THE EFFECT OF DIRECTION OF ILLUMINATION UPON THE VISIBILITY OF A SMOKE COLUMN [1]

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INTRODUCTION

Preliminary investigations in the detection of forest fires at the California Forest and Range Experiment Station were based on the assumption that the visibility of smoke columns in the field would vary as the visibility of the landscape with varying conditions of atmospheric suspensoid concentration and with the position of the sun. This led to the determination of the effect of direction of the sun with respect to the observer's line of sight upon the visibility of natural features in the landscape through analysis of a large number of lookout observations of natural targets on the Shasta National Forest. Later observations of test-fire smokes, however, indicated clearly that the visibility of smoke columns as reflected in fire-discovery time does not vary in the same manner as landscape visibility. The following laboratory experiment was devised, therefore, to determine in just what manner the visibility of a smoke column varies with different positions of the sun with respect to the observer's line of sight.

MATERIAL AND METHODS

With other factors constant, the visibility of a smoke column varies as a function of its brightness. In order to isolate and measure the variation in visibility due to changes in brightness, the variable influences of background, glare, and atmospheric suspensoid were eliminated from the experimental set-up.[3] The two elements primarily concerned in the relationships to be determined, then, were a column of smoke and a light beam of parallel rays.

Figure 1 shows the arrangement in plan and elevation of the equipment as it was set up for the experiment. The beam of parallel rays was produced by a 400-watt projection lantern (*a*) with the projection lens removed, operating on an alternating-current circuit. A wooden frame in the form of a tank, 3 feet deep and 12 feet in diameter, was built and set 1 foot above the floor. This tank was

[1] Received for publication June 15, 1935; issued February 1936.

[2] The authors wish to acknowledge indebtedness to A. A. Brown, associate silviculturist at the California Forest and Range Experiment Station, who initiated the experiment, made arrangements for obtaining the laboratory in which it was performed, and gave considerable time to the general supervision of the work. They also wish to thank Professor Minor of the optometry division of the University of California for his interest and for suggestions offered in organizing the experiment, and Professor Boelter of the engineering department of the university for his cooperation and for his kindness in offering criticisms of the original manuscript.

[3] Certain conclusions, however, relative to the effect of atmospheric suspensoid material upon visibility have been drawn from the laboratory observations.

Journal of Agricultural Research, Washington, D. C.

