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ANTICOLLISION LIGHTS FOR THE SUPERSONIC TRANSPORT (SST)

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I. INTRODUCTION

Notwithstanding the progress made in air traffic control and operational procedures to cope with increasing traffic density and flying speeds, a visual collision avoidance system is still considered necessary to the safe operation of subsonic aircraft through their entire flight regime. In accordance with the principles of visual flight rules, that the pilot must be given the opportunity "to-see-and-be-seen," certain means and tools are provided to the pilot for VFR flights, such as windows and mirrors to look for other aircraft, colored surface paints and markings, and exterior aircraft lights to enhance conspicuity. A wealth of information is available on this subject, including the requirements of exterior lights for subsonic and supersonic aircraft. The references on this subject, given in this report, can only be considered as a selected sample. Additional information specifically concerning the SST is contained in the papers prepared for the French-Anglo-United States on Supersonic Transport (FAUSST) which are given at the end of this report.[1] [2] [3] [4] [5]

The importance and controversial nature of this subject indicates a need for careful review of previous studies, projecting their results into the new environment in which commercial supersonic airplanes will soon be operating.

II. ASSUMPTIONS

The following assumptions form the basis for this argument and will be considered in the discussion of anticollision lights for the SST:

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A. Separation from other aircraft by positive control (air traffic monitoring and advisory service from the ground) is the primary means of collision avoidance. Visual warning is of secondary importance, but is considered necessary or desirable.

B. Air-derived inflight warning equipment, such as proximity or pilot warning devices, will be available at the time of SST operations.

C. During the subsonic phase of operation, the anticollision lighting needs of the SST are the same as those for current subsonic aircraft.

D. Supersonic flight favors altitudes which are characterized by relatively high atmospheric transmissivity and, therefore, long visual range.

E. Experiments with steady and flashing lights have shown that under operational conditions the most conspicuous signal is one which flashes about two or three times per second and which is at least twice as bright as its background.[6] The signal efficiency of flashing light has been found to depend on frequency, contrast, flash duration, and brightness of the signal. Color filters may reduce signal light efficiency to 20% or 50% of its unfiltered value. Point light sources are most efficient. As to signal conspicuity, the shorter the flash duration at a given energy, the higher its conspicuity. Below about one-tenth of a second there is little to be gained by reducing the duration of the signal.[7]

F. External lighting on aircraft, particularly the anticollision lights, is used to increase the visual range beyond the potential danger zones in commercial aviation. A technical study made by the Applied Psychology Corporation for the FAA in 1962, concluded that the desirability "for higher intensity (of the lights) need not be ignored; it can be strongly recommended without being required."[8] The policy of the Federal Aviation Administration has followed this recommendation, and effective intensities higher than the present regulatory requirements are proposed for U.S. transport aircraft.*

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* FAA Notice of Proposed Rule Making, 28 May 1970.

G. Any anticollision light on an SST, regardless of its use during subsonic or supersonic flight, should provide maximum warning capability to crews of other airplanes within their visual range.[9] The minimum effective intensity, color, flash rate, and field of coverage as required by Federal Aviation Regulations* and the International Civil Aviation Organization, Annex 8,** seem inadequate to provide useful warning and to reduce significantly the probability of collision between the SST and another aircraft likely to be in the same airspace.[10]

H. Not only the supersonic speed but also the structural design of the aircraft—particularly its nose section—may seriously limit the pilot's view and his ability to see other aircraft.

I. At supersonic speeds, the so-called distance scotoma, perceptual latencies, and the fixity problem limit the pilot's capability to take corrective action when he is on a collision course.

J. Although the probability of occurrence of head-on collisions may be very remote, anticollision lights should provide maximum practicable warning in the forward direction and proportionate warning in all other directions.

III. BACKGROUND

The use of navigation lights and, particularly, anticollision lights has been instrumental in collision avoidance during subsonic operations under reduced lighting conditions. Hence, the use of these lights during subsonic cruise and takeoff and landing is thought to be equally effective, and it is intended that anticollision lights be employed on the SST in the usual manner during this phase of flight. The effectiveness of a flashing light as a warning signal is a function of several variables, some of which are more or less affected by the flight envelope of the aircraft.

A. Effective Intensity

The effective intensity of a light signal is directly proportional to the power used when the other parameters are constant.

The effective illumination on a surface from a given light source varies inversely as the square of the associated distance; expressed mathematically as:

$$\frac{E_1}{E_2} = \frac{R_2^2}{R_1^2} \; ; \qquad (1)$$

and the square of the visual range varies directly as the effective intensity of a light source. This can be expressed as:

$$\frac{R_1^2}{R_2^2} = \frac{Ie_1}{Ie_2} \, . \qquad (2)$$

Therefore, the visual range after a change in effective intensity of the light source is given by:

$$R_2 = R_1 \sqrt{\frac{Ie_2}{Ie_1}} \quad . \qquad (3)$$

The effective intensity can be substantially increased, without an increase in power usage, by removing the filters which reduce the output of the light source.

In the supersonic portion of the flight profile, outside the influence of ground lights, atmospheric conditions with absence of backscatter or halation indicate the possibility and desirability of displaying white flashing anticollision lights for indication of presence at greater range. Removal or retraction of an aviation red filter would permit a given light source effective intensity increase of four times for incandescent and five times for condenser discharge (blue-white) light. Separate anticollision lights for red (subsonic) and white (supersonic) operation would also perform the intended function.

B. Visual Range

Visual range is related to effective intensity of a light signal according to the inverse square law at any given transmissivity of the atmosphere. The atmospheric transmissivity at the cruising altitude of the SST (above 40,000 ft.) usually is quite high. In a perfectly clear atmosphere, the effective intensity (E) at the observer's eye can be expressed as:

$$E = \frac{IWt^D}{D^2} \; ; \qquad (4)$$

where: I is the intensity of a light source; t is the transmissivity of the atmosphere per unit distance; D is the distance; and W the transmissivity of the windshield. The international visibility scale categories of the atmosphere are given in Table I.

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* Paragraph 25.1401 of Federal Aviation Regulations Part 25, Airworthiness Standards, Transport Category Airplanes.

** ICAO Annex 8, International Standards, Airworthiness of Aircraft, Fifth Edition, April 1962.

Table I.—Visual properties of the atmosphere; international visibility code.

Atmospheric designation	Daylight visual range (miles)	Transmissivity (transmission/mile)
Exceptionally clear	over 31	over .88
Very clear	12 to 31	.73 to .88
Clear	6.2 to 12	.53 to .73
Light haze	2.5 to 6.2	.21 to .53
Haze	1.2 to 2.5	.004 to .21

Figure 1 illustrates how the range for observing a light varies as a function of light intensity and atmospheric conditions. The ordinate is range in miles on a log scale. The abscissa is light transmissivity per mile. This scale varies from 0.2 in a light haze to 1.0 in a very clear atmosphere. The family of curves shown on the figure illustrates how the maximum detection range is increased as the atmosphere becomes more nearly clear. The curve for 100-effective-candlepower lights illustrates how these FAR type intensity lights would be visible at distances of 2 to 3 miles in a light haze and at distances of 10 to 15 miles in a very clear atmosphere. The figure shows how the effectiveness of lights at the very high altitudes is improved by the lack of meteorological conditions causing haze and clouds. It should also be noted that the maximum detection range is increased more rapidly when the candlepower of the light is increased.[11] [12]

In order to reduce drag and frictional heating, the optical surfaces of aircraft during supersonic flight must be slanted. As the angle between the line-of-sight and the angle of incidence of the light rays increases, the light transmitted is reduced due to absorptions and reflections. Existing subsonic jets have panel transmissivities which vary from about 0.50 down to less than 0.22, considering the different angles at which the line-of-sight of the pilots intersects the different segments of the windshield.

C. Contrast

Expressed in percent, contrast is equal to:

$$\frac{L_2-L_1}{L_1\times 100},$$

where: L_2 is the luminance of the signal, and L_1 is the background luminance. The effectiveness of the light signal increases as a function of

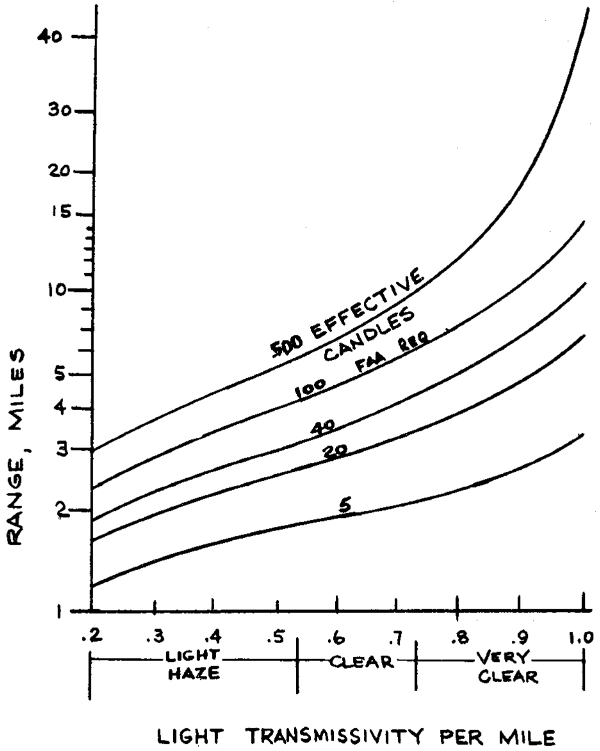

Figure 1. Visibility range as a function of light intensity.

brightness contrast. For large signal contrasts, the comparative effectiveness of conspicuity of steady and flashing signals is approximately equal. Threshold contrasts, i.e., the least contrast required for an object to be detected against a background, decreases as luminance increases until it reaches a limit at relatively high illumination (about 100 millilamberts). This limit determines the effectiveness of light signals during daylight.

The contrast threshold depends not only on such characteristics as luminance and size of the signal, but also on the wavelength of the light, the shape of the light source, and the characteristics and/or the region of the retina stimulated by the signal. The relatively low luminance of sky brightness at extremely high altitudes may yield substantial effectiveness of very bright light signals for the SST during certain lighting conditions.

