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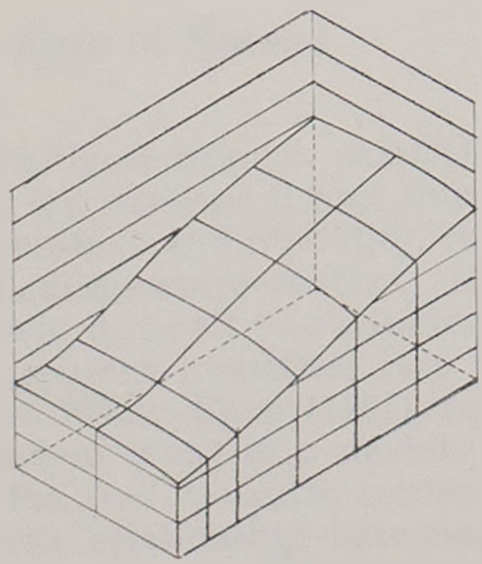

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Introduction

The direction and rate of spread of fires in forest fuels are determined primarily by wind and slope. For this reason fires normally spread faster in one direction than in others. The portion of the fire's periphery with the most rapid spread is known as the heading fire or front; that with the slowest spread, usually the opposite side, is known as the backing fire.

The objective of this study was to quantify the relationship between heading and backing rates of spread in special circumstances. These rates have not yet been well established under identical conditions. Our experiments were conducted in a wind tunnel at the Northern Forest Fire Laboratory, using a comparatively uniform, artificial fuel. Wood flour and potassium mixed in a 4-to-1 ratio proved suitable for the purpose. Future measurements will be made with natural forest fuels in both laboratory and field situations.

Ultimately, the information gathered during such experiments may be applied to wildfires as well as to prescribed burning. In either case, knowledge of the relative rates of spread of heading and backing fires can aid in predicting fire behavior; for prescribed burning it can be particularly useful in planning ignition points and sequences.

Factors Affecting Rate of Spread

Fuel Characteristics

Rate of spread of a flame front in particles of organic fuels is determined not only by windspeed and slope angle but also by environmental temperature and humidity, fuel composition, fuel bed geometry, and fuel moisture content. The characteristics of the fuel itself are most difficult to evaluate.

As fuel moisture content increases, rate of spread decreases (Byram 1957; Jacobs 1962). Fons (1961) reported that rate of forward flame spread in wood crib models varies inversely as the square root of the fuel moisture content. Anderson (1964) demonstrated a linear relationship between rate of spread in needle beds of ponderosa pine *(Pinus ponderosa)* and western white pine *(P. monticola)* and fuel moisture content within the 5-to-15-percent range.

Size and arrangement of fuel particles affect flame propagation by establishing the amount of fuel surface exposed to preheating and to air. In general, loosely distributed small particles sustain higher rates of spread than large pieces arranged in a compact mass (Byram 1957; Curry and Fons 1940; Jemison 1944). Anderson and Rothermel (1964) showed fuel particle size and fuel bed porosity to be major determinants of rate of spread.

Rate of spread increases with the quantity of available fuel per unit of area (Fahnestock 1960). Rodger (1959), working with eucalypt *(Eucalyptus* spp.) fuels in Australia, found that the heading lineal rate of spread roughly doubled for each 4-ton-per-acre increase in fuel.

Specific gravity of fuels also affects rate of spread. Bruce *et al.* (1961) reported an inverse relationship between rate of spread and the specific gravity of wood fuels. They also noted a greater rate of spread with increasing thermal diffusivity of the fuel.

Fons *et al.* (1962), using ½-inch square wood sticks in fire model studies, found that rate of spread varies with the species of wood burned. These variations may be due to the oils and resins characteristic of different tree species.

Fuel variability must be controlled in order to assess the effects of wind and slope in rate-of-spread studies. A suitable artificial fuel for small-scale experiments must be simple to prepare and easy to replicate, and must burn at a constant lineal rate. Rowland (1939) described a fuel with qualities approaching these specifications. He used a mixture of wood flour and sodium nitrate to simulate small fires for training purposes, adding the sodium nitrate in a 1-to-23 ratio to sustain combustion. In our tests, potassium nitrate was substituted for sodium nitrate to reduce spotting at high air velocities.

Windspeed

After observing 33 fires in forest fuels, Show (1919) concluded that the rate of spread in the perimeter of a fire varies as the square of the windspeed. Rodger (1958) supported Show's hypothesis following measurements of lineal spread in Monterey pine *(Pinus radiata)* needle beds. On the other hand, Curry and Fons' (1938) studies of the fire spread in ponderosa pine needles showed that the effect of wind on the rate of perimeter increase was linear, but was modified relative to moisture content. The differences in the above findings may have been due to variation in fuel densities and the position of wind-measuring instruments.

Fons (1946) analyzed the rate of spread in artificial beds of ponderosa pine needles; film conductance, or rate of heat transfer, varied approximately with the square root of windspeed. He found that most of the increase in fire spread due to windspeed is caused by the influences of moving air on the temperature ratio coefficient—an expression of the temperature gradient between the fuels away from the flame and those near the flame.

Preheating becomes greater as increasing air velocity bends the flame toward the unburned fuel. With air velocities measured at 1 foot above the fuel bed, Fons ascertained that the lineal rate of spread is about proportional to the first power of air velocities under 5 m.p.h., and to the 1.5 power for velocities from 5 to at least 12 m.p.h. The upper limit to which the 1.5 power holds was not fixed. The first-power effect for winds less than 5 m.p.h. had been confirmed in test fires under field conditions by Curry and Fons in 1938.

Anderson and Rothermel (1964), expanding upon their previous work in still atmospheres, found that increasing free air velocities to 700 feet per minute caused forward rate of spread in ponderosa pine and white pine fuel beds to advance exponentially or by power functions.

As reported by Byram (1958, 1959), the backing rate of spread also increases with windspeed but more slowly than that of the heading front. He attributed the higher backing rate to greater oxygen supply. His observations were based on tests made during prescribed fires in fairly uniform mixtures of grass and pine needles in open stands of longleaf and loblolly pine *(Pinus palustrus, P. taeda)*. There was no control of fuel moisture, and only limited data were taken on the rates of spread of the heading fronts. Byram did not attempt to draw conclusions regarding the relative rates of spread of backing and heading fires. Since the fires occurred on level ground, the effect of slope was not tested.

Slope

Slope has a strong influence on the average size of wildfires in the Intermountain West (Barrows, 1951). It has the same effect as wind in bringing the flame closer to the fuel and preheating it. As a slope becomes steeper, the average size of a fire on the slope thus becomes greater. Laboratory fires by Curry and Fons (1938) exhibited a curvilinear relationship between rate of spread and slope. In these fires the influence of slope appeared to be relatively slight at low windspeeds but grew correspondingly more important with higher windspeeds.

Humidity and Temperature

Relative humidity of the air surrounding a fire can affect rate of spread. Show and Kotok (1925) concluded that average fire size in California increased as relative humidity decreased and that the influence of wind became greater. This relationship was substantiated by Morris (1954) in observations of rates of spread in fern fires in Washington. Fahnestock (1953) determined that high humidities greatly reduced the rate of spread in light and medium logging slash but had no significant effect on fires in heavy slash. Higher temperatures of air and fuel increase combustion rate by reducing the temperature rise necessary for ignition (Fons 1946).

