NATIONAL BUREAU OF STANDARDS REPORT

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Development of Optimum Runway Lights for Jet Aircraft

Interim Report No. 1

By

C. A. Douglas
I. Nimeroff
A. N. Hill

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Development of Optimum Runway Lights for Jet Aircraft

Interim Report No. 1

ABSTRACT

This report is the first of a series describing the development of runway lights for jet aircraft at the National Bureau of Standards for the Equipment Laboratory, Wright Air Development Center, under contract number 33(616)-54-6.

1. OBJECTIVE OF THE PROJECT

The objective of the project as outlined in Exhibit WCLEE5-42, dated 4 June 1953, "Study to Determine the Optimum Runway Light Design for Jet Aircraft" was 1) the study of the operational procedures of jet aircraft in landing and on the ground and the effects of these procedures upon the optical and mechanical design of the runway light; 2) the development of a suitable compromise between the conflicting optical and mechanical requirements and the recommendations of a design based upon this analysis; 3) fabrication of sample lights conforming to this design.

During the early phases of the project it became apparent that the operational and intensity-distribution requirements of runway lights could not be developed without considering the functions and intensity distributions of the other components of the visual landing aids system. Therefore, the scope of the project was expanded to include a study of the performance of these components with the development of the intensity-distribution requirements of all components of an integrated system of landing aids other than approach lights. The intensity-distribution requirements of these components are based on the following premises.

The runway lighting system and related lighting systems should 1) furnish all the visual guidance required for circling approaches performed under visual flight rules (VFR) with no consideration given to the guidance supplied by the approach lights, if any, or from extraneous lighting, from the time the airfield is located until the aircraft has turned off the runway after completing the landing; 2) furnish the visual guidance required for straight-in approaches on runways where no approach lights are installed; and 3) provide the visual guidance required for the final stages of landings on runways with high-intensity approach lights.

2. SCOPE OF THE INVESTIGATION

The development program is being conducted along the following courses:

1. Determination of the optical requirements of the components of a runway lighting system by means of: a) pilot interviews to determine the operational requirements of the system, the deficiencies of the present system, and the acceptability of proposed modifications; b) photometric testing of existing and prototype lights; and c) computation of the visual range and glare zones of these lights.

2. Determination of the mechanical requirements of the lights by interviewing maintenance personnel and inspecting facilities to determine deficiencies in the present units, by computing loads imposed upon landing gear by obstructions on the runway surface, by testing the mechanical strength of present and prototype lights, and by tests of the electrical characteristics of the lights.

3. Procurement and laboratory testing of prototype lights.

4. Preparation of specifications for lights proposed for service tests.

The four phases of the investigation are being conducted concurrently. The results of the investigation to date have been reported in 32 reports and memoranda (in addition to monthly reports) which were prepared and forwarded to Wright Air Development Center as individual tasks were completed. The reports are listed in Appendix A.

3. VISUAL-GUIDANCE REQUIREMENTS OF A VISUAL LANDING-AIDS SYSTEM

A satisfactory visual landing-aids system should supply the following visual guidance during a visual approach to an airfield and during a landing.

1. During the initial penetration:
   a. Location and identification of the airport.
   b. Location and identification of the runway.

2. During a circling approach:
   a. Distance from and direction of the runway, so that the downwind leg can be flown parallel to and at the desired distance from the runway.
   b. Location of and distance from the threshold and direction of the runway during the turn from the downwind leg to the base leg, on the base leg, and during the turn from the base leg to the final leg of the approach pattern.

3. On the final leg:
   a. Location of and distance from the threshold.
   b. Location of the horizontal plane through the threshold.
   c. Location and direction of the runway axis.
   d. Height above the runway or distance above or below a preferred glide path.

4. During flareout and touchdown:
   a. Height above the runway.
   b. Direction of the runway.
   c. "Horizon."
   d. Lateral boundaries of a safe landing area.

5. During rollout:
   a. Lateral boundaries of the runway surface.
   b. Direction of the runway axis.
   c. Location of turnoffs.
   d. Distance from and location of the upwind end of the runway.

During takeoff the visual guidance required of the runway light system is essentially the same as that required in the last phase of the approach and in the rollout. A system meeting the requirements for guidance during landing should also meet the requirements for guidance during takeoff.

4. RESULTS OF PILOT INTERVIEWS

In order to determine the effect of the performance characteristics of and operating procedures with jet aircraft on the operational requirements of runway light systems, eleven air bases were visited where more than 80 pilots representing the organizations operating from these bases and 20 Air Installations personnel were interviewed. The air bases visited during the survey are listed in Appendix B.

In general, pilots from each squadron operating jet aircraft assigned to the Air Base attended the pilot interview conference. During the conference all phases of the landing, from the time the airfield is sighted until the aircraft is turned off the runway, were discussed with reference to the use of the present visual landing aids and their deficiencies for jet aircraft operation, and to needed improvements or modifications. The data obtained during these visits and their effect upon the design of the components of the visual landing-aids system will be discussed in detail in the sections of this report covering the components. Detailed reports of the interviews were prepared and sent to the sponsor immediately after each visit. [21-32] *

4.1 Summary of Pilot Interviews.

1. The pilots desire to locate and identify the airport and the runway from as great a distance as possible. This is of particular importance to the pilots of jet aircraft because of the high fuel consumption at low altitudes and the lower fuel reserve.

2. The present airport beacon is not visible at the altitudes at which jet aircraft are operated. The pilots were unanimous in their opinion and emphatic in their statement that the present beacon is inadequate.

3. Many pilots considered an approach light system which provides adequate guidance during the approach more important than an improved runway light system.

4. The type C-1 high-intensity runway lights are considered satisfactory for straight-in approaches, rollout and takeoff.

5. The present runway light systems, both medium-and high-intensity, are not sufficiently visible from positions off the runway axis when they are operated at the clear-weather brightness settings.

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*Figures in brackets indicate references to the detailed reports listed in Appendix A.

6. The pilots desire a more positive means of identifying the runway lights as a runway lighting system.

7. Pilots sometimes lose the runway lights when turning on to the downwind or base legs of the approach pattern.

8. The downwind corner of the runway should be well marked and identified, as the start of the turn onto the base leg is determined by the position of that corner.

9. Many pilots consider the present system of threshold lights inadequate.

10. At some bases the pilots were well satisfied with the way the intensity of the lights was controlled. At others, they complained that the lights were always too bright. In particular, pilots did not want to have the glare increased on the final leg of the approach pattern in order to obtain better guidance on the other legs.

11. Few pilots were concerned with loss of dark adaptation on takeoff.

12. Gaps in the runway lighting system caused by intersections are not considered serious except in the touchdown area. There was definite opposition to having lights that project above the runway surface in the intersections.

13. Turnoffs from the runway are inadequately marked, particularly where there are no taxiway lights.

14. The majority of the pilots either favor or have no objection to using red lights to mark the upwind end of the runway.

15. In very low visibility landings the pilots are more concerned with finding and seeing the runway (or approach) lights than they are with the adverse effects of glare from the lights.

16. The only unusual type of damage to runway-light units that could be attributed to the operation of jet aircraft was that to the cone-mounted M-1 units.

17. Some means of lighting the arresting barrier at the upwind end of the runway is considered desirable.

18. The pilots have very little depth perception at night when flaring out over a black-top runway without runway markings. The runway lights alone do not provide adequate depth perception.

19. Rain or snow on the center panel of the canopy of fighters causes so much distortion that under these conditions the pilot obtains guidance only from the lights he sees through the sides of the canopy. Thus, lights located across the threshold or the upwind end of the runway are of little value in judging distance from these points. Distance marking is, therefore, considered essential and some elevation guidance, preferably in the approach-light system, is desirable. Threshold lights should extend outboard of the runway lights.

20. Lack of uniformity in the lighting systems from airfield to airfield results in unnecessary confusion.

5. LOCATION AND IDENTIFICATION OF THE AIRPORT

The location and identification of the airport is properly the function of the airport beacon and not of the runway lighting system. However, in the design of a runway lighting system, the visual guidance supplied by visual aids other than the runway lights must be considered. The pilots interviewed were unanimous in their statement that the vertical coverage of the present airport beacon (Specification MIL-L-5630) is inadequate for the operation of jet aircraft. When the aircraft is above an altitude of 20,000 feet during VFR conditions, the airport is located not by means of the beacon, but by extraneous lighting on the field or in surrounding areas when the pilot is familiar with the location of these lights, or by radio aids. To be useful, the beacon should be visible and identifiable from a distance of 30 miles at altitudes of 20,000 to 30,000 feet when the visibility is "unrestricted," and from the range station from altitudes of 3000 to 5000 feet when the visibility is somewhat restricted.

When the beacon could be seen, the flash coding of the present beacon was considered adequate.

Since it is impracticable to design runway lights having the intensity distribution necessary to cover the region in which the beacon should be visible, and since the design of an efficient runway lighting system presupposes a knowledge of the location of the airport, consideration was given to the intensity distribution requirements for the beacon.[6]

In computing the required intensity distribution, an atmospheric transmissivity, T, of 0.9 per mile was taken as the minimum transmissivity for "clear" weather. The visibility of a 25-candle light is approximately 10 miles with this transmissivity. Similarly, a transmissivity of 0.3 per mile was taken as the minimum transmissivity for approaches under Visual Flight Rules. The visibility of a 25-candle light corresponding to this transmissivity is 3 miles. (See Appendix C for definitions of terms and a discussion of the laws pertaining to visibility.)

The proposed regions of guidance of the beacon for the two visibility conditions are shown in figure 1. For clear weather the region of guidance is defined by lines joining the points a, b, and c. Point a is 30 miles from the beacon at an altitude of 30,000 feet; b is directly above the beacon at an altitude of 10,000 feet; and c is 30 miles from the beacon at an altitude of 5,000 feet. For restricted visibility, a is 5 miles from the beacon at an altitude of 5,000 feet; b is directly over the beacon at an altitude of 3,000 feet; and c is 5 miles from the beacon at an altitude of 3,000 feet.

The effective intensities, I_e, required for a light at point 0 to be seen from selected positions on the boundaries of the regions of guidance were then computed using the selected transmissivities. The angles of elevation, θ, of each of the selected positions were also computed. From the results of these computations recommended minimum effective intensities were developed and are listed in table I.

Table I. Recommended Minimum Effective Intensity of Airfield Beacons

Elevation Angle (Degrees)	Minimum Effective Intensity White (Candles)	Green (Candles)
0 to 2	7,500	1,100
2 to 12	50,000	7,500
12 to 15	7,500	1,100
15 to 20	1,000	150
20 to 30	500	75
30 to 60	200	30
60 to 90	100	15

As the exact location of the airport beacon is given by the white flashes, the minimum effective intensity of the green flashes can be as low as 15% of that of the white flashes.

The regions of guidance determined from these specified intensities are shown in figure 1. In addition, the region of guidance expected of the minimum beacon meeting the specification is shown. For comparison the regions of guidance of the present beacon, computed from intensity-distribution measurements made at the Equipment Laboratory* are included.