D. Color

Light of different wave length passing through the atmosphere is absorbed at different amounts. The longer wavelengths (red) penetrate the atmosphere better, that is, they are less absorbed by the water vapor than are the shorter wavelengths (toward blue and violet). Moreover, cone sensitivity of the retina reaches a maximum at about 550 millimicrons, i.e., in the yellowish-green zone, and falls rapidly to either side. Thus, a green or yellow light appears brighter than a violet or red light of equal intensity. When the color or the flux emitted by a light source must be changed by the use of filters, its luminance may be substantially reduced. Filters to produce aviation red and aviation green (approximately 640 millimicrons and 520 millimicrons, respectively) have a transmission in the order of 20% to 25%. If the light source is a condenser-discharge light, the transmission for green is about the same as for an incandescent light, but the red transmission is only about half as much, or less, depending on the light source. The transmission for a blue filter is considerably higher. Virtually no filtering at all is necessary to obtain bluish-white discharge light; whereas a bluish filter for an incandescent source might have a transmission of 25% to 50%. Aviation red is presently required for subsonic aircraft (fixed and rotary wing) as the standard anti-collision light. This present standard was developed using the following rationale:

1. Red is associated with danger and is generally accepted as a warning indicator.[21]
2. Red lights presumably cause less confusion with ground lights of a metropolitan area, when viewed from above, than do white lights.[23]
3. Backscatter produced by a red light seems to be less annoying than backscatter produced by a green or a white light.[24]
4. Red light retains its saturation better than any other color at long distances.[25]

E. Time and Distance Scotoma

Of the various sense organs, which provide the pilot with information about his environment, the eye is the most sensitive and reliable. However, its physical and neural characteristics are adequate for the terrestrial environment in which they developed and to the moderate velocities with which they normally have to cope. This means that every visual perception follows a definite and limited time pattern. When an object produces a stimulus, a certain period elapses until it is perceived. The sensation reaches a maximum and then subsides. This is the reason that an intermittent light which produces many sensations is physiologically more effective than a constant signal.

Under ideal conditions, the reception of a stimulus through the peripheral organs takes about 20 msec. (milliseconds), the passage through the centripetal nerve fibers and synapses about 2 msec. and the excitation of the visual cortex about 13 msec. This adds up to about 35 msec. however, the perception time under flying conditions can amount to about 100 msec.; and this delay does not include the central transmission of stimuli associated with mental processes, nor the response time delay due to motor impulses and muscular action of the eye.

The latent period of perception varies with the intensity of the stimulus, the part of the retina stimulated, and the state of the attention of the observer. In order to see the object distinctly enough for useful recognition, it must be projected on the fovea to attain greater visual acuity. The average time required to prearrange the eye movement is about 175 msec., and the eye movement itself consumes another 50 msec. Foveal perception takes about 70 msec., and the average recognition time is considered to be 650 msec. Thus, from the time of first sensation until the recognition of the object, 1.045 seconds may elapse during which one is not totally aware of the situation.[12]

This delay of visual perception means that one lives almost as much as one second in the past. While this may not be of great consequence in subsonic flight, it becomes critical at supersonic velocities. During this one second, two aircraft approaching each other at a closing speed of 5.4 Mach will have narrowed the gap by almost 1 mile. If the pilots were to see one another at this distance, they actually would collide at the moment of distinct perception. Or if the two airplanes flying at this speed were on a collision course, neither of the pilots would become aware of the other craft if the distance of detection was somewhat less than a mile. It should be noted that the perceptual latent periods cannot be reduced by any amount of mechanical or electronic ingenuity, because they are caused by the characteristics of the human eye. However, the distance traveled during these periods will increase directly as speed increases, due to the distance-speed-time relationship. This is shown in the upper part of Table II.[12]

TABLE II.—Time intervals required first sighting of object and changing flight path to avoid impact and distances traveled in those intervals.[12]

Operation	Time (seconds)		Distance traveled (ft.)					
			Two aircraft closing @ 3,400 m.p.h.		Two aircraft closing @ 3,200 m.p.h.		Two aircraft closing @ 2,200 m.p.h.	
	For operation	From first sighting	During operation	From first sighting	During operation	From first sighting	During operation	From first sighting
Perception:								
Sensation (light travels from retina to brain)	0.1	0.1	499	499	470	470	322	322
Motor reaction to prearrange eye movement	0.175	0.275	873	1,372	822	1,292	564	886
Eye movement	0.05	0.325	249	1,621	245	1,537	161	1,047
Focusing with fovea	0.07	0.395	349	1,970	329	1,866	225	1,272
Perception (minimum recognition)	0.65	1.045	3,241	5,211	3,055	4,921	2,094	3,366
Decision:								
Deciding what to do (estimated minimum)	2.0	3.045	9,973	15,184	9,398	14,319	6,442	9,808
Response:								
Operating controls	0.40	3.445	1,995	17,179	1,880	16,199	1,288	11,096
Clearance deviation from flight path (50 ft. vert. clearance)	3.5	6,945	17,453	34,632	16,447	32,646	11,273	22,369

F. Pilot and Vehicle Reaction Time

The reaction time required to initiate an approximate response consists of a neural and a motor component. The neural part, that is, the impulse transmission to the muscles takes only a few msec., but the prearrangement of the arm, hand, and leg muscles and the entire motoric response to operate the controls consumes about 40 msec. If one assumes an evasive maneuver to obtain a clearance deviation of 50 feet from the flight path, which is just barely sufficient to miss the other aircraft, the control response should add about 3.5 more seconds.[12] This is a very optimistic figure and should be considered as the absolute minimum. If, as in Table II, a decision time of 2 seconds and the time of first sensation until recognition of 1.045 is added, the total time taken from first sighting of the object to changing the flight path to avoid collision is almost 7 seconds, during which time the two SSTs would have covered a distance of almost 7 miles. Similar time-distance relationships are also given in Table II for other closing speeds.

When dealing with human and aircraft reaction times, the variables cannot be determined with great accuracy and average values must therefore be accepted. Moreover, the detection of another aircraft, the determination of a collision threat, and the resulting control actions are complex functions which contain a series of elements or intervals which consume more or less time depending upon the situation. For example, if the pilot shifts his eye focus from outside the aircraft to check his instruments after he has picked up the target, the time required for eye movements and the accommodation of the eye muscles from far to near and back may consume an additional 2.5 seconds. Eye movement times and distances traveled are shown in Table III. Probably the greatest variable to be considered,

TABLE III.—Time intervals required to shift sight from outside aircraft to instrument panel and back, and distances traveled in these intervals.[12]

Operation	Time (seconds)		Distance traveled (ft.)					
			Two aircraft closing @ 3,400 m.p.h.		Two aircraft closing @ 3,200 m.p.h.		Two aircraft closing @ 2,200 m.p.h.	
	For operation	From first sighting	During operation	From first sighting	During operation	From first sighting	During operation	From first sighting
To panel:								
Muscle movement	0.175	0.175	873	873	821	821	565	565
Eye movement	0.05	0.225	249	1,122	235	1,056	161	726
Foveal perception	0.07	0.295	349	1,471	329	1,385	226	952
Accommodation	0.50	0.795	2,494	3,965	2,347	3,732	1,614	2,566
Recognition of instrument reading	0.80	1.595	3,990	7,955	3,754	7,486	2,581	5,147
Back to distance:								
Reaction time	0.175	1.770	873	8,828	821	8,307	565	5,712
Eye movement	0.05	1.820	249	9,077	235	8,542	161	5,873
Relaxation of accommodation	0.50	2.320	2,494	11,571	2,347	10,889	1,614	7,487
Foveal perception	0.07	2.39	349	11,920	329	11,218	226	7,713

however, is the time needed by the pilot to arrive at a decision about the possible threat of a collision and to take appropriate action to avoid it.

Assuming a practical set of values for threshold of visibility, atmospheric transmissivity, and recognition-decision-response of crew, a minimum warning time of 14.2 seconds (see Table IV) was assumed by FAA and, without considering windshield transmissivity, was associated with an anticollision light with an effective intensity of 1,200 candles in a head-on collision threat of two Mach 2.7 airplanes. For other angles of converging flight paths, the warning time increases as the resultant closing speed decreases; hence a progressive decrease in intensity at angles other than dead ahead is proposed. An intensity of 300 candles of red light is considered an acceptable minimum for the SST during the subsonic portions of its flight profile. This is comparable to the supplemental warning lights attached to many present air carriers, most of which considerably exceed the current FAR requirement of 100 candles.

G. Additional Factors Which May Limit the Usefulness of Anticollision Lights for Supersonic Flight

Pilots know and make use of the fact that they are on a collision course when another aircraft appears at a fixed position within the visual frame of reference. The application of the fixity criterion is useful only when both aircraft maintain straight and level flights at constant speeds. Frequently, aircraft are not flying such courses, and in many cases, the pilot cannot be sure whether the intruder is on such a course. Sometimes the course estimation of the other aircraft is extremely difficult, especially when other references are not available.[13] For example, an altitude difference of 1,000 ft. may not be perceived at high altitudes and great distances against a dark sky. In the most severe conditions at night, the autokinetic illusion may make the light signal appear to move on an undistinguishable background while the intruder actually is on a collision course.[14] On the other hand, a flashing light sighted away from a window frame may seem to be fixed in the center of the window, for the motion threshold of a flashing light may be appreciably higher than that of a steady light. Because of inadequate information, the pilot may not be able to determine the intruder's possible maneuvers, and he may find himself on a collision course wherein evasive action is taken too late.

The distance to a faint, unfamiliar light source is extremely difficult to estimate.[15] A close light of low intensity looks very much the same as a strong light seen at a correspondingly longer distance. Differences of atmospheric transmissivity existing even at the SST altitudes may make the range estimates difficult for the pilot. If standardized lights of a certain intensity are used, the pilot's task can be facilitated. This could be particularly true at ranges where the higher intensity light is above the visual threshold while the lower intensity light cannot be seen. The high intensity anticollision lights presently used together with the lower intensity position lights meet these conditions. However, a number of exterior lighting systems including strobe lights have been designed and attached to aircraft. These systems have not been tested as to their effectiveness on a comparative or competitive basis and, since they are not of standard intensities and in regard to the number and patterns of lights used, contribute little to distance estimation.