All these previous studies indicate that increases in windspeed and slope result in greater fire size and rate of spread, due to a reduction in the angle between flames and unburned fuels. Wind action also causes intensified mixing of air and fuels, which in turn enhances the combustion process and thereby rate of spread. In this study we attempted to control the influence of these and the many other variables affecting rate of spread and to isolate the results of changes in wind and slope on both heading and backing fires. By creating a burning front without flame, we expected to minimize convective preheating of fuels at the head.

Study Methods

We achieved uniform, flameless combustion fronts by using the mixture of wood flour and potassium nitrate mentioned previously. The wood flour was Douglas-fir *(Pseudosuga menziesii)* ground to pass a 63-micron sieve; the potassium nitrate was ground to pass a 44-micron sieve. This finely powdered oxidizer minimized sputtering during combustion. Fuels were mixed in a dry blender, then conditioned over a saturated solution of lithium chloride at 27° Celsius (80° F.). Mean fuel moisture content, as determined during the experiments, was 4.67 percent (standard deviation, 0.13 percent). Relative humidity of the atmosphere in the burning chamber was 13 percent; dry bulb temperature was 27° C.

We burned the conditioned fuels in asbestos-board trays with internal dimensions 53 cm. long, 8 cm. wide, and 0.6 cm. deep. Four trays were burned simultaneously in each of 21 test fires. The trays were arranged in four parallel rows. Small sample trays loaded with fuel were treated in the same manner as the burning trays. These samples were removed for determination of moisture content immediately before ignition.

The burning trays were placed in a frame in a 90-cm.-square wind tunnel. The tunnel was modified to ensure uniform air velocity over the surface of the fuel beds. The frame had a glass top through which photographs could be taken. Air passing through the wind tunnel was conditioned to $\pm\frac{1}{2}^\circ$ C. of the temperature of the fuel and ± 1 percent of the relative humidity necessary to maintain the fuel's moisture content. The fuel was ignited across the midpoint of the trays by a heated nichrome wire.[2]

After ignition, each fire was photographed periodically throughout its duration. Time intervals were determined from a stopwatch placed in the field of view of the camera. We calculated rates of spread from these photographs, measuring distances to the nearest millimeter by reference to a scale inked on the side of each tray.

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[2] In preliminary testing of ignition points, rates of spread were found to be identical, regardless of whether the center or both ends of a tray were ignited.

The heading and backing rates of spread in centimeters per minute were compiled for each combination of windspeed and slope in the 21 fires. Windspeeds, measured 5 cm. above the burning surface, were 0, 1, 2, 4, 6, 8, and 10 m.p.h. (0, 45, 89, 179, 268, 358, and 447 cm./sec.). Slopes of 0, 25, and 50 percent were obtained by tilting the burning trays.

Study Results

The mean rates for each combination of wind and slope are presented in Figures 1 through 3. An analysis of variance of these data is summarized in Table 1. Significant differences due to wind and slope were noted in both heading and backing directions. Also, the burning rates of the first row of beds were significantly different from those of the other three rows. The latter variation was probably caused by a slowing of the layer of air next to the tunnel wall by boundary friction. For this reason, the analysis is based on data from the three rows not so affected.

The mechanisms of heat transfer must be examined closely in order to understand why the backing fires burned as well as the heading fires at low windspeeds. Heat is conveyed from the burning edge to unburned fuel by conduction, radiation, and convection. In our experiments, we assumed that very little heat was transferred by the first means, due to the poor conductivity of wood fuels. Also, since the fuel used in these tests burned without flame, radiant transfer took place beneath the surface

Table 1—Analysis of variance of heading and backing fronts.

Source of variation	Degrees of freedom	Mean square	Sample F
Heading Fronts			
Wind	6	42.3374	993.84[1]
Slope	2	1.4132	33.17[1]
Wind × slope	12	0.4986	11.70[1]
Residual	59[2]	0.0426	
Total	79[2]		
Backing Fronts			
Wind	6	13.0694	650.17[1]
Slope	2	0.3696	18.39[1]
Wind × slope	12	0.1236	6.40[1]
Residual	63	0.0201	
Total	83		

[1]Significant at the 1-percent level.
[2]One missing item in data—degrees of freedom reduced by unity.

of the beds, yet transfer of heat by radiation appeared to be the major cause of fire spread.

The actual situation was much more complex, however, because flame action also contributes to convective heat transfer, and if flame is not present, convection is greatly weakened and the entrainment of fresh air is reduced. Fresh air is vital to the combustion process in that it both supplies oxygen to the burning fuel and removes some of the gaseous products such as carbon

