. Any single observation may offer but a small clue toward explaining the true picture of fire behavior.

Careful observations and measurements of fire parameters are needed. Equipment is already available for improving the researcher's ability to document fire behavior. Compact radiosonde units, aircraft-mounted infrared scanners, and portable stations for recording weather exist.

Fire modeling has not matured. Theories concerning convection columns, particularly those regarding entrainment of peripheral air, velocity cross sections, height of the column, dimensions of the column, the capacity to carry firebrands and particulate and gaseous contents, are fragmentary. Modeling experiments depend on the identification and measurement of critical parameters on site; only then can proper scaling be accomplished.

SUMMARY

The Air Force Bomb Range Fire started on a military bomb range in the pocosin area of eastern North Carolina and was not controlled until 4 days later. More than 23,000 acres (9,300 ha.) of the 29,300-acre (11,860-ha.) total burned during two major runs within the first 20 hours.

The fire crowned immediately upon entering a young forest of pond pine adjacent to the target area. Fire pulsations resulted in bands of unconsumed tree crowns that outlined the fire's perimeter during the first 5 miles (8 km.) of its run. After the fire crossed Navy Shell Road, its intensity increased and the convection column reached a height of about 15,000 ft. (4,570 m.) during the next hour while the fire traveled 4.5 miles (7.2 km.). Fire intensity during this 1-hour period averaged over 18,000 B.t.u./sec./ft. (148,680 cal./sec./cm.) of fireline, with a rate of total energy release of roughly 114 million B.t.u./sec. (2.883×10 cal./sec.). Fuel was consumed at a rate in excess of 11.4 tons/sec. (10.3 M.T./sec.). It was calculated that the fire produced 1,380 lb. of particulates/sec. (515 kg./sec.) during this run. Average concentration of the plume was about 4,000 $\mu g./m.^3$, with visibility in the plume considerably less than 1,000 ft. (300 m.). The fire front eventually ran out of dry fuel near Croatan Sound after traveling 14 miles (22.5 km.) in about 7 hours. Passage of a dry, cold front early the next morning resulted in a 6-mile (9.7-km.) run perpendicular to the first. This second run terminated within 100 yards (90 m.) of the town of Stumpy Point because of wet fuel.

Basically, the reasons for the fire's buildup were (A) a continuous expanse of homogeneous fuel, (B) abundant fine fuels--both live and dead, (C) low moisture content of both live and dead fuel, (D) 15 to 20 m.p.h. (7 to 9 m./sec.) winds gusting to 40 m.p.h. (18 m./sec.), (E) minimum relative humidity of 25 percent, (F) moderate-to-extreme turbulence, and (G) an adverse windspeed profile with a low-level windspeed maximum.

A theoretical parameter, N_C (the ratio of the energy in the convection column to the energy in the wind field above a fire at a given time), which was developed by Byram for predicting the potential for blowup fires, was applied to the Air Force Bomb Range Fire. It is hypothesized that, during the first 5 miles (8 km.), the buoyancy created by the fire was sufficient to override the gradient wind forces, allowing formation of a convection column for brief periods of time. During the 4.5-mile (7.2-km.) run after the fire crossed Navy Shell Road, N_C values were very large near the surface and greater than unity above the low-level windspeed maximum.

We have postulated that, after a run of less than 1 mile (1.6 km.) through the tree crowns, the fire spotted far enough ahead to allow a strong convection column to form as the spot fires coalesced. Because of the more westerly winds aloft, the firebrands in the convection column were ejected and transported to the right of the direction of the main fire. These spot fires coalesced with a higher intensity and stronger indrafts along the fire perimeter. This phenomenon resulted in the fire's

backing under the tree crowns for a short period of time. The cycle of spot fires forming to the right and then coalescing to form a strong convection column in which indrafts overrode prevailing winds occurred three times, and a 50-ft. (15-m.) band of unburned tree crowns outlining the fire perimeter was formed with each cycle.

Pond pine, especially trees smaller than 5 inches (12.7 cm.) in diameter, are well adapted to a fire environment. Even though more than 20,000 acres (9,000 ha.) of young pond pine were defoliated, it is probable that a stand of pond pine of equal quality will regenerate from basal sprouts.

A high water table during the Air Force Bomb Range Fire prevented the consumption of large quantities of organic soils but instead created other problems of fire control. The damp peat would not support the usual tractor-plow units, and final control of the fire was not achieved until over an inch of rain and snow fell on the area.

Until the behavior of blowup fires is understood, methods of controlling them will remain ineffective. The optimum role of fire in the management of pocosin fuels is unknown. As long as vast unbroken acreages containing abundant fine fuels exist in eastern North Carolina, the potential for frequent blowup wildfires will remain.

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APPENDIX

CONVERSION FACTORS FOR ENGLISH AND METRIC SYSTEMS

1 inch (in.)	2.54 centimeters (cm.)
1 foot (ft.)	0.30 meter (m.)
1 mile	1.61 kilometers (km.)
1 mile per hour (m.p.h.)	0.45 meter per second (m./sec.)
1 acre	0.40 hectare (ha.)
1 milacre	4.05 square meters ($m.^2$)
10 stems per acre	25.00 stems per hectare (stems/ha.)
1 pound (lb.)	0.45 kilogram (kg.)
1 ton	0.91 metric ton (M.T.)
1 pound per acre (lb./acre)	1.12 kilograms per hectare (kg./ha.)
1 ton per acre (ton/acre)	2.24 metric tons per hectare (M.T./ha.)
1 pound per ton (lb./ton)	0.50 gram per kilogram (g./kg.)
1 British thermal unit (B.t.u.)	252.00 gram calories (cal.)
1 British thermal unit per pound (B.t.u./lb.)	0.56 calorie per gram (cal./g.)
1 British thermal unit per second per foot (B.t.u./sec./ft.)	8.26 calories per second per centimeter (cal./sec./cm.)