Consideration was given to the flash cycle of the airport beacon. The flash characteristics of the present beacon are considered unsatisfactory since the flash characteristic varies with the angle of elevation from which the beacon is observed and the transmittance of the light path between the beacon and the observer. When the angle of elevation is 10 degrees or more, the separation of the two white beams is so small that these beams will appear as a single flash. At lower angles of view when the threshold intensity is less than the intensity between the two white beams, the white signal will appear to be a single flash with two peaks. When the threshold intensity is greater than the intensity between the two peaks, the signal will be two separate flashes. In addition, because of the higher speeds of modern aircraft, it is desirable to decrease the interval between the white and the green flashes. Therefore, increasing the interval between the white flashes to at least two-tenths, and preferably to one-third, of the flash cycle appears desirable. Consideration should also be given to decreasing the period of the flash cycle from 10 seconds to 5 seconds. This change would, however, decrease the effective intensity of the flashes.

Note that the intensity-distribution requirements of the beacon are given in terms of effective intensity. When a light signal consists of separate flashes, the instantaneous intensity during the flashes must be greater than the intensity of a steady light in order to obtain threshold visibility. The effective intensity of a flashing light is defined as the intensity of a steady light which will produce the same visual effect as does the flashing light. Effective intensity is computed from the

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* Photometric Curves, Numbers 1198A to F, of Lighting Section, Equipment Laboratory, Wright Air Development Center.

equation developed by Blondel and Rey,*

$$I_e = \frac{\int_{t_1}^{t_2} I dt}{0.2 + t_2 - t_1}, \qquad (1)$$

where I_e is the effective intensity, I is the instantaneous intensity, and t_1 and t_2 are the times of the beginning and end of the flash. The times, t_1 and t_2, are chosen so that the value obtained for I_e is a maximum. Methods of easily determining these limits were developed in NBS Report No. 4554. [16] The effective intensity of the white and green flashes of the present beacon is about 25% of the peak intensity of these flashes.

6. LOCATION AND IDENTIFICATION OF THE RUNWAY

One of the problems reported in the pilot interviews was that of locating and identifying the runway at night. The farther out the runway is located and identified, the more easily the pilot can plan the approach. The pilots, naturally, desire to see the runway lights from as far out as possible and from all directions. The minimum acceptable visual range for VFR approaches is five miles, and the maximum visual range required was considered to be ten miles. The aircraft is generally less than 5000 feet above the ground during the period when the runway lights are used for guidance.

The difficulties are twofold. The off-runway intensity of the present high-intensity runway lights is sufficient (about 1500 candles) to provide the desired visual range in clear weather when the light system is operated with an intensity step 5 corresponding to an intensity setting of 100%. The off-runway intensity of the medium-intensity runway lights under these conditions is marginal, about 400 candles. The off-runway intensity of both types of lights is much too low to provide the desired visual range when the lights are operated on intensity steps 1 or 2. These steps give intensities of 0.2% or 1% when a type C-3 regulator is used and 1% or 3% when a type C-2 regulator is used. Thus in clear weather, if the intensity setting of the

* A. Blondel and J. Rey, Journal de Physique **1**, 530 and 643 (1911).

light system is adjusted so that the runway lights will not be glaring during the flareout and touchdown, the intensity in the off-runway directions will be only a few candles.

A pilot familiar with a field is often able to obtain sufficient guidance from such extraneous lighting as ramp lights, security lights, etc., which have a much higher intensity than the off-runway intensity of runway lights operated on a low-intensity step. These lights furnish little guidance to a pilot approaching a strange field.

The second difficulty is that of identifying the runway lights as runway lights once they are seen. When the lights are operated on intensity steps 4 or 5 (25% or 100% relative intensity) the intensity of the main beams of the runway light is so much greater than the intensity of the extraneous lights that the runway lights are conspicuous to aircraft near the extended centerline of the runway. When the system is operated on steps 1 or 2 this is not the case, and runway lights are often confused with street lights even when the aircraft is within the main beams of the lights.

These difficulties can be solved in a direct manner: a) install lights that will have sufficient intensity in the off-runway directions when the runway light system is operated on intensity steps 1 and 2; and b) install lights at the ends of the rows of runway lights that by means of their coding will identify the runway lights.

7. RUNWAY IDENTIFICATION LIGHTS

There are several possible methods of coding the runway identification lights so that they can be distinguished from the extraneous lights and will identify the runway lights: visibility of the scattered light from a vertical beam, color, intensity, and flash characteristics. The use of high-intensity vertical beams was rejected because the visual range of such beams is not sufficient under twilight conditions and under many nighttime conditions. The visual range of the beam of the ceilometer projector is typical of projectors of this type. The ceilometer at Washington National Airport is about 7 miles from the National Bureau of Standards grounds. Its beam has never been seen during night tests from the roof of the East Building of the Bureau although many of these tests required observation of lights of the airport and surrounding area.

The use of color alone or intensity alone as a means of identification would require more power than is considered desirable. Several lights with 180-degree horizontal coverage and extended vertical coverage would be required, and the intensity of these lights would have to be at least ten times the intensity of the surrounding extraneous lights. The use of flashing lights appears to be the most practical solution. It can be shown by means of Blondel and Rey's law that, for a given power input and lamp efficiency, the effective intensity of a rotating beacon will be about a hundred times that of a fixed light having 360° horizontal coverage. Langmuir and Westendorp* found that extraneous lights near a flashing light had a surprisingly little effect on the time required to find the flashing light even though the intensities of these lights were many times the effective intensities of the flashing light. Therefore, obtaining suitable intensities in a rotating beacon-type identification light is relatively easy.

7.1 Beam Spread.

The vertical beam spread of the runway identification lights should be sufficiently great that an aircraft at an elevation of 2000 feet and 10 miles from the runway and an aircraft at an elevation of 5000 feet and 5 miles from the runway will be within the beam of the light. Thus the beam should extend vertically from 2° to 10°.

7.2 Intensity-Distribution Requirements.

The choice of effective intensity of this beam is somewhat arbitrary. An effective intensity of 250 candles is sufficient to produce an illuminance of 1 mile candle at a distance equal to the reported visibility. This is, however, considered insufficient since these lights should be conspicuous at this distance. Field observations of steady lights indicate that an illuminance of about 20 mile candles is the optimum illuminance.** To obtain this illuminance an effective intensity of 5000 candles is required.

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* Langmuir and Westendorp, Physics 1, 273 (1931).

** F. C. Breckenridge and C. A. Douglas, Ill. Eng. 40, 785 (1945).

This intensity will also provide a visual range about 1.5 times the visibility. The intensity toward the runway should be sufficiently low that these lights will not be glaring to pilots of aircraft on the final leg of the approach pattern. A maximum intensity of 100 candles toward the runway, that specified for the type C-1 runway lights, is considered suitable. Since the sources in these units will not be point sources, even with mechanical shielding an appreciable region is required for the transition between an intensity of more than 5000 candles to one of less than 100 candles. With PAR 56-type lamps this transition will require about 20° of azimuth.

Since the distance the runway identification lights should be visible is not constant but is proportional to the visibility, the lights should be operated at constant intensity and not adjusted for the visibility. No adverse effects of glare are expected from this procedure. The National Bureau of Standards Field Laboratory at Arcata, California, has operated flashing lights located 1000 feet from the threshold on the extended runway centerline with an effective intensity of about 15,000 candles with no complaints of glare.

7.3 Flash Frequency.

Tests of the flashing rates for aircraft position and anticollision lights indicate that the flash frequency of these lights should be at least 40 flashes per minute. Flight observations of an experimental runway identification lighting system made at the Technical Development and Evaluation Center, Indianapolis, indicate that 40 flashes per minute is the minimum flash rate which should be used for runway identification lights.

7.4 Specification Requirements for Runway Identification Lights.

The use of flashing lights to identify the runway lights is recommended. These lights should be installed at the four corners of the runway, outboard of the threshold lights. Thus they will not only identify the runway lights but will also mark the ends of the runway, a feature pilot interviews showed desirable. Synchronizing the lights so that they appear to flash simultaneously seems desirable. The runway identification lights should meet the following general requirements.

a. The lights shall be designed so that they will operate from a 6.6-ampere series runway-light circuit.

b. The change in intensity shall be as small as feasible as the intensity setting of the runway lights is changed from step 1 to step 5.

c. The flash frequency shall be at least 40 flashes per minute and preferably higher.

d. The effective intensity of the light should be at least 5000 candles for all angles of elevation between 2° and 10° for all azimuth angles greater than 10° outboard of the runway axis.

e. The effective intensity for all azimuth angles greater than 10° inboard of the runway axis shall not exceed 100 candles.

A specification based on these requirements has been developed in cooperation with the Lighting Section, Equipment Laboratory, Wright Air Development Center, and has been issued as Exhibit WCLEE5-68A, dated 18 October 1955. In order to obtain runway identification lights for service testing, bids have been requested twice for lights conforming to this exhibit, but no satisfactory bid has been received. Therefore the National Bureau of Standards Shops are now preparing preliminary design drawings and an estimate of the cost of producing lights for service test.

8. CIRCLING-GUIDANCE LIGHTS

In addition to the runway identification lights, lights are required which outline the runway in sufficient detail so that the pilot can plan and execute his approach pattern. The pilot interviews indicated that the present runway lights are inadequate for this purpose.

8.1 Intensity-Distribution Requirements.

The intensity-distribution requirements for circling-guidance lights which will provide adequate guidance during circling approaches of both bomber and fighter aircraft were determined as follows. The approach patterns used by various types of aircraft were determined from data given in technical orders and from statements obtained during the pilot interviews. Selected points in the approach paths were described in terms of altitude, a, pitchout radius, r, and position, p. These points, I to VIII, are shown schematically on figures 2a and 2b. Elevation angles, θ, azimuth angles, Ø, and line-of-sight distances, d, were then computed relative to the first runway light, A, on the left side of the runway for each of the selected points in each approach path. The results of these computations are shown in figures 2c and 2d. For each position the elevation angle relative to the first light is given.

The minimum intensity required to produce visual ranges equal to the maximum distance between the light at A and the selected points in the approach paths was computed for several transmissivities, assuming a pilot threshold of 1 mile candle. These intensities are listed in tables 2a and 2b.