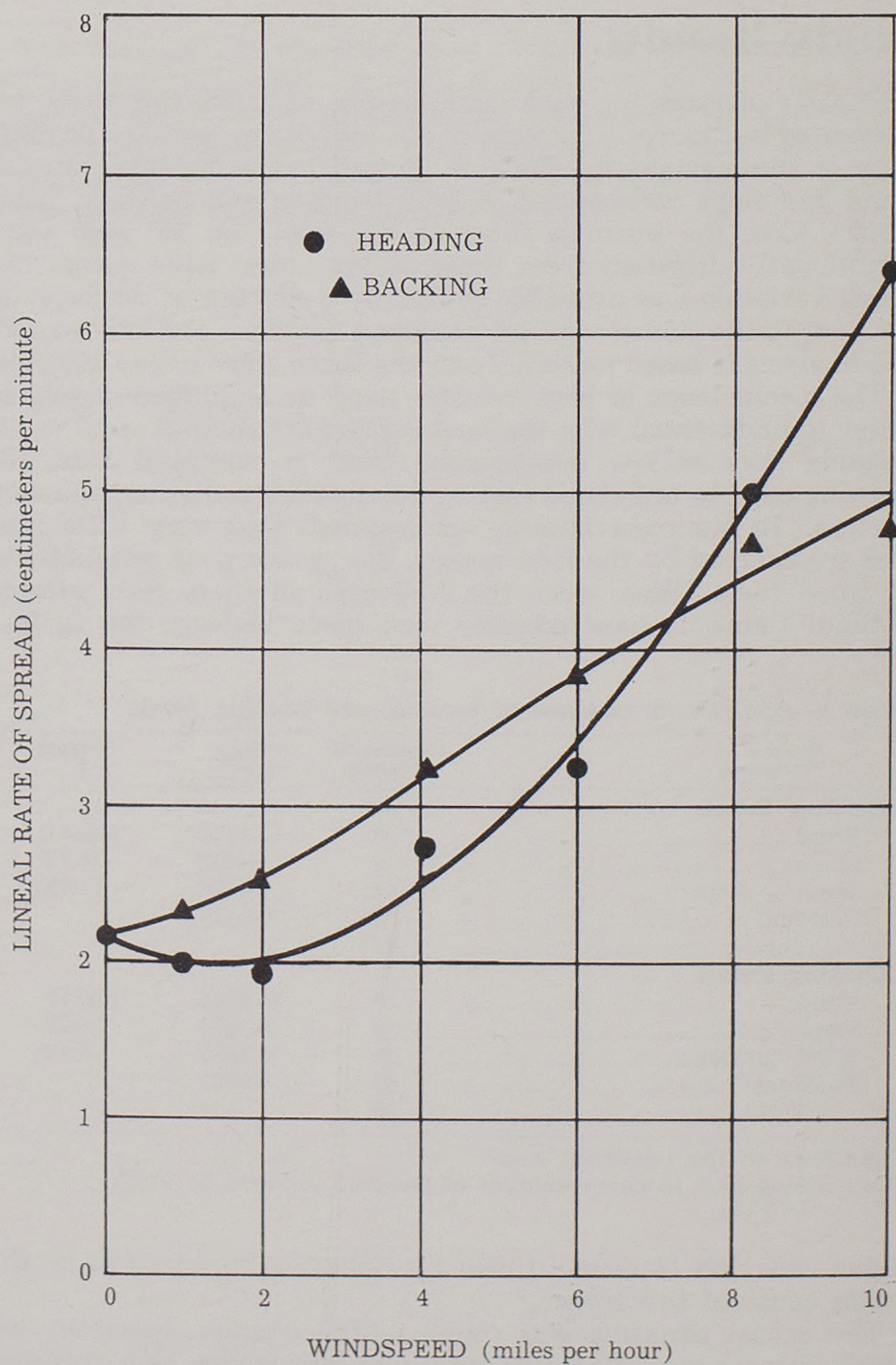

Figure 1—Rates of spread of heading and backing fires in the no-slope position.

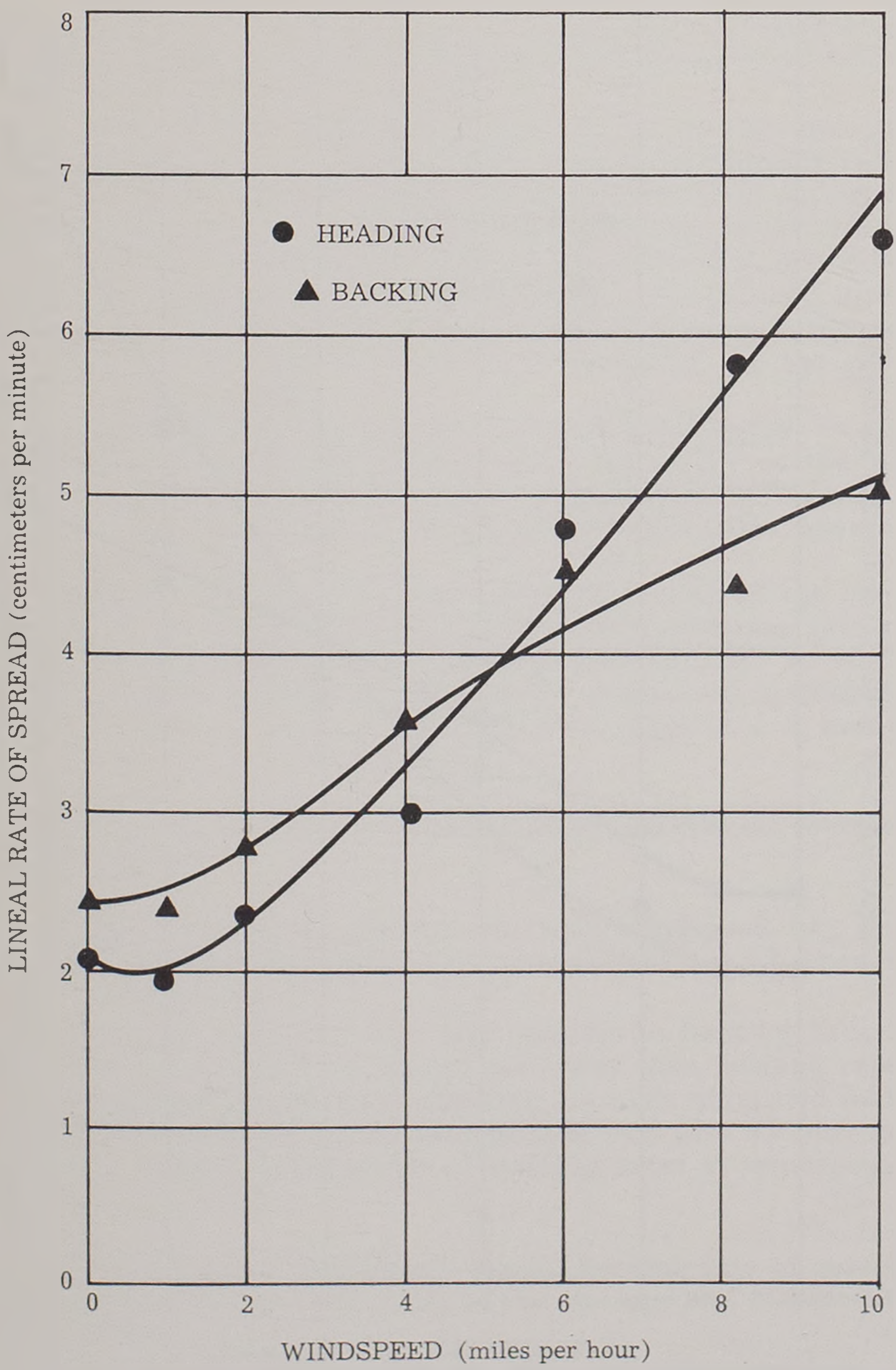

Figure 2—Rates of spread of heading and backing fires in the 25-percent-slope position.

