A STUDY OF THE VISIBILITY AND GLARE RANGES OF SLOPE-LINE APPROACH LIGHTS

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SUMMARY

This report includes a mathematical and graphical analysis of the visibility distribution of the slope-line approach-light system using the standard 250 PAR lamp Some consideration also is given to the 400-watt 115-volt lamp which is the standard of the U S Air Force The analysis, based on Allard's Law, is made for the dual purpose of determining the distance from which a slope-line light can be seen by approaching pilots, and the distance from which it will appear to be excessively glaring to them, under a variety of daytime and nighttime visibility conditions and lamp brightness settings These data are then used as a basis for a study of the angular settings of the lamps, and for a study of a possible modification in lamp sizes at the inner end of the system

INTRODUCTION

When the preliminary design of high-intensity approach lights was being considered, in order to make successful approaches possible under extremely restricted visibility conditions, it was deemed desirable to make available the highest candlepowers economically obtainable The preliminary study showed that a value of the order of 100,000 candlepower would be sufficient for landing aircraft under visibility conditions down to approximately 1/16 mile, but, that multiplying this value up to several times added relatively little to the visual range [1] It was recognized that the lights would require a substantial degree of dimming for use under higher visibility conditions, and a means was provided for dimming them in steps, so that each step would reduce the intensity to 1/5 of the intensity of the preceding step Intensity changes of less than 3 1 on signal lights are practically indiscernible

The horizontal distribution of light in the approach area can well be obtained by the use of a spread lens on the lamps, and for this reason the lamps were designed with a 30° horizontal lens

The vertical spread of the beam of the approach lamps was established from a consideration of glare control It is possible to arrange the distribution of a narrow beam projector so that to an observer in any given plane, not passing through the projector, maximum visibility of the light source can be provided with a minimum of glare As experience has shown that on an instrument approach pilots tend to keep much closer to the correct height than to the correct line, it was decided to control the light distribution to eliminate glare, as far as practical, from the ideal approach plane For this purpose it was decided to use lamps producing very narrow vertical distribution, and to mount them so that their axes would intersect the glide approach plane at a carefully controlled distance The distance selected was 1,200 feet, the maximum distance to which the maximum candlepower would penetrate effectively in a night visibility of 1/8 mile, the worst visibility condition under which the system was intended to be used for the next several years

For slope-line approach-light installations at civil airports the CAA standardized on a 250-watt, 12 5-volt, PAR-56 lamp with approximately 94,000 cp (max), 36° horizontal and 7° vertical spread It was recognized that there would be less glare with the narrower vertical spread, but Air Force engineers felt that a standard voltage was more desirable from their standpoint and the glare might not be excessive

After several CAA slope-line installations were made and observed from the air a number of times, it was reported that except for the lowest visibility conditions the lights nearest the runway tended to be somewhat annoying from the glare standpoint, even at the lowest intensity setting of 0 16 per cent Due to the narrow vertical spread, however, the greater part of the system was not troublesome from glare As a result of these observations, it appeared that CAA might be able to use lower intensity lamps in the section of the approach system nearest the runway

Before recommending any changes in the standard system, it was believed advisable to make an analytical study in order to determine what might be expected under various conditions of visibility when lamps are dimmed or reduced in capacity, or adjusted through several different angles The

[1] H J Cory Pearson and M S Gilbert, "Some Considerations of High Intensity Approach Lighting," CAA Technical Development Report No 60, October 1948

procedure followed in making this study and the results obtained are discussed in detail in this report Although these studies are based on the lamps used in the slope-line pattern or configuration, the data on visibility range, glare distance and vertical angular setting also are applicable to other proposed approach-light configurations using the same lamps

BASIS FOR CALCULATIONS

Before discussing the actual mechanics of the mathematical and graphical work involved in this analysis, a brief review of some of the available information on visibility calculations and measurements is in order

Threshold

A source candlepower that produces on the retina of an observer's eye an amount of light just sufficient to be detected is said to be at threshold visibility A generally accepted service night-threshold value is 0 5 mile-candle[2] This was obtained from observations on a clear moonless night with the light observed against a green grass background This value, although based on a specific condition, is widely used as a basis for calculation with generally satisfactory results Assuming threshold to be a matter of illumination produced on the retina, the candlepower value necessary to produce the minimum amount of illumination required for threshold (with visibility conditions and background remaining constant) would vary as the square of the distance or

$$E = I_1 d_1^{-2} = I_2 d_2^{-2} = I_3 d_3^{-2}, \text{ etc} \qquad (1)$$

Where

E = Illumination, a constant
I = Candlepower
d = Distance between source and retina

Allard's Law is useful in determining the candlepower required to produce threshold visibility for a given distance and transmissivity[3] It can be stated conveniently by the following formula

$$I = E_o D^2 T^{-D} \qquad (2)$$

Where

I = Required candlepower of signal light
E_o = Threshold illumination, or 0 0020 hectometer candle (the metric equivalent of 0 5 mile-candle previously given)
D = Distance in hectometers
T = Transmissivity per hectometer

Background Brightness Factor

The threshold value is raised considerably when the background brightness is increased This is especially noticeable when comparing daytime and nighttime results It was found that the following formula would apply to either daytime or nighttime conditions[4]

$$De^{BD/2} = 16\ 4\ I^{1/2} b^{-1/4} \qquad (3)$$

Where

D = Distance in sea miles
B = Atmospheric attenuation per sea mile
I = Candlepower of signal light
b = Background brightness in milli-microlamberts
e = 2 718, the base of natural or Naperian logarithms

This is essentially Allard's Law with an added factor to take into consideration, the background brightness Equation (3) can be rearranged as follows

$$I = KD^2 e^{BD} b^{1/2} \qquad (4)$$

Since e^{BD} can be replaced[5, 6] by T^{-D}, this formula can be used to introduce the background brightness factor $b^{1/2}$ into Allard's Law by substitution of $K_1 E_o$ for K

Then

$$I = K_1 E_o D^2 b^{1/2} T^{-D}$$

Where

b = Brightness[7] in candles/hectometer^2

[2] Middleton, "Visibility in Meteorology," The University of Toronto Press, Toronto, Canada, 1940, Chapter IV, Sec 1

[3] Transmissivity is defined as the percentage of light flux from a source that penetrates the atmosphere for unit distance

[4] H S Knoll, D B Beard, R Tousey and E O Hulburt, Naval Research Laboratory Report No H-2627, Oct 1945, Pp 7, 8, 9

[5] See footnote 4

[6] Middleton, Chap II, Sec 2 and 3

[7] See footnote 2

D = Distance in hectometers
T = Transmissivity per unit distance D
E_o = Threshold illumination in hectometer candles
K_1 = A constant[8]

A number of background brightness readings were taken at Arcata, Calif, during low visibility testing of approach lights These varied from 79 to 1,400 foot-lamberts in daytime, and 0 0003 to 0 0008 foot-lamberts at night, during the period in which the tests were made Using these values to determine the brightness factor in equation (4), $b^{1/2}$ would vary from 1,645 to 6,945 for daylight, and from 3 21 to 5 23 for nighttime

While these values could be substituted in equation (5) in calculating data for the flight tests made at Arcata, further consideration should be given to the selection of a factor suitable for general use, since the fogs at Arcata, though frequent and plentiful, tend to be shallow in depth, thus permitting greater background brightness than might be found where the fogs are deeper and permit less light penetration It is practical, rather, to assume a condition that is more prevalent generally, such as a dark cloudy sky, and to use the brightness factor applicable to that condition From Table I it can be seen that for a dark cloudy sky the brightness factor would be of the order of 1,000 for daytime and 1 for nighttime As these figures give generally satisfactory results, they are used in this analysis

[8] A value of K_1 = 1 appears reasonable as the brightness factor is about 1 0 for the conditions under which the night threshold value was determined

Visibility Measurements

In determining visibility distances it is customary to make daytime observations by locating known landmarks, the farthest one that can be seen providing an indication of the visibility distance For nighttime observations a method that is widely used employs a 25-cp lamp as a standard The distance from which this lamp can be seen is called the "night visibility range" or "night visibility distance " The use of a standard lamp is convenient because unlighted objects obviously cannot be seen on dark nights, and lamps of varying candlepowers would not give consistent results

For scientific purposes, such as the

TABLE I

Brightness and Brightness Factor Values for Various Conditions*

Condition Day Scene	Brightness (Candles per sq ft)	Brightness (Lamberts)	Brightness Factor ($b^{1/2}$) (b = candles/hectometer^2)
Sunny Sky	100 - 2,000	0 34 - 6 8	1,043 - 4,680
White Cloud in Full Sunshine	3,000	10 2	5,725
Dark Cloudy Sky	80 - 600	0 272 - 2 04	935 - 2,559
Forest in Leaf in Sunshine	50 - 150	0 17 - 0 51	738 - 1,285
Grassy Field	200	0 68	1,480

Condition Night Scene	Brightness (Milli-micro-Lamberts)	Brightness Factor ($b^{1/2}$) (b = candles/hectometer^2)
Clear Starry Sky		
Horizon	60	1 382
Zenith	100	1 785
Milky Way	180	2 400
Dark Cloudy Moonless Sky	20 - 50	0 797 - 1 263
Sky, Full Moon, Some Haze	10,000	17 85
Forest	10 and up (Depending on clouds and moon)	0 565 and up

* Naval Research Laboratory Report No H-2627

tests carried on at Arcata, the transmissometer,[9] an instrument which employs a photocell to receive light from a lamp of constant candlepower over a fixed outdoor range, is used The transmissivity can be converted into equivalent object visibility distances by application of Koschmieder's constant in the formula

$T^d = K$, or

$$d = \log K (\log T)^{-1} \qquad (6)$$

Where

T = Transmissivity proportion per hectometer
d = Equivalent object visibility distance in hectometers
K = Koschmieder's constant = 0 02

There is some question as to the value for Koschmieder's constant, and some physicists prefer to use a value of 0 05

The effect of selecting a different constant in this relationship is only to establish a different value of the meteorological range or visibility distance for each value of transmissivity This difference in distance can be obtained from

$T^{D_1} = K_1$ and $T^{D_2} = K_2$

Then

$$D_1/D_2 = \log K_1/\log K_2$$

This will not affect the shape of any curves or the relationship of any values computed with one or the other value It would affect only the label such as "1/4-mile visibility" assigned to the condition

In connection with test work done by personnel of the Landing Aids Experiment Station at Arcata, it was discovered that there were considerable differences between the visibility measured horizontally over the ground by meteorological observers and the visibility experienced by the pilot on actual approach This is due in part to the phenomenon of horizontal stratification, the pilot seeing the lights through varying strata of fog, while the ground observation is made through only one stratum Furthermore, due to lack of homogeneity in the fog itself, there always will be sampling error unless the same path is used, and even then there is still the problem of the constant change and movement of the fog In general, in all visibility calculations based on observations in fogs, it is impossible to obtain results which are exact, and which will not vary an appreciable amount from what might be anticipated Therefore, the values shown later in this report for visual range and glare distance should be taken as approximate and not exact values The visual range and glare distance will be of the order of the values shown

Visual Range of Lights Seen Through a Series of Transmission Strata

Since the introduction of high-intensity approach lights has justified a lowering of landing minimums to a point where the pilot may be still above the ceiling when he passes the ILS middle marker and is looking for the lights, it is necessary that some consideration be given to the effect, on the visual range, of signal lights when seen through fog strata of varying transmissivities For this purpose it is necessary to set up a means of determining the reduction in illumination when light passes through a given distance of atmosphere of a given transmissivity By this means, it would be possible to determine the visual range of a signal light when seen through any given series of transmission strata A simple formula can be developed from Allard's Law to provide this information by rearranging equation (2)

$E_o = I_1 D_1^{-2} T_1^{D_1} = 0.002$ hectometer candles = threshold brightness

Where

I_1 = known candlepower of a signal light
D_1 = visual range of I_1 in hectometers
T_1 = transmissivity per hectometer

Then

$$E_o = I_2 D_2^{-2} T_1^{D_2}$$

Where

I_2 = effective candlepower of the same source from some known point at distance $D_1 - D_2$
D_2 = visual range of I_2 in hectometers

Then

$$I_2 D_2^{-2} T_1^{D_2} = I_1 D_1^{-2} T_1^{D_1}$$

[9] C A Douglas and L L Young, "Development of a Transmissometer for Determining Visual Range," CAA Technical Development Report No 47, February 1945

And

$$I_2 = I_1 (D_2 D_1^{-1})^2 T_1^{(D_1 - D_2)} \qquad (7)$$

With a different transmissivity T_2 prevailing in the overcast, the visual range D_3 of the effective candlepower I_2 into the overcast can readily be calculated or determined from a curve plotted on logarithmic paper for predetermined visual ranges versus their corresponding candlepower A different curve can be drawn for each value of T_2 selected

The total visual range of the light through two strata of atmosphere, then, can be stated

$$D_4 = (D_1 - D_2) + D_3 \qquad (8)$$

Where

D_4 = total visual range of light source of known brightness
$D_1 - D_2$ = distance from source to point of entry into second stratum
D_3 = distance from point of entry into second stratum to final threshold point

Under actual conditions there seldom is a clear-cut plane separating two strata of different transmissivities, and the strata usually will merge into each other, probably with a considerable degree of irregularity In making calculations involving several strata, however, it is convenient to assume that the separation between the two is sharp in order to simplify the problem Any error resulting from this assumption will be within the normal limits of uncertainty in dealing with visual calculations

If it is desired to find the illumination E at an observer's eye in restricted visibility a fixed distance from a light source, it is necessary only to substitute E for I_o and solve for E in Allard's formula The curves in Fig 1 illustrate how this illumination varies with distance

The nomographs Fig 2, furnish a graphical means for convenient determination of visibility distances under various conditions, either by day or by night, and also allow the determination of the intensity necessary to provide visibility under any weather conditions

Glare

In addition to the visibility of a light signal, consideration must be given to glare or dazzle The relationship of brightness to glare was investigated by Breckinridge and Douglas,[10] who found that when the illumination reaches a value of the order of 1,000

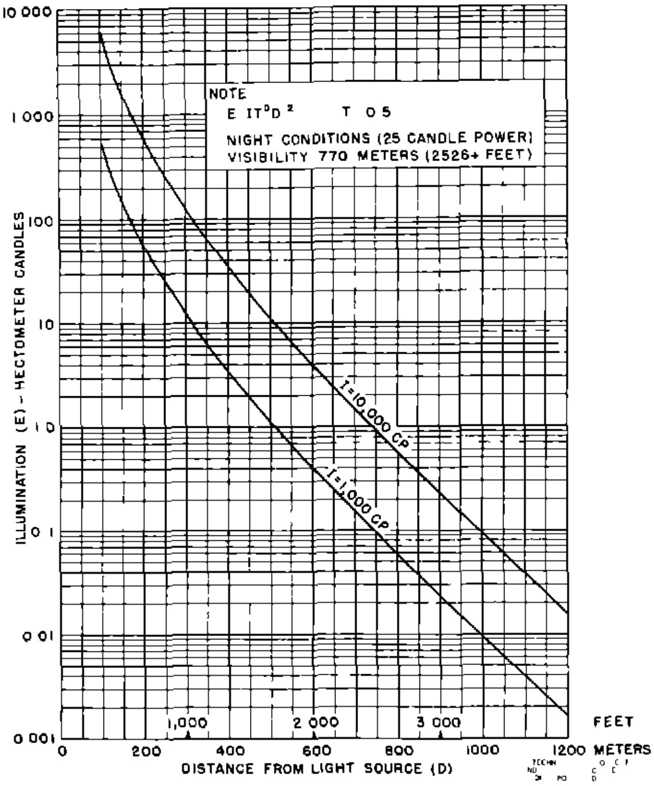

Fig 1 Curves Showing Illumination at Observer's Eye From Fixed Light Source

times threshold, glare begins to be experienced

The specific area of the eye upon which the light impinges has a material bearing on the glare effect, an off-line or parafoveal view of a bright source causing less discomfort than could be tolerated in a direct view

