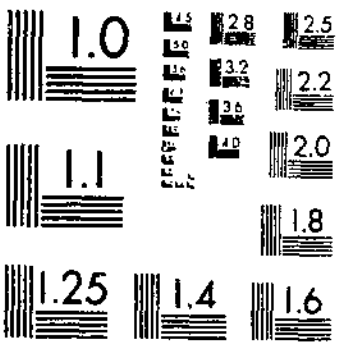
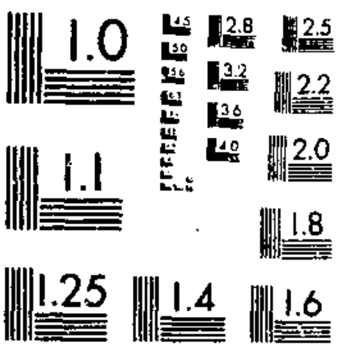
TB 954 (1948) USDA TECHNICAL BULLETINS UPDATA
SOME PRINCIPLES OF VISIBILITY AND THEIR APPLICATION TO FOREST FIRE
BYRAM, G M , JEMISON, G M 1 OF 1

START



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Technical Bulletin No. 954 • *March 1948*

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

Some Principles of Visibility and Their Application To Forest Fire Detection[1]

By George M. Byram, *physicist*, and George M. Jemison, *silviculturist*, *Southeastern Forest Experiment Station, Forest Service*

CONTENTS

[1] Submitted for publication September 1947.

772294°—48——1

INTRODUCTION

Early and reliable detection of forest fires is the keystone of efficient fire control. It means the discovery of fires while they are small and results in lower suppression costs and damages. Private, State, and Federal fire-protection agencies throughout the country, recognizing this fact, have spent considerable time and effort planning lookout systems which will give the best coverage for the investment in towers, living quarters, roads, trails, and telephone lines. This work has been reported by Abell and Beeman,[2] Show and Kotok (*27*),[3] Show *et al.* (*28*), and others.

Detection time standards, which are arbitrary discovery time goals, vary from day to day and season to season. When the fire occurrence rate or fuel flammability is high, action must be faster and surer if fire losses are to be held down. Visual range [4] also fluctuates from day to day or month to month and is a factor controlling the number of lookout men needed on duty to attain a given detection time standard. For example, Jemison (*19*) found that the smoke from a ⅛-acre fire could be seen at noon on the Cumberland National Forest in Kentucky an average of 8.0 miles in September, but only 4.4 miles in November. Since, in this particular forest, the ⅛-acre fire is considered the maximum allowable size on discovery for average burning conditions, lookout points during November need to be operated not more than 8.8 miles apart, but the points manned could be 16.0 miles from each other during September. In September, only about one-fourth as many lookout stations as are needed in November would have to be operated to cover an area. This spacing would ordinarily be modified by topographic conditions.

Studies were started in 1932 [5] to answer two questions:

1. How far can an object of small angular diameter, such as a standard-sized smoke column, be seen through a hazy atmosphere?
2. How can visibility distance be measured by methods useful to the fire control agency?

A fundamental approach has been followed throughout the investigation in order to establish the basis upon which the answers to many practical detection problems rest. Incidental to the main study a number of useful devices have been developed, including an eye test for selecting keen-eyed observers, a haze-cutting filter, and goggles for

---

[2] Abell, C. A., and Beeman, R. M. Planning a lookout system. U. S. Forest Service, Appalachian Forest Expt. Sta., 44 pp. 1937. [Processed.]

[3] Italic numbers in parentheses refer to Literature Cited, p. 43.

[4] The "visual range" of an object is the distance at which it is barely visible. The term is slightly more general than "visibility distance," used by the Forest Service, which is the distance at which a smoke column of specified size and density can be seen and recognized as a smoke by the unaided eye. These terms, as well as certain others, are defined in more detail later.

[5] These studies were begun by R. E. McArdle at the Pacific Northwest Forest and Range Experiment Station, Portland, Oreg., and were later continued at that station and at the Southeastern Forest Experiment Station by the senior author. Other forest experiment station workers have also been engaged in various phases of visibility research, but the discussion here concerns chiefly the work at the two experiment stations mentioned above.

lookout men. In addition, several principles useful in fire detection have been evolved.

It was apparent throughout the investigations that although the visual range of a small body of smoke (or any other object of small angular diameter) was determined to a large extent by the scattering and absorption of light by the lower atmosphere, the nature of vision itself was equally important. It is not possible to derive the basic expression for the visual range of a small object unless the relation between visual acuity[6] and such factors as brightness, object-background contrast, and structure of the object is known.

VISIBILITY AND THE EFFECT OF HAZE UPON IT

The Eye as an Optical Instrument

An understanding of some of the mechanisms of vision is basic to any discussion of the fundamentals of visibility. When light from a distant object enters the eye, it is focused by the optical system of the eye so as to form an image of the object on the retina (fig. 1).

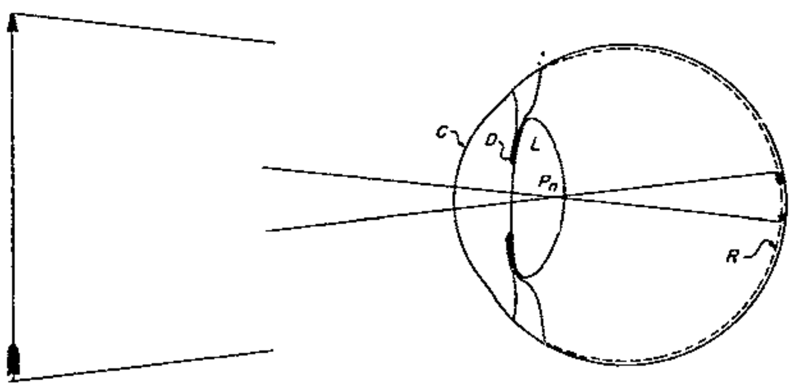


Figure 1.—Diagram showing the optical system of the eye: *C*, cornea; *D*, iris diaphragm; *L*, crystalline lens; P_n, posterior nodal point; *R*, retina.

The retina corresponds to a photographic film, and, like a film, it has a characteristic grain. The retinal grain consists of closely packed individual light-sensitive receptors which are connected by nerve fibers to the visual center of the brain.

Unlike a photographic film, the retina is not equally sensitive over its entire surface. If the eye is adapted to daylight conditions, critical vision is confined to a very small central area of the retina, known as the fovea, which is less than 1.5 degrees in angular diameter. The sensitivity of the outer retina decreases rapidly with increasing distances from this central highly sensitive area. This variation in the sensitivity of the retina has an important effect on the ability of an observer to detect smoke and also on his methods of observation.

[6] "Visual acuity" is defined as the reciprocal of some arbitrary angular dimension (usually the angular diameter in minutes) of an object when it can just be resolved or identified.

There is more to seeing than a study of the visual mechanisms would indicate, and an efficient observer must possess certain qualities in addition to good eyesight. Successful seeing may be regarded as the integration of many different phases of visual experience. Differences in the illumination, color, and shape between different parts of the retinal image are meaningless until they are interpreted by the observer. His ability to make subtle distinctions when these differences are small will therefore depend not only on the quality of his eyesight but also on his intelligence and on his judgment built up from previous experience. A keen-eyed but untrained observer might find it difficult to distinguish a small smoke from dust or a small patch of cloud. An experienced observer with eyesight of the same quality would be less likely to have this difficulty and might even be able to give additional information from the meager details of the retinal image; for example, he might be able to judge the type of fuel in which the fire was burning.

Haze and Air-Light

The term "haze" may be defined as the luminous veil which obscures distant objects and makes them difficult to see. This veil is caused by the scattering, refraction, and reflection of light by the innumerable particles suspended in the atmosphere between the observer's eye and the distant object at which he is looking. However, the concept of haze as a luminous veil is not as simple as it might at first appear. The veil is actually three-dimensional, and its presence is a joint phenomenon between the existence of a light source (or sources), particles in the atmosphere, and their ability to change the direction of some of the light coming through the atmosphere. Haze defined in this manner does not have quite the same meaning as it has in certain other meteorological uses, but this definition seems more compatible with the ordinary use of the word and with its relation to forest fire detection.

The atmosphere is never a perfectly transparent medium even where the air is exceptionally clear. Usually it contains a suspension of small particles of many kinds, such as smoke, dust, spores of fungi, pollen, and bacteria, which absorb and scatter light. Even the molecules of the pure gases comprising the atmosphere contribute to the scattering of light. In certain regions near the seacoast, the air may contain salt particles which are left when droplets of ocean spray evaporate.

Probably most haze is caused by smoke. In the eastern United States, industrial smoke and smoke from dwellings seem to be the main sources, and hazy conditions in any given region are determined to a large extent by the population density.

According to the definition given here, haze would not exist on a completely dark night even though the atmosphere was loaded with scattering particles. At night, particles interfere with fire detection because they reduce the apparent brightness of the flames, which an observer sees as though he were looking through a neutral filter. Nighttime detection of fires is much less important, however, than daytime detection. In the eastern United States, for example, 94 percent of 10,131 fires in 1942–43 started during daylight hours (7:31 a. m. to to 7:30 p. m.), and it is conservatively estimated that about 90 percent of all fires are discovered during daylight. In northern California, 86 percent of all fires during the period 1921 to 1930 originated between

6:31 a. m. and 8:30 p. m. (*27*). A detailed discussion of visibility of fires at night is not attempted in this paper, although nighttime detection may constitute an important problem regionally.

"Haze brightness" is a quantitative photometric term and can be expressed in any of the common brightness units.

The term "haze particle" may denote an individual particle suspended in the atmosphere which is capable of changing the direction of a light ray. Fog or cloud particles could perhaps be called haze particles, but it is probably best to consider them as separate, and to reserve the term "haze particle" for the smaller and more permanent particles.

"Air-light" may be defined as the luminous flux which is emitted by haze. Air-light bears the same relation to haze as skylight does to sky. It is not possible to make a clear-cut distinction between sky and haze or between skylight and air-light. Sky becomes haze or skylight becomes air-light when an observer is looking in a more or less horizontal direction.

The air-light is the result of resonance scattering, diffraction, reflection, and refraction of sunlight, skylight, earthlight, and a repetition of the same process for the air-light itself. The last phenomenon is known as multiple scattering, and the inclusive term "scattering" is generally used to describe the resultant effect of all of the processes which can change the direction in which light is traveling.

If the suspended particles are very small compared with the wave length of light, scattering is of the resonance type. In resonance scattering, the light scattered at right angles to the original beam is completely plane-polarized and has only half the intensity of the unpolarized light scattered in either the forward or backward direction. For intermediate directions the scattered light is partially plane-polarized. Knowledge of this phenomenon of polarization led to the development of the haze-penetrating filter, described later.

If the particles are large compared with the wave length of light, such as the particles in fog or mist, scattering will be due mostly to reflection and refraction by the individual particles and only a negligible amount of the scattered light will be plane-polarized. Since the diameters of the particles are distributed over a considerable range, all types of scattering usually exist simultaneously. The following tabulation, modified from a diagram given by Davidson (*15*), shows the range of diameters of different kinds of particles:

Suspensoid	*Diameter (microns)*
Smokes	0.001 to 0.3
Smokes (average)	0.25
Permanent atmospheric impurities	0.001 to 1.0
Dust causing lung damage	0.5 to 6.0
Bacteria	1.0 to 15
Plant spores	10 to 30
Pollens causing hay fever	20 to 70
Fog or cloud	5 to 50
Mist	50 to 100

Smoke particles are droplets of nearly transparent substance of low vapor pressure, formed by the condensation of the unburned gaseous fractions of fuels such as wood, coal, and oil. Incomplete combustion often causes the precipitation of carbon particles and, to a small extent, ash particles, which are nearly opaque. If such particles are present in any great number, scattering will be accompanied by true absorption, and the haze will have a darker appearance than when the scattering processes only are present.

The appearance of distant objects seen through thin smoke or through a hazy atmosphere is much different from that of similar objects seen nearby. In the immediate landscape, color and brightness contrasts are high. Shadows are deep and clearly defined, and the deepest shadows occasionally have a bluish hue of marked saturation. In the distant landscape, color and brightness contrasts are greatly reduced, and the distant scenes have a much softer appearance than those nearby. Most colors undergo a change of hue, and with the exception of the whites and grays, the saturation of the colors is greatly decreased. The reds and browns take on a purplish hue, the greens appear bluish green, but bluish hues change little. The contrast between the deepest shadows and the brighter parts of the scene is small. The bluish veil of haze takes on considerable brightness, but its color is less saturated than that of the nearby deep shadows. The apparent color of distant colored objects is discussed in considerable detail by Middleton (*24*).

The brightness of a distant object is decreased by the scattering and absorption of light by the intervening atmosphere, but is increased by the air-light from the haze between the observer and the object. The apparent brightness of the object may be computed by means of the Koschmieder equation which is discussed in the Appendix. A detailed derivation of this equation as applied to smoke column brightness is given by Bruce (*3*).

Although the color changes caused by varying the distance from an object are very noticeable, their effect on the visual range is negligible compared with that of the corresponding brightness and contrast changes.

The Visual Range of Small Objects

DEFINITIONS

The "visual range" of a given object may be defined as the maximum distance at which the object can just be seen by an observer with normal vision. For complex objects the various parts of which are to be resolved,[7] the visual range is the maximum distance at which resolution is just possible.

The term "visibility distance" is used to denote the maximum distance at which a small smoke can be seen and recognized as a smoke. To simplify conversion from one unit to the other, it is arbitrarily assumed that the visibility distance of a smoke column is 70 percent of its visual range. Such an assumption is necessary, as will be brought out later, in order to provide a practical safety factor in detection.

The word "visibility" is overworked and often vague. Much of the meaning of the word could be retained and vagueness avoided by introducing a more specific concept, the visibility angle. This term would be defined as the angular distance between the direction of vision (binocular) and the direction of the object when it can just be detected. For example, an observer might be able to see an object

[7] A complex object may be defined as one having two or more parts, which must be resolved or seen as separate.

plainly by looking directly at it. If the object were moved to one side (his direction of vision being unchanged, and the distance of the object kept constant), it would finally reach a position where it would be barely visible. The visibility angle would be measured in degrees and for any given object its numerical value would depend on the angular dimensions of the object, the contrast between the object and its background, the background brightness, and the quality of the observer's eyesight. Illustrative test objects and their visibility angles when viewed in daylight by an observer with normal eyesight are listed in the accompanying tabulation.

Test object:	*Approximate angular dimensions (minutes)*	*Visibility angle (degrees)*
Telephone pole (85 feet distant) viewed against a background of green trees	34 x 700	40
Gray automobile (200 feet distant) viewed against a mottled background of green vegetation and light soil	100 x 240	37
Dandelion blossom on green lawn	4 x 8	29
Large, light-colored billboard against background of green vegetation	480 x 960	92
Fence post viewed against green lawn	15 x 90	51
Black spot on yellow paper	2 x 2	9
The word "vision" typed on yellow paper (3 feet distant); just visible	8 x 48	47
The word "vision" typed on yellow paper (3 feet distant); just readable	8 x 48	2

The visibility angles for black disks of different angular diameters, viewed against a white background in daylight, can be readily determined from the curve in figure 3, discussed later, the ordinates of which are plotted in terms of the reciprocal of the angular diameters of the disks.

The concept of a visibility angle has a number of drawbacks, but would be directly applicable to many of the problems in which the position of the object is unknown and a process of searching or scanning is involved, as in detection of forest fires. Its application to scanning problems will require information on the relation between visual acuity, object-background brightness contrast, and background brightness for different zones of the outer retina. Such information is not available at the present time, hence the visibility problems discussed in this paper necessarily apply to foveal vision.

Of a number of objects, all of which are located at the same distance from the observer, those with the largest visibility angles will usually have the greatest visual range if the objects are moved away from the observer. Owing to complex contrast relations, this is not always true and there is no simple direct relation between visibility angle and visual range.

DETERMINATION OF THE VISUAL RANGE

The answer to the question, "How far can an object of small angular diameter be seen through a hazy atmosphere?" depends on the solution of two problems:

1. The determination of the effect of atmospheric haze on the contrast between a distant object and its background.

2. The development of a general theory of visual acuity, and in particular the determination of the function relating visual acuity to

the brightness contrast between a given test object and its background.

The first of these two problems has been discussed in considerable detail in other publications (*3, 7, 8, 18, 24*), two of which (*3, 24*) also give some discussion of the second problem. The theory of visual acuity and its relation to contrast has been investigated by Byram (*12, 13*). The results of recent comprehensive investigations of the second problem, including studies of the effect of background brightness, have been published by Blackwell (*2*). The solution of problems concerning the visual range of small objects is a process of combining the two problems just mentioned. In general this is a complex procedure and a description of the mathematical methods for doing this is beyond the scope of this paper. However, a discussion of the mathematical theory of the visual range is given in the Appendix.

The visual range of small bodies of smoke can under certain conditions be expressed as a function of a single variable representing the clearness of the atmosphere. The clearness of the atmosphere can be expressed in terms of the maximum distance at which a large black object, such as a distant mountain ridge covered with dark vegetation, can be seen. This unit is sometimes referred to as the meteorological visual range, or dark ridge visual range. For many purposes a smaller unit approximately one-fourth as large as the dark ridge visual range is more convenient. This smaller unit can be measured with instruments to be described later, and is designated as the haze-meter reading. Another unit, the mean free photon path, is nearly equal to the haze-meter reading; this unit and its physical meaning are discussed in the Appendix.

The visual range of a smoke body can be expressed in terms of a single variable only when it is viewed against a dark background or against the horizon sky, and only when the scattering function of the particles composing the smoke body is identical to that of the particles suspended in the atmosphere (see Appendix, p. 50). Under such conditions the brightness of the smoke would be directly proportional to the brightness of the horizon sky in the same direction from the observer as the smoke. This should be true regardless of the position of the sun or other sources of light.

This condition is seldom realized, but on hazy days the approximation may be fairly good. It should be best when the haze particles are similar to those composing the smoke body. This often occurs in the Western States when the prevailing haze is caused by forest fire smoke. The approximation is never good when the atmosphere is clear. Another source of error is the intrinsic brightness of landscape backgrounds, but this error can be partially compensated for by taking haze-meter readings against backgrounds which have about the same intrinsic brightness as the backgounds against which the smokes are observed.

The points plotted in figure 2 show the results of a large number of observations on the visual range of small test smoke columns of approximately constant size, viewed against dark backgrounds. The data are plotted as a function of the haze-meter reading in miles taken at the time the smoke was observed. The smoke columns were furnished by burning specially prepared candles (see figure 8 and pages 19 and 20 for description).