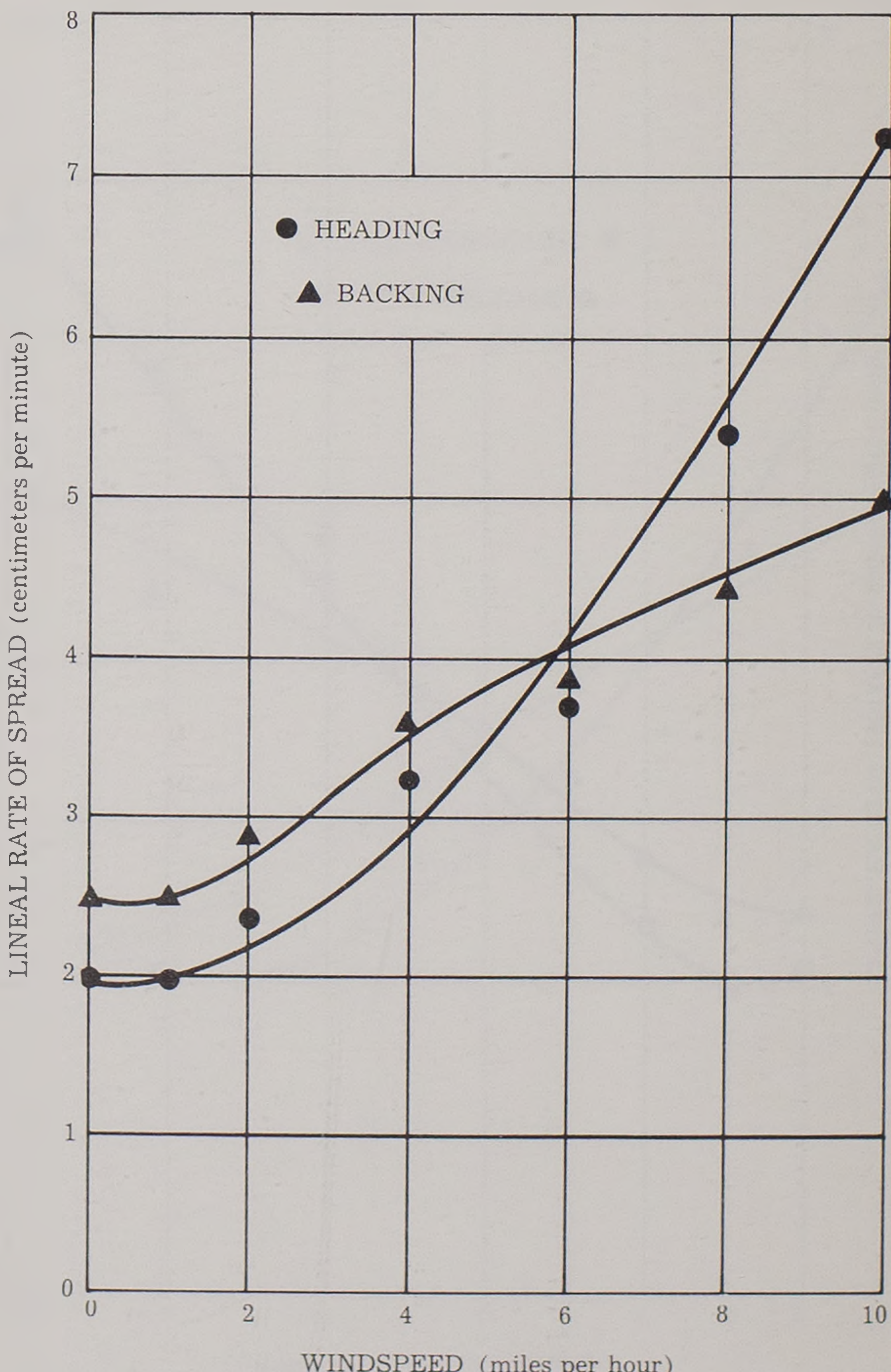

Figure 3—Rates of spread of heading and backing fires in the 50-percent-slope position.

dioxide and water vapor that inhibit combustion by restricting the oxygen supply. If entrainment is limited, these products tend to concentrate at the burning edge.

As a result of weak convection, the flow of air over the test beds appeared to be laminar at the lower windspeeds. The gaseous products were held close to the fuel surface in the heading fires, and heat was transferred to the unburned fuel primarily by conduction from these gases. The combined effect was a reduced rate of spread in the heading fires. The backing fires, though deprived of radiation from above, were able to spread a little faster because they were not "smothered" by the combustion-inhibiting gases.

Air temperature and density should also be considered. In our tests temperature increased and density decreased as the air passed over the backing fires and the burned areas.[3] The consequent reduction of oxygen for the heading fires further lowered their rate of spread.

We believe, however, that the smothering action of the combustion-inhibiting gases is more significant in reducing rate of spread of heading fires than is decreased air density. In all 21 fires the combined effects of both factors varied with windspeed and slope angle. From the results shown in Figures 1, 2, and 3, we can make eight observations:

1. Heading rates of spread generally show curvilinear increase with windspeed.

2. Backing rates of spread increase with windspeed, but less than heading rates. The portions of curves above 4 m.p.h. suggest a linear relationship.

The dominant mechanism of heat transfer in backing fires is radiation. Backing rates of spread are lower than heading rates at higher windspeeds because incoming air cools unburned fuels rather than preheating them. This cooling may also account for the slight delay in acceleration of backing rates at windspeeds between 0 and 2 m.p.h.

3. At windspeeds of less than 2 m.p.h., heading rate of spread decreases from the no-wind value in the no-slope and 25-percent-slope positions.

When fuel was burned with no wind in these positions, a vertical convection column formed. Entrainment of air into the

[3]A fuel bed similar to the experimental beds was instrumented with thermocouples and a differential pressure transducer 1 cm. above the bed to measure temperature and density.

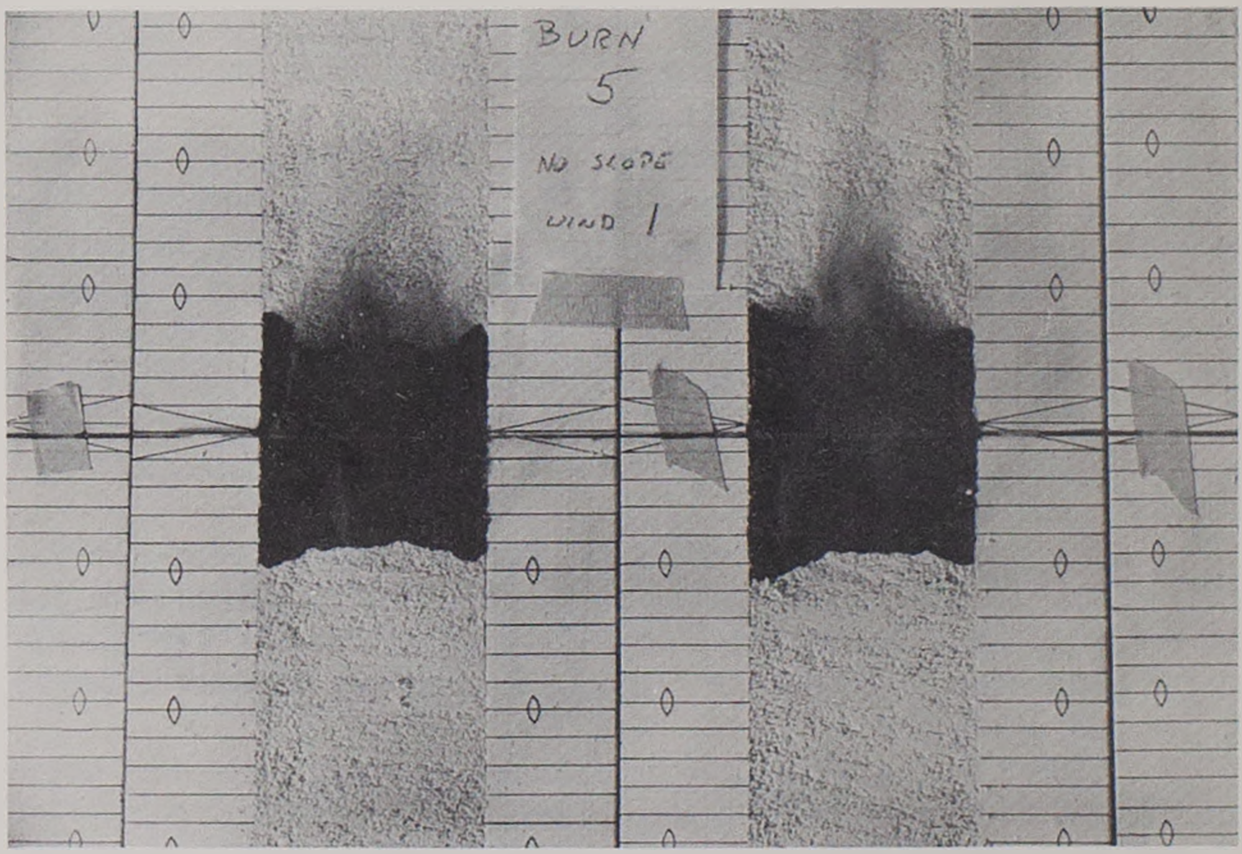

Figure 4—Artificial fuels burning at slope 0, wind 1 m.p.h.

column occurred at the fuel surface on both the burned and unburned sides. However, as shown in Figure 4, a wind of 1 m.p.h. bent the smoke column over the heading front, preventing entrainment of fresh air from the burned side and causing the available oxygen to be diluted by combustion-inhibiting products. The decreased density of the air reaching the front after passing over the burned area probably contributed to the oxygen-diluting process. Note that the heading rate of spread at the edges of the tray, where there was entrainment of fresh air from the sides, was greater than at the center.

