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LETTER REPORT NO. 64

HUMAN FACTORS IN ANTICOLLISION LIGHTING FOR VTOL AND V/STOL AIRCRAFT

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Avia on Branch
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HUMAN FACTORS IN ANTICOLLISION LIGHTING FOR VTOL AND V/STOL AIRCRAFT

INTRODUCTION

New and higher intensity anticollision lighting systems are presently in development for use on helicopters. These new systems are being recommended for day and for night flight. The VTOL and V/STOL flight regimes are sufficiently different from those of fixed wing aircraft to magnify certain aspects of the collision avoidance problem. For example, high rates of climb and the capability for lateral translation may require increased visibility vertically and laterally. In addition, the contrasts and intensities required for light visibility against high luminance day-lighted surfaces are very different from those required for night flight conditions. These considerations have initiated a review and re-examination of anticollision lighting requirements.

Anticollision lighting is only one of several ways to make an aircraft conspicuous, and therefore, more visible against a background. The daytime visibility problem is illustrated by the fact that some helicopters provide rather ambiguous form characteristics against a ground. For example, an observer can see through and around an OH-23 or TH-55A, and the aircraft can become lost like an embedded figure. Against daytime backgrounds of moderate luminances or nighttime skies with little clutter (or visual noise) anticollision lighting has been demonstrated to be effective. Against high brightness skies, the addition of one or more point light sources may be ineffectual and other devices may be required to give an aircraft conspicuity. Multi-directional mirror surfaces, diffraction gratings, or moiré patterns, in addition to high reflecting white and phosphorescent colored surfaces against contrasting dark surfaces may be worthy of consideration.

This preliminary review will consider only anticollision lighting, with discussion of flash frequency, color, effective intensity, and directional distribution or beam shape, as related to velocity vectors and atmospheric

transmissivity. Navigation lights other than anticollision lights and coding of light signals will not be discussed here. This review is intended to reopen and re-examine anticollision lighting standards and criteria for selection, but is not intended to provide a statement of requirements or specifications.

FREQUENCIES AND WARNING TIMES

At contrast levels below 6 (600%) and at relatively low levels of retinal illumination, a flashing signal is more conspicuous (detectable, attention-getting, and yielding brief response times) than a continuous or constant light source. (2, 3, 4) Response times are slowed at frequencies below one per second (presumably) by failures to detect or confirm until at least two flashes have occurred. However, as Gerathewohl has indicated, no practical difference in conspicuity exists within the range from one to four flashes per second, except at very low contrast levels (below 100%) where faster flashing signals show a trend toward greater conspicuity. Gerathewohl has recommended a flash frequency of three per second with a minimum of 200% contrast. (3)

Flash frequency of anticollision lighting is limited at lower values by the time required for "reading", that is the time needed to detect or recognize the signal, locate it in azimuth and elevation, apply fixity of bearing or other criteria for judgment as to the probability of a collision course, and make a decision on collision avoidance. Thresholds for the perception of movement of a flickering light signal are not well defined. It is probable that detection of movement of a flashing signal by a pilot on a vibrating platform requires rates and times far in excess of the one minute of angle per second laboratory threshold reported. (11) Decision times in judgments of fixity-of-bearing are not well known. Analysts have used a concept called "warning time" to subsume the operations described above as "reading" the signal and to include in addition the time required for the actual evasion maneuver in the aircraft. (17, p.4) Warning times used have varied from 10 seconds to 60 seconds or more depending upon the method of analysis and the maneuverability of the aircraft concerned. With reference to VTOL and V/STOL aircraft, it can be assumed that an evasion maneuver can be completed in ten seconds provided the decision based on the "reading" has been made. The reading can be completed within 5 to 10 seconds, given frequencies of one per second or more, according to current estimates. Therefore, the total estimate of warning time in the VTOL and V/STOL regime ranges from 15 to 20 seconds.

The upper values of flash frequency are limited by the phenomena of flicker fusion and photic driving. Point sources of light have relatively low fusion frequencies and these fusion rates are reduced still more at low levels of retinal illumination (as for a light at a considerable distance). (1) Flashing red lights (below 10 trolands retinal illuminance) fuse at lower frequencies than lights of shorter wave lengths, the critical frequency falling below 10 cycles per second for levels of illuminance below 1 troland. (5) Photic driving may occur at higher intensities at frequencies of 8 to 14 cps.

Federal Air Regulations call for effective flash frequencies not less than 40 nor more than 100 cycles per minute with overlap flash frequencies not in excess of 180 cycles per minute. Military specifications call for flash rates between 80 and 100 cycles per minute (12). Rotating beacons as used in pairs on helicopters are not ordinarily synchronized so that overlap frequencies up to 200 cycles per minute are possible.