Vol. 51, no. 10
Nov. 15, 1935
Key no. F-75

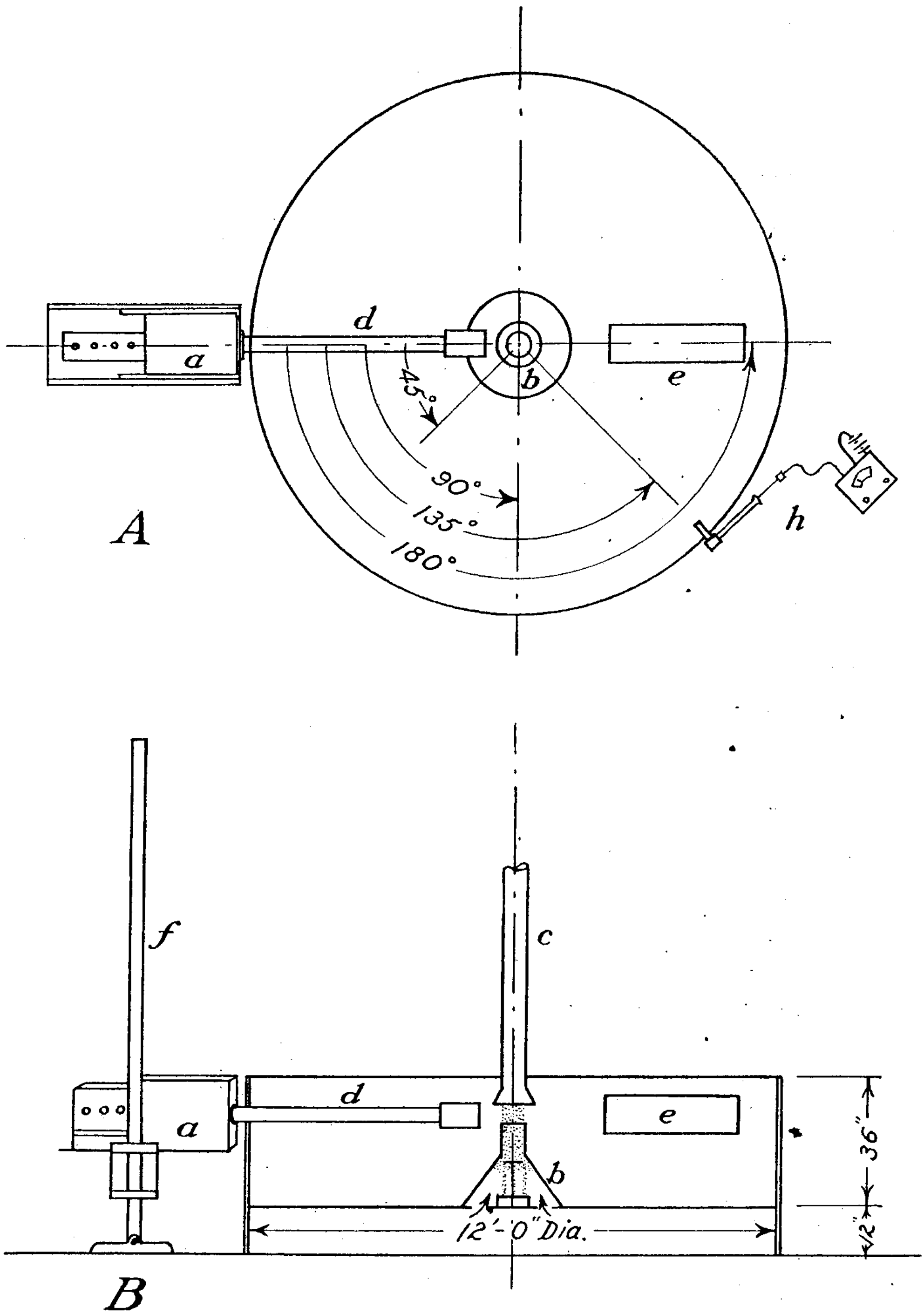

FIGURE 1.—Arrangement of experimental apparatus: *A*, Plan; *B*, elevation. Explanation in text.

lined with black builder's felt to eliminate variations in background and minimize the reflection of stray light. In the center of the tank was placed an inverted funnel-shaped hood (*b*) in which the smoke was produced. Eight inches above the top of the hood was placed a flue (*c*) to carry off the smoke and create a draft to keep the smoke in a uniform column. A specially constructed tube (*d*) was placed in front of the projector to adjust the size of the light beam and absorb the small amount of nonparallel rays produced by the projector. The beam of light was directed through the side of the tank at a height 2 inches above the top of the hood in the center of the tank. An 8-inch tube 3 feet long with one end closed (*e*) was hung in line with the beam of light to intercept it after it had passed through the smoke column, thus eliminating any reflection from the opposite side of the tank. The projector was mounted on an elevating frame (*f*) so that the light source could be adjusted to correspond with various elevations of the sun. All equipment was painted with flat black paint and observations were made in a totally darkened room.

The smoke column was produced by burning Chinese punk, the desired concentration of smoke being obtained by varying the number of punks burned at one time. A baffle plate at the lower end of the neck of the hood broke up the smoke and produced a uniform column 2¼ inches in diameter regardless of the number of punks burned. The punk burned at a uniform rate and produced a smoke similar in color to actual smokes observed in the field.

The diameter of the light beam was adjusted to the diameter of the smoke column so the apparent illuminated area of the smoke remained approximately the same regardless of the position from which it was observed.

A Macbeth illuminometer was used to measure the brightness of the illuminated smoke column. Measurements of smoke visibility given are based on the brightness of the smoke measured with this instrument in international candles per square foot.

Measurements of brightness and visibility of the illuminated smoke column were made at observation stations placed at intervals of 22½° around the tank in the same horizontal plane as the illuminated portion of the smoke column. These stations are designated by the angle *abh* in the diagram, in which the illuminometer (*h*) is shown at station 135°.

EXPERIMENTAL DATA

In the preliminary laboratory tests, observations with the Bennett-Casella visibility meter,[4] used for visibility measurements in the field, were made simultaneously with observations with the Macbeth illuminometer in order to establish the relationship between the brightness of the smoke and the visibility-meter readings with a black background. Table 1 is a summary of the average brightness

[4] Bennett, M. G. A visibility meter. Jour. Sci. Instruments 8 (4): 123–126. 1931.

values obtained. In figure 2 visibility-meter readings are plotted over these values on a logarithmic scale. Since the plotted points fall along a straight line it follows that the visibility-meter readings are a simple multiple of the logarithm of the brightness.