Above 2 m.p.h., the heading rate in the 0- and 25-percent-slope positions increased with windspeed. This was probably due to an accelerated oxygen supply coupled with greater turbulence. The latter enhances mixing and assists in clearing combustion-inhibiting products from the combustion zone.

4. Backing rates of spread are higher than heading rates on all slope positions until windspeeds reach 5 to 7 m.p.h.

Backing rates increase with air velocity due to greater oxygen supply and removal of combustion-inhibiting gases. As indicated above, heading fronts undergo an initial delay; their rate of spread does not increase until after winds exceed 1 or 2 m.p.h. The crossing of the curves between 5 to 7 m.p.h. is largely determined by this critical 1-to-2-m.p.h. transition, in which acceleration of the heading rate begins.

5. Both heading and backing rates of spread accelerate with increasing slope in a curvilinear manner, except for the heading fronts at windspeeds of 1 m.p.h.

The backing rate does not accelerate as rapidly as the heading rate under these conditions because slope narrows the angle between combustion-inhibiting gases and uphill unburned fuel. However, at windspeeds of 1 m.p.h., these gases probably reduce the heading rate. The observation supports the contention of Curry and Fons (1938) that the influence of slope is relatively slight at low windspeeds.

Figure 5 shows the behavior of smoke on a 50-percent slope with no wind. The unburned fuel at the front is stained with condensate for a distance of over 4 cm. The staining suggests that unburned fuels have been in contact with warm but combustion-inhibiting gases.

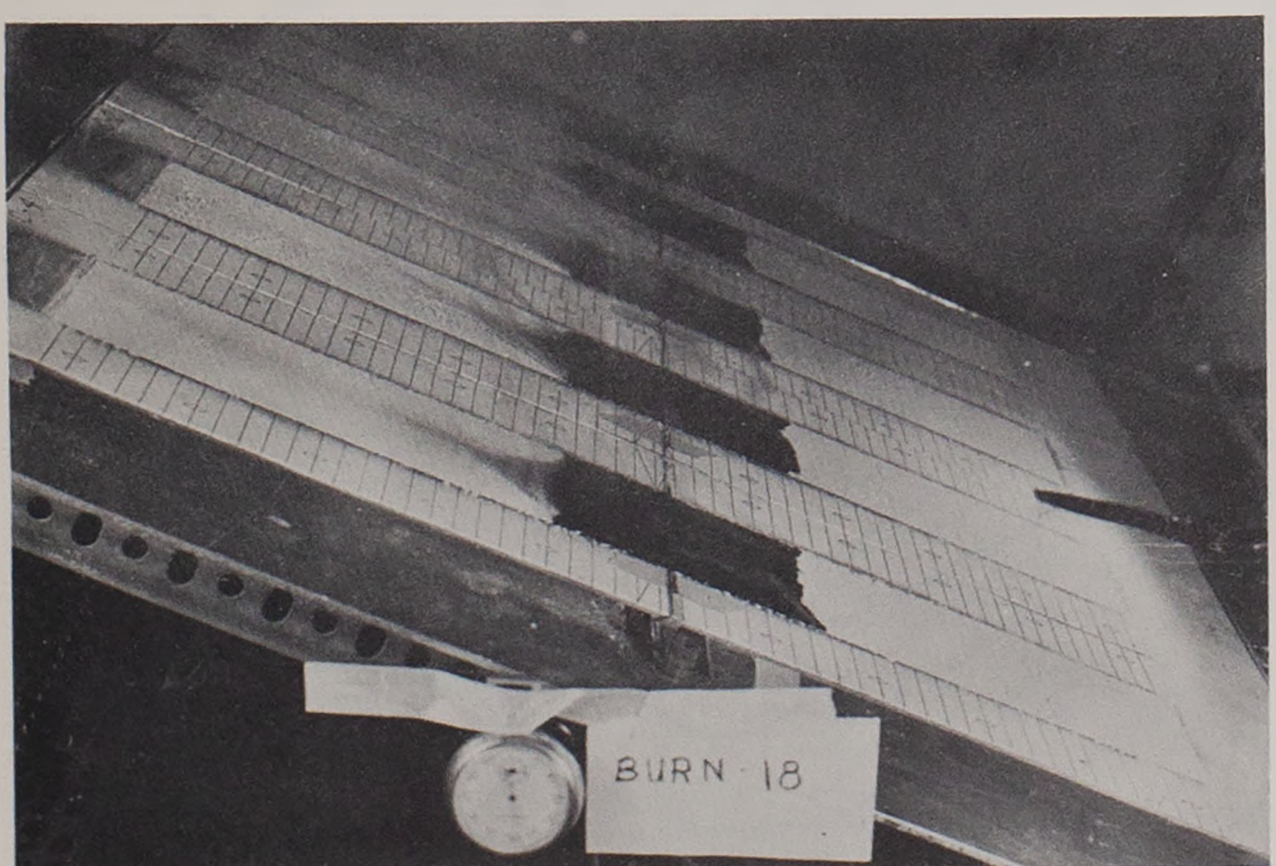

Figure 5—Artificial fuels burning at 50-percent slope, wind 0 m.p.h.

6. Slope and wind effects are not entirely additive on the heading front until the extreme combination of wind and slope is reached.

The relationship between wind, slope, and rate of spread at each front is illustrated in Figures 6 and 7.