Curve *A* is theoretical and is a plot of equation 11 in the Appendix which expresses the visual range of a test object in the form of a very long thin band or rectangle. This curve gives the best fit to the data, although the smokes tended to have the form of slender inverted cones rather than long rectangles. However, the wider parts of the cones were not as bright as the narrow parts, and the total luminous flux given off per unit length should be constant. This is probably why curve *A* agrees closely with the plotted points. Curve *B* is also theoretical and is a plot of equation 13 in the Appendix. If the smokes had been in the form of globular puffs with approximately circular cross sections,

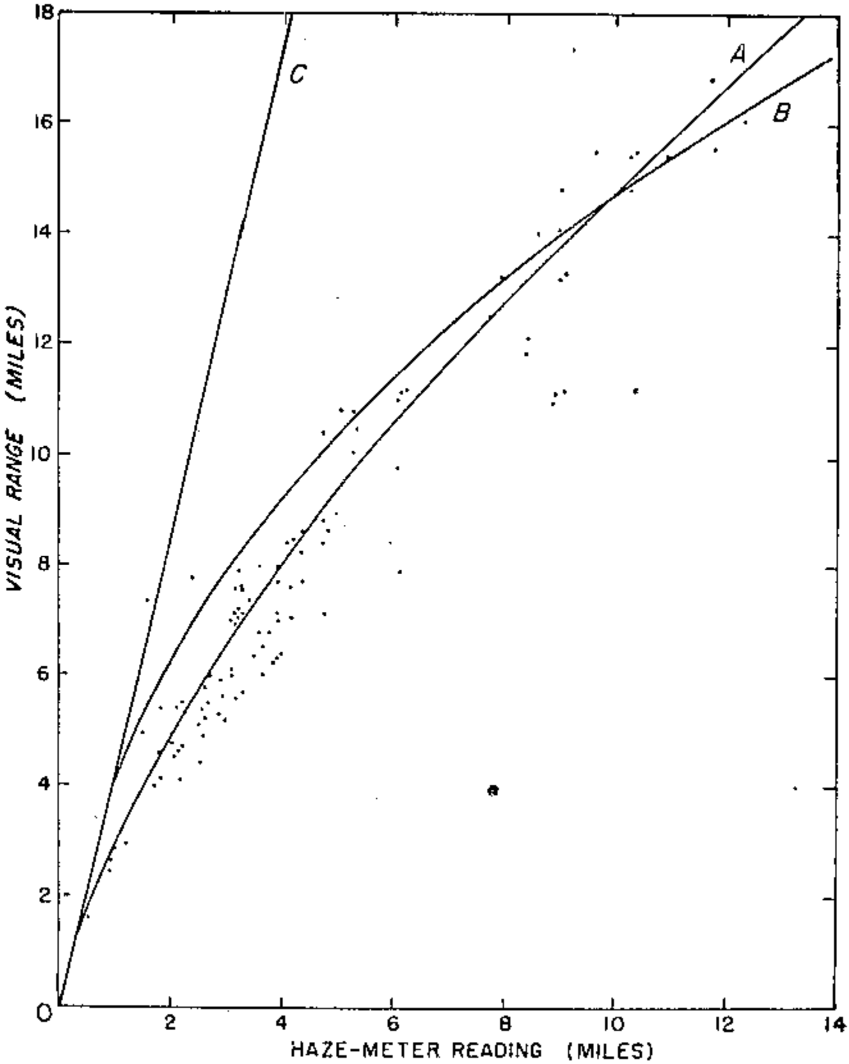


FIGURE 2.—Measurements of the visual range of a small standard smoke column plotted as a function of the haze-meter reading. Curve *A* is the theoretical curve for a long, thin rectangular test object; curve *B* the theoretical curve for a disk test object; and curve *C* is the theoretical curve for a large bright object viewed against a dark background or a large black object against the horizon sky. The dots represent actual observations of test smokes and apply to curve *A* only.

772291°—48——2

the data should have followed a curve of this type. Curve *C* is theoretical and represents the visual range of a large object equal in brightness to that of the horizon sky and viewed against a dark background. It is assumed that the angular diameter of the object is sufficiently large that its size is not a factor affecting its visual range. Curve *C* also represents the visual range of a large black object viewed against the horizon sky.

The scatter of the points in figure 2 around curve *A* probably has three different sources. One factor causing scatter is the variability of the test smokes which were not always of uniform brightness and shape. Wind and vertical air temperature gradients affected their appearance. Also, the edges of the smokes were somewhat blurred, thus making it difficult to assign definite values to their angular diameters. Another factor is the random variation associated with visual threshold determinations. The third factor is probably the variation in the position of the sun, as no attempt was made to control this variable.

If the smoke particles and the haze particles had the same scattering function, the position of the sun should have no effect. However, Bruce (*4*) shows definitely that the smoke-horizon brightness ratio increases somewhat with decreasing angular distances from the sun, at least for the artificial smokes used in tests of this kind. It is probable that this is also true for actual smokes from forest fires with the possible exception of thin blue smokes, which are sometimes given off by fires burning in very dry nonresinous fuels.

The increase in the smoke-horizon brightness ratio with decreasing angular distances from the sun is one reason why smokes can be seen farther when the observer is facing a low sun, than when he is looking in the other direction. On light backgrounds, such as dried grass or light-colored soils, an even more important factor contributing to good smoke column visibility toward the sun is the large decrease in the intrinsic background-horizon brightness ratio (see Appendix) which occurs at small angular distances from the sun.

The effect of the angular position of the sun on smoke visibility has been known for a number of years, but has not been understood and accepted by many fire control specialists. In 1933, when investigating the effect of the background-horizon brightness ratio on smoke visibility, the senior author noticed that smoke visibility was best toward the sun. The same point has been emphasized in a number of papers (*4, 5, 6*). The visual range of ordinary landscape objects such as houses, trees, and landmarks, however, is much less toward the sun than away from it.

Shallenberger and Little (*26*) give an equation for the visual range of conical smokes (viewed on dark backgrounds) which rests upon entirely different assumptions than those upon which curve *A* in figure 2 was based. They assumed that a smoke at the limit of its visual range had an angular diameter of 1 minute (at least for that part of the smoke recognizable as a smoke), and that the brightness contrast between the smoke and its background was constant (about 3.2 percent). Neither of these assumptions can be justified on the basis of retinal image structure (*12*), although their equation gives a relation between the visual range of a "conical" smoke and the visual range of a black ridge which closely resembles curve *A* in figure 2. Smoke columns at the limit of their visual range may have angular diameters which may be only a fraction of a minute, or they may be several minutes. Similarly, the contrast between the smokes and their backgrounds may vary from some large value (seldom greater than 40 or 50 percent) down to perhaps only 2 percent.

LIMITATIONS OF THE VISUAL RANGE THEORY IN ACTUAL PRACTICE

From the reasonably good agreement between theory and the experimental data in figure 2, one might conclude that the determination of the visual range of a small object would be a simple matter if the atmospheric variable is known. Unfortunately, this is not so. In obtaining the data for figure 2, the observers knew just where to look for the test smokes, and the effects of extraneous details were minimized by using uniform backgrounds.

In making visual acuity measurements, it is almost necessary that the observer know where to look for the test object so that its image will fall on the fovea, the central sensitive part of the retina.

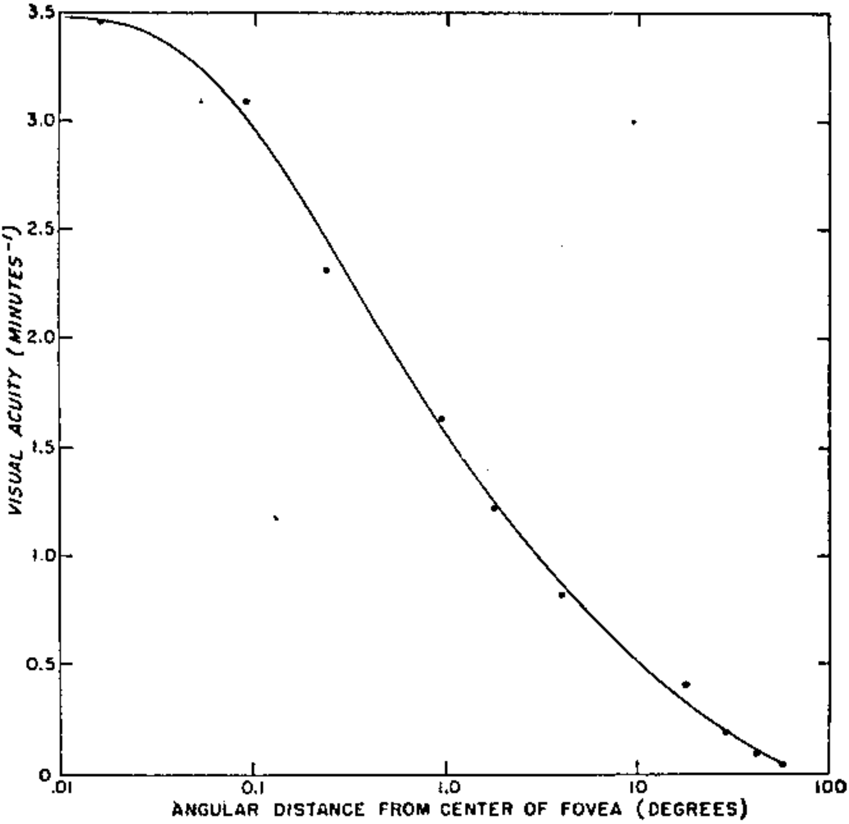


FIGURE 3.—The visual acuity for a black disk on a white background when the image falls on the outer retina; visual acuity is plotted as a function of the angular distance of the image from the center of the fovea. Note that the abscissa is a logarithmic scale.

Figure 3 shows the results of visual acuity measured for a black disk when the image falls at different angular distances from the center of the fovea. Visual acuity is defined as the reciprocal of the angular diameter of the disk in minutes when it is just visible. The sensitivity of the outer retina drops off so rapidly that the angular distance of the image from the central fovea must be plotted on a logarithmic scale in order to show the trend of the curve. If the region of critical vision is arbitrarily defined as that area about the fovea for which any part of the area can yield visual acuity values (for the disk test object) at least one-half as great as are possible for the central fovea, then figure 3 shows that this region is about 1.5 degrees in angular diameter.

The data in figure 3 were obtained for binocular vision in the horizontal plane, but if it is assumed that the rate of decrease of retinal sensitivity is approximately the same in all directions, then critical vision is confined to a cone 1.5 degrees in angular diameter. In order to see a small object which is near the limit of its visual range, the direction of the observer's vision would have to pass within 45 minutes of the direction of the object. It is thus apparent why a small object such as a smoke, even on a uniform background, is very difficult to detect unless the direction of an observer's gaze is within a small angular distance of the smoke.

It is for these reasons that visibility distance is defined as 70 percent of the visual range. Such a safety factor is necessary in good detection practice because smokes may occur at random over much of an observer's territory, and he never knows exactly where to look for them.

Motion is also an important factor in the identification of smokes. The difference between the sensitivity of the fovea and the sensitivity of the outer retina for detecting motion is much less than the corresponding difference for perception acuity or resolving power acuity. It is even sometimes stated that the sensitivity of the outer retina for detecting motion is greater than that of the fovea, and that an observer is more likely to see an object move if he does not look directly at it. This belief probably is incorrect (at least for small objects viewed in daylight) and seems to be based on the assumption that the sensitivity of the retina to motion is closely related to its sensitivity to flicker. At high brightness levels, critical flicker frequency is greater for the outer retina than for the fovea (*31*).

PRACTICAL MEASUREMENTS OF VISIBILITY DISTANCE

Visibility distance, visual range, and visibility angle are three quantities associated with the seeing of small smoke bodies. The first two are closely related, since the visibility distance of smoke is defined here as equal to 70 percent of its visual range. The visual range is a very useful quantity in experimental work because measurements made at the threshold of vision are the most reliable. However, for actual practice the smaller quantity, visibility distance, is more suitable because it gives a certain safety factor by increasing the visibility angle.

As stated earlier, the efficient placement of forest fire detection forces requires current knowledge of fluctuations in visibility distance. More lookout men are needed as the atmosphere becomes hazy, fewer when it is clear. But experience showed long ago that personal estimates of visibility distance were far too erratic to be dependable. Since the visibility distance of smoke columns is closely related to the atmospheric attenuation coefficient, it is essential that means be available to measure or estimate this quantity.

The degree of accuracy demanded in the measurement or estimation of visibility distance varies with values at stake and rate of spread of fire. Where fires would cause great damage to a valuable resource, large errors in determining visibility distance could not be tolerated because an inadequate detection system might be the direct cause of excessive damages. In fuel types and under flammability conditions conducive to rapid spread of fire, large errors in visibility distance would likewise be costly.

Reliable standards of accuracy in measuring visibility distance can best be determined after establishment of over-all fire protection standards for a given region. Once these standards, including a speed-of-detection objective, have been set up, the significance of accurate visibility distance determination can be judged. In parts of eastern United States, a 15-minute detection time standard is recognized, which may or may not be the most desirable. But on this basis it is believed that for this region visibility distance should be measured within ± 10 percent because, in the high-rate-of-spread fuel types commonly found there, such an error is significant. A 10-percent error in visibility distance would mean, conservatively, a 35-percent increase in size of smoke or in size of fire at discovery. (In eastern fuel types, general observations indicate that the size of a smoke is directly proportional to the diameter of the fire.) Increases in the size of smoke necessary to compensate for an error of estimate in visibility distance can be determined from a family of curves which show the effect of either size or magnification on the visual range. Effect of size of smoke and magnification on the visual range is discussed in more detail in the section "Periscopes, binoculars, telescopes, and filters," and in the Appendix.

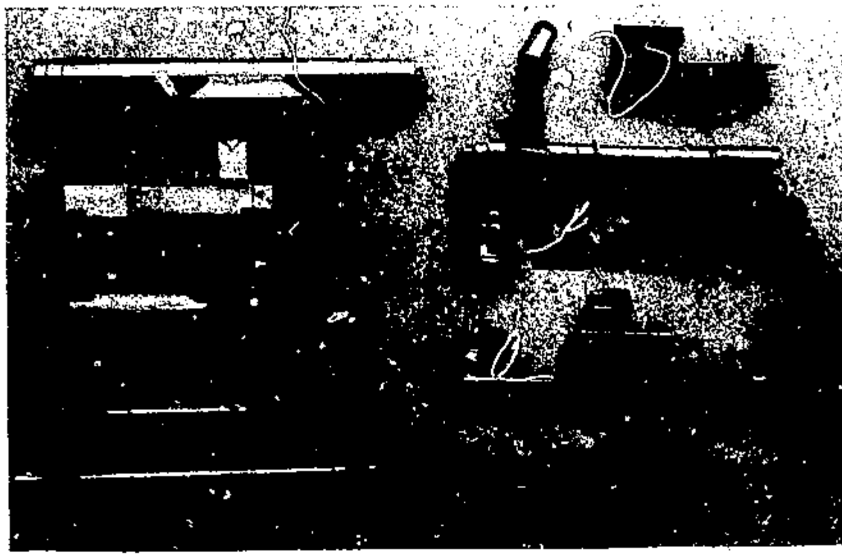
The significant point to keep in mind is that relatively small errors in visibility distance determination are associated with large changes in size of fire on discovery at those distances. If rates of spread are known, it is possible to approximate the effect of an error in visibility distance on size of fire at discovery, assuming a detection network set up to operate over the measured visibility distances.

Visibility Meters

The best method of estimating the visual range of small objects is by the use of telephotometers which are instruments designed to measure the apparent brightness of a small distant part of the landscape or horizon sky. Middleton (*24*) gives a comprehensive summary and discussion of the several different types of telephotometers and empirical visibility meters. The photometric fields of the telephotometers usually consist of two parts and are of the balance or null method type; that is one part of the field can be made to appear brighter or darker than the other part of the field and a balance is obtained when both parts appear equally bright.

THE BYRAM HAZE-METER

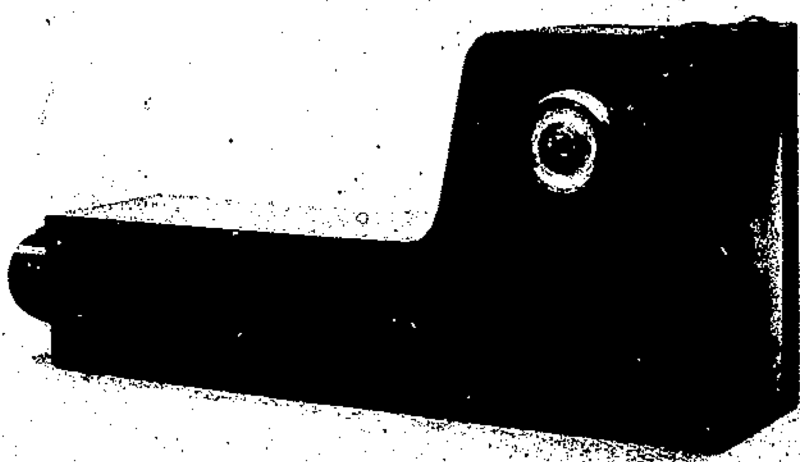
During the course of this study a number of visibility instruments were constructed and tried. Some of them are shown in figure 4. Most



F-388352

FIGURE 4.—Early models of visibility instruments developed in the course of the visibility studies. Most of the instruments are telephotometers.

of the instruments shown here are telephotometers. The standard model, called the Byram haze-meter (fig. 5) has been described by



F-388341

FIGURE 5.—The Byram haze-meter, designed for use in mountainous country.

Byram (*7*) and McArdle (*20*) and is designed for use in mountainous country.

The instrument, roughly L-shaped, is about 9 inches long with the eyepiece at the small end. Looking through the slit in the eyepiece, an observer sees a small colored bar superimposed on the field of vision. This bar is 60 percent as bright as the horizon sky. When the observer turns the knob in the upper part of the instrument slowly, reflections of topography are brought into view, ridge by ridge. When a ridge is reflected that is 60 percent as bright as the horizon sky, the bar and that ridge appear equally bright and the bar, in effect, disappears. The observer then notes the ridge and scales off its distance from the observation point on a map. Visibility distance may be determined by referring the ridge distance to the tabulation on page 21, prepared from curve *A*, figure 2. Construction details of the Byram haze-meter are given in the Appendix.

There may be certain topographic situations in which the Byram haze-meter cannot be used satisfactorily, such as stations where there are not several successive ridges to serve as targets. Sometimes, also, the bar in the meter will not exactly match either of two adjacent ridges, one being too far from, the other too close to the observer. Under such circumstances, the observer should be instructed to interpolate visibility distance based on a point somewhere between the two ridges. This can be done accurately with practice. Probably a better procedure, however, is to select lookout points topographically adapted to the taking of haze-meter readings, since considerable selection is usually possible. The same applies to other visibility meters, to be discussed later, which also have limitations imposed by topography.

Some workers have criticized the Byram haze-meter because it has a blue filter in the optical system. According to Shallenberger and Little (*26*) the use of a blue filter in a telephotometer introduces an error into estimates of visibility distance if the objects are to be viewed without a filter, as is true of forest fire smokes. Such an error would ordinarily be very small. It can be shown that a haze-meter reading for blue light is directly proportional to the reading for red light, regardless of the values of the respective readings, provided the selectivity of the haze particles remains constant. The selectivity of the particles of a haze caused by forest fire smoke is probably almost independent of their density; hence only a negligible error is introduced if the haze-meter reading is determined for blue light. Tables or graphs will then show visibility distance without filters as a function of haze-meter readings obtained with a blue filter. Such tables should always be used with the Byram haze-meter.

Two instances have been called to the attention of the writers in which the blue filter faded in use. Fading to 50 percent of its original intensity would cause errors of 0.2 to 0.3 mile at a 4-mile visibility distance or about 6 percent. This is an appreciable error, but it can be avoided by keeping the instrument encased in the wooden box supplied for that purpose.