It is recognized also that glare is related to the duration of the exposure of the eye to the light source, as has been experienced by anyone who has taken a quick glance at the sun without suffering the discomfort resulting from a more prolonged look Even in the thickest weather a pilot making an approach is exposed to a succession of light sources for a sufficient length of time to experience discomfort if glare is present Some claims have been made that certain bright sources, whose intensity is measured in the millions of candlepower and whose duration is meas-

[10] F C Breckinridge and C A Douglas, "Development of Approach-and-Contact-Light Systems," Illuminating Engineering, Vol XL, No 9, November 1945, Fig 21

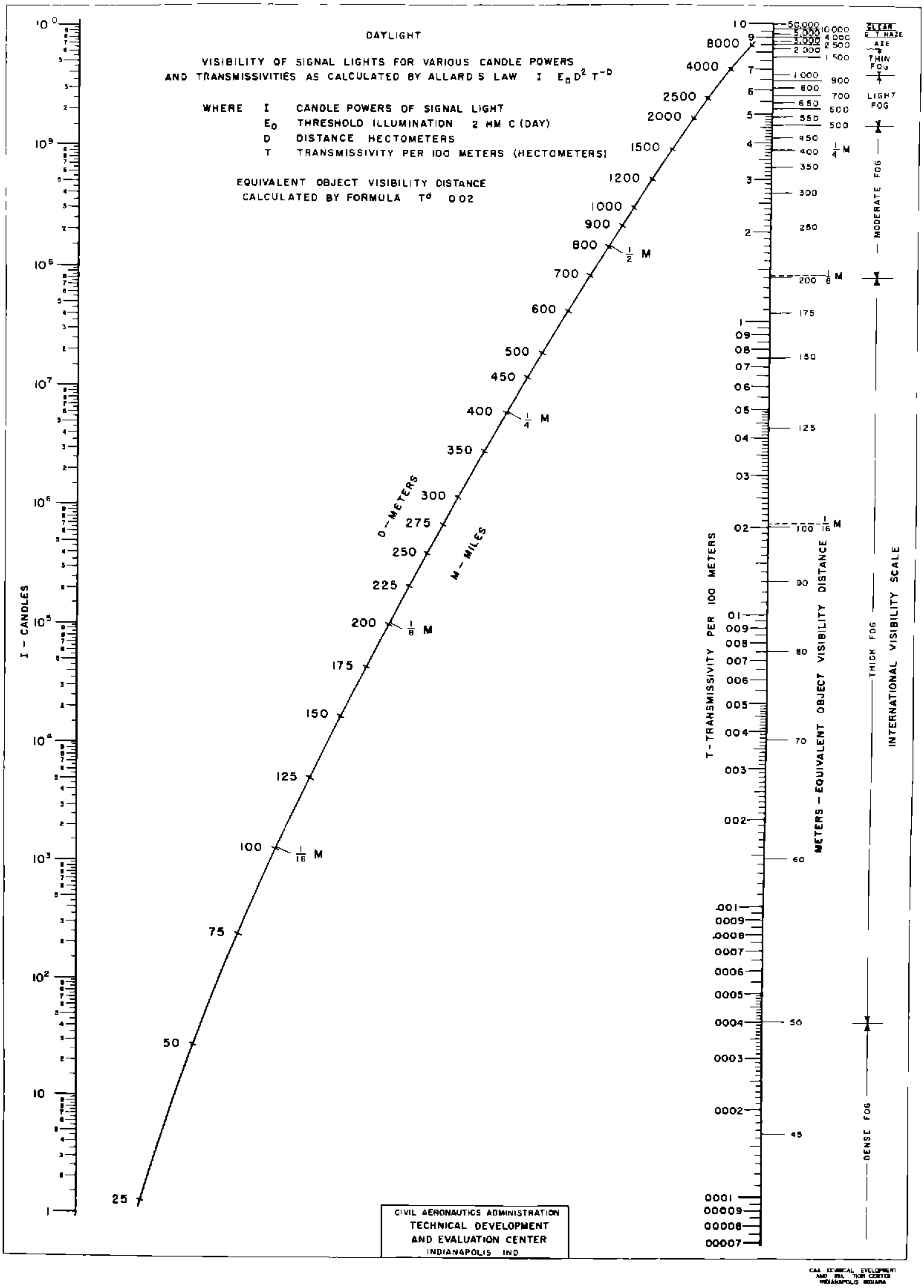
DAYLIGHT
VISIBILITY OF SIGNAL LIGHTS FOR VARIOUS CANDLE POWERS
AND TRANSMISSIVITIES AS CALCULATED BY ALLARD S LAW I E0 D2 T-D
WHERE I CANDLE POWERS OF SIGNAL LIGHT
E0 THRESHOLD ILLUMINATION 2 MM C (DAY)
D DISTANCE HECTOMETERS
T TRANSMISSIVITY PER 100 METERS (HECTOMETERS)
EQUIVALENT OBJECT VISIBILITY DISTANCE
CALCULATED BY FORMULA Td 002
I - CANDLES
D - METERS
M - MILES
T - TRANSMISSIVITY PER 100 METERS
METERS - EQUIVALENT OBJECT VISIBILITY DISTANCE
INTERNATIONAL VISIBILITY SCALE
CLEAR
LT HAZE
HAZE
THIN FOG
LIGHT FOG
MODERATE FOG
THICK FOG
DENSE FOG
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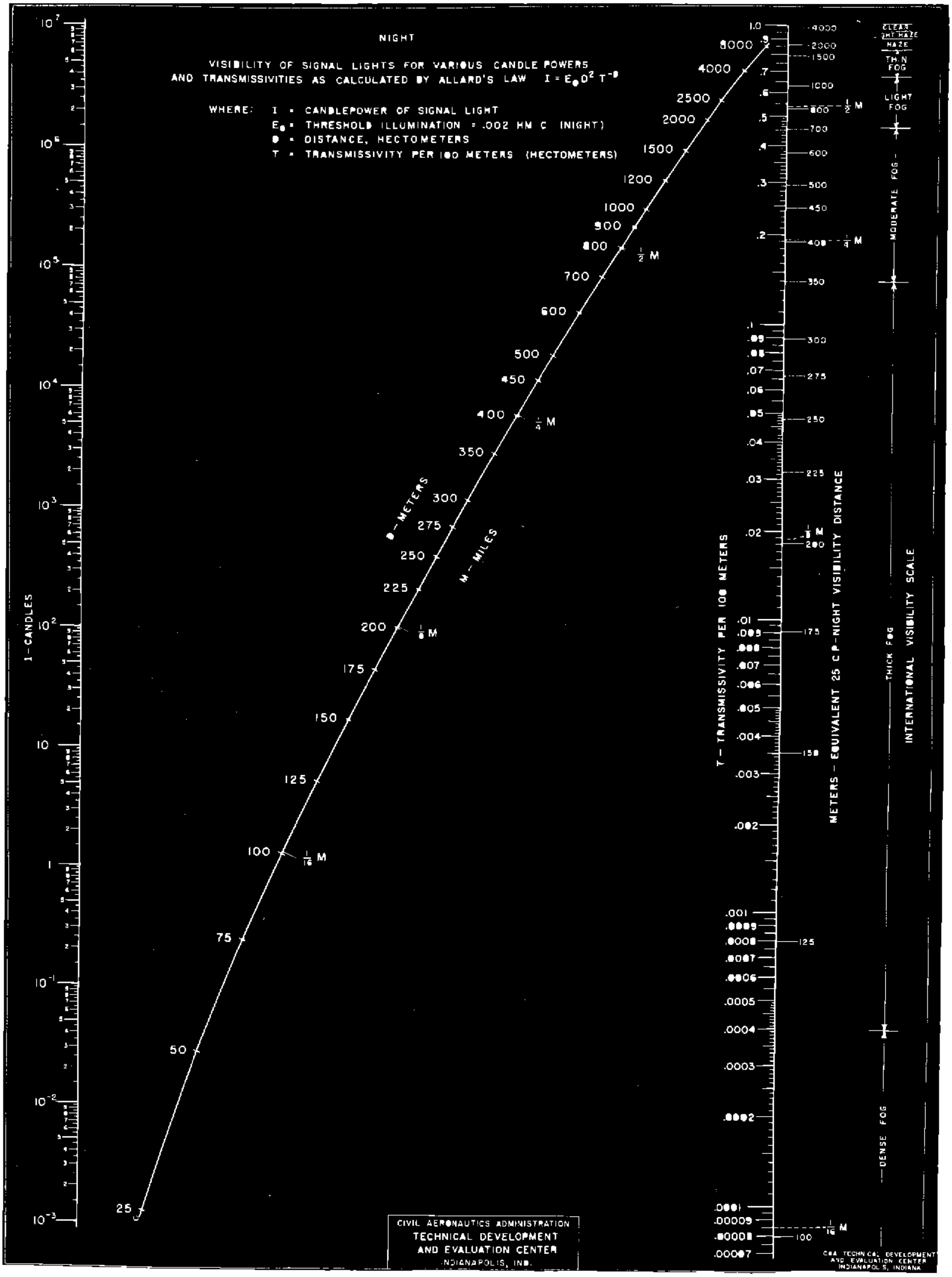
Fig 2A



NIGHT
VISIBILITY OF SIGNAL LIGHTS FOR VARIOUS CANDLE POWERS AND TRANSMISSIVITIES AS CALCULATED BY ALLARD'S LAW I = E₀D² T⁻ᴰ
WHERE: I = CANDLEPOWER OF SIGNAL LIGHT
E₀ = THRESHOLD ILLUMINATION = .002 HM C (NIGHT)
D = DISTANCE, HECTOMETERS
T = TRANSMISSIVITY PER 100 METERS (HECTOMETERS)
I - CANDLES
D - METERS
M - MILES
T - TRANSMISSIVITY PER 100 METERS
METERS - EQUIVALENT 25 C.P.-NIGHT VISIBILITY DISTANCE
INTERNATIONAL VISIBILITY SCALE
CLEAR
LIGHT HAZE
HAZE
THIN FOG
LIGHT FOG
MODERATE FOG
THICK FOG
DENSE FOG
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Fig 2B

ured in microseconds, can be observed without discomfort There are not sufficient quantitative data on this subject, however, to show how rapidly the eye can recover normal vision after observing such flashes of almost blinding intensity It should be borne in mind that glare and maximum brightness are much more critical considerations for nighttime unrestricted visibility operations, when the eye is dark-adapted, than for operations under normal conditions On the other hand, minimum brightness becomes a critical factor as the visibility decreases, especially in daylight operations when the eye is light-adapted and the background brightness presents little contrast to the source brightness

Generally it is accepted, on the basis of actual experience, that under normal night-operating conditions a signal light with a source intensity on the order of 100 cp is tolerable to the average pilot, since the eye can readily adjust itself to this condition

The problem of glare is important as it places a limit on the relative brightness that can be used for any given condition Because of this, it is necessary to provide intensity control so that the approach lights can be dimmed by the tower controller to produce a tolerable brightness when visibility conditions become less severe than those for which the system provides The slope-line system and aiming of the lamps are designed to indicate to the approaching pilot a path that will coincide with the ILS path while permitting him to see the lights with a minimum amount of glare

A pilot flying on instruments at night maintains his dark-adaptation by using very low brightnesses on the instrument panel When he comes within sight of high-intensity approach and runway lights, this dark-adaptation is lost Under such conditions it will be very difficult for him to glance back and read his instruments, as it will require several seconds delay to readapt his vision

Conditions and Assumptions

It was considered desirable to make the study described in this report for selected visibility steps from 1/2 mile down to 1/16 mile At present the 1/2-mile value, with a few exceptions, is the allowable minimum visibility for instrument approaches The other steps are considered from the standpoint of possible future reductions in minima It was not thought advisable, in this study, to attempt an individual solution for each of several possible glide slope settings and the great number of combinations of light-unit mounting elevations The charts and analyses in this report are based on the assumption that the glide slope is 2 1/4°, that all approach lights are mounted at runway level and that the touchdown point is 800 feet beyond the approach end of the runway While it is recognized that the results will vary in some details with various glide slope settings, it is believed that the relationships developed for a representative angle will parallel closely those which would be obtained for other angles, and the recommendations developed from this study will be generally applicable

For most of the calculations it was assumed that each lamp was aimed vertically to intersect the glide slope at a point 1,200 feet ahead of it, as measured along the axis of the extended runway This is a requirement in the CAA standard slope-line installation, which is based on a preliminary study showing 1,200 feet to be a satisfactory value for normal approaches under representative conditions

Some analysis was made, however, to determine the effect of lowering this angular setting Calculations showed that, as far as visual range is concerned, the results would be the same whether the observer was on course or somewhat to the right or left of it This is due to the wide horizontal spread of the beam It was assumed that homogeneity prevails in the fog at all points in the approach area and that visibility is the same all along the glide slope over the range involved No allowance was made for source size, or the integrated effect of the light from a number of closely associated lamps impinging upon the eye It is believed that this would increase the visibility slightly, but the exact amount is not known

All night-visibility conditions referred to in this report are based on the visibility distance of a 25-cp lamp While ceiling limitations were not considered in most of the calculations, a special study was made to determine the effect on visual range of a ceiling at 200 feet, and at 100 feet

In accordance with the preceeding discussion, the following assumptions were made

Nighttime background brightness factor	1
Daytime background brightness factor	1,000
Koschmieder's constant	0 02
Brightness glare factor	1,000

It was first necessary to determine the transmissivity per hectometer T for the various visibility conditions selected These values are shown in Table II

The next step was to determine the candlepower at various angles, over a 16° spread, from the vertical candlepower dis-

TABLE II

Transmissivity Values
for Various Visibilities

Visibility			Transmissivity per Hectometer T	
Miles	Feet	Hecto-meters	Night (25 cp)	Day (Object)
1/16	330	1 006	0 0000839*	0 0205·*
1/8	660	2 012	0 0179	0 143
1/4	1320	4 025	0 1890	0 378
1/2	2640	8 050	0 5201	0 615

* Night $T^D = \frac{E_0 D^2}{I}$ $T^{1\ 006}$ =

$\frac{0\ 002 \times 1\ 006^2}{25}$ = 0 00008 T = 0 0000839

* * Day T^D = 0 02 $T^{1\ 006}$ = 0 02

T = 0 0205

tribution curve of the 250-watt lamp, taken from National Bureau of Standards test No 15A-21/49 See Fig 3 The 16° spread covers the entire visible portion of the lamp and is greater than the 10 per cent cutoff point, which for this lamp is approximately 3 6° from the vertical axis These values were selected from both quadrants of the curve and an average was taken in order to reduce the number of calculations They were then substituted in Allard's formula and visibility distances for each angle were determined for the various values of candlepower It was not necessary to calculate each of the values, since with a few values determined by calculation and plotted on logarithmic paper, the intermediate values could be picked from these curves The visibility distance values were then tabulated

