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Summary Technical Reports of NDRC

Div 16

Vol 2

CAMOUFLAGE

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Div 16
Vol 2

CAMOUFLAGE

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SUMMARY TECHNICAL REPORT

OF THE

NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 16, NDRC

VOLUME 2

VISIBILITY STUDIES AND SOME APPLICATIONS IN THE FIELD OF CAMOUFLAGE

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 16
GEORGE R. HARRISON, CHIEF

WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report which runs to over twenty volumes. The extent of the work of a division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC; account must be taken of the monographs and available reports published elsewhere.

Division 16 carried out a broad program in the fields of light and optics. Among the studies undertaken were a number involving the principles and techniques of camouflage, and perhaps the outstanding success achieved in this field was the development of the "black widow" finish for night-flying aircraft. Significant improvements were made in aerial mapping and photography. Devices depending on the use of infrared light were developed for the detection of enemy craft, the recognition of friendly ones, and for intercommunication by voice and code. The sniperscope, using image-forming infrared rays, was a spectacular weapon which enabled our troops to fire accurately on an enemy 100 yards away in utter darkness.

The Division 16 Summary Technical Report, prepared under the direction of the Division Chief, George R. Harrison, describes the technical achievements of the Division personnel and its contractors, and is a record of their skill, integrity and loyal cooperation. To all of them, we extend our grateful praise.

Vannevar Bush, Director
Office of Scientific Research and Development
J. B. Conant, Chairman
National Defense Research Committee

FOREWORD

At the time of its formation late in 1942, Division 16, the Optics Division of NDRC, was assigned both the general task of stimulating and supervising OSRD research in optics and the immediate problem of overseeing a large number of contracts which had previously been initiated by the Instruments Section. Inasmuch as the new Division consisted to a large extent of personnel associated with the Instruments Section during 1940 and 1941, the reorganization involved few important changes.

The present Summary Technical Report describes the accomplishments of both Division 16 and Section D-3, and covers the principal developments in optics made in America during World War II. This report should be considered as intermediate in character between the detailed contractors' reports of Division 16, to which reference is frequently made herein which are complete scientific reports of the investigations carried on, and the historical volume entitled *Optics and Applied Physics in World War II*, which presents in less technical form the accomplishments of the Division and its contractors, and assigns credit to those who took part.

The contents of the present volume demonstrate impressively the great contribution made by the optical industry of America and the university optical laboratories to the war effort. While less glamorous than some of the newer fields brought into existence during the war, optics nevertheless made significant contributions which were by no means confined to mere extension or application of optical methods or apparatus previously in use. The stress of the emergency produced many new optical developments, and the genesis of a large proportion of these will be found recorded in the following pages.

The science of optics and the optical industry have both benefited greatly by the intensive research which took place during the war. Many of the new devices developed under emergency conditions have contributed and will contribute more to our fundamental understanding of optics, and many of them will have peacetime applications. New lines along which optical research should be directed have been made apparent. In particular, the infrared field has benefited greatly, and the art of infrared phosphor development and utilization has been elevated to an entirely new level.

Consideration of the developments in optics, as in other fields, emphasizes that, once adequate immediate defense has been insured, more important than having weapons for a possible future war is having available a large body of trained personnel who can step into any breach that occurs and be available to produce the new devices that may be needed.

The Optics Division of NDRC is especially indebted to the chiefs and members of its Sections, whose names are listed at the end of this volume. They have provided the essential leadership, combined with scientific knowledge, without which the work of the Division could not have been planned or completed.

George R. Harrison
Chief, Division 16

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This book summarizes the principal activities of the Camouflage Section of NDRC (Section 16.3) during World War II as they appear in retrospect more than a year after the Section ceased to exist as a body and more than eight months after the close of hostilities. Unlike most groups in the NDRC organization, the Camouflage Section was not primarily concerned with the development of the instrumentalities of war but rather with techniques for their concealment. By studying the inherent limitations of human vision, and by making proper allowance for the effects of the atmosphere, the concealment aspects of camouflage have been reduced, in most cases, to an engineering procedure. The results of these studies naturally have an important bearing on the solution of military and naval visibility problems of all kinds.

Because the subject of camouflage has little peacetime interest, the Section was forced to create a large part of its research facilities. For the same reason, it seemed prudent to concentrate the efforts in a few central laboratories. A central laboratory for camouflage field studies was established at the Louis Comfort Tiffany Foundation, Oyster Bay, New York, and many of the Section's activities were centered there. Because of the many special problems that arise in connection with camouflage finishes, another central laboratory was established at the Research Laboratories of the Interchemical Corporation, New York City. These two laboratories, because of their propinquity, supplemented each other very effectively. For example, the Black Widow finish, which provides effective antisearchlight protection for aircraft, was developed at the Research Laboratories of the Interchemical Corporation, following suggestions by the Section Chief. This finish was supplied, in turn, to the Tiffany Foundation, where its value was demonstrated by field tests on a model scale.

The activities of the Section's contractors have been recorded in the customary contractor's reports. Eleven of these reports have been published in uniform format and binding, and each contains a foreword by the Section which explains its relation to the war effort. The purpose of this Summary Technical Report is to present the work of the contractors in abstract form and to supply enough coordinating material to make the results useful to the Armed Services. It has been divided into three parts: the first is a broad summary of the entire program; the second an interpretation by Section personnel of the researches on the general subject of visibility; and the third is an account of two projects that seemed of sufficient importance to justify more than the usual summary, namely, the Yehudi project and the Black Widow project.

The members of the Camouflage Section were Arthur C. Hardy, Chief, Massachusetts Institute of Technology; Edwin G. Boring, Harvard University; Herbert E. Ives, Bell Telephone Laboratories; Lloyd A. Jones, Eastman Kodak Company; and Frank C. Whitmore, The Pennsylvania State College. The Technical Aides were Seibert Q. Duntley, Massachusetts Institute of Technology; Arthur W. Kenney, E. I. du Pont de Nemours & Company, Inc.; and Ernest T. Larson, now with General Aniline & Film Corporation. Consistent with the several aspects of camouflage studies, the personnel of the Section represented widely diversified interests. These interests include optical physics (Duntley, Hardy, Ives, Jones), psychology (Boring), chemistry and chemical engineering (Kenney, Whitmore), meteorological optics (Duntley), photometry and spectrophotometry (Duntley, Hardy, Larson).

The published history of OSRD can be consulted for a complete list of all the many contractors' personnel who contributed to the success of the work. However, mention should be made here of certain persons whose contributions proved to be especially important: Kenneth V. Thimann of Harvard University developed a chlorophyll paint from plant materials; Betty T. Mesier of American Cyanamid Company developed a camouflage for water surfaces originally suggested by E. I. Kropa of the same company; Carl F. Foss of the Tiffany Foundation conducted the original experiments on Yehudi camouflage and later J. W. Tumavicus of Pratt, Read & Company was in charge of applying this camouflage to Navy Glombs. John E. Tyler and Harry E. Ross of Interchemical Corporation developed an automatic photoelectric control mechanism for the Yehudi lamps. Edward C. Dench, Charles A. Wesley, and Clifton B. Kinne of the Interchemical Corporation built numerous special electronic instruments; and David L. MacAdam of the Eastman Kodak Company designed and supervised the con-

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struction of the spectrogeograph. Later, MacAdam supervised an investigation of the visibility of colored targets, and was the author of several contractors' reports as well as Chapter 3 of this volume. Willard P. Greenwood of the Tiffany Foundation operated the spectrogeograph on all of its flights and was in charge of the research program which centered about that instrument. Meteorological correlations with the spectrogeograph experiments were provided by C. A. Elford of the U. S. Weather Bureau, who accompanied Greenwood on his flights during the spring of 1944. H. Richard Blackwell was in charge of the visibility research program at the Tiffany Foundation during the time when all of the data reported in this volume were secured. During the earlier part of the visibility program at Tiffany, psychometric techniques were developed by Helen Peak and Helen M. Richardson. William F. Little of the Electrical Testing Laboratories served throughout the project as a consultant in photometry. The special apparatus required for the visibility research was devised and constructed by Carl E. Foss, William Kerbs, Schell Lewis, and Benjamin Pritchard. The nomographic visibility charts were prepared by Raymond D. Douglass of Massachusetts Institute of Technology, who served as the consultant in mathematics to the Tiffany Foundation.