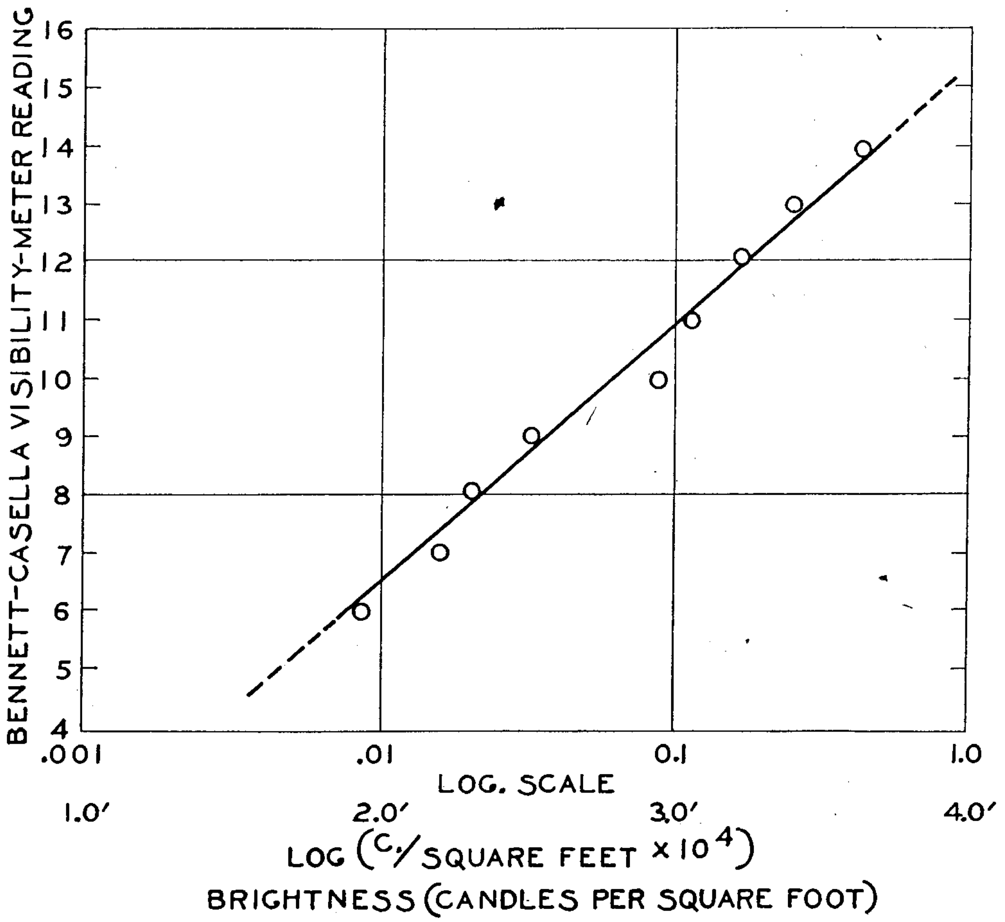

FIGURE 2.—Relationship of Bennett-Casella visibility-meter reading to brightness of smoke column.

TABLE 1.—*Relationship between Bennett-Casella visibility-meter readings and brightness measurements of smoke columns*

Visibility-meter reading	Brightness (candles per square foot)	Log $\left(\frac{\text{candles}}{\text{square foot} \times 10^4}\right)$
6	0.0087	1.940
7	.0158	2.199
8	.0198	2.297
9	.0314	2.497
10	.0825	2.916
11	.1140	3.057
12	.1680	3.225
13	.2490	3.396
14	.4210	3.624

There is a decided inequality in the graduations of opacity of the various filters in the visibility meter, resulting in the failure of the plotted values in figure 2 to fall exactly on a straight line. This inequality in the steps of opacity also gives visibility-meter readings slightly too low for low values and approximately the same amount too high for high values (fig. 3). The approximate relationship indicated, however, when brightness is expressed in candles per square foot, is—

$$V=3.6\left[\log \frac{\text{(candles)}}{\text{(square foot)}}\times 10^4\right]$$

where V is visibility-meter reading.

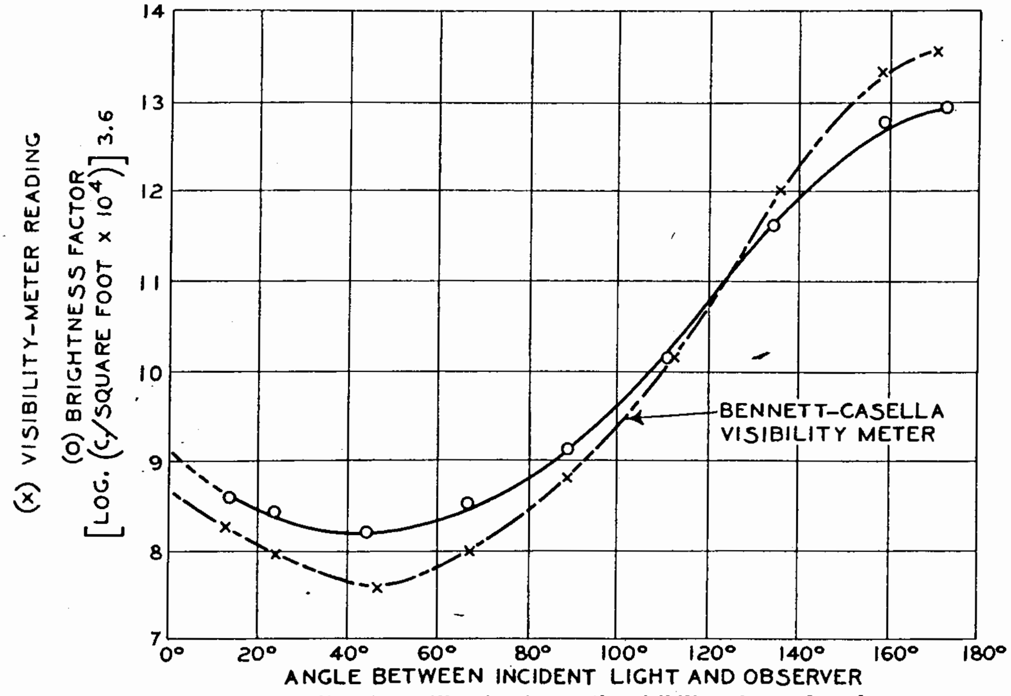

FIGURE 3.—Effect of direction of illumination on the visibility of a smoke column.