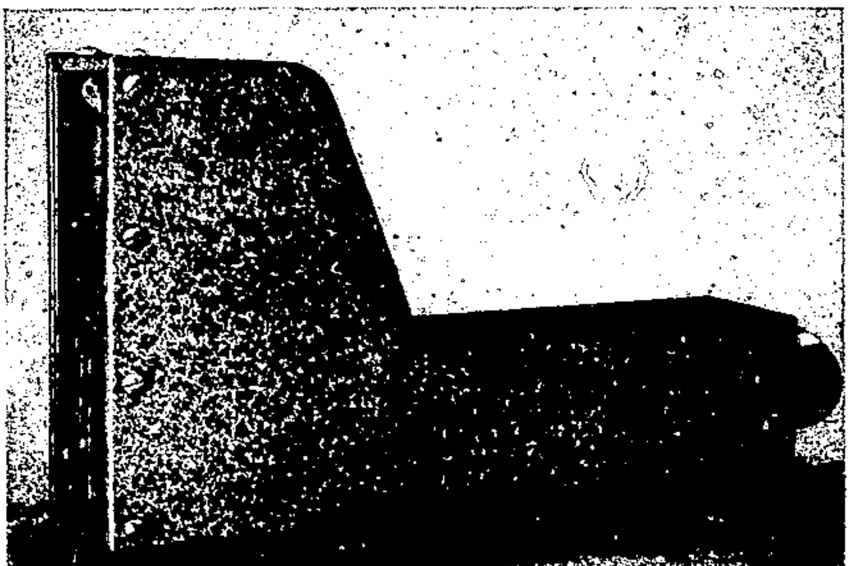
Telephotometers do not require a blue sky at the horizon for accurate operation, as has sometimes been asserted. On a cloudless day, the horizon seen from most lookout points in the mountains is white or nearly so. The horizon would appear blue only where the lookout point was lower than adjacent topography so that the line of sight to the horizon would slant upwards to an appreciable degree. Such a lookout point would not be suitable for haze-meter readings with any type of instrument.

Clouds on the horizon seen from the usual mountain lookout station change but little the brightness of the white horizon. For example, on an average day when the haze-meter reading is 8 miles, clouds on a 16-mile distant horizon would cause an error of 22 percent in the reading. For a 24-mile horizon the error would be 8.5 percent, and for a 32-mile horizon 2.5 percent. Clouds on a 40-mile horizon would be invisible. It is good practice, therefore, to choose lookout points with distant horizons to minimize this source of error. On rainy days when white clouds lie on top of nearby mountain peaks, the error in Byram haze-meter readings would be appreciable, although visibility distance measurements are not required with a high degree of accuracy when fuels are wet.

The dark ridge system of estimating visibility distance described later has the same type and magnitude of error if used under conditions when clouds lie on the horizon. In the northern Rocky Mountain region, however, Shallenberger and Little (*26*), recommend a method of fading one ridge against a more distant ridge, which eliminates the error due to clouds. This method is standard practice in that region.

THE PLAINS HAZE-METER

An instrument similar to the Byram meter, called the Plains haze-meter (fig. 6), was developed by Byram (*9*) for use in flat or rolling country. Although designed primarily for the Coastal Plain, it has worked satisfactorily in mountain topography such as the southern



F-368342

FIGURE 6.—The Plains haze-meter, used for measuring visibility distance in flat or rolling country.

Appalachians. It is simpler mechanically than the Byram meter, but is based on the same principle.

The Plains haze-meter resembles the Byram haze-meter in appearance, but it has no moving parts. When the instrument is directed toward a selected target, 13 numbered slits may be seen in front of an optical wedge of smoked glass. Those opposite the thick part of the wedge appear to be the darkest. Successively, the observer superimposes slits on the target until one disappears, that is, is found to be of the same brightness as the target. Visibility distance is based on slit number and target distance. The shaded side of clumps of trees or other natural targets may be used by the observer. These may be at any distance up to 4 or 5 miles.

Errors in visual range associated with using the Plains haze-meter on cloudy days are insignificant because the horizon seen from a lookout point in flat or rolling country is always distant, and the horizon sky appears white even on cloudless days. The presence of clouds on such a distant horizon does not change its brightness materially.

The Plains haze-meter should not be used in the mountains, unless targets not more than 2 degrees below the horizon are available. If used in the mountains, errors in readings obtained on a cloudy day are of the same magnitude as those obtained with the Byram haze-meter. Greater detail on the optical design and directions for using the meter are given in the Appendix.

The Plains haze-meter, as well as the Byram meter, is photometrically accurate within about ±6 percent. In the hands of a competent lookout man their error should not exceed ±10 or 12 percent.

THE NRM VISIBILITY METER

Shallenberger and Little (*26*) have developed an instrument called the NRM (or Northern Rocky Mountain) visibility meter (fig. 7).

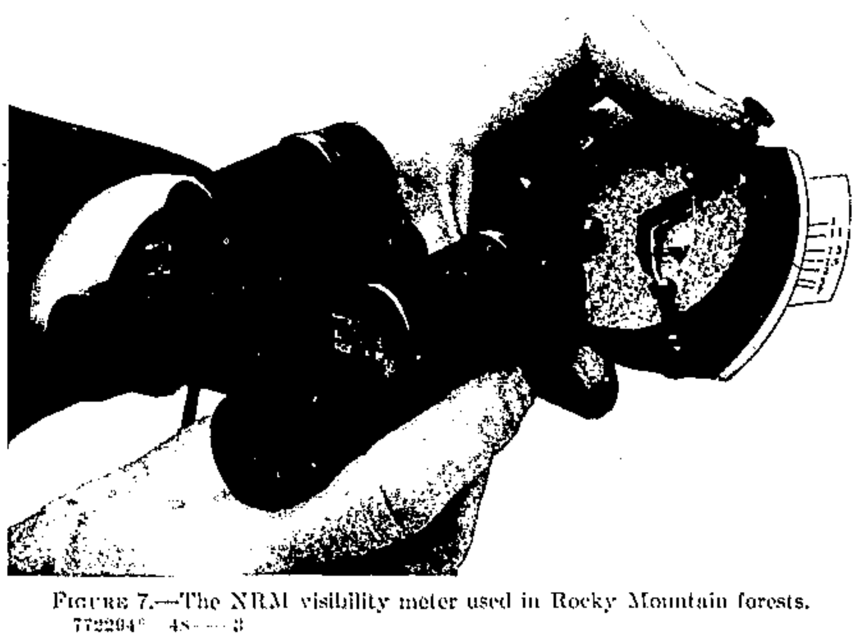


FIGURE 7.—The NRM visibility meter used in Rocky Mountain forests.

It is based on the air-light theory, but is not a balance type telephotometer such as the Byram and Plains haze-meters. A small angle prism is placed over one of the objectives of a binocular to form a double image of the border between a distant black ridge and its background (which may be another ridge or the horizon sky). By moving the prism across the objective, light from one side of the border in one image is added to both sides of the border in the other image. By assuming that a constant contrast differential exists when this border disappears, it is possible to compute the brightness ratio between the ridge and its background and hence obtain the attenuation coefficient.

If the black ridge is near the limit of its visual range, about 50 or 60 miles on a fairly clear day, the accuracy of this instrument exceeds that of any balance type telephotometer, including the Byram and Plains haze-meters, although in this situation an instrument is hardly necessary for measuring the attenuation coefficient. If the ridge is well within the visual range and located at a distance corresponding to the visibility distance of a small smoke, the error in the NRM meter may be ±40 percent, 5 or 6 times greater than the error associated with any of the balance type telephotometers.

Errors in using the NRM meter on cloudy days would be about the same as with the Byram meter, but observers are instructed not to use the former device on cloudy days. Estimates of visual range under such conditions are made by using a ridge rather than the horizon sky as a reference.

A vertical gradient of haze density, which usually exists in mountainous country and is commonly marked in the morning, introduces an error in visibility distances obtained by the NRM, the Byram, and Plains haze-meters. Visibility distances recorded are too large under such conditions.

There are likely to be fewer cases with the NRM meter than with the others where topography is not well adapted to their use. Selection of observation points should entirely eliminate difficulties associated with topography.

THE MILLER VISIBILITY METER

A visibility meter, invented by Miller,[8] has not been seen or tested by the writers, but from the available description it seems to be based on questionable principles. The observer using this device focuses one eye on a photographic print mounted behind an optical wedge, and the other eye on a distant target or section of the landscape. The measurement of visibility distance is based on matching the brightness of the photograph and the target. Since each of an observer's eyes adapts independently, it is difficult to understand how serious errors can be avoided in matching the brightness of objects seen with separate eyes.

EMPIRICAL INSTRUMENTS FOR MEASURING VISIBILITY

A number of empirical instruments have been devised for measuring the visibility of objects. These instruments usually employ one or both of the following principles:

[8] Stanley Miller, the inventor, was employed by the United States Forest Service, Missoula, Mont., at the time this instrument was developed. It was patented July 22, 1941, United States Patent Office No. 2250333.

1. Neutral filters or wedges decrease the brightness of the object and its background until the object fades from view. The reading of the wedge or number of filters required is a measure of the object's visibility.

2. Light is added to both the object and its background until the object fades from view. The amount of added light is a measure of visibility.

The Bennett-Casella meter (*1*) employs both principles and has been tested in this country. It is not suitable for measurement of visibility distance.

These instruments may be useful for comparing the visibility of nearby objects, but seem to be of little value in predicting how far the objects can be seen through a hazy atmosphere. Visibility instruments of the empirical type are discussed in considerable detail by Middleton (*24*).

TEST SMOKE CANDLE

The smoke candle, or smoke pot as it is sometimes called, was developed in conjunction with the haze-meters to serve as the standard for their calibration. In studying the visibility of small smokes it is

F-258782

FIGURE 8.—A smoke candle used as the standard for calibrating haze-meters.

important to have them uniform in color, size, and density, something that cannot be achieved with fires kindled from ordinary fuel.

The smoke candle has been used as a standard with full realization of its variability, largely caused by air currents. It does not always have sufficient heat to make its smoke rise in a column. However, it produces, a standard volume of smoke of unvarying color. Natural smokes are much more variable in color, appearing thin blue or black in dry fuels and heavy and white in wet fuels.

The smoke candle was developed by McArdle (*21*), in cooperation with a fireworks manufacturer, to simulate the smoke produced by fire covering 200 square feet of Douglas-fir or ponderosa pine duff, on a hot summer day, or about 150 square feet of burning, dry, hardwood leaf litter. Such a smoke column can be seen in very clear weather about 15 miles by keen-eyed lookout men. The smoke candle (fig. 8) is about 1½ inches in diameter and 7 inches long, and burns from 4 to 5 minutes, emitting a thick, bluish-white smoke. The smoke generally behaves about as illustrated in figure 9. Smoke candles are useful in

F-273596

FIGURE 9.—The smoke from a single smoke candle appears similar to that from an actual fire.

checking the alertness of lookout men and may be used in dry weather with comparative safety, when actual fires would be too risky.

METHODS FOR ESTIMATING VISIBILITY DISTANCE WITHOUT THE USE OF INSTRUMENTS

The visual range of small objects can be estimated from observations of the visual range of a large black object, such as a dark mountain ridge, viewed against the horizon sky. Although not as accurate as instrumental methods, the black target method has been used for a number of years by various investigators. In 1938 Gisborne outlined in unpublished correspondence to forest supervisors in Idaho and Montana a system by which they could use dark ridge visual range in place of haze-meter readings. He points out that this method should be used only when a good distribution of ridges is available around the lookout point or when the observer happens to have a given ridge just visible against the horizon sky.

At present it is customary to express the visibility distance of a smoke as the distance at which the small standard-sized smoke can be seen and recognized as a smoke; this distance is about 15 miles on a comparatively clear day. The visual range of the smoke would be about 21 miles and the corresponding dark ridge visual range would be about 75 miles. Detection problems in different regions, however, call for other sizes of smoke as standard. For instance, in the southern Appalachians, the smoke produced by a ⅛-acre fire is considered as the basis of reference in determining visibility distance.[9] See page 58 in Appendix for table of visibility distance.

The use of a standard-sized smoke is convenient in establishing a visibility scale, but it has several disadvantages. The smokes discovered by lookout men are distributed over a considerable range in both size and distance from the lookout station, and a fire has no standard size at the time of its discovery. Therefore, there might be some advantage in establishing a visibility scale which would apply to smokes of all sizes. The present concept of a standard smoke would be replaced by the concept of a population of smokes varying both in size and distance from the observer.

The simplest type of visibility scale would be one with visibility distance expressed in the form of an index independent of the size and shape of the smoke. The index could be expressed as a function either of the dark ridge visual range or the haze-meter reading if instruments are used. Visibility distance can be expressed as an index nearly independent of smoke size. It is impossible, however, to make the index independent of the smoke shape. Thus, a smoke column requires a different index scale than a globular smoke body with a circular section area. The accompanying tabulation shows the visibility distance index for both smoke columns and smoke puffs for different values of the dark ridge visual range.

	Visibility distance index	
Dark ridge visual range (miles):	*Smoke columns*	*Smoke puffs*
100	100	100
70	78	83
50	62	70
36	40	58
24	37	47
16	28	38
8	17	26
4	10.5	18
2	6.5	12.3

The visibility distance index is arbitrarily assumed to be 100 when the dark ridge visual range is 100 miles; any other dark ridge visual range could have been selected for the 100 point on the index scale.

[9] Jemison, G. M. Relation of Byram haze meter readings to safe visibility distance of smoke from an eighth-acre fire. U. S. Forest Service, Appalachian Forest Expt. Sta. Tech. Note 28, 2 pp., 1938. [Processed.]

On exceptionally clear days, the dark ridge visual range can exceed 100 miles in which case the index can exceed 100, but this causes no discrepancy in the scale.

To use the visibility distance index scale, the observer estimates the dark ridge visual range and notes the corresponding index. For example, if the dark ridge visual range is 50 miles, the visibility index is 62 for smoke columns and 70 for smoke puffs. These two visibility distance indices can be readily converted to visibility distances in miles for any desired sizes of smoke. If the smokes were of such a size that they could be seen 20 miles when the visibility distance indices were 100, then the smoke column can be seen 62/100 of 20 miles or 12.4 miles when the index is 62. Similarly, the smoke puff can be seen 70/100 of 20 miles or 14 miles when the index (for smoke puffs) is 70. The dark ridge visual range would be 50 miles in both instances. To convert visibility distance indices to miles, it is necessary only to select a hypothetical smoke which can be seen at some desired distance when the index is 100. Multiplying that distance by the appropriate index and dividing by 100 gives the visibility distance in miles.

As previously pointed out, the most likely source of error in a visibility scale not requiring the use of instruments would be in estimating the value of the dark ridge visual range when the ridges are too few, are poorly spaced, or both. This probably could be overcome to a considerable extent by the use of haze silhouettes similar to those shown in figures 10 and 11. Each lookout man could be furnished a series of about 10 of these silhouettes for his lookout station, each prepared for a different visual range of a dark ridge. He could then choose at any given time the silhouette which most nearly resembled the view from his station. In the use of the silhouettes, the lookout

F-439627

FIGURE 10.—A haze silhouette for a dark landscape for which the haze-meter reading is 6 miles. Starting with the first dark gray ridge, the distances to the different ridges are 1, 2, 4, 8, and 16 miles respectively.

man would have to note the distances of the ridges marked on the silhouettes and observe how their contrast with the horizon sky and with other ridges compared with that of ridges at similar distances in his landscape.

The use of haze silhouettes for estimating visibility without instruments shows considerable promise, but more work will be required to determine how successful they will be in actual practice.

The haze silhouettes shown in figures 10 and 11 were prepared from mixtures of black and white pigments. The brightness of the pigments (relative to a white titanium dioxide standard) was computed from the air-light equation (*3, 7, 24*) for a theoretically black landscape. Similar silhouettes could be prepared for a landscape with any given intrinsic brightness.

F-439628

FIGURE 11.—This silhouette is the same as the one shown in figure 10, except that the haze-meter reading is 3 miles.

APPLICATION OF FINDINGS TO OTHER FIRE DETECTION PROBLEMS

Lack of transparency of the atmosphere is one of the most important factors in forest fire detection, but many other problems are involved which must be considered in the design and efficient operation of a lookout system. The visibility studies have contributed to the solution of the following practical fire detection problems:

1. Methods of searching for forest fire smokes.
2. The quality of an observer's vision as related to smoke detection.
3. The use of special filters to penetrate haze.
4. The use of telescopes and binoculars to increase the observer's seeing power.
5. Prevention of fatigue and eyestrain.
6. Optical considerations in the design of the lookout house.

Methods of Searching for Forest Fire Smokes

Searching a landscape for forest fire smokes has been widely discussed, but little has been written on the subject. Show *et al.* (*28*) discuss a systematic method of scanning a landscape by checking on the visibility of selected landmarks. The operation usually requires 5 minutes, followed by 10 minutes of rest. These writers point out that "a quick running glance moving from near objects to distant ones, if it covers the ground systematically, represents not only the minimum of eyestrain but the most effective way to detect smoke." While the present studies were not planned to yield answers to the many questions regarding how best to look for smoke, some of the principles developed apply to the problem. No field study has been made by the authors to test the methods suggested.

It has been pointed out that smokes highly visible attract the eye of the observer; that is, they are readily seen even though the observer may not be looking directly at them. If an observer does not know where to look for a smoke, and if its position can be anywhere at random in some given area in his field of view, then the probable time required for him to find it by scanning the area will be determined by the visibility angle of the smoke. The planet Venus can sometimes be seen in broad daylight, but is seldom noticed because its visibility angle is very small. For a similar reason a lookout man may not see a small smoke which is well within the visual range because he has a large area to watch and does not know where a smoke is likely to occur. The size of the smoke may therefore have to increase considerably before its visibility angle is high enough for him to see it "out of the corner of his eye." In the discussion of figure 3, it was shown that the sensitivity of the outer retina drops off so rapidly that critical vision is confined to a cone of about 1.5 degrees angular diameter. An observer would have to look within 45 minutes (one-half of 1.5 degrees) of a small smoke near the limit of its visual range in order to see it.

These points suggest that the most effective coverage of a landscape from a lookout station would be accomplished if an observer scanned the terrain in pie-shaped wedges, giving most attention to the extremities of his territory. Even though he were looking at more distant sections he would be able to see smokes close to him readily because of their high visibility angle.

An observer's territory could be divided into wedges. The wedges could be zoned and a schedule of searching time set up for each zone, greater time being allowed per unit area of each more distant zone.

Smokes are difficult to see when their backgrounds are not of uniform brightness. Bruce (*4*) has made extensive observations of the visual range of small smoke columns viewed against several different types of backgrounds, and has also isolated the effect of the angular position of the sun on the visual range of the test smokes. He found that mottled backgrounds, which are common in parts of California, had a pronounced effect in reducing the visual range of smokes when the angular distance between the sun and smoke was large (greater than 70 degrees).

His tests on light-yellow grass backgrounds showed a similar decrease at large angular distances, but they also showed a marked decrease for angles less than 35 degrees. This is an exception to the rule of good visibility toward the sun, and Bruce attributes the decrease to the shadows and high lights which produce a peculiar mottling effect for an observer facing a low sun. Probably this phenomenon would not occur on light backgrounds, which are good diffuse reflectors, but might exist to some extent in hardwood forests during the leafless period; the glossy hardwood leaves on the forest floor would be favorable for the formation of high lights.

According to Bruce, it is evident that background factors affecting contrast would necessarily modify any searching schedule. If parts of a lookout man's territory were light-colored, such as areas of dry grass, more time should be allotted for searching them. Where backgrounds are mottled, as a dry grassy area covered by patches of evergreen trees, resolution of smoke is difficult, and more searching time would be needed.

It has been previously mentioned that dry fuels give off darker or lesser amounts of smoke when burning than do wet fuels. The blue thin smokes, having less contrast with their backgrounds, are less visible and harder to see. Consequently, more searching time should be allowed for areas known to have dry "smokeless" fuels such as dry grassy hillsides or south slopes.

