THE SLOPE LINE APPROACH LIGHT SYSTEM

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SUMMARY

This report describes a three-dimensional pattern of lights developed as an approach light system for landing aircraft under conditions of restricted visibility In this design the lights are linear in form, and are mounted in two geometric planes which intersect at right angles along the line of the approach path This system of approach lights provides a pilot with a unique and distinctive pattern which can be identified readily as an approach light system and which indicates visually his attitude and position relative to the proper approach path

With the aid of these indications a pilot is enabled to make a visual contact landing under visibility conditions materially more restricted than has hitherto been possible

The slope line approach light system has been adopted as standard for the United States by the Air Force-Navy-Civil Subcommittee for Visual Aids to Air Navigation, and confirmed by the Aircraft Committee of the Munitions Board

INTRODUCTION

Approach lights were developed originally to assist a pilot to line up with a runway in weather that was clear or nearly clear Their effectiveness was judged by the appearance of the lights as seen from a distance of several miles Lack of facilities for instrument flying restricted aviation operations to periods when visibility was reasonably good, and emphasis in the design of approach lighting was placed on conspicuity and distinguishability

Radio navigation aids now have been developed to a point where instrument flying has become routine and such aids can guide an aircraft on the landing path safely, to a point near the ground It is a function of the approach lights to supplement the radio aids by providing visual guides for the final stages of approach (the last 200 feet of letdown) and the actual contact with the runway The emphasis is now on approach lights to give accurate visual information to the pilot who is making a letdown in thick weather

Much work has been done on this problem in the past Breckenridge and Douglas have reported on experimental work done at the Civil Aeronautics Administration Technical Development and Evaluation Center at Indianapolis, Ind , and at Nantucket, Mass [1], and Kevern has reported on work done at Newark, N J and at Wright Field, Dayton, Ohio[2] The Navy, Bureau of Aeronautics, has conducted extensive experimental work on approach lights at Patuxent, Md , and has reported the results[3] Cutrell, of American Airlines, has done a considerable amount of bad-weather flying with the Air Transport Command and later as a civilian[4] The late A J Sweet made an intensive study of the problem, and the results of his work are included in this report The Air Transport Association has been very interested in approach light development, and has financed a major portion of the installation of two experimental patterns of approach lights at Newark, N J

The study of approach lighting has produced more widely varying suggestions than any other phase of aviation lighting The axial single line system and the multirow system, consisting of eight parallel rows, represent extremes to which designers have been forced by the logic of the elements to which they attribute most importance Relatively low

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

[2] G M Kevern, "Approach and Runway Lighting for Adverse Weather Conditions," Army Air Forces, Air Technical Command Report TSEFE 656-1566, February 1944

[3] A Soucek, "Test of High-Intensity Approach and Threshold Lighting," U S Naval Air Center, TED No PTR SE 209, September 8, 1948, and TED-PTR Test No 4333, 4333 1 2 and 3

[4] A E Cutrell, "All-Weather Flying Facilities," A paper presented at the SAE Annual Meeting, Book Cadillac Hotel, Detroit, Mich , January 7-11, 1946

brightness neon tubing and condenser discharge light sources producing flashes of many million candlepower represent extremes of equipment currently suggested

Many different patterns and systems of approach lighting have been proposed and studied These include, in addition to the slope line system, the following patterns

1 Axial single row, with fixed lights
2 Axial single row with flashing lights
3 Axial single row, with fixed and flashing lights
4 Single row on the left parallel to axis, and with fixed lights
5 Single row on the left parallel to axis, and with fixed and flashing lights
6 Two rows, parallel to and symmetrical with the axis
7 Multirow pattern, lines parallel to and symmetrical with the axis
8 Four row path-of-flight system
9 Two row path-of-flight system with both rows on left
10 Two row funnel system
11 Funnel system with axial line and cross rows [5]

Systems 1, 2, 3, 4, and 5 are single dimensioned, and 6, 7, 8, 9, 10, and 11 are two dimensional All of them consist basically of patterns of lights in a level plane, that of the threshold of the runway These patterns introduce difficult problems if the terrain does not fit this level plane If the ground falls off, the lights must be elevated to bring them up to the plane If the ground rises, the lights must be mounted in a series of parallel planes, letting down successively to the plane of the runway

Most of these systems have been installed and flight tested Serious difficulties were experienced in attempting to appraise the results of these tests, which were made under various conditions, at different locations, by different pilots and under various procedures In most cases no accurate record of meteorological conditions was available, and few records of flight paths were made It was found to be impossible to achieve any degree of co-ordination of the results of such testing

The greatest impetus to progress in the solution to the problem was the establishment of a joint project by the Departments of the Air Force, and the Navy, and the Civil Aeronautics Administration for the installation and flight testing of low visibility landing aids at the Landing Aids Experiment Station, Arcata, Calif There, at an airport whose weather history shows more consistent and frequent fog than any other available area, a complete system of radio and radar aids, fog dispersal equipment and various systems of visual aids were installed, and are being flight tested for objective data whenever fog occurs The project is under the technical supervision of a steering committee composed of members from the Departments of the Air Force, and Navy, Civil Aeronautics Administration, Civil Aeronautics Board, Air Line Pilots Association, and Air Transport Association Careful attention is paid to obtaining factual data, as complete as possible, and to the recording and reporting of such data More than 500 fog approaches had been made up to the end of 1947 and 600 additional fog approaches were made in 1948, and data have been tabulated and made available to the committee for study and to form the basis of recommendations [6]

APPROACH LIGHT SYSTEM REQUIREMENTS

In considering the development of an approach light system, it is necessary first, to establish the conditions under which it will be used, and the aid which the system should give the pilot To a pilot making a circling contact approach the function required of approach lights is very different from that required by a pilot making an instrument letdown This does not mean that one system of approach lighting cannot fulfill both functions but that the function must necessarily be adapted to the type of operation with which it is employed The system of approach lights described in this report is designed essentially to give visual aid to a pilot making an instru-

[5] E S Calvert, "Visual Aids for Low Visibility Conditions " Journal of the Royal Aeronautical Society, July 1948

[6] Landing Aids Experiment Station, "Airfield Lighting " Final Reports for 1946, 1947, and 1948

ment letdown in fog See Appendix I. Its application to other approach problems will be discussed also

It should be borne in mind that an approach light system is only a part of the coordinated landing aids In order to use these lights effectively adequate radio guidance, adequate threshold lighting, and adequate high-intensity runway lighting also must be provided The radio aids are required to bring the pilot within sight of the approach lights, on approximately the correct course, and to a point within 200 feet of the ground See Appendix V The approach lights, by means of visual references, guide him correctly on the proper path down to where the threshold lights mark the beginning of the runway, and the high-intensity runway lights give him guidance and height reference for the final touchdown

Region of Guidance

The Steering Committee for the Landing Aids Experiment Station, (Air Force-Navy-Civil Subcommittee on Visual Aids to Air Navigation) appointed an Approach Light Evaluation Committee, which formulated Operational Requirements for Approach Light Systems These requirements are given in Appendix VII, and are based on test flying done up to the end of the fog season of 1947 The region of guidance is defined in the Operational Requirements for Approach Light Systems as the region from which the approach lights must be effective This region, as defined, is predicated on visibilities not less than one-quarter mile (402m) by daytime, and it is necessary to reconsider its application to a range of visibilities extending down to the ultimate through which it is practical to make lights effective

The region of guidance can be considered from several different standpoints One of these is the maneuvering limitations of the aircraft, and a second is the limits in divergence of aircraft from the correct approach path, experienced when operating by instrument guidance

In considering the region of guidance in connection with the maneuvering ability of the aircraft, it is obvious that the limits of the region need not be set any farther from the approach path, laterally or vertically, than the maximum distance within which an aircraft can safely be maneuvered for a landing in the distance available Any lights which may be visible from outside this area can serve only as indications of missed approaches

In considering the lateral displacement from which an airplane can maneuver to the approach path within the space from the outer end of the approach lights to the threshold of the runway, and make a successful landing, a study was made of the path of an airplane at various speeds and at various angles of bank This is shown in Figs 1 to 3 inclusive The curves represent the path of an airplane making a banked turn, and are independent of the type of airplane Some aircraft can be slipped or skidded to achieve a somewhat greater lateral correction, but it is believed that such a maneuver would be little used so close to the ground and in weather thick enough to be critical In many discussions with pilots familiar with transport aircraft, none expressed willingness to use a bank of more than 10° after he had sighted approach lights during a letdown in fog From these data it is believed that, in thick weather, a transport airplane more than 150 feet to one side of the proper approach path, could not normally be brought in to this path from 3, 500 feet out, in time to make a successful landing This limitation will become more and more severe

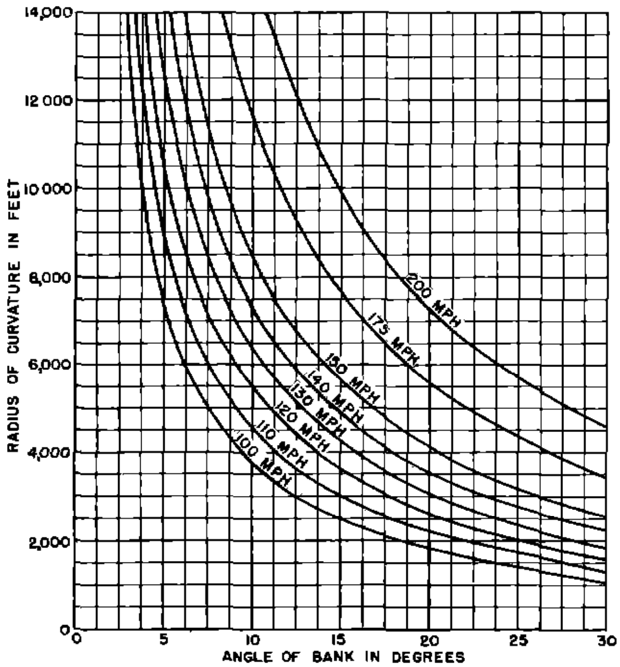

Fig 1 Radius of Curvature of Path of Airplane Plotted Against Angle of Bank

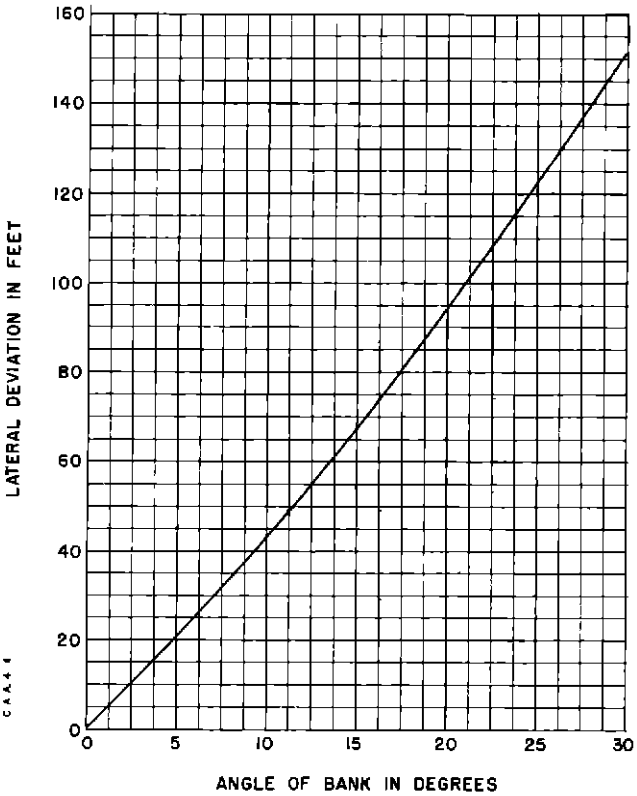

Fig 2 Maximum Lateral Deviation of Airplane From Original to Parallel Path Within 1,000 feet Forward Travel at 120 mph With Varying Angle of Bank

with larger and faster aircraft See Appendix VI

The upper limit of the required region of guidance is established automatically by the maximum desirable rate of descent for aircraft If the rate of descent is limited to 700 fpm the height of an aircraft approaching at a speed of 120 mph can not exceed 280 feet above the runway level as it crosses the middle marker (3,500 feet from the threshold) This is 80 feet above a normal ILS glide slope installation

Since the purpose of the approach lights is to supplement radio guided approaches, the region of guidance throughout which the approach lights are required to be effective should not exceed the limits of the accuracy with which normally skilled instrument pilots follow such guidance Data are available from many test approaches under the hood See Appendix II A series of such flights, conducted by the All-Weather Flying Service of the USAF at the Clinton County Air Force Base, was tracked instrumentally by recording theodolites[7] The results of a series of these flights are shown in Fig 4 From this it can be seen that 46 per cent of the flights were within 50 feet, 73 per cent within 100 feet, and 97 per cent within 150 feet horizontally, of the approach path at a distance from the threshold corresponding to the location of the middle marker, and approximately at the beginning of the approach pattern

In considering the height of the area to be served by the approach lights, an examination of Fig 4 will show much less variation from the approach path vertically than horizontally Ninety-three per cent of the approaches are within 50 feet of the approach path and 99 per cent are within 100 feet These data indicate that the region of guidance should extend up to 50 feet above the glide slope at 3,500 feet from the threshold.

In considering the length of the region of guidance, the height of the glide slope is the limiting factor It has been found that a pilot normally can expect to see approach lights when he is not over 200 feet above the level at which the lights are mounted Most approach paths, as established by ILS, place an airplane 200 feet above the level of the threshold at the middle marker, at 3,500 feet from the threshold If the length of the approach light system is made 3,000 feet, it would appear to extend as far as it can be made effective in critical weather

Operational Requirements

The visual guidance required to assist a pilot in landing an aircraft under low visibility conditions can be considered under the following elements (1) longitudinal, (2) lateral, (3) vertical (4) attitude or roll, (5) directional, and (6) identification All of these elements

[7] Air Force All-Weather Flying Division, "Measurements on the Flyability of the AAF Instrument Low Approach System" Report No AWTL-6-2, dated August 22, 1947, and "Measurements on the Flyability of the AAF Ground Control Approach System and Comparison with the Results Obtained for USAF Instrument Low Approach System" Report No AWTL-6-3, dated March 17, 1948