The chemical projects summarized in this volume were carried out by the staff of the Research Laboratories of the Interchemical Corporation, directed by Albert E. Gessler. Investigations involving pigments, enamels, and lacquers were supervised by Earl K. Fischer, Edmund N. Harvey, and P. A. Henry. Walter C. Granville was in charge of spectrophotometric measurements and calculations. The synthesis and manufacture on a pilot plant scale of novel pigments were executed in the organic field by Sylvester A. Scully, and in the inorganic field by Charles A. Kumins. Problems concerned with the paint vehicles were handled by L. S. Ingle and C. J. Rolle. The efforts of all these groups were coordinated by David M. Gans on behalf of the Interchemical Corporation.

The efforts of the Camouflage Section were aided by the liaison officers assigned to its projects by the Armed Forces and by numerous other officers who, although not officially designated as liaison officers, followed the work with keen interest and helped in many ways. Among the long list of liaison officers special mention should be made of the following men who visited the laboratories on many occasions, accompanied field expeditions, and provided invaluable assistance: Captain Charles Bittinger, BuShips; Commander Dayton R. E. Brown, BuShips; Lieutenant Commander David F. Leavitt, BuAer; Major Arthur W. Van Heuckeroth, Corps of Engineers; and Major F. L. Winsburg, A.A.F. The Section gratefully acknowledges the courtesies extended by the staff Photo Technical Unit, AAFTAC, Orlando, Florida, and to Major John Larkin, Captain P. K. Rock, and Lieutenant S. T. Jennings for their services in flying the spectrogeograph. The adoption of the Black Widow antisearchlight camouflage by the United States and British Air Forces was due primarily to the efforts of Major Paul L. Hexter, A.A.F., who conducted the original flight tests at Eglin Field and subsequently introduced this camouflage measure in England and throughout the Pacific theater. The OSRD Office of Field Service cooperated with Major Hexter in bringing about the adoption of the Black Widow finish in all theaters of operation.

SEIBERT Q. DUNTLEY
Technical Aide, Section 16.3

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PART I

SUMMARY OF THE ACTIVITIES OF THE NDRC CAMOUFLAGE SECTION

INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

On December 10, 1941, the National Defense Research Committee [NDRC] appointed an ad hoc Committee on Camouflage to "review the status of camouflage developments, the research now under way, and to make recommendations to Dr. Vannevar Bush in regard to extension of the present research." The final report [1] of the ad hoc committee begins with the following discussion of the definition of camouflage:

> The term *camouflage* came into use in France during World War I to describe certain defensive measures made necessary by the introduction of new offensive weapons, principally the airplane and the submarine. If interpreted broadly, *deception* may be regarded as a synonym for camouflage. The deception may comprise concealment of the type exemplified by the protective coloration in the case of animals, or it may merely create confusion with respect to the identity or velocity of the objective (especially a ship), a form of camouflage that is sometimes equally effective and less difficult of attainment. To include all the ramifications of the subject, camouflage must be understood to include the use of smoke screens, dummies, and other deceptive practices.
>
> Although the detection or breaking of camouflage is a separate profession when considered with respect to the methods employed, it is closely related in the sense that it defines the problem of the *camoufleur*, who undertakes to achieve a concealment that cannot be penetrated. It so happens that the principal methods of detection possess important peacetime applications that have fostered their continuous development. Camouflage, being essentially a wartime activity, has not received a corresponding amount of attention during the years of peace. As a consequence, advances in camouflage techniques have not kept pace with improvements in the techniques of detection. Because this report is concerned primarily with the research and development aspects of camouflage, it must necessarily survey the methods of detection which are now available or are in the process of development.
>
> In its most elementary form, camouflage undertakes to provide concealment against detection by the unaided human eye. Because of the widespread use of photography and the possible use of image-tubes and other visual aids, however, the requirements of successful concealment have become more stringent. By extension, camouflage has sometimes come to mean concealment against any method of detection. Thus, the firing of several guns simultaneously may provide concealment against sound ranging; and the jamming of radio signals may hide an objective from radio detection. For the purpose of this report, camouflage is understood to mean concealment against detection by means of electromagnetic radiations whose wavelengths lie either in the visible region of the spectrum or so closely adjacent thereto that the detector is not radically altered by the extension of the wavelength range.

1.2 RECOMMENDATIONS OF THE AD HOC COMMITTEE

The ad hoc committee made the following report [a] and recommendations:

> The Committee has failed to find any problem or group of problems whose solution appears to depend upon an extension of existing knowledge in the sciences with which camouflage is concerned. It is, therefore, unwilling to recommend that all research and development activities be concentrated in a single research laboratory created especially for the purpose.
>
> This Committee believes, furthermore, that the prosecution of the war effort is likely to handicap the research and development programs now conducted under Army or Navy cognizance because of increasing demands on the personnel in connection with both operations and training. In the main, optics in its physical and physiological aspects, photography, and certain branches of chemistry are the fields of science most concerned in the development of new camouflage techniques. It is common knowledge that there are many university and industrial laboratories possessing both adequate facilities and competent personnel in these fields, and that these facilities are not at present utilized to full capacity in the war effort. Since progress in the improvement of camouflage techniques involves a study of a large gamut of individual problems which are technically dissimilar and have only their major purpose in common, it would seem that the needs of the armed services can best be met by an arrangement under which each problem or closely related group of problems can be referred for solution to the proper university or industrial laboratory.
>
> The NDRC is uniquely organized to coordinate activities under the above recommendation. The Committee therefore recommends the establishment of an NDRC Section on Camouflage. In view of the fact that the NDRC has already organized a Section on Illumination (C-6) which is concerned with the nocturnal aspects of camouflage, it is suggested that the Section on Camouflage be estab-

[a] The report of the ad hoc committee contains five appendices of special interest: *History and Literature of Camouflage*; *Camouflage Developments Under Army Cognizance*; *Camouflage Developments Under Navy Cognizance*; *Camouflage Developments Under Civilian Cognizance*; [illegible] See reference 1.

lished under Division C. To facilitate the desirable liaison between the two sections the Chairman of each should preferably be made a member of the other.

1.3 THE NDRC CAMOUFLAGE SECTION

Upon the recommendation of the ad hoc committee, the NDRC established a Camouflage Section. The new Section (C-8) was organized and, at its first meeting, agreed that as a matter of fundamental policy its primary concern should be the camouflage of offensive weapons (ships, planes, tanks, etc.) rather than defensive camouflage against aerial bombardment, upon which most previous research effort had centered. Although this policy ultimately dominated the activities of the Camouflage Section, its first efforts were directed toward completing certain researches in defensive camouflage that had received the attention of some of its personnel before the Japanese attack on Pearl Harbor.

1.3.1 Camouflage Research Before Pearl Harbor

Before the attack on Pearl Harbor, no research in camouflage was conducted under NDRC auspices. This was not the result of an oversight but a deliberate policy which stemmed from the close connection of certain NDRC personnel with an Army-sponsored civilian camouflage research organization known as the Passive Defense Project (PDP). Operated by funds from the Work Projects Administration, the PDP conducted an extensive program of research in defensive camouflage. The researches described in Sections 1.3.2 and 1.3.3 were initiated by the PDP and were continued by the NDRC Camouflage Section.

1.3.2 Chlorophyll Paint

Research on a camouflage paint made from chlorophyll-bearing plant material had been conducted at Harvard University for PDP by Kenneth V. Thimann. Promising progress had been made on this project, and it appeared that a relatively small amount of additional work might produce a paint having the exact spectral characteristics of vegetation. Recognizing that such a paint would make possible the construction of detection-proof camouflage in vegetated areas, the Section placed a short term contract (OEMsr-551) with Harvard University to enable Thimann to complete his research. The final results are embodied in Report on *The Preparation and Properties of Chlorophyll Paints*.[2]

No military application of chlorophyll paint is known to have been made. This was due partly to the fact that the procurement of camouflage paints by the Army was well under way, and partly to experience in Europe and Britain which seemed to indicate that infrared-bright green paints made of chromium oxide and kindred materials afforded satisfactory concealment against the detection means employed by the Germans.

1.3.3 Camouflage Design by Engineering Methods

The course of World War II in Europe during 1940 and 1941 caused the Army to begin laying plans for extensive camouflage installations designed to protect key factories and airfields from bombing attacks. PDP was charged with the creation of such designs. It became apparent that huge sums of money and large amounts of labor would be expended on camouflage construction designed without knowledge of the optical requirements that must be met in order to achieve successful concealment. British experience had shown that trial-and-error methods often lead either to costly failures or to needlessly expensive successes. For this reason, it became the primary objective of the Physics Department of PDP to produce an engineering basis for the selection of camouflage materials. This required (1) laboratory instrumentation, (2) instruments for field use, and (3) data on the ability of atmospheric haze to obscure distant objects.