In the preliminary observations a large number of brightness measurements was made with the line of sight in a horizontal plane and the light source in positions varying from horizontal to a vertical

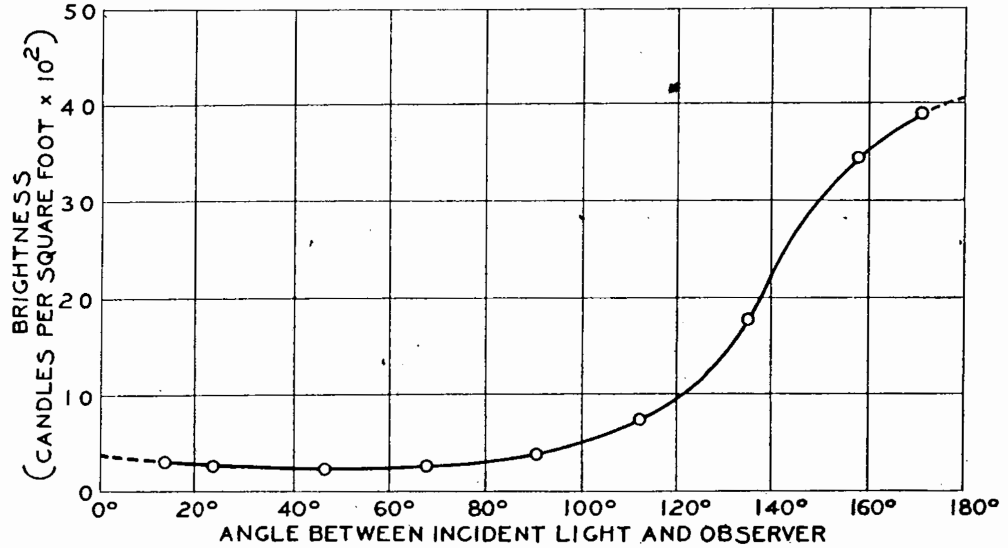

FIGURE 4.—Effect of direction of illumination on the brightness of a smoke column.

angle of 50° with respect to the smoke column, and the effect of direction of illumination on the brightness of the smoke column was determined. Considerable variation was noted in brightness measurements taken at different times, resulting in differences in the numerical values obtained. A representative set of measurements is given in table 2 and shown graphically in figures 3 and 4. The angles indicated are the angles measured at the smoke between the light source and the observer. Visibility-meter readings given are determined from the brightness measurements through the relationship shown in figure 2. This was done to smooth out the roughnesses in individual visibility-meter readings.

TABLE 2.—*Effect of direction of illumination upon the brightness of a smoke column* [1]

Station (degrees)	Illuminometer reading [2]	Brightness (candles / square foot)	Log ($B \times 10^4$)	[Log ($B \times 10^4$)]×3.6	Visibility-meter reading
0.0		0.0300	2.477	8.9	8.6
11.25	3.19–49	.0249	2.396	8.6	8.2
22.5	2.76–49	.0216	2.334	8.4	8.0
45.0	2.24–49	.0176	2.246	8.1	7.6
67.5	2.81–49	.0220	2.342	8.4	8.0
90.0	4.23–49	.0331	2.520	9.1	8.8
112.5	8.71–49	.0684	2.835	10.2	10.2
135.0	6.16–12	.1710	3.233	11.6	12.0
157.5	12.30–12	.3410	3.533	12.7	13.3
170.0	14.05–12	.3890	3.590	12.9	13.5
180.0		.4000	3.602	13.0	13.6

[1] Smoke density=5 punks; vertical angle: incident light=0°, observation=0°. Variation in illumination at smoke column=91.6 to 90.0 foot-candles. Tabulated values in column 2 are averages of values taken at plus and minus horizontal angles; values for 0° and 180° in column 3 are extrapolated; values in column 6 taken from figure 2.

[2] Filter no. 49—candles/square foot=reading × 0.00784; filter no. 12—candles/square foot=reading × 0.0277.

Several sets of observations resulted in variations in the numerical values of brightness obtained, but the trends of increasing brightness with increasing angle were all of the same shape. These variations were traced to two varying factors in the set-up: Light intensity of the source, affected by changing voltage in the light circuit; and density of the smoke column, affected by changes in the draft up the flue, which depended both upon outside air temperature and temperature of the room. To eliminate these variations, a voltmeter was placed in the light circuit and a photronic cell[5] in the light beam behind the smoke column. It was assumed that when the voltage remained constant any variation in the reading of the photronic cell was caused by variation in the smoke density. In the final observations readings were taken only when the voltmeter and photronic cell measured constant values.