IV. COLLISION AVOIDANCE ANALYSIS

A. Geometrical Considerations

E. S. Calvert (1958) who has spent more than two decades in helping to prevent the collision of vehicles on the ground, on water, and in the air, analyzed the collision problem very thor-

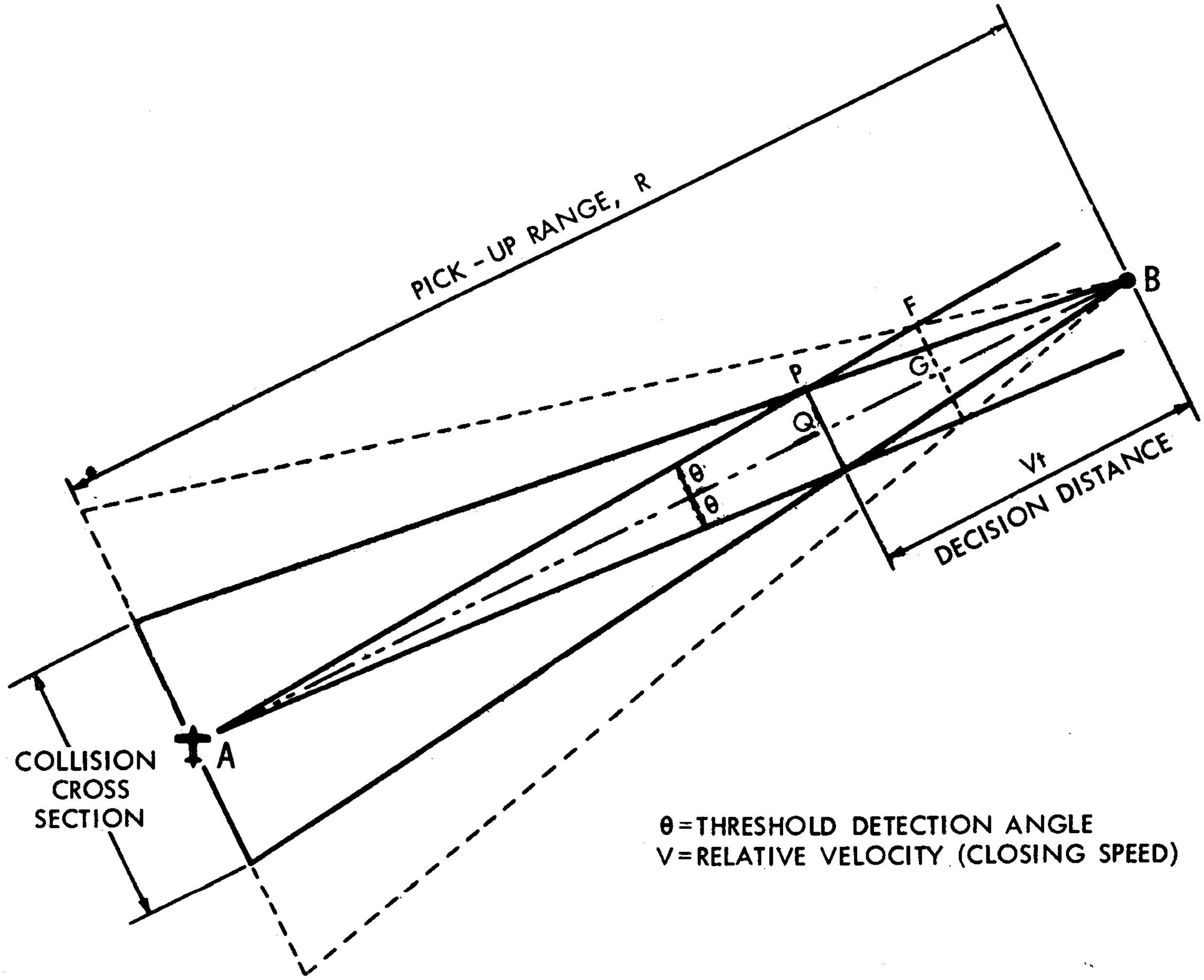

FIGURE 2. Collision course analysis: Fixed bearing criterion.

oughly. His geometrical analysis of the problem and its mathematical solution has had profound implications as to the usefulness and limitations of anticollision light systems (see Fig. 2).[16] The main parameters which he considers in his analysis are the threshold detection angle or bearing angle θ of the intruder aircraft, the distance between the two aircraft at the time of detection (which he calls the pick-up range), the relative velocity or closing speed, and the so-called "decision distance"; i.e., the time which the pilot needs to make a decision about a collision threat and the appropriate action. Calvert has made use of the well-known phenomenon that another aircraft poses a collision threat if it appears fixed in the field of view of the pilot, and he has called it the "fixity-of-bearing" criterion. The fixity-of-bearing criterion is valid if the two aircraft are on converging courses and fly straight at constant speed.[17]

A number of factors affect the accuracy with which an observer can make this determination. In addition to the inherent limitation in the ability of a pilot to detect the motion of an object in his field of view, the aircraft is not a stable platform. There are two ways in which a pilot might judge bearing fixity:

(1.) The pilot tries to detect a change in bearing of the other aircraft;

(2.) The pilot tries to detect drift in the bearing or target motion.

For method (1), Calvert assumes a threshold detection angle of 1/30 radian or about 2° based on estimates of aircraft and light characteristics. For method (2), a threshold detection velocity of 0.2° to 0.4°/sec. is assumed. In Figure 2, the threshold detection angle θ is the half-angle PAQ of a "cone of uncertainty" with its apex at A. So long as B stays within this cone, A will not be able to detect a change of bearing and will, therefore, have to assume a probability of collision.

After A sights B at range R, he observes him for a "decision time", t, before deciding whether or not he is a collision threat. During this time, B has closed on A a distance, vt, the "decision distance." If B's bearing appears to A to be fixed, then he may be on a course anywhere within the "collision cone" or "zone of danger," the half-angle of which is PBQ. The projection of the cone is on a plane through A perpendicular to the axis of the cone. It defines a possible "collision cross section." If, for purposes of analysis, a collision is said to occur when B passes through a specified area in the immediate vicinity of A, then the probability of collision may be defined as the ratio of that area to the "collision cross section." By initiating evasive action, A can reduce the probability to zero only if he gets out of the zone of danger before or after B reaches his vicinity.

The observation time, t, has an important effect on the size of the collision cone. If, for example, pilot A had made a decision by the time B reached the plane FG instead of PQ, the collision cone would be the one shown by the broken lines (with the half-angle FBG, and—by simple geometry—the danger zone would be correspondingly larger). Pilot A has gained time—the time for B to travel the distance GQ—but A's maneuver must now carry him a larger distance to escape the cone of collision. While pilot A has thus gained escape time, he needs it again. These two corresponding parameters, for any set of conditions, result in there being not only a *maximum* decision time after which it is too late to escape, but also a *minimum* decision time, before which initiation of a maneuver will not reduce the probability of a collision.

The basic equation of Calvert's analysis is:

$$t^2 - \frac{Rt}{V} + \frac{2R\theta}{a} = 0; \qquad (5)$$

where: R = pick-up range in ft.
V = closing speed in ft./sec.
a = escape acceleration in ft./sec./sec.
θ = threshold detection angle in radians.
t = observation time, or decision time.

The roots of equation (1) are:

$$t = \frac{\frac{R}{V} \pm \sqrt{\frac{R^2}{V^2} - \frac{8R\theta}{a}}}{2}. \qquad (6)$$

The two values of t obtained from equation (6) are the minimum and maximum decision times after pick-up at range, R, (above a minimum range) within which the escape maneuver must be initiated to insure escape from the cone of collision within the available time. The minimum range for pick-up is

$$R_{min} = \frac{8V^2\theta}{a} \qquad (7)$$

Equation (7) is plotted in Figure 3 for values

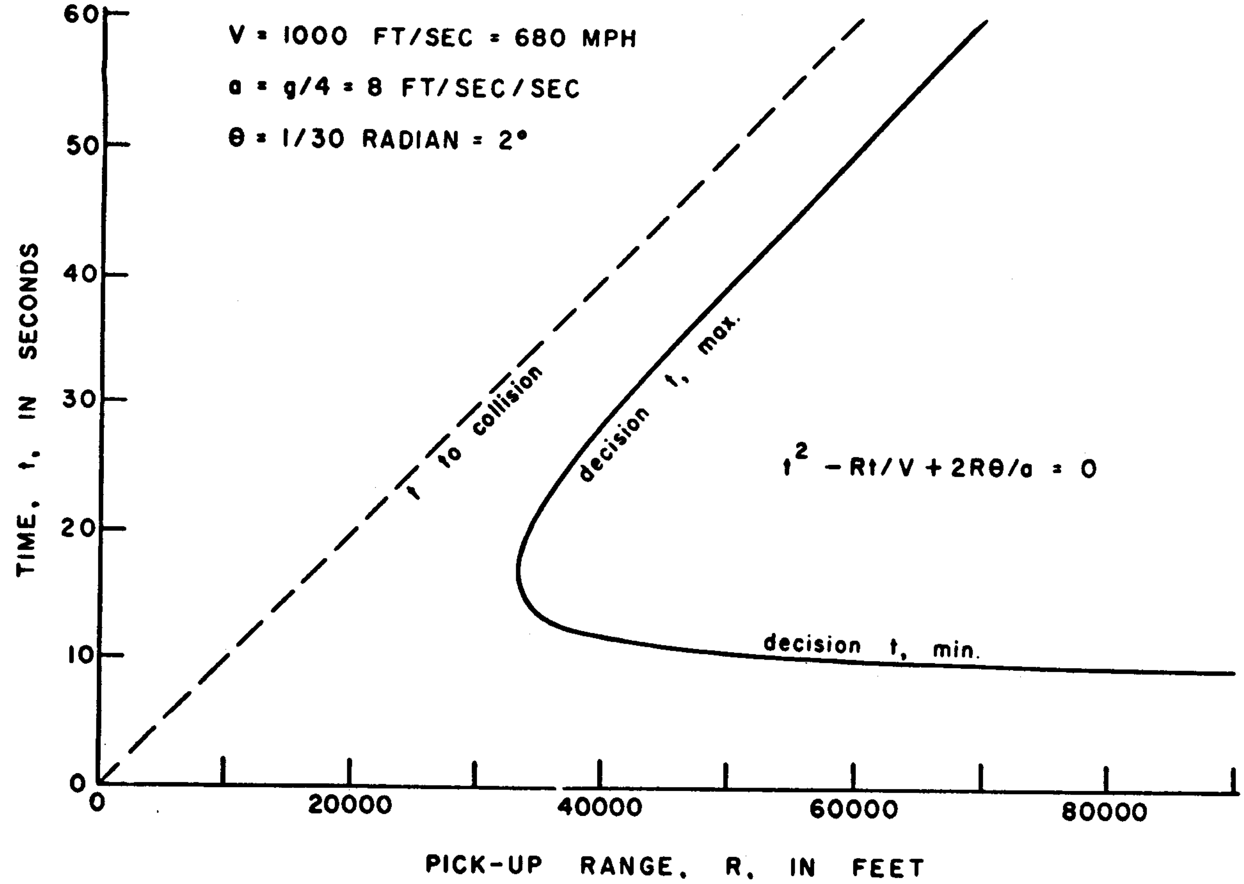

FIGURE 3. Decision time limits vs. pickup range.

of the parameters V, a, and θ given. The figure shows that if the pilot does not pick up the other aircraft at a range greater than R_{min}, he cannot escape the zone of danger in time and he cannot determine what maneuver will reduce the probability of collision.

Now, even if a pilot detects the intruder at a range larger than R_{min}, he is faced with a difficult problem because he does not have the information essential for its solution, namely closing speed and distance of the other aircraft, both of which determine his decision time limit. Figure 4 shows the relationship between closing speed and decision time. At low closing speeds, e.g., at 250 ft./sec. his problem is relatively easy to solve. If he picks up the other aircraft at 3 miles, observes it for at least 3 and up to 20 seconds, he will still have time to maneuver out of the "cone of collision." If, however, the closing speed is much higher, say, 1,250 ft./sec. (850 miles/hr.), his pick-up range would have to be at least 12 miles, and his task would be very difficult due to the uncertainties of the main parameters, namely range, closing speed, target motion, and escape mode. The interrelationship of these variables is depicted for certain values in Figure 5.