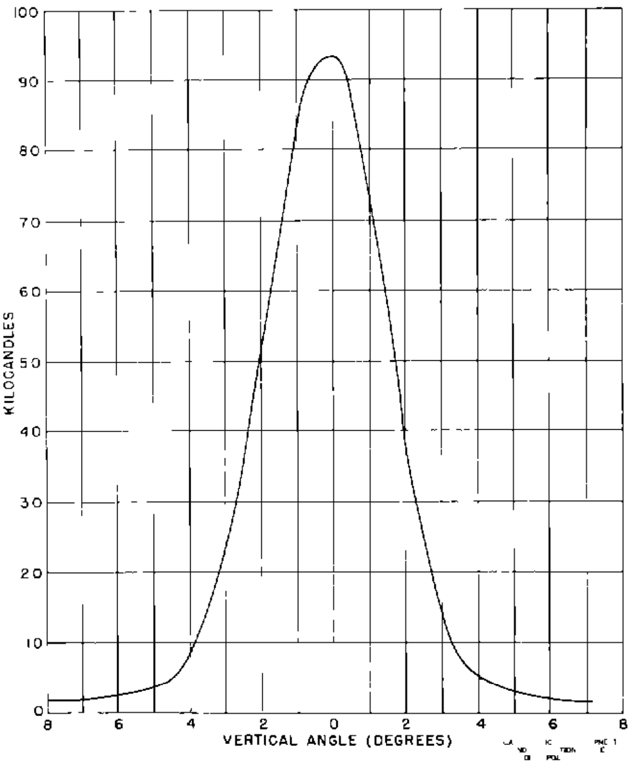


Fig 3 Vertical Candle Power Distribution of 250-watt, 12 5-volt, PAR-56 Approach Lamp With Spread Lens

and used to plot polar co-ordinate curves of visibility distance against angle See Fig 4 Table III is a sample tabulation for the 1/4-mile night visibility condition, T = 0 189

A similar tabulation was made for glare The glare distance was determined by dividing the various values of candlepower by the glare factor, 1,000, plotting curves and selecting values in the same manner as described above for the visibility values

TABLE III

Visibility Distances for 1/4-Mile Night Condition, 250-Watt Lamp

Angle (Degs)	Candlepower (100%) Left	Right	Average	D Feet	CP 20%	D Feet	CP 4%	D Feet	CP 0 8%	D Feet	CP 0 16%	D Feet
0	---	---	94,000	2,652	18,800	2,390	3,760	2,126	752	1,860	150 5	1,599
1/2	91,250	88,500	89,875	2,650	17,970	2,380	3,594	2,120	719	1,850	143 8	1,595
1	83,000	74,000	78,500	2,624	15,700	2,360	3,140	2,100	628	1,830	125 6	1,570
2	51,000	39,000	45,000	2,530	9,000	2,275	1,800	2,000	360	1,740	72 0	1,475
3	23,500	14,500	19,000	2,390	3,800	2,135	760	1,860	152	1,600	30 0	1,330
4	8,500	5,250	6,875	2,225	1,375	1,960	275	1,695	55	1,430	11 0	1,175
5	3,750	3,250	3,500	2,115	700	1,850	140	1,585	28	1,320	5 6	1,065
6	2,500	2 250	2,375	2,050	475	1,780	95	1,520	19	1,260	3 8	1,000
7	2,000	1,750	1,875	2,010	375	1,745	75	1,485	15	1,225	3 0	965
8	1,500	1,500	1,500	1,975	300	1,710	60	1,450	12	1,185	2 4	925

TABLE IV

Glare Distance for 1/4-mile Night Condition, 250-watt Lamp

Angle (Degs)	CP 100%	D Feet	CP 20%	D Feet	CP 4%	D Feet	CP 0 8%	D Feet	CP 0 16%	D Feet
0	94,000	1,520	18,800	1,250	3,760	995	752	739	150	485
1/2	89,875	1,515	17,970	1,245	3,594	985	719	730	144	475
1	78,500	1 495	15,700	1,225	3,140	965	628	710	126	450
2	45,000	1,400	9,000	1,135	1,800	875	360	615	72	360
3	19,000	1,255	3,800	1,000	760	740	152	490	30	225
4	6,875	1,095	1,375	830	275	575	55	325	---	---
5	3,500	990	700	725	140	475	28	220	---	---
6	2,375	925	475	665	95	405	19	150	---	---
7	1,875	880	375	625	75	370	15	110	---	---
8	1,500	850	300	590	60	340	---	---	---	---

Table IV shows the glare-distance values for the 1/4-mile night visibility condition

These glare-distance values were used to plot polar co-ordinate curves as illustrated in Fig 5 The same procedure was carried out for 50-watt lamps A special 50-watt, 12-volt, PAR-56 lamp which was used in experimental slope-line lights was found to have approximately 37 1/2 per cent of the candlepower with the same angular distribution as the 250-watt lamp Consequently, all of the candlepower values used in the 250-watt calculations were multiplied by 0 375 for use in the 50-watt calculations

Strictly, the visibility and glare curves are correct only for the one vertical plane through which the vertical candlepower distribution curve was determined Since the lights which are mounted at the sides of the approach lane are aimed straight ahead and not toed-in, it might be possible that these computed values differ from those prevailing in a plane oriented inward toward the ideal approach path Previously, however, isocandle curves were used to compute a number of values in vertical planes oriented to intersect the approach path 1,200 feet ahead of the lamps for check purposes, and the values thus obtained were found to be substantially the same as the values in the plane through which the vertical candlepower curve, Fig 3, was taken The final computations were made as described, therefore, in order to avoid the tedious work involved in the use of isocandle curves

The visibility and glare curves, Figs 4 and 5, were plotted on heavy paper, then cut out, placed on profile diagrams of the glide plane and traced in order to show where they intersect the glide plane when aimed such that the main axis intersects the glide plane 1,200 feet ahead of the light mounting location See Figs 6 to 12 It can be seen from these diagrams that, when the aircraft is on a section of the approach path covered by the visibility curve of a given light, that light and any others between it and the pilot are near enough to be visible to him Similarly, when the aircraft is on a portion of the approach path covered by the glare curve for a given light, that light can be causing the pilot eye discomfort In order to avoid confusion due to a large number of closely spaced curves, only those for lights at 500-foot intervals were drawn

A study was made of the various diagrams to determine which is the most suitable intensity for each visibility condition (greatest brightness possible without glare on the glide path) and the results form the basis of Table V Similar calculations then were made to determine the same data for the 400-watt, 115-volt approach lamp For this purpose the distribution curve of the 400-watt lamp was taken from National Bureau of Standards test No 15A-16/49 See Fig 13 These data then were plotted and traced on diagrams as was done with the data on the 250-watt and 50-watt lamps and are shown in Figs 14 to 20

To assist in evaluating the vertical coverage of the approach lights, lines representing the upper and lower vertical limits of the ANC "region of guidance"[11] are shown in the diagrams

Curves shown in Figs 21 and 22 were plotted to show the maximum visibility distance of each unit of a system, as measured along the horizontal, for each size lamp and each visibility condition These curves were plotted only for the brightest step that was free of glare in each instance In the case of the 1/2-mile night visibility condition,

[11] LAES Progress Report — 1949 Test Season, "Airfield Lighting " Fig A-27

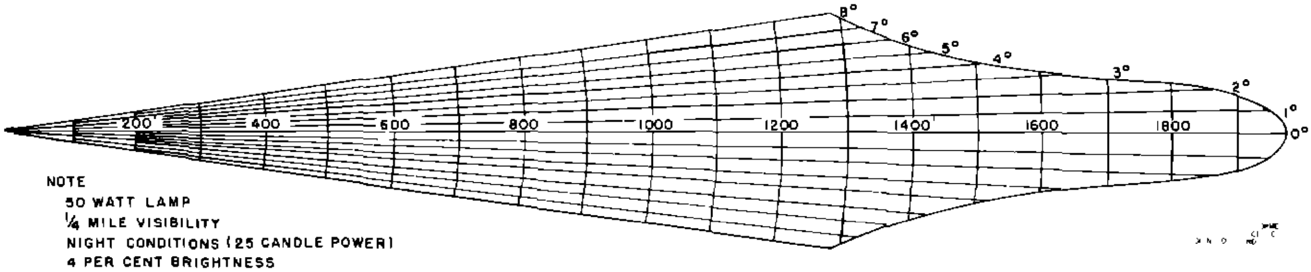


Fig 4 Typical Curve Showing Visibility Distance of Approach Lamp at Various Angles

TABLE V

Intensity Settings

Visibility		Optimum Intensity Setting	
Miles	Feet	Night (25 cp)	Day (Object)
1/16	330	100 per cent*	100 per cent
1/8	660	4 per cent	100 per cent
1/4	1320	0 8 per cent	100 per cent
1/2	2640	0 16 per cent* *	4 per cent

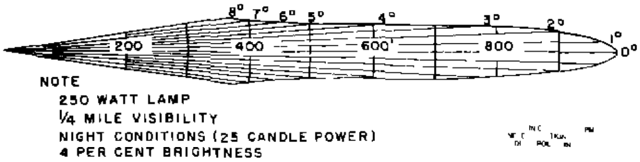


Fig 5 Typical Curve Showing Glare Distance of Approach Lamp at Various Angles

* Although 100 per cent intensity is shown in this table for the 1/16-mile night condition, the full candle power of the 250-watt lamp is still inadequate for this very severe condition, as the lights would be visible for a distance on the order of only 500 feet, which, after allowance is made for cockpit cutoff, would permit an insufficient number of units to be seen for a safe and comfortable approach In order to ensure a successful approach, it is necessary that a pilot see approximately five pairs of approach lights Taking into consideration normal current cockpit visibility cutoff, the farthest light must have a visual range of 800 to 1,000 feet, assuming that lights are installed at 100-foot intervals and that the aircraft is on the proper glide slope

* * A slight amount of glare appears when lights are observed from the glide slope under the 1/2-mile night condition at the lowest intensity step of 0 16 per cent or 150 cp peak In this connection, it should be pointed out again that it has been found from experience that airport signal lights with intensities of the order of 100 cp are tolerable to pilots on a clear night Under this condition of restricted visibility, there should be little difficulty for a pilot's eye in becoming adjusted to a brightness produced by 150 cp

however, there was still some glare at the lowest brightness step, 0 16 per cent In plotting the curves for the 50-watt lamps, it was assumed that it would be necessary to consider this size only for the 1,000-foot section nearest the runway

In order to determine the width of horizontal area covered by the approach lights, a method of plotting horizontal diagrams similar to the one used for the vertical diagrams was employed Candlepower values were picked from the horizontal distribution curve, NBS Test 15A-21/49 See Fig 23 Allard's formula was used again, and distances in the horizontal plane were plotted on polar co-ordinates to be cut out and traced on the diagrams These diagrams were drawn for only two conditions The 1/16-mile daylight, and the 1/8-mile, 25-cp nighttime, both very severe conditions These diagrams, Figs 24 and 25, were drawn to show the effects of using 50-watt lamps at the runway end and of turning alternate lamps 30° inward toward the approach-lane axis at the outer end of the system Lines were then drawn to show the outer limits of the area from which both sides of the lighting system can be seen

ANALYSIS AND CONCLUSIONS

Optimum Intensity Settings

A study of the curves for the 250-watt lamps reveals that the intensities shown in Table V will give the greatest visibility distance without troublesome glare

It can be seen from the various diagrams that, under all conditions studied, the use of 50-watt lamps (at the best intensity setting in the 1,000 feet of approach lane nearest the runway) either eliminates the glare along the glide slope entirely or

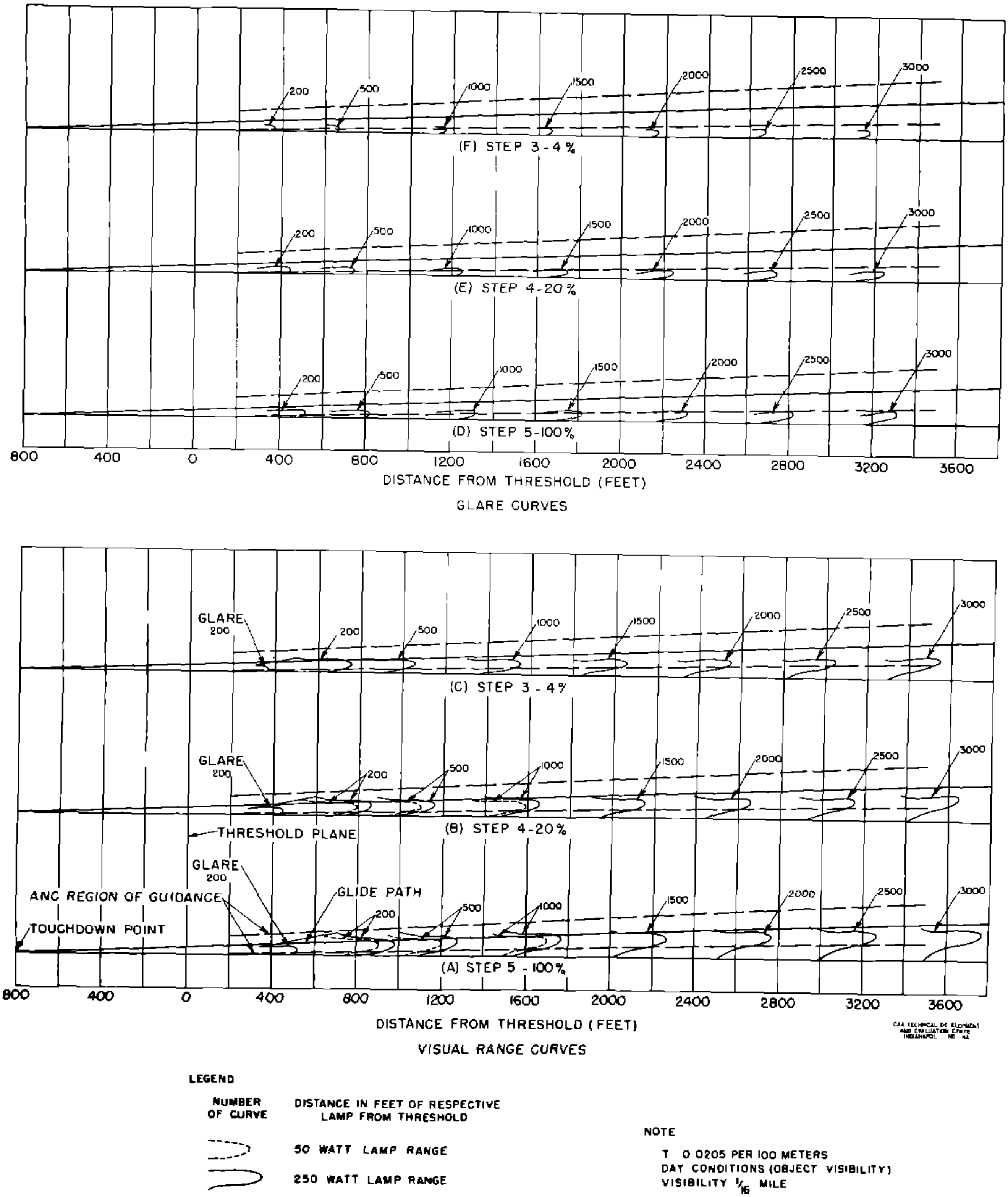
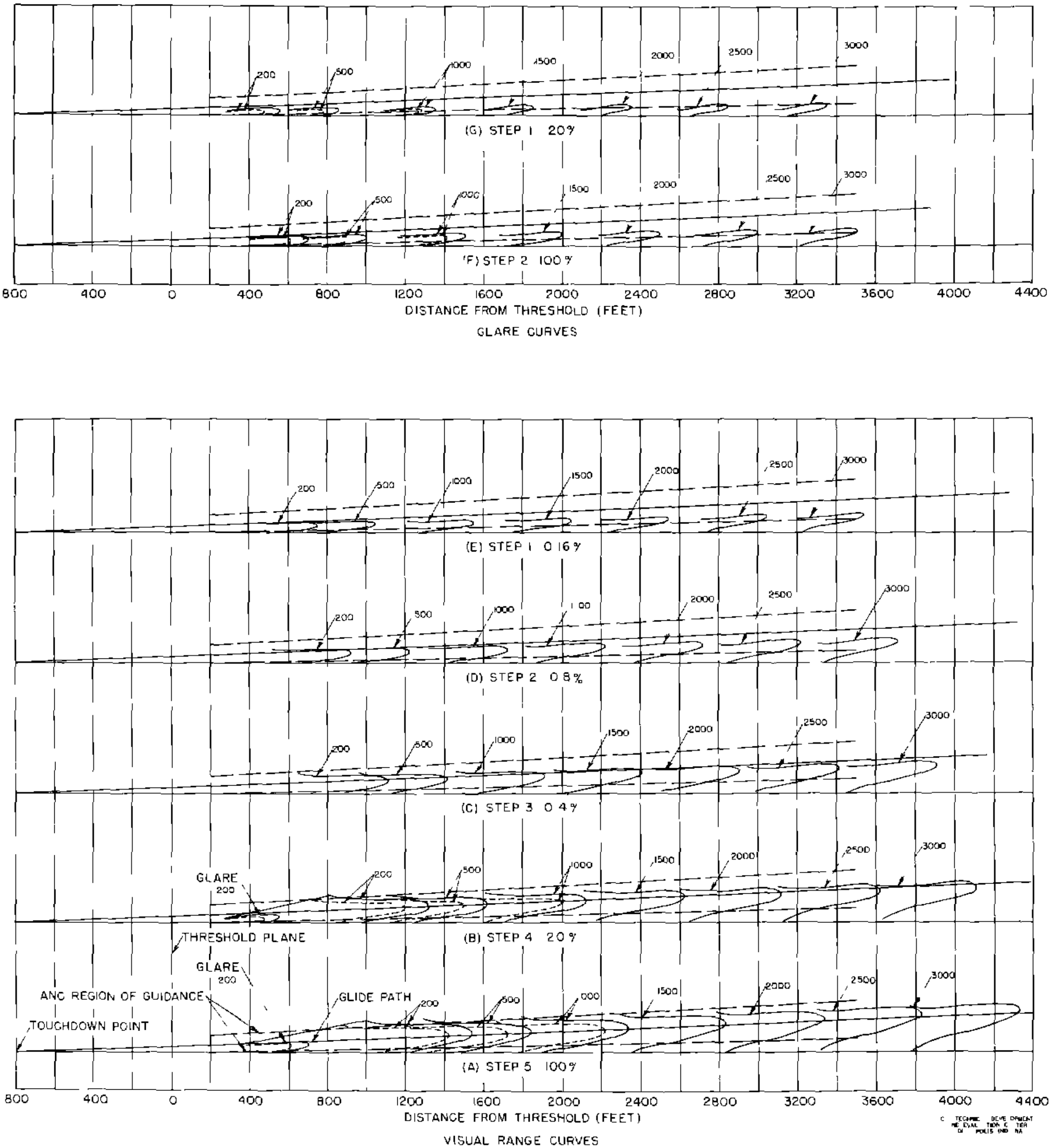