The low frequencies required by military specifications are in a range appropriate for accurate recognition and for reading within five seconds. The lower limit of the Federal Air Regulation requirement appears excessively low, however, slowing reading and response time unnecessarily. Therefore, it is recommended that both day and night anticollision lighting systems be required to maintain frequencies of 90 ± 9 cycles per minute. (14)

VELOCITIES, WARNING TIMES, AND DISTANCES

A number of recent helicopter collisions have involved rear approaches and relatively low closing speeds of approximately 30 to 50 knots in clear daylight conditions. For this reason relatively high intensity anticollision lights have been considered for day use. It is doubtful whether anticollision lighting will appreciably reduce the incidence of such accidents in crowded traffic patterns and instrument training areas. But where anticollision lighting is used in future aircraft, it is assumed in this discussion that the intensities and warning times in each application must be based on the worst possible cases (head-on or vertical collisions) and maximum horizontal or vertical velocities rather than on low closing velocities in a small empirical sample. Fig. 1 relates maximum velocities in knots to head-on closing velocities and distances traveled, in feet, given warning times of 10, 20, and 30 seconds, respectively.

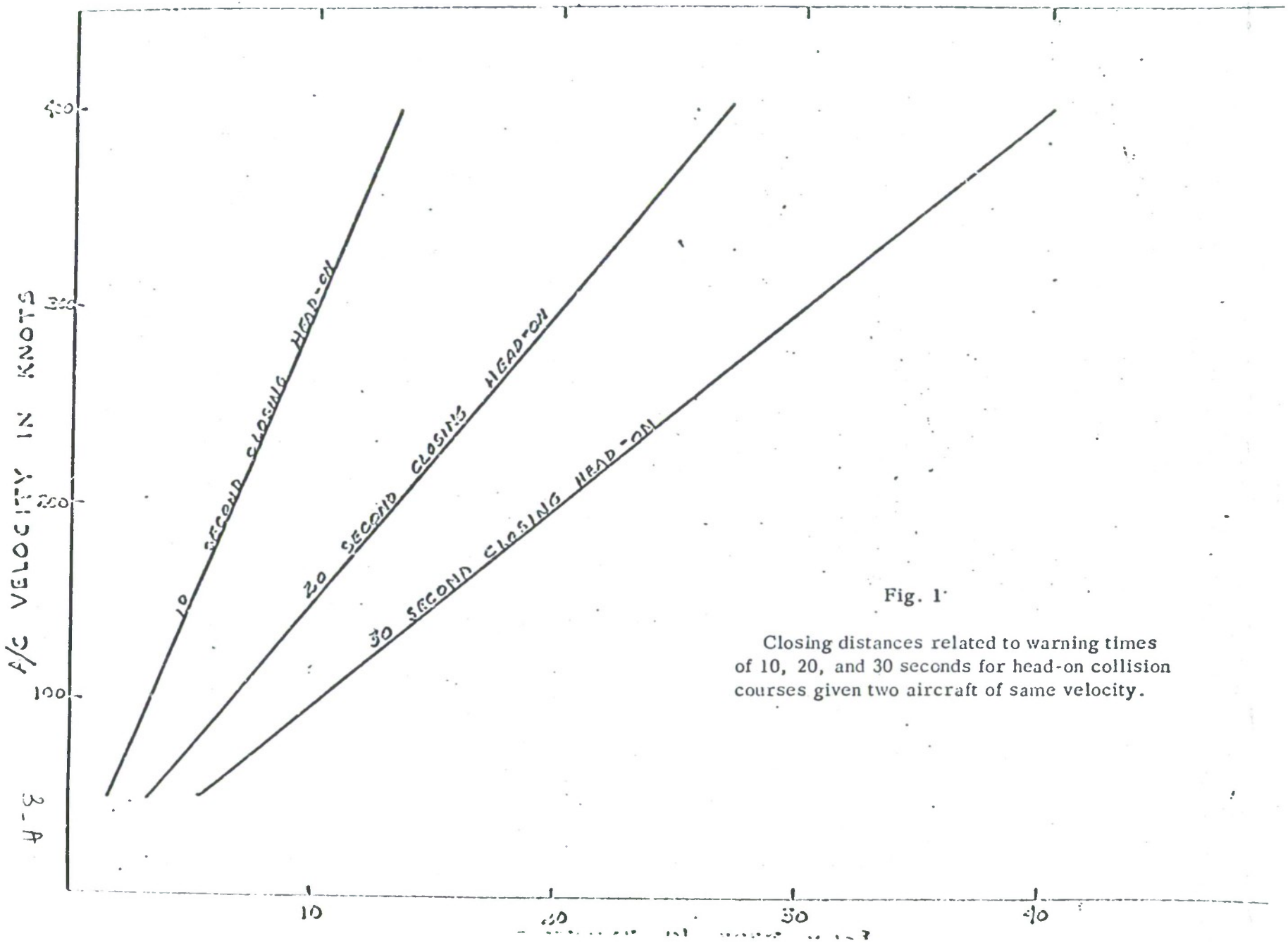

Fig. 1

Closing distances related to warning times of 10, 20, and 30 seconds for head-on collision courses given two aircraft of same velocity.