Figure 5 shows that a decrease of the threshold of detection angle or an increase in escape acceleration results in two important improvements of the situation: a reduction of the minimum required pick-up range and of the minimum decision time. In other words, the pilot's ability to take effective action to get out of the danger zone is greater, the more he is capable of detecting range rate changes smaller than those given by Calvert, and the higher g.-forces he is willing to accept. Calvert's values for the angle θ are by no means well established, and experiments are being planned accurately to determine the motion detection thresholds of pilots.

Considering the effects of assumed warning time shown in Figure 5, and by re-evaluating the human factors, one may accept a reaction time of 14.2 seconds without significantly affecting the light intensity requirement (See Table IV).

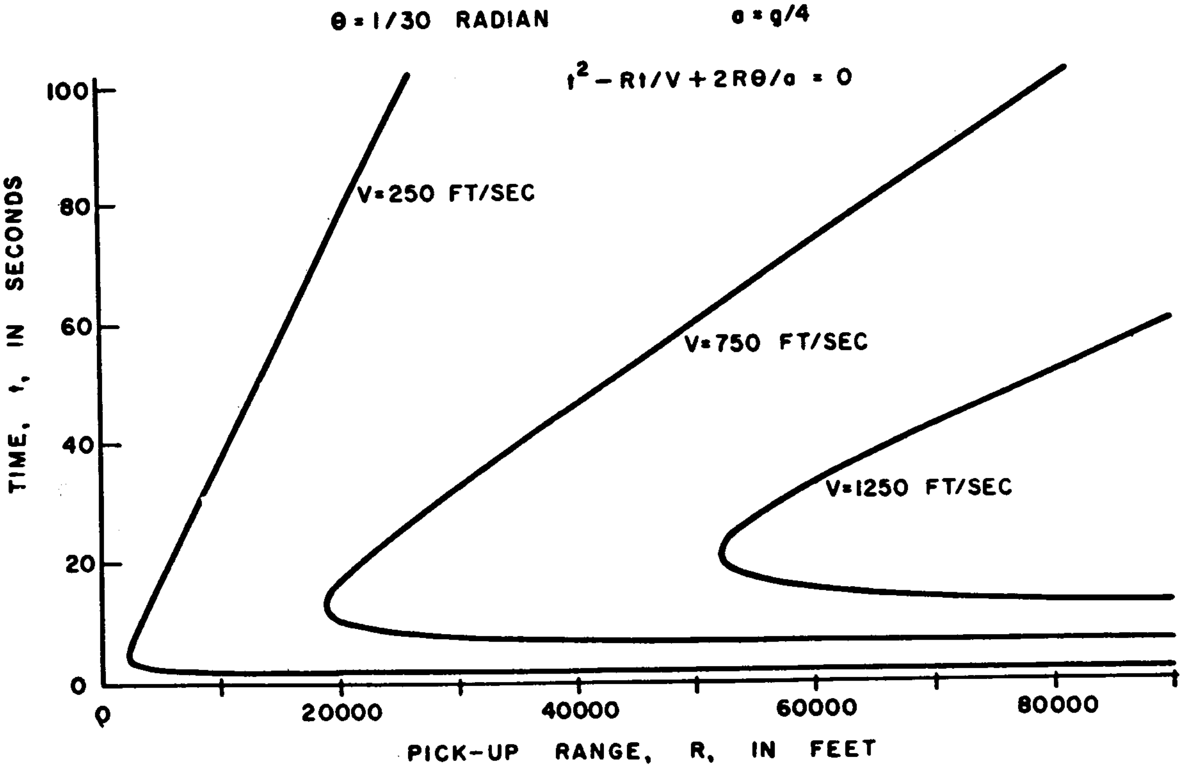

FIGURE 4. Decision time limits vs. pickup range: The effect of changing V (closing speed).

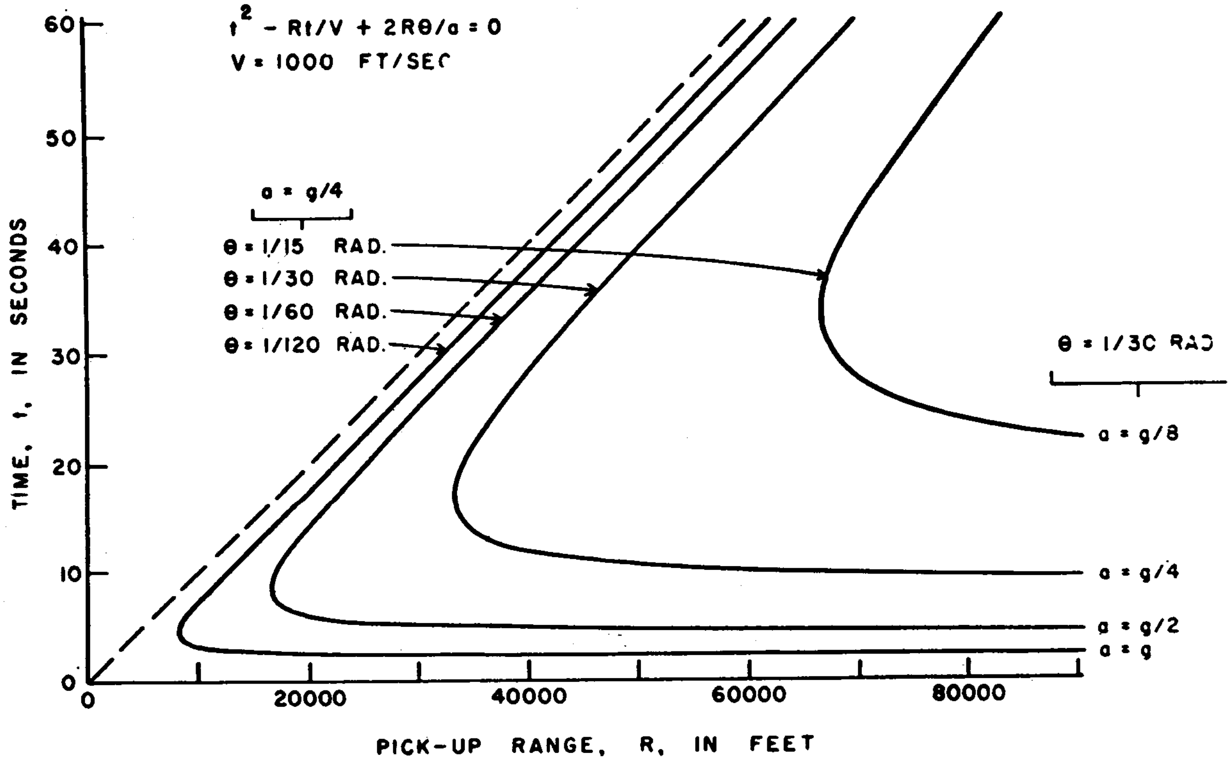

FIGURE 5. Decision time limits vs. pickup range: The effect of changing θ (threshold detection angle) or a (escape acceleration).

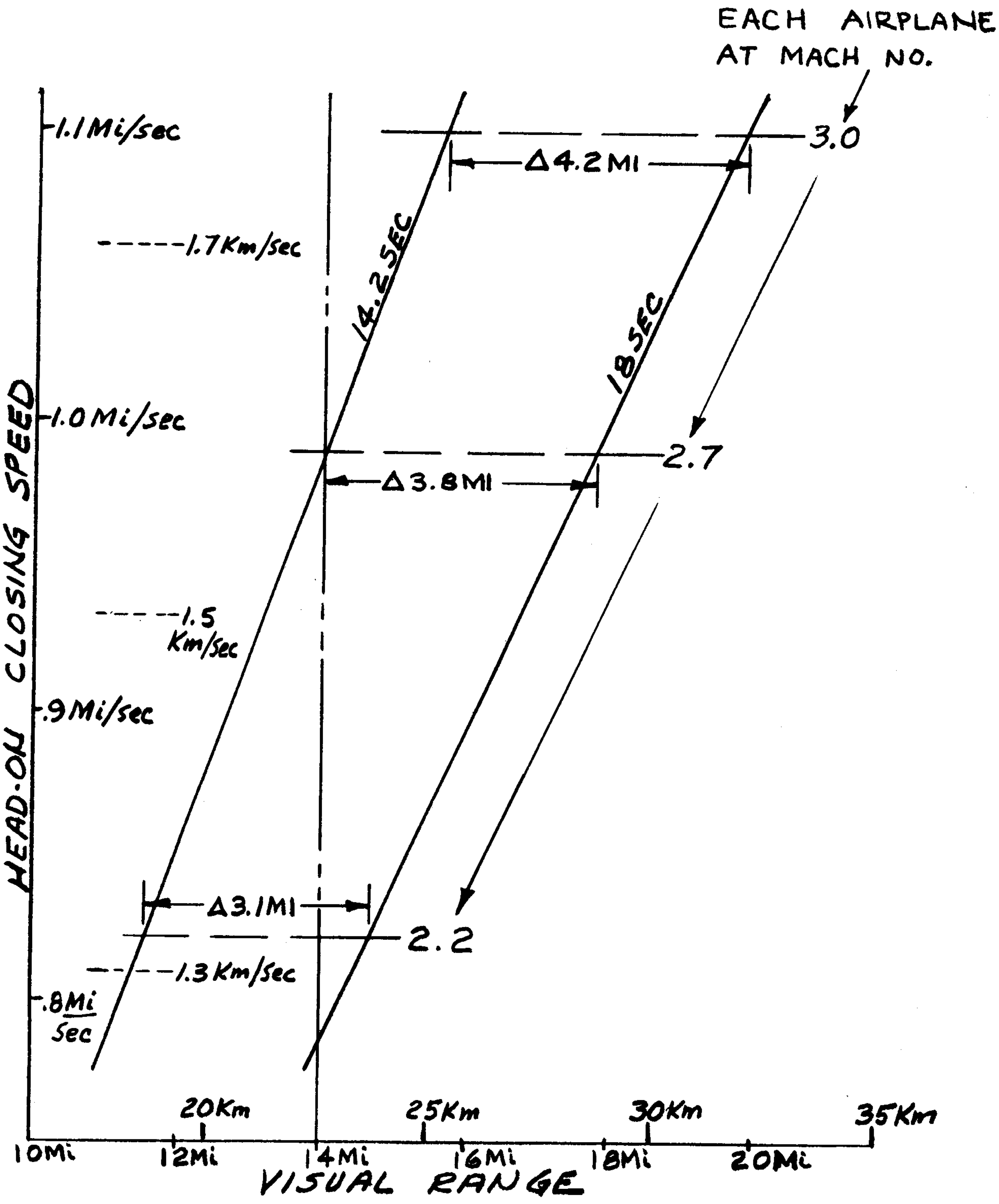

FIGURE 6. Effect of warning time on range vs. closing speed.

TABLE IV.—Reaction time for collision avoidance.

Pilot:		
Perception and recognition	1.0 sec.	
Decision — selection of course of action	4.5 sec.	
Physical response — movement of controls	0.5 sec.	
Total pilot reaction time		6.0 sec.
Aircraft:		
Control reaction		1.0 sec.
Maneuver — 500 ft. clearance		7.2 sec.
Total collision avoidance time		14.2 sec.