Fig 6 Visibility and Glare Diagrams



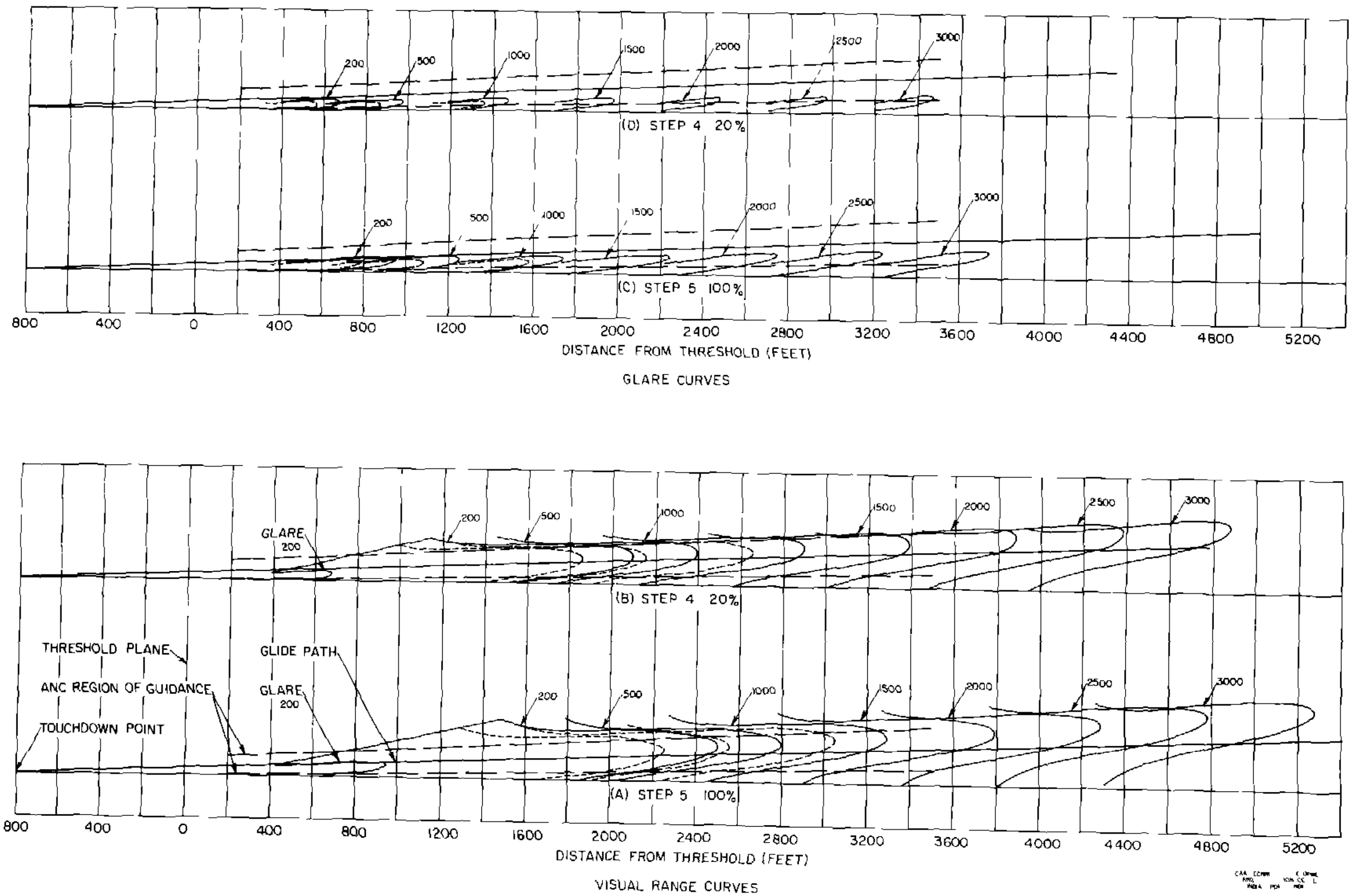
LEGEND

NUMBER OF CURVE	DISTANCE IN FEET OF RESPECTIVE LAMP FROM THRESHOLD
(dashed curve)	50 WATT LAMP RANGE
(solid curve)	250 WATT LAMP RANGE