LABORATORY INSTRUMENTATION

Infrared Spectrophotometer. An automatic recording photoelectric spectrophotometer[3,4,5] manufactured by the General Electric Company was modified by PDP to extend its wavelength range to cover the near-infrared spectral region. Subsequently the Interchemical Corporation, a contractor of the NDRC Camouflage Section, made a like modification on its General Electric spectrophotometer. Data secured with the latter instrument played a prominent part in the researches supervised by the Camouflage Section.[28]

Infrared Reflectometer. The use in aerial cameras of photographic film sensitive to infrared[6,7] made it necessary to evaluate the reflectance of camouflage materials in this spectral region. An instrument for this purpose was designed and nearly completed by PDP. Later, at the request of the Army, the instrument was completed by the electronics staff of the Research Laboratories of the Interchemical Corporation under Contract OEMsr-697, supervised by the Section. The completed reflectometer was set up in the laboratory of the Materials Branch of the Engineer Board at Fort Belvoir, Virginia. Reports from that laboratory indicate that the instrument was in constant use throughout the war. Figures 1 and 2 are photographs of the reflectometer. It has been described in detail in the contractor's report.[8]

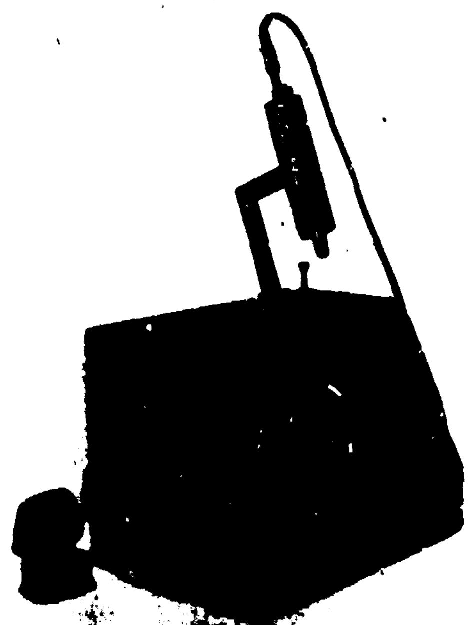

FIGURE 1. Infrared reflectometer.

The sample to be measured is presented at the window of the integrating sphere in the upper center of the panel. The reflectance is indicated by an illuminated dial located at the left of the window. The instrument is self-balancing by means of the motor. The tube above the instrument permits adaptation for measuring transmission as shown in Figure 2.

Recording Goniophotometer. As viewed from the air, vegetated areas have goniophotometric properties[9,10] which differ widely from those of ordinary flat surfaces. To facilitate an investigation of the corresponding properties of camouflage material, an automatic, recording, photoelectric goniophotometer was designed and partially completed by PDP. Later, at the request of the Army, the instrument was completed by the electronics staff of the Re-

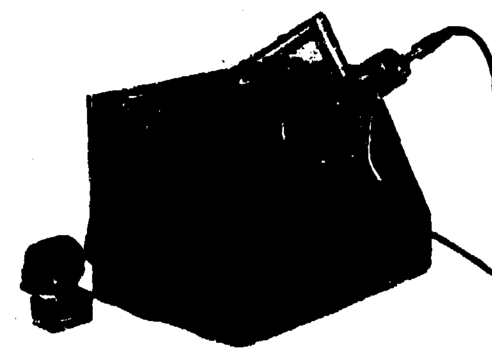

FIGURE 2. Infrared reflectometer arranged for transmittance measurements.

A neon-crater lamp in the exterior tube is imaged by means of microscope objective to form a spot approximately 1/100 inch in diameter on the sample. The light transmitted by the sample is collected by the integrating sphere within the instrument. When used in this way the reflectometer serves as a microdensitometer.

search Laboratories of the Interchemical Corporation under Contract OEMsr-597, supervised by the Camouflage Section.[11] The completed instrument was delivered to the Materials Laboratory of the Engineer Board, Fort Belvoir, Virginia. The recording goniophotometer, shown in Figure 3, can trace in a few minutes a complete curve showing reflectance as a function of angle, thus yielding data that formerly required hours to obtain. Typical curves are shown in Figures 65 and 66 of Chapter 5. The instrument is described in OSRD Report No. 6556.[12]

INSTRUMENTS FOR FIELD USE

The Spectrogeograph. The plans of PDP included a number of instruments for field measurements, the most important of which was a spectrophotometer for aerial use. Although PDP had been unable to secure funds and materials to construct such an instrument, the NDRC Camouflage Section placed a contract (OEMsr-717) with the Eastman Kodak Company, under which a special spectrograph adapted for aerial use was constructed. This instrument, called the *spectrogeograph* (see Figure 4), is described in Chapter 5 of this volume and in Report

No. 5444.[11] After the war had ended, the spectrogeograph was given by OSRD to the Naval Research Laboratory.

Atmospheric Scattering of Light

Since all camouflage measures are viewed through an intervening layer of atmosphere, the effects due to atmospheric scattering of light govern, in large measure, the color tolerances of camouflage requirements. In order to estimate the magnitude of these tolerances, PDP devised and built a number of *haze boxes* similar to the one shown in Figure 5. These boxes were used for viewing and photographing accurately colored scale models.

Two important phases of the study of atmospheric scattering may be separately identified: one representing the effect of the atmosphere along a vertical light path, and the other the effect along a horizontal light path. The first of these cases is of importance in connection with the visibility from aircraft, and the second is typical of the case of a ship at sea viewed against the horizon. (See Chapters 4 and 5 of this volume.)

Both the Army (Project CE-24) and the Navy (Project NS-147) requested the Camouflage Section to make a quantitative study of the reduction of contrast due to atmospheric scattering. A preliminary survey of existing experimental data and theoretical treatments[12] of meteorological visibility disclosed both a lack of data and the need for further development of the theory.

A theoretical analysis of the effects along a hori-

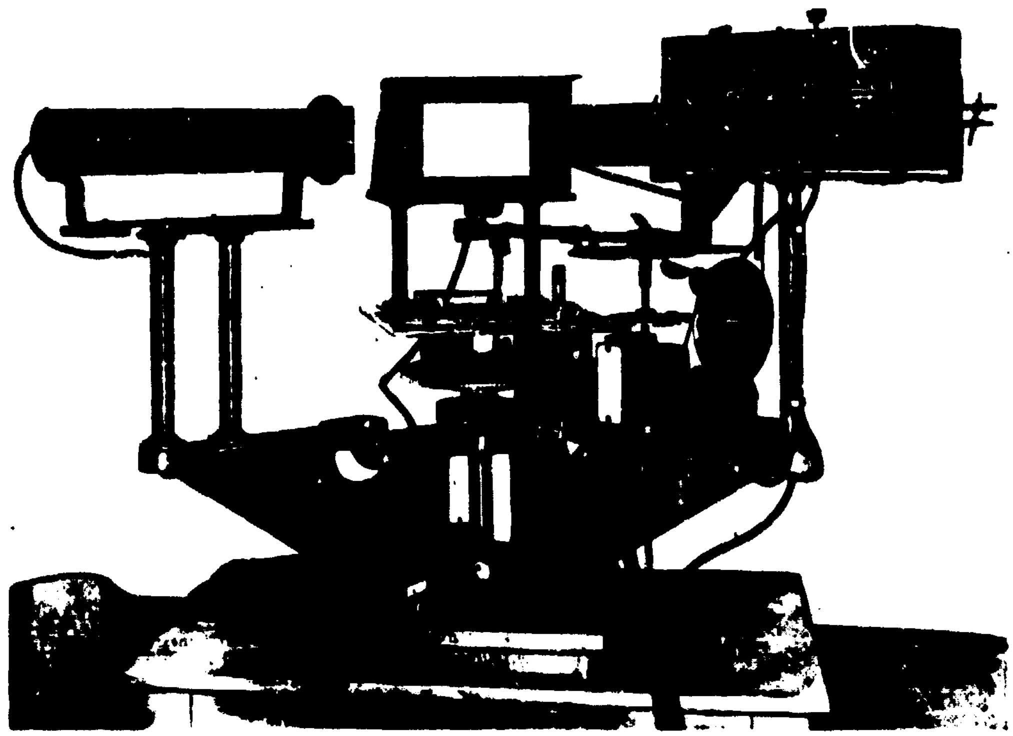

Figure 3. Recording goniophotometer.