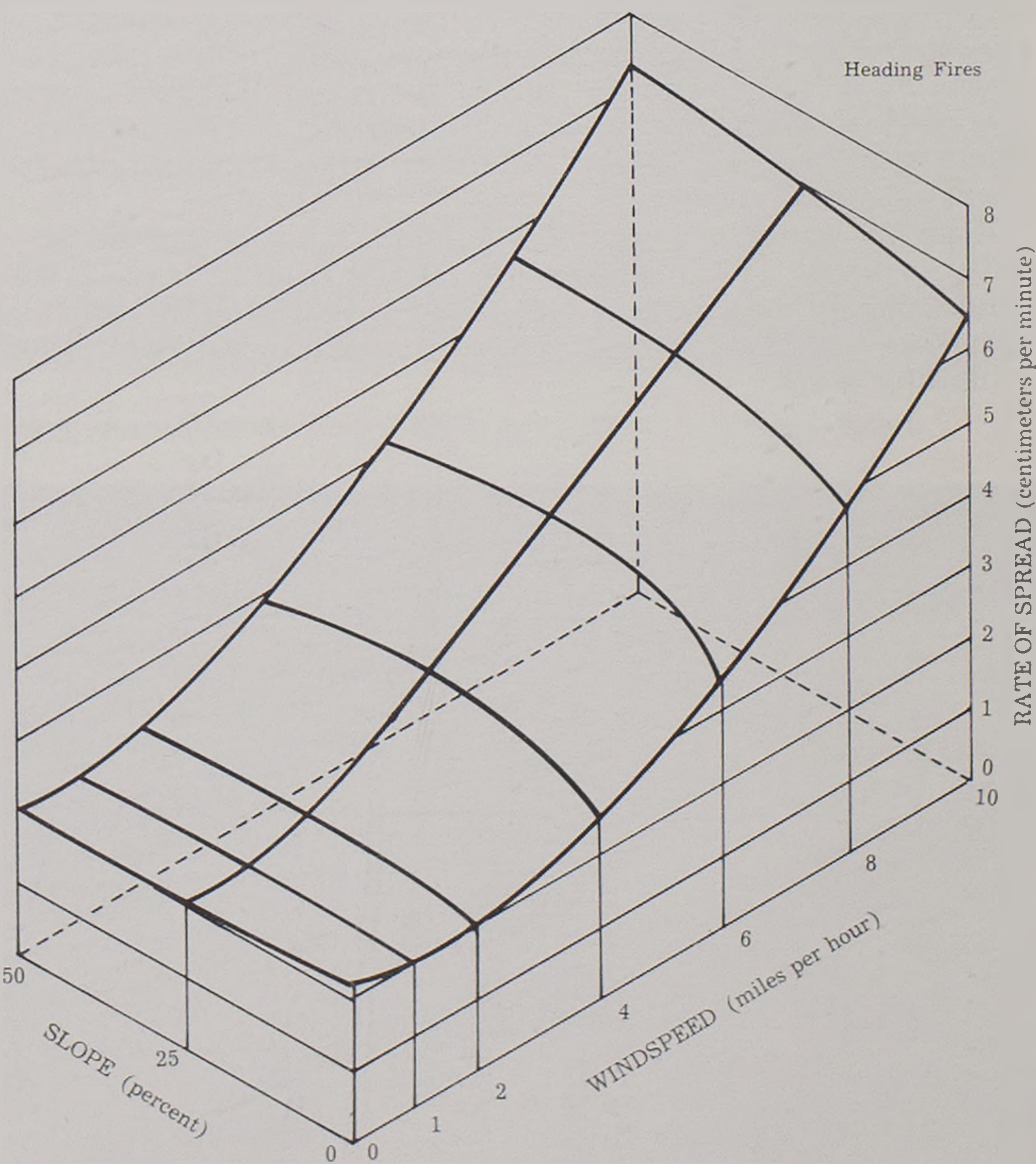

Figure 6—Rates of spread of heading fires as related to windspeed and slope.

As the slope increases above 25 percent, the diluting and inhibiting gaseous combustion products were brought closer to the fuel surface. The fact that the rate did not accelerate further until the highest wind and slope combination was reached indicates that mixing had overcome these inhibiting effects.

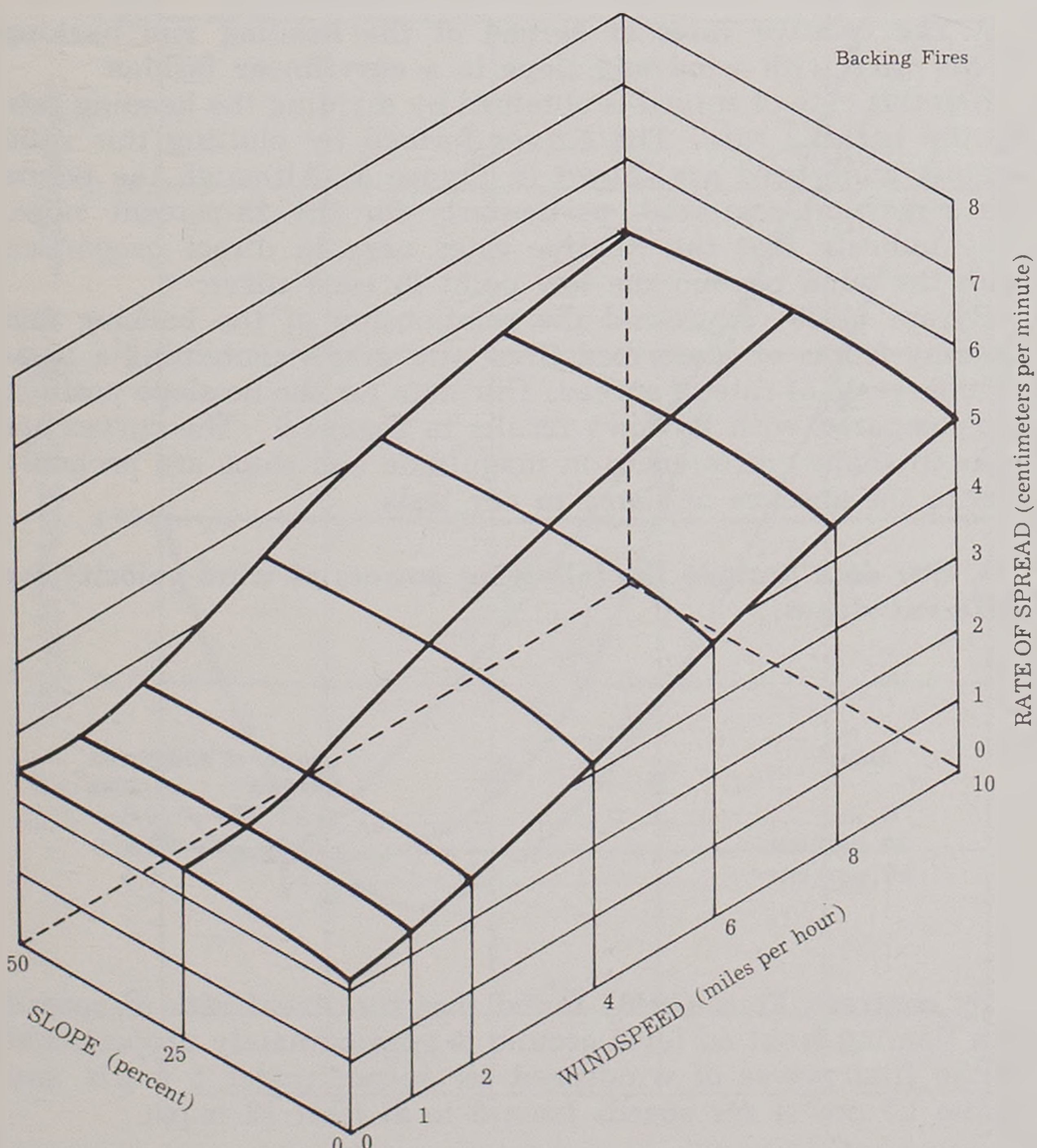

Figure 7—Rates of spread of backing fires as related to windspeed and slope.