No evidence is available from these studies to show how large the zones of search should be or how frequently they should be scanned. The importance of systematic looking for smoke should not be minimized, for it is likely that careful, thorough searching outranks in importance features given considerably more emphasis here. Study is needed to compare effectiveness of different methods of searching for smokes.

The advances in flying in recent years make the airplane a potential tool which may later have an important place in the detection system. The use of planes in detection work will present a number of problems in searching techniques which are not associated with stationary detections. Some of these problems are discussed by Morris (*25*).

Eye Test for Lookout Men

Manning a fire detection network with men having keen eyesight has two important advantages: (1) They cover a greater visual range than men with poor eyesight, and thus fewer lookout stations are needed; and (2) size of smoke within the visual range is smaller on discovery because these men are able to sight it more quickly.

The senior author developed an eye test for lookout observers and determined the advantages associated with it (*10*).[10] The device is now in use throughout the Forest Service and has been tested extensively. The original Forest Service eye test was developed by McArdle and Byram (*22*) in connection with other experiments. Its use was limited to specific lighting conditions and, as the authors pointed out, was not in final form for use by those who wished to rate lookout men in terms of distance that each could see a small smoke. The latest eye test gives ratings proportional to the distance at which lookout men can see small smokes (allowing for a haze correction), gives ratings independent of light intensity, and is sufficiently simple for field use.

[10] Byram, G. M. An eye-test for lookout men. U. S. Forest Service, Appalachian Forest Expt. Sta. Tech. Note 57, 10 pp., illus. 1944. [Processed.]

772294°—48——4

The design of a vision test, like the design of any tool, depends on the uses for which it is intended. The test described here is designed to measure the ability of an observer to see small, individual objects on backgrounds that are fairly uniform in brightness. If an observer were required to resolve minute details, then a resolving-power test, such as a series of parallel lines on a uniform background, or even the usual letter-type chart, would perhaps be more suitable.

The eye test (fig. 12) consists of measuring how far an individual can see a black spot $\frac{1}{16}$ inch in diameter on a white background 7 inches

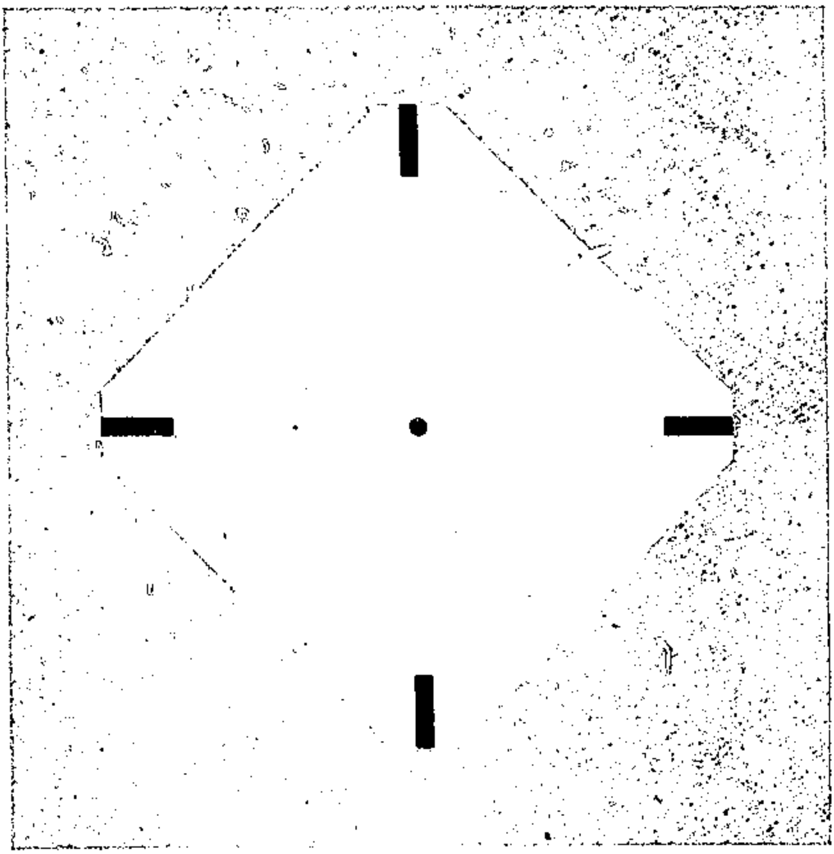


FIGURE 12.—The eye-test pattern for testing ability of observers to see smoke columns.

square. The eye-test pattern, made from glossy white photographic paper by means of a master negative (see Appendix for description), is cemented to a stiff, inflexible backing. A $\frac{1}{16}$-inch black dot is located on a diagonal half way between a central $\frac{1}{4}$-inch spot and one of the four diagonal corner strips. These strips and the central spot are for reference purposes only, enabling the observer to know where to look for the spot target.

To take the test, an observer walks away from the eye-test board until the $\frac{1}{16}$-inch spot becomes faint. The eye-test board is then whirled by the examiner and stopped so that the small spot is up or down, or to the right or left. The observer indicates the position of the spot and, if correct, he steps back about 5 feet, where the procedure is repeated. Successive changes in position are made until the observer has reached the maximum distance at which he can identify the position of the spot consistently. From this distance (his rating in feet), his ability to see smoke columns is determined.

Figure 13 shows the effect of brightness on the visual range of three different types of eye-test targets. The brightness of the white com-

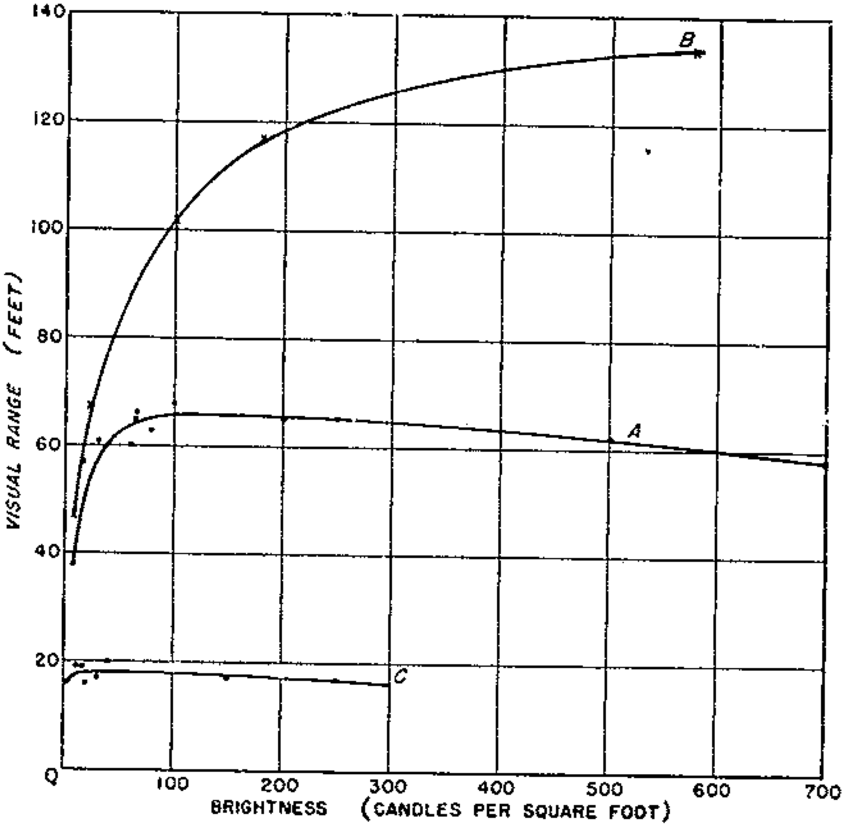


FIGURE 13.—The visual range of three different target-background combinations plotted against the brightness of their white components. Curve *A*, black on white; curve *B*, white on black; curve *C*, white on gray.

ponent of the target is expressed in candles per square foot. Curve *A* is plotted from observations made with the new eye-test board under various light intensities. Only at low brightness levels are the ratings seriously affected. For this reason the tests should always be given out of doors, where even on rather dark, cloudy days the brightness is high enough (about 75 candles per square foot for a white surface) to give reliable ratings. On the other hand, the target should not be in direct sunlight (about 800 candles per square foot for a white surface) or ratings will be slightly lowered.

Curve *B* shows the relation between light intensity and the visual range of a 1/16-inch white spot on a black background which had a reflection factor of about 6 percent. The visual range of the white spot is considerably affected by light intensity. Curve *C* is a similar curve for a white spot on a light gray background. This type of target would also be suitable for a lookout eye-test, but it is difficult to construct so that the white and gray components will always have the same brightness ratio.

There are a number of reasons why the eye test described here is superior to the Snellen or other types of "letter" charts for testing ability to see small, individual objects. There is a definite limit to the distance at which a man can see letters of a given size, and still recognize them as letters, no matter how keen his eyesight. There is no definite physical limit to the visual range of the black spot on the eye-test target or the visual range of a small smoke. Consequently, letter-type charts may fail to identify especially keen-eyed observers; such identification is highly desirable in selecting fire detection men.

It can be shown that the eye test should give ratings directly proportional to the distance that observers can see small smokes. This was verified by laboratory experiments on smokelike targets. Field tests were made also on actual smokes with men of known but different eye-test ratings. While this was a less satisfactory method, it showed that the men who were rated poor on the test could not see smokes as far as the men who rated average. Similarly, observers who rated average could not see smokes as far as men who rated good.

The relation between the eye-test rating and actual visibility distances, for different haze-meter readings, is given in table 1. It might appear from this table that the visual range of a small smoke is not directly proportional to the eye-test ratings. This apparent discrepancy is due to a haze correction; men with high ratings will have to look through more haze than men with low ratings and this tends to decrease their superior visual range.

TABLE 1.—*Visibility distance of small smokes for various eye-test ratings for different haze-meter readings*

Eye-test rating (feet)	Haze-meter readings							
	2	4	6	8	10	12	14	16
	Miles	*Miles*	*Miles*	*Miles*	*Miles*	*Miles*	*Miles*	*Miles*
72	3.8	6.2	8.2	10.0	11.6	13.0	14.3	15.7
64	3.7	6.0	7.9	9.6	11.1	12.5	13.8	15.0
56	3.5	5.8	7.6	9.2	10.6	11.9	13.2	14.3
48	3.4	5.5	7.2	8.7	10.0	11.3	12.5	13.5
40	3.2	5.2	6.8	8.2	9.4	10.6	11.6	12.6
32	3.0	4.8	6.3	7.6	8.7	9.7	10.7	11.6

From these data it is apparent that differences in eyesight, although small in comparison with some factors affecting visibility, are significant. It will be remembered (see page 13) that a 10-percent error in visibility distance, comparable to a 10-percent reduction due to poor eyesight, would mean a 35-percent increase in the size of a fire on discovery in the high-rate-of-spread fuels in the eastern United States. Eyesight affects visibility distance more on clear days than on hazy days, although the percentage difference between average and keen vision is about the same, approximately 10 percent. The eye-test rating and the relative smoke-seeing ability for different qualities of eyesight are given as follows:

Eyesight quality:	*Eye-test rating (feet)*	*Relative smoke visibility rating (miles)*
Exceptional	64 or more	11.0 or more
Good	58–63	10.5
Average	50–57	10.0
Fair	44–49	9.5
Poor	43 or less	9.0 or less

Individuals have been found to have eye-test ratings as high as 80 feet and as low as 20 feet. This range would result in a difference of about 3 miles in visibility distance (or about 20 percent) due to eyesight alone for normal haze conditions. The variations between typical groups of workers are:

Group:	*Men tested (number)*	*Average eye-test rating (feet)*
Regular Forest Service personnel	19	57. 0
CCC enrollees	15	55. 5
College students	11	54. 3
Enlisted men, U. S. Army	110	50. 9
WPA relief workers	9	43. 4
Weighted average		51. 8

Recent tests with 110 Army men emphasized the fact that quickness to see a target is closely associated with keenness of eyesight. Men who rated high on the eye test were able to identify the spot faster when it was within the visual range than others with less keen vision.

Tests of this same group showed that competition increases ability to perceive small objects. This feature was reported by Hayes and Byram (*17*) and was mentioned by Show *et al.* (*28*). Some individuals have been able to increase their score 15 to 20 percent under the stimulus of competition. Experience and practice also seem to improve the ability to perceive small objects. A group of 13 experienced artillery observers averaged 20-percent keener vision, when tested, than the group of 110 men as a whole.

The frequency distribution curve of eye-test ratings approaches the normal curve as shown in figure 14. If the normal law is valid for high ratings of the eye test, one man in about 1,500 should be able to see the 1/16-inch spot consistently at 90 feet or more. Because of the large fluctuations in visual thresholds,[11] however, a man who rates 75 or 80 feet may occasionally get a glimpse of the spot at 90 feet, although he cannot see it that far ordinarily.

---

[11] Byram, G. M. Visual thresholds and the quantum nature of light. [Unpublished manuscript.] U. S. Forest Service, Southeastern Forest Expt. Sta.

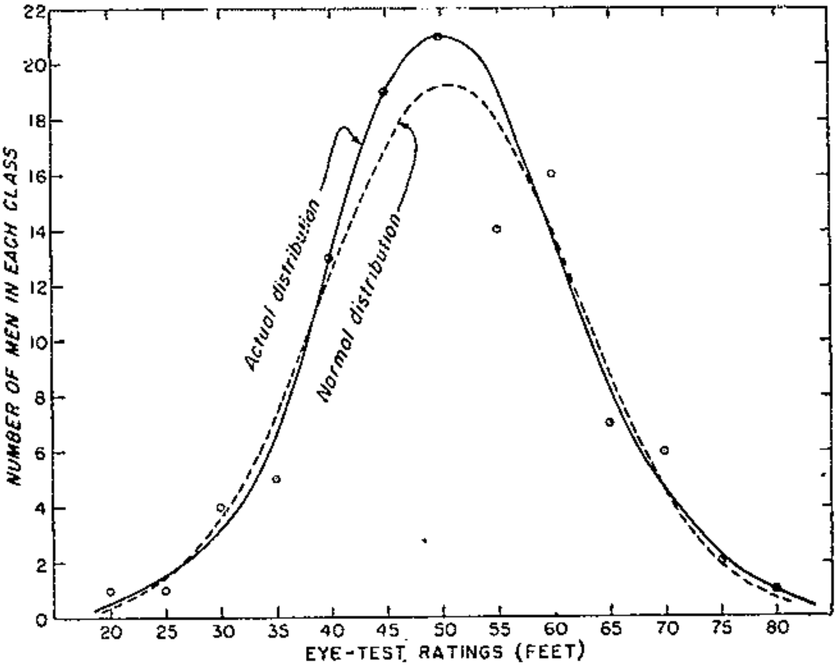


FIGURE 14.—Frequency distribution of eye-test ratings for 110 men compared with the normal curve.

Contained in the Appendix are specifications for the eye-test target, specifications for its master negative, and condensed instructions for using the eye test.

The vision test described here and the letter-type charts are inadequate in one important respect. They measure the visual acuity only for the central fovea, but give no information about visual acuity for the outer retinal zones, which are also important in detecting small objects when their location is not known.

HAZE-PENETRATING FILTER

Probably from the very beginning of forest fire detection activities, men have wished for some device that would enable them to see through haze. A great deal of thought and effort has gone into the development of haze-cutting or haze-penetrating filters. Tests show that ordinary colored filters have little or no value for smoke detection except to reduce glare or intense brightness that may interfere with the comfort of the observer.

Tests made by the senior author showed that a neutral polarizing screen, or one combined with a red filter, penetrates haze much farther than colored filters used alone (*11*). The use of this screen is limited to directions approximately at right angles to the sun's rays and to sunny days, but, even so, it has considerable practical value.

The haze-cutter, as the device is called, is based on the principle that the air-light is partially plane-polarized in directions at right angles to the sun. (See discussion of scattering of light, p. 5.) Therefore, a polarizing screen, oriented to exclude polarized light, will reduce the

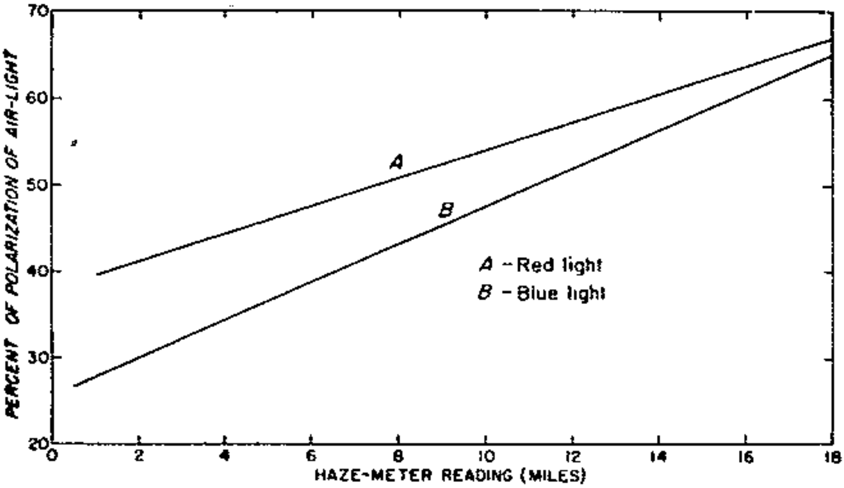


FIGURE 15.—Percent of polarization of air-light in directions at right angles to the direction of the sun, plotted against haze-meter readings. On hazy days, the longer wave lengths (red—line *A*) are more strongly polarized than the shorter wave lengths (blue—line *B*).

apparent intensity of air-light and increase the contrast between a smoke and its background. Figure 15 shows the percent of polarization of haze in relation to visibility conditions. On hazy days the air-light is less strongly polarized than on clear days. This fact tends to reduce the practical utility of the device for fire detection.

Best results with the polarizing screen are obtained on white smokes because these give off unpolarized light. It is of little value for smokes, the light from which is polarized to about the same degree as the air-light. The light from some thin blue smokes is almost completely plane-polarized, and the visual range of such smokes can be increased somewhat by using the haze-cutter in reverse (orienting it to transmit polarized light).

Visibility distance is increased from 20 to 50 percent at right angles to the sun with the haze-cutter, depending on atmospheric clearness. Approximately 4 miles is gained on days when the limit at which small white smokes can be seen is 10 miles. Figure 16 shows this relation between visibility distance with and without the filter, for thin blue smokes and white ones. Figure 17 indicates that the added area that can be covered with a haze-cutter for assumed conditions amounts to 50 percent. The curves in both figures 16 and 17 are theoretical and were not determined by field tests.

An experimental model of the haze-cutter consisted of a sheet of polarizing film mounted between two circular pieces of plate glass 4 inches in diameter. This glass was fastened in the center of a dark metal shield to exclude stray light. Some models had a red filter mounted with the polarizing film between the glass.

In 1941, some preliminary field tests of the device were made at 12 localities in California, Oregon, Idaho, and Montana. Of the 12 observers, 6 thought that the instrument had value as a fire detection aid, 1 thought it had no value, and 5 were noncommittal.