From the comparisons shown in Figures 6 and 7, it appears that one precise value of the required effective intensity is not readily determined. Transmissivity of the transparency used in the windscreen is a sensitive variable. The atmospheric transmissivity is particularly sensitive, as shown in Figure 8 which presents the effect of values other than 0.9 per mile for atmospheric transmissivity.

The calculation of intensity required for Figures 7 and 8 are based on the equation:

$$I_{reqd} = \frac{EoD^2}{Wt^D}; \qquad (8)$$

where:

$Eo = 0.5$ mile-candle visual threshold.
$t =$ Atmospheric transmissivity; for Figure 7, $t = 0.9$.
$D =$ Visual range in miles.
$W =$ Windshield transmissivity.

Figure 9 presents a correlation of range analysis by closing speed versus warning time and Calvert's values for threshold of detection angles.

V. DISCUSSION

A. Fixity Criterion

Before the implications of this subject will be discussed, several objections raised by Calvert and newer critics must be considered. The first one is the assumption that the motion of the observer aircraft significantly impairs the accuracy with which to detect the angular displacement or velocity of the other aircraft. It is true that head or aircraft movements indeed affect the apparent motion of an object within the visual field to a certain degree. However, if the warning light of another aircraft appears within a well-structured visual field, the increase in decision time caused by this uncertainty will be relatively small compared with the other factors which determine the action of the pilot.

The second objection concerns the phenomenon of high-altitude myopia, in which the environment of a featureless sky may cause the eye to focus at a very short distance. This phenomenon is unlikely to occur in SST operations because of the many features of the night sky such as stars, planets, moon and cloud strata, or of the earth (land masses, seas and oceans). Pilots and astronauts flying at SST cruising altitudes and in space did not report the disturbance of observations owing to empty-field myopia.

The third factor concerns the possibility of a pilot executing his maneuver too early for an effective evasion of the intruder. This possibility, which has been pointed out by Calvert and has led to the definition of "minimum decision time," exists in situations in which the closing speed is relatively slow. An evasive maneuver initiated too early may actually increase the probability of a collision instead of reducing it. In supersonic flight, this could occur during overtaking. In all other cases, the time available to the pilot will be so short that he will need the "maximum decision time" in order to make a correct decision. This situation has been called by Calvert "the technique of the bull fighter's jump"; and it is probably the most effective technique to get out of the "cone of danger."

According to Calvert's analysis of the pilot's dilemma in coping with a collision threat, its solution depends mainly on his ability to detect a change in bearing (θ) and on the acceleration (a) that can be applied to the aircraft. The pilot's ability to make an escape depends on $\frac{a}{\theta}$ The acceleration (a) depends upon the structural characteristics of the aircraft; whereas θ and k (the threshold velocity for detection) depend upon the characteristics of the human observer. Calvert does not consider, however, that with increasing flying speed the values for θ and k will change accordingly. And Calvert completely neglects another visual cue, namely, the increase in brightness of a light during its approach, which follows a square function. This may not be a very strong cue during low closing speeds, but it may become a powerful visual range rate indicator at supersonic speeds in addition to θ and k, the values of which should be smaller and larger, respectively, at increasing flight velocities.

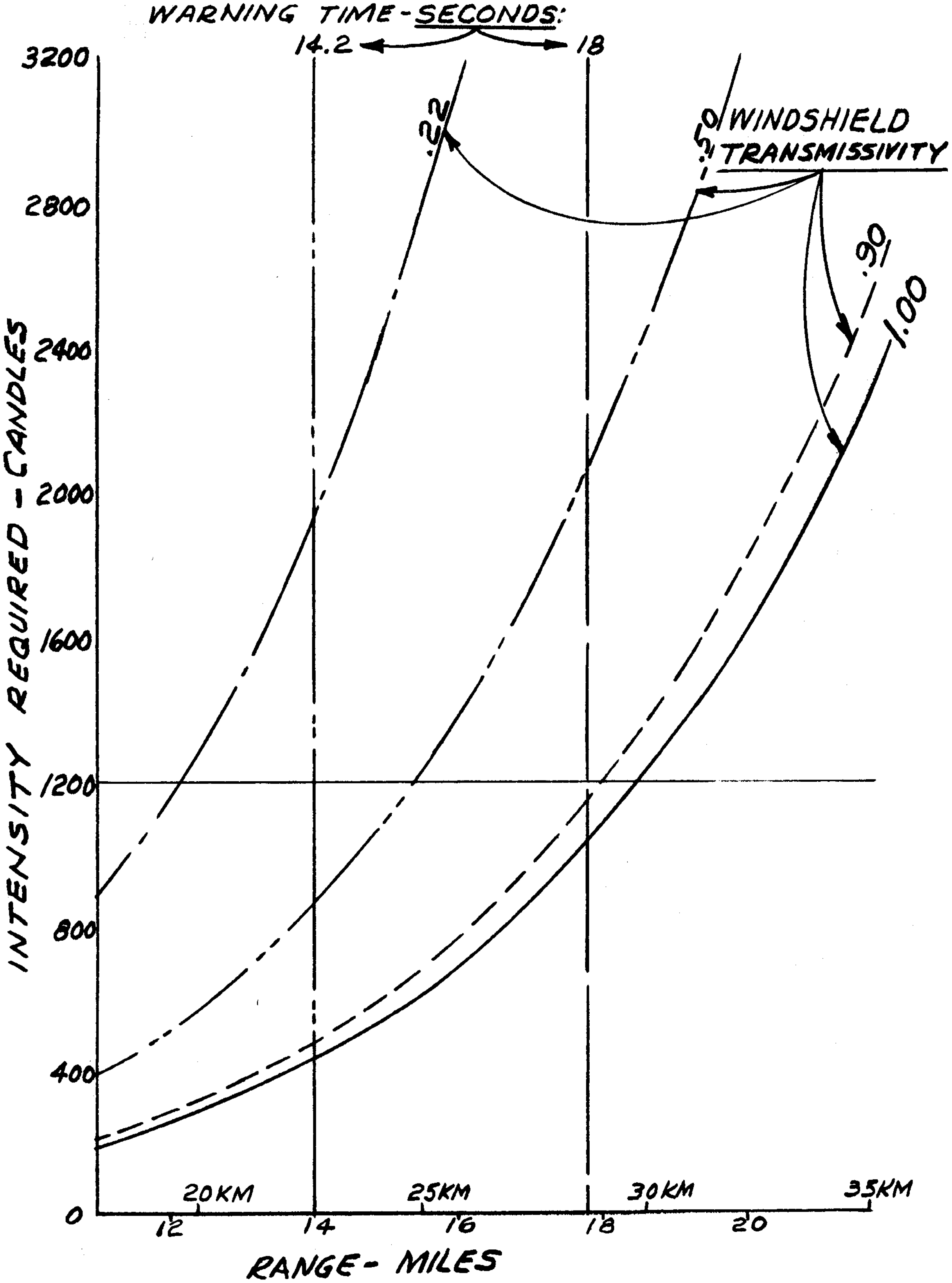

FIGURE 7. Light intensity—distance diagram of two airplanes on a head-on collision course at Mach 2.7.

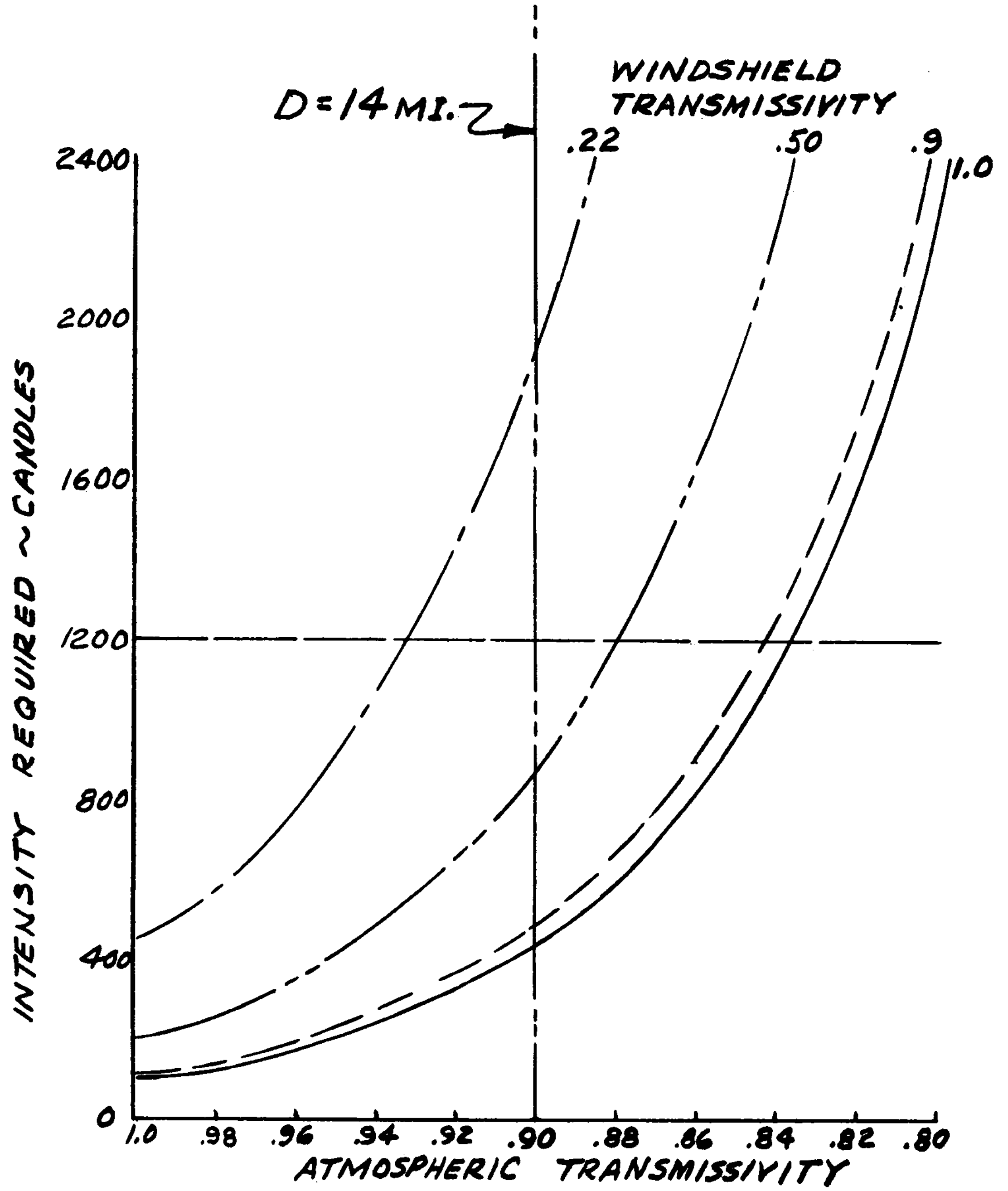

FIGURE 8. Light intensity—atmospheric transmissivity of diagram of three windshield transmissivities.