Table 2a. Intensity Requirements of Fighter-Aircraft Approach Pattern

Approach Position	Elevation Angle Range (degrees)	Intensity (candles) for Indicated Transmissivity, T, (per mile) and Equivalent Visibility, V, (miles)					
		T → 0.005 V → 1	0.05 1.5	0.1 2	0.3 3	0.6 5	0.9 10
I	2 - 3	$>10^{10}$	6×10^7	2×10^6	1×10^4	250	40
I_a	3 - 5	6×10^7	6×10^4	7×10^3	360	40	11
I_b	6 - 8	8×10^4	900	250	37	10	4.0
I_c	10 - 13	145	17	8.5	3.0	1.6	1.0
I_d	20 - 24	3.9	1.4	0.9	0.5	0.3	0.2
I_e	39 - 45	0.2_5	0.1_4	0.1_2	0.1	0.1	0.1
I_f	83 - 84	0.1	0.1	0.1	0.1	0.1	0.1
II	9 - 14 11 - 18	230 42	21 7.0	11 4.0	3.5 1.8	1.9 1.0	1.2 .7
III	15 - 18 22 - 26	130 60	16 9.0	8.0 5.0	3.0 2.0	1.5 1.1	1.0 0.8
IV	28 - 34 39 - 45	48 40	7.5 6.5	4.4 3.8	1.9 1.7	1.0 0.9	0.8 0.8
VI	18 - 22 39 - 45	90 40	11 6.5	6.0 3.8	2.5 1.7	1.2 0.9	0.9 0.8
VII	9 - 11 11 - 19	120 18	13. 4.0	7.0 2.5	2.8 1.2	1.5 0.7	1.0 0.5
VIII	11 - 26	3.0	1.0	0.8	0.4	0.3	0.2

Table 2b. Intensity Requirements of Bomber-Aircraft Approach Pattern

Approach Position	Elevation Angle Range (degrees)	Intensity (candles) for Indicated Transmissivity, T, (per mile) and Equivalent Visibility, V, (miles) T → 0.005 V → 1	0.05 1.5	0.1 2	0.3 3	0.6 5	0.9 10
I	7 - 11	6×10^3	170	68	15	5	2.5
I_a	11 - 16	240	22	12	4	1.8	1.2
I_b	18 - 26	12	2.7	1.8	0.9	0.6	0.4
I_c	45 - 56	0.8	0.3	0.25	0.2	0.1	0.1
I_d	84 - 86	0.4	0.2	0.15	0.1	0.1	0.1
II	3 - 5 4 - 6	2×10^8 4×10^7	1×10^5 4×10^4	1×10^4 6×10^3	380 300	50 37	14 10
III	5 - 8	2×10^7	4×10^4	6×10^3	250	34	10
IV	10 - 15	6×10^5	4×10^3	800	75	15	6
V	10 - 13	6×10^5	4×10^3	800	75	15	6
VI	3 - 4	2×10^9	5×10^5	5×10^4	1×10^3	80	20
VII	2 - 3 4 - 6	$>10^{10}$ 8×10^4	1×10^6 900	8×10^4 250	1.5×10^3 75	100 15	28 6
VIII	3 - 4 8 - 11	6×10^7 210	6×10^4 20	8×10^3 10	350 3.5	40 1.7	13 1.0

Intensity-distribution diagrams can be obtained from the intensities given in tables 2a and 2b. For example, figure 3 is a polar plot of the intensities required for both the bomber and the fighter approach patterns when the atmospheric transmissivity is 0.3 per mile (visibility 3 miles).

Note that, except for the initial approach, the intensities required for the fighter-aircraft approach pattern are low and that the angles of elevation at which the lights are viewed are generally greater than 10°. Because of the short viewing distances, there is little decrease in the intensity required on the downwind and base legs as the visibility increases from 2 miles to 10 miles. The present runway lights provide adequate guidance during the initial approach when the aircraft is near the runway axis and within the main beam of the lights. The intensity in the off-runway directions is marginal at the required elevation angles during clear weather when the lights are operated on the lowest intensity settings.

The intensities required for the bomber approach pattern are, of course, greater and at lower angles of elevation on the downwind and base legs. Over much of the pattern these intensities are of the same order as the intensity of the main beam and much greater than the off-axis intensity of present runway and overrun lights operated at the settings recommended for the corresponding visibility as indicated in table 3.

Table 3. Representative Intensities of Runway and Overrun Lights

Reported Visibility (miles)	Recommended Intensity Setting (percent)		Representative Main Beam Intensity (candles)			Representative Off-Axis Intensity (candles)		
	C-1 & C-2 Lights	M-1 Light	C-1 Light	C-2 Light	M-1 Light	C-1 Light	C-2 Light	M-1 Light
>10	0.2	1	30	40	20	2	6	1
5-10	1	3	150	200	60	10	30	3
2-5	5	10	750	1000	200	50	150	10
1-2	25	30	3750	5000	600	250	750	30
<1	100	100	15000	20000	2000	1000	3000	100

Source of Data:
C-1 Light, NBS Report 21P-5/54
C-2 Light, Photometric Curves Numbers 1170A-J, 1169A-I, Lighting Section, Equipment Laboratory, Wright Air Development Center
M-1 Light, NBS Report 21P-17/55

It is obvious that a simple redesign of the runway light to provide the intensities required in the off-axis directions during clear weather is not sufficient. Such a light would require about a tenfold increase in lamp wattage. Most of this additional power would be wasted during periods of low visibility when straight-in approaches are used and intensity-setting steps 4 or 5 are used. Separate lights operating at intensity settings different from those used in the lights providing light down the runway are necessary.

The intensity-distribution requirements for this light were developed from the data of table 2 and figures 2 c and 2 d, and through discussions with personnel of the Equipment Laboratory, Wright Air Development Center. The recommended distribution is plotted in figure 4 and tabulated in table 4.

Table 4. Recommended Intensity Distribution of Circling-Guidance Lights

Elevation Angle (degrees)	Azimuth Angle (degrees)	Minimum Intensity (candles)
2 to 8	95 - 100 260 - 265	1,000
	100 - 120 240 - 260	5,000
	120 - 130 230 - 240	1,000
	130 - 150 210 - 230	800
	150 - 210	600
0 to 2, and 8 to 12	95 - 100 260 - 265	800
	100 - 120 240 - 260	1,000
	120 - 150 210 - 240	600
	150 - 210	400
12 to 20	95 - 265	200
20 to 60	95 - 265	100

The distribution was made symmetric about the 0° - 180° line although figure 4 indicates that the intensities required in the direction of the base leg are higher than those required in the upwind direction. (The differences for lights in the center of the runway are greater than those shown in figure 4 for a light near the threshold of the runway.) This decision was based upon the premises that circling-guidance lights of only one type would be used on a runway and that both left-hand and right-hand patterns would be flown. The intensities recommended are a compromise between the essentially uniform horizontal intensity distribution required to locate the runway, the high intensities needed in the direction of the base leg during restricted visibility, and power consumption.

8.2 Comparative Regions of Guidance.

Comparative visual ranges of present runway and overrun lights and of circling-guidance lights with the recommended intensity distribution when the atmospheric transmissivity is 0.9 (10-mile visibility) and 0.1 (2-mile visibility) are shown in figures 5 and 6. (The choice of the intensity settings for the circling-guidance lights will be discussed below.) Note the difference in visual range in the direction of the base leg. When considering the relatively small differences in visual range in the direction of the downwind leg during poor visibility it should be remembered that for the conditions shown the type C-1 and M-1 lights provide no guidance whatever for an aircraft flying a pattern in which the downwind leg is 2 miles from the runway and the only guidance obtained on the base leg is that obtained when the aircraft comes within the main beam of the runway lights on the far side of the runway.

8.3 Intensity Control of Circling-Guidance Lights.

If these circling-guidance lights are to be operated from the series circuits supplying the runway lights, some method of reducing the change in intensity and power consumption as the current in the series circuit is varied is necessary. Otherwise, circling-guidance lights which provided adequate intensity when the system was on step 1 would consume excessive power when the system was on steps 4 and 5. (The power consumption would increase about 10 times between steps 1 and 5.)

In order to reduce the required regulator capacity, it is highly desirable that the circling-guidance lights be turned off when the system is on intensity setting 5 (100% intensity). This is permissible since circling-guidance lights are of little, if any, value in weather conditions which require this intensity setting. If the circling-guidance lights are turned off when the system is on step 5, then a regulator which is loaded to capacity by the runway lights when on step 5 will not be overloaded on step 4 by these runway lights plus a group of circling-guidance lights which have a power consumption on step 4 equal to 30% of the capacity of the regulator.

Use of saturable isolating transformers was first considered. This method is unsatisfactory in several ways: a) It does not provide the constancy of intensity desired; b) The power required on step 5 is greater than on the lower steps; therefore, over-current relays would be required at each circling-guidance light if the load is to be reduced when the system is on step 5; c) Since these transformers operate at low power factor when the system is on the higher intensities, the additional regulator capacity which would be required is considerably greater than the rated load of the lamps of the circling-guidance lights; d) The distortions produced in the waveform of the system adversely affect the regulation of some types of regulators.

Following a suggestion made by the Lighting Section, Equipment Laboratory, Wright Air Development Center, that use of a saturable reactor connected in parallel with the lamp be considered as a means of controlling lamp current in place of a saturable isolating transformer, the principles of such a control were developed in cooperation with the Lighting Section. This control would utilize a direct-current winding to increase the saturation. The direct current would be obtained by using a rectifier connected into the circuit so that its output current is a function of the system current. With such a control it is hoped that it will be possible to obtain a relative intensity of at least 30% in the circling-guidance lights when the relative intensity of the runway lights is 0.2% (step 1) and to obtain a relative intensity in the circling-guidance lights of approximately 100% when the relative intensity of the runway lights varies from 1% to 25% (steps 2, 3, and 4). It should also be possible to decrease the reactance of this shunt control when the relative intensity of the runway lights is 100%, so that the relative intensity of the circling-guidance lights is 5% or less, thereby producing a significant unloading of the regulators.

8.4 Procurement of Circling-Guidance Lights.

The intensity-distribution and control requirements have been incorporated in Exhibit WCLEE5-69, dated 20 October 1955, which was prepared in co-operation with the Lighting Section, Equipment Laboratory. This exhibit was used by the National Bureau of Standards in obtaining quotations for the design and manufacture of circling-guidance lights. A contract for 22 lights conforming to this exhibit has been awarded to the A'G'A Division of Elastic Stop Nut Corporation.

8.5 Required Spacing of Circling-Guidance Lights.

The pilots indicated during the pilot interviews that they desired, as would be expected, a circling-guidance light at each runway light. This requires a spacing between lights of 200 feet. Such an installation, although desirable, would require more power than is available in most runway lighting systems. To determine the maximum useful spacing, simulated circling-guidance lights were installed by the Civil Aeronautics Administration, Technical Development Evaluation Center, at Indianapolis, under a Wright Air Development Center project. Test flights were made using spacings between lights of 400, 800, and 1200 feet. [20] The appearance of the pattern with these spacings indicates that a spacing of 1000 feet is optimum.

9. THRESHOLD LIGHTING

9.1 Function.

Threshold lights have two primary functions; to indicate the location of the ends of the runway, and to provide a "horizon." Indication of the location of the ends of the runway implies that a judgment of distance from the threshold lights can be made. This requires that there be sufficient "texture" in the pattern of threshold lights for adequate judgment of distance. This texture can be obtained by means of the spacing of the lights in the threshold bars. Providing a horizon requires that the length of the bars be such that the bars subtend an angle of about 1° at the pilot's eye.

9.2 Placement.

Because of the poor forward visibility of some types of fighter aircraft when in the flareout attitude, and because of the adverse effects of rain and snow on the center panels of the canopies of fighter aircraft, the fighter pilots interviewed preferred that the threshold bars be outboard of the runway lights. This placement will also increase the "horizon" effect.

9.3 Required Beam Spread.

The minimum required horizontal beam spread of threshold lights was computed on the premise that the aircraft should be within the main beam of these lights as the turn is made from the base leg to the final leg of the approach pattern. The relation between minimum horizontal beam spread θ, aircraft speed v, angle of bank β, and distance x, between the base leg of the approach pattern and the threshold is

$$x \doteq \frac{v^2}{g} \frac{\cot \beta}{\tan \theta} \qquad (2)$$

where g is the gravitational constant. (See Appendix D for derivation of equation.) Figure 7 shows the relation between x and β for representative values of θ and for four approach speeds.