NOTE

T 0 143 PER 100 METERS
DAY CONDITIONS (OBJECT VISIBILITY)
VISIBILITY 1/8 MILE

Fig 7 Visibility and Glare Diagrams



LEGEND

NUMBER OF CURVE — DISTANCE IN FEET OF RESPECTIVE LAMP FROM THRESHOLD

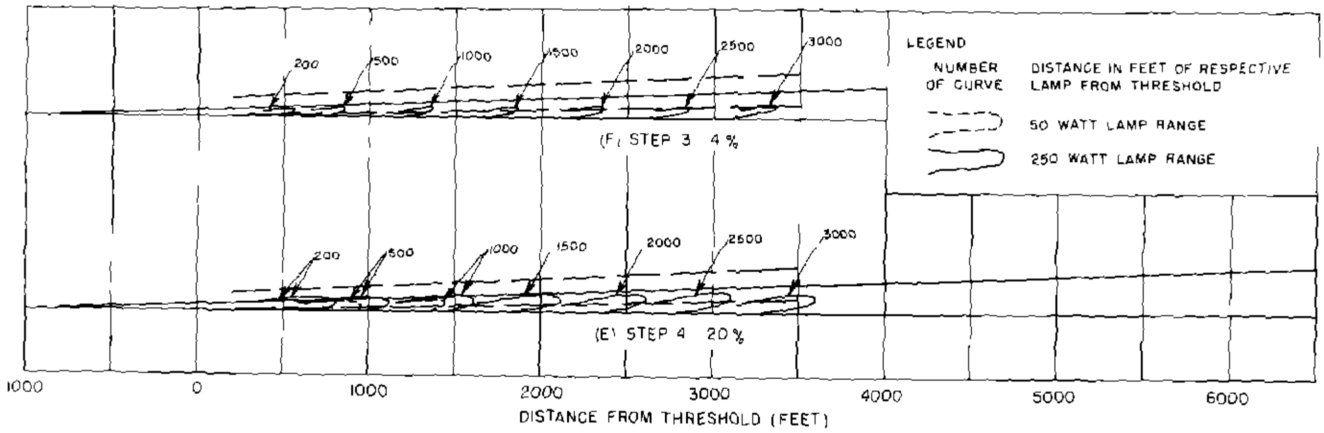
50 WATT LAMP RANGE

250 WATT LAMP RANGE

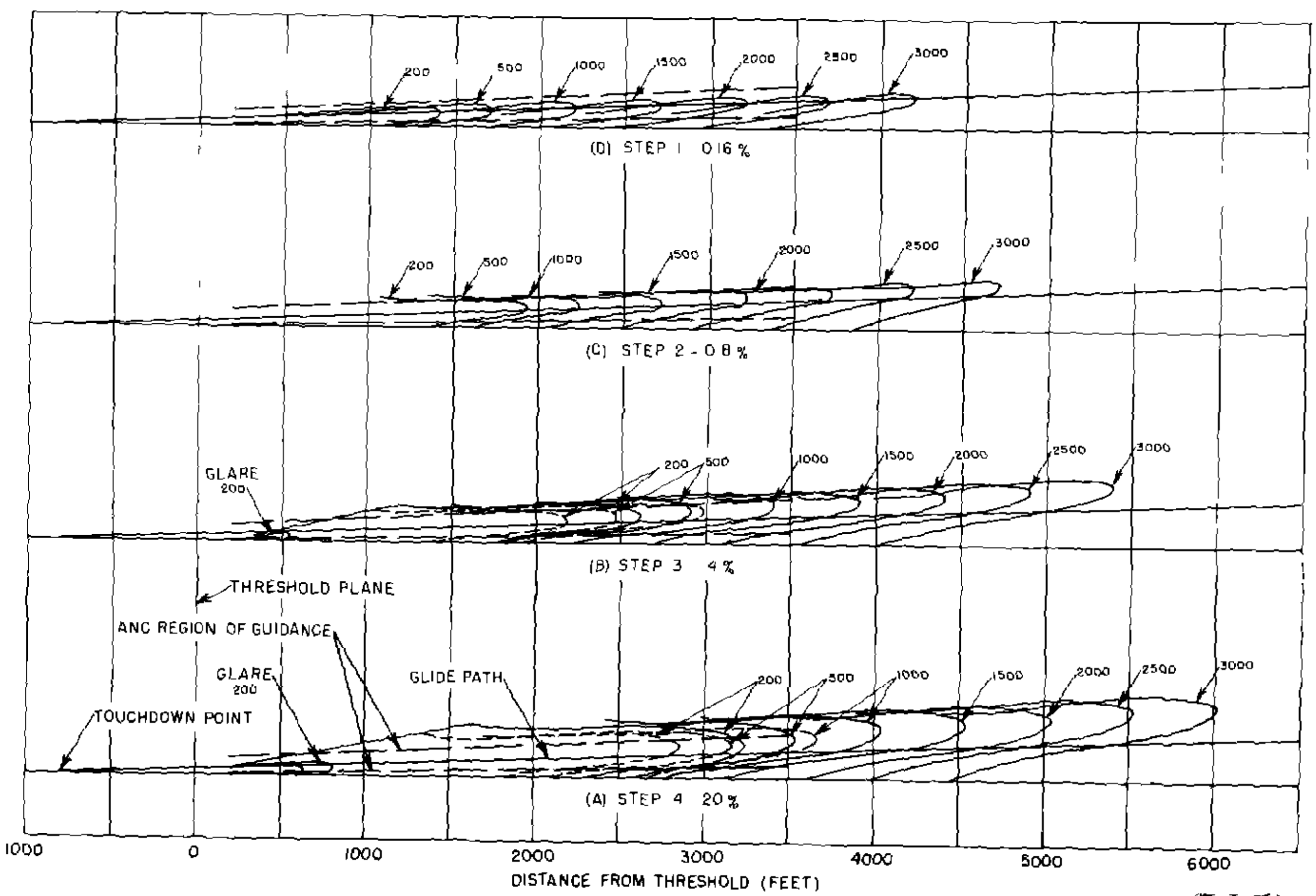
NOTE

T 0 378 PER 100 METERS
DAY CONDITIONS (OBJECT VISIBILITY)
VISIBILITY 1/4 MILE

Fig 8 Visibility and Glare Diagrams



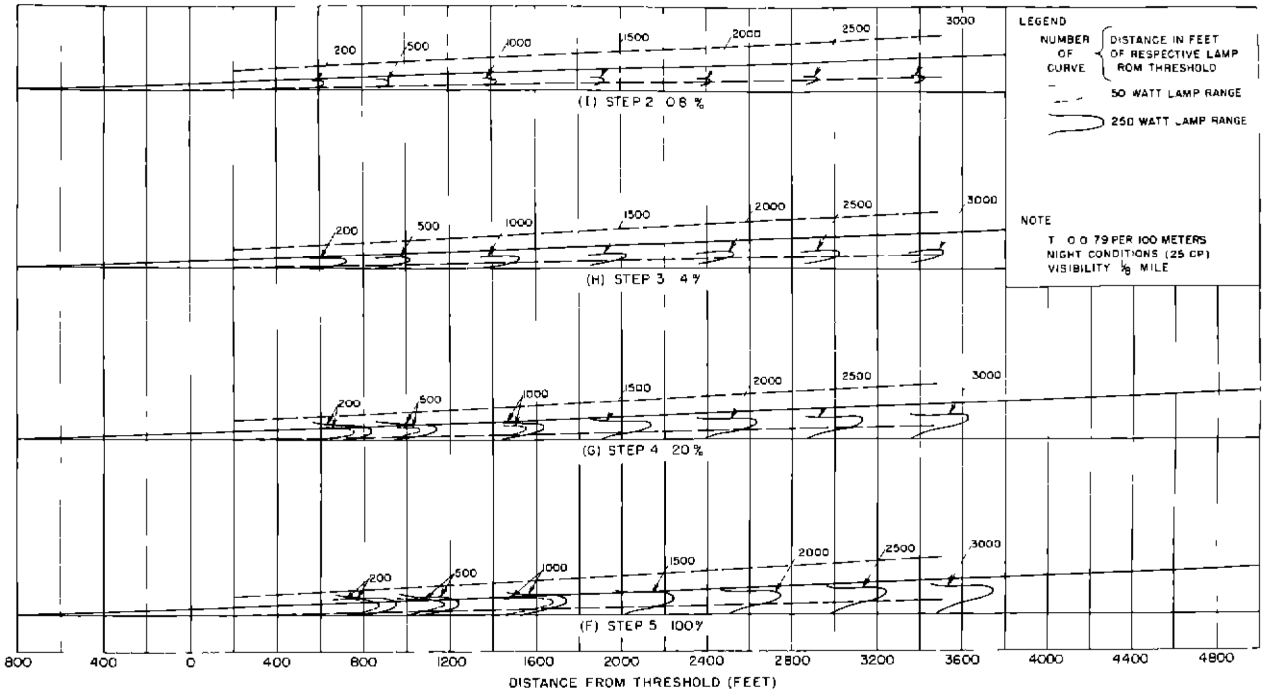
GLARE CURVES



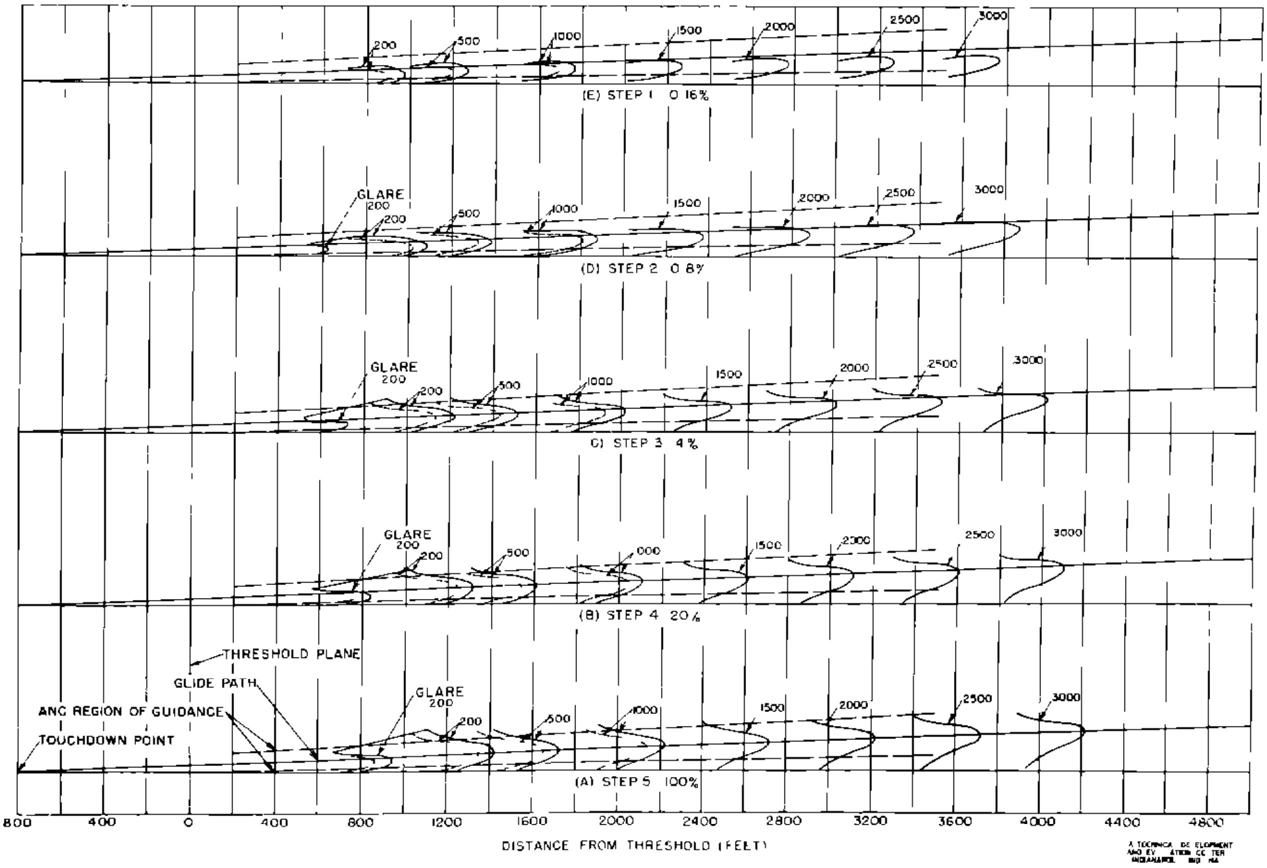
VISUAL RANGE CURVES

NOTE
T 0 615 PER 100 METERS
VISIBILITY 1/2 MILE
DAY CONDITIONS (OBJECT VISIBILITY)

Fig 9 Visibility and Glare Diagrams



GLARE CURVES



VISUAL RANGE CURVES

Fig 10 Visibility and Glare Diagrams

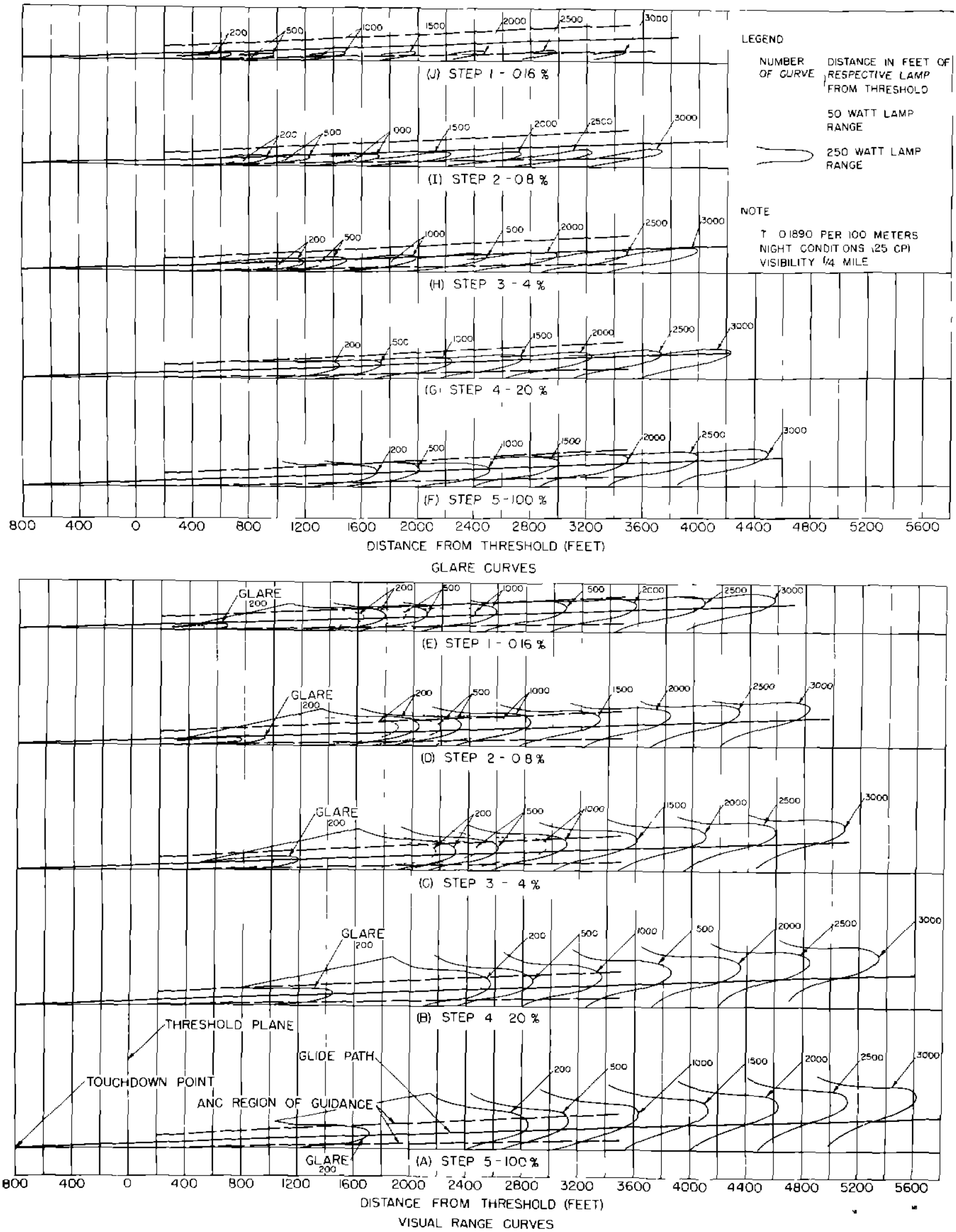


Fig 11 Visibility and Glare Diagrams

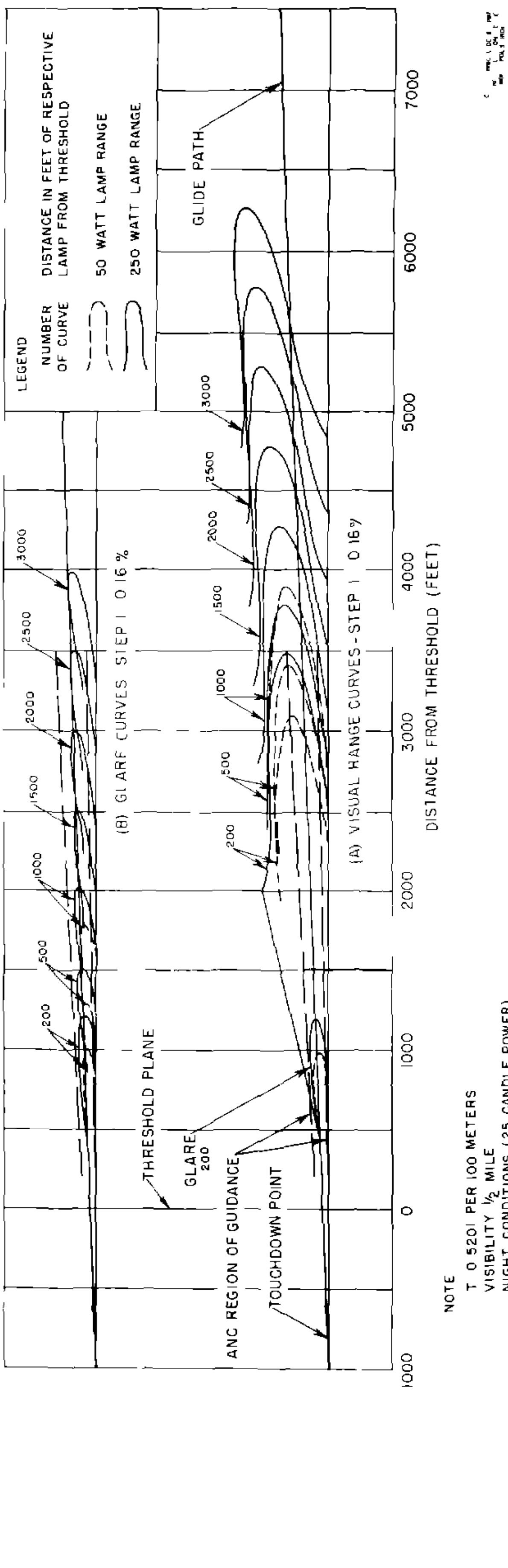


Fig 12 Visibility and Glare Diagrams

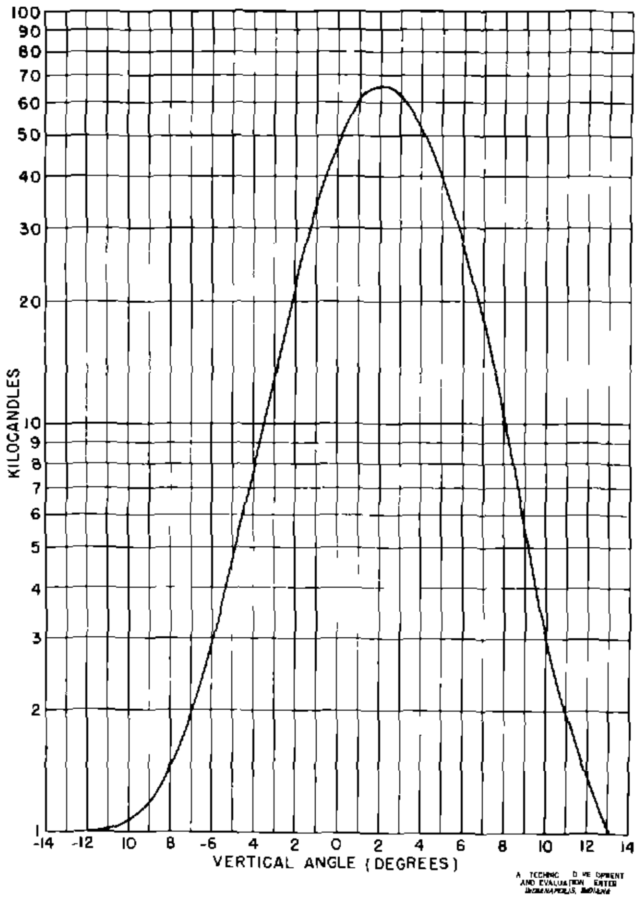
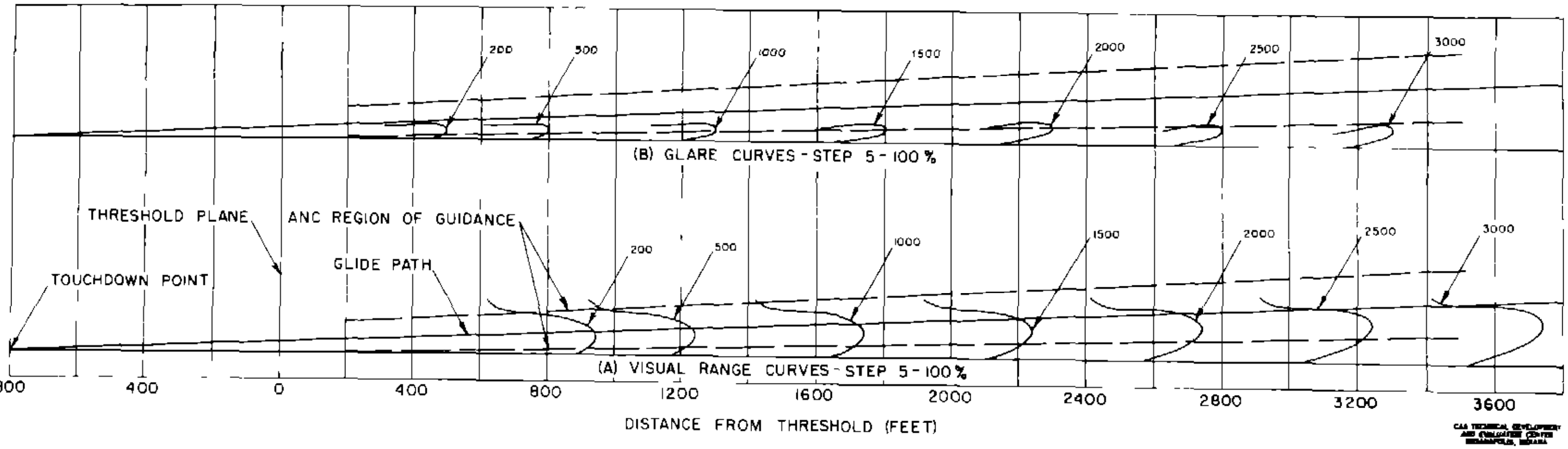


Fig 13 Vertical Candlepower Distribution of 400-Watt, 115-Volt, PAR-56 Approach Lamp With Spread Lens

reduces it to a value that can be tolerated In practically every case there is no glare on the glide slope due to any of the lights that are farther out than 1,000 feet

Vertical Coverage and Glare (250-watt, 12 5-volt, versus 400-watt, 115-volt lamps)

Table VI presents a comparison between the 250-watt, 12 5-volt, PAR and the 400-watt, 115-volt, PAR lamp on the basis of visibility and glare distance of the lamps as seen from the glide slope It should be *pointed out at this time that the inherent difference* in shape of the beam is due to voltage rather than wattage, the lower voltage lamps with a more concentrated filament tending to give the narrower vertical beam spread A study of Table VI reveals that, from the standpoint of visual range for the conditions considered, there is little advantage to be gained by the use of one lamp in preference