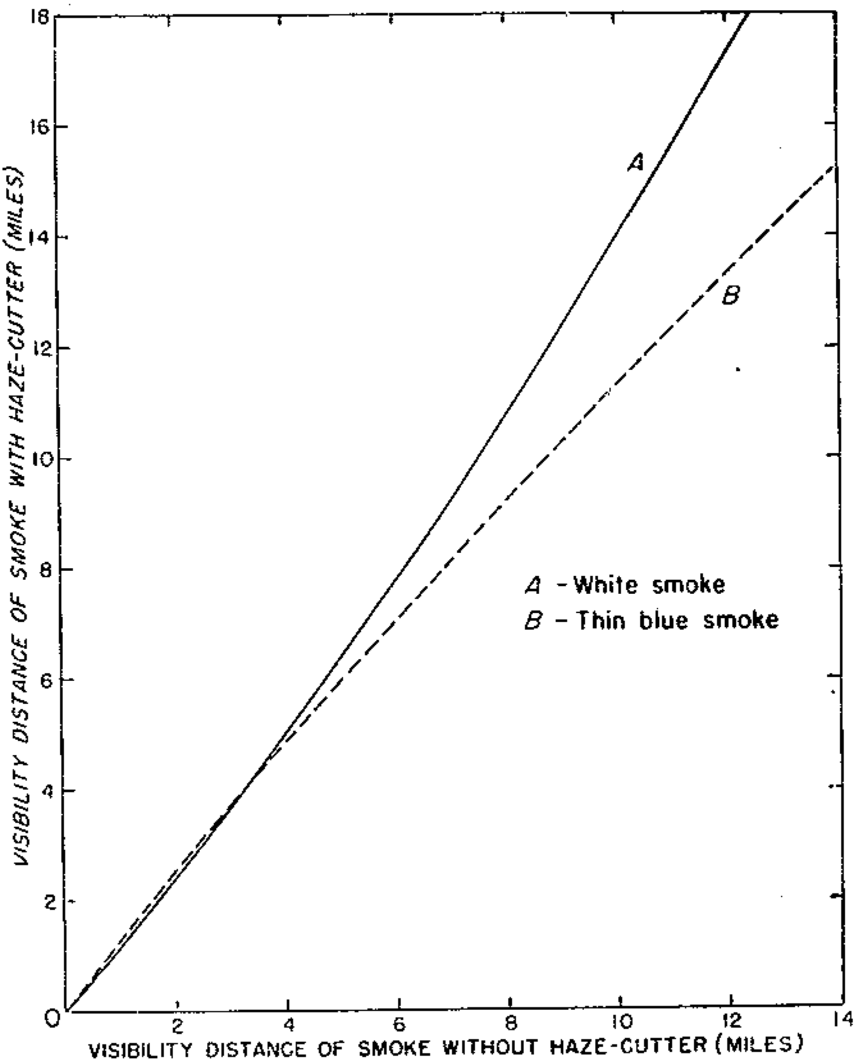


FIGURE 16.—Curve *A* is the visibility distance of a small white smoke viewed through the haze-cutter; *B* the visibility of a thin blue smoke viewed through the haze-cutter reversed or oriented to transmit polarized air-light. Values on both curves are plotted against the visual range of the smokes as seen with the unaided eye.

In 1942, a more extensive field trial was made in 7 States the results of which are shown in table 2. Of 14 observers, 10 recommended continued use of the haze-cutter, 3 thought it had no value, and 1 was noncommittal. Of the 176 fires reported in table 2, 85 (or 48 percent) could be seen better with the haze-cutter than with the unaided eye. This may be higher than the true proportion because a tendency was noticed on the report forms to favor the haze-cutter.

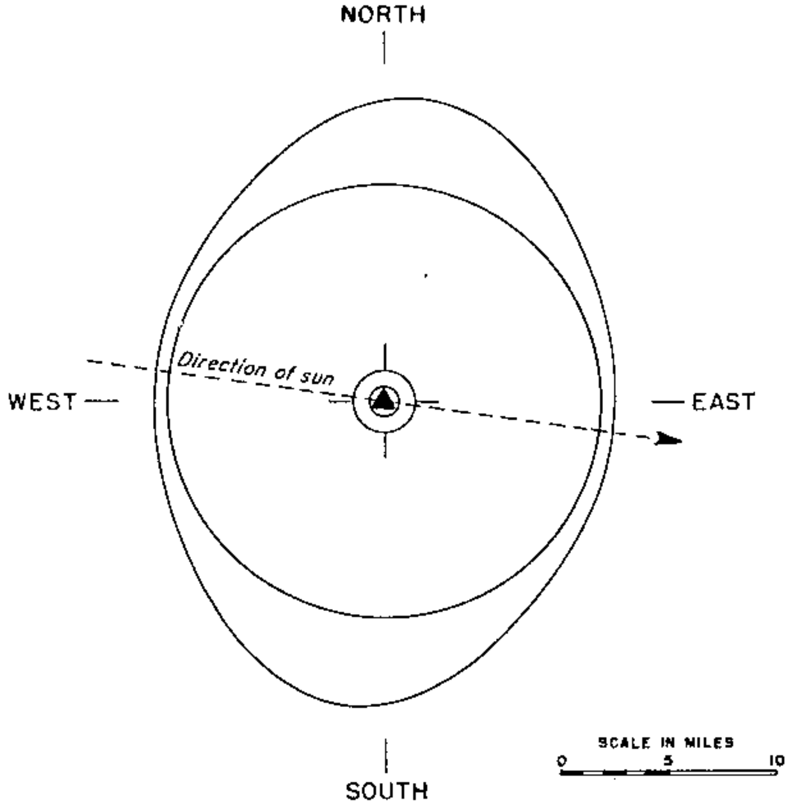


FIGURE 17.—Curves computed for 8 a. m., August 21, latitude 35°, showing visibility distance of a small white smoke. The circle is for smoke viewed with unaided eye; the ellipse, for smoke viewed through haze-cutter. Long radii are perpendicular to the direction of the sun. The ellipse expands until it becomes almost circular at noon, and then resumes its elliptical form during the afternoon. The short axis always points toward the sun.

Of the 176 smokes listed in the table, 13 were first discovered with the haze-cutter. While records are not complete, some of this number were seen through the haze-cutter but not at all with the unaided eye. Others were discovered 5 to 10 minutes sooner than the eye alone permitted. Such savings in discovery time are significant and of practical value in fast-burning fuel types.

It is significant to note that many observers have stressed the value of the haze-cutter in identifying questionable smokes or topographic features partially obscured by haze. The result is fewer false alarms and more accurate location of fires. Thus the haze-cutter may serve as a useful accessory for forest fire detection. A mounting arranged so that the polarizing screens may be fitted over the ends of binoculars and rotated for orientation has been widely recommended, but has not yet been tried extensively.

TABLE 2.—*Field test of haze-cutter, 1942*

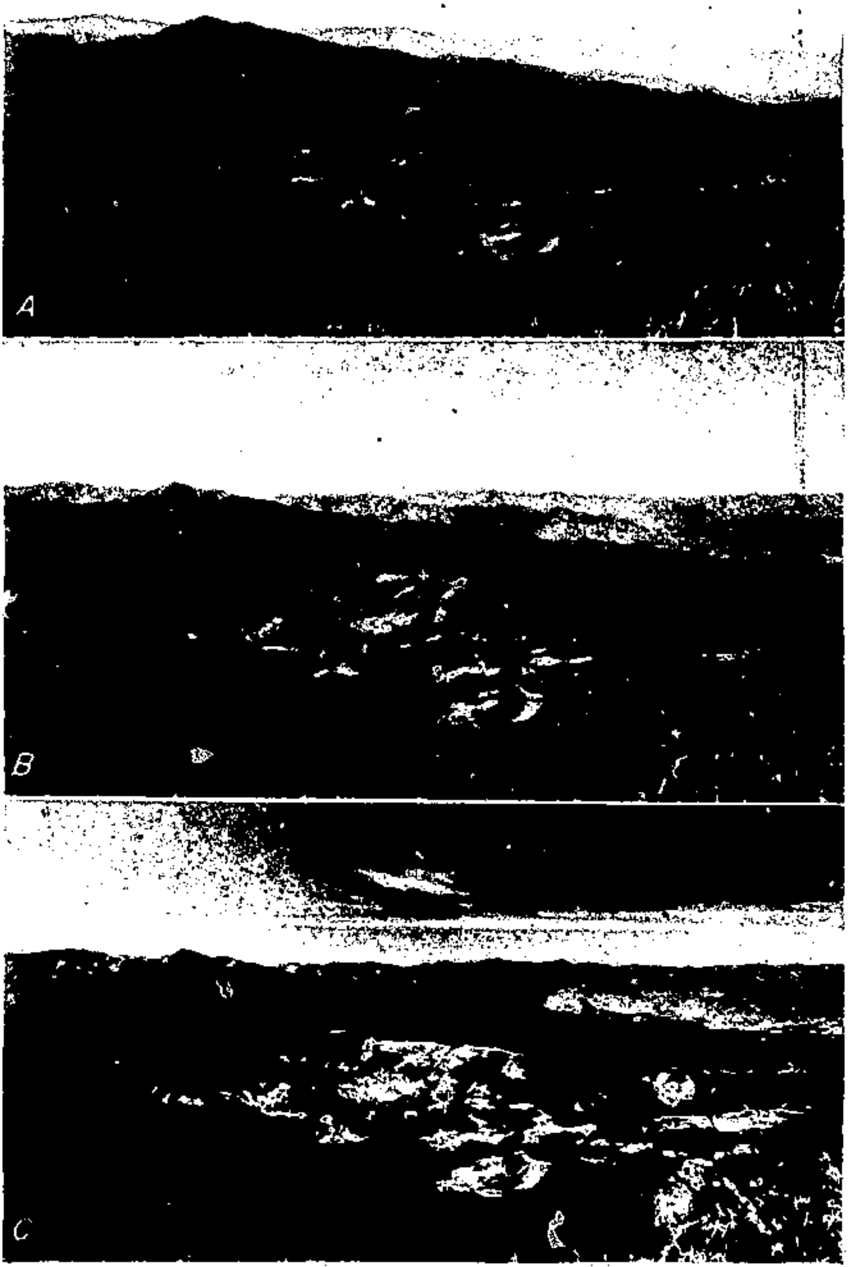
Location of observers	Total fires recorded	Fires seen better with haze-cutter
	Number	*Number*
Montana:		
Helena National Forest	13	3
Lolo National Forest	5	3
Oregon:		
Deschutes National Forest	7	5
Mt. Hood National Forest	10	6
Kentucky:		
Cumberland National Forest	4	3
Mississippi:		
Holly Springs National Forest:		
Observer A	16	11
Observer B	29	11
DeSoto National Forest	21	10
Louisiana:		
Kisatchie National Forest	13	13
North Carolina:		
Croatan National Forest	9	2
South Carolina:		
Sumter National Forest:		
Observer A	1	1
Observer B	14	9
State Forest Service:		
Observer A	8	1
Observer B	26	7
Totals	176	85

The haze-cutter may be of considerable value in landscape or aerial photography. For distant work, negatives are obtained on ordinary panchromatic film almost as sharp and clear as those registered on infrared-sensitive emulsions. An example of what can be done with the haze-cutter is shown in figure 18, which includes one photograph obtained through a red filter. Mountains 130 miles away have been registered on panchromatic film by means of a camera equipped with a haze-cutter. The haze-cutter could be adapted to the photo-recording transits used on western national forests to photograph panorama from lookout points. However, such photographs obtained with the haze-cutter would have no particular advantage over those made on infrared film and would be more difficult to obtain.

PERISCOPES, BINOCULARS, TELESCOPES, AND FILTERS

The use of periscopes as an aid in forest fire detection was thought of 20 years ago when an arrangement of mirrors was tested on the Boise National Forest in Idaho. Varner and Nichols (*30*) reported that mirror images of smoke, under certain conditions, appeared much sharper than smokes viewed directly. They claimed that in some cases mirror reflections were sharp when direct observation of smoke was almost impossible.

Tests were continued by Varner and Nichols in 1936 with a naval periscope equipped with various colored filters and led to the conclusion that the device enabled detection of some smokes invisible to the



F-413628, 413629, 413630

FIGURE 18.—Three photographs taken on panchromatic film from Mt. Pisgah, N. C. All were taken within a few minutes of one another. *A*, taken with no filter; *B*, with red Wratten filter; *C*, with haze-cutter.

naked eye or with a binocular of equal or greater magnification. "Seven different filters of extreme value" were developed from these tests. The experimenters imply that these filters used with the periscope provide a means of seeing smokes through haze.

The writers agree with further conclusions of Varner and Nichols; namely, that periscopes are of value in fire detection because: (1) Added height contributes to the area visible from a lookout point, especially in flat country; (2) their magnification brings out detail of distant objects; (3) there is likely to be less eyestrain associated with periscope use than with binoculars or telescopes, because firmness of mounting eliminates motion in the field of view; and (4) views are not obstructed by structural elements of the lookout house.

The writers disagree with the statement of Varner and Nichols, however, that the filters are of extreme value in viewing smokes. These filters were examined and, like any other colored glasses, do not increase appreciably the apparent contrast between a smoke and its background.

The authors see no reason why mirror images of smokes should appear sharper than the direct views of smokes. This belief on the part of Varner and Nichols was probably due to the magnification by the periscope and to the steadiness of the instrument and lack of eyestrain in using it. These are significant advantages, as pointed out, but should not be mistaken for haze-penetrating abilities of the periscope.

Binoculars and, occasionally, telescopes are common lookout station equipment and are valuable accessories for effective fire detection. They aid in verification of questionable smokes and bring out topographic detail enabling accurate location of fires. Curry (*14*) discusses in detail the use of binoculars in forest fire detection and recommends for lookout station use a 6- or 7-power instrument with 30-mm. objective and a clear field of at least 120 yards at 1,000 yards. Such an instrument, of the prismatic type, is standard for the Forest Service (*29*, p. B-4).

A wide-field binocular is superior for lookout observer use. Width of field depends in part on magnification, the apparent width of field being the product of magnification and the actual field. Since the apparent field is limited to about 45 degrees (*14*), a 7-power binocular has a maximum actual field of about 6.5 degrees, an angle corresponding to approximately 120 yards at 1,000 yards.

If it were possible to retain the same apparent field (at least 45 degrees) in a lower power binocular, then a 3- or 4-power instrument would probably be more effective than the present standard. The major increase in the visual range of smokes viewed with telescopes or binoculars comes during the first 3 or 4 diameters of magnification as shown in figure 19. Magnification actually has less effect on the visual range than figure 19 indicates; smoke columns have blurred edges and too much magnification spreads out these edges until the border effect responsible for contrast recognition is lost (*12*). However, the design of a low-power binocular with a wide field presents difficult optical problems, and for equal apparent fields, a 3-power binocular would not have as clear definition at the edge of the field as would a binocular of higher power.

The ability of the eye to recognize detail and to detect borders of small contrast depends to a large extent on small rapid movements of the eyeball (*18*). Any motion of the whole field of view interferes seriously with the benefits of these small eye movements. For this reason even low-power binoculars should be placed on a steady mounting, if at all possible, when being used.

Telescopes, although somewhat less expensive, have no advantage over binoculars. They are more difficult to use, and their greater size is a slight disadvantage.

It should be pointed out that magnification is much more effective for resolving distant landscape details than for detecting individual small objects on a fairly uniform background.

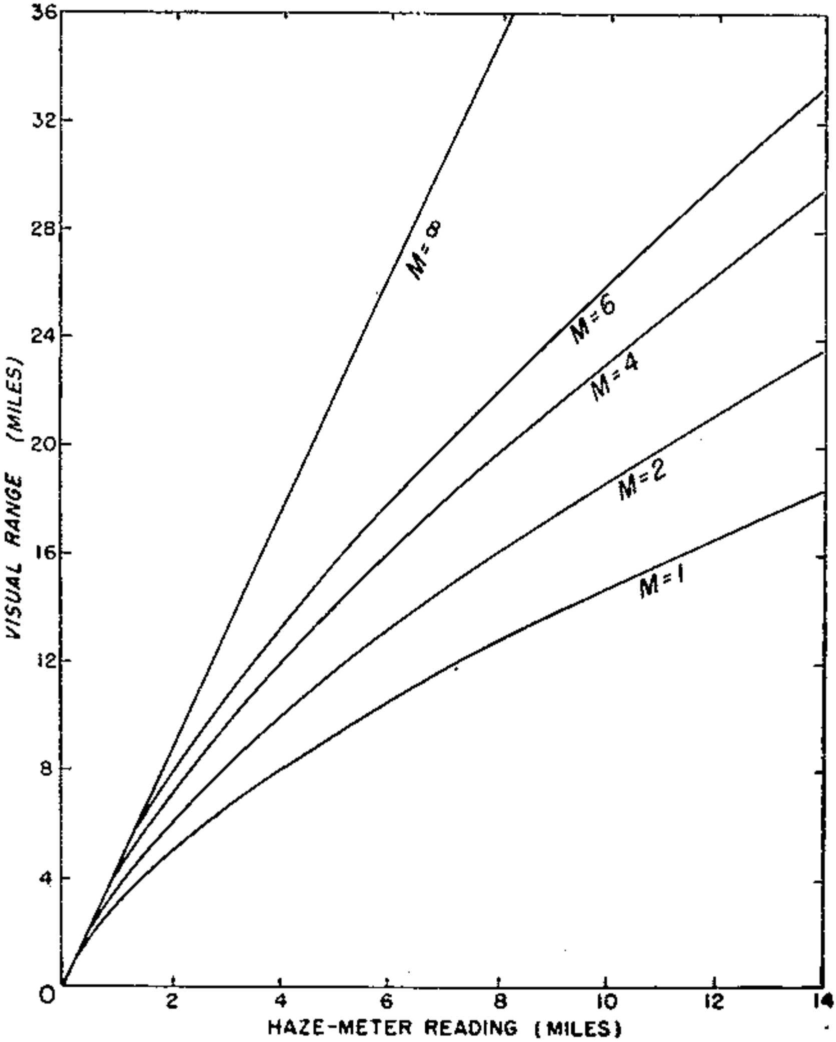


FIGURE 19.—Curves showing the relation between the magnification *M*, visual range, and haze-meter readings. These curves are theoretical and are based on the assumption that the smoke column has sharp borders. If the borders are blurred, then a given change in magnification would produce a smaller change in the visual range. The curve for $M=1$ is identical with curve *A* in figure 2.

Use of Goggles by Lookout Observers

Lookout observers sometimes suffer from eyestrain at high levels of illumination common on mountain peaks where the air is clear. This condition is exaggerated because about two-thirds of all fires discovered by lookouts are sighted in the direction of the sun (*21*). McArdle and Byram (*23*) developed goggles for lookout men to relieve the discomfort of eyestrain and thus remove the cause of decreased efficiency.

Smoked glass was found to be more satisfactory than blue or amber because it reduces light intensity approximately the same amount for all wave lengths (fig. 20). The smoked glass finally selected after numerous field tests transmits 26 percent of the visible radiation.

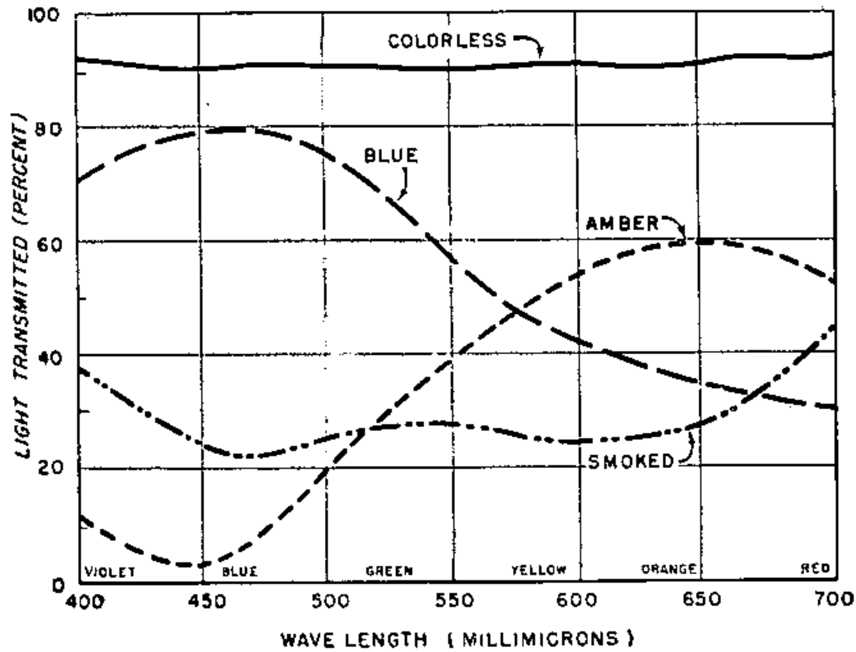


Figure 20.—Light-transmission qualities of sunglasses of different colors. After McArdle and Byram.