In considering these figures the following should be noted:

1. These computations assume that the beams of the threshold lights are horizontally aligned so that one edge of the main beam is parallel to the runway axis.

2. The beam spread of 8° was selected as being representative of the present threshold lights, and 15° as being representagive of PAR 56 approach lights. (Since the axis of these lights is aligned with the runway, only half of the beam spread is effective.)

3. If the intensity of the runway lighting system is adjusted so that there is no glare along the runway, the runway and threshold lights will be very difficult to see from base-leg positions until the region of their main beams is entered.

The following conclusions may be drawn:

1. The horizontal beam spread of the present threshold lights is not sufficient for the threshold lights to provide adequate guidance during the turn from the base leg to the final leg of the approach unless the distance of the base leg is kept large and/or the angle of bank is large.

2. If the maximum desirable angle of bank is limited to 15° and the base leg is to be kept within 2 miles of the runway, a minimum beam spread of about 40° is required for approach speeds of 150 knots or less.

3. If the maximum desirable angle of bank is 30°, and the base leg is 2 miles from the runway, the minimum horizontal beam spread is about 20° for approach speeds of 150 knots or less and 40° for approach speeds of 250 knots or less.

4. Therefore, to provide threshold lights to permit an aircraft to land from a base leg as near as 2 miles from the runway, flying at speeds up to 250 knots, and turning with an angle of bank of 30°, a 40° minimum horizontal beam spread for threshold lights is recommended.

9.4 Spacing of lights in Threshold Bars.

Flight tests were made at the CAA Technical Development Evaluation Center, Indianapolis, using several spacings between the lights in threshold bars. [20] There was no noticeable difference in the appearance of the bars when 2.5-foot and 5-foot spacings were used. However, when the bars are viewed from distances of one mile or more, the effective intensity of a bar with a 2.5-foot spacing will be twice that of the bar with a 5-foot spacing.* A 10-foot spacing appeared slightly too great. From these observations it appears that a spacing of 5 to 8 feet will be satisfactory.

9.5 Length of Threshold Bars.

The choice of length for the threshold bars, or wings, is somewhat arbitrary since no data applicable to the problem were available. When some fighter-type aircraft are within a half mile of the threshold, only one bar or wing will be visible because of the obscuration produced by the aircraft structure as the aircraft

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* J. B. DeBoer, Philips Research Reports, 6, 224 (1951)

approaches the flareout or nose-up attitude. In addition, during rain and snow, vision through the center panels of some canopies is poor. Therefore the threshold bars should be long enough so that the desired horizon guidance will be obtained from one bar when the aircraft is within a half mile of the threshold.

If an angular length of 1° is taken as the minimum, then the bars should be at least 45 feet long. Flight observations at Indianapolis indicated that a length of 40 feet would be satisfactory. Current Air Force regulations require 40-foot wings for new installations.

9.6 Color of Threshold Lights.

Present standards specify the use of green lights to mark both ends of the runway. Under poor visibility conditions, the differentiation between green and white lights is less certain than that between red and white lights. This suggests the use of red lights to mark the upwind end of the runway. The pilot interviews indicated no serious objection to this use of red lights and many of the pilots favored it.

9.7 Unidirectional vs. Bidirectional Threshold Lights.

The use of bidirectional threshold lights with a beam spread of 30° to 40° is considered unnecessary. On rollout or takeoff the aircraft is sufficiently close to the centerline of the runway that the beam spread of the present threshold lights is adequate for marking the upwind end of the runway. In addition, pilots report that on takeoff they make little use of the horizon guidance of the threshold light. Thus, long bars are not required on the upwind end of the runway. Therefore, a system using a combination of some unidirectional and some bidirectional lights appears desirable.

9.8 End-of-Runway Lights.

Some lights are needed between the threshold bars to mark the end of the runway paving for aircraft taxying out for takeoff or completing their rollout. These lights should be mounted at the edge of the runway paving and should, therefore, be flush-type lights. The intensity required for this use is relatively low, only a few candles. However, unless saturable transformers are used, obtaining this intensity when the runway lighting system is operating on step 1 requires that the intensity be above 1000 candles when the system is on step 5. Thus, consideration should be given either to the use of low-intensity lights connected to the taxiway lighting circuits or to the use of lights of such intensity that they will be compatible with the other threshold lights.

9.9 Recommended Threshold Lighting Systems.

A proposed threshold lighting system based upon the above considerations is shown in figure 8. It is recommended that tests be made of this system.

10. CONCLUSIONS

1. The coverage of the present airfield beacon is inadequate for jet aircraft operation.

2. For jet aircraft operation it is essential that the runway be located and identified from as great a distance as practicable. The off-axis guidance of the present runway lights is inadequate when the lighting system is operated on the brightness settings used for clear weather. The present runway lighting systems provide no positive means of identification.

3. It is not practicable to obtain sufficient off-axis guidance from the lights of a high-intensity runway lighting system which supply the axial guidance.

4. The downwind corner of the runway should be well marked and visible from the downwind leg. None of the lights used in present runway lighting systems has a satisfactory intensity distribution for this function with the landing pattern used by the large jet bombers.

5. The beam spread of the present threshold lights is not sufficient to provide satisfactory guidance during the turn from the base leg to the final leg of the approach with aircraft with high approach speeds.

6. The intensity distribution of the present high-intensity runway lights is satisfactory for straight-in approaches when the distance between the rows of runway lights is 200 feet or less and is marginal when the distance between rows is 300 feet. These lights appear to be satisfactory mechanically.

7. Gaps in the runway lighting system are not considered serious except in the touchdown area and where the gaps are very long.

8. In low-visibility approaches the pilots are more concerned with finding and seeing the runway lights than they are with the adverse effects of glare.

9. The marking of the turnoffs from the runways is inadequate.

10. Information relative to the length of runway remaining is considered essential on both landing and takeoff. Lights located across the upwind end of the runway are of little value in indicating this distance, particularly when there is rain or snow on the center panel (bullet-proof glass) of the canopy of fighters.

11. The use of red lights to mark the upwind end of the runway appears desirable and is acceptable to the pilots.

12. Lack of uniformity in the lighting systems from airfield to airfield results in undesirable confusion.

11. RECOMMENDATIONS

It is recommended that:

1. Airfield beacons meeting the intensity distribution requirements of table I be obtained and tested for operational suitability.

2. Tests be made of a beacon in which the interval between the "white" flashes is at least two-tenths of the flash cycle, to determine pilot acceptance of this coding.

3. Runway identification lights conforming to the requirements of Section 7 be procured and installed outboard of the threshold lights on a runway with high-intensity lighting at two or more airfields for tests of operational suitability and pilot acceptance.

4. Circling-guidance lights conforming to the requirements of Section 8 be procured and installed on runways with high-intensity lighting at two or more airfields for tests of operational suitability and pilot acceptance.

5. Service tests be made of threshold lighting systems modified by the addition to the outboard ends of the threshold lighting system of unidirectional lights having a horizontal beam spread of approximately 30°.

6. Development of a light suitable for installation across the end of the runway between the wings of the threshold lighting system be made a task of this project.

7. Development of an improved system of marking the principal taxiway turn-offs be made a task of this project.

8. A system providing information as to the length of runway remaining, suitable for use by day and by night, be developed and tested for operational suitability.

9. Flight and service tests be made to determine pilot acceptance of the use of red lights to mark the upwind end of the runway.

10. A study of the feasibility and design considerations of lights suitable for use on the runway between heavy-duty pavement and paved shoulders and in intersections be made a part of this project.