If we can accept a 20-second warning time as sufficient, then the TH-55A requires only 5400 feet visibility, whereas the TH-13T and the OH-23 require 6080 feet and the Cobra, AH-1G, requires 12,840 feet. In each case the aircraft must be fitted with an anticollision light which makes it visible to the pilot of another aircraft at distances proportional to its own maximum vertical and horizontal velocities.

DISTANCES, VISIBILITIES, AND INTENSITIES

Daytime Conditions

The luminance of a day sky varies through a range of 10^7 or more times its lower values. Even the earth's surface on a clear day with a new snow cover can approach 8000 fL. (15, p.64) as can the upper surface of a cloud cover in bright sunlight or the region of the sky near the sun. Under conditions of clear sky of high brightness Hopkinson found more than 90% of the sky at brightnesses less than 5000 fL., whereas under cloud cover 80-90% of the sky fell below 1000 fL. in brightness. (7) It is estimated here that 95-99% of observations in day flight will be made against background luminances less than 5000 fL. However, this limit excludes an area within 20-30 degrees azimuth or elevation from the sun on a clear day, within which background luminances higher than 5000 fL. will be found.

To be visible against such a background at distances of a mile or more requires very high intensity lighting, not only because of the spherical distribution from a point source as calculated by the inverse square of the distance rule, but also because of the atmosphere and its contents which act as a filter of varying transmissivity. Table 1 from the International Visibility Code relates transmission per mile to the daylight visual range under various atmospheric conditions.

Visibility requires more than threshold intensity since the concept includes not merely 50% positive response under laboratory conditions, but also detection within the field of vision, usually recorded at 95-99% probability level. Allard's Law relates transmissivity of the atmosphere (t), illumination at the observer's eye (E), distance (D), and intensity of the source (I).

TABLE 1

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	.044 to .21

(17, p.42)

(1) $$E = \frac{I}{D^2} \cdot t^D$$

(2) $$I = \frac{ED^2}{t^D}$$

However, application of Allard's Law requires the specification of a standard E, which is determined by the luminance of the background and the probability of detection desired. One rule of thumb suggests that for daylight visibility 1000 times the intensity for night visibility will be acceptable. (16) This extrapolation from Projector's calculations would yield 500 mile candles (e.g., 500 candles as viewed at one mile through an ideal atmosphere) as a standard E. Knoll's data on 100% visual thresholds under laboratory conditions yield approximately 250 mi. candles as a standard of visibility against a 1000 fL. field..(10) Application of Allard's Law to Howell's data yields a more modest 25 mi. candles. (9) But Howell suggested that sighting distances under operational conditions are 3 times shorter than under experimental conditions where the subject knows where to look and is not distracted by many other duties. While this may appear to be a small numerical change, its application to the calculation above raises E to 920 mi. candles.

Comparison of these calculations with Fig. 2, Middleton's nomogram (13) which incorporates transmissivity of the atmosphere and 95% probability of detection yields consistent results; i.e., an E of approximately 500 candles.

If we can accept an E of 500 candles as a visibility standard for day contrast conditions, we are in a position to apply Allard's Law to various closing speeds (2 times maximum velocity) and warning times. Table 2 illustrates such a calculation, providing effective intensities required for 10, 20, and 30 second warning times for aircraft with maximum speed of approximately 90 knots such as the TH-13T and OH-23 and aircraft with maximum speed approaching 200 knots such as the AH-1G.

Using the 20 second warning time as a standard, a minimum of 4100 candles is recommended for daytime use with aircraft of maximum velocity of 90 knots. The 4100 candles will have very sharply curtailed value on a higher performance aircraft such as the AH-1G which must be equipped with at least 4 times as much candlepower for effective warning even under clear meteorological conditions.