These goggles are optically correct and therefore muscular strain and fatigue associated with faulty lenses are avoided. Specifications for the recommended type are given in the Appendix.

It is doubtful whether polarizing spectacles should be used by lookout men to reduce eyestrain unless the polarizing glasses are rotatably mounted, in which case they could be used as haze-cutters. If the polarizing glasses were rigidly fixed, they would exaggerate the relative haze brightness in certain directions and actually make smokes less visible in those directions. Some newer types of spectacles, containing two polarizing glasses for each eye, would not be suitable for use by lookout men.

Optical Problems in the Design of the Lookout House

There are a number of factors in the design of the cabs of lookout towers which may either contribute to or detract from the maximum visual efficiency of the lookout man. Some of these factors increase the discomfort of the observer by causing fatigue and eyestrain. Other features of cab design may not be best suited to maximum visual acuity.

In experimental cabs now being designed by the Forest Service, most of the problems that are discussed have already been recognized and taken into consideration. The objectionable optical features of the present cabs will be greatly reduced in the new design.

WINDOWS

The ordinary grade of window glass (pressed glass) is not suitable for the best visual acuity. The flaws and distortions in this type of glass may also contribute to eyestrain, although this has not been demonstrated directly. Binoculars and telescopes of even the lowest power cannot be used to advantage through pressed glass windows. Plate glass would be much more desirable for the cab windows than pressed glass. It has been ground and polished so that its optical qualities are good. Its great thickness and strength would permit the use of larger panes, thus reducing the number of supporting strips which obstruct vision. Binoculars and telescopes of moderate power (5- to 10-diameters magnification) can be directed through plate glass windows without serious loss in definition. However, even with plate glass windows, an instrument with a magnification greater than 10 diameters should be directed through an open window or else used outside the cab.

The reflections in cab windows probably are not serious as far as eyestrain is concerned, but they decrease the visibility of distant smokes. For example, if an observer is looking through the east windows he will see a reflection of the western landscape superimposed on the eastern landscape. The resulting loss of contrast between a distant smoke and its background may be as much as 30 percent, although the corresponding percent of loss of visibility distance would be considerably less than this.

Reflections are particularly troublesome where lookouts are required to report lightning strikes which occur at night. It is almost impossible for a lookout to tell whether he is seeing a real strike or the reflection of a strike occurring in the opposite direction.

Window pane reflections can be eliminated either by using panes coated with nonreflecting films or by tilting the panes at the proper angle. The nonreflecting films can be made completely effective for light of only one wave length (yellow green is usually chosen) so they will reflect some residual light of other wave lengths. Also the films are inefficient for light passing obliquely through the windows. This might not be an objectionable feature, as the observer is usually looking through the glass at angles which do not depart appreciably from the perpendicular.

At the present time it appears that tilting the windows is the most practical method of eliminating reflections. If they are tilted in at the top, the angle of tilt necessary to eliminate landscape reflections probably would be about 12 or 15 degrees. If tilted in at the bottom, the required angle would perhaps be 20 degrees or even more. Tilting the windows in at the bottom would require a steeper tilt, but there would be no danger of sunlit patches on the floor being reflected in the windows. Such reflections might occur in windows tilted in at the top unless sunlight were excluded from the cab by adequate awnings or shutters.

Glass with a pronounced bluish tint would cause a slight loss in the visibility of distant smokes because it would exaggerate the brightness of the bluish haze. Red glass or amber glass would not decrease the visibility of smokes, but, on the other hand, they would not produce any noticeable increase in visibility.

PAINT

Visual acuity measurements have shown that vision is keenest when all parts of the field of vision are approximately of the same brightness. This condition cannot be met if the interior of the cab is painted dark. Also, a dark color could possibly cause eyestrain because of the high contrast between the dark interior and the brilliant exterior landscape.

From the physical standpoint the whole interior of the cab (with the possible exception of the floors and lower walls) should be painted a brilliant white to obtain the optimum visual acuity. The brightness of the interior would then most nearly match the brightness of the exterior landscape. However, the most serious cause of eye fatigue and eye irritation among lookout men is an excess of light, and painting the interior of the cab white might aggravate this condition. The excess light could be eliminated, however, either by neutral smoked-glass windows (of plate glass quality), or perhaps even better by neutral smoked goggles. The transmission of either the goggles or windows should be about 25 or 30 percent. A transmission higher than this would not give adequate protection, and if the transmission were too low (6 or 8 percent) the lookout might have some difficulty in seeing such things as details on his maps and scales on his instruments.

Because of the adaptation mechanism of the eye, visual acuity in very bright daylight is almost independent of the density of goggles or windows, provided they transmit at least 2 or 3 percent of the incoming light. However, this is not true in faint light, in which case the eye needs all the light it can get. This condition in itself might be sufficient reason for not using smoked glass in the cab windows, as vision would be impaired during the night and twilight hours. Goggles, of course, would not be worn at these times.

Esthetic and psychological factors should be considered in choosing the color of interior paints. A pure white interior could be monotonous, in which case a very light "cool" color such as green or blue green might be more desirable. The color should be very light, and its reflection factor should not be much less than that of pure white paint.

There are some parts of the cab, such as the floors and lower walls, from which it is it not possible to exclude sunlight even with the best shutter arrangements. Glare patches could be avoided only by using dark paint on the floors and lower walls.

A glossy paint would probably be more suitable than a flat or non-glossy paint. It is much easier to keep clean and is more durable. A glossy paint gives a small amount of glare by direct reflection, but since an oil film has a reflection factor of only 4 percent, glare due to this cause would be small.

Prominent objects, such as catwalk railing and nearby buildings outside the cab but plainly visible from inside, may produce a troublesome glare unless they are painted some dark color having about the same brightness as their surroundings.

SHUTTERS

From the optical standpoint the main value of shutters is in keeping out direct sunlight which would otherwise cause glare patches on the floors and lower walls and illuminate small dust particles on the windows. The more serious problem of the two is the illumination of the dust particles. Even on a clean window the light scattered by the particles which can accumulate in a few hours may be equivalent to an extra mile or two of hazy atmosphere.

Since sunlight cannot strike the under sides of the shutters, they should probably be painted the same color as the ceiling of the cab—a bright white or light green.

SUMMARY

Damages caused by forest fires and the costs of suppressing them can be held to a minimum by quick action that extinguishes them before they become large. Early detection of smoke is a first requisite of satisfactory fire control. For this reason, considerable emphasis has been placed on improving fire detection systems.

The studies discussed here had as their primary objective the development of ways of determining visual range, a measure useful in the efficient operation of detection systems; but a number of other devices and principles useful in fire detection were also developed.

Visual range of a small object, defined as the maximum distance at which it can just be seen, is shown to depend upon a complexity of visual, physical, and meteorological factors. However, by making certain approximations the visual range of smoke bodies can be expressed in terms of the dark ridge visual range or in terms of the haze-meter reading. The effect of size and shape of smoke, color, atmospheric haze, and other factors on visual range are discussed.

The most practical method of determining atmospheric attenuation is with balance-type telephotometers. Two such devices were developed; namely, the Byram haze-meter for use in mountainous country and the Plains haze-meter for use in flat or rolling terrain. Other types of visibility meters, their advantages and disadvantages, are discussed.

When instruments are not available, visibility distance may be estimated by means of a visibility scale for columns and circular puffs of smoke. Such a scale is based on estimates of dark ridge visual range. Under certain conditions the use of haze silhouettes for estimating visibility has shown considerable promise, but has not been tried on an extensive scale.

Some of the principles of seeing and visibility of smoke bodies contribute to defining the best method of searching an area for smokes. No field test was made of the suggestions arising from the theoretical aspect of the study.

The basic principles of visibility were used in the development of an eyesight test for lookout observers. With this test the ability of lookout men to see small smokes can be rated. By selecting keen-eyed men as observers, the visual range may be increased about 2 or 3 miles, or 30 percent, under normal haze conditions. An increase of 10 percent in visibility distance is associated with keen vision compared to average vision.

A haze-penetrating filter which improves visibility distance about 20 percent under some conditions is described. Its use is limited to clear days and to directions at right angles to the sun. It has proved to be a distinct advantage in the identification of questionable smokes and is of value in photography.

A discussion of periscopes, telescopes, and binoculars shows binoculars to be the only instrument of material aid in smoke detection. Periscopes have no haze-penetrating capabilities, as has been claimed heretofore. Telescopes are impractical to use because of their size. The ideal binocular for smoke detection should have a magnification of 3 or 4 diameters and an apparent field of at least 45 degrees; the design of such an instrument would present difficult optical problems. Colored filters are thought to have little or no value in increasing visual range.

Neutral goggles which transmit about 26 percent of visible radiation eliminate much eyestrain and discomfort caused by the high brightness levels encountered by lookout men.

Structural features of lookout houses that will eliminate eyestrain and loss of effectiveness of observers working at different brightness levels are discussed. Recommendations include painting the interior of houses white, with lower walls and floors a dark color, and using plate glass at eye level, slightly tilted to improve visibility and eliminate glare. Lookout structure designers in the Forest Service have made plans for testing some of these features.

LITERATURE CITED

(1) Bennett, M. G.
1931. A VISIBILITY METER. Jour. Sci. Instruments 8: 123–126, illus.

(2) Blackwell, H. R.
1946. CONTRAST THRESHOLDS OF THE HUMAN EYE. Jour. Optic. Soc. Amer. 36: 624–643, illus.

(3) Bruce, H. D.
1941. THEORETICAL ANALYSIS OF SMOKE-COLUMN VISIBILITY. Jour. Agr. Res. 62: 161–178, illus.

(4) ———
1944. OBSERVATIONS ON THE VISIBILITY OF A SMALL SMOKE. Jour. Forestry 42: 426–434, illus.

(5) Buck, C. C.
1938. FACTORS INFLUENCING THE DISCOVERY OF FOREST FIRES BY LOOKOUT OBSERVERS. Jour. Agr. Res. 56: 259–266, illus.

(6) ———, and Fons, W. L.
1935. THE EFFECT OF DIRECTION OF ILLUMINATION UPON THE VISIBILITY OF A SMOKE COLUMN. Jour. Agr. Res. 51: 907–918, illus.

(7) Byram, G. M.
1935. VISIBILITY PHOTOMETERS FOR MEASURING ATMOSPHERIC TRANSPARENCY. Jour. Optic. Soc. Amer. 25: 388–392, illus.

(8) ———
1936. PHYSICAL FACTORS AFFECTING THE VISIBILITY OF SMALL SMOKE COLUMNS. Monthly Weather Rev. 64: 259–264, illus.

(9) ———
1940. A PLAINS HAZE METER. Jour. Forestry 38: 401–403, illus.

(10) ———
1940. AN EYE TEST FOR LOOKOUT MEN. Fire Control Notes 4: 123–128, illus.

(11) ———
1942. FILTERS FOR PENETRATING ATMOSPHERIC HAZE. Jour. Forestry 40: 530–532, illus.

(12) ———
1944. THE PHYSICAL AND PHOTOCHEMICAL BASIS OF VISUAL RESOLVING POWER. PART I. THE DISTRIBUTION OF ILLUMINATION IN RETINAL IMAGES. Jour. Optic. Soc. Amer. 34: 571–591, illus.

(13) ———
1944. THE PHYSICAL AND PHOTOCHEMICAL BASIS OF VISUAL RESOLVING POWER. PART II. VISUAL ACUITY AND THE PHOTOCHEMISTRY OF THE RETINA. Jour. Optic. Soc. Amer. 34: 718–738, illus.

(14) Curry, J. R.
1933. BINOCULAR TELESCOPES IN FOREST FIRE DETECTION. Jour. Forestry 31: 51–58, illus.

(15) Davidson, W. F.
1942. A STUDY OF ATMOSPHERIC POLLUTION. Monthly Weather Rev. 70: 225–234, illus.

(16) Hardy, A. C.
1946. ATMOSPHERIC LIMITATIONS ON THE PERFORMANCE OF TELESCOPES. Jour. Optic. Soc. Amer. 36: 283–287, illus.

(17) Hayes, G. L., and Byram, G. M.
1944. THE EFFECTS OF GOOD VISUAL POWERS, EFFORT, AND PRACTICE ON SEEING. Jour. Forestry 42: 53.

(18) Hulbert, E. O.
1941. OPTICS OF ATMOSPHERIC HAZE. Jour. Optic. Soc. Amer. 31: 467–476, illus.

(19) JEMISON, G. M.
1940. THE INFLUENCE OF LOCALITY, SEASON, TIME OF DAY, AND YEAR ON THE VISIBILITY OF SMOKE COLUMNS. Jour. Forestry 38: 435-437, illus.

(20) MCARDLE, R. E.
1935. A VISIBILITY METER FOR FOREST FIRE LOOKOUTS. Jour. Forestry 33: 385-388 illus.

(21) ———
1936. SOME VISIBILITY FACTORS CONTROLLING THE EFFICIENT LOCATION AND OPERATION OF FOREST FIRE LOOKOUT STATIONS. Jour. Forestry 34: 802-811, illus.

(22) ———, AND BYRAM, G. M.
1936. AN EYE TEST FOR FIRE LOOKOUTS. Jour. Forestry 34: 794-796.

(23) ———, AND BYRAM, G. M.
1936. GOGGLES FOR INCREASING THE EFFICIENCY OF FOREST FIRE LOOKOUTS. Jour. Forestry 34: 797-801, illus.

(24) MIDDLETON, W. E. K.
1941. VISIBILITY IN METEOROLOGY. Univ. Toronto Press. 165 pp., illus. Toronto.

(25) MORRIS, W. G.
1946. A PRELIMINARY SURVEY OF FACTORS OF VISIBILITY OF SMALL SMOKES IN AERIAL DETECTION. Fire Control Notes 7, No. 2: 22-25.

(26) SHALLENBERGER, G. D., AND LITTLE, E. M.
1940. VISIBILITY THROUGH HAZE AND SMOKE, AND A VISIBILITY METER. Jour. Optic. Soc. Amer. 30: 168-176, illus.

(27) SHOW, S. B., AND KOTOK, E. I.
1937. PRINCIPLES OF FOREST-FIRE DETECTION ON THE NATIONAL FORESTS OF NORTHERN CALIFORNIA. U. S. Dept. Agr. Tech. Bul. No. 574. 32 pp., illus.

(28) ———, KOTOK, E. I., GOWEN, G. M., CURRY, J. R., AND BROWN, A. A.
1937. PLANNING, CONSTRUCTING, AND OPERATING FOREST-FIRE LOOKOUT SYSTEMS IN CALIFORNIA. U. S. Dept. Agr. Cir. No. 449. 55 pp., illus.

(29) UNITED STATES DEPARTMENT OF AGRICULTURE, FOREST SERVICE.
1946. THE FIRE-CONTROL EQUIPMENT HANDBOOK. Illus. Washington, D. C.

(30) VARNER, I. M., AND NICHOLS, G. L.
1937. POSSIBILITIES IN PERISCOPE DETECTION. Fire Control Notes (Jan. 1937), pp. 69-80, illus.

(31) WRIGHT, W. D.
1939. THE PERCEPTION OF LIGHT. Chem. Pub. Co. 100 pp., illus. New York.

APPENDIX

The Mathematical Theory of the Visual Range

In the analysis presented in this section, the symbols and notation are as follows:

H = apparent brightness of a distant background
H_o = apparent brightness of a distant object
H_b = intrinsic brightness of a distant background
H_t = intrinsic brightness of a distant object
H_h = brightness of horizon sky
v = apparent contrast between a distant object and its background
u_t = threshold retinal illumination contrast in the retinal image of the object and its background
α = angular diameter of object
D = linear diameter of object
M = magnification
x = visual range of object
y = visual range of a black ridge viewed against the horizon sky
d = haze-meter reading
σ = atmospheric attenuation coefficient
λ = wave length
p = fraction of air-light polarization

The brightness H and H_o are given by the Koschmieder equation (*8, 24*), and may be written in the forms

$$H=H_h(1-e^{-\sigma x})+H_b e^{-\sigma x} \tag{1}$$

and

$$H_o=H_h(1-e^{-\sigma x})+H_t e^{-\sigma x} \tag{2}$$

The contrast v between a distant object and its background may be defined by the equation

$$v=\pm\frac{H_o-H}{H}, \tag{3}$$

in which v is always considered positive regardless of whether $H_o>H$ or $H_o<H$. The retinal threshold contrast u_t is related to the object-background contrast by the equation (*12, 13*)

$$u_t=vf(\alpha), \tag{4}$$

where $f(\alpha)$ is some function of the angular diameter of the object, and its form depends on the nature of the object. In general, u_t depends on the background brightness H, but the nature of this relation is such that for observations in daylight u_t is nearly independent of H. In radian measure the apparent angular diameter of the test object may be written to a close approximation as

$$\alpha = MD/x. \tag{5}$$

If binoculars or telescopes are not used, the magnification M is set equal to unity.

For an object in the form of a long thin band or rectangle, $f(\alpha)$ may be written approximately (*13*) as

$$\begin{aligned} f(\alpha) &= A\alpha \\ &= A(MD/x) \end{aligned} \tag{6}$$

where A is a constant. Substituting equations (1) and (2) in equation (3) and simplifying gives for the contrast v

$$v = \frac{\pm\left(\frac{H_t}{H_h} - \frac{H_b}{H_h}\right)}{e^{\sigma x} - \left(1 - \frac{H_b}{H_h}\right)} \tag{7}$$

Eliminating v and α between equations (4), (6), and (7) gives as the visual range equation for an object in the form of a long rectangle

$$\frac{\pm\left(\frac{H_t}{H_h} - \frac{H_b}{H_h}\right)}{e^{\sigma x} - \left(1 - \frac{H_b}{H_h}\right)} = \left(\frac{u_t}{A}\right)\left(\frac{x}{MD}\right) \tag{8}$$

For a disklike object, the function $f(\alpha)$ is approximately (*13*)

$$\begin{aligned} f(\alpha) &= B\alpha^2 \\ &= B(MD/x)^2 \end{aligned} \tag{9}$$

where B is a constant.

Eliminating v and α between equations (4), (9), and (7) gives as the visual range equation for a disklike object

$$\frac{\pm\left(\frac{H_t}{H_h} - \frac{H_b}{H_h}\right)}{e^{\sigma x} - \left(1 - \frac{H_b}{H_h}\right)} = \left(\frac{u_t}{B}\right)\left(\frac{x}{MD}\right)^2 \tag{10}$$

Equations (8) and (10) can be used to estimate the visual range of an object if all of the other variables in the equation are known. They can also be used to estimate the effects of color filters, polarizing filters, and magnification on the visual range. Color filters exert their effects in a rather complex manner. The transmission properties of the filter determine the appropriate value of σ to use in equations (8) and (10), since σ is a function of wave length. The ratios H_t/H_h and H_b/H_h will be affected by the transmission properties of the filter because there are usually differences in the chromaticities of the object, its background, and the horizon sky. Color filters also affect the value of the constants A and B in equations (8) and (10) because wave length determines the size of the basic diffraction pattern in the retinal image (*12*); this effect partially offsets the effect of the color filter on the value of σ. Computations from equations (8) and (10) show that even red filters should make but slight contributions to the visual range.