Regions of Guidance
Airfield Beacons

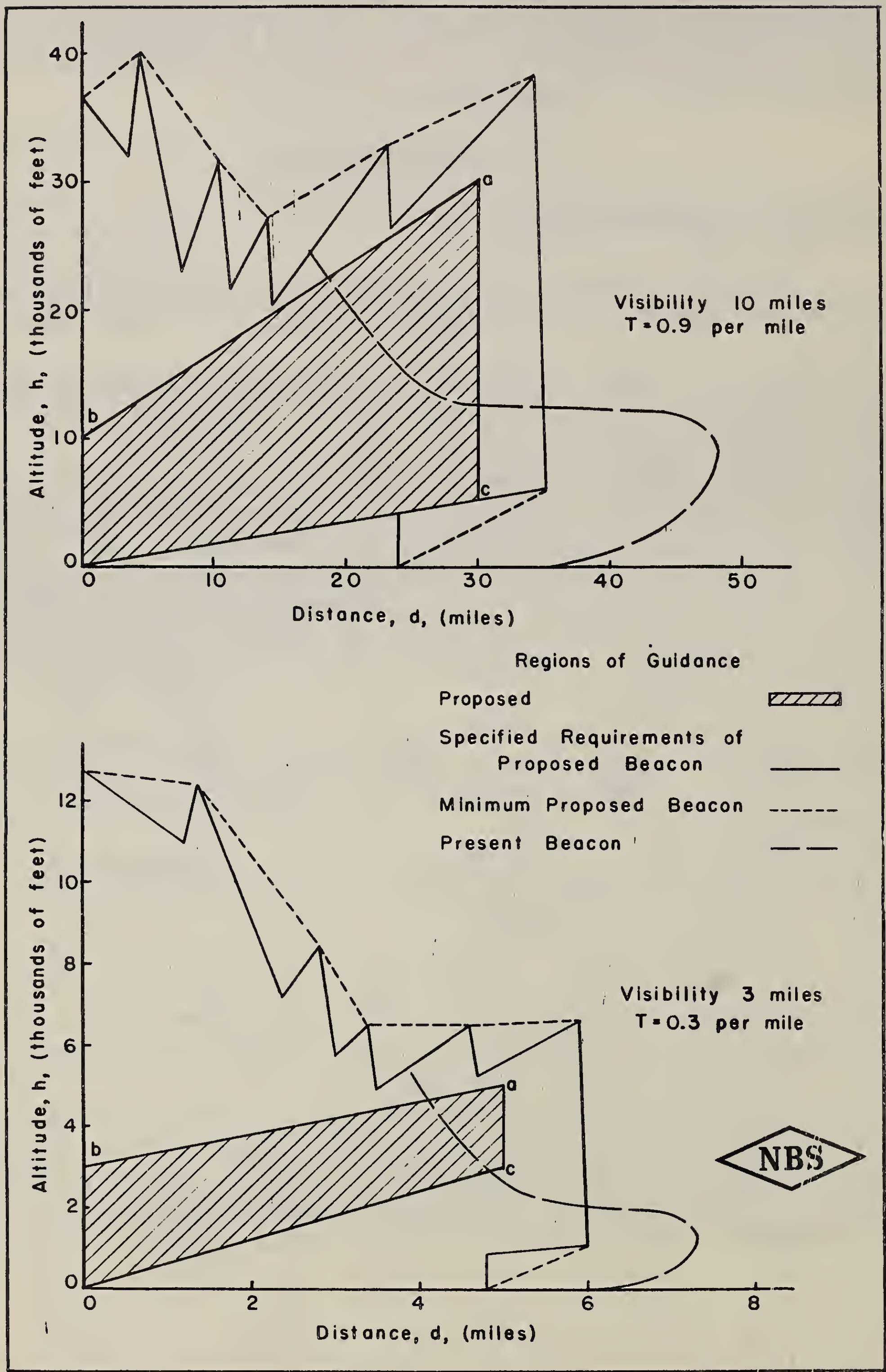

Figure 1

Circling Approach Patterns

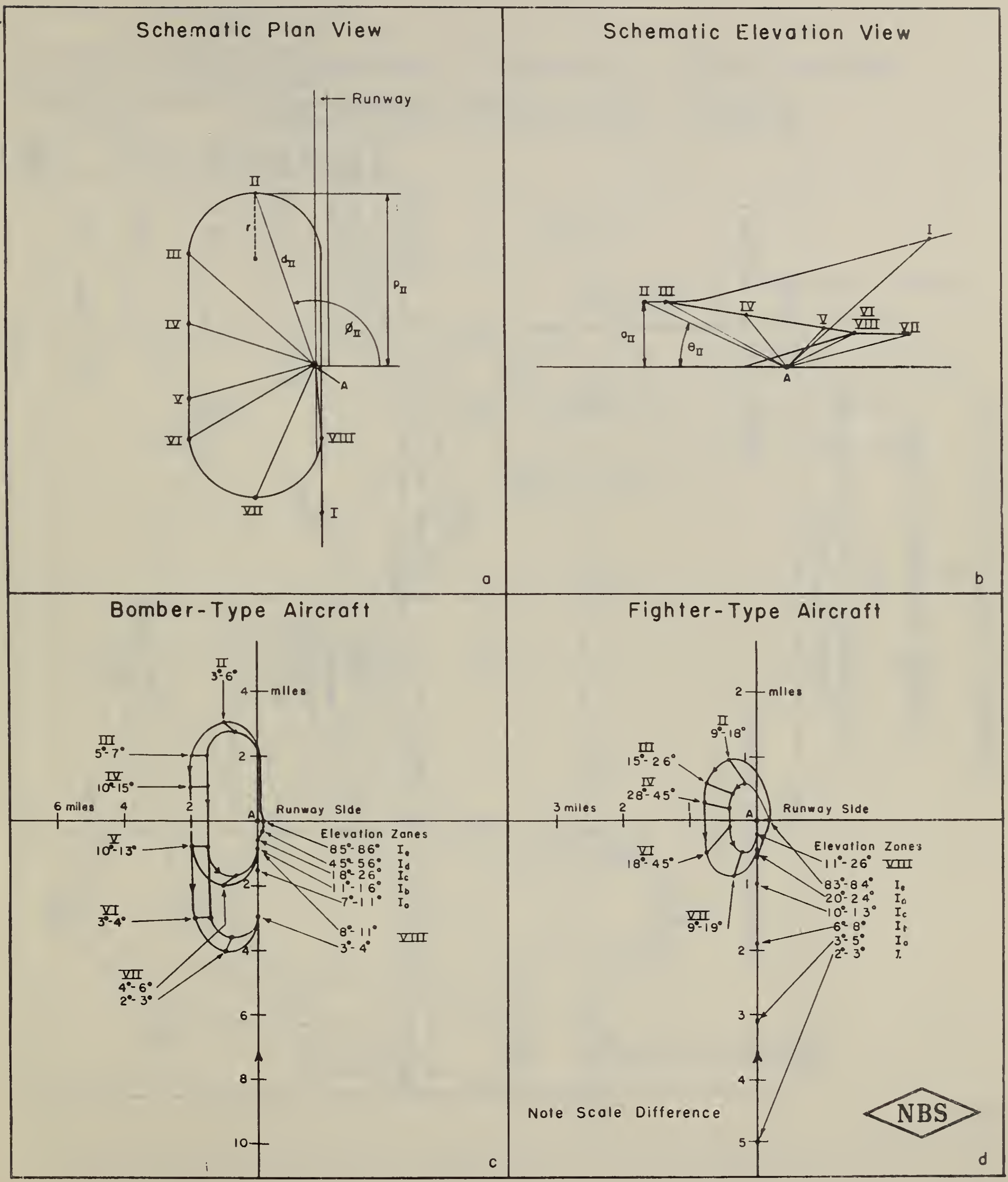

Figure 2

Minimum Intensity Distribution of Circling-Guidance Lights for Transmissivity of 0.3 per mile (3-mile visibility)

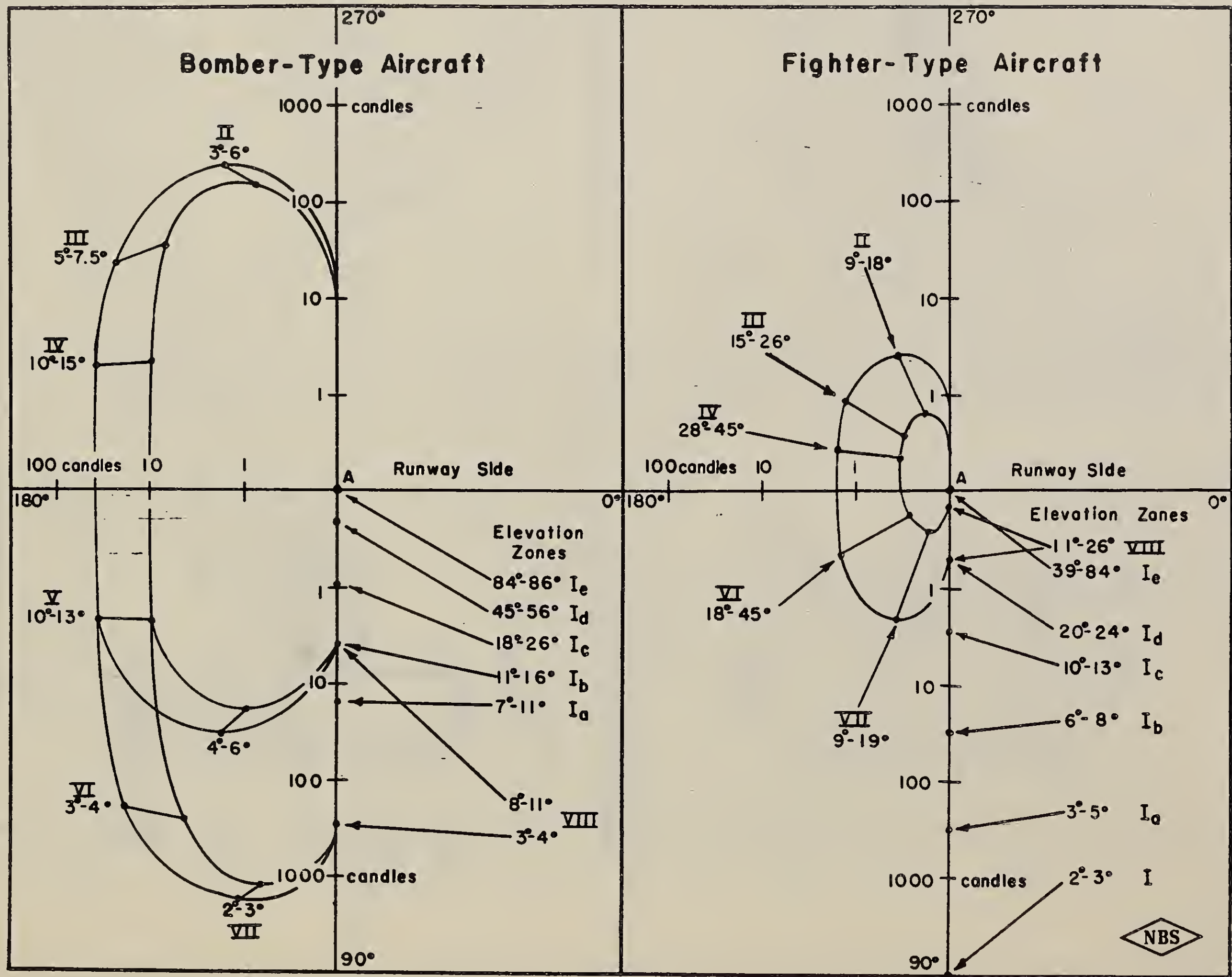

Figure 3

Recommended Intensity Distribution
Circling-Guidance Lights

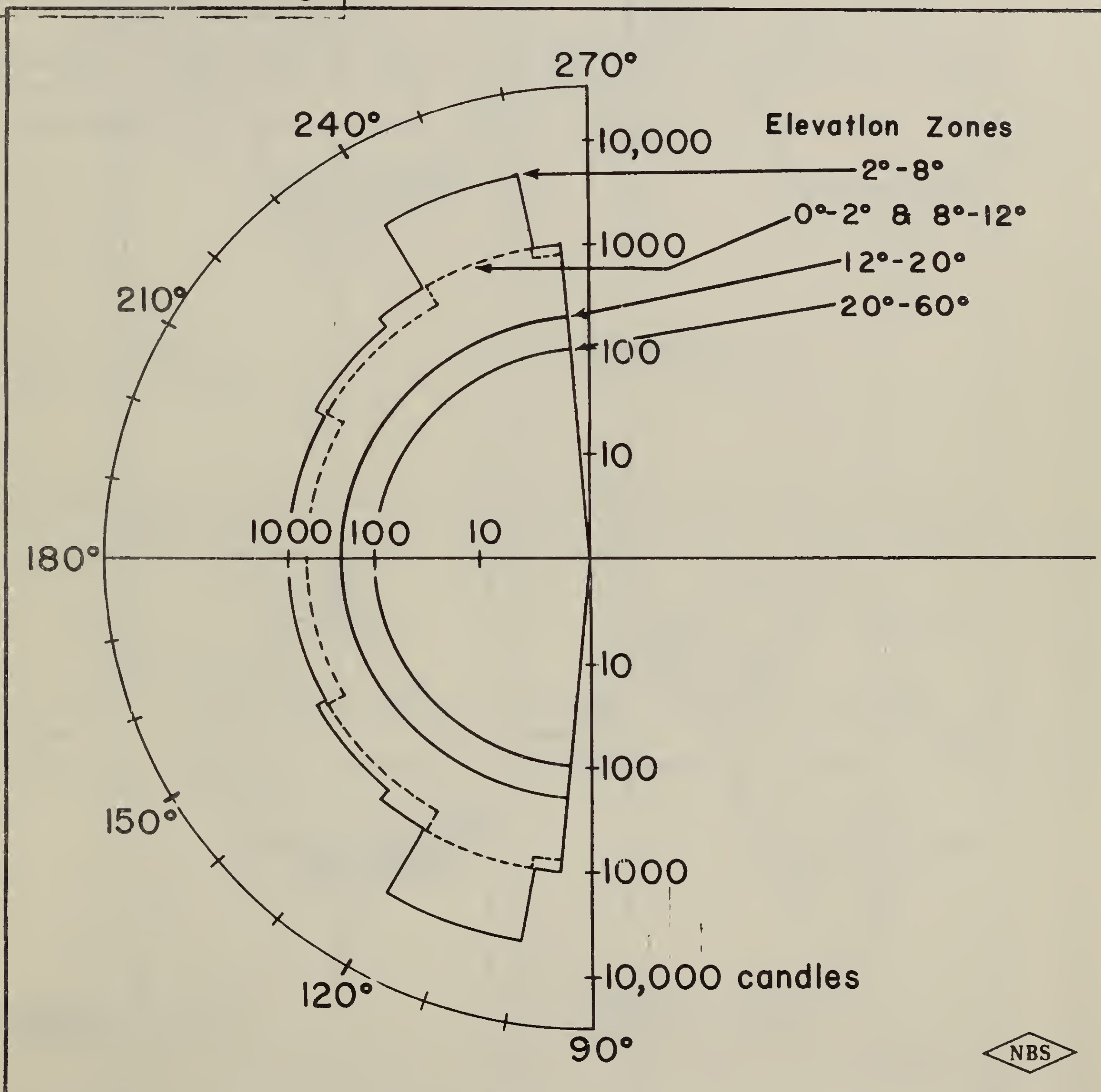

Figure 4

Regions of Guidance of Runway Lights:
Transmissivity 0.9 per mile
(10-mile visibility)