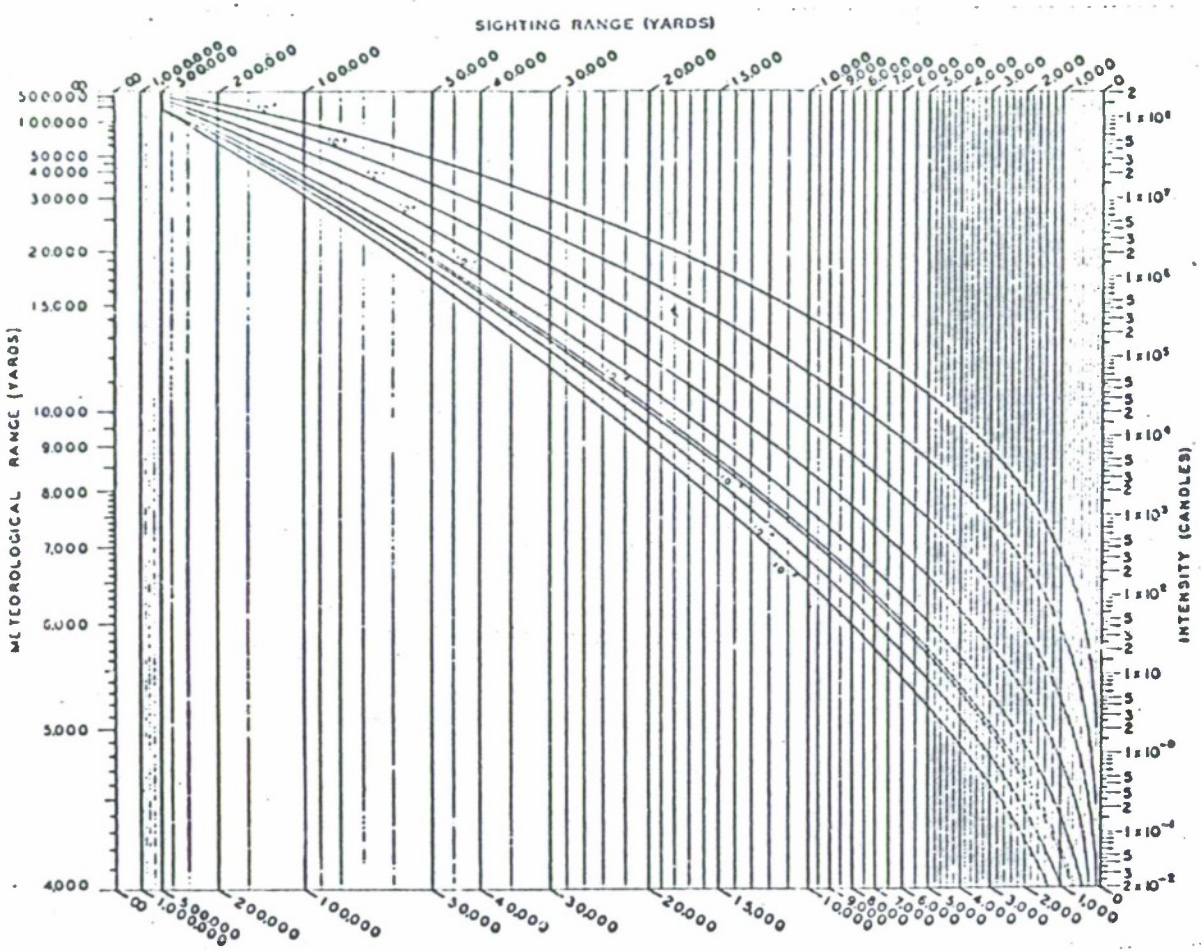

Fig. 2

Middleton's nomogram for estimation of sighting range from relationship between background luminances from 10^{-5} to 10^{3} foot Lamberts, intensity of light source in candles, and visibility range. Place straight edge across nomogram intersecting correct meteorological range on left edge and source intensity on right edge. Point at which background luminance is intersected is projected vertically to estimate sighting range. (13, p.139)

TABLE 2

DAYTIME INTENSITY-VELOCITY INTERACTIONS

Minimum visible effective intensities in candles for warning times under atmospheric transmissivity of 0.53 per mile.

Warning time	90 knot max. v.	200 knot max. v.
10 sec.	239	1,846
20 sec.	1,375	16,641
30 sec.	4,466	84,397

Minimum visible effective intensities in candles for warning times under atmospheric transmissivity of 0.21 per mile.

Warning time	90 knot max. v.	200 knot max. v.
10 sec.	407	6,071
20 sec.	4,018	178,170
30 sec.	22,098	2,962,352

Nighttime Conditions

The background luminances of night sky and earth surfaces vary from below 10^{-5} to above 10^{-2} foot Lamberts. Under these conditions a point source giving 0.01 mile candle illumination yields a high probability visibility. However, the field value of illumination accepted as a "practical or useful" threshold is 50 times this figure, 0.5 mile candle (13, 17), allowing for search and detection under high workload conditions. This problem has been discussed by Projector (17) who provided the following figure (Fig. 3) illustrating visibility under various atmospheric transmissivities.

The current military specifications (14) call for a light emitting 100 candles (100 foot candles in the direction of flight) which is sufficient for low performance (e.g., 90 knot maximum velocity) aircraft, but may be insufficient for higher performance aircraft. (See Table 3)

Fig. 4 illustrates the ranges at which the 4100 candle day anticollision light and the 100 candle night anticollision light can be expected to be visible under low level visual flight reference conditions $0.21 \leq t \leq 0.53$ as in light haze.