After the trend of brightness had been established for various angles between the light source and the observer with both in a horizontal plane, several series of observations were made with the line of sight of the observer in a horizontal plane but with the light source raised to various vertical angles to correspond with the varying elevations of the sun. The results obtained from these observations did not check with computed values, for the reason that elevating the light source increased the volume of smoke illuminated, thus increasing its apparent brightness. In the field, where the entire smoke column is in sunlight, an increase in the elevation of the sun does not increase the volume of smoke illuminated. With the light source in a horizontal plane, a series of measurements of brightness was made from

[5] GOODWIN, W. N., JR. THE PHOTRONIC ILLUMINATION METER. Illuminating Engin. Soc. Trans. 27: 823-835, illus. 1932.

various vertical angles at different horizontal stations. The values thus obtained corresponded with the values obtained in a horizontal plane at an angle equal to the "spherical" angle between the light source and the observer. These observations indicated that the angle measured at the smoke column between the light source and the observer determines the effect of direction of illumination on the visibility of a smoke column regardless of the azimuths and elevations of any of the three points. All later observations were taken in a horizontal plane, since the horizontal angles between light source and observer could be substituted for "spherical" angles directly. In figure 5 is shown the effect of direction of illumination for different

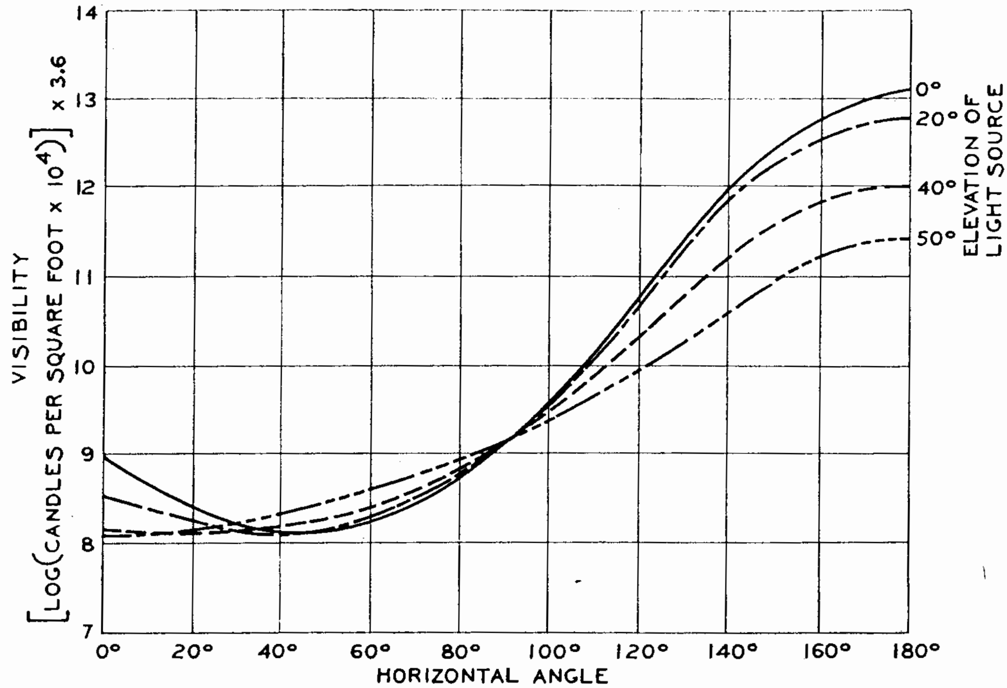

FIGURE 5.—Effect of different elevations of the light source on visibility of a smoke column.

elevations of the light source. Table 3 gives the equivalent angles for different horizontal and vertical components.

TABLE 3.—*Angle between light source and observer for given horizontal and vertical angle components*

Horizontal angle (degrees)	Equivalent for vertical angle (degrees) indicated									
	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°
0	5	10	15	20	25	30	35	40	45	50
10	12	15	19	23	27	32	37	42	47	52
20	21	23	26	29	32	36	40	45	49	54
30	31	32	34	36	39	42	46	50	54	57
40	41	42	43	45	47	50	52	55	57	61
50	51	52	53	54	55	57	59	61	63	66
60	60	61	61	62	63	65	66	68	70	72
70	70	71	71	72	72	73	74	75	76	78
80	80	80	80	81	81	82	82	83	83	84
90	90	90	90	90	90	90	90	90	90	90
100	100	100	100	99	99	99	99	98	98	97
110	110	110	110	109	109	108	108	106	105	104
120	120	120	120	119	118	116	115	113	112	110
130	130	130	129	128	126	124	122	120	118	116
140	140	140	139	137	135	132	130	127	124	122
150	150	150	148	145	143	140	137	134	130	125
160	160	160	157	153	150	146	142	138	134	128
170	170	170	167	162	158	150	146	140	136	130
180	175	170	165	160	155	150	145	140	135	130

Measurements of the effect of concentration of the smoke column on its brightness and on its light-transmission factor were made at