The theoretical effect of monochromatic color filters on the visual range of test objects in the form of disks and long thin bands is shown in figure 21. Curves A, A', and A'' represent the visual range of an

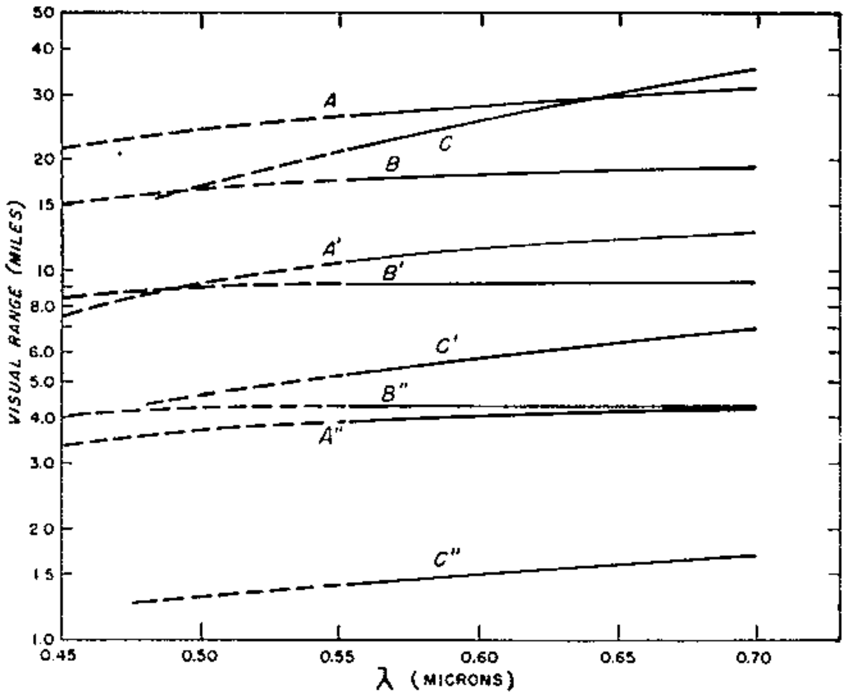


FIGURE 21.—Curves A, A', and A'' show the visual range of a long rectangle as a function of filter wave length. Curves B, B', and B'' show this relation for disklike test objects. Curves C, C', and C'' show the corresponding values of $1/\sigma_\lambda$. The visual range of a black ridge viewed (without filters) against the horizon sky is approximately 4 times $1/\sigma_{.555}$. It was assumed that both objects were viewed against dark backgrounds and that their brightness was equal to that of the horizon sky.

object in the form of a long band, 3 feet in diameter, for filters transmitting different wave lengths. Curve A represents the visual range on a very clear day, curve A'' for a very hazy day, and curve A' for intermediate conditions. Curves B, B', and B'' are similar curves for a disk test object 10 feet in diameter. It is assumed that both objects are viewed against a black background and that both have an intrinsic brightness equal to that of the horizon sky in the direction in which the object is viewed. It is also assumed that the chromaticity of the objects is the same as that of the horizon sky. Curves C, C', and C'' are plots of the quantity $1/\sigma_\lambda$ which, as will be shown in the next section, is the mean free photon path. Since the visual range of a black ridge is approximately 4 times the mean free photon path, the C curves may be regarded as representing one-fourth of the visual range of a large black ridge viewed against the horizon sky. The relation between σ and λ was computed from the equation

$$\sigma_\lambda = \sigma_{.555}\left(\frac{\lambda}{.555}\right)^{-r}$$

where σ_λ is the attenuation coefficient for some wave length λ and $\sigma_{.555}$ the attenuation coefficient for a wave length of $.555\mu$. The exponent r is not constant but depends on σ. Middleton (*24*) presents data showing the relation between r and the mean value of σ for wave lengths of $.459\mu$, $.528\mu$, and $.636\mu$, respectively. However, it is more convenient to show this relation in terms of $\sigma_{.555}$ instead of the average value of σ. The conversion can be made by means of the equation

$$\sigma_{.555} = \frac{3\sigma_{av.}(.555)^{-r}}{[(.459)^{-r}+(.528)^{-r}+(.636)^{-r}]}$$

The three values of $\sigma_{.555}$ used in figure 21 for computing $1/\sigma_{.555}$ were 0.711, 0.192, 0.455. The corresponding values of r from Middleton's data are 0.82, 1.26, and 2.09. It may be assumed that the effective value of σ for observations made without filters is approximately equal to $\sigma_{.555}$.

Polarizing screens exert their effects in an entirely different way from that exerted by color filters, and the resulting changes in the visual range are much easier to compute. If polarizing screens are used, the quantity H_h in equations (8) and (10) should be replaced by $(1 \pm p)H_h$ where p is the fraction of air-light polarization. The negative sign is used if the filter is oriented so as to exclude the polarized light (it is usually used in this way). The positive sign is used if the filter is oriented so as to transmit the polarized light. The only advantage of using the filter in this manner is with occasional thin blue smoke columns which sometimes give off light that is more strongly polarized than the air-light.

If the sky is nearly cloudless, polarizing filters are much more effective than color filters if the direction of view is approximately at right angles to the direction of the sun. On hazy days when σ is large, a polarizing screen and red filter combination are more efficient than a polarizing screen alone. When used with a polarizing screen, a red filter becomes effective by bringing about an increase in p rather than any appreciable decrease in σ. The variation of p with wave length is more pronounced on hazy days. On clear days when σ is small, p is less dependent on wave length and is comparatively high for all wave lengths. The combination polarizing screen and red filter is especially effective for photographs or visual work when landscape detail is desired; it is not so effective for columns of smoke as the polarizing screen alone. Figure 22 shows the relation of the visual range of the previous two test objects plotted as a function of the fraction of air-light polarization. On hazy days at low elevations this fraction may drop as low as 0.3 even in directions perpendicular to the direction of the sun. On clear days at high elevations the fraction may exceed 0.8.

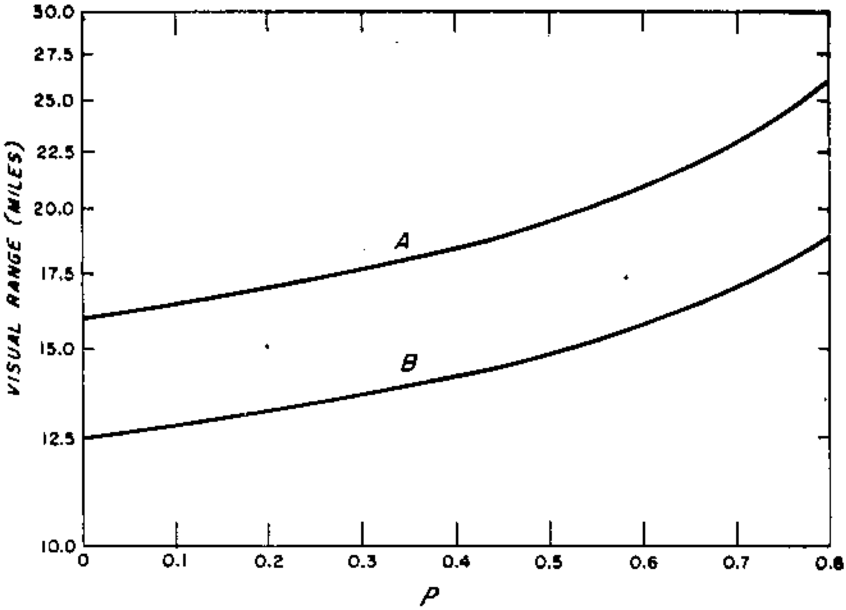


FIGURE 22. - Curve *A* shows the theoretical relation between the visual range of a long rectangle and the fraction of air-light polarization. Curve *B* shows the corresponding relation for a disk test object. The quantity $1/\sigma$ was 10 miles for both curves.

Increases in the visual range resulting from magnifying devices are comparatively small. An optically perfect binocular or telescope on a steady mounting increases the visual range more than do either color filters or polarizing screens but accomplishes this at the expense of field of view. The benefit from magnification is not the same for all test objects. Magnification is most effective for resolving detail in a distant landscape object and may increase appreciably the distance at which such detail (such as grating structures or other fine details) can be resolved. It is less effective for increasing the visual range of disklike objects such as were recently discussed by Hardy (*16*), and still less effective for objects resembling long, thin rectangles. Magnification is of no benefit whatever for objects so large that $f(\alpha) \rightarrow 1$.

By a series of linear transformations equations (8) and (10) can be reduced to forms that permit the calculation of the visual range x by means of slide rules. However, even such computing devices require more information than is usually available to lookout observers, so in their present forms equations (8) and (10) are not suitable for field use. By making certain approximations, these equations can be simplified considerably, although some accuracy must be sacrificed.

Most forest fire smokes are seen against backgrounds of dark vegetation so the first approximation is to set H_b equal to zero. The next approximation is to assume that the angular scattering function is the same for the particles in small bodies of smoke as it is for haze particles, hence H_t would be directly proportional to H_h regardless of the position of the sun or other sources of light such as the sky or surface of the earth. Fortunately this approximation is best on very hazy days; the error may be considerable when the air is very clear.

On placing $H_b=0$, and assuming that

$$H_t = cH_b$$

where c is a constant, equation (8) can be reduced to the form

$$\sigma x = \log (1 + K_1/x). \qquad (11)$$

The constant K_1 is

$$K_1 = cAMD/u_t \qquad (12)$$

If the same assumptions are made for disklike objects, equation (10) reduces to the form

$$x = \log (1 - K_2/x^2), \qquad (13)$$

where the constant K_2 is

$$K_2 = cB(MD)^2/u_t \qquad (14)$$

Curve A in figure 2 is a plot of equation (11) with a value of 42.1 for K_1. For the purpose of comparing the two curves, curve B was made to coincide with curve A when the haze-meter reading was 10 miles. This required a value of 617 for K_2. The abscissa readings in figure 2 are expressed in terms of the haze-meter reading d rather than in terms of σ. These two variables are related by the equation

$$\sigma = -\frac{1}{d} \log .40$$

The quantities K_1 and K_2 can be considered constant only when the rest of the quantities in equations (12) and (14) are constant. For smokes of fixed diameter and with a given magnification, the only source of variation in K_1 and K_2 would be in the quantities A, B, and c. The quantities A and B can be considered constant as long as the angular diameters of the objects are less than the angular diameter of the central bright disk in the diffraction pattern of the retinal image of a point source of light. The approximation of $f(\alpha)$ given by equation (9) appears to be better than one could expect considering the changes which take place in the retinal image of a disklike object for increasing values of α. This means that u_t is not constant for this object, but varies in such a way that the ratio B/u_t is nearly constant for values of α up to 3 or 4 minutes. When α is less than 0.35 minute, u_t is approximately 0.10 for disk test objects.

For larger values of α, u_t increases slowly and approaches a constant value as α becomes very large. The most likely source of variation in K_1 and K_2 is in the quantity c, since its value depends on the angular scattering function of both the haze particles and the particles composing the smoke bodies. Because of the predominantly forward scattering in smokes there is a tendency for c to increase when the scattering angle is small. This results in greater visual ranges when the observer is looking into a low sun. However, the variation in c is less on hazy days than on clear days.

For smokes viewed against the horizon sky, equations (8) and (10) take simplified forms. In this situation H_b is placed equal to H_h. Equation (8) then becomes

$$\sigma x = -\log (x/K_3) \tag{15}$$

where

$$K_3 = \pm(c-1)AMD/u_t \tag{16}$$

The positive sign is used if $H_t/H_h > 1$, and the negative sign if $H_t/H_h < 1$. Similarly equation (10) becomes

$$\sigma x = -\log (x^2/K_4) \tag{17}$$

where

$$K_4 = \pm(c-1)B(MD)^2/u_t \tag{18}$$

If the size of the smoke bodies is increased without limit, both equations (8) and (10) approach the same form. The approximations in equations (6) and (9) are no longer valid and the function $f(\alpha) \rightarrow 1$. From equation (4) it follows that for large objects $u_t = v$; hence the right numbers of equations (8) and (10) in this case become equal to u_t. For large smokes viewed against dark backgrounds, equations (11) and (13) become

$$\sigma x = \log (1 + c/u_t) \tag{19}$$

If the smokes are viewed against a horizon sky background the visual range equation is

$$\sigma x = -\log \left[\frac{u_t}{\pm(c-1)} \right] \tag{20}$$

The simplest of the visual range equations is that for a large black object viewed against the horizon sky which is

$$\sigma x = -\log u_t$$

The threshold contrast u_t is usually assigned a value of .02 for high brightness levels, but it is probably higher than this for large bodies of smoke which seldom have sharply defined boundaries. Also, large brightness differences in the field of view may produce negative after sensations which may increase the value of u_t (*18*).

The validity of the Koschmieder equation has been sometimes questioned and it is probable that it may be in error for many field conditions. Variation in the reflectivity of the earth's surface, and partial cloudiness of the sky are both factors which limit the application of the equation. Also, its derivation is based on the assumption that the earth's surface is flat. The curvature of the earth's surface would result in a horizon sky brightness slightly less than for a flat earth. Computations of σ made from photometric measurements of a black target viewed against the horizon sky would give values of σ slightly larger than they should be and would show a spurious effect in that σ would appear to increase with the distance of the target. Ordinarily this error would be negligible but might be noticeable for observations made at high altitudes in very clear weather.

The validity of the Koschmeider equation depends also on the validity of the exponential law of light degradation in the atmosphere. This law is discussed in the next section.

The Degradation of Light Passing Through the Atmosphere; the Mean Free Photon Path

If a beam of parallel light rays is passed through a scattering and absorbing medium, such as a hazy atmosphere, its intensity decreases with the distance traversed. The differential equation describing this change is

$$dI = -\sigma I dx \qquad (21)$$

When integrated this equation gives the intensity I at a distance x as

$$I = I_0 e^{-\sigma x} \qquad (22)$$

where I_0 is the initial intensity, and σ the attenuation coefficient representing the total coefficient for both scattering and absorption processes.

Equation (21) cannot be regarded as self evident and some investigators have felt it necessary to test the exponential law experimentally. As might be expected, the results are in close agreement with equation (22). Perhaps some of the misgivings about equation (22) could be avoided by deriving it from a more basic level using statistical rather than thermodynamic concepts.

The photons in a long cylindrical element in a light beam may be regarded as originating on an element of area dS on some arbitrary reference plane and expending their energy on a similar element of area on a receiving plane after traveling a distance x between the two planes. For convenience, both planes may be assumed perpendicular to the light beam. However there a number of events which can prevent the photons from making their energy contribution at the appropriate element of area on the receiving plane. The direction of travel of a photon may be changed by reflection or refraction by intervening particles, its energy may be converted into heat by absorbing particles, or its energy may be taken up by a gas molecule and re-emitted after a brief time as a new photon with a different direction of travel.

These events may be regarded as occurring at random and will be referred to as "accidents." The probability of a photon reaching the element of area on the receiving plane will be the probability that it traverses the distance x without accident. This probability may be designated as $P(x)$ which is assumed to be a continuous function of x. The probability that a photon will be transmitted through a distance $x+dx$ is $P(x+dx)$. However

$$P(x+dx) = P(x) \cdot P(dx), \qquad (23)$$

where $P(dx)$ is the conditional probability that the photon will travel a distance dx provided it has already traveled a distance x.

The probability that it will suffer an accident in the distance dx is σ dx where σ is a constant. The probability $P(dx)$ may therefore be written as

$$P(dx) = 1 - \sigma dx \tag{24}$$

The probability $P(x+dx)$ may be expanded in a Taylor series about the point $x = x$ which gives

$$P(x+dx) = P(x) + P'(x)dx + \frac{P''(x)(dx)^2}{2} + \ldots\ldots \tag{25}$$

where $P'(x)$ and $P''(x)$ are the first and second derivatives of $P(x)$. Substituting equations (24) and (25) in equation (23) gives after simplifying and omitting terms containing powers of dx higher than the first

$$\frac{1}{P}\frac{dP}{dx} = -\sigma$$

where $P(x)$ is now written as P. Integrating equation (25) gives

$$P = Ke^{-\sigma x}$$

Since P can take on any value between 0 and 1, it follows that $K=1$, hence

$$P = e^{-\sigma x} \tag{26}$$

If there are a large number of photons in the beam the expected number N arriving at the element of area ds in the plane per second is

$$N = N_o e^{-\sigma x} \tag{27}$$

where N_o is the number leaving the element of area ds in the reference plane per second. However, the initial and terminal intensities I_o and I are directly proportional to N_o and N, hence

$$I = I_o e^{-\sigma x}$$

This rather roundabout derivation of equation (22) has the important advantage of showing that $e^{-\sigma x}$ may be treated as a probability. The expected or mean free path $\bar{x}$ of a photon in the atmosphere may then be computed from the equation

$$\bar{x} = \int_0^\infty x \cdot P dx = \int_0^\infty x e^{-\sigma x} dx$$

which when integrated gives

$$\bar{x} = 1/\sigma \tag{28}$$

The average photon path is therefore equal to $1/\sigma$ and is the distance that will reduce the intensity of the light beam to $1/e$ of its initial value.

The distance $\bar{x}$ is nearly equal to the haze-meter reading d which is the distance that will reduce the intensity of a light beam to 0.40 of its initial value. It is recommended that in the instruments manufactured in the future, the transmission of the filter in the haze-meter be decreased slightly so as to make d and $\bar{x}$ numerically equal. This would reduce by one the number of variables involved in visual range problems. The dark ridge visual range y is related to $\bar{x}$ by the equation

$$y = -\bar{x} \log_e(.02)$$
$$= 3.912\bar{x}$$

The statistical derivation of equation (22) is valid only if it can be assumed that the photon accidents are independent in the statistical sense. The failure or success of one photon to traverse the distance x must have no effect on the probability of the success or failure of other photons to traverse this distance. This condition would be realized if the number of opportunities for accidents was very large in comparison to the number of accidents actually occurring. Computations for an atmosphere consisting of pure gases shows that the number of molecules per unit volume of the atmosphere is very large compared to the photon density for an atmosphere in bright sunlight. This condition should not be effectively changed for an atmosphere containing particles each of which consists of a considerable number of molecules. Apparently the only situation in which the exponential law could be questioned would be for radiation fields far more intense than those associated with visual problems.

Additional Information on the Byram Haze-Meter

The brass case of the haze-meter is an L-shaped box (fig. 23) about 9 inches long, 1¾ inches square along the shank of the L, and 1¾ by 3 inches at the foot of the L. The brightness of any part of the landscape can be compared with the horizon brightness by means of the mirrors M_1 and M_2. The silver is removed from the left side of the lower mirror M_2 and from a section in the center of this mirror to make a slit S projecting into the silvered portion. A neutral filter F_1 is placed directly in front of this slit so that objects seen through the slit will be 60 percent as bright as when they are seen in the silvered portion of M_2. The small end of the meter is the eye end.