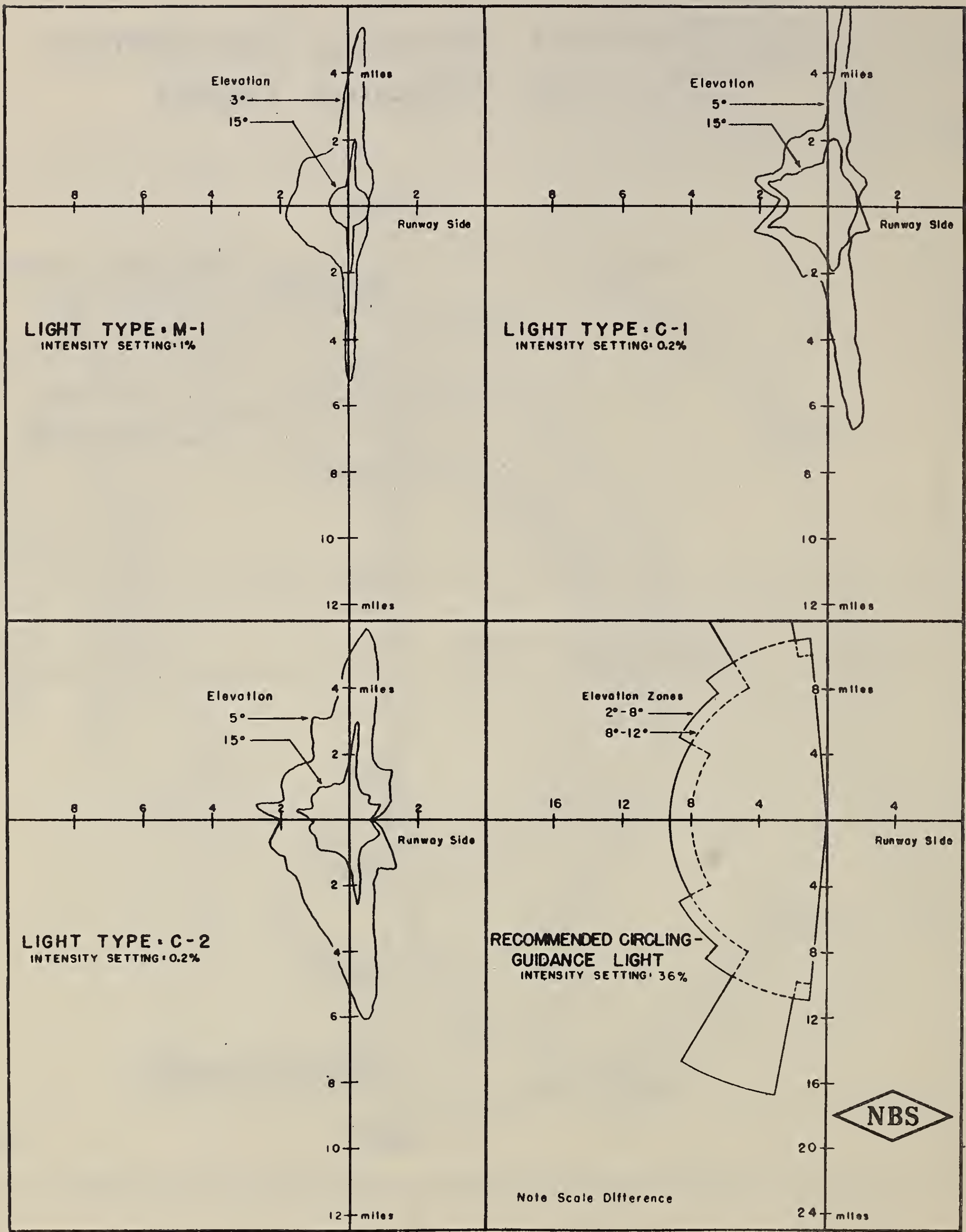

Figure 5

Regions of Guidance of Runway Lights

Transmissivity 0.1 per mile

(2-mile visibility)