The sample to be measured (white rectangle, upper center) is illuminated at any selected angle by a collimated beam of modulated light from a neon crater lamp in the tube supported by the fixed arm (left). The source spread is ½ degree in order to simulate the geometry of sunlight. The sample is photometered by a type PJ46 photoelectric cell on a movable arm (right) which also carries a comparison lamp modulated with a phase opposite to that of the lamp in the fixed arm. A recording pen, attached to the same arm, automatically produces a polar plot of goniophotometric [illegible] on the graph paper carried by a platen (center) which is fixed with respect to the sample. The movable arm also carries a balance motor, [illegible] and pen-positioning mechanism.

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FIGURE 4. The spectrograph.

zontal path within the atmosphere was made[13] (Section 2.2.1), and the results were expressed in a convenient form for use. For an experimental verification, a series of black and white targets was erected on the shores of Cold Spring Harbor, Long Island, New York, at ranges up to 6,000 yards. In order to determine the apparent contrast of these

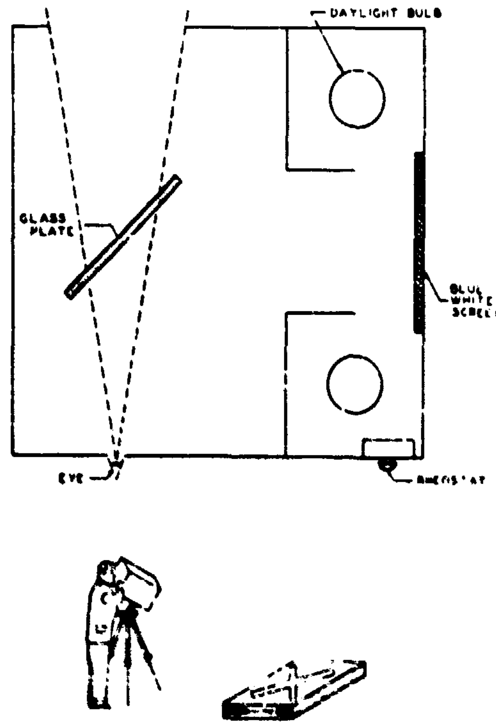


FIGURE 5. Schematic plan of the PDP haze box.

The observer's field of view is flooded with light from an illuminated blue-white screen by reflection from a glass plate. The amount of the simulated atmospheric haze can be adjusted by means of the rheostat. Lower sketch: Haze box in use by observer of model airfield.

targets, a high-precision a-c photoelectric telephotometer was built (Section 2.2.3). Data secured with this instrument serve to support the theoretical analysis. Theoretical and experimental conclusions reached during this study were combined with data on the perceptual capacity of the human observer (Chapter 3) in a series of nomographic charts (Chapter 4) especially suited for use by ships at sea in predicting the limit of visibility of naval targets under the full range of outdoor lighting conditions.

An expedition was sent to Orlando, Florida, to secure a variety of data with the spectrogeograph, including data on the vertical scattering of light. A B-17, based at Orlando, was assigned to work in collaboration with the members of the expedition, which was under the direct supervision of one of the Section's technical aides. By invitation, a representative of the U. S. Weather Bureau accompanied the expedition. A laboratory for processing the film and reducing the data was set up in Orlando, and a series of flights over a large gray scale laid out on the Orlando Army Air Base was made up to altitudes of 16,000 feet. An analysis of the data obtained during these flights enabled the construction of nomographic charts for predicting the visibility of objects on the surface of the earth as seen from the air (Chapter 5).

REFLECTIVITY OF NATURAL TERRAINS

The spectral reflectivity of natural terrains was measured by means of the *spectrogeograph* (Chapter 5). These data serve two purposes: (1) they indicate immediately the proper reflectivity for paints or other camouflage materials designed to match any type of terrain; (2) when combined with data on atmospheric scattering, they enable acceptable tolerances in the color match to be prescribed. Camouflage treatments designed in accordance with the results obtained under this project should therefore evade detection by the use of color filters, either visually or photographically.

Field Studies in Florida and California. In Florida, data[14] were obtained of such typical terrains as fields, forests of coniferous and of deciduous trees, lakes, rivers, roads, airports, and the ocean. The spectrogeograph was then flown to California. This flight was for the purpose of securing data on kinds of terrains not available in the East, especially desert areas of different types, such as shifting sands, lava beds, dry lakes, and brush-covered areas; and also mountains, including both forested and snow-clad peaks.

THE COLOR OF OCEAN SHOALS

Prior to the departure of the expedition to Florida, the Section was requested by the Coordinator of Research and Development, U. S. Navy, to supply data on the spectral quality of light reflected by the ocean in the vicinity of shoals. It was hoped that such data might point the way to the development of new photographic materials capable of showing the presence of shoals better than the film usually used for aerial reconnaissance.

The measurements were made over a series of shoals which fringe the coast of Dania, Florida. A line of buoys was anchored perpendicular to the shoreline, soundings were taken, and samples of the bottom were obtained. Data on the reflectivity of the sea along this course were obtained with the spectrogeograph, both from an airplane and from a glass-bottomed boat.[15] These data, similar in trend, have suggested several improvements in photographic techniques both in black-and-white and in special color photography. The data and the suggestions of the Section for improved techniques were furnished to the Navy, and it is understood that the Navy asked the Eastman Kodak Company to cooperate in the development and testing of new types of sensitized products for use in surveying underwater terrains.

1.3.4 Color Transients

Representatives of the Corps of Engineers requested the assistance of the Camouflage Section in exploring certain mysterious effects which were being reported by camouflage artists returning from California, where preparations were in progress for the impending battles on the African desert. It was reported that standard camouflage materials often behaved in an unexpected manner when seen against desert landscape, the camouflage being considered quite inadequate at certain times of the day. Personnel and equipment, successfully camouflaged for most conditions in the desert, were occasionally seen with vivid color contrast against a typical desert terrain. Although the contrasts were reported to appear at any time of day, they most commonly were seen when the sun was low, in the early morning or the late afternoon. These *color transients* were usually of short duration, at least in their most vivid phases.

PROJECT CE 28

The representatives of the Camouflage Section who conferred with the Army engineers concerning the color transients expressed the opinion that they are attributable to the normal color changes that occur as a consequence of gross variation in the quality of the illumination. In the hope that procedures might be devised for the selection of camouflage materials that would exhibit a minimum of the transient effect, the Corps of Engineers requested NDRC to send a field expedition to the desert to study the transient phenomena. This request bore A N Project Control Number CE-26.

The conclusions reached after the field expedition had returned from the desert are described in a report entitled *Transient Color Phenomena in a Desert*.[10] The conclusions presented therein are in general agreement with the earlier a priori opinions. The report also includes recommendations with respect to procedures in the selection of camouflage materials that should result in reducing the transient effects to a minimum.

1.3.5 Camouflage of Water Surfaces

A method of camouflaging water surfaces (ponds, reservoirs, smooth rivers, etc.) by the use of thin, self-spreading and self-healing, pigmented films was suggested to NDRC by the American Cyanamid Company. Since it was well known that bodies of water are among the principal visual aids to bombers in locating their targets, the Section explored the interest of the Army in camouflage measures for water surfaces. After being informally advised by an official representative of the Camouflage Section of the Engineer Board, Fort Belvoir, that the subject of water camouflage was of definite interest to the Army, and after a survey of potential contractors had disclosed that the American Cyanamid Company, Stamford, Connecticut, was best suited to conduct the needed research, an OSRD contract (OEMsr-726) was placed with this organization. Self-spreading, self-healing films composed of treated woodchips were produced and tested on ponds (see Figure 6). Later, a powder of sulfur and polystyrene was developed which remains on the surface indefinitely and forms a self-spreading film which may be of any color. A pound of this material completely obscures 300 sq ft of water surface at an estimated cost of about 8 cents. These materials were tested both on fresh and salt water. The results of the experiments are described in *Report on Water Camouflage*.[11]

1.3.6 Camouflage Paints

The activities of PDP thoroughly acquainted the Army and most manufacturers of camouflage paint with the problem of matching the spectral characteristics of vegetation, both in the visible region of the spectrum and in the near infrared. However, much valuable research on camouflage paints re-

FIGURE 6. The nearby portion of this pond is covered by a self-spreading camouflage film. Note the specular reflection from the untreated portion of the pond.

mained to be done in 1942, when the NDRC Camouflage Section was organized. The analysis of the situation by the new Section showed that:

1. A laboratory should be found capable of making small quantities of special paints for field experiments by other contractors of the Section.