Looking through the instrument, the observer has a direct view through the left side of M_2 and also through the slit in the center of this mirror. Objects seen in the right side of M_2 are reflected down from the rotatable mirror M_1. If the observer directs the slit at the sky 1 or 2 degrees above the horizon and slowly rotates the mirror M_1, he can see different parts of the landscape reflected in the silvered part of M_2 and surrounding the slit. When a ridge which is about 0.60 as bright as the horizon sky is reflected opposite the slit, the slit will disappear. The distance of this ridge from the observer is the haze-meter reading. When no ridge happens to match the slit exactly, the observer must interpolate to determine the distance of a matching ridge. This

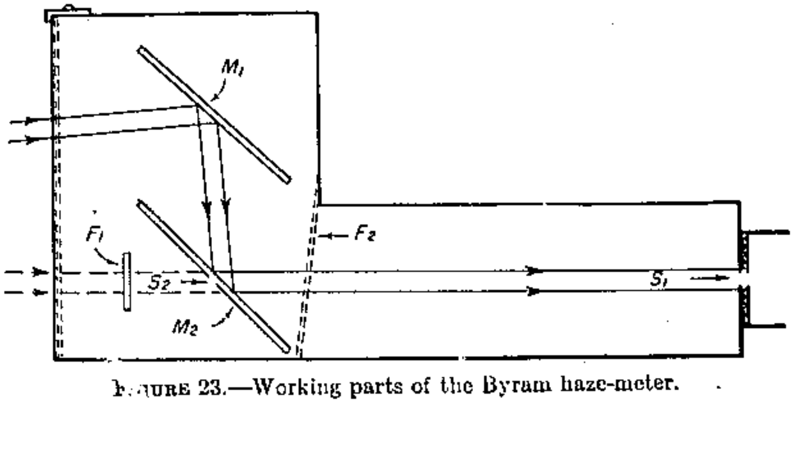


FIGURE 23.—Working parts of the Byram haze-meter.

requirement is a source of error for the Byram meter, but one that can be readily minimized by adequate instruction.

A narrow slit S_1 at the eye end of the instrument makes the slit in the mirror M_2 sharply in focus even when the observer's eye is focused on the horizon. A blue filter F_2, as wide as the mirror bar is long, is placed in the haze-meter, as shown in the figure. This filter makes it easier to match the slit with the images around it.

Visibility distance in miles of a small standard smoke as related to haze-meter readings from 1 to 15 miles is given in the first half of table 3. This small standard smoke is roughly equivalent to that given off by a 12- by 12-foot fire in dry hardwood leaves. Values of visibility distance for this table for any given haze-meter reading were obtained by multiplying the visual range values from curve *A* in figure 2 by 0.70.

The second half of table 3 gives similar information for a smoke from a ⅛-acre fire. It was assumed that a smoke column from a fire of this size would have a diameter about 6 times as great as that of the small standard smoke.

TABLE 3.—*Visibility distance of small standard smoke and smoke from ⅛-acre fire, as related to meter readings in even tenths of miles*

SMALL STANDARD SMOKE

Meter reading (miles)	0.0	0.2	0.4	0.6	0.8
	Miles	*Miles*	*Miles*	*Miles*	*Miles*
1	2.1	2.4	2.7	2.9	3.2
2	3.4	3.7	3.9	4.1	4.3
3	4.6	4.8	5.0	5.2	5.4
4	5.6	5.8	6.0	6.2	6.4
5	6.5	6.7	6.9	7.1	7.2
6	7.4	7.6	7.7	7.8	8.0
7	8.2	8.3	8.5	8.6	8.8
8	8.9	9.0	9.2	9.3	9.5
9	9.6	9.7	9.9	10.0	10.1
10	10.3	10.4	10.6	10.7	10.8
11	11.0	11.1	11.2	11.3	11.5
12	11.6	11.8	11.9	12.0	12.1
13	12.2	12.4	12.5	12.6	12.7
14	12.9	13.0	13.2	13.3	13.4
15	13.5				
SMOKE FROM ⅛-ACRE FIRE [1]					
1	3.1	3.6	4.1	4.6	5.0
2	5.5	5.9	6.3	6.7	7.1
3	7.5	7.8	8.2	8.5	9.0
4	9.3	9.6	9.9	10.3	10.6
5	10.9	11.3	11.6	11.9	12.2
6	12.5	12.8	13.1	13.4	13.7
7	14.0	14.3	14.6	14.8	15.1
8	15.4	15.7	16.0	16.2	16.5
9	16.7	17.0	17.3	17.6	17.9
10	18.1	18.3	18.6	18.9	19.1
11	19.4	19.6	19.9	20.2	20.4
12	20.7	20.9	21.1	21.4	21.7
13	21.9	22.2	22.4	22.7	22.9
14	23.2	23.4	23.7	23.9	24.2
15	24.4				

[1] Applicable to fires in hardwood leaf litter fuel type, when fuels are dry.

Additional Information on the Plains Haze-Meter

The working parts of the Plains haze-meter (fig. 24) are an optical wedge of smoked glass W; a blue filter F; a narrow horizontal slit S, cut in a thin metal strip at the eye end of the meter; two parallel mirrors M_1 and M_2; and a series of slits numbered from 1 to 13 which are cut in the silver of mirror M_2.

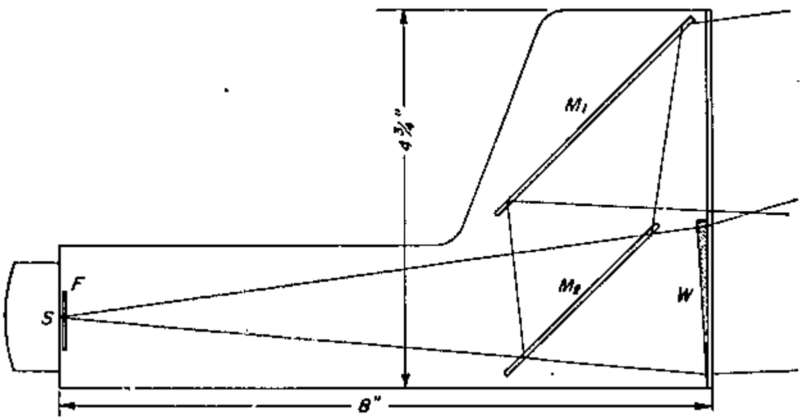


Figure 24.—Working parts of the Plains haze-meter.

A light beam coming from the horizon sky passes through the optical wedge, where its original intensity is diminished and the whole beam is deflected slightly upward. Thus the wedge also serves as a prism to bring down a small section of the horizon sky so that its brightness can be compared with the brightness of a landscape target.

The beam next passes through the slits in the lower mirror M_2 and then through the eyepiece slit. The portion of the beam which passes through the thick part of the wedge will suffer a greater loss in intensity than that part of the beam passing through the lower thin part, hence the slits in M_2 appear progressively darker from No. 1 at the bottom to No. 13 at the top. A light beam from a landscape target is reflected down from the upper mirror M_1 to the lower mirror M_2 and then into the eyepiece slit. Each slit in the lower mirror serves as a photometric unit by which it is possible to compare the brightness of a target with the horizon brightness; for instance, if slit No. 2 disappears when superimposed on a distant target, it is known that the target is 60 percent as bright as the horizon sky, and if slit No. 13 disappears, it is known that the target is 14 percent as bright as the horizon sky. The brightness ratio for slits between 2 and 13 will be between 14 percent and 60 percent. However, the meter is so constructed that this ratio does not appear in the visibility measurement and the observer needs to know only the target distance and the number of the disappearing slit. The eyepiece slit makes distant targets and the slits in the lower mirror always appear focused. The blue filter eliminates color differences in the landscape and subdues the brightness of horizon clouds.

DIRECTIONS FOR USE

To estimate a visibility distance with the Plains haze-meter:

1. Select a natural target, such as the shaded side of a clump of trees at the edge of a clearing. This clump of trees must be in the direction of the sun, hence different targets must be used for different times of day.
2. Starting with slit No. 1, direct first one slit and then another at the target until a slit is found which disappears. The number of the slit which disappears and the distance from the observer to the target in miles and tenths are the two readings needed to obtain the visibility distance from table 4. For instance, if slit No. 7 disappears on a clump of trees at 1.1 miles away, the visibility distance is 4.2 miles.

In selecting natural targets and in making measurements with the haze-meter, the following points should be carefully observed:

1. Always select targets in the direction of the sun. The shaded sides of clumps of trees at the edges of clearings make good targets. In slightly rolling country, dark wooded coniferous slopes may be used. The most important requirement for a suitable target is that it be dark.
2. Select targets that are as far away as possible, yet large enough to cover fully and surround any given slit when viewed through the instrument. If a target is too far away, it will appear smaller than the haze-meter slits. In this case it is necessary to select a larger target or one nearer the observer.
3. Select targets that are seen against the horizon or within 1 degree of the horizon. If this condition is satisfied, the position of the second slit above the slit which is directed at the target will be above the horizon. For instance, if slit No. 4 is pointed at a bank of trees or any other dark spot on the landscape, then slit No. 6 should be above the horizon. For this reason measurements can sometimes be made to greater advantage from the ground than from the top of a tower. On very hazy days it is possible to use targets nearer the observer than could be used if the day were clear.
4. Always keep the front window glass of the haze-meter shaded from direct sunlight when using the meter. The front window glass should also be kept clean. Never take readings through window panes.

It is possible that on certain days there will be no slit which disappears on some given target, for two possible reasons:

1. The air is too hazy.
2. The air is too clear.

If the air is too hazy, all of the slits will appear dark. This indicates that a target nearer the observer should be selected. If the air is too clear, all of the slits will appear light. This indicates that a more distant target should be selected. If this is not possible, record the visibility distance as that distance corresponding to slit No. 13 and the distance of the target used.

The Plains haze-meter can also be used for estimating visibility in mountainous regions. In this case mountain ridges are used for targets. As before, the second slit above the one under consideration should be kept just above the horizon. For instance, if slit No. 3 is pointed directly at a ridge, then slit No. 5 should be above the horizon. It is also desirable to keep this second slit as near the horizon as possible yet still above it. If readings are taken with any of the slits above No. 3, the readings should always be in the direction of the sun. Slits Nos. 1, 2, and 3 may be used in any direction.

Never take the haze-meter apart.

TABLE 4.—*Visibility distance in miles as determined from target distance and haze-meter slit number*

Target distance (miles)	Haze-meter slit numbers												
	1	2	3	4	5	6	7	8	9	10	11	12	13
0.5	0.9	1.0	1.2	1.5	1.7	2.0	2.2	2.5	2.9	3.2	3.6	4.0	4.4
0.6	1.0	1.2	1.5	1.7	2.0	2.3	2.6	2.9	3.3	3.8	4.1	4.6	5.0
0.7	1.1	1.4	1.7	1.9	2.2	2.6	3.0	3.4	3.8	4.3	4.7	5.1	5.5
0.8	1.2	1.5	1.8	2.1	2.5	2.9	3.3	3.8	4.2	4.7	5.1	5.6	6.1
0.9	1.4	1.7	2.0	2.3	2.8	3.2	3.7	4.1	4.6	5.0	5.5	6.1	6.7
1.0	1.5	1.8	2.2	2.5	3.0	3.5	3.9	4.5	5.0	5.4	6.0	6.6	7.2
1.1	1.6	2.0	2.4	2.8	3.3	3.8	4.2	4.8	5.3	5.8	6.5	7.1	7.7
1.2	1.7	2.1	2.5	3.0	3.6	4.0	4.5	5.0	5.6	6.2	6.8	7.6	8.1
1.3	1.8	2.2	2.7	3.2	3.8	4.3	4.8	5.3	6.0	6.6	7.3	8.0	8.6
1.4	1.9	2.3	2.9	3.4	4.0	4.6	5.0	5.6	6.3	6.9	7.6	8.4	9.0
1.5	2.0	2.5	3.0	3.6	4.1	4.8	5.3	5.9	6.7	7.3	8.0	8.8	9.5
2.0	2.5	3.1	3.8	4.4	5.1	5.8	6.5	7.2	8.0	8.8	9.7	10.7	11.6
2.5	2.9	3.8	4.5	5.2	6.0	6.8	7.6	8.5	9.3	10.3	11.4	12.3	13.4
3.0	3.3	4.3	5.2	6.0	6.8	7.7	8.7	9.7	10.6	11.7	12.8	14.0	------
3.5	3.8	4.8	5.7	6.7	7.6	8.6	9.7	10.7	11.7	12.9	14.2	------	------
4.0	4.2	5.3	6.3	7.4	8.4	9.5	10.7	11.8	12.8	14.2	------	------	------
4.5	4.6	5.8	6.8	8.0	9.2	10.3	11.6	12.7	13.9	------	------	------	------
5.0	5.1	6.3	7.3	8.6	9.8	11.1	12.3	13.6	------	------	------	------	------

Additional Information on Lookout Eye Test

SPECIFICATIONS FOR LOOKOUT EYE-TEST TARGET

Eye-test target to consist of a black and white pattern mounted on a 7.0-inch square back, in the center of which is mounted a handle for rotating the target.

The eye-test pattern to be printed from a brass master negative on double-weight, high contrast (No. 4 or 5), smooth, glossy, photographic paper. The brass negative must be placed with the upper or beveled surface away from the paper when prints are made. The master negative or plate is to be cut from smooth, flat, 22-gage half hard sheet brass to the pattern shown in figure 25 and drilled on a diagonal

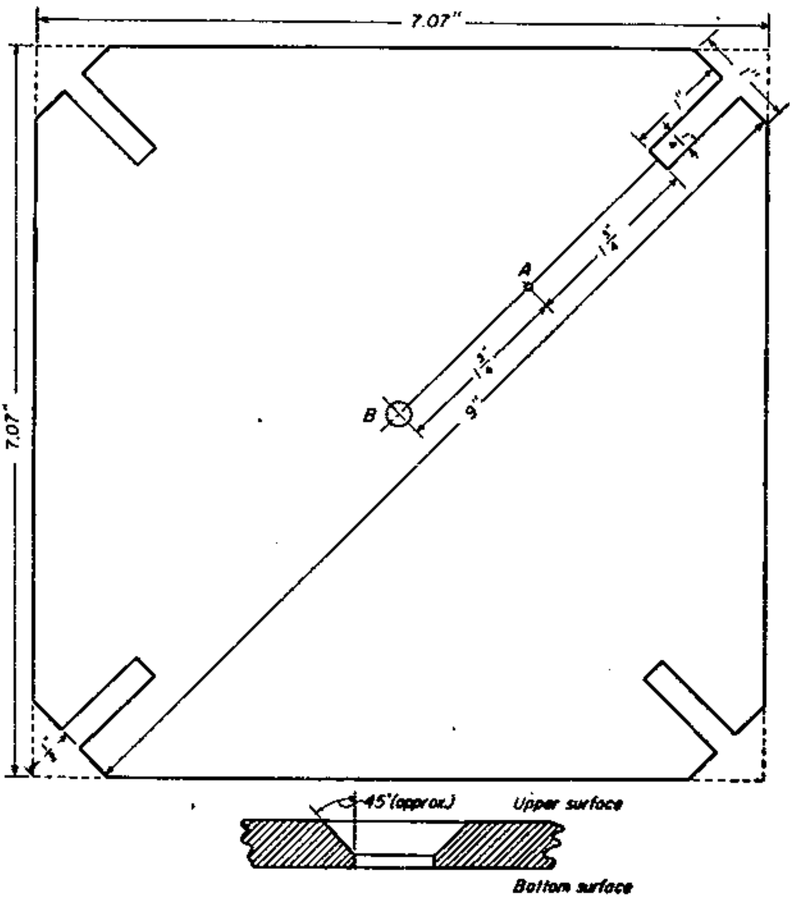


Figure 25.—Master plate and enlarged cross section showing how holes *A* and *B* are to be beveled.

at the two points indicated. Hole *A* is ¹⁄₁₆ inch in diameter ±0.002 inch; hole *B* is ¼ inch in diameter. Holes *A* and *B* are to be beveled to a distance of one-third the thickness of the metal from the bottom of the plate as shown in the cross section. The upper edges of the corner slots are beveled in the same manner. On the bottom (unbeveled) surface, print plainly: PUT THIS side of plate next to paper when making photographic prints from THIS MASTER PLATE.

The eye-test backing material to be hard fiberboard (Masonite, tempered Presdwood, or equal) of about ⅛-inch thickness, varnished on both sides.

After varnish is thoroughly dry, pattern to be cemented with shellac to smooth side of fiberboard back.

Both print and fiberboard back to be at least 8 inches square to insure good contact around the edges of the pattern, and to allow space for trimming. Eye-test board to be trimmed on black-white border to leave smooth edge. Corners to be trimmed.

A square or circular block, about 1½ inches in diameter and ⅜ inch thick, and drilled through the center to receive a ⁵⁄₁₆-inch dowel handle 3 inches long in a tight fit, is to be glued to center of eye-test back. Handle is not to be glued in block.

A small black spot is to be painted on back of eye-test target directly behind the ¹⁄₁₆-inch spot.

Instructions for use of eye-test are to be printed or pasted on front of an envelope 7½ by 10½ inches, in which eye-test is kept when not in use.

INSTRUCTIONS FOR USE OF FOREST SERVICE EYE TEST FOR FIRE LOOKOUTS

The lookout eye-test is a device designed to measure the relative ability of lookouts to see small smokes. The eye-test target consists of a square white board with a large black spot in the center, black bars on the diagonals, and a *small* black spot midway between the center and one diagonal bar. The maximum distance that a man can see this *small* spot is a measure of his power to see small columns of smoke at long distances. The eye test is given as follows:

Select a suitable place *out-of-doors*. Either a sunny or cloudy day will do. A dark foreground, such as green grass or earth is necessary. Avoid bright foregrounds, such as dusty or graveled roads.

Insert the round peg in the block on the back of the board to form a handle. Hold eye-test board in full light of open sky but shaded from direct rays of sun. Avoid getting under eaves of buildings or tree crowns.

Hold eye-test board upright so that one diagonal black bar is vertical, the other horizontal (the *small* spot will be up, down, to right, or to left), with white side of eye-test board facing toward person being tested.

Have man being tested back away from eye-test board until *small* black spot almost disappears (usually 35 or 40 feet). He should not face sun.

Whirl eye-test board several times so the *small* black spot may assume a new position, either up, down, right, or left. Have observer signal or state new position of the *small* spot. If correct, have him step back 2 or 3 feet. Repeat procedure until the observer indicates position of *small* black spot incorrectly. Have him guess when he is no longer certain. He may rest his eyes if he wishes.

Record the observer's rating as the distance in feet *from eye-test board to the last point from which he can indicate position of the small black spot correctly*. The distance at which this small spot can be seen is definitely related to the distance at which small smoke columns can be easily detected. The following tabulation indicates quality of eyesight in relation to eye-test rating in feet:

Maximum distance at which small black spot can be seen (feet)	*Quality of eyesight*
64 or over	Exceptional.
58–63	Good.
50–57	Average.
44–49	Fair.
43 or under	Poor.

Specifications For Glare-Reducing Goggles

Glare-reducing goggles to be made of crown glass, optically finished to eliminate all distortion. Glass to be of neutral tint, giving approximately constant absorption for all visible radiation. (There must not be a deep selective absorption band within the visible range of the spectrum.) The transmission of visible radiation to be from 20 to 30 percent; the two lenses in one pair of goggles must transmit approximately the same amount of light, not varying in this respect more than 4 percent. The lenses and frames to be of the pear-shaped ("sport") type, approximately 2⅛ inches in greatest width and 2⅝ inches in greatest length.

The frames are to be of noncorroding metal. The bows are to be flexible and easily adjustable without tools to individuals' requirements. Goggles must be hinged at the bridge to permit adjustment to individual requirements for fitting. A broad, comfortable nose rest shall be provided. Each pair of goggles to be provided with a metal case to reduce possibility of breakage.

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C. - Price 45 cents

END