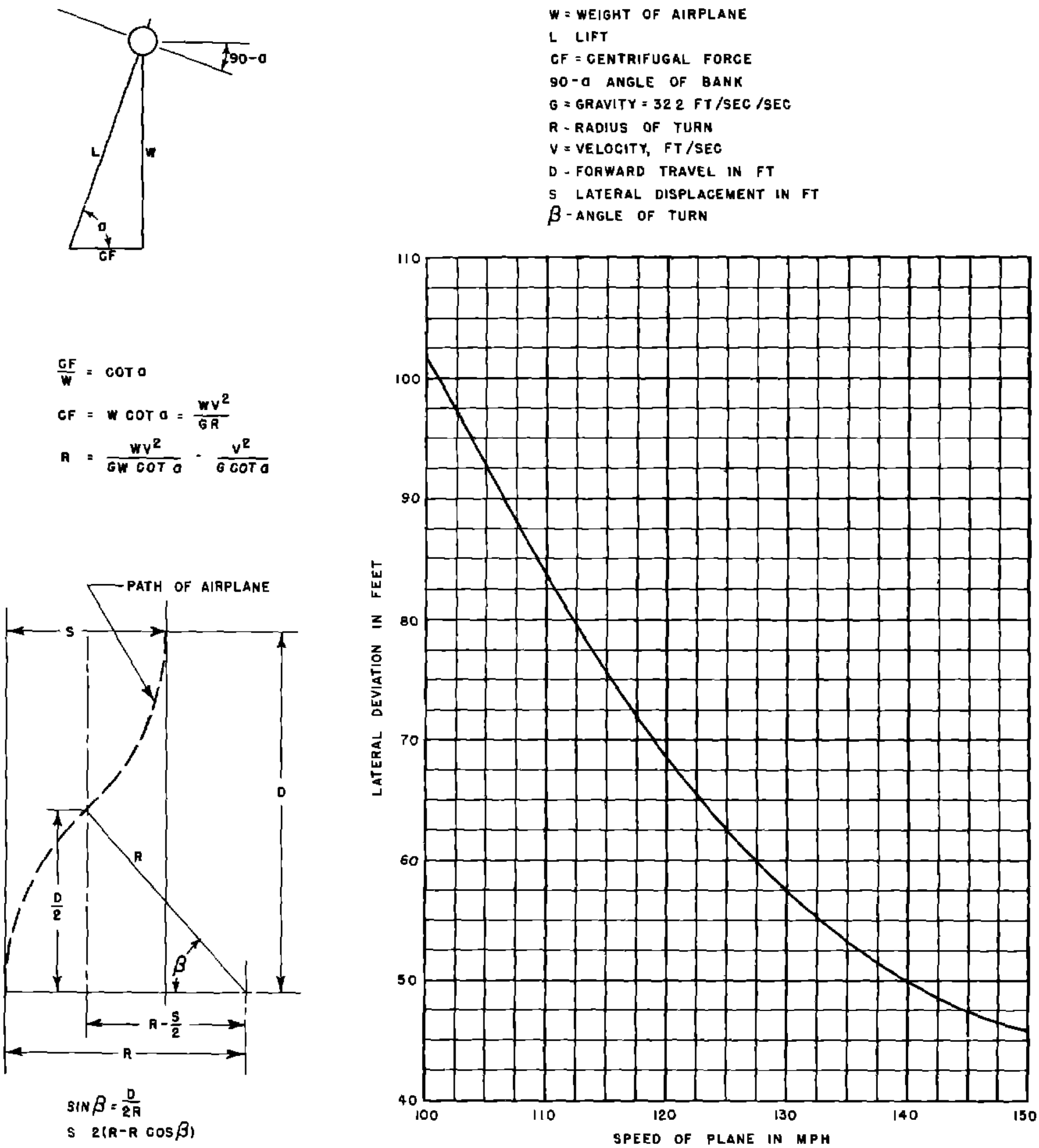

Fig 3 Maximum Lateral Deviation of Airplane From Original to Parallel Path Within 1,000 feet Forward Travel With 15° Bank and Varying Speeds

are required in some degree Longitudinal guidance has been given little importance in the past, and, while its need is now recognized, it still is probably the least important element Lateral guidance, roll guidance, and directional guidance are essential They are so interrelated that they cannot be evaluated individually, and one cannot even exist in the absence of one or more of the others Vertical guidance has been given little importance in

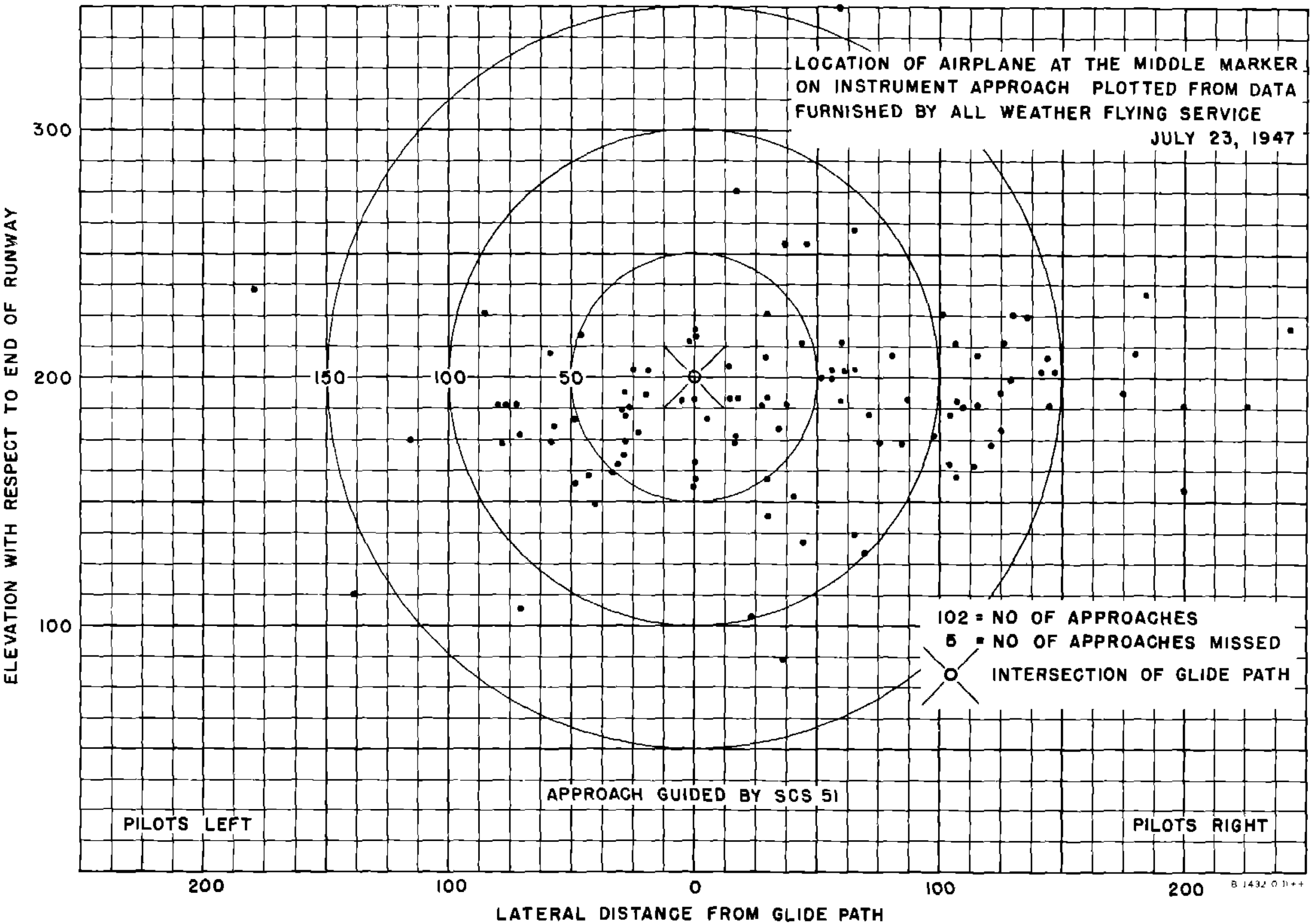

Fig 4 Charted Record of Approaches Made Under the Hood

the past, and has been ignored or given only a minor place in the design of most other approach systems Yet vertical guidance is of prime importance and cannot be stressed too highly A recent study[8] states, "The most critical component of the pilot's job, as determined from all sources, is that involving the skills of establishing and maintaining a proper angle of glide, rate of descent and speed of glide on the approach Failure to perform this part of the job adequately was found to result in three times as many accidents as does failure to perform any other part of the job "

Attitude guidance, or the establishment of a visual horizon reference by means of the approach light pattern is very important, although it is ignored by the advocates of a single-line pattern, and its importance is still largely overlooked or even denied strenuously by some experienced pilots Calvert[9] attributes great importance to this function, and has, in fact, designed his system around it This function is discussed at greater length in Appendix II A horizon reference is best given by horizontal lines at right angles to the course of the airplane It cannot be given by a single line parallel to the course, or even by two or more lines parallel to the course The best horizon reference afforded by any of the approach light patterns proposed is that given by the funnel system with an axial line and a series of cross lines described by Calvert

Identification is essential before any other element has any meaning, and so is interlinked with every other element of the list

It is not practical to try to evaluate these elements separately without consideration of the interrelationship of each with the other Efforts have been made to assign numerical weighting to the various elements of visual guidance and to the adjective ratings of the effectiveness reported by the test pilots, and to arrive at a numerical rating of the systems being compared at Arcata These ratings were assigned by the test pilots and other participating pilots, but the results showed anomalies and distorted comparison evaluations which were widely at variance with the opinions and effective results shown in the analysis of the flight data A more effective means of evaluating the guidance required of approach lighting is based on consideration of the operating conditions If the function of the approach lighting system is so considered, the various elements can be appraised in their proper subordinate relationships to the basic function of the system

An aircraft making a landing under low visibility conditions is guided to the portal, approximately on course by the radio aids These aids mark a path in space which is essentially a straight line The approach light system, whose function is to supplement the radio aids and to provide visual reference for a contact landing, also should delineate the same line in space In order to define a line in space three dimensions are necessary and any system of visual reference which does not possess three dimensions cannot define such a line

Requirements discussed so far have been considered on the basis of a straight-in approach in thick weather The pilot making a circling contact approach requires a different type of guidance Such approaches are made only when visibilities are three-quarter mile (1207m) or better The normal procedure consists of a down-wind leg, a 90° turn, a base leg, a turn into the line of approach, and the final approach During this procedure the pilot should be able to see the location of the approach area from any angle up to 90° from either side and from a vertical angle of 30°, and also should be able to see a directional marker indicating the line of approach Requirements for circling approaches are outlined in Sections 4 4 and 4 5 in Appendix VII

Functional Requirements

Lights used for guidance of aircraft are used as luminous signals, and the light sources themselves must be made visible to the pilot When visibility is restricted, the distance from which a light can be seen depends on the brightness of the light, the brightness of the background against which the light is seen, and the loss of light in the

[8]Thomas Gordon, "The Airline Pilot A Survey of the Critical Requirements of His Job, and of Pilot Evaluation and Selection Procedure " Civil Aeronautics Administration Division of Research, Report No 73, November 1947

[9]See footnote 5

atmosphere between the light and the observer

Fig 5 shows the relationship between the brightness of a light, the transmissivity of the atmosphere, which is the proportion of light penetrating a unit distance, the equivalent daytime visibility distance and the distance from which the light can be seen It is more fully described in Appendix III The curves of candlepower in this chart are given double values, one for a moonless starlit night, and one which applies to lights viewed in a daylight fog in heavily overcast weather

The tabulation on the right of this chart is 'Equivalent Object Visibility" By this is meant a degree of fog which would just permit a tree or a house to be distinguished at a distance indicated, and if observed by daylight Should the same degree of fog occur at night, it would be defined by the same figure on the chart, even though the house or tree would be concealed by the darkness "Object Visibility" as used in this report refers to the "Equivalent Object Visibility" defined above, regardless of whether daylight or dark conditions are considered From the chart it is evident that in a fog restricting object visibility to 450 feet (137m) a light of 100,000 candles can be seen from 1,000 feet (305m) by daylight and can be seen from 1,600 feet (486m) distance if viewed at night Similarly, with a 300-foot (92m) object visibility this same light could be seen from 700 feet (213m) by day or from 1,250 feet (380m) by night

It is obvious that a light signal designed for effective use in fog, and with a brightness of 80,000 to 100,000 candles is entirely too bright to be tolerated in clear weather In order to avoid uncomfortable glare*, it is necessary to be able to reduce the brightness of these lights by degrees to the order of 100 candles for use in varying degrees of fog and haze up to clear weather For this purpose brightness control is necessary

In order to be able to use lights for guidance, it is essential that a pilot be able to identify and distinguish the lights he sees The various means whereby lights can be identified are by shape, pattern, color, and flashing characteristics These means for identifying and distinguishing light signals are discussed and compared in Appendix IV

SLOPE LINE SYSTEM

Basic Concept

The slope line approach light system is the result of a new and radically different concept of a solution to the problem of guiding an aircraft to a landing This concept recognizes that the problem is basically one of defining the pilot's relationship to a line in space, the necessity of providing three dimensions to define such a line, and of providing the pilot with a visual guide that is positive and easily followed

The most effective means of defining a line in space, where the defining elements are necessarily located remotely, is to define two planes whose intersection forms the desired line The visual defining elements conveniently consist of parallel lines lying in the two planes Planes intersecting at right angles were chosen, as shown in Fig 6, because the sensitivity of the definition reaches a maximum when the planes are at right angles to each other

Configuration

The slope line approach light system consists of two rows of linear light units, one

* The matter of glare is of vital importance, as everyone who has driven an automobile at night can appreciate Breckenridge and Douglas discuss the problem of distribution of light intensities with respect to dazzle on page 814 et seq and develop a chart shown as Fig 21, page 816 of their report, (see footnote 1) This chart indicates that glare or dazzle occurs when a light is approximately 1,000 times threshold brightness Kevern (see footnote 2) recognizes glare, but accepts it as a necessary evil Glare is affected by several factors, including the background illumination, the relative brightness of the light source and the threshold brightness, the part of the retina on which the light falls, and the duration of exposure of the eye to the lights Lacking sufficient data to evaluate these various factors, we can still recognize that glare or dazzle is objectionable and even dangerous, and that every effort should be made to avoid it