LEGEND

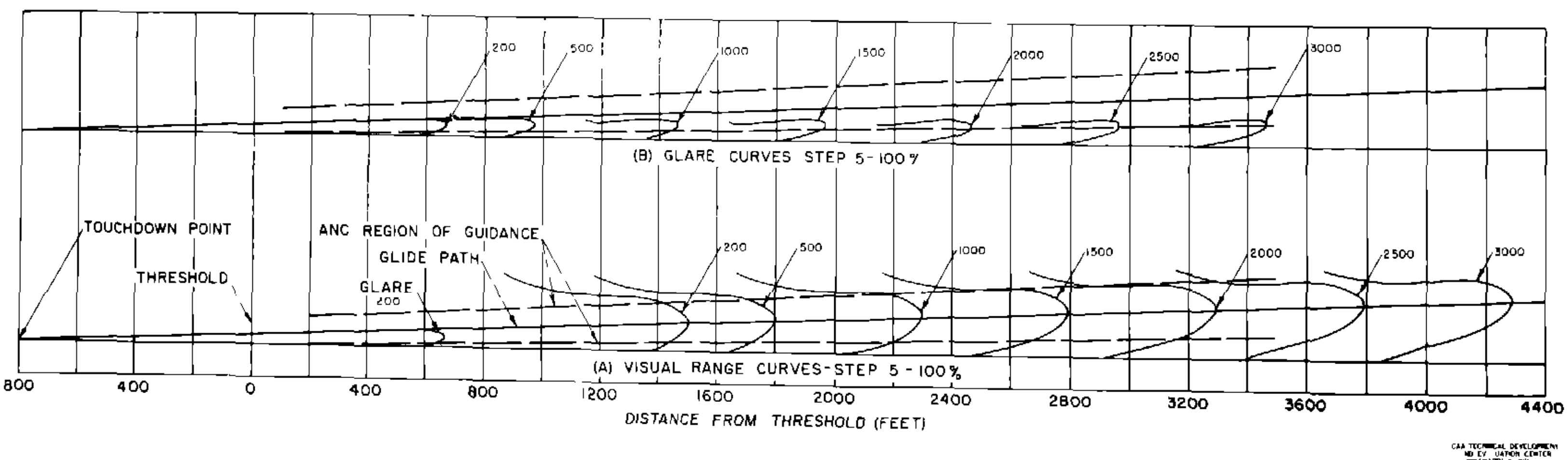
NUMBER OF CURVE — DISTANCE IN FEET OF RESPECTIVE LAMP FROM THRESHOLD

400 WATT LAMP RANGE

NOTE

T 0 0205 PER 100 METERS
DAY CONDITIONS (OBJECT VISIBILITY)
VISIBILITY 1/16 MILE

Fig 14 Visibility and Glare Diagrams



LEGEND

NUMBER OF CURVE — DISTANCE IN FEET OF RESPECTIVE LAMP FROM THRESHOLD

400 WATT LAMP RANGE

NOTE

T 0 143 PER 100 METERS
DAY CONDITIONS (OBJECT VISIBILITY)
VISIBILITY 1/8 MILE

Fig 15 Visibility and Glare Diagrams

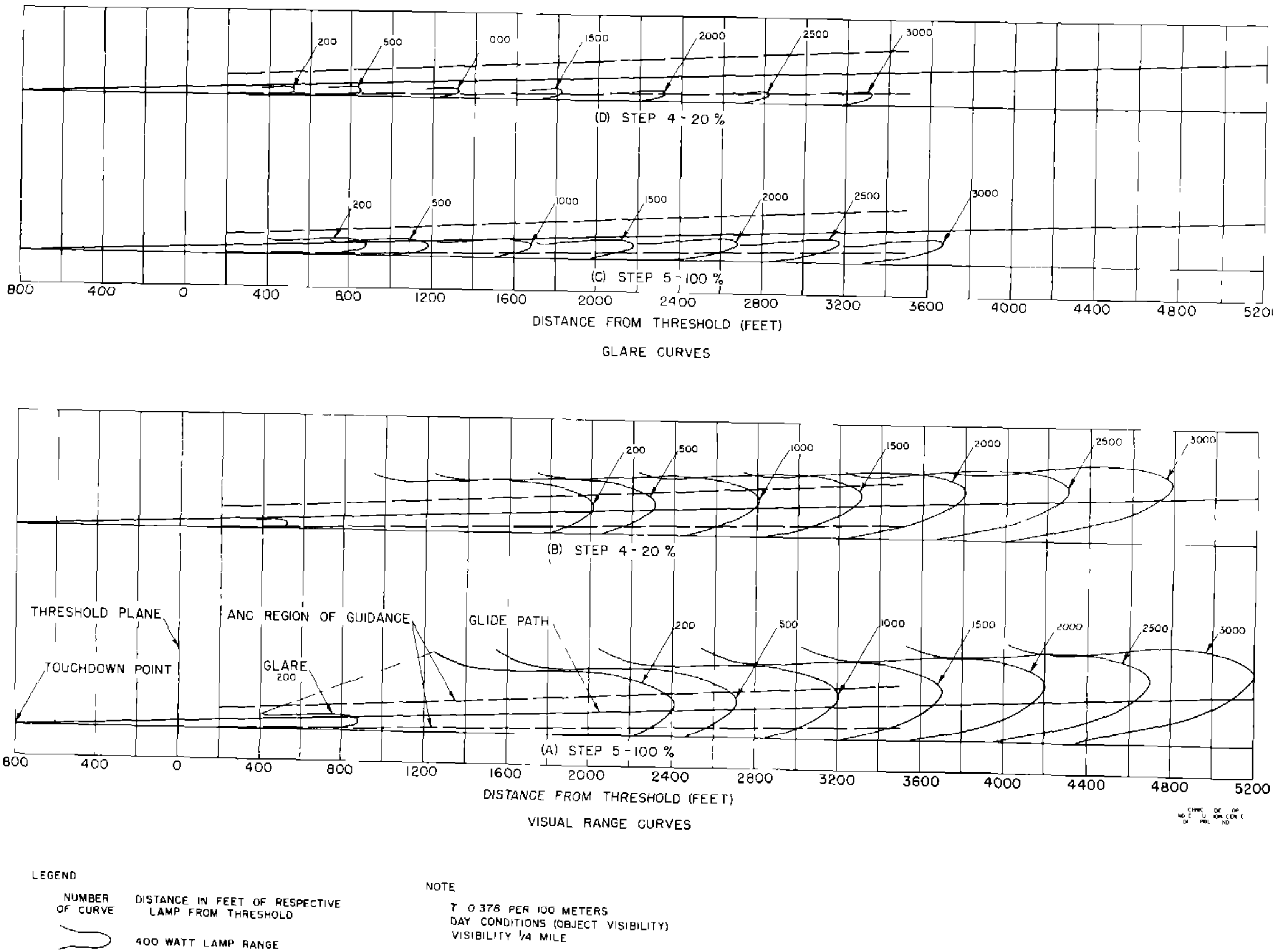


Fig 16 Visibility and Glare Diagrams

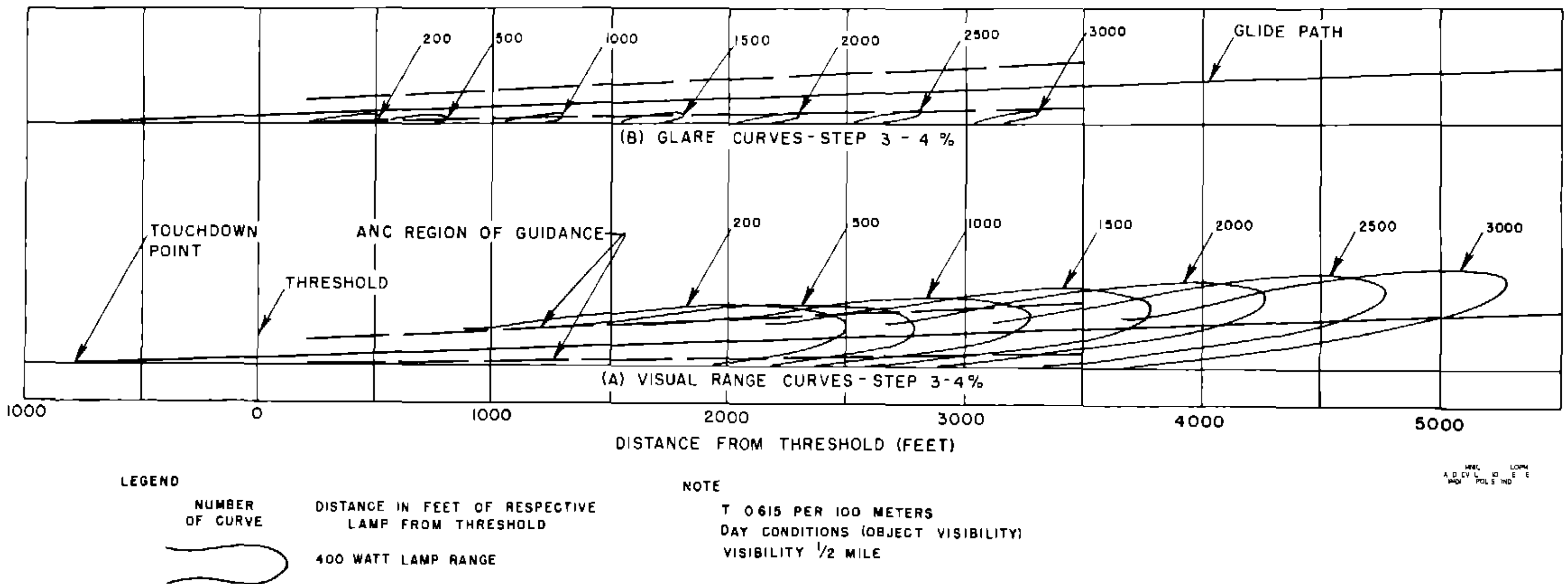


Fig 17 Visibility and Glare Diagrams

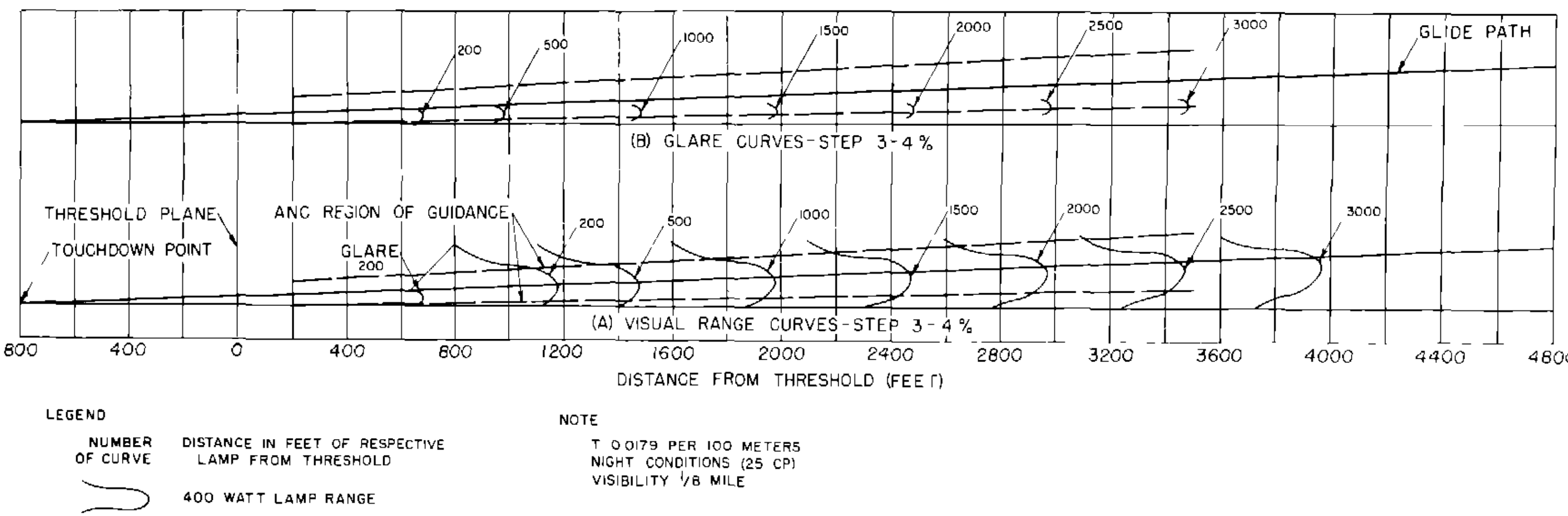
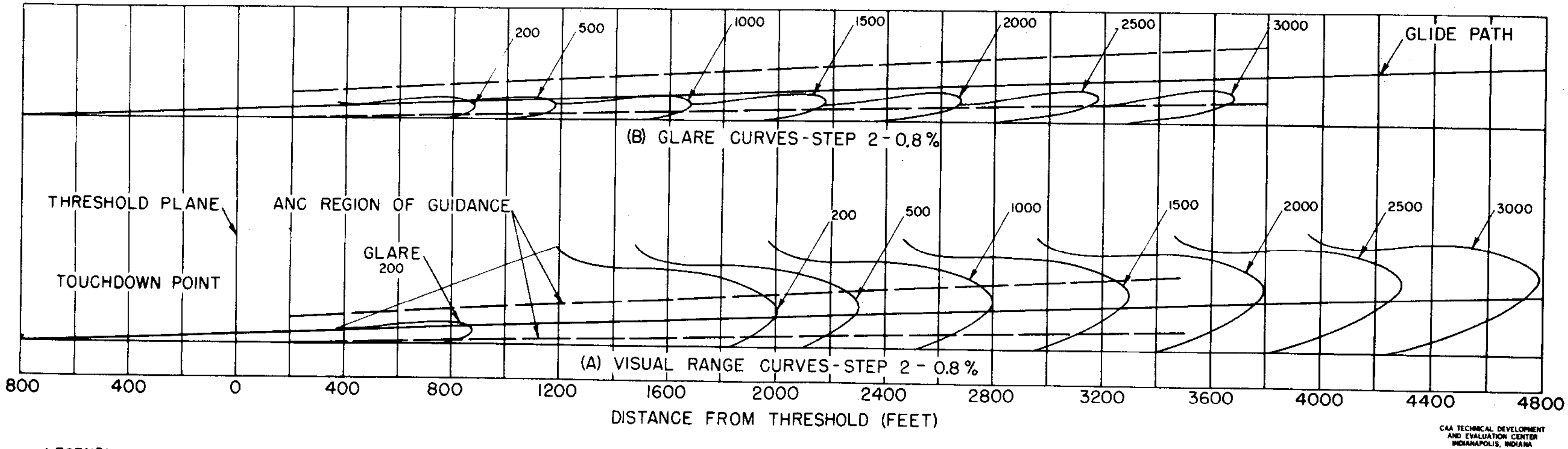


Fig 18 Visibility and Glare Diagrams



LEGEND:

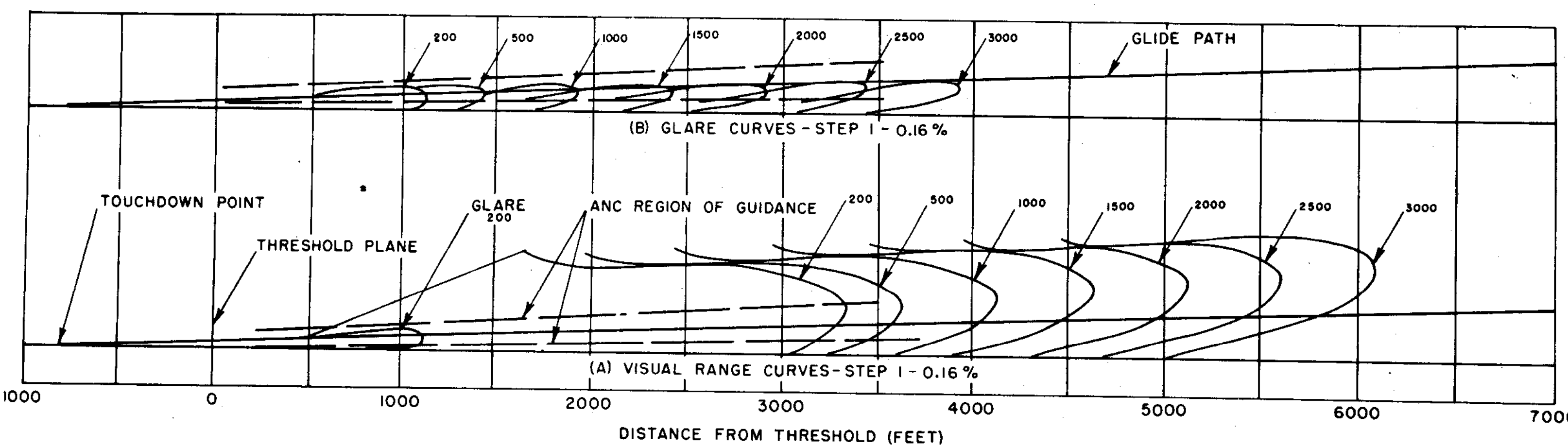
NUMBER OF CURVE — DISTANCE IN FEET OF RESPECTIVE LAMP FROM THRESHOLD

400 WATT LAMP RANGE

NOTE:

T = 0.1890 PER 100 METERS
NIGHT CONDITIONS (25 CP)
VISIBILITY 1/4 MILE

Fig. 19 Visibility and Glare Diagrams



LEGEND:

NUMBER OF CURVE — DISTANCE IN FEET OF RESPECTIVE LAMP FROM THRESHOLD

400 WATT LAMP RANGE

NOTE:

T = 0.5201 PER 100 METERS
NIGHT CONDITIONS (25 CP)
VISIBILITY 1/2 MILE

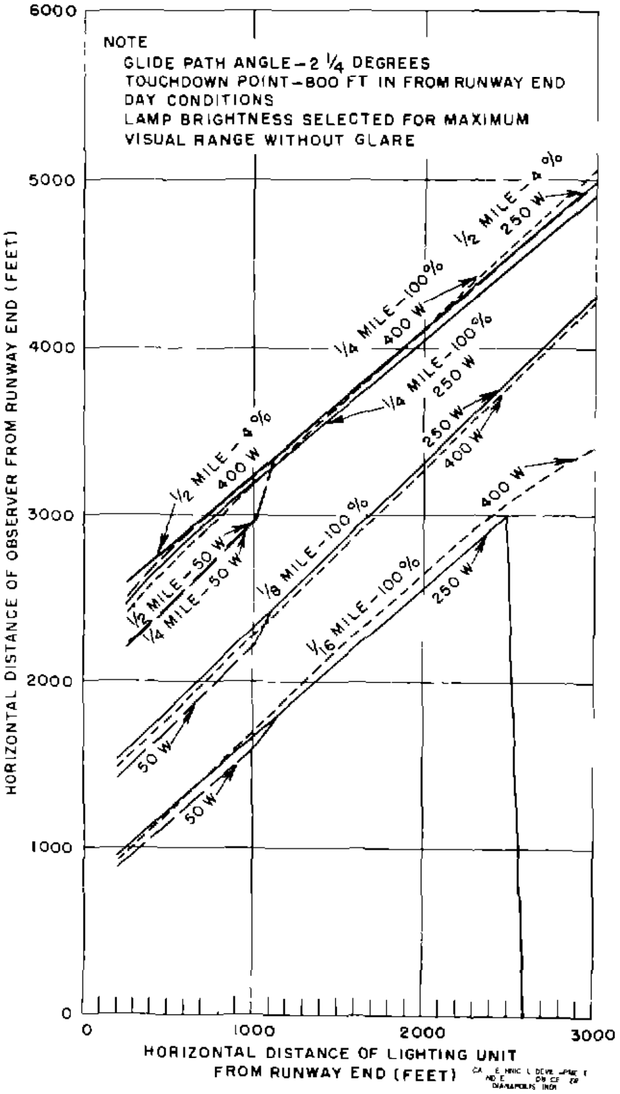


Fig 21 Curves Showing Distances Approach Lights Can be Seen by Pilot on Glide Path

to the other This is true with one exception, viz , under the 1/16-mile daytime condition, the system using the 400-watt lamp begins to give the pilot guidance when he is 3, 500 feet from the runway end as compared to a distance of 2, 500 feet with the 250-watt lamp

As to glare, the advantage is with the 250-watt lamp 1nfour of the seven conditions considered In the other three conditions, neither lamp has the advantage The greatest amount of glare is found under the 1/2-mile night condition when a pilot begins to notice this excessive brightness in the field of vision from a point approximately 3, 900 feet out from the runway end This glare, however, is borderline for the most part as the intensities directed at the pilot are of the order of 100 cp or less for the night condition

It can be seen from the curves that under some conditions the 250-watt lamp gives less vertical coverage above the glide path than does the 400-watt lamp The authors do not consider this to be a material disadvantage, however, because the slope-line system gives such accurate vertical guidance that pilots using it properly show an almost universal tendency to follow the actual glide slope It seems to be indicated that the narrow vertical spread, such as is obtained from the low voltage lamp, has sufficient advantage to justify its continued use

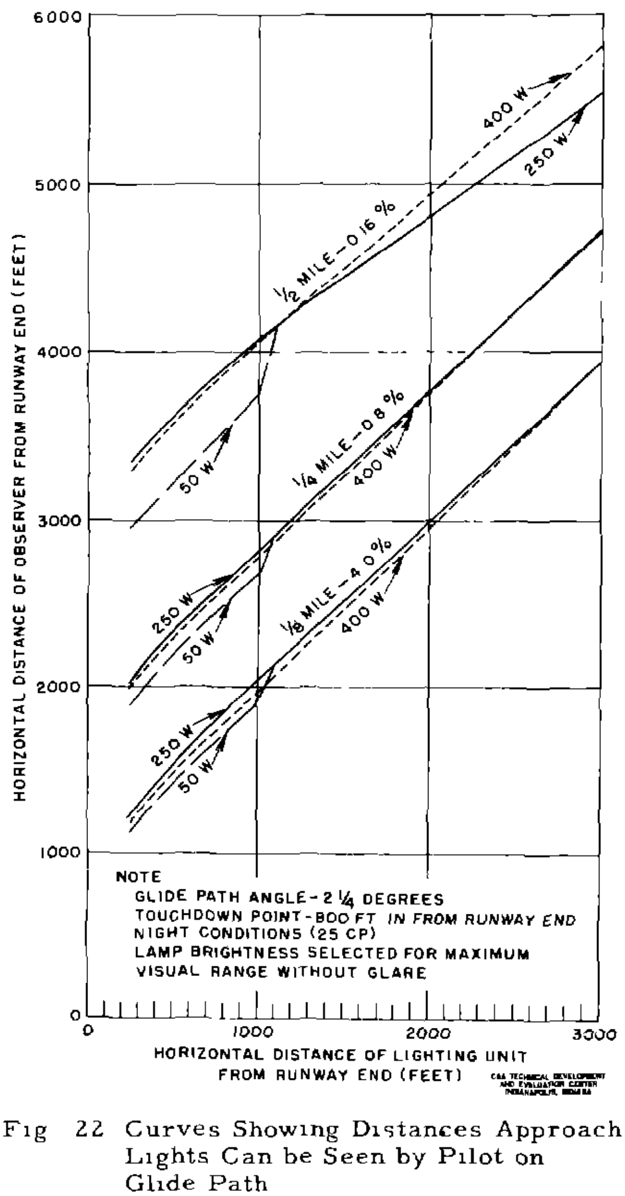


Fig 22 Curves Showing Distances Approach Lights Can be Seen by Pilot on Glide Path

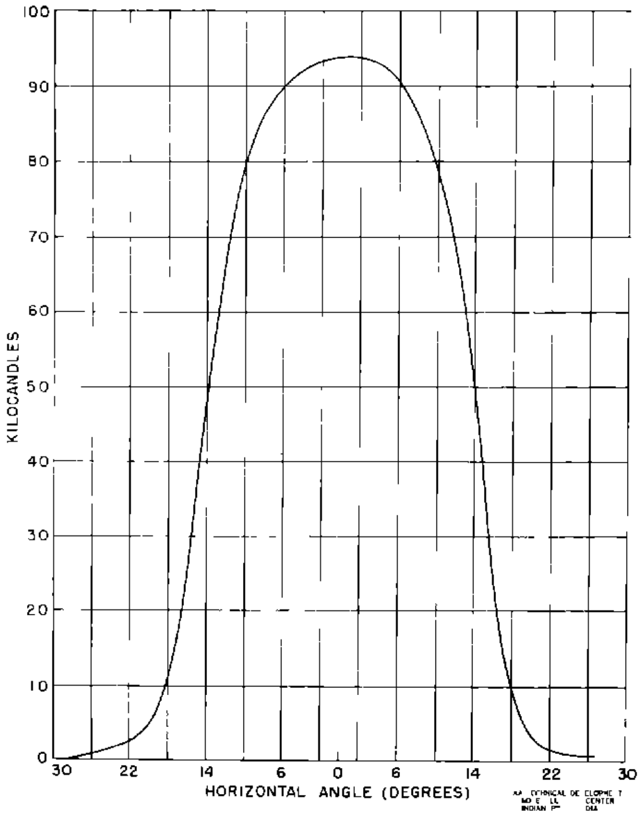


Fig 23 Horizontal Candlepower Distribution of 250-Watt, 12 5-Volt, PAR-56 Approach Lamp With Spread Lens

Vertical Angular Settings of Lamps for Various Glide Angles Under Restricted Visibility

A study of the diagrams indicates that under restricted visibility conditions, with the possible exception of the 1/16-mile day condition (which is borderline), the practice of aiming the lights to intersect the glide slope at a horizontal distance of 1,200 feet ahead is satisfactory for all glide angles from 2 1/4° to 3° from the standpoint of visibility

Horizontal Coverage

From Fig 24A it can be seen that for the 1/16-mile daytime visibility condition, unless the pilot is near the center line at the outer end of the approach or between the two rows of lights and within 2,000 feet of the runway, he will not be able to see both rows of approach lights To enable him to align his aircraft to make a proper approach under such a low-visibility condition, it is very important that the pilot be able to see both lines from a wide area at or beyond the outer end of the approach-light system, while at the inner end a narrow area would suffice, since by the time he has approached that far he should be properly aligned for a landing Fig 24B shows the effect of toeing-in alternate lamps of each unit in the outer 1,000 feet, 30° toward the axis of the approach lane It can be seen that the area within which both lines are visible, starting outward from the

TABLE VI

Visibility Range and Glare Distance Comparison Between 250-watt PAR-56 and 400-watt PAR-56 Lamps in Slope Line Approach Light System

Visibility Condition	Maximum Visibility Range as Seen From Glide Path (Horizontal distance in feet between pilot and runway end when lights are first seen)		Maximum Glare Distance of System as Seen from Glide Path (Horizontal distance in feet between pilot and runwav end when lights begin to cause glare)	
Night (25 cp)	250-watt lamp	400-watt lamp	250-watt lamp	400-watt lamp
1/8 mile, 4 0 per cent	3950	3950	No glare	800
1/4 mile, 0 8 per cent	4700	4700	1200	1600
1/2 mile, 0 16 per cent	5600	5800	3900	3900
Day				
1/16 mile, 100 per cent	2500	3500	No glare	No glare
1/8 mile 100 per cent	4300	4300	No glare	600
1/4 mile, 100 per cent	4900	5100	1100	1500
1/2 mile, 4 0 per cent	4800	4750	No glare	No glare

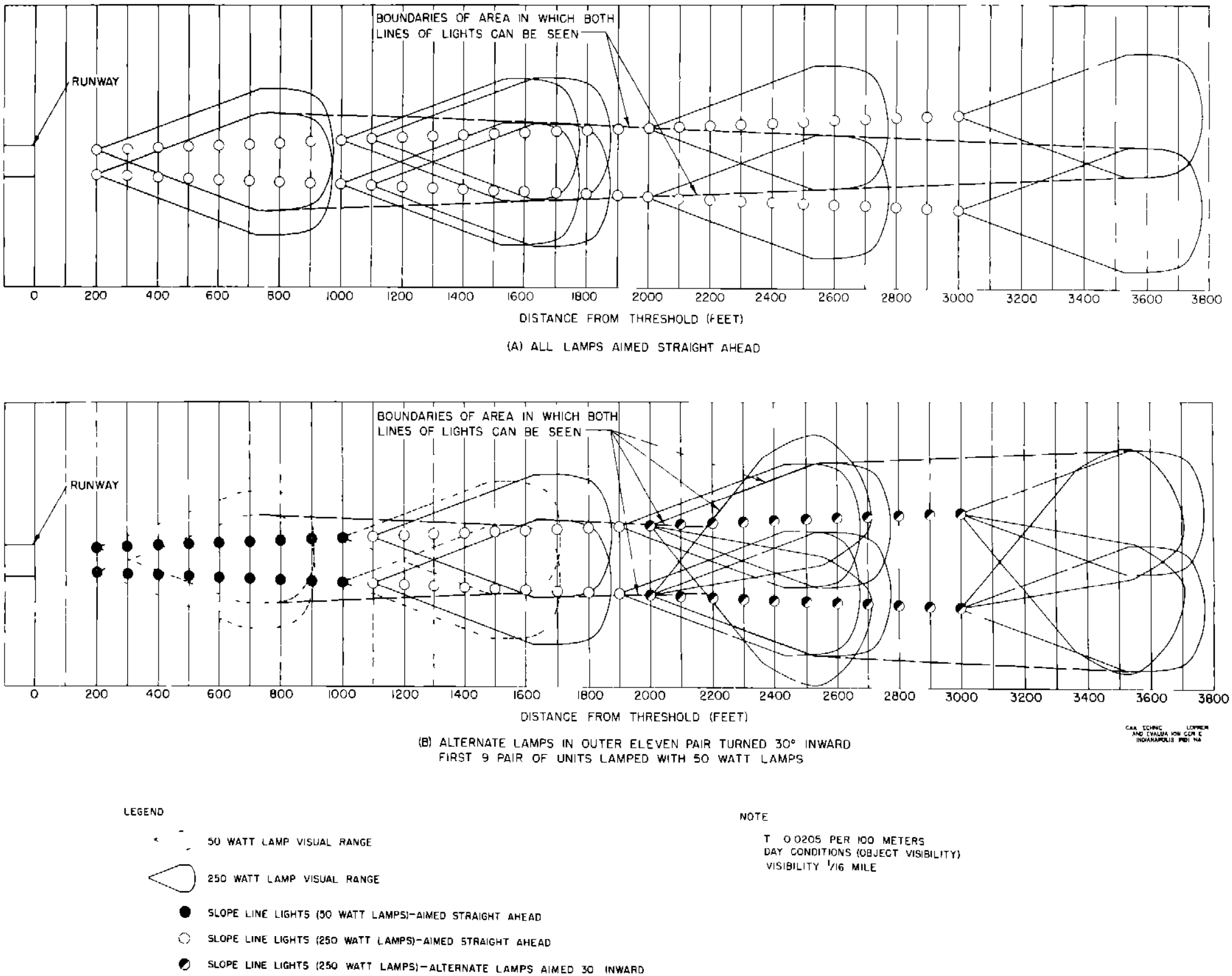


Fig 24 Diagrams Showing Area in Horizontal Plane Covered by Slope-Line Approach Lights - 100 Per Cent Brightness Setting