B. Pilot Opinion

While there seemed to be agreement by pilots and lighting engineers of several aircraft companies in this country about the need for anticollision lights during subsonic flight and the desirability of an increase in their effectiveness, the merit of anticollision lights at supersonic speeds has not been established experimentally. However, in a recent study the opinion of high-performance pilots and possible users of SSTs was assessed by means of a questionnaire which was constructed by scientists of the RAF Institute of Aviation Medicine, Farnborough and Hants.[4] It was sent to pilots who were already experienced in supersonic flight, both in France and in the United Kingdom. The answers, collected from 24 pilots in France and from 20 pilots in the United Kingdom, were similar. All

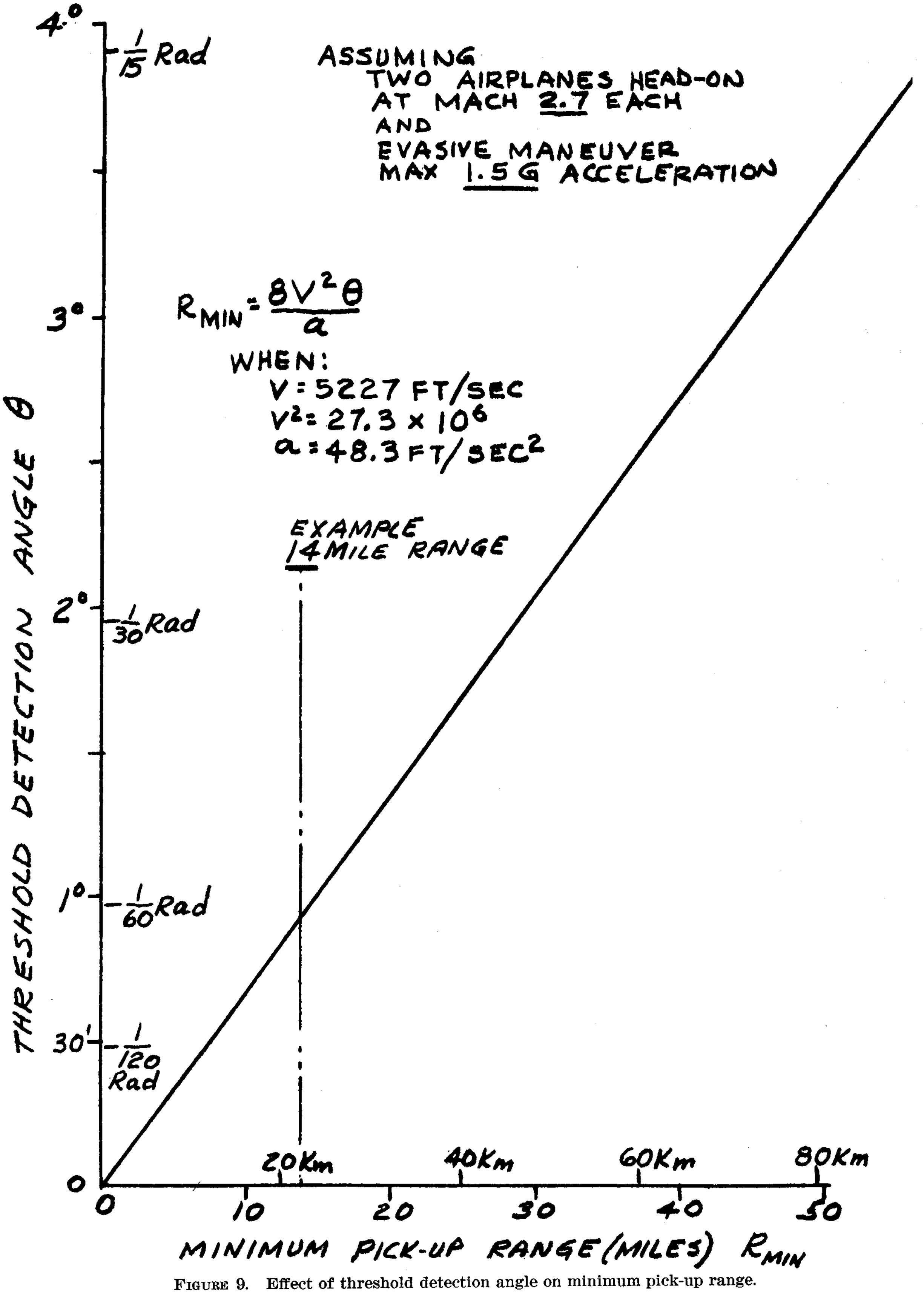

FIGURE 9. Effect of threshold detection angle on minimum pick-up range.

the pilots agreed that collision warning lights should be fitted to subsonic aircraft. In the United Kingdom, pilots agreed that such lights should be attached to supersonic aircraft as well; but among French pilots there were slight qualifications, 80% being in favor of lights on the SST as well as on subsonic aircraft.

*"In regard to the strength with which these opinions were held, the UK pilots were usually more strongly convinced than their French counter-parts. In explaining the reasons for these answers, the pilots considered, in general, that a flashing light at altitude could be perceived at a sufficiently great distance to be effective in giving sufficient warning. None the less, some thought that the time between perception and the response of the aircraft to the alteration of control surfaces might be too long.

*"The color preferred seems to be red in two out of three cases and many pilots believed that white was not a good color. The opinion of Mr. John Cochrane, Test Pilot of BAC, is particularly worth mentioning here since it differs from the others in that he feels that blue should at least be considered as a potential color. He comments that at night over towns it certainly is the color which particularly stands out.

*"This seems physiologically to be a useful suggestion, for, in the dark adapted state, blue appears relatively brighter than in the light adapted state, because of the Purkinje shift.** For this same reason, red in the dark adapted state seems less bright than in the nondark adapted state. Furthermore, on the basis of color contrast, it seems probable that blue may well have a considerable advantage since most natural and artificial light sources have general black body characteristics with a color temperature in the region of that of sunlight.

*"In the questionnaires, the flash frequency suggested was between 1 and 2 cps.

*"The optimal intensity should be the strongest compatible with maintenance of dark adaptation.

"The number of lights suggested was two (on wing tips) and one either ventral or dorsal."

C. Collision Analysis

Obviously, the value of our present lights would be limited to the overtaking case only. The argument is that at relatively low closing speed the pilot of an overtaking supersonic airplane has adequate time to assess the collision threat potential and to change his course. If this were accepted, the pilot of a high flying aircraft—whether subsonic or supersonic—would be unable to see an approaching SST so lighted, regardless of whether he is on a collision course or not.

Under favorable atmospheric, lighting, and viewing conditions, the 14.2-second warning period mentioned above may appear sufficient. Assuming a closing speed of 1 mile per second for the dead-ahead collision threat, all warning lights clearly visible at distances in excess of 15 miles theoretically could be considered sufficient. This is shown in Figures 10 and 11. In Figure 10, the ranges and bearings are given at which two 1,800 m.p.h. SSTs would appear 14.2 seconds before a possible collision; and in Figure 11 similar data are presented for an 1,800 m.p.h. SST and a 600 m.p.h. subsonic aircraft. However, while the range at which the aircraft must be seen decreases with increasing bearing, the advantage of shorter range needed, or more time available for action, is now offset by the unfavorable viewing angle. Thus, in Figure 10, an SST approaching on a bearing of 60° is beyond the collision zone at half the distance of an SST approaching head on, but the danger now consists in its displacement from the forward line of sight. Although better visibility is provided in the SST toward the sides than directly ahead, the pilot may not see the intruder because he is beyond his normal search limits. In Figure 11 it can be seen that the zone of greatest danger exists in a fairly narrow corridor about ±19°27′ directly ahead. A comparison of the last two figures reveals that the size and location of the collision zone is not only a function of the closing speeds of the two aircraft, but also that the danger of colliding with another aircraft cutting in from the side is increased as the velocity of the intruder approaches that of the other aircraft.

In 1963, Catalano and McKown[18] studied experimentally in an F-151 Gunnery Trainer the

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* The quotations are from reference No. 4.

** Purkinje's shift; if the spectrum is viewed in bright light (cone vision), the region of maximal brightness is in the yellow; when the illumination of the spectrum is reduced and the eye dark adapted (rod vision), the region of maximal brightness will be found to have shifted toward the blue end of the spectrum, the blues becoming brighter and the reds darker.

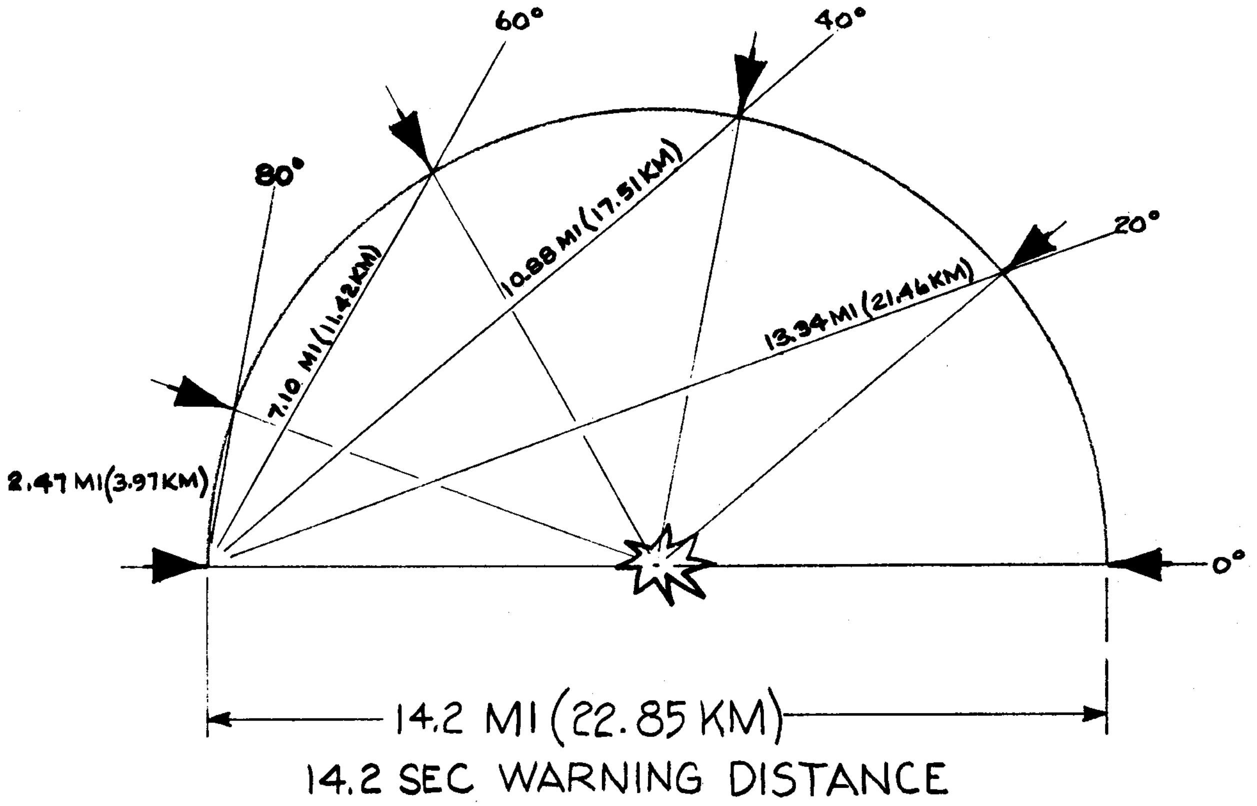

Figure 10. Range and bearing at which two 1,800 m.p.h. (2,896 km.p.h.) SST aircraft would appear 14.2 sec. before collision.