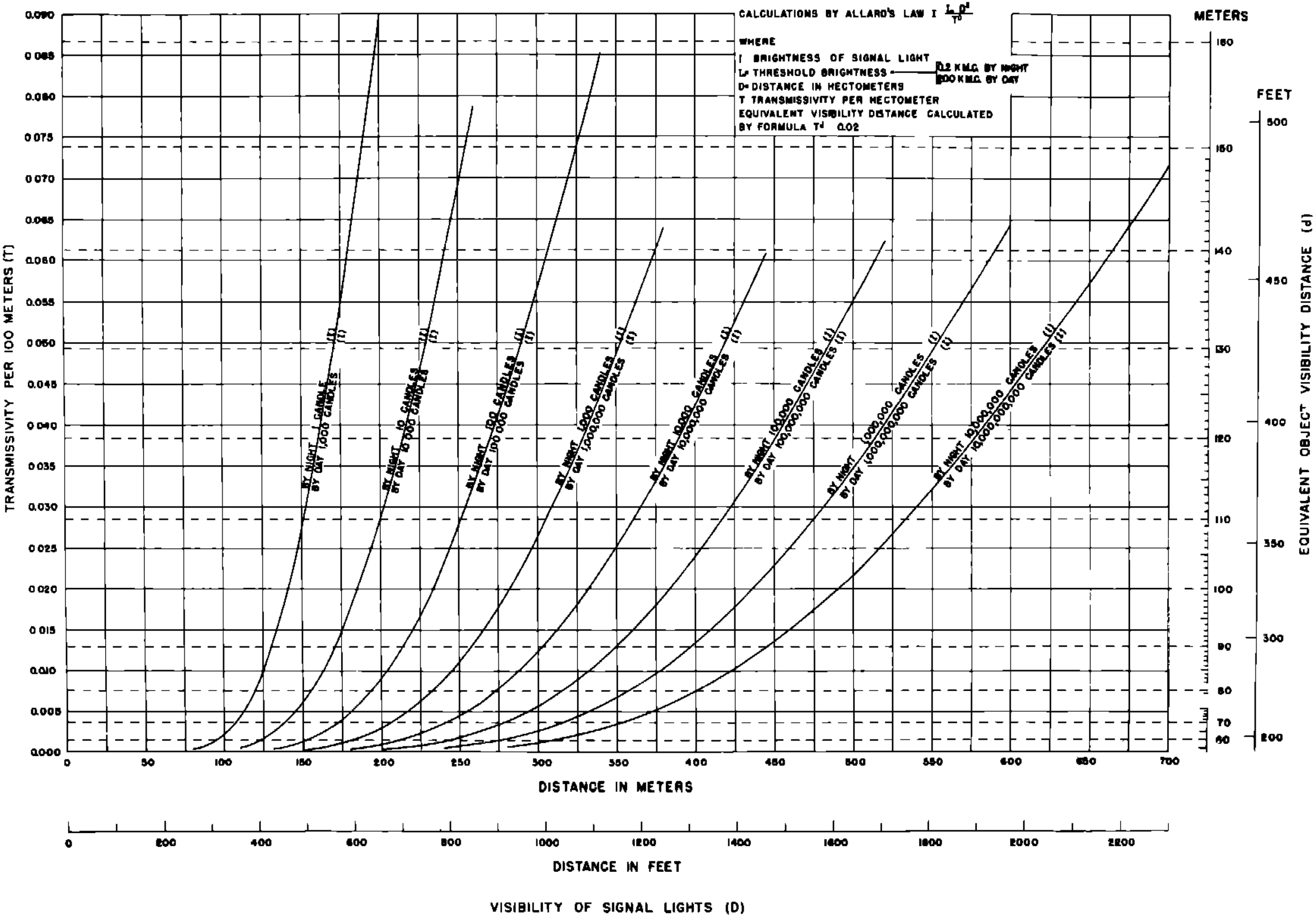

Fig 5 Chart of Visibility of Signal Lights

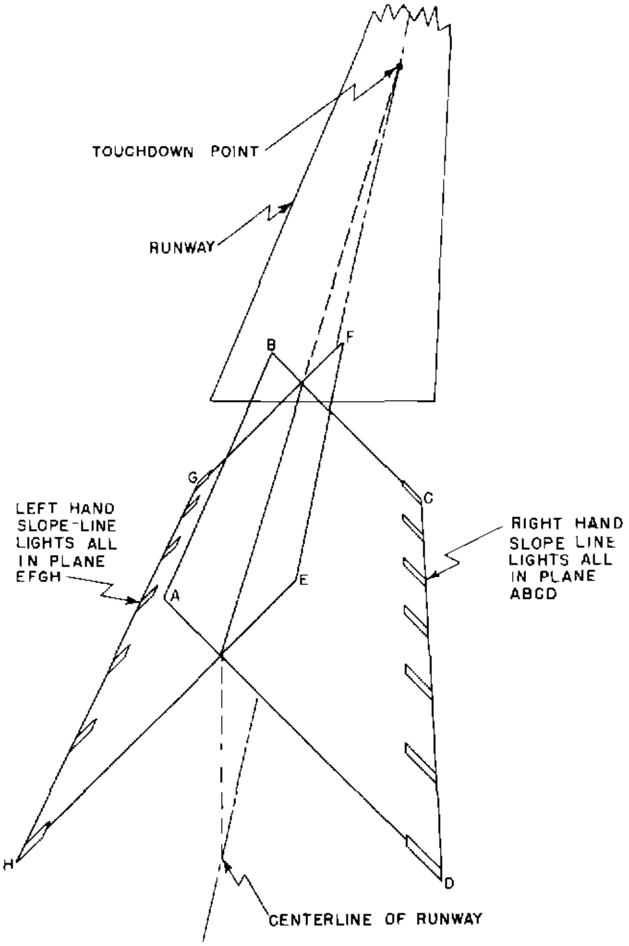

Fig 6 Diagram of Intersection of Planes

on either side of the approach, each row consisting of a series of parallel lines, all lying in the same plane The two planes in which the parallel lines lie intersect on the approach path as delineated by the radio aids This can be visualized as a skeleton of a roof, with the approach path forming the ridge pole, and the linear lights forming the lower part of the rafters To an observer on the ridge pole, all of the rafters on both sides will line up exactly If the observer moves from this position, the rafters will separate and break up into series of parallel lines These relationships are illustrated in Fig 7

The lines formed by the intersection of the planes with level ground in the approach will converge toward the threshold at double the vertical angle of the approach path Each pair of linear light sources also lies in a vertical plane which is normal to the axis of the approach These vertical planes are spaced at 100-foot intervals for a distance of 3,000 feet into the approach

The spacing of the pairs of lights in a direction parallel to the approach axis is affected by several factors

(a) The distance between pairs should be short enough so that at least five pairs are visible at one time under the lowest visibilities with which the system will be used, in order to develop clearly the characteristic broken-line pattern
(b) The distance between pairs should be great enough to maintain an angular separation between successive pairs, and prevent over-lap as seen from the glide slope
(c) The pairs should be close enough so that the characteristic pattern is easily interpreted

Referring to Fig 8, it can be shown that the following relationship applies

$$\cos \alpha = 2D\left\{(D-L) + 2H(H-S) + W^2 + U^2\right\} \times 2\left\{(D-L)^2 + W^2 + (H-S)^2\right\}^{-1/2} \times (D^2 + U^2 + H^2)^{-1/2} \quad (1)$$

Where

H = height of the observer above ground

D = distance of a given pair of light units ahead of the observer

L = distance between pairs of light units

S = vertical projection of the light unit

U = lateral distance to the outer end of light at D distance

W = lateral distance to the inner end of light at D-L distance

α = angle subtended at the eye of the observer between the ends of lights at distance D and D-L

If we assume an observer on a 2 4° glide slope, 3,000 feet from the end of the runway, observing the angle between linear lights 14

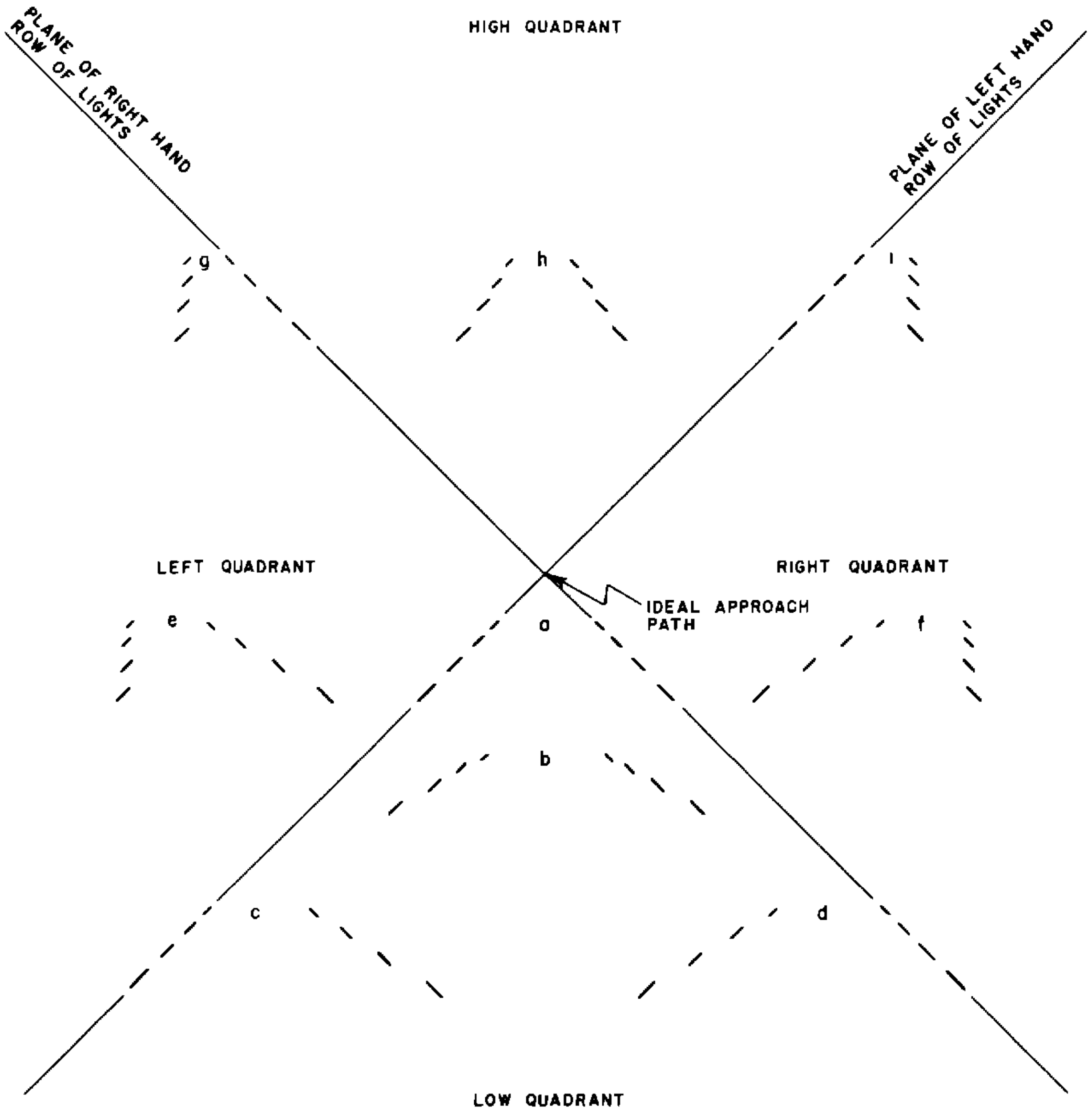

Fig 7 Characteristic Perspective Views of Slope Line System Letters Represent Relative Locations of Observer

feet long and 900 and 1,000 feet ahead of him

then

H = 180 feet
D = 1,000 feet
L = 100 feet
S = 10 feet
U = 140 feet
W = 134 feet

Substituting these values in equation (1), we get

$\cos \alpha = 1.0$ approximately, and $\alpha = 0$

In other words, the linear lights at that distance will tend to form a continuous line, with no break and no over-lap when the system is installed on level ground The angle will be increasingly greater on closer

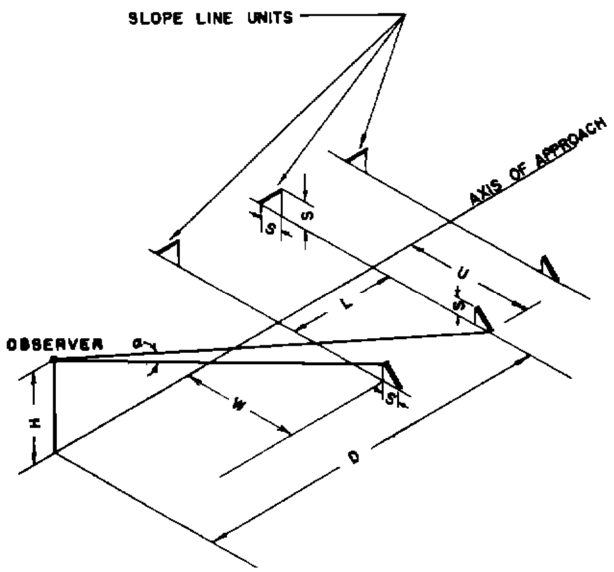

Fig 8 Diagram Showing Angle Between Adjacent Units Subtended at Eye of Observer

lights, whereas the lights will over-lap on others more than 1 000 feet distant A spacing of 100 feet between pairs of linear lights appears to satisfy adequately requirements (b) and (c) and also satisfies well requirement (a) Lights of 100,000 candles, which are economically available, can be seen from 1,000 feet distance in visibilities to 456 feet by day and 256 feet by night, and from 700 feet distance in visibilities down to 297 feet by day and 165 feet by night, as shown in Fig 7 Under these conditions, all lights up to these limiting conditions are visible also, giving ample pairs for pattern determination,

This system adapts itself readily to uneven terrain As the units are mounted in sloped planes, and as these planes intersect the ground, there is no need to bring the units up to any common level, but they can, in general, follow the intersections of the planes with rolling or uneven ground If sharp changes of ground level occur, it is advisable to limit the difference in elevation between adjacent units, not to exceed about ten feet There is one other limiting factor which should be kept in mind If the ground falls off so that the outer end of the approach light system drops materially below the inner end, the lights can be so far below the observer on the approach path that meteorological restrictions to visibility will make the system inoperative under conditions when otherwise it would furnish adequate guidance

Lighting Units

The basic unit for the slope line approach light system is a linear light source, i e , one which appears as a line instead of a point or an area The ideal source would be a tubular gaseous discharge lamp if such lamps with sufficient brightness were available, but, as these are not yet available, the linear light unit can be formed by a series of incandescent sources in reflectors mounted side by side, as shown in Figs 9, 10, and 11 The dimensions are governed by considerations of visual reaction The minimum angle normally discernible by the eye is about one minute and standard visual charts use a letter five minutes high, composed of strokes one minute wide An approach light system is seen from a distance not over 2,000 feet when conditions are severe enough to emphasize its importance, and from about 1,000 feet maximum when conditions are critical Hence, while it is vital to make the characteristic linear shape apparent up to a distance of about 2,000 feet, it is relatively unimportant at greater distances, because when the light can be seen from more than 2,000 feet away, the visibility is good enough so that no problem is involved

The individual linear lightsource selected consists of ten lamps mounted in a line The lamps are sealed beam PAR-56, with 7 in reflectors, 20 amp , 12 5 v filaments, and 30° spread lens forming the face See Fig 12 These lamps are mounted so that the lens spreads the beam over about 38° horizontally The vertical axis, which has a spread of almost 8° can be adjusted vertically Isocandle distribution curves of a 12 5 v, 250 w lamp are shown in Fig 13

The linear unit which forms the light source is 14 feet long This was adopted as a result of comparative tests made with units 8 and 14 feet long Thus the linear light is made up of a series of light sources, spaced approximately 17 in on centers, each of which has a horizontal spread of about 38° and a vertical spread restricted to about 8° The horizontal spread is designed to make the lamp visible from as wide an area as is feasible in producing candlepower high enough to be effective With 38° spread the beam

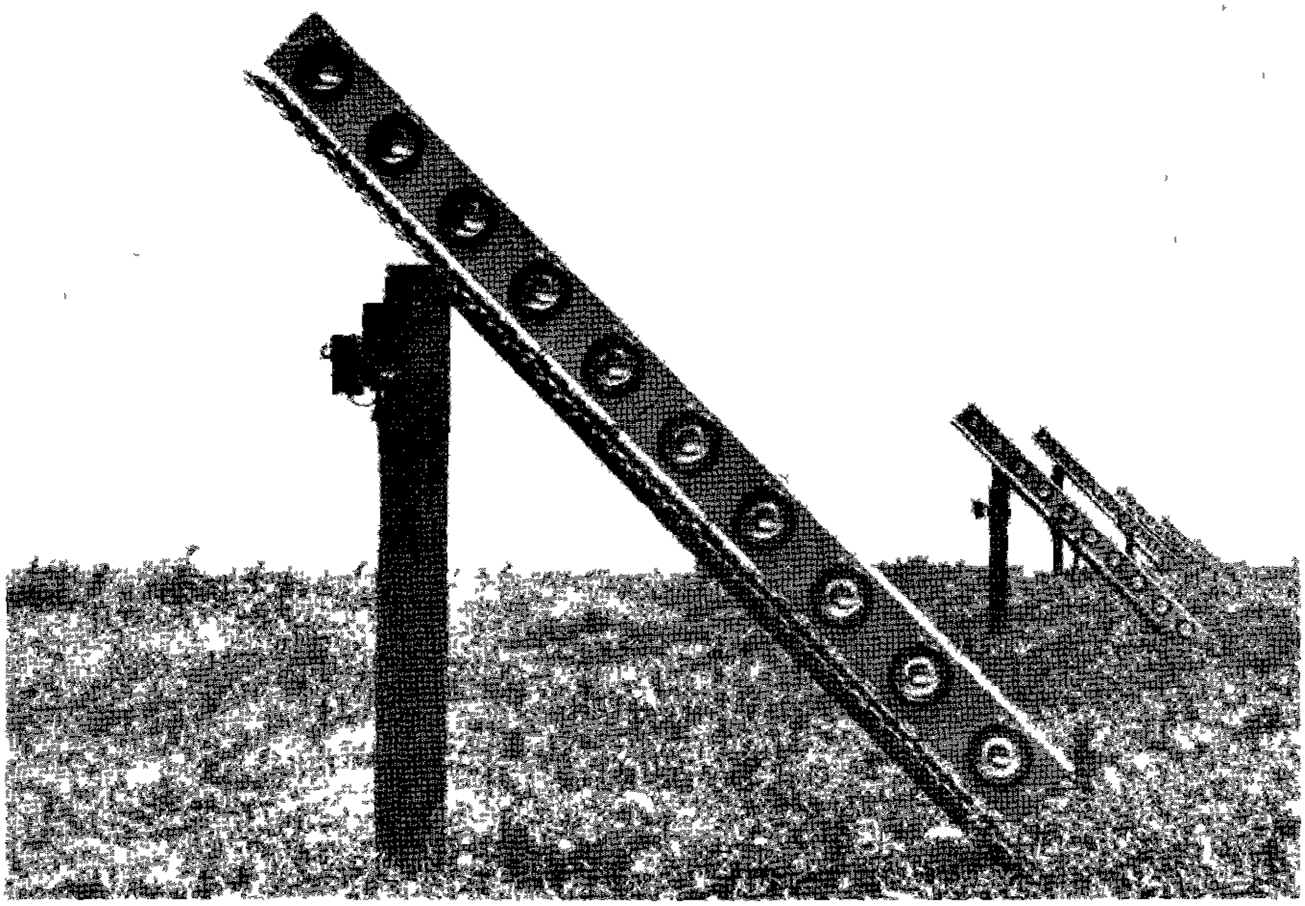

Fig 9 View of Units of an Experimental Slope Line Approach Light System at Indianapolis