It is interesting to note that the rate-of-spread curves for the 50-percent slope position are practically identical to those for the no-slope position with an additional 1-m.p.h. windspeed. In this study it appears that the effect of a 50-percent slope was actually equivalent to a 1 m.p.h. increase in windspeed. However, the 25-percent-slope curves do not fit this pattern, which suggests that there is an optimum slope position for rate of spread at low windspeeds.

7. The relative rates of spread of the heading and backing fronts vary with wind and slope in a curvilinear fashion.

Relative rate of spread is obtained by dividing the heading rate by the backing rate. The curves formed by plotting this ratio against windspeed are shown in Figure 8. Although the points are somewhat scattered, particularly for the 25-percent slope, they indicate that the relative rates vary in direct proportion with the wind beyond the low point in each curve.

Byram (1959) expressed the relationship of the backing and heading fronts of prescribed fires on a graph containing a logarithmic scale of rate of spread. Our data for the no-slope position are compared with Byram's results in Figure 9. The curves are alike in shape; differences in magnitude and slope are probably due to the absence of flame in our tests.

8. Our data provide the following powers of wind velocity for different slopes:

Slope	Power of Windspeed	
	Heading	Backing
0	1.1	0.5
25 percent	0.9	0.4
50 percent	1.1	0.4

By contrast, Fons (1946) found that the lineal rate of spread of a flaming front on level ground is approximately proportional to the first power of windspeed for speeds under 5 m.p.h. and to the 1.5 power for speeds from 5 to at least 12 m.p.h.

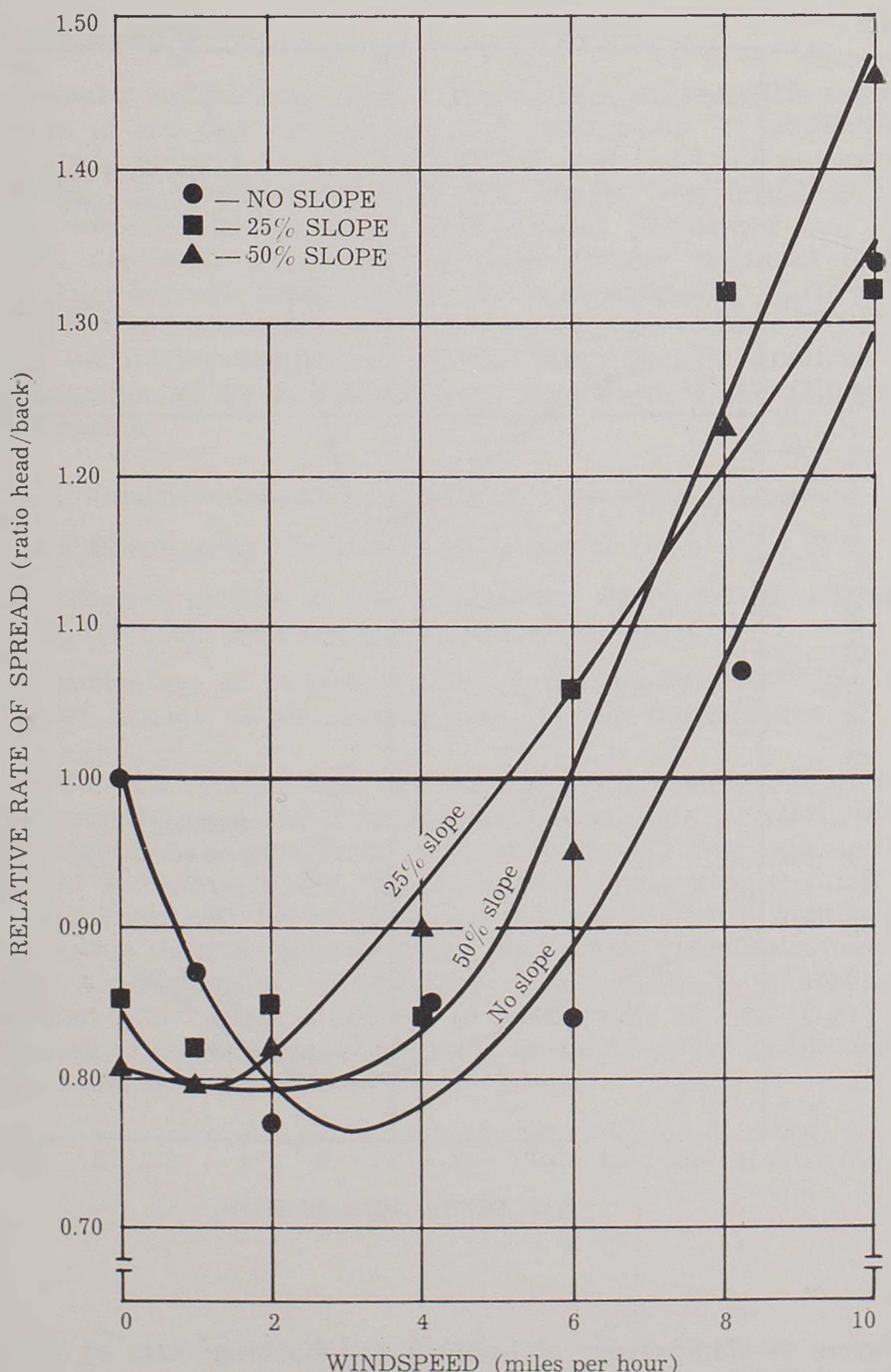

Figure 8—Relative rates of spread of heading and backing fires for each slope angle.