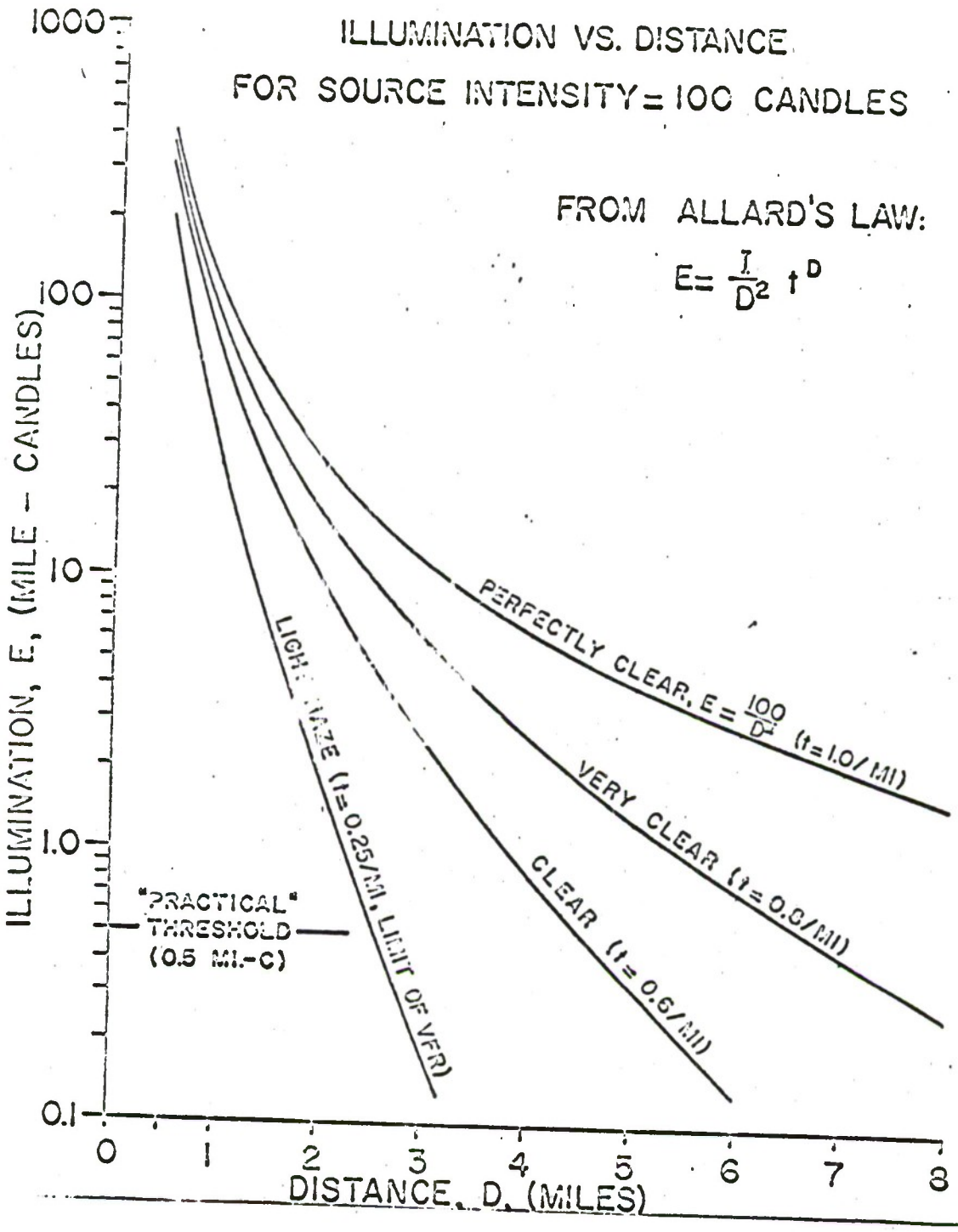
ILLUMINATION VS. DISTANCE
FOR SOURCE INTENSITY = 100 CANDLES
FROM ALLARD'S LAW:
$E = \frac{I}{D^2} t^D$
ILLUMINATION, E, (MILE - CANDLES)
1000
100
10
1.0
0.1
PERFECTLY CLEAR, $E = \frac{100}{D^2}$ (t = 1.0/MI)
VERY CLEAR (t = 0.8/MI)
CLEAR (t = 0.6/MI)
LIGHT HAZE (t = 0.25/MI, LIMIT OF VFR)
"PRACTICAL" THRESHOLD (0.5 MI.-C)
0
1
2
3
4
5
6
7
8
DISTANCE, D, (MILES)

Figure 3

6-A

Table 3

NIGHTTIME INTENSITY-VELOCITY INTERACTIONS

Minimum visible effective intensities in candles for warning times under atmospheric transmissivity of 0.53 per mile.