will cover a width of nearly 540 feet at a distance of 700 feet

The vertical spread is kept narrow to avoid excessive glare Mr J. B Bartow, an early advocate of high intensity approach lighting, used the principle of reducing the brightness of a light in proportion to the distance from which the light will be seen, assuming that the pilot is on a predetermined path at a constantly varying angle to the light This method was very successful when the pilot was in the predetermined path, but proved impractical when he deviated from this path The method adopted to reduce glare with the slope line approach lights is based on the principle used by Bartow, but applied under conditions which should minimize the difficulties experienced by him The middle unit of a fixture is so directed that the vertical axis of the beam intersects the glide plane 1,200 feet in advance of the fixture, and all other units are set with the beams parallel to that of the middle unit Thus the beam is controlled vertically instead of horizontally, since experience has demonstrated that approaches normally are much more accurate in the vertical than in the horizontal dimension, as is shown in Fig 4 Another factor tending to improve the approach accuracy and, consequently, the effectiveness of distribution control as preventive of glare, is the definite and effective indication given to the pilot by the configuration of the slope line lights, which encourages him to fly the proper path

The sealed beam 250 w lamp will produce a beam of approximately 80,000 candles This brightness is necessary in order to provide adequate visibility for daylight fog and for the most severe night fog, but it necessitates a stepped brightness control to adjust the brightness to varying needs, and to avoid uncomfortable or even dangerous glare The brightness control used in experimental installations consisted of seven steps, each

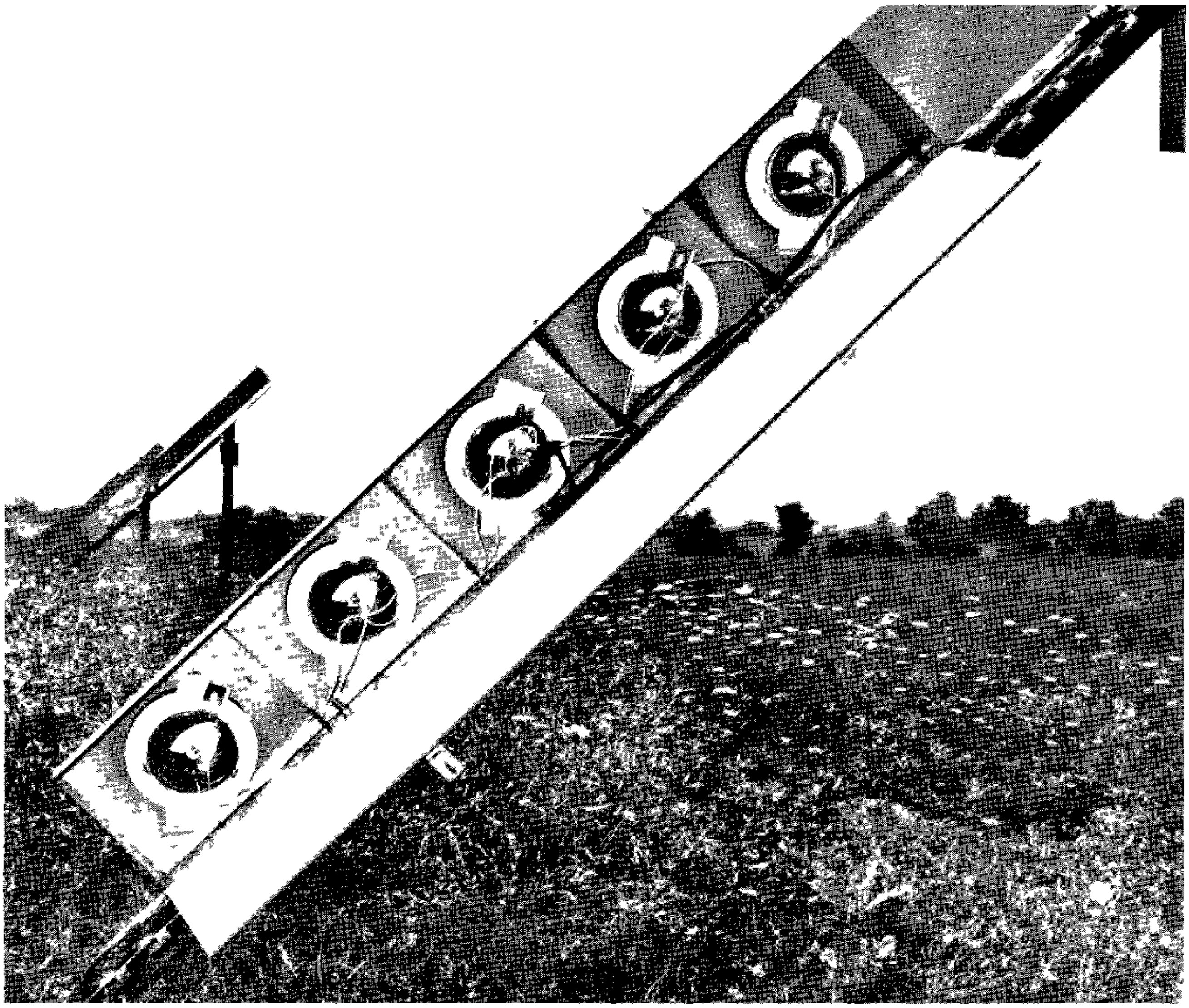

Fig 10 Rear View of Slope Line Unit, With Doors Opened to Show Hinged Mounting Plates and Method of Adjustment of Vertical Axis of Beams

reducing the brightness to about one-third that of the preceding step The per cent brightness versus candlepower for the seven step control is listed in Table I Since seven steps are somewhat unwieldy to use and, since it has not been established that brightness intervals of 3 1 are necessarily optimum, two other lists (six step and five step) each with a fixed interval are included in the table Step control is most conveniently exercised by varying the primary feeder voltage

Circuits and Control

The power distribution and circuits for the lamps are very simple, and can be handled in any one of several ways The lamps can be operated in series, with film cutouts for the individual lamps, but, because of the high current rating, the distribution should be at a standard low ampere rate, such as 6 6 amp with a transformer (6 6 to 20 amp) for each linear unit With series feed it is necessary to use a tapped autotransformer for the steps of brightness control Series distribution requires the use of high voltage in the order of 11, 700 v, or the splitting of the load between several regulators

Multiple operation appears to be a more practical system of distribution Due to the high current rating of the lamps, it is ad-

TABLE I

Brightness Steps For Controls
(See Fig 14)

7 Steps		6 Steps		5 Steps	
Per Cent Brightness	Candlepower	Per Cent Brightness	Candlepower	Per Cent Brightness	Candlepower
100	80,000	100	80,000	100	80,000
30	24,000	25	20,000	20	16,000
10	8,000	6 25	5,000	4	3,200
3	2,400	1 55	1,250	0 8	640
1	800	0 39	312	0 16	128
0 3	240	0 10	80		
0 1	80				

visable to use a separate transformer for each linear unit, and, if a suitable primary is selected, these transformers can be of the dry type The recommended system will distribute at 4,160 v, step-down to 240 v through 15 transformers, then distribute at 240 v to individual 240 v/12 5 - 25 v, 3-wire unit transformers With this distribution, either a tapped transformer or a motor-driven regulator can be used in the primary for brightness control

GUIDANCE PROVIDED BY THE SLOPE LINE SYSTEM

The basis for guidance provided by the slope line system is that of alignment of short lines This is optically and psychologically sound The system uses "vernier vision", which is an extremely sensitive means of indicating small deviations Psychologically, the system satisfies an innate sense of orderliness and, when alignment is achieved, there is established a feeling of confidence and assurance The three-dimensional arrangement gives a clear, definite and reassuring pattern to a pilot who is on the approach path, and a characteristic modification of the pattern whenever he deviates from the approach path into any of the four quadrants formed by the intersecting planes containing the linear lights.

The pattern of the slope line approach lights is not a natural pattern, and, consequently, the pilot will have to learn to interpret and use this pattern to its full capabilities This is not difficult A short briefing, with diagrams or photographs to show him what to look for and how to interpret the patterns are normally all that is needed Making approaches in good visibility, with the approach lights turned on at low brightness has been found to be an excellent method of gaining experience in the full interpretation of the lights

Identification of an approach light system, as such, is essential before any use can be made of it The slope line system is identified by the unique shape and setting of the individual linear light units A series of night photographs is reproduced in Figs 15 to 19 to illustrate the characteristic appearance of the system from various points in the approach zone

Longitudinal guidance is given principally by the beginning and the end of the pattern Some additional longitudinal indication is given to a pilot who is thoroughly accustomed to the pattern by his recognition of the dimensions of the units and consequently his height over them Distance markers, in the form of horizontal marker lines, may be added, and experiments are being conducted to determine the most effective arrangement

Lateral guidance is given very effectively by the alignment of the lights in the pattern To a pilot who is on or nearly on course, this guidance is sensitive to within about ten feet To a pilot who is off course and can still see both lines, the pattern gives him an unmis-

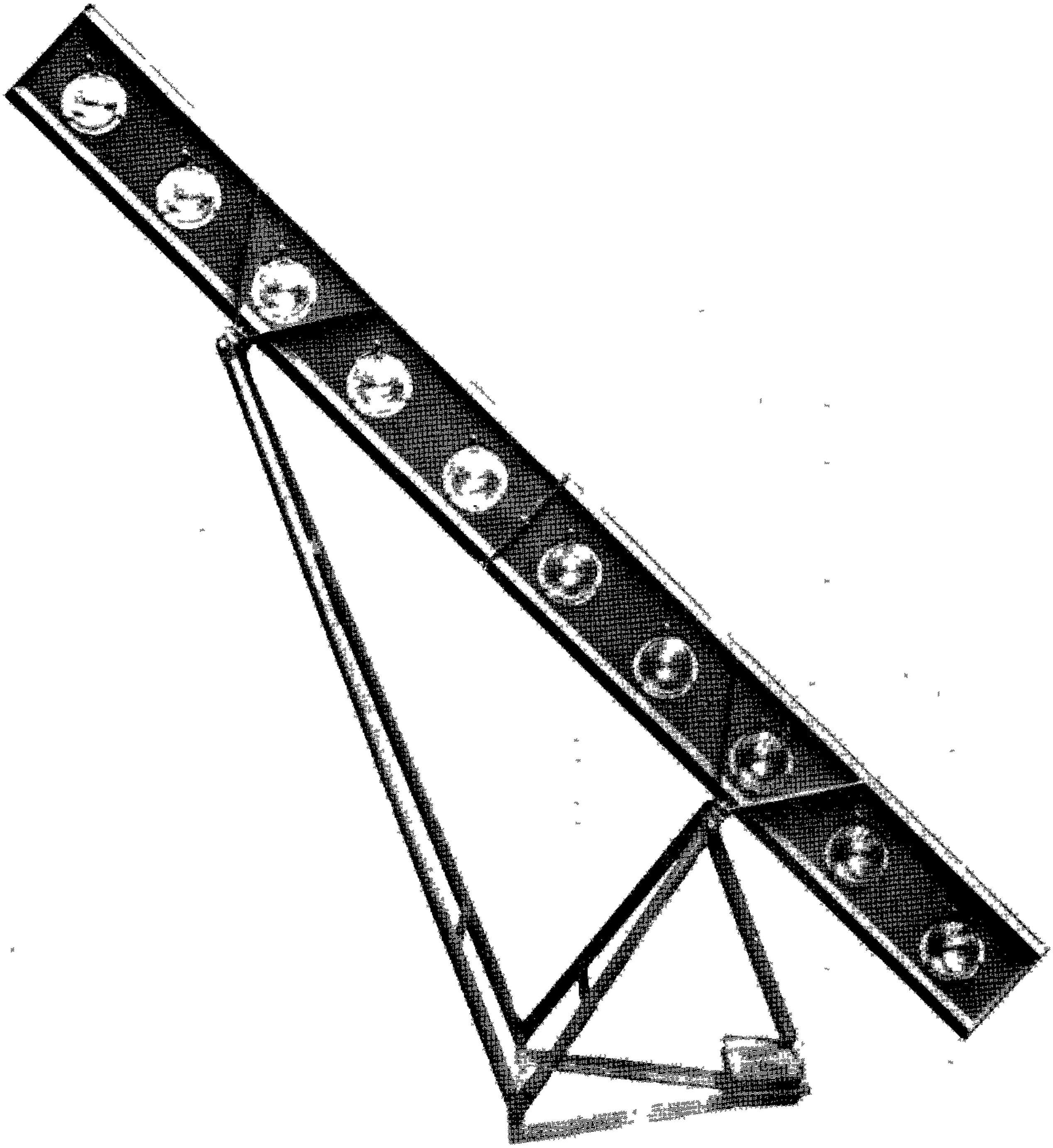

Fig 11 View of Production Slope Line Lighting Unit

takable indication of the direction in which he must go in order to correct his course See Figs 15 and 16 To a pilot who is so far off course that he can see only one line, any movement on his part to close up the elements of the line he can see will be in the direction toward the plane in which the lights lie and toward the axis of the approach In this case, in addition to the direction of correction given him by the closing of the line, he also will have an indication of height above the units by his recognition of their dimensions