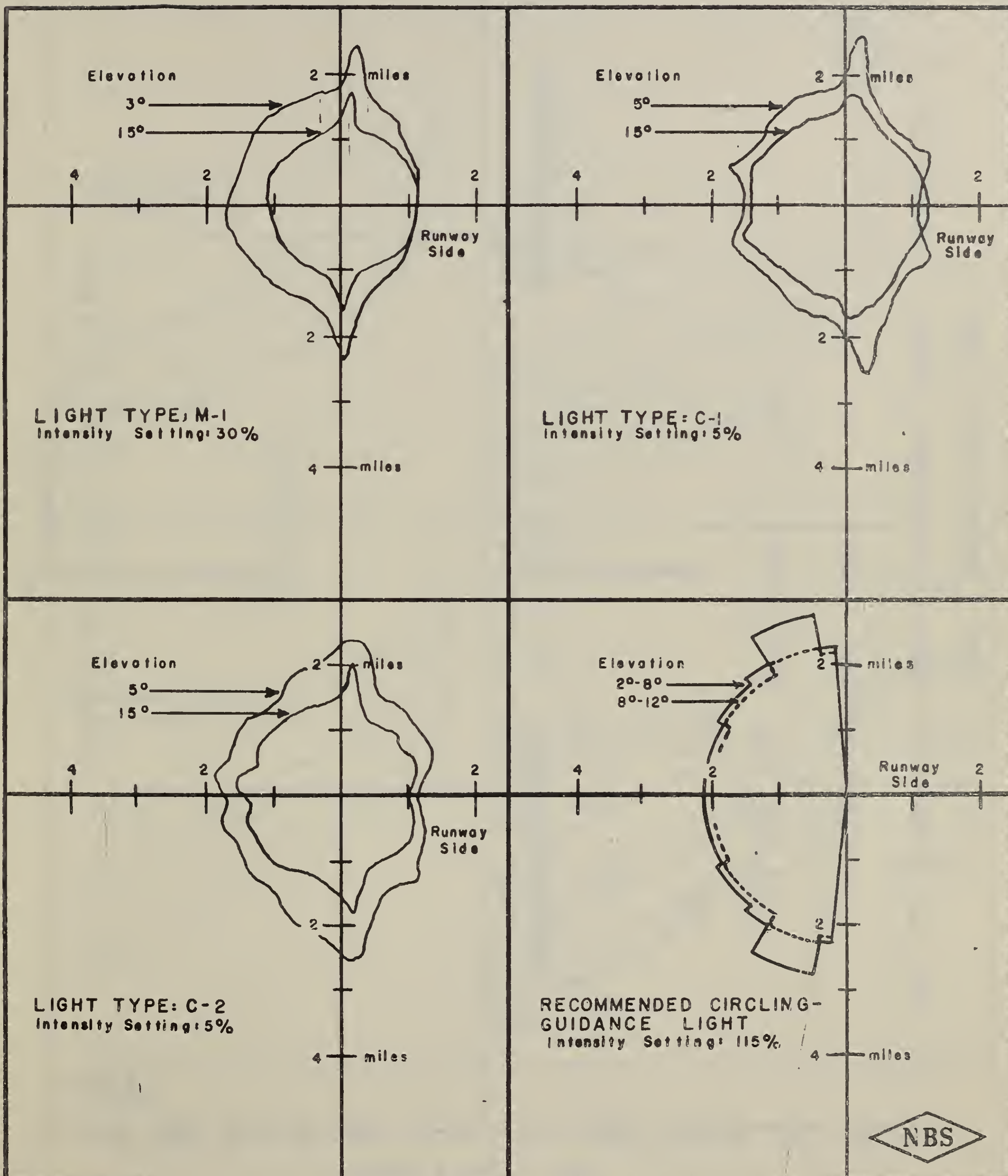

Figure 6

Required Beam Spread of Threshold Lights

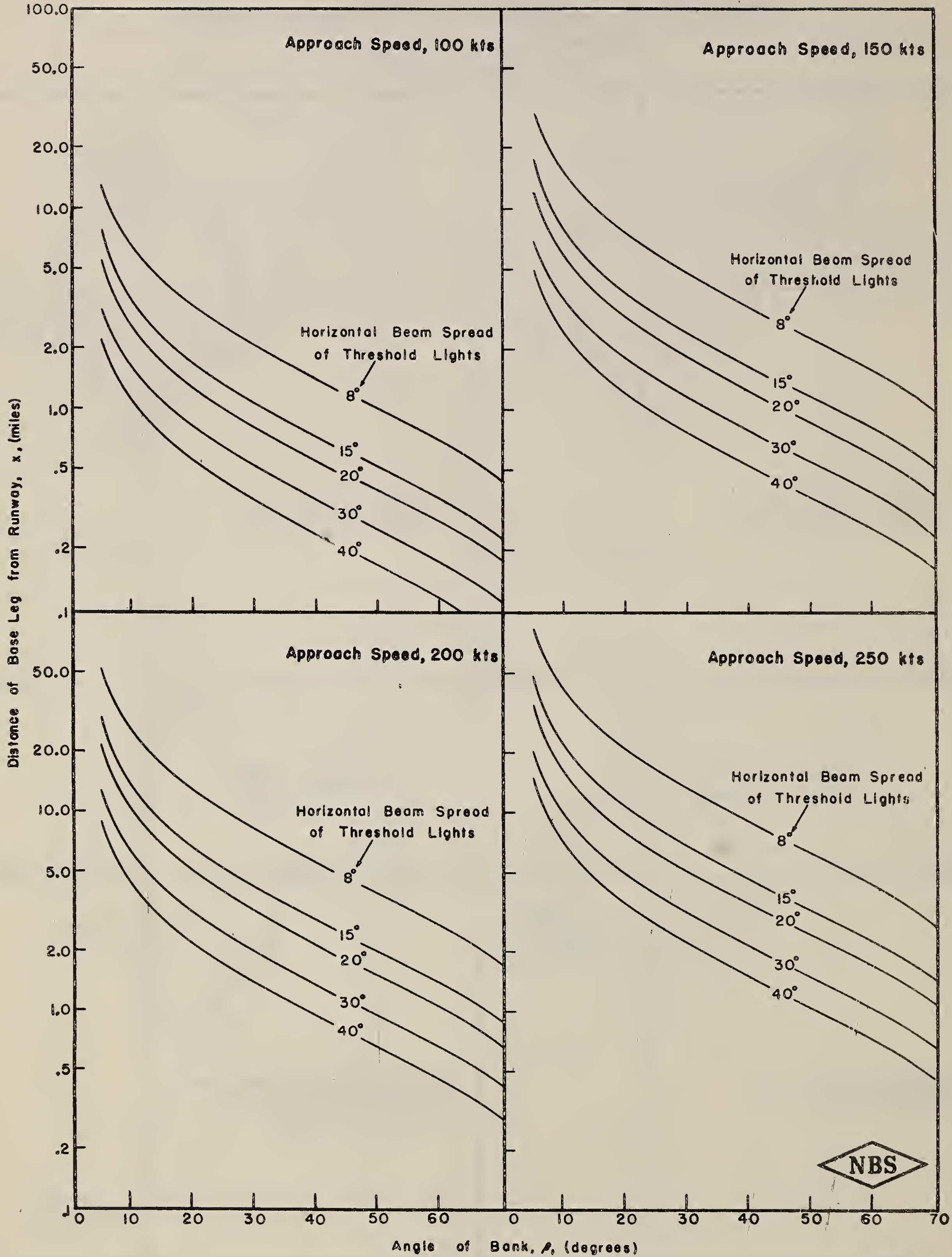

Figure 7

Proposed Threshold Lighting System

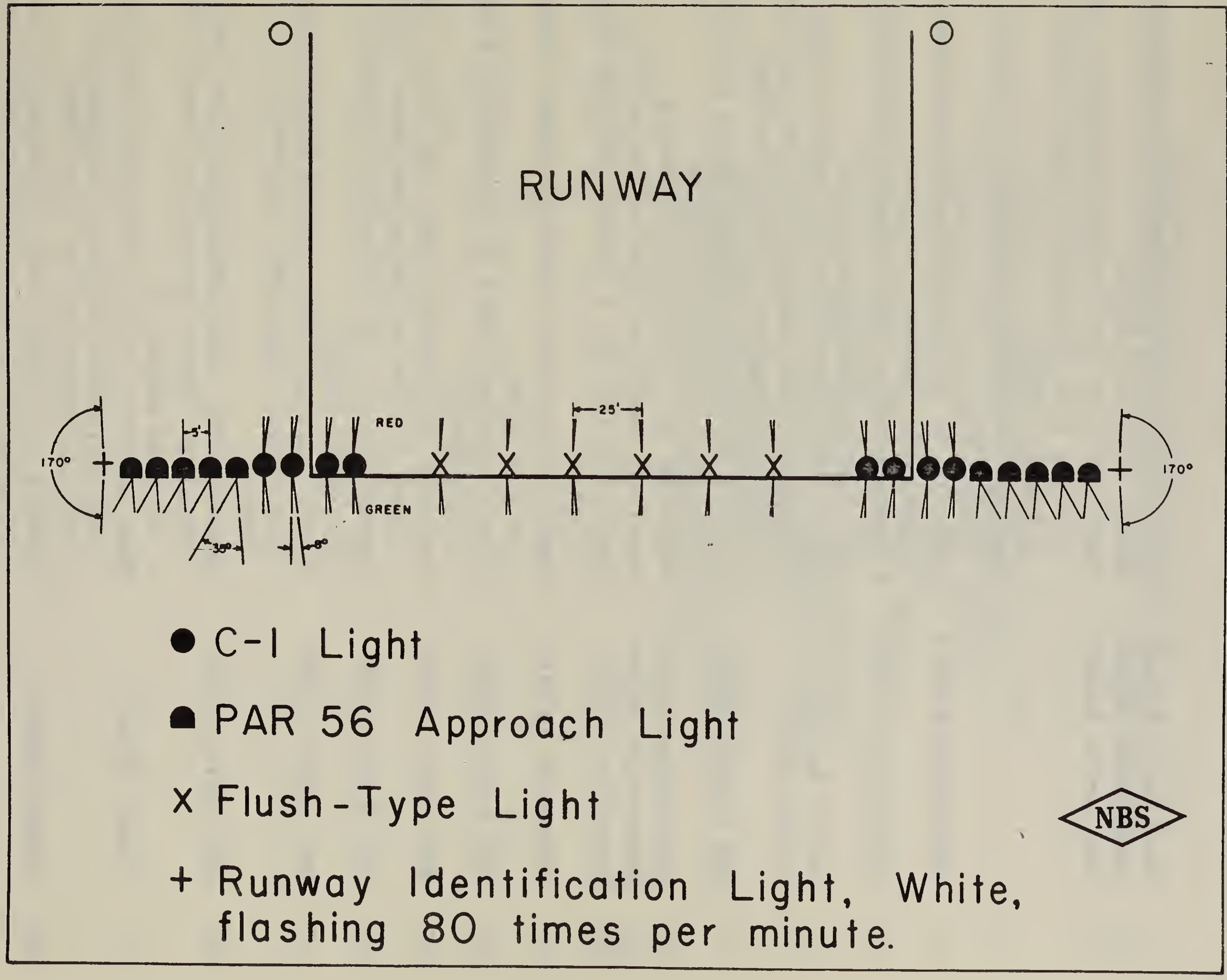

Figure 8

APPENDIX A

REPORTS AND MEMORANDA FORWARDED TO WRIGHT AIR DEVELOPMENT CENTER

1.	Memorandum Report	Feasibility of Using Completely Flush Lights
2.	Memorandum Report	Runway Locator Lights
3.	Memorandum Report	Computation of the Loads Developed in the Landing Gear When an Airplane Taxies Over a Runway Light
4.		Overlays of Runway Patterns of Selected Airfields
5.	Memorandum Report	Analysis of the Operational Requirements of Threshold Lights
6.	Memorandum Report	Recommendations for Intensity Distributions of Airport Beacons
7.	Letter Report	Effective Intensity of Flashing Lights
8.	Letter Report	Intensity Requirements for Circling-Guidance Lights of Runway Lighting Systems
9.	NBS Report 4086	Results of Static Loading Tests of Elfaca Gratings by Aircraft Tires
10.	Memorandum Report	Guidance for Circling Approaches
11.	Memorandum Report	Required Length of Flush-Type Lights
12.	Tentative Draft	Specification for a Fixed Circling-Guidance Light
13.	Tentative Draft	Specification for Flashing Runway Identification Light
14.	NBS Report 4358	Static Loading Tests of Flush-Type Runway-Light Heads
15.	NBS Report 4449	Analysis of Mercury Lamps and Filter Combinations for Use as Aviation-Green Lights
16.	NBS Report 4554	Computation of the Effective Intensity of Flashing Lights
17.	NBS Report 4565	Static Loading Tests of A.G.A. Expendable-Top Runway-Light Head Assemblies with Glass Covers
18.	NBS Report 4574	Landing Gear Loads Resulting from Taxying Airplane Over a Projecting Runway Light. Progress Report 1
19.	Travel Report	Memo of Visit to CAA Technical Development and Evaluation Center, Indianapolis, Indiana, February 16 - 18, 1955
20.	Travel Report	Summary of Flight Tests of Downwind and Threshold Lights at Indianapolis, Indiana, April 13 & 14, 1955
21 - 32.		Reports of Interviews at Air Force Bases

APPENDIX B

AIR BASES VISITED DURING SURVEY OF OPERATIONAL REQUIREMENTS OF RUNWAY LIGHTS FOR JET AIRCRAFT

Wright-Patterson Air Force Base, Ohio
Andrews Air Force Base, Maryland
Shaw Air Force Base, South Carolina
Hunter Air Force Base, Georgia
Presque Isle Air Force Base, Maine
Dow Air Force Base, Maine
Westover Air Force Base, Massachusetts
Barnes Field, Westfield, Massachusetts
Lockbourne Air Force Base, Ohio
James Connally Air Force Base, Texas
Headquarters, Flight Training Command, Waco, Texas
McChord Air Force Base, Washington

APPENDIX C

VISIBILITY AND VISUAL RANGE

Explanation of Terms and Symbols.

V_o Visibility:

(Day) The maximum distance at which large black objects can be seen and identified when seen against a sky or fog background.

(Night) The maximum distance at which a light with an intensity of 25 candles can be seen.

These definitions are analagous to the information to the information reported by the Weather Bureau.

V Visual Range: The maximum distance at which a particular light (or object) can be seen.

K Visibility Factor: The ratio of the visual range of the object or light of interest to the visibility.

$$K = V/V_o. \tag{1}$$

I Candlepower or Luminous Intensity: The luminous intensity or candlepower, in a particular direction, of a light source.

E Illumination: The density of luminous flux incident upon a surface. In this report the unit of illumination used is the mile candle. A mile candle is the illumination produced on a surface by a source with an intensity of one candle one mile distant when the air is perfectly clear.

E_t Illumination-Threshold: The minimum illumination of the eye at which a light of small angular extent can be found and seen steadily. In this report a value of 1 mile candle at the outside of the canopy is used for the pilot's threshold at night. This is twice the classic value of 0.5 mile candle. The use of the higher value is considered desirable because of the increased absorption in the center panel of the canopy, the increased number of lighted instruments, and the greater complexity of the cockpit of modern aircraft, which reduces the time and effort the pilot can use in visual search.

APPENDIX C (cont.)

E_0 "Standard" Illumination-Threshold: The illumination-threshold applicable to a weather or ground observer. A value of 0.1 mile candle is used for E_0 in this report. This value is approximately equal to that obtained in field tests during periods of low visibility.* These studies indicate that the threshold decreases with increasing visibility. However, in view of the uncertainties in the other parameters of interest, a constant value of illumination-threshold is used in this report.

T Transmissivity: The ratio of the light which remains in a collimated beam after passing through a unit distance of the atmosphere to the incident light.

Allard's Law.

The illumination produced by a source of intensity I at a distance x when the atmospheric transmissivity is T is found by means of the familiar relation

$$E = IT^x/x^2. \qquad (2)$$

This relation, generally known as Allard's Law, follows from the inverse-square law and the definition of transmissivity. When E becomes equal to E_t, the illumination-threshold, x is equal to V, the visual range of the light, so that

$$E_t = IT^V/V^2. \qquad (3)$$

If a standard value, E_0, is assigned to E_t, the illumination-threshold, and a standard intensity, I_0, to the lights being used as visibility marks, the visual range of the light is equal to V_0, the visibility, so that

$$E_0 = I_0T^{V_0}/V_0^{\,2}. \qquad (4)$$

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* Douglas and Young, CAA Technical Development Report #47 (1945). U. S. Weather Bureau, Final Approach Visibility Studies Fiscal Year 1952, Progress Report Part II, March 1953; and Fiscal Year 1953 Progress Report, November 1953.

APPENDIX C (cont.)

An intensity of 25 candles for I_0 is assumed for the reference lights used in visibility observations. This intensity was selected as being representative of the lights used as visibility marks* and has been generally accepted in the United States.** If E_0 is 0.1 mile candle and I_0 is 25 candles, then

$$T^{V_0} = 0.004 V_0^2. \qquad (5)$$

The transmissivities, T, selected for use in the computations of visual range in this report and the corresponding visibilities, rounded to the nearest value used in meteorological reports, computed from equation (5) are given in table C-I.