Warning time	90 knot max. v.	200 knot max. v.
10 sec.	0.24	1.85
20 sec.	1.38	16.64
30 sec.	4.47	84.40

Minimum visible effective intensities in candles for warning times under atmospheric transmissivity of 0.21 per mile.

Warning time	90 knot max. v.	200 knot max. v.
10 sec.	0.41	6.07
20 sec.	4.02	178.17
30 sec.	22.10	2,962.35

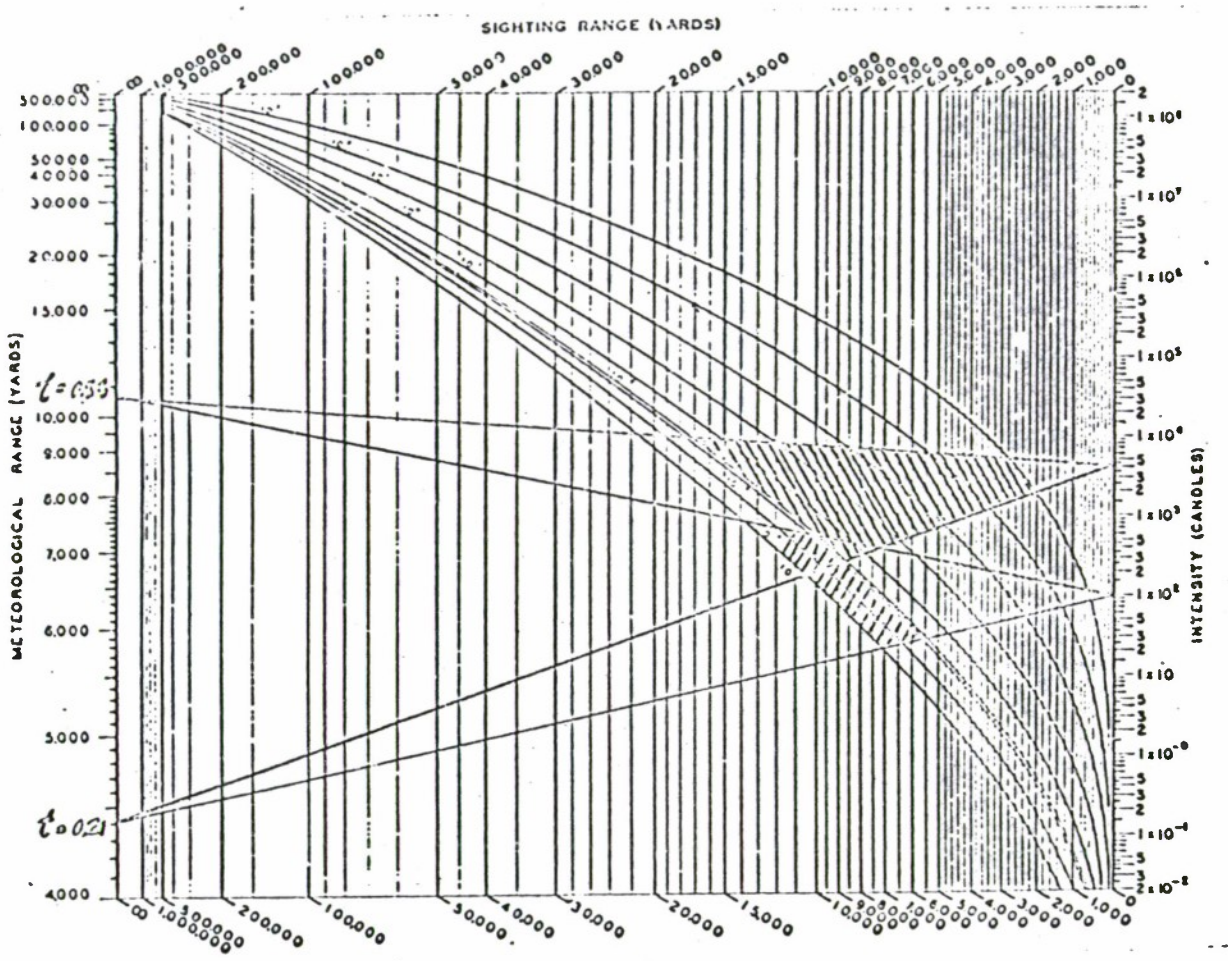

Fig. 4

Middleton's nomogram adapted to illustrate ranges of visibility of 4,100 candles day anticollision light and 100 candles night anticollision light under low level VFR conditions.