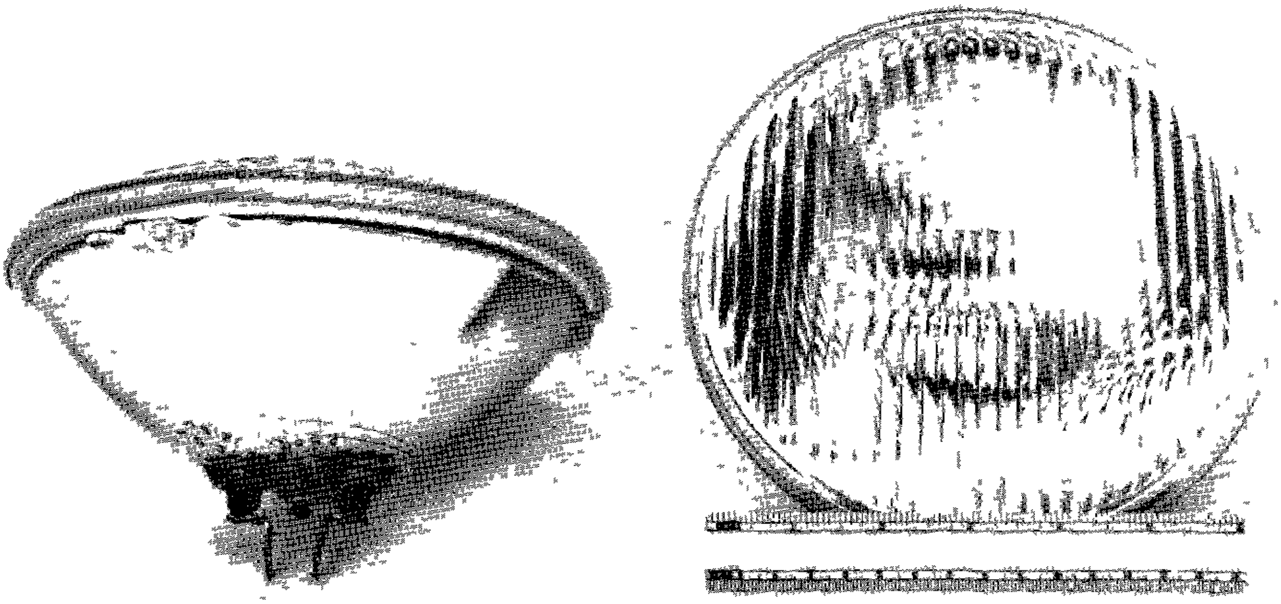

Fig 12 A 250 w PAR 56 Lamp Developed for Slope Line Approach Lights

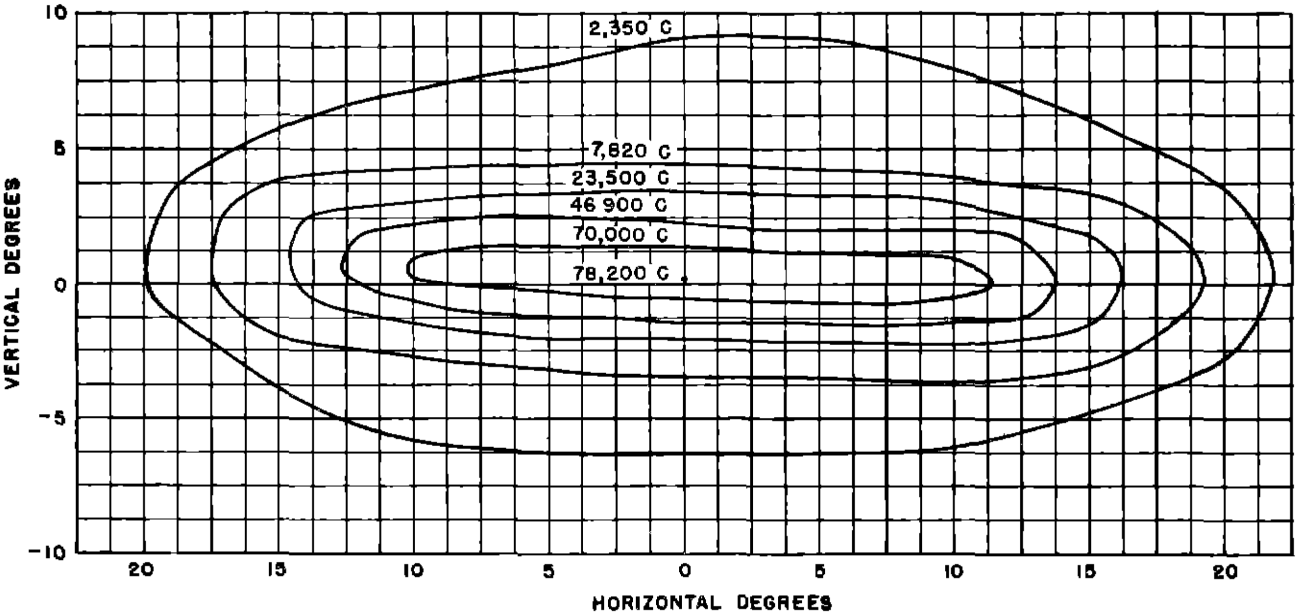

Fig 13 Isocandle Distribution of 250 w 12 5 v Slope Line Lamp

As long as he can see two units he cannot mistake the direction of correction

The slope line approach light system provides accurate and sensitive vertical guidance This is given by the sensitive alignment of the linear units, similar to lateral guidance This guidance is illustrated in Figs 17, 18, and 19

The system provides a horizontal reference and attitude or roll guidance by means of the symmetry of the angle formed by the two lines about a vertical axis This guidance is adequate and satisfactory when both lines are visible, but is reduced when only one line can be seen

Directional guidance is considered by many pilots to be of the highest importance, next to the identification of the system Di-

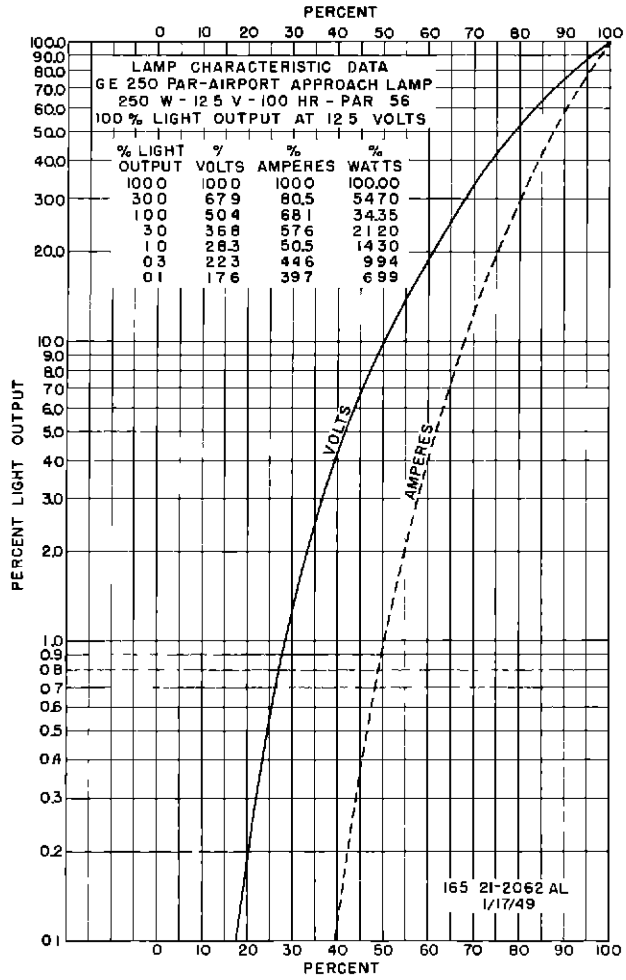

Fig 14 Characteristics of Approach Light Lamp

rectional guidance, however, is merely a function of attitude and lateral guidance Since these two elements are furnished, directional guidance is provided automatically

A recent report[10] includes perspective studies of the slope line pattern together with those of all other patterns of approach lights which are being considered seriously These studies demonstrate that the slope line pattern furnishes clear and unmistakable indications of lateral position, height, direction, and attitude The analysis also indicates that all the other patterns studied fail in one or more points, and that some of them can give indications which are misleading and confusing

After a full season of comparative testing at the Landing Aids Experiment Station at Arcata, the Air Force-Navy-Civil Subcommittee on Visual Aids to Air Navigation recommended to the Aircraft Committee of the Munitions Board that the slope line approach lights be approved as standard for the United States The Aircraft Committee approved this standardization

Further Developments

Circling approaches require guidance from outside the approach zone and off course, which is not normally afforded by the slope line system In order to provide for this need, the addition of the following elements is proposed

1 A light unit providing 90° horizontal and 30° vertical spread at the outer end of each pair of units nearest the runway
2 A light unit at the middle marker providing 315° horizontal and 30° vertical spread, having a distinctive and easily recognizable characteristic on the axis of the approach This unit can be a condenser discharge lamp

Extensive flight tests under actual fog conditions point to several other possibilities for further improvement of the slope line approach light system Experience has also modified the emphasis on the various elements of guidance Considerably more recognition is being given to the importance of vertical guidance and roll guidance Roll guidance, as given by the slope line pattern, can be improved by the addition of horizontal lines and these lines can serve also as distance markers

Although the slope line lights give excellent identification by means of the unique shape and setting of the linear light units, comparative testing indicates that the most distinctive and easily recognized lights are the flashing lights, such as those produced by condenser discharge lamps In order to take advantage of this conspicuity, it is proposed to test an axial line of flashing lights ahead of the approach light lane

The spacing of the individual light units forming the linear unit and the overall length

[10]R E Warren, "Perspective Analysis of Approach Light Patterns " Technical Development Report No 96, August 1949

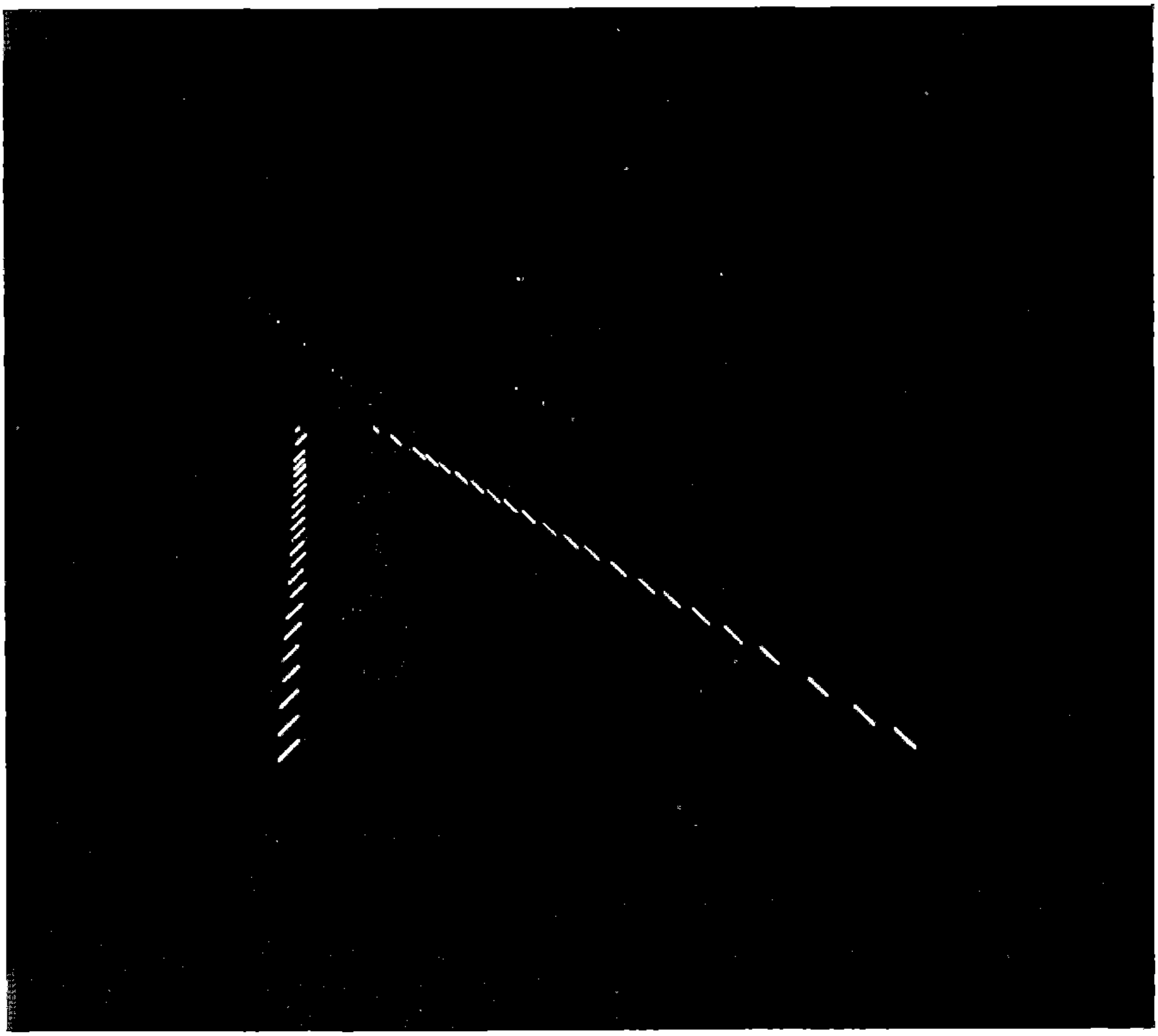

Fig 15 View of Slope Line Approach Lights From Airplane to Left of Course (Note Echelon Elements Pointing to the Right)

of the unit were decided by the results of several comparisons, but it is possible that further investigation into the visual effect of the proportions of luminous lines of various degrees of brightness and the spacing of units forming the line, will establish a different length of the unit as optimum, and a different spacing of lamps The individual lamps spaced 17 in on centers provide a possibility of turning lamps alternately to the right and left so that the width of the beam is doubled This is to be tried in practice, and should eliminate any tendency for one line to disappear

The use of linear lamps as a substitute for the associated groups of lamps used in the slope line unit offers possibilities, especially for installations where less severe weather limitations normally are anticipated Some work has already been done on stub approaches, intended for non-instrument runways, and based on the slope line prin-

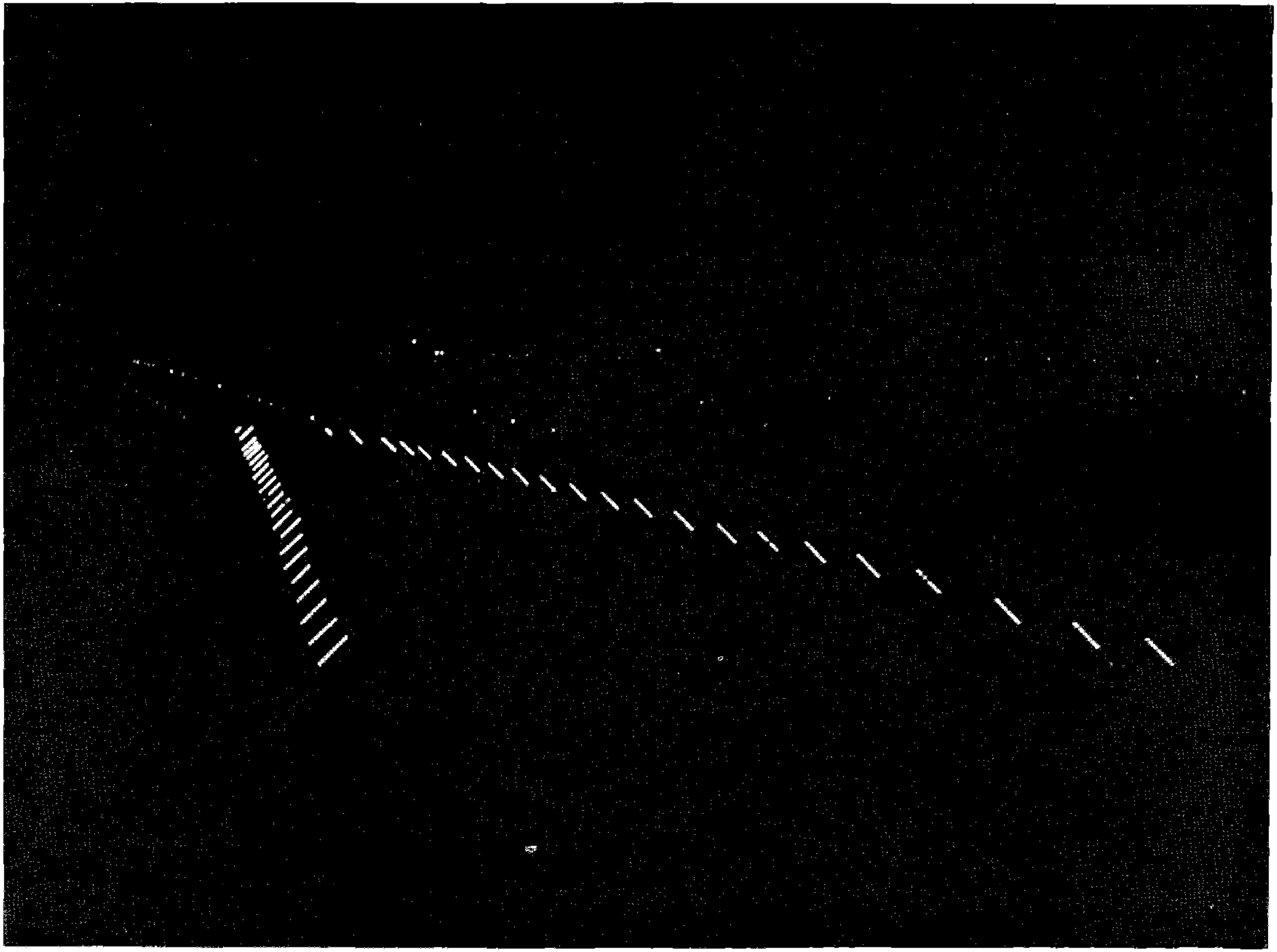

Fig 16 View of Slope Line Approach Lights From Airplane Low and to the Left
(Note Echelon Elements Pointing to the Right)