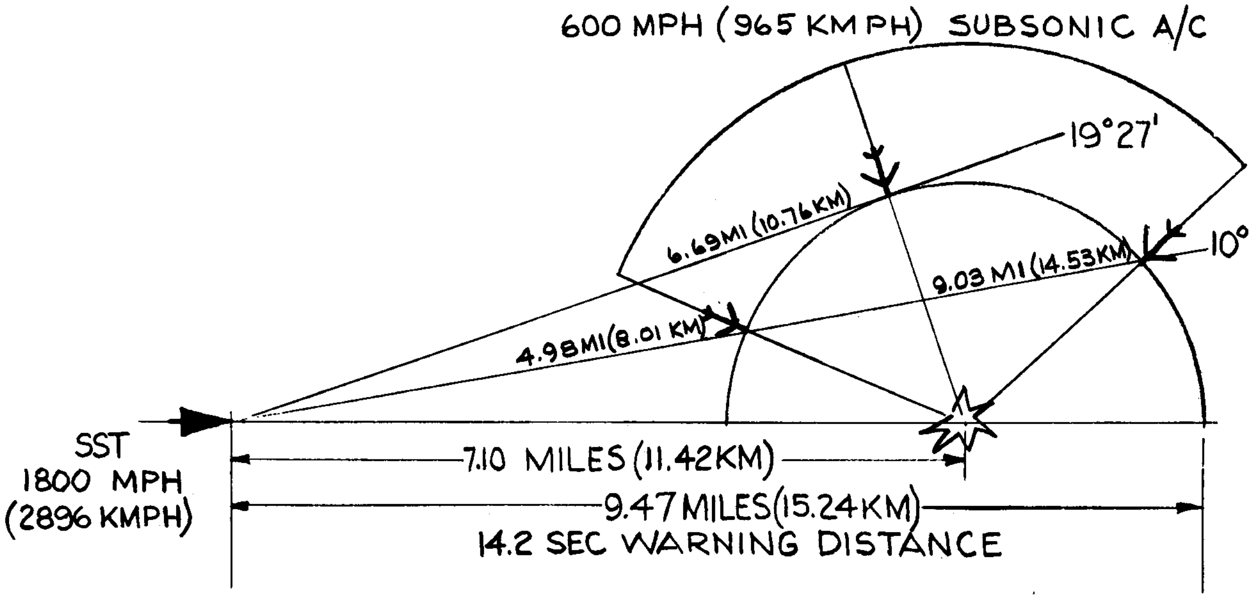

Figure 11. Range and bearing at which an 1,800 m.p.h. (2,896 km.p.h.) SST and a 600 m.p.h. (965 km.p.h. aircraft would appear 14.2 secs. before collision.

activity of a pilot who is confronted by an intruder, viz., detection of the intruder, evaluation of the collision threat, and the resulting avoidance maneuver. They found that when an intruder on a true collision course was detected, a maneuver resulted almost 100% of the time, and its effectiveness depended on such factors as closing rate and aircraft maneuvering capability. For closing rates up to 900 knots, evasive maneuvers reaching 3g.'s were effective when observation time was at least 20 seconds. For a given closing rate, increasing detection time or range increased the separation resulting from the maneuver. In a few cases involving intruders not on a collision course, an unnecessary maneuver might have initially placed the aircraft on a collision course. For the most part, however, unnecessary maneuvers were in the safe direction. Even at 1,800 knots, miss distances of 500 ft. were obtained in about 75% of the cases.

It may be of interest to compare the speeds associated with the sighting distances and approach angles shown in Figures 10 and 11 with those obtained at subsonic flight and used in simulated collision experiments so far. The closing speeds are shown in Table V. By assuming that Catalano's and McKown's results obtained under daylight conditions would equally apply to anticollision warning at night, evasive maneuvers would be effective in at least 75% of head-on approaches of two aircraft cruising at Mach 1.5. Moreover, protection would be provided by anticollision lights to two Concordes approaching each other at a speed of Mach 2.2 at a flight path angle of about 90°, to the two Mach 3 aircraft in Figure 3 up to 60°, and to the case in Figure 4 up to 70° from behind. Hence, these cases would be covered by the present Concorde standards if a far enough visual detection range can be attained.[19]

TABLE V.—Closing speeds obtained in Figs. 10 and 11.

Figure 10:

Sighting distance (miles)	Closing velocity		Collision angle
	Miles/sec.	Miles/hour	
2.47	.1736	625	20°
7.1	.5000	1,800	60°
10.88	.7660	2,758	100°
13.34	.9397	3,383	140°
14.2	1.0000	3,600	180°

Figure 11:

Sighting distance (miles)	Closing velocity		Collision angle
	Miles/sec.	Miles/hour	
4.98	.3507	1,263	23°
6.69	.4711	1,696	71°
9.03	.6359	2,289	138°
9.47	.6667	2,400	180°

Finally, Figure 12 shows the minimum pickup range as a function of acceleration (a) for two values of the threshold detection angle θ. This graph represents the worst case, namely, two 1,800 m.p.h. SSTs on a head-on collision course. It can be seen that if a collision is to be avoided without exceeding an escape acceleration of 1g., the other aircraft must be detected at a range greater than 44 miles (70.8 km.) if $\theta = \frac{1}{30}$ radian, and 22 miles (35.4 km.) if θ can be reduced to one-half of this value. At 44 miles, however, a light on an approaching aircraft may not present sufficient data on which to base a decision regarding evasive action. The "threshold detection angle" used in the paper is the physiological limitation of the human eye, assumed as an average of 1/30 of a radian (1°54′35″). Projected to 44 statute miles visual range, this would amount to approximately 7,750 ft. This means that a point of light may be anywhere within ±3,873 ft. of where it appears to be.

D. Visual Illusions

If there were no refraction in the atmosphere, a point at a distance of 44 statute miles at 60,000 ft. altitude would be 2,535 ft. below the horizon of the viewer, due to curvature of the earth and its envelope of air. At a visual range of 15 statute miles, again assuming 60,000 ft. altitude, the earth curvature effect becomes 860 ft. and the altitude range of uncertainty, within the threshold detection angle, becomes 2,634 ft. This is substantially more than the earth curvature effect. Thus, the curvature of the earth itself does not produce an illusory effect in regard to altitude estimates of high flying aircraft.

However, a pilot may be deceived by the so-called "rising airplane illusion." The major factor of this visual illusion which occurs predominantly within the atmosphere is refraction due to changes in air density along the line of sight. This is extremely variable and depends upon meteorological changes but will be relatively rare at the cruising altitude of the SST.[20]

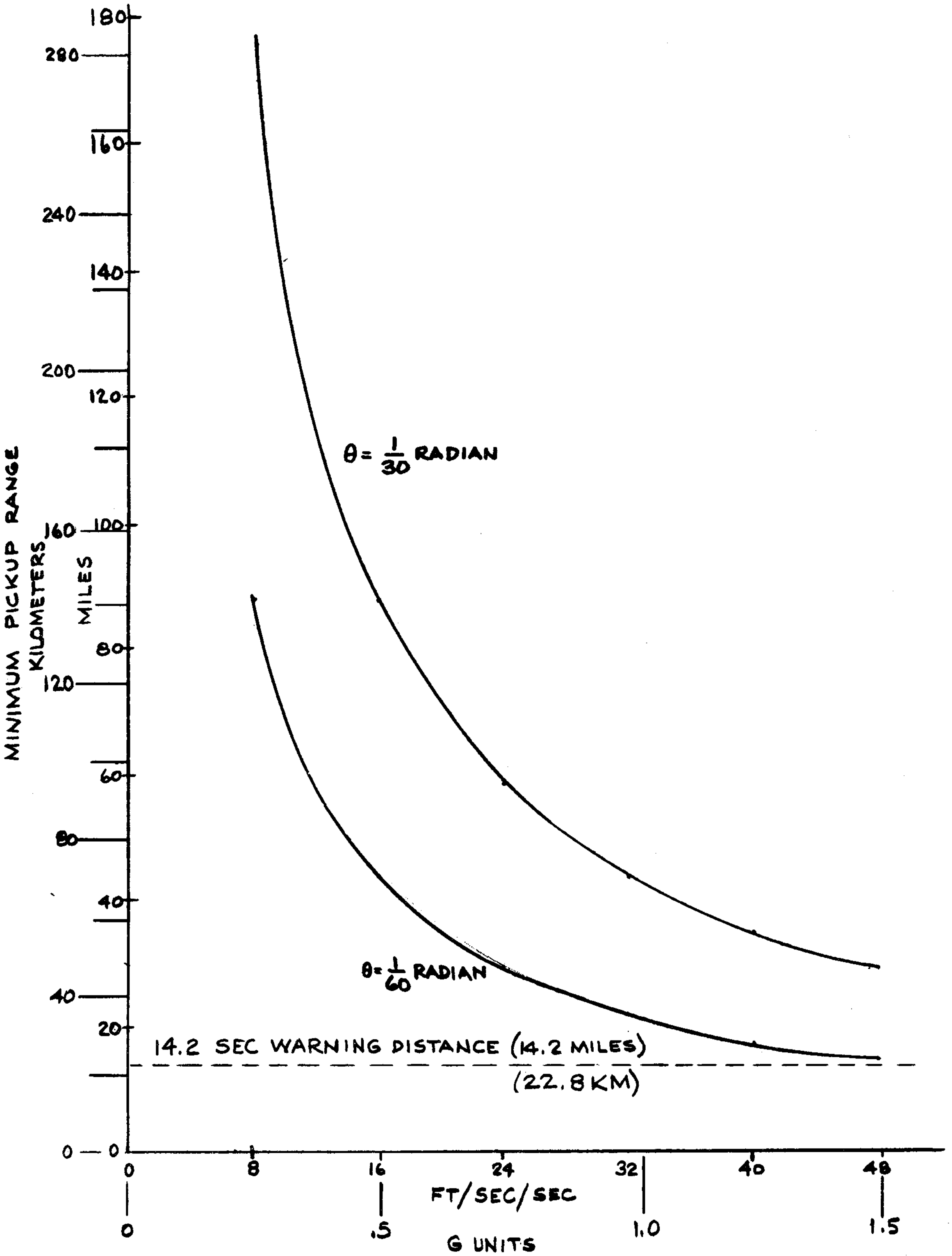

FIGURE 12. Minimum pickup range, (R_m) vs. escape acceleration, (a).