VERTICAL VISIBILITY

The present and projected helicopters have anticollision light systems similar to those used by fixed wing aircraft. These systems fulfill the criteria set forth in MIL-L-21652A(ASG), but there is a grave doubt as to their fulfillment of criteria necessary for the prevention of mid-air collisions in the helicopter's unique realm of flight.

These aircraft achieve vertical speeds of 30 mph and their mission requirements are such that this is an ordinary rather than an unusual mode of operation. The hover maneuver is another of the unique modes of operation during which the present anticollision lights give little protection. The present systems as shown in Fig. 5 provide a rotating cone of light that varies in intensity from 100% intensity through the first 5 degrees of arc away from the aircraft surface to 10% intensity at 30 degrees of arc away from the aircraft surface. The remaining 60 degrees of arc are unspecified and generally no light is transmitted in a vertical direction. The actual description of this area of no transmittance depends upon the individual type (manufactures) of beacon used. This is an area of concern in helicopter flight.

To provide the maximum anticollision protection available from a light system to the helicopter it will be necessary to account for the areas directly above and below the vehicle and to provide a system that will be readily discernible when the helicopter is moving vertically or hovering in relation to the observer. This system will have to provide light throughout the full 90 degrees of arc from the aircraft fuselage; it will also have to provide and maintain a much greater percentage of the original intensity throughout the arc. In terms of the 4100 candle day source, it will require a minimum of 615 ft. candles vertical illumination. In a like manner for the 100 candle night source, a minimum of 15 ft. candles will be necessary in vertical illumination.

The placement of the anticollision lights is also of some concern and poses a somewhat different problem. In addition to the present directives on placement, consideration should be given to the suggestion that at least one of the anticollision lights on a helicopter should be visible and completely unobscured from any angle of view. This would require that all helicopters be provided with two anticollision lights, one on the upper surface of the fuselage and one on the lower surface, as a minimum installation.

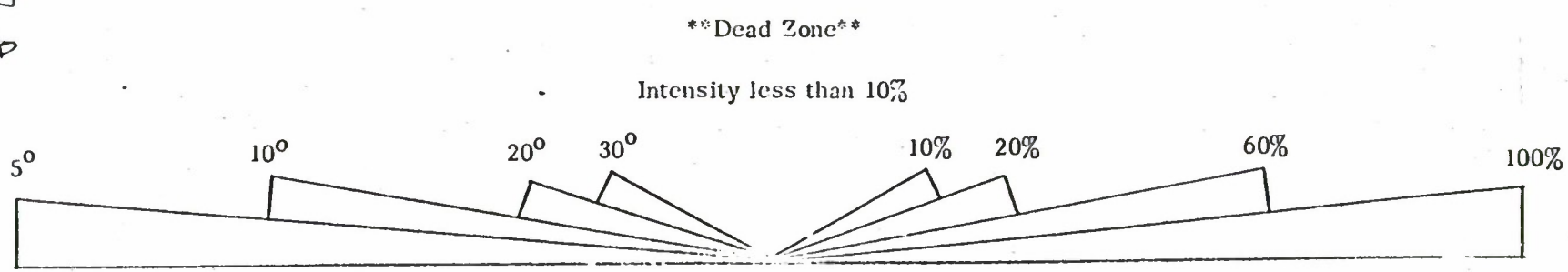

Fig. 5

Intensity dispersal pattern for conventional anticollision beacon. (MIL-L-21652A(ASG)

COLOR

Any cover placed over the light source serves as a filter, reducing the light output by an appreciable percentage and altering the color by selective transmission. Aviation red has been the standard for night anti-collision lighting as specified in MIL-C-25050A(ASG) 2 Dec 63. Aviation red has excellent transmissivity through aerosols and relatively low back-scatter along with good color constancy under varying meteorological conditions and distances. Though it is relatively inefficient in that the red filter removes from 70-90% of the light available from the source, this has been no serious disadvantage at the intensities required in night flight. Therefore, no change is recommended here for the night anticollision lighting system.

Significant backscatter does not ordinarily occur at the levels of background luminance characteristic of day operation. Furthermore, very high intensities are required for the velocities and warning times under consideration. Under these conditions it appears unlikely that aviation red will be adopted. A yellow or amber may prove acceptable as highly efficient systems are developed which can compensate for transmission losses of about 50%. However, in this stage of development, it is recommended that only clear covers with high and flat transmission characteristics be used with day anticollision lighting systems. This will permit the achievement of high illumination levels with color characteristics determined by the source and by the prevailing meteorological conditions.