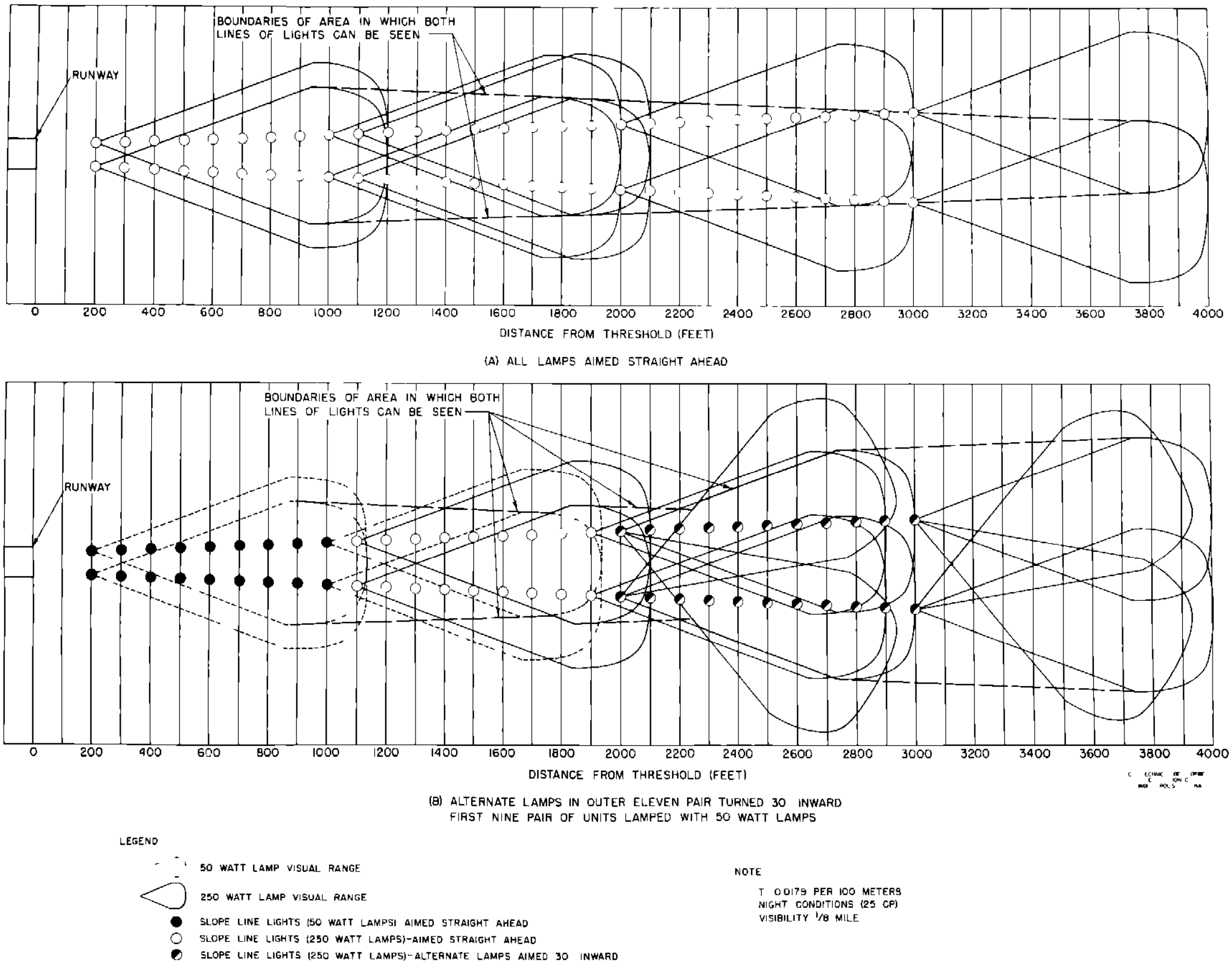


Fig 25 Diagrams Showing Area in Horizontal Plane Covered by Slope-Line Approach Lights - 4 Per Cent Brightness Setting

2,200-foot station, widens to approximately 700 feet, or more than double the distance between the outermost pair of lights projected on a line approximately 600 feet beyond the end of the approach-light system. The 30° toe-in is optimum for this condition since it gives the maximum coverage of the approach lane area. From Figs. 24 and 25 it will be noted that even though the visual coverage without toe-in might be enough to cover the entire area between the two sides, the area from which both sides can be seen is greatly increased by toeing-in the alternate lamps. Although a comparison of the two curves shows that as the visibility conditions are improved the need for toe-in decreases, the extreme conditions are the ones that should govern the design, since the toe-in does not detract from the value of the system under the improved visibility conditions.

Vertical Angular Settings of Lamps for Good Visibility Conditions

The foregoing discussion has covered the use of approach lights under conditions of restricted visibility. Under better visibility conditions (one mile or more), the lights have their peak visual range in the region above the glide slope, while clear weather approaches are made from below the glide path. Fig. 26 shows that if a pilot is below the glide slope with the lights aimed to intersect the glide slope at 1,200 feet, he will see the lights from a considerably lesser distance than if he were on or above the glide slope. If these lights are used as lead-in lights under good visibility conditions, the pilot first will be inclined to call for full intensity when he is at his greatest distance out and below the glide slope, and very likely he will later complain of the excessive brightness when he intersects the glide slope over a point nearer to the runway. This condition can be alleviated somewhat by depressing alternate lights in each bar of the middle 1,000-foot section, aiming them to parallel the glide slope. It will be seen from Fig. 26 that by doing this the effect will be to increase the visual range and also the brightness along and below the glide slope considerably, without requiring a higher intensity setting.

In view of the fact that considerably more approaches are made under good visibility conditions than under the more restricted conditions, in the case of the second 10 pairs of bars, consideration should be given to depressing alternate lamps of each bar so that the direction of their beams parallels the glide slope.

Effect of Overcast on Visual Range

The curves in Figs. 27 and 28 show how the visual range of a slope-line approach light is reduced by an overcast or low ceiling. These curves were plotted for various visibilities in the overcast, and it was assumed that there is a night (25 cp) visibility condition of 1/2 mile below the ceiling. Calculations were based on the use of 250-watt lamps at 100 per cent brightness. It can be seen from

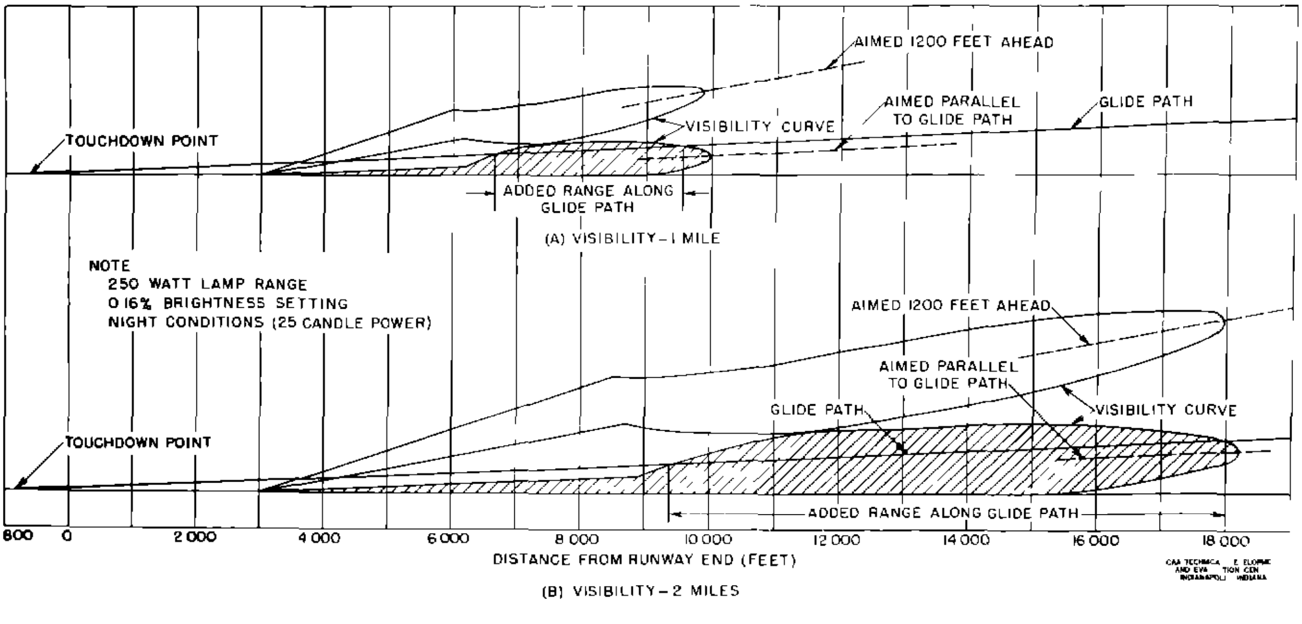


Fig. 26 Diagrams Showing Effect of Lowering Approach-Light Beam for Clear Weather Conditions

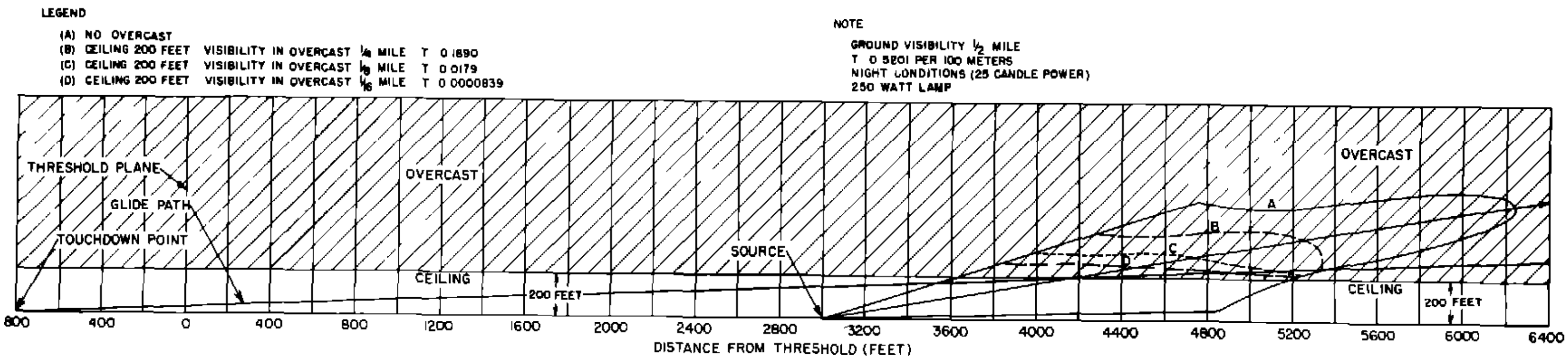


Fig 27 Diagrams Showing Visual Range in Overcast of Outermost Slope-Line Approach Light

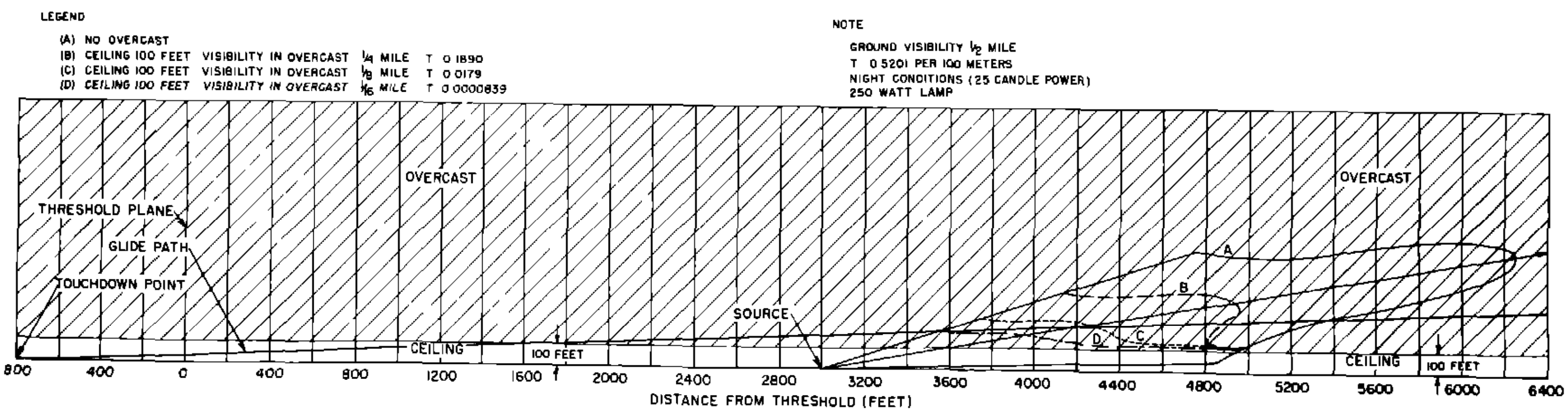


Fig 28 Diagrams Showing Visual Range in Overcast of Outermost Slope-Line Approach Light

Fig 27 that, with a ceiling of 200 feet, a pilot approaching along the proper glide slope will break out of the overcast approximately 1,200 feet before passing the outermost approach light As long as he stays on the proper glide slope, he will see lights 700 to 1,200 feet (depending on the visibility in the overcast) before breaking through When the ceiling is down to 100 feet, however, he breaks through the overcast at a point approximately 1,700 feet from the runway end Although the curves in Fig 28 show that the pilot will see the lights 1,800 to 3,200 feet before breaking through, it also can be seen that with the lower ceiling the range of the outermost lights is reduced considerably as the thickness of the overcast increases, and he will be much closer to the runway end before seeing any lights, than with the same intensities and the 200-foot ceiling

Since the studies of glare and visibility indicate that the higher intensities, which are required and tolerable for the lower transmissivity values in the overcast, cause too much glare when seen from below the ceiling, it would appear desirable to use higher intensities when an aircraft is in the overcast and lower intensities after it has broken out of the overcast This would add a serious burden on the control tower operator and require very accurate timing coordination It also would impose a requirement for rapid intensity change that would tax the capacity of existing control equipment It is apparent that study should be given to the possibility of dividing the approach-light system into sections, with individual intensity control provided for each section, so that the tower controller can set the lights for full intensity at the outer sections of the system, depending upon the ceiling height, and for the intensity as required for the region where the aircraft will be below the overcast

Recommendations

Various aspects of signal lighting as related to the application of the slope-line approach-light system have been covered in this study It is appropriate to summarize the possibilities that appear to have merit from the standpoint of modifying or using the present system to its greatest advantage

1 Use the table of intensity settings, Table V

2 Use 50-watt lamps in the 1,000 feet of approach-light lane nearest the runway to reduce glare

3 Continue the use of 250-watt, 12 5-volt lamps in the outer 2,000 feet of the approach-light system

4 Continue the general practice of aiming the lights to intersect the glide slope at a horizontal distance 1,200 feet ahead for restricted visibility conditions

5 Use a 30° toe-in of alternate lamps of each unit in the outer 1,000 feet of the approach-light system to provide wider horizontal coverage

6 Depress alternate lamps of each unit in the second 1,000 feet of the approach-light system so that their beam direction parallels the glide path, in order to provide greater visual range at lower brightnesses under good visibility conditions

7 Subdivide the approach-light system into sections with individual intensity control for each section in order that lights can be used most advantageously under conditions of low ceilings (200 feet or less)

With reference to item 2 it can be reported at this time that the slope-line system at Indianapolis has functioned satisfactorily for several years with 50-watt lamps throughout, and daytime approaches were guided successfully by these lights in visibilities down to 3/16 mile and 100-foot ceiling Since, however, visibility conditions at many other airports will be more restricted, it is not advisable to use lower wattage lamps throughout the system

The major part of this report consists of analytical studies of well-known and accepted principles of visibility Other parts, such as glare considerations, are based on documented field observations and on the results of numerous discussions with pilots, but depend so largely on subjective reaction that flight checking is indicative only Some of the recommendations, such as 5 and 6 have been confirmed by flight checking Recommendation 7 will require extensive experimental work and prolonged testing

Such flight testing as has been conducted to date on the effects of glare and on the effects of the toe-in and depressing of some lamps, supports and substantiates the results of this study Such testing will be continued as weather conditions permit until a sufficient body of evidence is accumulated

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