2. Competent research chemists should be given an opportunity to produce improved camouflage materials.

Subsequent discussions with the Corps of Engineers led to a request (Project CE-25), called "Camouflage Paints and Pigments," in which the Army asked that these facilities be provided.

PROPOSAL TO SIMPLIFY PALETTE

The Section proposed that an attempt be made to reduce from nine to four the number of standard camouflage paints supplied to troops in the field. This suggestion was based on the belief that any color in the required gamut could be produced by mixtures of three colored paints, and a fourth paint could be used to secure any desired degree of infrared reflectance. A Section member reported that research on a tricolor palette for aircraft had been conducted by the Research Laboratories of the Interchemical Corporation in New York City. Since the research laboratory of this company was one of the few research groups in the country possessing spectrophotometric equipment, a contract (OEMsr-697) with the Interchemical Corporation was drawn up whereby this laboratory could serve both of the purposes mentioned earlier.

Summary of Completed Paint Projects

Throughout the activities of Section 16.3, bimonthly summary reports were issued in accordance with NDRC policy. The last report has been used as a pattern for the following summary of the camouflage paint projects completed by Section 16.3 of NDRC. In all cases, the projects are fully discussed in the contractor's report.[18]

Matte Surface Paints

Light incident upon natural terrains, such as grasslands and woodlands, is mostly trapped by the texture of the surface. The small fraction of light reflected from such terrains has a goniophotometric distribution quite unlike that of painted surfaces. Therefore camouflage treatments often involve elaborate texturing procedures such as the erection of flat tops having a texture introduced by garnishing. At the instance of the Section, the Interchemical Corporation evolved a method of pigmentation enabling a paint to be produced having colorimetric and goniophotometric properties approaching those of natural terrains. Because of special interest expressed by the Camouflage Section of the Engineer Board, Fort Belvoir, Virginia, in a green paint having the appearance of a textured surface such as grass or moss, a paint of the new type was developed which possesses many of the desired optical properties (Section 5.4.3).[18a]

Emulsifiable Paints

The desirability of reducing the shipping weight and bulk of general utility camouflage paints for field use has been recognized by the development of paints employing an emulsifiable, oleoresinous vehicle that can be thinned in the field, either with water or with gasoline. When the Camouflage Section of NDRC was organized, emulsifiable paints were only beginning to be used extensively, and many troubles were encountered. At the request of the Engineer Board at Fort Belvoir, Virginia, the Section had the Interchemical Corporation investigate the rheological properties of pigmented emulsions. Satisfactory emulsifiable paints are now being supplied to the Armed Forces in conformity with present Army specifications.[18b]

Paint Concentrates

The Interchemical Corporation formulated a paint that can be shipped in powder form and mixed either with water or with gasoline. If mixed with gasoline, the paint is readily removable with gasoline; and, consequently, can be used where temporary, easily removable paints are desired. The Materials Laboratory at Fort Belvoir, Virginia, has advised, however, that the advantages to be gained by a powder paint of this sort are not great enough to warrant their substitution for the emulsifiable paints now employed by the Services.[18c]

Foliage-Simulating Pigments

Most common green pigments, which appear on visual examination to match the color of chlorophyll, are open to the objection that camouflage using them is readily detected by infrared photography. This difficulty can be met by using paint in which chlorophyll itself is used as a coloring material (Section 1.3.2). However, before recommending the large-scale development of such a paint, the Camouflage Section addressed letters to all the principal manufacturers of colored pigments and secured approximately one hundred samples for spectrophotometric analysis. These samples were coded and tested under standard procedures designed to evaluate the relevant optical properties and the permanency of the pigments. The results of these tests are presented in the final report of the contractor.[18d]

Temperature-Sensitive Pigments

Materials exhibiting reversible color changes in response to changes in temperature might have uses in camouflage paints. For instance, a paint which changes from dark green to white within the range of temperature between summer and winter might find applications in certain latitudes. A survey was made of temperature-sensitive materials, the mechanism of color change was studied in specific cases, and new materials were synthesized which exhibit temperature-sensitive properties. Efforts to decrease the temperature range in which the color changes take place were unsuccessful.[18e]

Camouflage Adhesive

Natural materials available in the field are often useful for camouflage purposes. To cover smooth surfaces with materials such as dirt, leaves, grasses, etc., an adhesive is required that is water resistant yet readily removable, capable of being modified to suit the field conditions, and readily available. At the instance of this Section, a material was formulated that is tacky, water resistant, and inexpensive. This material can be thinned with gasoline to the appropriate consistency before application, and its tackiness can be controlled by the addition of cylinder oil or crankcase oil. The adhesive can be removed with gasoline.[18]

Claray Project

Scales and reticles of optical instruments for fire control and other purposes are often illuminated by an integrating cavity containing a small lamp. In such a cavity, a white paint reflecting **98** per cent is twice as efficient as one reflecting **96** per cent, although this difference in reflection factor is barely discernible when the two paints are compared visually. The Navy Bureau of Ordnance sought advice from this Section concerning the possibility of securing white paints of higher reflectivity than are commercially available. The Interchemical Corporation was known to have experimented with a material called Claray, which has a reflectance relative to magnesium oxide of **95** per cent. Subsequent work produced a product having a reflectance of **98** per cent; and samples were furnished to the Bureau of Ordnance and elsewhere.[19]

Coffin Paint

A new type of black pigment that requires no flatting agent was developed and incorporated in a paint which is extremely matte and which reflects only 2.2 per cent of the incident light instead of the 4 or 5 per cent characteristic of standard-type matte black paint. This paint was tested as an antisearchlight camouflage measure for aircraft, but was found to be less effective than the antisearchlight camouflage described in the next paragraph. However, it appears that this "coffin paint" may be useful in the simulation of shadows on the ground, and at the request of the Materials Branch of the Engineer Board at Fort Belvoir, Virginia, information was furnished that would enable an Army procurement specification to be written.[20]

Antisearchlight Camouflage

It is a fact of common experience that *even black-painted aircraft look white when caught in searchlight beams*. The inference to be drawn from such a statement is that, if the visibility of aircraft is to be reduced, there must be a reduction of at least an order of magnitude in the diffuse reflectivity of conventional matte black finishes. Such a reduction has not been found possible with a matte surface, but it has been accomplished with a glossy surface. A glossy black enamel was developed, whose diffuse reflectance is less than 0.1 per cent. Model trials at the Tiffany Foundation and Service tests at Eglin Field, Florida [see AAF Proving Ground Command Report Serial No. 3-43-11[1], AAF Board Project No. (M-1) 17] indicated a high degree of success in rendering the camouflaged plane invisible in searchlight beams and in making it extremely difficult for searchlight operators to fix and hold on the plane. Orders issued from the commanding general, AAF, required all U. S. night fighters to use this camouflage, and procurement specifications were subsequently issued by the AAF Materiel Command at Wright Field. At the request of the Army Air Forces, specialists were sent by the OSRD Office of Field Service to the Fifth, Eleventh, Thirteenth, and Fourteenth Air Forces to supervise the application of this finish. The Assistant Chief, Miscellaneous Section, Proving Ground Command, supervised the application of the antisearchlight camouflage to aircraft of the Eighth Air Force in England and demonstrated it to the RAF. He also visited all U. S. Army Air Forces engaged in the war with Japan, where he introduced antisearchlight camouflage and supervised its initial application. Tests of this camouflage measure were conducted by the Navy Department, Bureau of Aeronautics, at the Naval Air Station at Patuxent River, Maryland. A final report, ***Tests of Jet Paint Night Camouflage***, concurs with the favorable findings described in the Eglin Field report, and adds that the antisearchlight camouflage is never more visible than is matte black under moonlight or starlight.

The Black Widow finish, as it came to be called, was widely used both in the European theater of operations and in the Pacific war. It is understood that this camouflage was adopted in production by the RAF during the closing months of the war and that during the same period B-29's were being produced with Black Widow finish. It is further understood that the Army Air Forces have issued standing orders that all military combat aircraft, including both fighters and bombers, intended for night-time operation shall be equipped with Black Widow finish. Chapter 7 of this volume is devoted to the Black Widow project.[18b]

Self-Luminous Night Camouflage

At the time of the reorganization of NDRC, another section of NDRC had proposed the use of self-luminous paint as a means of enabling aircraft to match the brightness of the night sky. Exploratory conversations with Army and Navy personnel evoked only slight interest in this project, presumably because it did not appear feasible to combine the characteristics of a self-luminous paint with those of the antisearchlight paint.