DISCUSSION

Helicopter flight characteristics underscore the need for revision of the standards for anticollision lighting. The 100 candle aviation red rotating beacon has been a satisfactory horizontal and lateral signal for night flight in low velocity fixed wing aircraft. But the daytime effectiveness of the red anticollision beacon is practically nil, and in vertical movement its signal is weak or completely ineffective. Consideration of the maneuverability envelope of the VTOL aircraft has led to the conclusion that the beam shape of the anticollision light must not fall below 15% of its horizontal illumination at 90 degrees from the aircraft surface and must yield larger percentages throughout the range 0-90 degrees than have been required for fixed wing aircraft. Furthermore, using the head-on collision course, and a 20 second warning time as a criterion, the nighttime intensities required for higher velocity aircraft are higher than the present minimum specified. For example, 100 candles effective intensity is regarded as sufficient for the night anticollision light on the TH-13T with a maximum velocity of about 90 knots or even on the OH-6A, with a maximum velocity of about 130 knots. However, an aircraft with a maximum velocity of about 200 knots will require 180-200 candles effective intensity for nighttime signalling under low level VFR conditions.

Daytime conditions with high luminance background pose a difficult problem in anticollision lighting. Nighttime intensities must be multiplied by a factor of approximately 1000 to achieve positive contrast and conspicuity against skies of medium brightness (about 10^3 foot Lamberts). Even the relatively slow OH-23 and TH-13T will require a light source of 4100 candles effective intensity for head-on closing velocities of 180 knots and 20 seconds warning time under low visibility-high brightness VFR conditions. These conditions are not so rare if one considers light snow, rainfall, or morning haze, with sunlight shining through. Such difficult cases require consideration. Under these conditions the OH-6A will require 18,500 candles and the AH-1G will require in excess of 100,000 candles.

Such high intensity requirements, along with the associated weight and power requirements on the flight system, leave one in serious doubt as to the extension of anticollision light signalling into the high velocity-high brightness daytime flight regime. Reference to Table 1 indicates that under VFR conditions an approaching aircraft can always be seen as a dark object against the brighter ground (assuming sufficient size and contrast) before the anticollision light itself becomes conspicuous.

Unfortunately, the structural characteristics of some helicopters are such that they present poor visual forms to the observer. The skeletal, open, and transparent aspects of tail boom, landing gear, and fuselage on the TH-13T and the OH-23 give these aircraft a coincidental camouflage effect so that the observer may not detect the aircraft even at close range. This ambiguous or embedded figure effect is even more likely to occur when the aircraft must be seen from above against a background of foliage or man-made structures. Camouflage has been accidentally enhanced, and object visibility still further degraded, by the placement of identification markings.

Fortunately, the higher performance aircraft in current operation tend to have more substantial and conventional aircraft fuselage shapes. Object visibility of these aircraft can be enhanced by judicious selection and placement of contrasting colors. This may tend to compensate, at considerable distances and velocities, for the relative inconspicuity of daytime anticollision lighting on these aircraft. Anticollision lighting on these high performance VTOL and V/STOL will have a limited daytime usefulness in medium density, low altitude, and low speed flight.

Several problems susceptible to research solutions have emerged from this review. One problem, cited earlier by Projector (17), concerns the operational threshold of angular movement as observed from a vibrating turbulent platform. Experimental research in this area should provide a more precise standard for application of the fixity-of-bearing criterion in judgment of collision courses. Also related to fixity-of-bearing is another operational problem, decision times, as affected by flash rates and angular movement rates. Experimental data on the relationships among flash rates, angular movement rates, and decision times will improve accuracy in calculation of "reading" times as defined earlier. Still another problem raised by the current practice of mounting two anticollision lights on one aircraft involves the question of effects of synchronization of multiple flashes on conspicuity and identification. Asynchrony permits variation in overlap flash rates from approximately 80 to 200 cycles per minute presently, but it is a matter of some conjecture as to the effects of synchronization in phase, synchronization out of phase, or asynchrony on conspicuity and identification.

In view of the intensity-velocity-time relationships involved in anticollision detection under daytime conditions, it becomes apparent that anticollision lighting for daytime use must be considered within the entire context of detection, conspicuity, and collision avoidance. Consideration must be given to novel and untried ways of enhancing conspicuity as well as traditional forms, paints, and lights. This suggests that further research on fundamental areas of detection and conspicuity as related to VTOL maneuverability envelopes is presently needed.

SUMMARY

The flight envelope of the helicopter demands changes in the requirements for nighttime anticollision lighting, especially in beam shape or light distribution. Intensity requirements must also be increased for higher velocity aircraft to maintain a 20 second warning time on head-on collision courses. The intensities required for conspicuity against daytime sky luminances are much greater than those required for night visibility under comparable weather conditions. These daytime anticollision light intensities as calculated from Allard's Law are so great under high velocity closing courses as to sharply limit the usefulness of lighting as a daytime anticollision device. Other means of enhancing daytime aircraft conspicuity must be re-examined and researched anew.

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