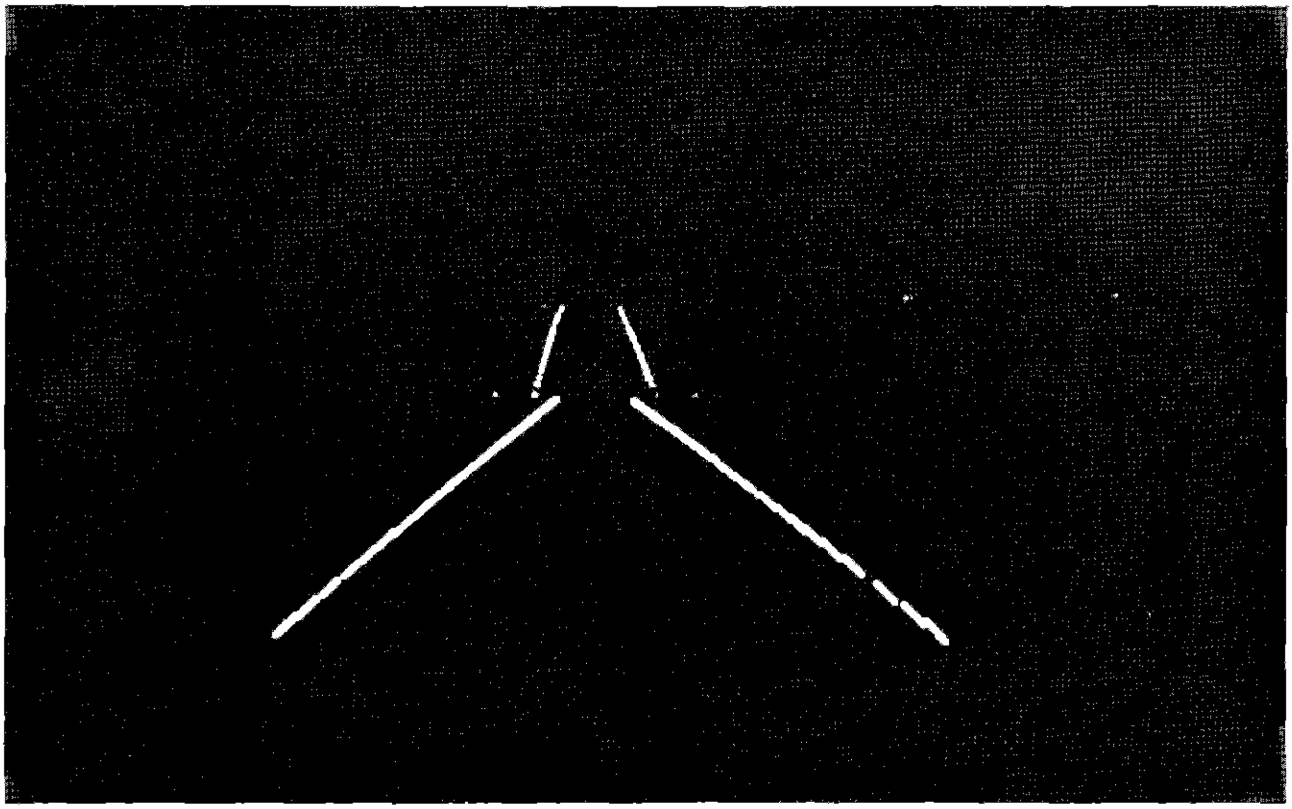

Fig 17 View of Slope Line Approach Lights From Airplane Slightly Below the Approach Path (Note Echelon Elements Pointing Up)

ciple[11] The relatively low candlepowers available from steady-burning gaseous discharge tubes are much more effective than a comparison of the brightness values would suggest At night these lights should be visible from 1,000 feet distance under visibilities well below one-eighth mile and, while their daytime visibility for the same distance would probably be limited to about one-quarter mile, sufficient assistance is given to a pilot by visibility of the ground plane in addition to the lights, such that daytime landings might be practical on these lights in fog somewhat denser than one-quarter mile (transmissivity down to about 0 32 to 0.35 per 100 meters)

The units of the slope line approach light system are installed where the 45° planes intersect the ground on both sides of the approach way Since the height of the intersection of these planes is determined by the height of the glide slope, (40 or 50 feet above the threshold) the lights normally will be not more than 100 feet apart laterally. In order to minimize physical obstructions, the pair nearest the runway were omitted and the second and third pair cut down to half length where they are installed on level ground in the experimental installation One method of further reducing this obstruction is to install the last 1,000 feet of the system on a 30° instead of 45° angle, resulting in a pattern resembling an arrow head, with a break in each line This modification is being installed for flight testing at Indianapolis This modification reduces the heights of the structures and moves them 73 per cent farther off the runway centerline Another development designed to lessen the hazard from obstructions caused by the light structures when the lights are not in use consists of a retractable unit, which could be used at the inner end of the approach light lane

[11] M S Gilbert and H J C Pearson, 'Development of a Stub Approach Light System " Technical Development Report No 75 December 1947

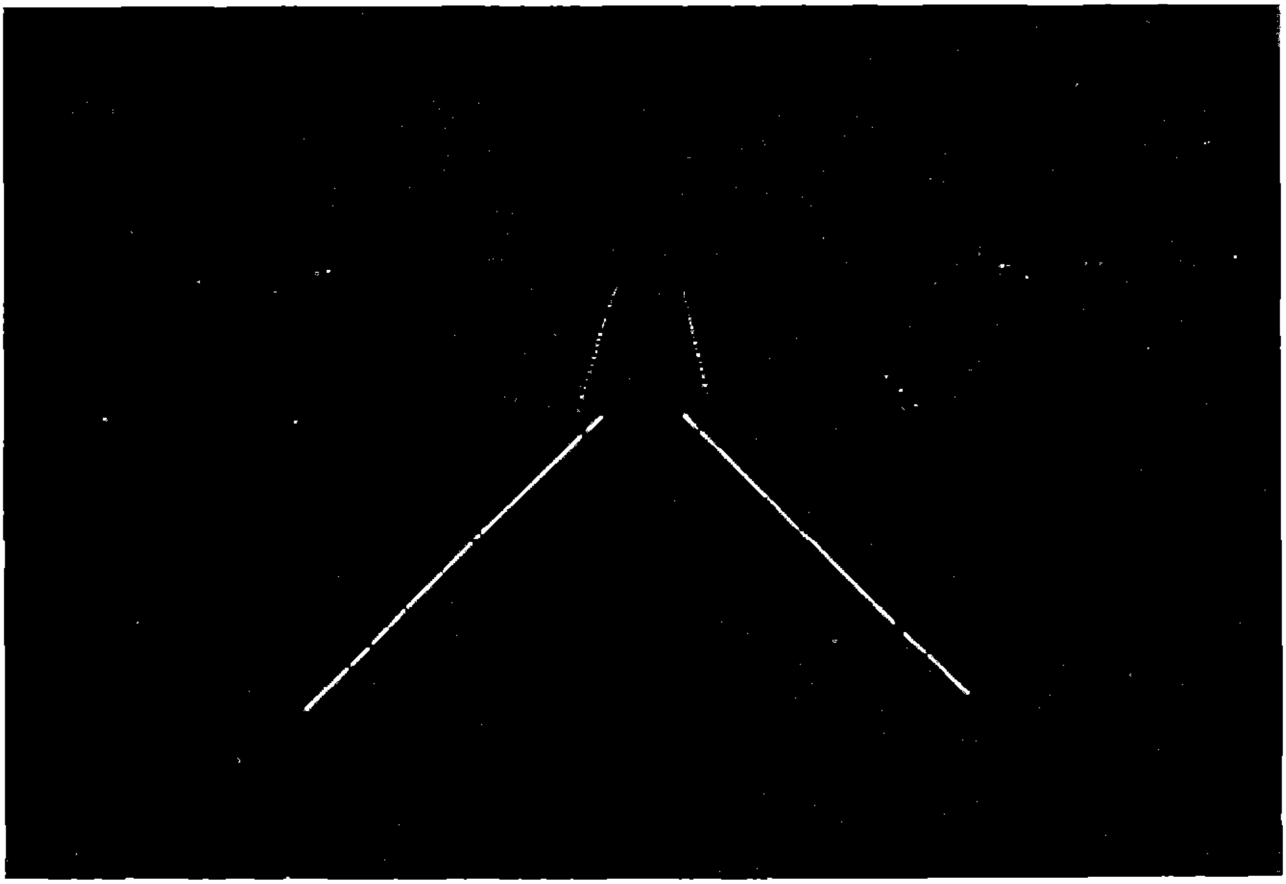

Fig 18 View of Slope Line Approach Lights From Airplane on the Correct Path (Note That all Elements Line Up)

ARCATA INSTALLATION

A complete system of slope line approach lights has been installed at the Landing Aids Experiment Station at Arcata, for flight testing in comparison with other approach light systems This installation was completed after the end of the 1947 fog season

The slope line approach lights are installed to indicate an approach path coinciding with that marked by the ILS and GCA Each light unit consists of a sheet steel box 14 feet long mounting ten lamps The lamps are airplane landing type sealed beam lamps, rated at 600 w at 28 v, but operated at 25 v. When operated at nominal 100 per cent brightness at 25 v , each lamp consumes 500 w All lamps on each fixture are connected in multiple and are fed by an individual 5 kva, 2,400/25-50 v, transformer Brightness control is provided by means of primary voltage variation, through the use of tapped transformers, relay-controlled by dial-type selectors in the control tower Each unit is mounted at 45° and is supported on a steel frame structure fabricated of war surplus perforated steel landing mat The structures are low, with fixtures close to the ground, except where one side of the approach is materially lower than the other, in which case the support on the lower side is elevated enough to bring the pairs of lights within five feet of the same elevation The structures appear very inconspicuous beside the 70 and 80 foot towers required to support units of other systems See Fig 20

Each lamp is provided with a 30° spread lens, mounted in the face of the fixture, and arranged to spread the light horizontally The lamp is mounted in a plate hinged at the bottom, with an adjustment to set the vertical angle of each lamp independently The

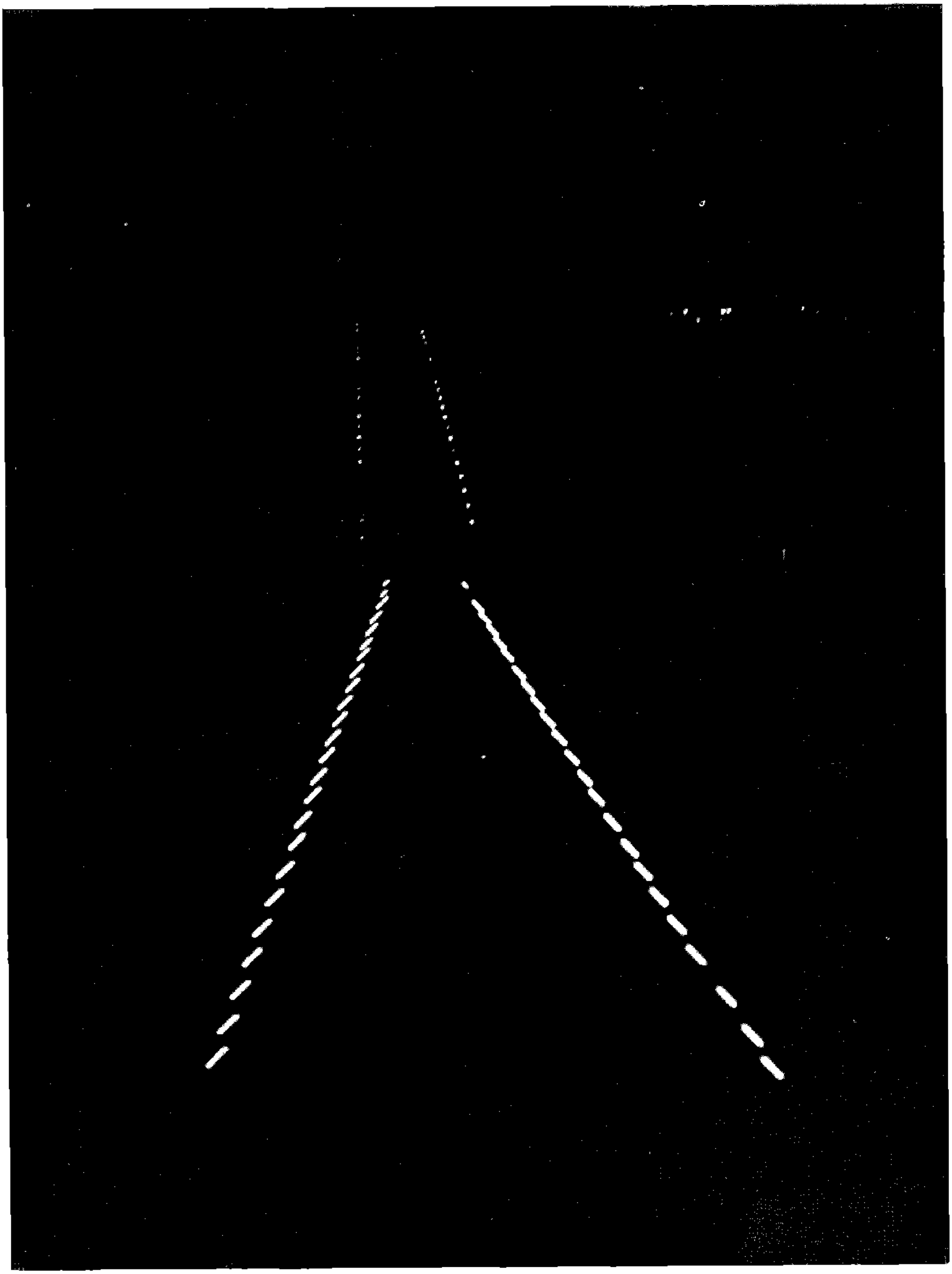

Fig 19 View of Slope Line Approach Lights From Airplane Above the Approach Path (Note the Echelon Elements Pointing Downward)

Fig 20 View of Slope Line Units at Arcata

characteristic isocandle distribution of the lamp and spread lens is shown in Fig. 21 and has a peak intensity of about 93, 000 candles Each individual lamp is tilted so that the axis of its beam will intersect the glide slope 1, 200 feet ahead of the fixture No horizontal adjustment is provided

The system is 3, 000 feet long, and requires 300 kva when operated at full brightness It was realized that this was an excessive load, but the lamps were chosen to provide brightness on the order of 100, 000 candles, partly because the demands were abnormal (on account of heavy fogs at Arcata), partly because the terrain dropped off so that the slope line lights were as much as 50 feet below the other lights with which they were being compared, and partly because this was the first test installation, and it was important to be able to test all degrees of brightness