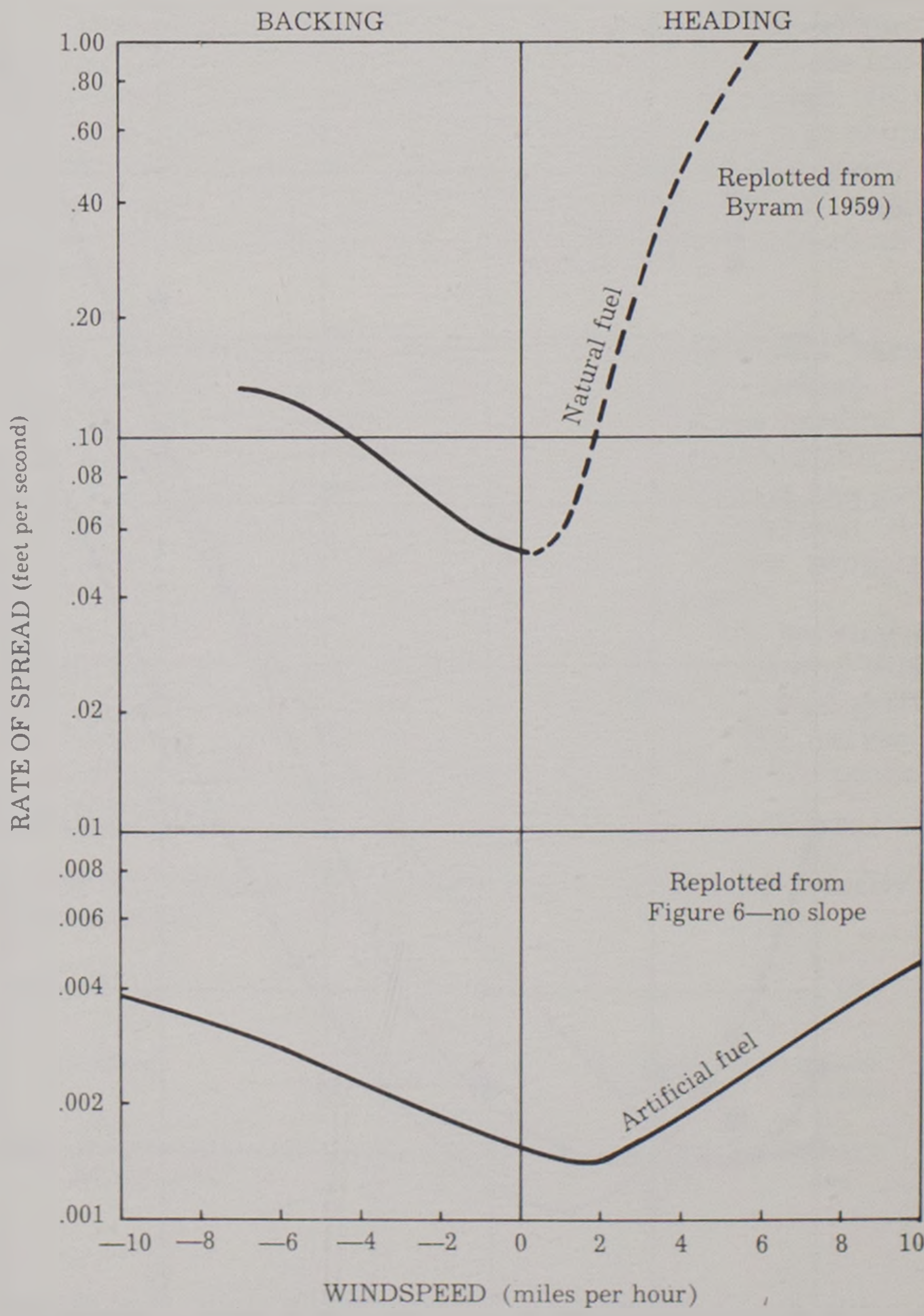

Figure 9—Comparison of heading and backing rates of spread for artificial and natural fuels.

Summary

Heading and backing rates of spread were measured in a wind tunnel at the Northern Forest Fire Laboratory. A smoldering front was induced on burning beds of wood flour and potassium nitrate. Air velocities during 21 tests ranged from 0 to 10 m.p.h. Beds were located on slopes of 0, 25, and 50 percent.

The dominant mechanism of heat transfer appeared to be radiation beneath the fuel bed. Surface preheating of fuels by radiation and convection was minimized by the absence of flame, thus permitting assessment of the other factors involved in propagation of the burning fronts. We observed the following phenomena:

a. Combustion-inhibiting effects of combustion products.

b. Preheating by conduction from gases.

c. Laminar airflow at low windspeeds, which minimized mixing of fresh air with combustion-inhibiting gases.

d. Reduction of oxygen supply at the heading front by decreased density of air passing over the hot burned area.

Under the specific fuel and environmental conditions of our experiments, we found that: (1) the heading rate varied directly with wind in a curvilinear manner, although low windspeeds caused a decline in the rate of heading-front progress due to little mixing; (2) the backing rate increased directly with wind, but less so than the heading rate; (3) backing rates were greater than heading rates on all slope positions until windspeeds reached 5 to 7 m.p.h.; and (4) at windspeeds of 5 to 10 m.p.h., heading rates varied approximately as the 1.1 power of the windspeed and backing rates as the 0.4 power.

LITERATURE CITED

Anderson, H. E.—1964. Mechanisms of fire spread—progress report No. 1. U. S. Forest Serv. Intermountain Forest and Range Expt. Sta. Res. Paper 8, 20 pp.

——— and Rothermel, R. C.—1964. Influence of moisture and wind upon the characteristics of free-burning fires. Preprint Tenth Internatl. Symposium on Combustion, Cambridge, England, Aug. 17-21, 1964.

Barrows, J. S.—1951. Forest fires in the northern Rocky Mountains. U. S. Forest Serv. Northern Rocky Mountain Forest and Range Expt. Sta. Paper 28, 251 pp.

Bruce, H. D., Pong, W. Y., and Fons, W. L.—1961. The effect of density and thermal diffusivity of wood on the rate of burning of wood cribs. U. S. Forest Serv. Pacific Southwest Forest and Range Expt. Sta. Tech. Paper 63, 14 pp.

Byram, G. M.—1957. Some principles of combustion and their significance in forest fire behavior. U. S. Forest Serv. Fire Control Notes 18(2): 47-57.

——— 1958. Some basic thermal processes controlling the effects of fire on living vegetation. U. S. Forest Serv. Southeast. Forest Expt. Sta. Res. Note 114, 2 pp.

——— 1959. Combustion of forest fuels. Ch. 3, pp. 61-69 in K. P. Davis, 1959. Forest fire: control and use. McGraw Hill, New York, 584 pp.

Curry, J. R., and Fons, W. L.—1938. Rate of spread of surface fires in the ponderosa pine type of California. Jour. Agr. Res. 57: 239-267.

——— 1940. Forest fire behavior studies. Mech. Engin. N. W., 219-225.

Fahnestock, G. R.—1953. Relative humidity and fire behavior in logging slash. U. S. Forest Serv. Northern Rocky Mountain Forest and Range Expt. Sta. Res. Note 126.

——— 1960. Logging slash flammability. U. S. Forest Serv. Intermountain Forest and Range Expt. Sta. Res. Paper 58, 67 pp.

Fons, W. L.—1946. Analysis of fire spread in light forest fuels. Jour. Agr. Res. 72: 93-121.

——— 1961. Use of models to study forest fire behavior. Paper presented at Tenth Pacific Sci. Cong., Honolulu, Hawaii.

——— Clements, H. B., Elliott, E. R., and George, P. M.—1962. Project fire model—summary progress report II—period May 1, 1960 to April 30, 1962. U. S. Forest Serv. Southeast Forest Expt. Sta., 55 pp.

Jacobs, M. R.—1962. Annual report Australia Forestry and Timber Bureau for year ended December 31, 1960, 57 pp.

Jemison, G. M.—1944. Forest fire danger indexes. Jour. Forestry 42: 261-263.

Morris, W. G.—1954. Rate of spread on a Washington fern fire. U. S. Forest Serv. Fire Control Notes 15(1): 32-34.

Rodger, G. J.—1958. Annual report Australia Forestry and Timber Bureau for year ended December 31, 1957, 45 pp.

———— 1959. Annual report Australia Forestry and Timber Bureau for year 1958, 45 pp.

Rowland, H. B.—1939. A fire control training map. U. S. Forest Serv. Fire Control Notes 3(2): 17-18.

Show, S. B.—1919. Climate and forest fires in northern California. Jour. Forestry 17: 965-979.

———— and Kotok, E. T.—1925. Weather conditions and forest fires in California. U. S. Dept. Agr. Cir. 354, 24 pp.