1.3.7 Camouflage Detection

Bifocal Goggles

Dichroic filters were developed during World War I as a means for differentiating actual foliage from camouflage materials of the same color. Such filters can cause foliage to appear red, whereas ordinary green paints remain green. Fliers ordinarily dislike wearing dichroic goggles because so much of the land surface is covered by vegetation that the appearance of the earth from an airplane is unnatural. On the other hand, unless dichroic goggles are worn continually, a period of time is required for the eyes to adapt themselves after putting on the goggles, due to their low transmittance. *Bifocal* goggles with a dichroic filter in the lower half of the lens and a neutral filter having the same transmittance in the upper half were proposed by the Section in order that these may be worn continually and the dichroic feature may be instantly brought into use at any time. A number of such bifocal dichroic goggles were made available to interested Army and Navy personnel.

Optical Aids for the Detection of Submerged Submarines

At the request of the Navy, the Section has reviewed all available optical aids for the detection of submerged submarines. Two series of special filters based on the known optical properties of sea water have been obtained. One series is intended to increase the contrast of a submerged object that is darker than the sea beneath it, while the second series of filters is intended to increase the apparent contrast when the submerged object is lighter than the sea beneath. These filters have been mounted in special goggles containing rotatable polaroid screens and provided with means for limiting the field of view in order to reduce the glare from the surrounding field. These goggles were tested by the Navy, and it was concluded that they did not produce a sufficient improvement in the visibility of submerged craft to warrant their adoption, in view of other methods of submarine search now available.

1.3.8 Laboratory for Camouflage Field Studies

In the belief that facilities would be required for making camouflage studies in the field, the Camouflage Section placed a contract (OEMsr-597) with the Louis Comfort Tiffany Foundation, Oyster Bay, New York. Actually, this contract served only to defray the special operating expenses of such field experiments, for the Tiffany Foundation generously gave NDRC the use of its 80-acre estate on Cold Spring Harbor without cost to the Government. An art school during the years of peace, the Tiffany Foundation faced the prospect of having its facilities lie unused during the war. It, therefore, offered them first to the Navy and later to NDRC. After an inspection of the estate had indicated that the grounds at Oyster Bay offered an admirable location for camouflage field studies, the above-mentioned contract was negotiated.

Facilities of the Tiffany Foundation

The 80-acre estate bordering on the shore of Cold Spring Harbor contains a wide variety of terrains, including ponds, lawns, and wooded hills. Adjacent to the property of the Foundation lay the 300-acre estate of Charles Tiffany, who generously permitted certain tests to be performed on his land when it proved to be more suitable than any owned by the Foundation. The studio buildings, which had been occupied by the art school, provided ample living and working facilities for the experiments required by the Section. The major portion of the researches described in this volume was performed there.

Use by the Armed Forces

On several occasions the facilities of the Tiffany Foundation were made available to the Armed Forces for special tests. The following case is an example.

Recognition Threshold of Colored Lights. The Navy Bureau of Ships requested this Section to collaborate in a study of the distance at which the color of colored lights can be recognized at night under conditions of poor visibility. Colored lamps provided by the Navy were set up on the shores of Cold Spring Harbor. The lights were viewed from 3,660 yards by a group of Tiffany observers on dark nights under weather conditions such that the range of visibility was considerably restricted. The intensity of the lights was varied in accordance with instructions communicated with the aid of police radio cars. A report incorporating the results obtained during these experiments has been issued by the Bureau of Ships.

Ship Camouflage

Wake Camouflage

Even at low speed, a motor torpedo boat is conspicuous because of its bow wave and wake. Experiments conducted informally by the American Cyanamid Company have indicated the feasibility of spraying suspensions of carbon black from bow and stern in such a manner as to conceal the white water. The Navy Department purchased the equipment for further tests, and asked this Section to consider the possibility of using the Tiffany Foundation at Oyster Bay as a base. Investigations disclosed a nearby boat yard where PT boats frequently are repaired. The Section reported to the Coordinator's Office that it had suitable facilities at its disposal, and indicated its willingness to undertake the tests. However, a request for this work was not made by the Navy Department and work on this project was not begun.

Model Trials

The Bureau of Ships requested that observations of ship camouflage be made under natural outdoor conditions on ship models in order to test the relative merits of camouflage designs. Two identical 20-foot cruiser models (Figure 7) were delivered by the Navy to the Tiffany Foundation at Oyster Bay where a boathouse and a marine railway were constructed. At a short distance from shore, a platform was erected from which to observe the models through an inverted periscope in order to simulate observations from a submarine. The periscope and a range finder were supplied by the Navy, and in-

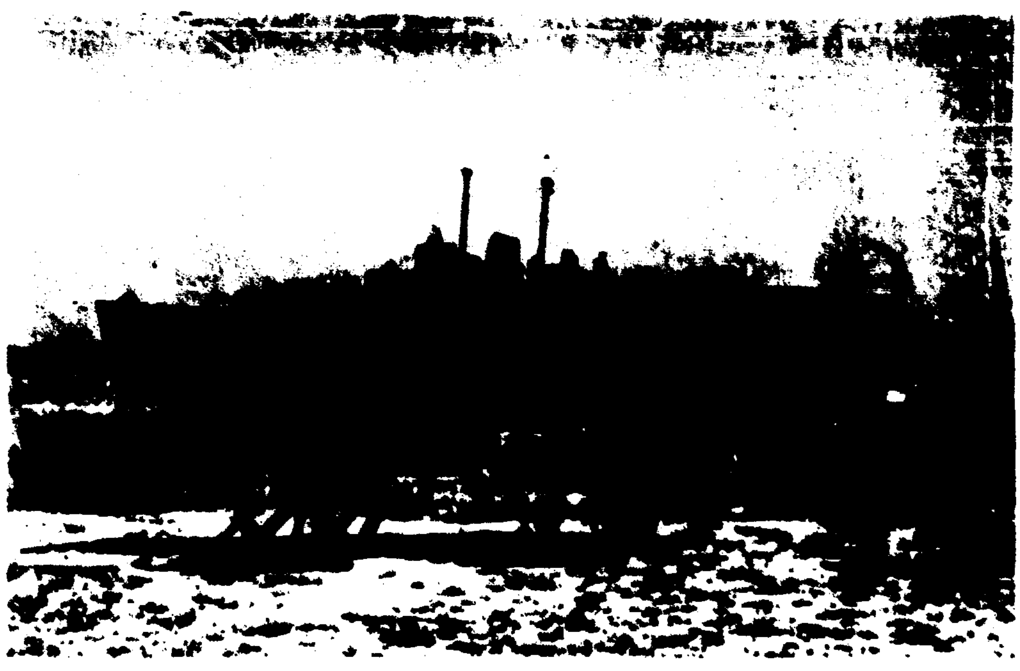


FIGURE 7. A 20-foot cruiser model used in Cold Spring Harbor.

struments were procured for determining the meteorological conditions, including the visibility, at the time observations were made. A series of observations resulted in the conclusion that the counter shading of contained shadows is ineffectual in the case of a medium-gray ship observed down-sun in clear weather. Following the destruction of the observing platform, the boathouse, and one of the ship models by a tropical hurricane, the Bureau of Ships recommended the termination of this project.

1.3.10 The Yehudi Project

When the menace of German submarines to allied Atlantic shipping constituted one of the major problems of World War II, the Camouflage Section was requested by the Director of Technical Services of the Army Air Forces to devise a method of camouflage which would enable a sea-search aircraft to approach within 30 seconds' flying time of a surfaced submarine before the aircraft became visible to members of the U-boat crew. Such an aircraft when flying at low elevations over water appears darker than the sky background, even when painted white. Calculations showed that the power required to eliminate the contrast by floodlighting the plane is prohibitive.

The solution to the problem proposed by the Camouflage Section involves the installation of automobile headlights, or the equivalent, in or near the leading edge of the wings and in the fuselage. It was pointed out that a minimum amount of power would be required when the headlights are designed to include the smallest angle consistent with the pitching and yawing of the plane.