INDIANAPOLIS INSTALLATION

A system of slope line approach lights also was installed at the Civil Aeronautics Administration Technical Development and Evaluation Center, Indianapolis These were installed for development study and demonstration, but are available also for use in fog, which occurs most frequently in the spring This system is 2, 500 feet long, due to limitations on available land, and is set to indicate a path coincident with that marked by the ILS, at 2 5° The system is operated from the control tower on request, so that visiting pilots may have an opportunity to study the appearance of the system, and familiarize themselves with the characteristic pattern As the requirements of this installation are less severe than those at Arcata, the lamps are only 50 w capacity, providing a peak in-

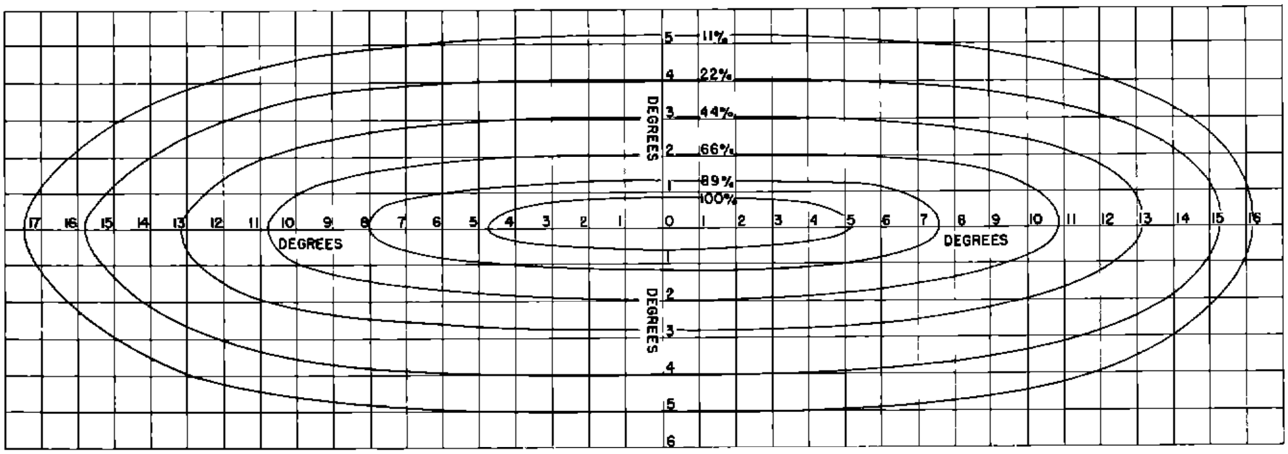

Fig 21 Isocandle Chart Showing Distribution of Sealed Beam Lamp and Spread Lens Installed at Indianapolis and Arcata

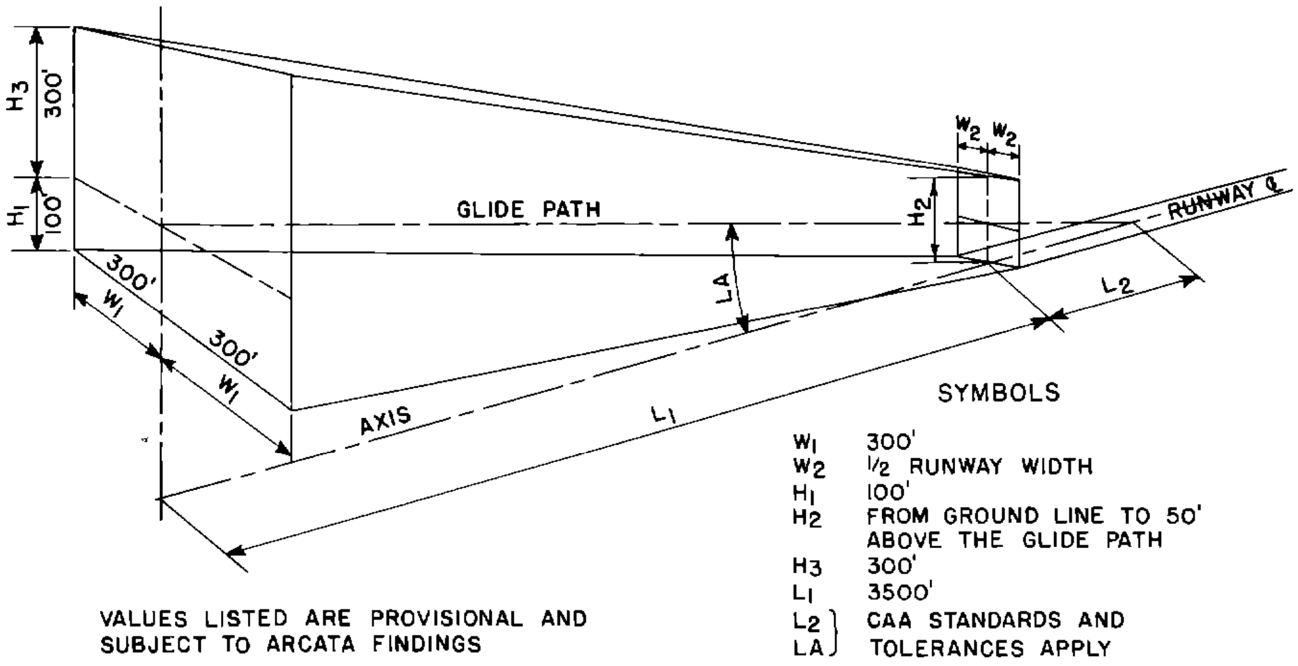

Fig 22 Region of Guidance for Approach Light Systems

tensity of 38,900 candles, and with the same general distribution as that shown in Fig 21

CONCLUSIONS

The slope line approach light system is based on a novel geometric principle designed to mark a line in space and to provide the pilot with visual indications of his position and course relative to that line In so doing, it provides adequate and effective visual guidance for straight-in instrument approaches under weather conditions below 1/16 mile (100m) by night and 1/8 mile (200m) by day The system provides the pilot with an accurate indication of vertical and horizontal position relative to the approach path and affords him a means of judging airplane attitude

Flight testing in actual fog has demonstrated that the basic concept of this pattern of lights is sound and practical, although additional conspicuity, additional roll guidance, and longitudinal indications would add value to the system Means for providing these features are being investigated and they can be added to any extent found necessary

The system is relatively simple and economical to install

APPENDIX I

The Effect of Fog

Fog occurs in many forms and in varying densities For consideration as a factor affecting the landing of aircraft, it probably is necessary to consider fog in only three forms These are

(a) A more or less homogeneous mass blanketing the ground and extending up several hundred feet
(b) An overlying stratus of cloud with relatively clear atmosphere beneath it
(c) A low-lying sheet of fog, covering the ground, but extending up only a short distance

In (a) the airplane is entirely surrounded by fog during the letdown and landing operation In (b) the descending airplane will break out of the fog, and the pilot can see clearly underneath it In (c) the airplane is flying in clear atmosphere and has to let down into a sea of fog beneath it The term "ceiling" applies properly only to condition (b) and refers to the height of the bottom of the cloud mass

All mathematical analyses of visual range in fog and the required brightness of light sources, which can be seen for a given distance, are based on homogeneous fog, and all fog densities referred to in this report are based on this same convention

Fog density can be defined in terms of transmissivity, which is the proportion of light which penetrates a fog a given distance, such as 100 meters, or by means of the equivalent visual range or visibility distance of objects seen in the fog by daylight

A Table of Visibility has been adopted by the International Commission for Synoptic Weather Information, and is given herein

A pilot making an approach in fog (a) depends on instruments and radio guidance to keep him on the approach path until he reaches a point from which the approach lights are visible From that point on he should be able to use the approach, threshold and runway lights as an outside visual reference, and make a visually-aided landing Under such circumstances the approach and runway lighted pattern must be continuous and reliable

A pilot making an approach in fog (b) will use radio approach guidance until he breaks out of the overcast From this point on he goes contact, but, in this case, the requirements of the guidance given by the approach lights are much less rigorous, as the entire pattern of the approach and runway lights generally will be visible at the same time

The most severe and critical condition affecting the use of lights on the approach is condition (c) If such fog occurs after dark,

TABLE II

Table of Visibility[12]

Code	Designation	Daylight Observations
0	Dense fog	Objects not visible at 50 m (165 feet)
1	Thick fog	Objects visible from 50 to 200 m (658 feet)
2	Moderate fog	" " " 200 to 500 m (1,645 feet)
3	Light fog	" " " 500 to 1,000 m (3,048 feet)
4	Thin fog	" " " 1,000 to 2,000 m (1 24 miles)
5	Haze	" " " 2,000 to 4,000 m (2 48 miles)
6	Light haze	" " " 4,000 to 10,000 m (6 2 miles)
7	Clear	" " " 10 to 20 km (12 4 miles)
8	Very clear	" " " 20 to 50 km (31 miles)
9	Exceptionally clear	" " " 50 to 150 km (93 miles)

[12] W E K Middleton, "Visibility in Meteorology " University of Toronto Press, 1941

and the fog layer is not more than approximately 200 feet thick, the lights may penetrate the fog sufficiently to create a visible glow in the upper layer, which will be visible before the pilot enters the fog. Several such instances have been reported, and these are very likely to cause a serious overestimation of the normal effectiveness of a system A series of approach tests were made at Newark under such conditions, with a line of condenser discharge lamps flashing in sequence from the outer to the inner end of the approach The glow of these lights on top of the fog bank created an extremely effective path indication, and resulted in highly enthusiastic endorsement of these lights as an approach system These endorsements entirely overlooked the more important phases of approach guidance, in which such lights can be seriously deficient, and did not consider what their effectiveness would be in a fog of greater depth

If such fog occurs in daytime with the upper surface of the fog illuminated by daylight, the most severe condition possible is set up, as the pilot's eyes are adapted to daylight illumination, and his threshold of visibility is raised enormously Under such conditions he must let down into the blinding fog with no chance to adapt his eyes to reduced brightness, and must then try to pick out the lights for his landing guidance For such operations the lights must be of maximum possible brightness, and under such conditions color may have some value in adding conspicuity

In any daylight fog, while the difficulty of making the lights visible to a pilot is increased enormously, there may be less difficulty in providing horizontal reference, as the ground plane frequently is visible

APPENDIX II

Psychological Aspects

There are certain psychological aspects of piloting an airplane which can be explored to find an explanation for some of the differences in opinion and emphasis held by various engineers and experienced pilots Reference is made in this report to the importance placed on horizon indication by the author and to the fact that such importance is not recognized by some expert and long-experienced pilots It is important to examine this function and the reason for the differences of opinion as to its value.

A pilot, when flying on instruments where he cannot see any references outside his cockpit is informed of airplane attitude by means of the artificial horizon on the instrument panel This is adequate and satisfactory as long as he is flying on instruments When he lets down on approach, guided by radio until he can see the approach lights, the situation changes He is then watching the approach lights, which are outside the cockpit, using them for guidance, and is flying contact The pilot, when flying contact, operates by reflexes which have been developed by associating the airplane with himself, and the controls as extensions of his own motor system His movements of the controls are then largely unconscious and automatic He operates the airplane by reference to outside stimuli, such as the apparent movement of the horizon or other outside visual reference When he is flying on instruments the stimuli and responses are entirely different In this case, movement of the controls results in the movement of indicators on instruments, and a conscious effort is required in order to interpret these indications in terms of attitude and movement of the airplane. Under these conditions his reflexes must be conscious and considered, and he operates the airplane as a vehicle separate from himself This develops a different set of reflexes, keyed to the instrument movement and not to his consciousness of his own movement Either set of reflexes can be employed, and is employed, but because they are essentially different, a conscious effort is required to change from one to the other Because the reflexes based on outside reference stimuli are more nearly automatic, and are much more frequently used, it is relatively easy to change from instrument reference to outside visual reference, and much more difficult to change from visual reference to instrument reference

When the pilot making an approach in fog comes in sight of the lights, he changes from instrument to contact flying, that is, he changes from the system of reflexes conditioned to instrument indications to the more normal system of reflexes conditioned to outside visual references This is comparatively easily done, but if he has to refer back to his instruments, as for a horizon reference, the transition is much more difficult In addition to this inherent psychological difficulty, he also is forced to readjust his eyes from the remote and relatively bright lights to the short focus and low level illumination of the instrument panel Such a readjustment, from bright to dim, takes from one to more than three seconds, and at a highly critical time when seconds are priceless

During the approach it is essential that the pilot have a horizontal reference, either inside the cockpit or from what he can see outside He is normally flying contact and if a satisfactory horizon reference is given him by the lights he can see, he will not have to make the difficult and dangerous transition from contact to instrument, or try to readjust his eyes to the instruments for this vital information

A procedure has been developed which eliminates this necessity In this procedure one pilot watches for the lights while the other flies the aircraft on instruments Thus one pilot keeps his attention on the instruments while the other directs his to lights, and either can advise the other, or can take control This has proved a satisfactory procedure for experimental approaches, and can be safely used on general operations, but it would not be considered as completely adequate, because it requires both pilots for the landing operation, and leaves no safety margin in case one pilot should become incapacitated Furthermore, many airplanes do not have copilots An approach light system should not be considered adequate if it gives the pilot only partial guidance, and requires additional information from instruments

It is interesting to examine the reasons why experienced pilots fail to recognize the importance of a level reference as an inherent element in the approach light pattern It is argued that an airplane is letting down with its wings level, as indicated by the artificial horizon, and when the pilot sees the lights he still can maintain the same level attitude and uses the line of lights only for directional indications This is quite possible if, and only if, the airplane is exactly on course and has to make no correction As soon as the course is changed, the attitude is also changed and the level must be restored It is also argued that a pilot following a single line of lights would soon perceive if he were off level because the course would swing to one side This is true, but an airplane letting down at 120 mph, and with a bank of as much as 10°, turns on a radius of 5,500 feet as shown in Fig 1 As an entire approach system is only 3,000 feet long, the change of course would be a very crude and inadequate means of judging the level

A peculiar psychological factor is important in the evaluation of the importance of a level reference A pilot flying contact, when he can see the landscape has very little need of an artifical horizon He knows which is up and down and which is level, not by any conscious effort, but by subconscious reference to the line of the horizon, the level of a cloud bank, the appearance of the ground, and a multitude of other data which are unconsciously observed, assimilated and integrated Similarly, a man walking or standing, or riding a bicycle, does not consciously refer to anything to know what is level He knows what is level by a completely subconscious reference to familiar horizontal indications When these indications are distorted or entirely removed, he is baffled and lost It was found impossible to ride a bicycle in a completely blacked-out street, entirely apart from the hazard of collisions The addition of a dim glow of a light in the rider's sight, however, gave him a reference with which he could co-ordinate his sense of balance, and he was again able to ride

One type of amusement park attraction puts a person into a room where all wall, floor and ceiling lines are at odd angles, and the person is hardly able to stand, and can not attempt to walk without falling His subconscious references are confused by distorted and untrustworthy stimuli and his natural sense of balance is destroyed Similarly many a pilot has emerged from a cloud and found himself at a crazy and unexpected angle with the ground Man depends on familiar outside references to enable him to adjust himself to the feeling he knows as level, and this adjustment is almost entirely unconscious Many experimental approaches and landings have been made in fog and thick weather, but very few of them have been made in weather so thick that the pilot could see no outside references when he neared the ground Probably not one pilot in a thousand has ever had that experience and few people who have not experienced it have any conception of the lost and bewildered feeling when all familiar references are lacking, yet, that is the condition under which airplane landings must be made if weather handicaps are to be conquered That is the reason why the designers of the slope line approach light system believe that it is essential to incorporate adequate horizon reference into the system, regardless of the lack of recognition of its importance on the part of many pilots and engineers