Table C-I. Reported Visibilities, D, Corresponding to Transmissivities, T

Transmissitivies (T) per mile	Reported Visibility (D) miles
0.005	1.
.05	1.5
.1	2.
.3	3.
.6	5.
.9	10.

The effect of source intensity upon the visual range of lights at night as a function of visibility is illustrated in figure C-1. In preparing this figure, visibilities, V_0, were computed by means of equation (5) and the visual ranges corresponding to the selected intensities by means of equation (3) using a value of 1 mile candle for E_t. Note that when the visibility is low, large changes in intensity have comparatively little effect on the visibility factor, or the visual range.

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* Douglas and Young, CAA Technical Development Report #47 (1945).

** U. S. Weather Bureau, Final Approach Visibility Studies, Fiscal Year 1952, Progress Report Part II, March 1953; and Fiscal Year 1953, Progress Report, November 1953.

Visibility Factor For Lights

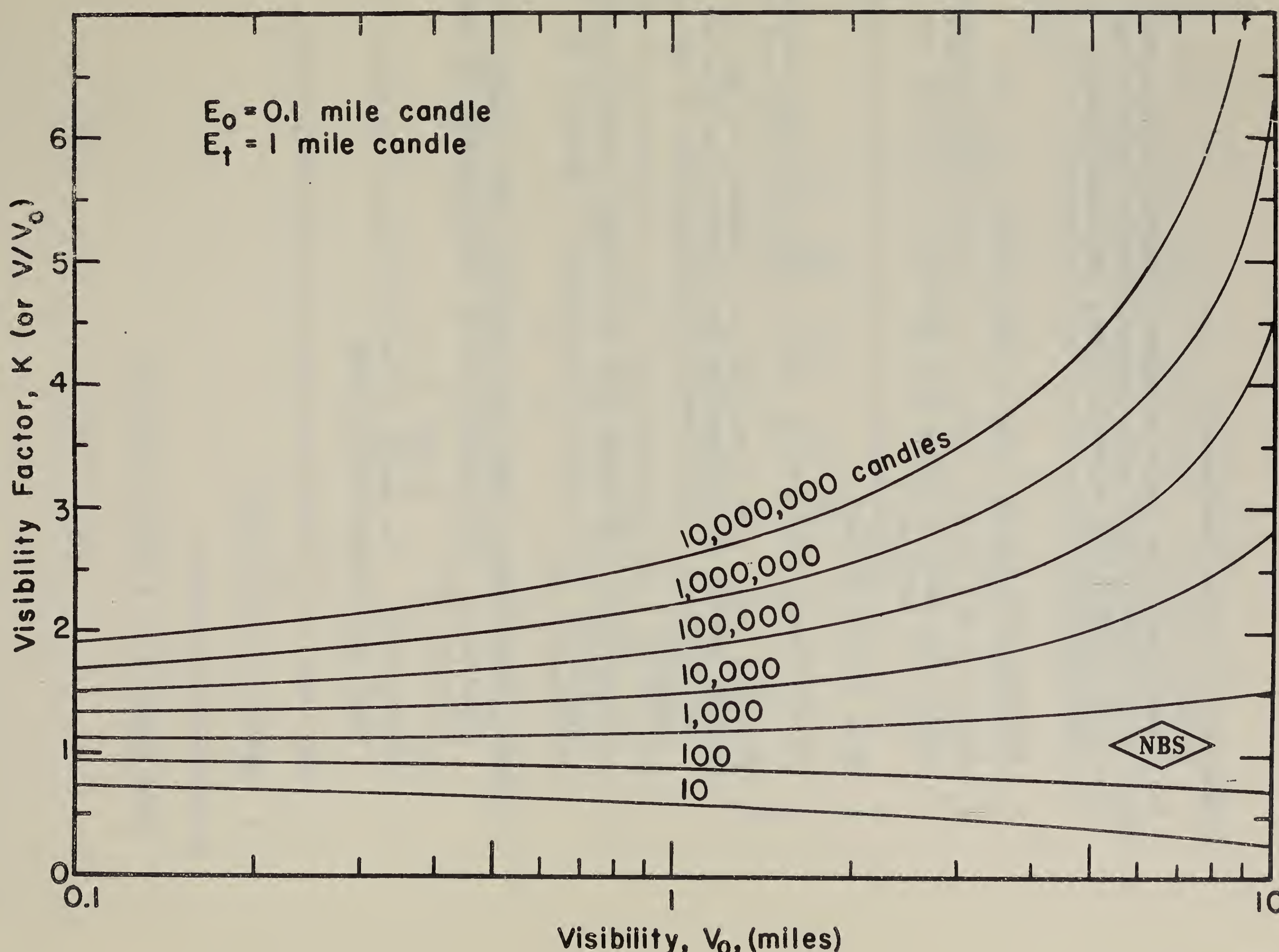


Figure C-1

APPENDIX D

THRESHOLD LIGHTS

Explanation of Terms and Symbols.

θ Beam spread: The angle in degrees between the extended centerline of the runway and the line of sight to the threshold lights when the lights are first detected from the base leg.

x Distance from the base leg to the runway.

r_θ Radius of the quarter-circular path of an aircraft during its turn onto the final leg, starting at the time the light is detected.

m Mass of the aircraft.

g Gravitational acceleration, equal to 32.2 feet per second.

F_w Dropping force: The force that acts downward on the aircraft because of the mass of the aircraft and gravitational acceleration. This force acts perpendicular to the earth's surface.

F_L Lifting force: The force that acts upward, essentially perpendicular to the plane of the wings, to maintain the aircraft aloft.

F_c Centrifugal force: Equal to, but acting in a direction opposite to, the resultant of the lifting force and the dropping force.

β Banking angle: The angle in degrees between the plane of the wings and the horizontal plane.

r_β The radius of the turn resulting from the banking angle.

v Speed of the aircraft.

Derivation of Equations.

From figure D-1 it can be seen that

$$r_\theta = x \tan \theta. \qquad (1)$$

APPENDIX D (cont.)

The point where the aircraft path coincides with the extended centerline of the runway is $x(1-\tan\theta)$. For beam spreads greater than 45°, $\tan\theta$ is greater than 1, that is, the coincidence point is over the runway. The beam spread of the threshold lights, therefore, need not exceed 45° under any approach condition, distance of base leg from the runway, and aircraft speed.

From figure D-1 it can be seen, assuming a perfectly coordinated turn, that

$$F_w = F_c \cot \beta . \qquad (2)$$

Applying elementary equations from mechanics,

$$F_c = \frac{mv^2}{r_\beta} \quad \text{and} \quad F_w = mg ,$$

to equation (2) gives

$$r_\beta = \frac{v^2}{g} \cot \beta . \qquad (3)$$

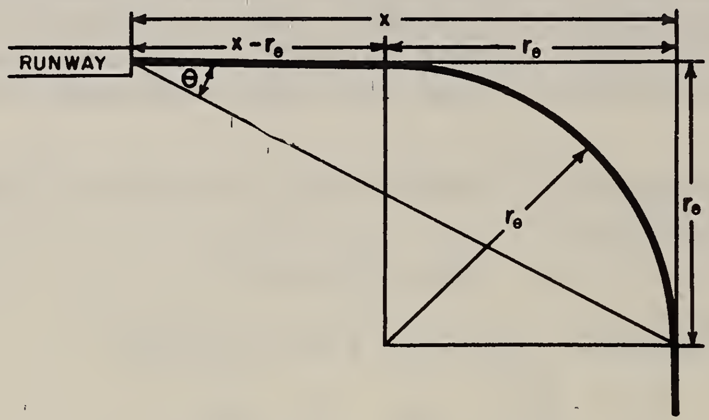
But as the radius of the turn resulting from β is the same as that of the quarter-circle turn onto the final leg,

$$r_\beta = r_\theta . \qquad (4)$$

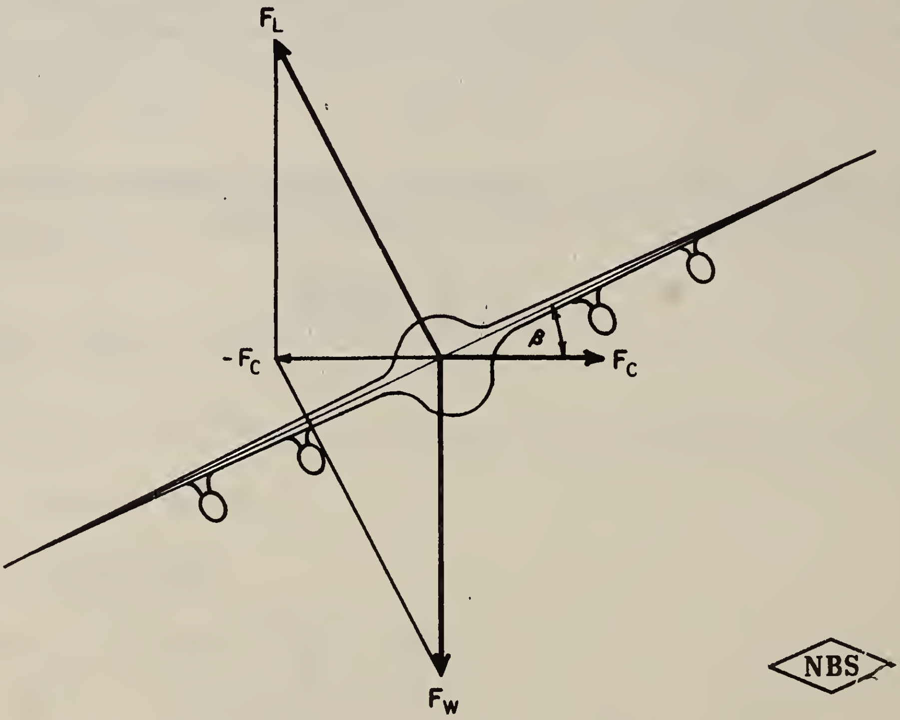
This implies that the right-hand side of equation (3) equals that of equation (1). Solving for x gives,

$$x = \frac{v^2}{g} \frac{\cot \beta}{\tan \theta} . \qquad (5)$$

Mechanical Considerations in Determination of Beam Spread of Threshold Lights



a. Plan view of the path of an aircraft during the turn into final



b. Forces acting on aircraft during a turn

Figure D-1

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to Government Agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. A major portion of the Bureau's work is performed for other Government Agencies, particularly the Department of Defense and the Atomic Energy Commission. The scope of activities is suggested by the listing of divisions and sections on the inside of the front cover.

Reports and Publications

The results of the Bureau's work take the form of either actual equipment and devices or published papers and reports. Reports are issued to the sponsoring agency of a particular project or program. Published papers appear either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau itself publishes three monthly periodicals, available from the Government Printing Office: The Journal of Research, which presents complete papers reporting technical investigations; the Technical News Bulletin, which presents summary and preliminary reports on work in progress; and Basic Radio Propagation Predictions, which provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: The Applied Mathematics Series, Circulars, Handbooks, Building Materials and Structures Reports, and Miscellaneous Publications.

Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards ($1.25) and its Supplement ($0.75), available from the Superintendent of Documents, Government Printing Office. Inquiries regarding the Bureau's reports and publications should be addressed to the Office of Scientific Publications, National Bureau of Standards, Washington 25, D. C.

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