Project AC-45

In response to a formal request from the Army Air Forces (A-N Project Control No. AC-45), the Section instructed the laboratory group at Tiffany to explore the suggested camouflage measure. The first experiments were at model scale, but later the principle was tested on a full-scale model of a B-24 airplane. The Yehudi project, as it came to be called, is described in detail in Chapter 5 and in three contractors' reports which appear in the microfilm supplement.[19,20,21] The information obtained by the contractors enabled the Army Air Forces to design and install Yehudi camouflage on a B-24 bomber. Figures 8, 9, and 10 are Army Air Forces photographs of this installation.

Project NA-188

Camouflage of a Torpedo Bomber. Section 16.3 was requested by the Navy to assist in applying the Yehudi camouflage principle to TBF torpedo bombers. The first flight test of a TBF so equipped occasioned favorable reaction. Further flight tests resulted in improvements in the adjustment of the equipment and in the technique for its use. It is

FIGURE 8. B-24 bomber equipped with Yehudi camouflage. (Army Air Forces photograph.)

FIGURE 9. Yehudi lamps mounted in the leading edge of the wing between the motor nacelles. (Army Air Forces photograph.)

understood that under conditions such that an uncamouflaged plane was visible at about 12 miles, the plane equipped with this camouflage could approach to within 3,000 yards without detection, even when its approximate location had been indicated by an accompanying "control" plane.

Camouflage of a Glomb. The Navy later requested Section 16.3 to design and install Yehudi camouflage on the LBE Glomb produced by the Gould Aeronautical Division of Pratt, Read & Company, Incorporated, Deep River, Connecticut. An OSRD contract was placed with this company in order that one of the experimental LBE Glombs being built under a Navy contract might be factory-equipped with Yehudi camouflage. The end of hostilities with Japan caused the Navy to terminate the contract under which the Glombs were being built, thus making it impossible for Pratt, Read & Company to complete this project. (See Chapter 6.)

1.3.11 Visibility of Targets

On December 30, 1942, the Section met to discuss camouflage problems of interest to the Navy. This meeting was attended by Navy officers from the Bureau of Ships and the Bureau of Aeronautics who were interested in the visibility of ships and of aircraft. It was the consensus of the Section that it would be possible to combine existing information on the perceptual capacity of the human observer with the known laws of atmospheric optics in such a manner that charts and tables for indicating the visibility of naval targets could be prepared. At a conference called by the Navy Department in Washington, the Section Chief was asked to undertake the preparation of such a set of charts and tables. The Navy formalized its action by requesting NDRC, under A/N Project Control No. NS-147 (Ship Camouflage), to undertake the study of the visibility of ships from other ships, ships from planes, planes from other planes, and planes from ships. The request was endorsed by the Bureau of Ships, Bureau of Aeronautics, and Bureau of Ordnance, the last requesting that consideration be given to the effect of the use of binoculars.

After a search of the literature had disclosed that usable data on the perceptual capacity of the human observer were not available, a large-scale program

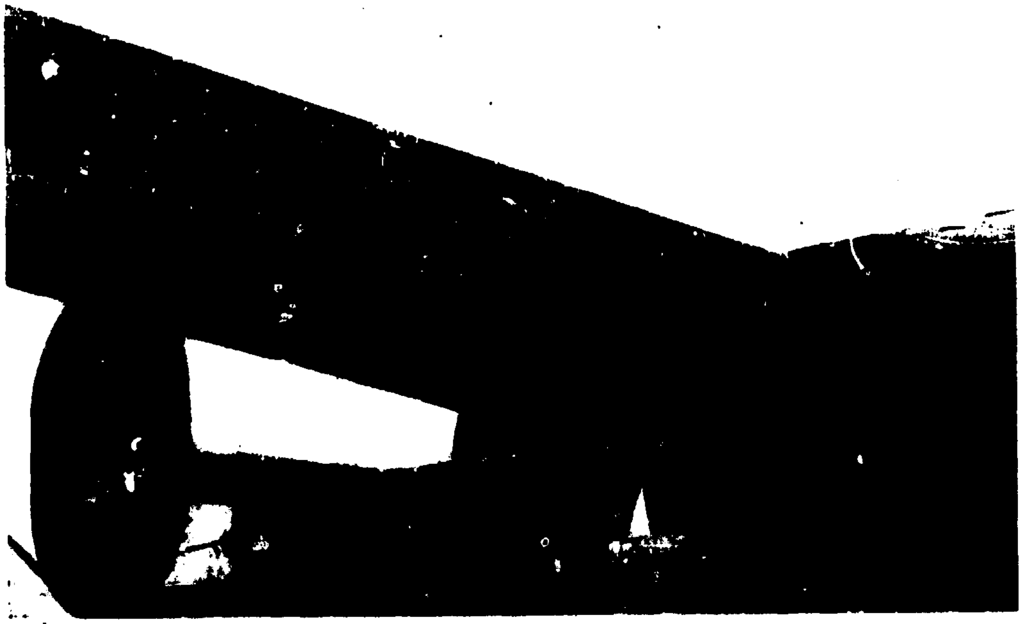


FIGURE 10. Yehudi lamps in streamline housings suspended below the wing. This method of mounting was found to be permissible on the outer portion of the wing. (Army Air Forces photograph.)

of visibility research was initiated by the Section.[22,23,24] Chapters 2, 3, 4, and 5 of this volume present a collation of the results of those researches by the Section and its contractors which now enable the visibility of targets to be predicted.

1.4 ORGANIZATION OF THE SUMMARY TECHNICAL REPORT

As explained in the preface of this volume, most of the projects which have been described in the foregoing summary have been completely discussed in the reports of contractors. However, the research on the visibility of targets was a Section program, the contractors being requested to obtain certain specific data. Responsibility for the direction of the research was assumed by the Section, and Section personnel collated the results after the contractors had finished their work. Since this synthesis does not appear elsewhere, it is presented in full in the following four chapters.

Two aircraft camouflage measures, the Yehudi project and the Black Widow project, are believed to be the outstanding camouflage contributions of the Section. Chapters 6 and 7 are devoted to more detailed accounts of these measures than appear in the foregoing summary.

Chapter 2

THE SCREENING OF TARGETS BY THE ATMOSPHERE

2.1 INTRODUCTION

ALL CAMOUFLAGE measures are viewed through a veil of atmospheric haze which, by reducing the apparent contrast of distant objects, aids the camoufleur in making even large targets invisible. This subject falls naturally into two categories which will henceforth be referred to as visibility along a horizontal path and visibility along a slant path, respectively. In the former category lie most problems of ship camouflage, including the important case of visibility through a periscope. In the second category are the many problems of camouflage against aerial observation and photographic reconnaissance. The basic principles are the same in both cases; but, because of the stratification of the atmosphere, the resulting laws are somewhat different. Visibility along a horizontal path can be regarded as a limiting case of visibility along a slant path; but the horizontal case will be treated independently because it affords a simple illustration of the principles.

2.2 THE VISIBILITY OF OBJECTS VIEWED ALONG A HORIZONTAL PATH

If a large, nearby, white object illuminated by full sunlight is viewed against the horizon sky, it usually appears bright in comparison with its sky background. If the distance between the object and the observer is increased, the contrast between the white object and the horizon sky decreases. Indeed, at some range, dependent upon the state of the atmosphere, this contrast may fall so low that the object is lost from view, even though it still subtends a large angle at the eye of the observer. The object may be said to be obscured by haze.

For example, imagine sister ships, both painted white, viewed from such a vantage point that one is seen nearby and the other at a considerable distance. If there is a slight haze, the distant vessel may appear but slightly brighter than the sky. Since the apparent sky background is identical for the two vessels, it is evident that some of the light reflected by the more distant ship has been attenuated in passing from the vessel to the observer.

In the case of black vessels, an opposite type of change takes place. The nearer ship appears very dark against the sky background, whereas the ship seen at a distance is but slightly darker than the sky. Since the sky background is the same for both, it is evident that the distant ship appears brighter because of light scattered toward the observer by the intervening air. It may be inferred from these two limiting cases that two processes are taking place simultaneously within the atmosphere: (1) light reflected by the target is gradually attenuated by scattering and absorption, and (2) daylight is scattered toward the observer all along the line of sight.