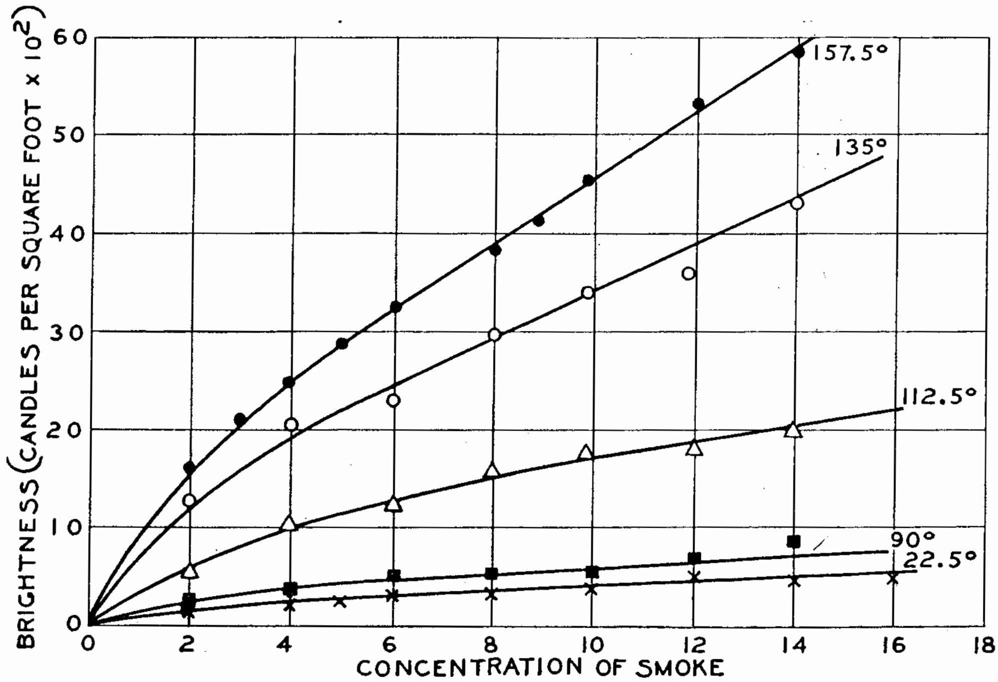

FIGURE 6.—Effect of concentration of smoke on its brightness for different angles (indicated on curves) between (horizontal) light source and observer.

the same time. The concentration of smoke was varied by placing additional punks under the hood, the number ranging from 1 to 14. The heat caused by more than this number produced an exceptionally

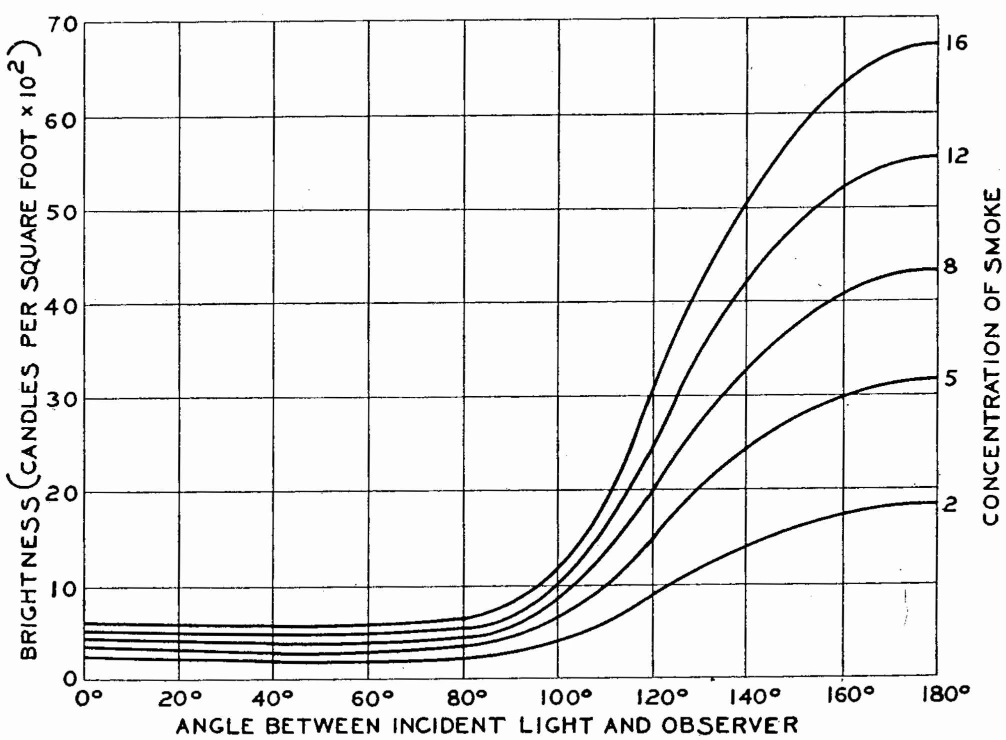

FIGURE 7.—Effect of direction of illumination on brightness of a smoke column for different concentrations of the smoke.

strong draft, which resulted in discrepancies in both brightness and light-transmission measurements. Readings of brightness were taken at five stations for each change in concentration of the smoke (table 4). These values are shown graphically in figure 6. Figure 7 is derived from figure 6 by cross-plotting the five curves in the latter.

The photronic cell was used to record the foot-candles of light passing through the smoke column. For each change in the concentration of the smoke, as determined by the number of punks burned, the meter of the photronic cell was watched, and the reading that seemed to represent the most stable and uniform condition of the smoke was tabulated. These values for the various concentrations are given in table 5 with their corresponding percentages of light transmission, which are presented graphically in figure 8.