E. Color

As to the origin of color coding of signal lights, F. C. Breckenridge of the U.S. National Bureau of Standards offers the following information:

> "While the limits for the red and green signals used in marine and railroad practice were selected before the researches mentioned in the last section (of NBS Monograph 76 1967) were carried out, their selection was not casual. The earlier limits used for railroad signal colors were not satisfactory and at its second meeting the newly organized Railway Signal Club appointed a committee in April 1895 (ARR, p. 74, 1953) to investigate the question of colors for night signaling. At first the problem was which color should mean clear, go ahead, and which danger, stop. At that time the usual colors for railroad signals were white for safety, red for danger, and green for caution. This was the practice in most countries in accordance with an agreement reached at a congress of railroad men in Birmingham, England, in 1841. The system had been developed in France and it is interesting to note that the originators had reached the conclusion in the course of their experimenting that 'the visibility of red light was but one-third of that of a white light of the same intensity; that of a green light one-fifth; and that of a blue light one-seventh' (AAR, p. 73, 1953)."[21]

This statement leads to the conclusion that the red color of anticollision lights in aviation was selected more for conventional reasons than because of its visual virtue. Since the attention getting quality of a flashing light also relates to danger, a flashing white anticollision light appears visually more effective as an attention getter at longer ranges than a flashing red light of equal candlepower.

With regard to color preference for anticollision lights, the majority of pilots questioned by Drs. Whiteside and Perdriel favored red. This has the advantage of being a traditional warning color; and it also causes less loss of dark adaptation than does white light of equal intensity. Whiteside and Perdriel then discuss the matter as follows:

> "Against the use of this color, however, there are technical and physiological arguments. The technical problems put forward by engineers are that it is difficult to produce a sufficiently powerful light in this wave length, and also that the filters being used at present, tend to darken with heat, so that the luminance decreases.
>
> "The physiological arguments are associated with the difficulty in detecting red lights in darkness at long range since, even for sources of equal physical intensity, the luminance of red is less than, for example, yellow. This is because of the position of these two wave bands on the eye sensitivity curve.
>
> "Against the use of white light there is the adverse pilot opinion and, if night vision is important, the disadvantage of loss of dark adaptation. Without the advantage of color to identify it, a white anticollision light will inevitably depend more upon its flashing characteristics to differentiate it from another light source in the sky, such as a star.
>
> "The suggestion made by Mr. Cochrane in regard to blue light must be considered by physiologists, for in the dark adapted state, compared with an equal physical intensity of red, it will appear brighter as a result of the Purkinje shift. The Purkinje shift is a shift of the curve of eye sensitivity to various wave lengths of light. The shift is towards the blue in the dark adapted eye.
>
> "Taking into account the arguments for and against the different colors, it seems that, especially with regard to distance sources, the color is less important, and that instead one should concentrate on obtaining as high an intensity as possible. If, as a result, the color temperature is increased considerably, this may have the advantage of providing color contrast with other light sources.
>
> "Inevitably, steps must be taken to reduce back scatter to the eyes of the pilot in the emitting aircraft. This might be effected by employing a lower intensity for use at lower altitude and nonsupersonic flight, for at the high altitudes at which supersonic flight will take place, back scatter will probably be minimal." *

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* The quotations are from reference No. 4.

F. Concorde Anticollision Lights

The current British and French anticollision lighting regulations, which for supersonic flight call for a flashing red light showing as far as is practicable in a sector 180° to the rear of the aircraft within 30° above and below the horizontal, are not considered as an ideal solution. They have, however, stated quite clearly in "Tentative Airworthiness Standards" (29 December 1967) their intention to re-examine these regulations for Supersonic Aircraft.

The retractable anticollision beacons mounted in the fuselage and currently in use on the prototype aircraft, besides being an undesirable cabin installation feature, have all the drag problems associated with a unit protruding above the outside skin line of the aircraft. In fact even the very low contour anticollision beacons which have been investigated, introduce inordinately large drag penalties, and also produce an undesirable level of aerodynamic noise. Thus, it is seen that the retractable type of anticollision beacon has not the desired development potential to meet the predicted regulations for supersonic flight. This statement is also based on the head-on closing speed attained by two current subsonic jets represents, in the view of the French and British authorities, the limiting point at which the concept of collision avoidance by referance to lights can be applied, having regard to the range of lights now in use. The closing speeds of two SSTs are much in excess of their subsonic counterparts, thus merely for an SST pilot to have the same warning time available, the effective range of the anticollision lights must be increased by an approximate factor of 3. The technical problems involved are, not only the obvious one of range itself, but also of heat transference and drag problems from a unit mounted in full airflow at supersonic speeds.

As a result of informal discussions with various operators and the U.S. aircraft industry, it became obvious that future anticollision lights should be faired into the aircraft structure in the appropriate positions to provide all round coverage, with minimum drag penalty. Thus the currently proposed flash tube system for the preproduction aircraft, with its flush-mounted light units in the wing roots and the tail cone, is considered to possess the required development flexibility, to meet all known and most predicted changes to the anticollision lighting regulations.

The system consists of three Xenon flash tubes mounted in a parabolic reflector; these assemblies are located one in each wing root, and one in the tail cone. The tail cone unit also includes a steady white light for navigation purposes. In addition, there are a master-timer unit and three power units, one for each tube, which are located in the pressurized area of the fuselage.

The effective intensity of the anticollision lights will be 300 candles (1500 candles (theoretically) without filters), flashing at a rate of 60 flashes per minute at nominal voltage with coverage to meet the requirements of the Concorde TSS Standard No. 48; the color emitted by the lights being aviation red. A picture of the proposed system is given in Figure 13.

VI. CONCLUSIONS

From this survey it should be clear that there is enough justification for equipping the SST with anticollision lights. First of all it must be recognized that the SST will fly subsonically part of the time. Secondly, there is no magic thresholds at Mach 1, but that operationally and visually closing speeds from a few knots to more than a thousand are encountered in present-day flying. Pilots have adapted very well to this sliding speed range, although there is little evidence how this applies to visual collision avoidance. For this reason, the FAA is engaged—in cooperation with the British and French authorities—in a research program, which includes the use of anticollision lights during the supersonic phase. If the results of these experiments show that anticollision lights during supersonic flight will contribute to flying safety, the most effective light signals should be used. Among the various factors, which bear on the ability of an observer to determine whether or not he is on a collision course, the maximum detection range is of major importance. As was shown in Figure 1, the range of visibility increases steeply at conditions of high atmospheric transmissivity. This means that anticollision lights will be seen much further at the cruising altitude of the SST than at that of the subsonic aircraft. The intensity of the light, plotted in Figure 1, is relatively low compared with the condenser discharge lights already used on many jet aircraft. When this ranging scale is extended to higher intensities, anticollision lights will become visible at ranges of 60 or more miles.

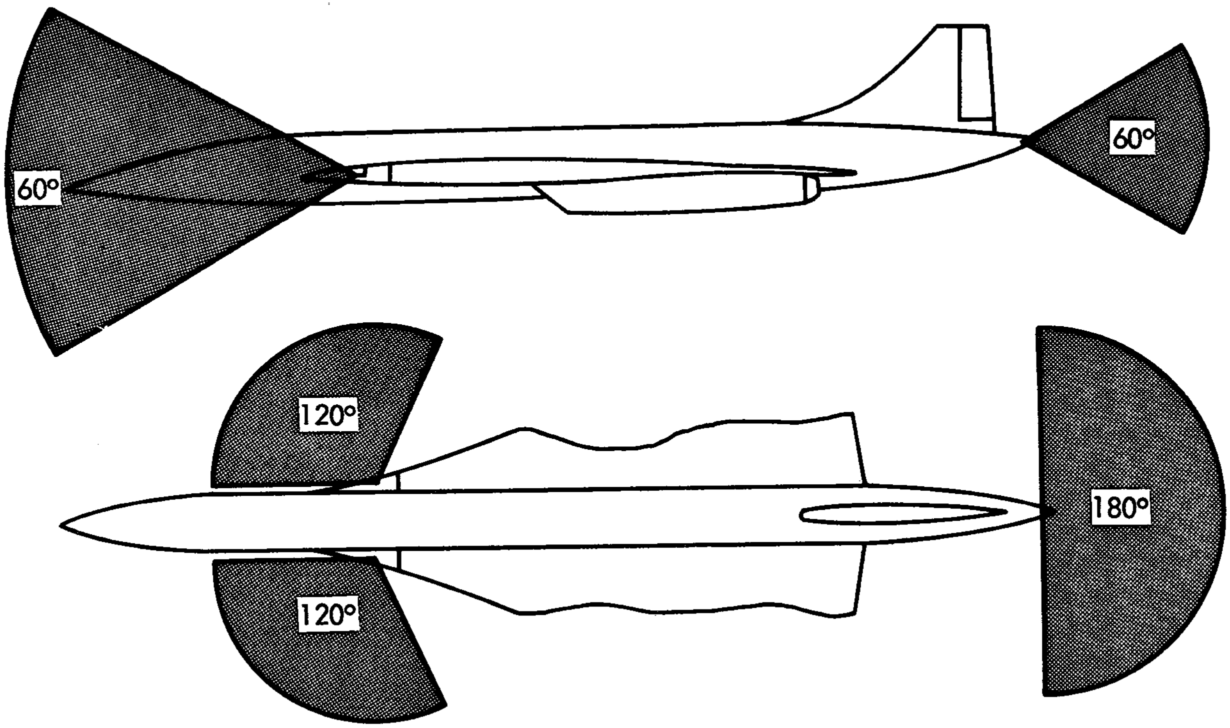

FIGURE 13. Concorde anticollision flashtube system—position of flight units showing degree of coverage.

In any case, it seems that visual collision avoidance during day and night flying conditions can be more effective and that the anticollision lights can furnish supplemental clues to the VFR pilot. Visual detection will be significantly improved and safety enhanced by waiving the red color requirement for the anticollision light to obtain maximum advantage of the total available light output.[22]

DEFINITIONS

Autokinetic illusion is a psychophysiological phenomenon involving the apparent movement of an actually stationary object, or a light, in a uniform field with no frame of reference.

Centripetal nerve fiber is a neural cell chain leading toward the central nervous system.

Foveal perception is vision in which the image is focused upon the most sensitive portion of the retina, hence the most acute vision.

Motor impulse is an outbound neural signal from the central nervous system toward a peripheral muscle.

Neuron is an individual nerve cell.

Perceptual latency is the time delay caused by psychophysiological and neural processes in the observer.

Peripheral organ is a sense organ located at the periphery of the body.

Purkinje's shift is the shift of the eye sensitivity curve toward the blue end of the spectrum in the dark adapted eye.

Scotoma is a deficiency in the visual field such as a blind spot.

Synapse is a point of contact between adjacent neurons across which nerve impulses are transmitted as low voltage current.

Visual cortex is that portion of the brain outer layer which has been adapted to processing and storing sight images.

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