Another psychological tendency is of importance There is an almost irresistible impulsion for a pilot who is using a line or pattern of light as a guide to edge closer to the lights for the added reassurance they give him Pilots refer to the tendency as "hugging the lights" If there is no vertical guidance given by the light pattern itself, this impulse will tend to cause a pilot to undershoot and land short If the pattern of approach lights gives a clear and unmistakable indication of the proper altitude, this tendency will disappear

Under The Hood

Test flying of various radio approach aids is normally conducted by a pilot under a hood, whereby he can see his instruments but cannot see any references outside the cockpit He is accompanied by a check pilot who has normal vision of outside references, and can take over the control in any case of emergency Under such conditions pilots flying blind have confidence in the check pilot and are under no abnormal nervous strain

The application of the accuracy obtained in such test operations under guidance by ILS or GCA as criteria of the accuracy to be expected from flying blind in actual fog under the same radio guidance has been challenged, and the results of test approaches made by

ILS or GCA without check pilots and in actual fog are cited as evidence

The author believes that experience gained by flying under the hood is reliable and can be considered a fair appraisal of what pilots can be expected to do in a fog with aids on which he could depend When adequate lights are available, and the pilot is familiar with them and knows he can depend on them for all the aid he needs, his confidence will be restored to that afforded by the check pilot, and his performance should show no material difference between approaches under the hood or actual fog

* See footnote 2

APPENDIX III

Visibility Chart

The basic relationship between brightness, transmissivity of the atmosphere, and distance from which a light can be seen is familiar to all engineers who work with signal lighting. This relationship, known as Allard's Law, is expressed by

$$I = I_o D^2/T^D$$

where

- I = brightness required of a light to be visible
- I_o = threshold brightness of the observer
- D = distance from the observer to the light
- T = transmissivity per unit length of the atmosphere

The threshold brightness I_o is not a constant, but varies through a wide range, depending on the individual degree of dark adaptation, and background brightness. The chart shown in Fig. 5 is based on two different values for I_o viz., 0.2 km candles representing the threshold under conditions of a starlit moonless night, and 1,000 times that value, or, 200 km candles, representing the threshold when viewed against the background of a representative daylight fog. The chart shows the distance that lights, successively brighter by increments of 1,000 per cent, can be seen under different degrees of transmissivity. The scale on the right shows the equivalent object visibility, or the meteorological range, which is the distance at which an object is just visible against a sky background in a fog producing the transmissivity indicated on the left column. As most pilots and observers define a fog in such terms as 1/4 of a mile, or 1/16 of a mile, this scale is of service in translating such definitions into transmissivity.

The equivalent object visibility is calculated from the transmissivity by the use of the relationship

$$T^D = K$$

where

K = constant (Koschmieder's constant)

The value used for K in the chart is 0.02, which is the value generally assigned.[13] This value, however, varies under different conditions, and has been assigned values from 0.015 to 0.06. Based on the work of Douglas at Nantucket and Arcata, the Landing Aids Experiment Station uses a value of 0.055.

The relationship of fog and required brightness can be plotted in a chart showing all degrees of transmissivity from zero to unity, which represent complete absorption to unlimited visibility. The chart shown as Fig. 5 represents only the lower 6 per cent of such a chart, and is magnified to facilitate readings for conditions of dense fog, with which approach lights are concerned.

When this chart is expanded to cover all conditions of visibility, the steps of the International Visibility Scale, given in Table II, Appendix I, can be shown conveniently as horizontal lines.

[13] See footnote 12.

APPENDIX IV

Identification of Signal Lights

Signal lights can be identified by shape, pattern, color, or flashing characteristics This appendix discusses briefly the application of these various characteristics to aviation signal lighting

If a light source can be given a distinctive shape, and is so placed that an observer can recognize that shape, the light cannot be confused with other lights Shaped light sources have not been used to any great extent in signal marking, particularly for aviation, because shape cannot be distinguished beyond a very limited distance The minimum angle subtended at the eye for a shape to be readily distinguishable is about three minutes, or a dimension of about 0 001 times the viewing distance This is further complicated by the tendency of the eye to lose resolution of the shape of a light when the light is much brighter than threshold Nevertheless when a luminous signal is required for a service for which it must be seen from only a short distance, a shaped source can be made entirely reliable, and will eliminate the need of color and color's inherent difficulties

Pattern is really an extension of shape By arranging a series of point sources in a recognizable pattern, the function of shape can be extended almost any desired degree, and a recognizable pattern can be made effective to a much greater distance than is practical for shape Pattern has been widely used in aviation, but it has its limitations The first is, of course, the limits of distance from which the individual lights can be seen, and next is the fact that when observed from nearby points the pattern can be lost because of excessive dimensions

The only real difference between the effectiveness of shape and pattern lies in the distance from which they are intended to be seen By keeping the limitations of visibility of the light sources, the limits of the eye, and the distance involved in mind, shape and pattern can be combined to be very effective

Color is one of the most effective and most widely-used means of giving distinctiveness to a signal light, but the use of color has serious limitations Color can be obtained by using a source which produces colored light, or by using a source which produces white light and then interposing a filter which absorbs the wave lengths not wanted

Nearly all sources of colored light, like fluorescent tubes or gaseous discharge tubes, are inherently of relatively low brightness, and a large area must be provided to produce any material volume of light Such a large area is very difficult to adapt to optical control, hence such lights are normally not available to produce accurately controlled beams or high brightness signals

Incandescent lamps, which are available with very high brightness and with sources of small dimensions, are readily adaptable to accurate optical control, but as these sources are white, they necessitate the use of filters when used as colored lights

Filters have a maximum transmission limited to the portion of the original white light which comes within the acceptable limits of the color desired In addition to this restriction of transmission, surface reflection, absorption by the glass and by possible impurities and partial absorption of the desired color, reduce the amount of colored light available. For practical purposes, the highest percentage of colored light which can be expected from filters is in the neighborhood of the values shown in Table III

Other colors are not practical in signal practice for aviation Orange is easily mistaken for red or yellow, violet appears as red

TABLE III

Transmission of Filters

With red filter	10 to 20 per cent of light is transmitted
With green filter	15 to 25 per cent of light is transmitted
With yellow filter	40 to 60 per cent of light is transmitted
With blue filter	2 to 5 per cent of light is transmitted

or blue, with a halo of the opposite color surrounding the light Even in the aforementioned restricted list, yellow is not completely reliable for use by itself, as it can easily be confused with a white light at low intensities A further difficulty is introduced in the use of color filters with high intensity lights as the amount of energy absorbed by the filter adds materially to its temperature rise, so that particular attention must be paid to the dissipation of the heat in order to avoid breakage

There is a widespread belief that some colors, such as yellow or red, can be seen through fog for greater distances than white light, or other colors While different colors have various values of visibility threshold brightness, no gain is achieved by filtering out part of the light, as all wavelengths penetrate a fog independently Breckenridge and Nolan[14] found no advantage in the use of red over white of equal candlepower, and this conclusion is supported by the fact that sunlight, filtered through fog or a cloud, shows no indication of one color penetrating more than another For practical purposes, as for approach lighting, no one color or combination of colors will penetrate farther than any other

There might be some advantage in using color for greater conspicuity when lights are to be seen against a background of fog illuminated by daylight on account of the contrast with the background Evidence is still lacking on the increase of conspicuity, but it is doubtful if the gain in conspicuity is enough to compensate for the losses in producing colored lights

Flashing characteristics are also widely used for providing distinctiveness to a light signal Flashing signals can be produced by several means, of which the following are the most common

1 By turning on and off an incandescent lamp
2 By turning on and off a vapor discharge lamp
3 By motion of a system of optics

[14]F C Breckenridge and J E Nolan, "Relative Visibility of Luminous Flashes from Neon Lamps and from Incandescent Lamps with and without Red Filters " National Bureau of Standards Journal of Research, March 11-25, 1929

The first method involves the heating and cooling of the lamp filament, and is practical only for a relatively small lamp, or for a slow rate of flash, because the time required for the incandescence and nigrescence of the filament of a large lamp is relatively long, sometimes taking nearly one-half second

The second method is readily applicable to low brightness vapor discharge lamps, which are not very effective for use under conditions of low visibility It can be used also with gaseous discharge lamps operated by condenser discharge These give extremely high brightnesses for very brief flashes The average power discharge through such a lamp is given by

$$W = \frac{CV^2 \times 10^{-6}}{2t}$$

where

W = power in watts

C = capacity of condenser in microfarads

V = voltage

t = time in seconds

The light output of such a flash employing xenon is in the order of 40 lumens per watt, and the duration of the flash is extremely brief, and is measured in microseconds As this time is dependent on the rate of discharge of the condenser, it is decreased by reduction of condenser capacity and increased by any inductance in the circuit, and to a limited extent, by increase of the voltage

The third method, that of rotating or moving an optic, is employed with lighthouse signals, airway beacons, and various other types of signals

The effective brightness of a flashing light source, which is the apparent brightness to the eye, is progressively less in proportion to the actual brightness as the flash duration decreases This relationship is defined by Blondel and Rey as follows

$$\frac{Ie}{I} = \frac{t}{K + t}$$

where

Ie = effective brightness

I = actual brightness

t = time in seconds

K is a constant, with values between 0.15 and 0.30. The value normally used is K = 0.20.

With flashes as brief as those produced by condenser discharge lamps, the ratio of effective brightness to actual brightness can drop to a value as low as 10^{-5}.

Flashing light signals may be used effectively where an individual light source is required, but attempts to employ them as elements of a pattern of signal lighting have not been very effective. Early tests of groups of independently flashing lights produced a reaction of confusion to an observer. Recent attempts to use flashing lights in controlled sequence as guidance to aircraft have indicated that such lights cannot give adequate guidance, and can cause added confusion by producing false indications of motion and stroboscopic effects.

APPENDIX V

Cockpit Limitations

Any visual aid, to be of service to a pilot in making a landing, must, from the meaning of the term, be visible to the pilot The structure of the aircraft and the restricted view from the cockpit interfere very seriously with the field of view of the pilot. Furthermore, there is a wide variation in the designs of different aircraft in this respect, some cutting off all forward visibility below the horizon, and others giving a clear forward field of vision to 15° or more below the horizon The trim, speed, and loading of an airplane and the flap setting, all affect the fore and aft attitude, and the angle between the longitudinal axis and the horizon There are, also, many additional variables, such as the position of the pilot's head, the height of his seat, his attitude (whether leaning or sitting erect) and his flying technique, that it appears impossible to establish any body of dependable data It would appear then that this is a problem which rests with the designer of the aircraft The approach light system should be designed on the assumption that it will be used by aircraft having adequate fields of view Aircraft having restricted visibility would not be able to use the facility afforded by the lights under as severe weather conditions, and would then be able to land only under higher limits Thus, aircraft manufacturers are provided with a powerful incentive to improve cockpit visibility

APPENDIX VI

The Effect of the Approach Speed of the Aircraft

It was pointed out, in the discussion on the length of an approach light system, that there is no practical value in extending the approach lights into the approach for more than 3,000 feet, because an airplane, coming in on a glide slope of 2 4° will be 200 feet high when within range of the lights, and, it is not feasible to make lights visible in a dense fog to a pilot at any height materially above this

Thus a pilot will be within the range of approach lights only for the time his aircraft takes to traverse 3,000 feet With an approach speed of 120 mph, the pilot will see the approach lights for only 17 sec, and that is not very much time to make course corrections It would appear, therefore, that approach speeds in the neighborhood of 120 mph are getting close to the maximum with which aircraft can make a visual approach under severe weather conditions

APPENDIX VII

Operational Requirements for Approach Light Systems

Formulated by Approach Light Evaluation Committee ANC Subcommittee on Visual Aids to Air Navigation

1 Definitions

As used in this statement of operational requirements, the following terms are to be understood as defined below

1 1 Limiting Visibility, the meteorological visibility for which the approach light system is designed

1 2 Region of Guidance, the region of space within which it is essential that the visual aids be sufficiently visible to the pilot to provide adequate guidance for the safe approach of aircraft for landing

1 3 Axis, a horizontal line extending the center line of the runway through the approachway, that is, in the same vertical plane as the centerline and intersecting it, or coinciding with it at the approach end

1 4 Threshold, a horizontal line perpendicular to the axis marking the approach end of the runway and also the vertical plane through this line

1 5 Portal, an area through which aircraft may be expected to pass lying in the vertical plane perpendicular to the axis and 3,500 feet from the threshold (The middle marker is generally located in this plane)

1 6 Glide Path, a path determined by electronic aids and designed to be followed by aircraft in landing The slope varies between 2° and 4°, and the intersection with the runway lies at a distance of from 500 feet to 1,500 feet from the approach end

2 Limiting Visibilities

2 1 For the purposes of these requirements, two limiting visibilities are recognized

2 1 1 For direct instrument approaches, the limiting visibility is one-fourth mile daylight object visibility (transmissivity, 0 375 per 100 meters)

2 1 2 For all other approaches and circling, the limiting visibility is three-fourths mile (transmissivity, 0 722 per 100 meters)

2 2 These operational requirements are based on visibilities of one-fourth mile unless otherwise stated

3 Identification

3 1 At all points within the region of guidance (Section 4), the lights visible shall be immediately identifiable as part of an approach light system

3 2 At all points within the region of guidance (Section 4), any lights on either side of the axis shall be immediately distinguishable from any lights on the other side of the axis, and any lights on the axis shall be recognized as such

3 2 1 This identification shall be accomplished without possible confusion with any means used to mark any portion of the runway, or with other lights in the area

3 3 At all points outside the region of guidance (Section 4), any approach lights visible shall immediately indicate to the pilot that he is left or right, and if possible, above or below the region of guidance respectively

4 Guidance

4 1 For instrument landings, the region of guidance shall have the form and dimensions shown in Fig 22

4 2 At all points within the region of guidance sufficient lights shall be

visible to indicate the location and direction of the axis

4 2 1 Within the region of guidance, the location of the threshold shall be positively identified for a distance of 500 feet

4 3 Within the region of guidance it is highly desirable that sufficient lights be visible to indicate the following

4 3 1 The approximate height above the runway, or, alternatively, the departure vertically from the glide path

4 3 2 The approximate distance to the threshold

4 3 3 The attitude of the aircraft with respect to the horizontal plane, both longitudinally and laterally, provided the means used shall not detract from the guidance furnished to indicate the location and direction of the axis and the location of the threshold

4 4 For visibility conditions of not less than three-fourths of a mile, daylight object visibility, the approach light system shall furnish guidance for a distance of three-fourths mile along any path of the approach within 90° left or 90° right of the axis, the vertex being the intersection of the threshold and the axis *

4 5 For all visibility conditions the location of the middle marker, or the point on the axis 3,500 feet from the threshold shall be indicated by a flashing light visible 3,500 feet under one-half mile daylight object visibility except within a sector directed toward the runway and extending 22 5° either side of the axis *

5 Illumination

5 1 The illumination provided at points from which lights are required to be visible shall be adequate for visibility without visual concentration in excess of what is readily feasible for a pilot whose attention must be divided among several responsibilities

5 2 The illumination visible at points on or above the level of the glide path shall not be excessive (There is no agreement as to the maximum acceptable degree of dazzling, and additional experimental results are urgently needed)

6 Colors

6 1 The numbers of different colors used in approach- and runway-light systems should be kept to a minimum to avoid possible confusion

7 Characteristics

7 1 At present, only fixed lights have been found satisfactory for guidance to meet the requirements in Section 4

7 2 Flashing lights used as auxiliary lights or satellites may be considered as meeting the requirements for identification (Section 3)

* This is a provisional requirement based upon currently available information and is subject to verification obtained from flight tests