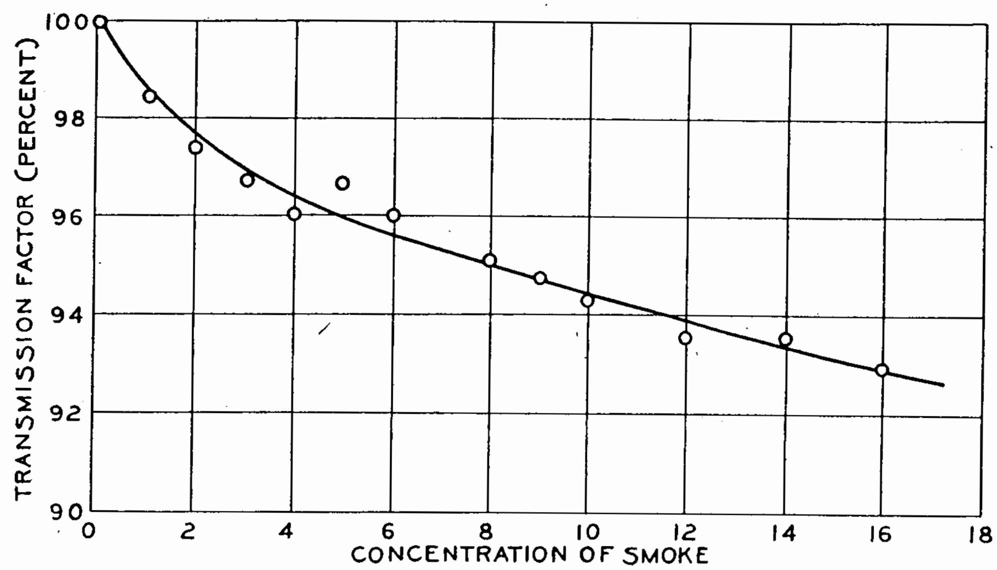

Figure 8.—Effect of concentration of a smoke column on its transmission of light.

Table 4.—*Effect of concentration of the smoke on the brightness of a smoke column at different angles between light source and observer* [1]

Concentration of smoke column (number of punks)	22.5°		90°		112.5°		135°		157.5°	
	Illuminometer reading	Brightness [2]	Illuminometer reading	Brightness [2]	Illuminometer reading	Brightness [2]	Illuminometer reading	Brightness [2]	Illuminometer reading	Brightness [2]
2	1.9 -49	0.0149	3.3 -49	0.0259	2.1-12	0.0582	4.6 -12	0.128	6.0 -12	0.166
3	3.3 -	.0259	4.0 -	.0314					7.75-	.215
4	3.0 -	.0236	4.7 -	.0368	4.0-	.1110	7.75-	.215	9.0 -	.250
5	3.55-	.0279	5.3 -	.0416					10.6 -	.293
6	3.6 -	.0282	5.37-	.0421	4.6-	.1280	8.3 -	.230	11.75-	.325
8	4.4 -	.0345	5.8 -	.0455	6.1-	.1690	10.6 -	.294	13.4 -	.372
9	5.6 -	.0439	6.75-	.0530					15.0 -	.416
10	4.4 -	.0345	6.8 -	.0532	6.1-	.1690	12.4 -	.344	16.5 -	.457
12	6.9 -	.0541	9.0 -	.0706	6.5-	.1800	12.6 -	.349	19.2 -	.532
14	6.2 -	.0486	11.5 -	.0902	7.1-	.1970	15.4 -	.427	12 6.5 -49	.586
16					7.3-	.2020				
18							18.0 -	.498		

[1] Illumination at smoke column: 130.0 foot-candles.

[2] $\frac{\text{Candles}}{\text{Square foot}}$.

TABLE 5.—*Effect of concentration of a smoke column on transmission of light*

Concentration of smoke column (number of punks)	Light transmitted	Transmission factor	Concentration of smoke column (number of punks)	Light transmitted	Transmission factor	Concentration of smoke column (number of punks)	Light transmitted	Transmission factor
	Foot-candles	*Percent*		*Foot-candles*	*Percent*		*Foot-candles*	*Percent*
0	33.1	100.0	5	32.0	96.7	10	31.2	94.3
1	32.6	98.5	6	31.8	96.0	11		
2	32.2	97.4	7			12	31.0	93.6
3	32.0	96.7	8	31.5	95.1	13		
4	31.8	96.0	9	31.4	94.8	14	31.0	93.6

No measurements were made of the effect of suspensoid in the atmosphere, since there was no way in which the suspensoid could be illuminated uniformly in the laboratory. The foot-candles of light from a point light source decrease as the square of the distance from the source; hence the atmospheric suspensoid would be much more strongly illuminated near the light source than at some distance from it. This relationship was checked in the laboratory. For the same reason no observations were made with illuminated backgrounds.

It was observed that the veiling brightness of the illuminated atmospheric suspensoid increased in the same manner as the brightness of the smoke column when the angle of observation with respect to the light source was increased. Incidentally it was noted that a smoke column illuminated only by diffused light was visible through a considerable density of atmospheric suspensoid as long as the line of sight through the suspensoid was in shadow. When the line of sight passed through a short distance of illuminated suspensoid, however, the smoke column became decidedly less visible even though the observer was in shadow. The observer here remained in shadow to eliminate the effect of glare.

DISCUSSION

Before any general conclusions can be drawn, some explanation of the various measurements of brightness and visibility must be made. In the laboratory, color contrasts were not considered and background was held constant with a brightness of zero. The visibility of the illuminated smoke column was therefore a function of its brightness.

According to Fechner's law, the eye reacts to variations in the stimulus as the logarithm of the stimulus. Thus the visibility of the smoke column varies as the logarithm of the brightness. A comparison of figures 3 and 4 indicates the relationship between the brightness of the illuminated smoke column and its visibility. The brightness measured in absolute units in figure 4 increases, from a minimum at an angle between light source and observer of 45°, to approximately 19 times this value at an angle of 170°. In figure 3, however, when the logarithmic values are plotted, it is seen that the visibility increases only by approximately 62½ percent in the same interval. A further study of figure 4 indicates that Bennett-Casella visibility-meter readings are approximately in proportion to the visibility of the smoke column.

Some consideration should be given to the cause of the phenomenon of increasing brightness with increasing angle between the light source and line of sight of the observer, as illustrated in the curves of figure 7. The brightness of the smoke column observed at angles of less than 90° is caused principally by light reflected by the smoke particles, while at angles greater than 90° the brightness is caused largely by transmitted scattered light. Since the smoke column transmits much more light than it reflects, the brightness of the column is considerably greater when observed from the larger angles. Light incident on a smoke column is either reflected or scattered and at least partially polarized, depending on the size and character of the individual smoke particles; and the light reflected or scattered by each particle may be reflected or further scattered many times by additional particles in its path. The minimum brightness measurements obtained were recorded at station 45°, the sum of the multiple reflected and scattered light being at a minimum at this point. This causes the curves to take the form of a trigonometric function of the angle between light source and observer 45° out of phase.

The phenomenon of increasing brightness of smoke with increasing angle between the sun and observer is of importance because it not only determines the relative intrinsic visibility of a column of smoke as determined by the direction from which the smoke is observed, but has a strong influence on the detrimental effect on visibility of haze in the form of solid suspensoid material in the atmosphere.

In addition to producing a veiling brightness which lowers visibility by decreasing the contrast between the smoke column and its background, suspensoid material in the atmosphere also decreases the visibility of an object by decreasing the transmission of light reflected from the object through the atmosphere to the observer. Figure 8 illustrates the manner in which this transmitted light is decreased by various concentrations of suspensoid material in a smoke column. It is assumed here that light transmission through a longer distance of less concentrated suspensoid would follow the same trend as that indicated for the smoke column. Further laboratory work is now being planned to determine the relative effects of concentration and distance upon the transmission of light through an atmosphere containing suspensoid material. The relatively high light-transmission factor of a smoke column obtained in the experiment indicates that in general the detrimental effect on visibility of an atmospheric suspensoid is probably more attributable to veiling brightness than to decreased light transmission.

CONCLUSIONS

Although it is unlikely that relationships observed in the laboratory would ever be as sharply defined in the field, where a large number of variable factors is inevitably encountered, the same trends will be followed. The results of a series of laboratory experiments to determine the effect of certain factors on the visibility of a smoke column may be given, then, in terms of field observations, as follows:

(1) The angle measured at the smoke between the sun and the observer determines the effect of direction of illumination on the visibility of a smoke column regardless of its azimuth or position of the sun as determined by the time of day.

(2) In an atmosphere containing little or no suspensoid material, the visibility of a smoke column is influenced appreciably by the relative position of the sun with respect to the line of sight of an observer. There is little variation in the visibility of the smoke column with changes in the angle between the incident light and line of observation from 0° to 90°—that is, with the sun varying in position from directly behind the observer to a line at right angles with his line of sight. When the angle is greater than 90° there is a very marked progressive increase in the visibility of the smoke until the observer is looking almost directly into the sun. The smoke is not visible when the sun forms its background.

(3) When there is an appreciable amount of suspensoid material in the atmosphere there is a decrease in the visibility of a smoke column viewed through the atmosphere owing to a combination of two factors—decreased light transmission factor of the atmosphere and veiling brightness of the suspensoid material. The first factor is constant for a given suspensoid concentration, while the second is present only when the suspensoid is illuminated and varies not only with suspensoid concentration but also with direction of illumination with respect to the observer's line of sight.

(4) The visibility of an object is decreased when the concentration of atmospheric suspensoid through which the object is viewed is increased. When the sun is behind or at right angles to the observer's line of sight, this decrease in visibility may be caused largely by decreased light transmission of the atmosphere, but with angles between the sun and observer greater than 90°, the detrimental effect of veiling brightness on visibility is much greater.

(5) The increasing brightness of suspensoid particles with increasing angle between the sun and observer's line of sight definitely affects the ease with which fires may be detected by lookout observers. When there is present an appreciable concentration of atmospheric suspensoid material, the visibility of landscape features in the general direction of the sun is decreased by the veiling brightness of the suspensoid material. The same factor, however, which causes the increased brightness of the atmospheric suspensoid also increases the brightness of a smoke column observed in that direction. The net result, then, is that even with a relatively high concentration of atmospheric suspensoid material present, smoke columns may be detected more readily and at greater distances in the general direction of the sun than in the opposite direction.