2.2.1 Quantitative Relations

The appearance of a distant object is governed by the balance between the transmitted fraction of the light originally reflected from the object and the space light contributed by the intervening air. An insight into the relation between these components can be gained in the following manner: Assume that the object in Figure 1 has a brightness B_0 in

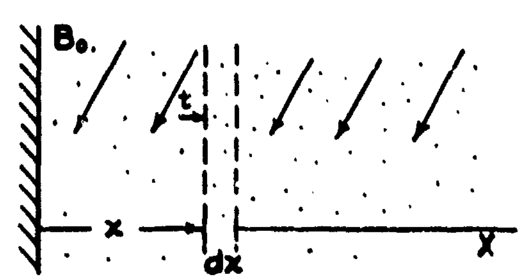


FIGURE 1. See text for explanation.

the direction of the observer. At some distance x imagine a parallel-sided flat lamina of atmosphere having a thickness dx to be located perpendicularly to the line of sight. Denote the amount of light (including both the transmitted component and the space light) incident from the left on each unit area of the lamina by t. In passing through dx, the attenuation is proportional to the amount of light present, the constant of proportionality β being called the *attenuation coefficient. This coefficient accounts for diminution by absorption as well as for diminution by scattering.*

In passing through dx, the light t is also augmented by the space light contributed by the air within the lamina, as shown by equation (1):

$$\frac{dt}{dx} = -\beta t + \sigma q. \qquad (1)$$

where q represents the luminous density at the lamina, and σ is the fraction thereof that is scattered each second through the right-hand boundary (Figure 1).*

Equation (1) can be integrated along the line of sight after it has been rewritten in the form of equation (2).

$$\int_{B_0}^{B_X} \frac{dt}{\sigma q - \beta t} = \int_0^X dx. \qquad (2)$$

In equation (2), B_X is the apparent brightness of the object when viewed from a distance X. The result of the integration is shown in equation (3).

$$\ln \frac{\sigma q - \beta B_X}{\sigma q - \beta B_0} = -\beta X. \qquad (3)$$

Equation (3) may be rewritten as follows:

$$B_X = \left(\frac{\sigma q}{\beta}\right)\left(1 - e^{-\beta X}\right) + B_0 e^{-\beta X}. \qquad (4)$$

The apparent brightness of an object at range X is shown by equation (4) to be the sum of two terms; the first represents the space light contributed by the air between the target and the observer, and the second represents that fraction of the light originally leaving the target which is transmitted by the atmosphere.

Optical Equilibrium

It will be noted from equation (1) that whenever $\beta t = \sigma q$, $dt/dx = 0$. Hence, under these circumstances t has a constant value that does not depend upon X. In other words, when the light incident from the left on the lamina in Figure 1 has the value

$$t' = \frac{\sigma q}{\beta}, \qquad (5)$$

the attenuation by the lamina is equaled by the added space light, so that the amount of light emerging through the right boundary of the lamina (Figure 1) is also t'. This condition has been called *optical equilibrium.*

The Brightness of the Horizon. In the special case of an optically homogeneous atmosphere, by which is meant an atmosphere wherein β, σ, and q have the same values at all points along the line of sight, an object having an inherent brightness $B_0 = t'$ will appear to have the same brightness when viewed from any distance.

Under optically homogeneous atmospheric conditions, the apparent brightness of the sky at the horizon in any given direction is not changed by moving toward the horizon or away from it. This observation implies that the brightness of the horizon (B_H) is the equilibrium value t'; that is,

$$B_H = \frac{\sigma q}{\beta}. \qquad (6)$$

Thus, under optically homogeneous atmospheric conditions, the brightness of the horizon sky is determined by σ, q, and β in accordance with equation (6). A discussion of the brightness of the horizon sky under certain types of optically nonhomogeneous atmospheric conditions appears in Section 2.2.6.

Extent of Optical Equilibrium. An estimate of the length of the path of sight along which optical equilibrium may be assumed can be obtained from calculations based upon equation (4). The result of such a calculation, assuming a homogeneous standard atmosphere (Section 2.3.2), is shown in Figure 2. It will be noted that the region of optical equilibrium occupies a range of many miles, several times the meteorological range (Section 2.2.5).

Apparent Brightness of Distant Objects

Under optically homogeneous atmospheric conditions, the apparent brightness of a distant object is given by equation (7), which was obtained by substituting equation (6) in equation (4).

$$B_X = B_H(1 - e^{-\beta X}) + B_0 e^{-\beta X}. \qquad (7)$$

The Transmittance of the Atmosphere. As has already been stated, the term $B_0 e^{-\beta X}$ in equation (4) represents that portion of the light originally leaving the target which is transmitted by the atmos-

* Since β and σ may be functions of wavelength, equation (1) is strictly true only if the light is monochromatic. The experimental results described in Section 2.2.3 and the results of other investigators seem to justify the use of equation (1) in discussing the screening of targets by the atmosphere.

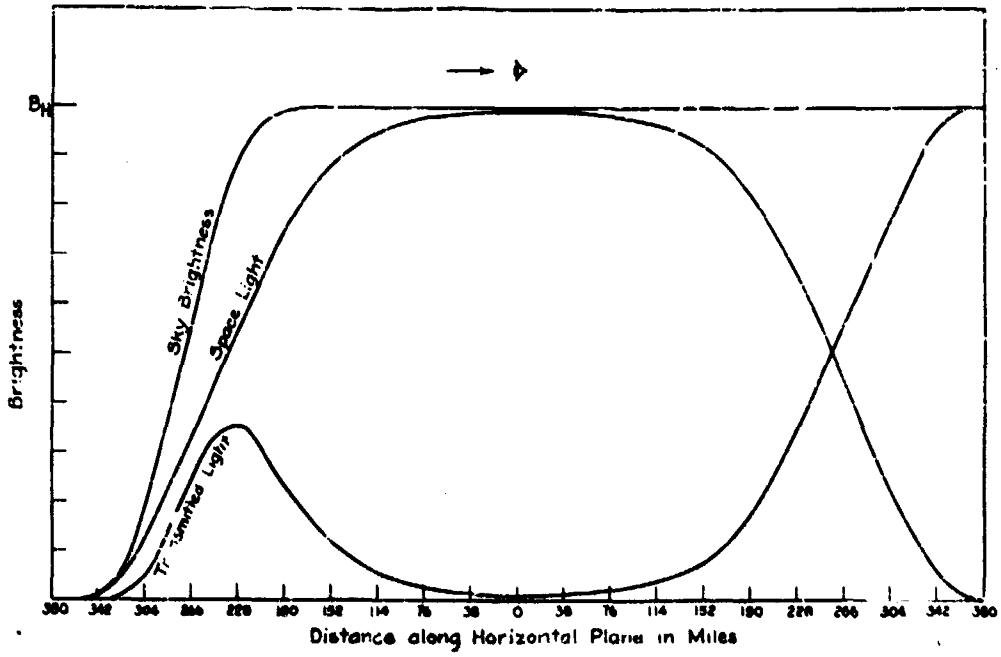


FIGURE 2. Apparent sky brightness along a path tangent to the surface of the earth on a very clear day when the meteorological range (Section 2.2.5) is 60,000 yards.

phere. The transmittance T_X of a path of length X is therefore

$$T_X = e^{-\beta X}. \tag{8}$$

The attenuation coefficient β can be determined with the aid of equation (8) from measured values of T_X. For this purpose equation (8) can be rewritten

$$\beta = \frac{2.303}{X} \log_{10} \frac{1}{T_X}. \tag{9}$$

A photoelectric *transmissometer* for measuring T_x has been developed by the National Bureau of Standards.[23]

The transmittance T of a unit distance (mile, yard, etc.) of atmosphere is shown by equation (8) to be

$$T = e^{-\beta}. \tag{10}$$

By substituting equation (10) in equation (7), the latter can be written

$$B_X = B_H(1 - T^X) + B_o T^X. \tag{11}$$

2.2.2 The Attenuation of Contrast

Within the region of optical equilibrium, the brightness of a distant object can be computed by means of equation (4), provided the brightness of the object at zero range and the atmospheric attenuation coefficient are known. However, the effect of atmospheric scattering on the visibility of distant targets can be represented more simply by rewriting equation (4) in terms of the contrast of the object against its sky background. Let the ***apparent contrast*** of a target seen at a distance X against a background of horizon sky be defined by the relation

$$C_X = \frac{B_X - B_H}{B_H}. \tag{12}$$

Similarly, let the ***inherent contrast*** of the target (as seen nearby) be defined by the relation

$$C_o = \frac{B_o - B_H}{B_H}. \tag{13}$$

As a consequence of the foregoing definitions, the contrast of dark targets can never exceed minus one, while the contrast of bright targets is unlimited. As will be shown in Chapter 3, *dark targets and bright targets of the same size and having numerically equal apparent contrasts are equally visible.*

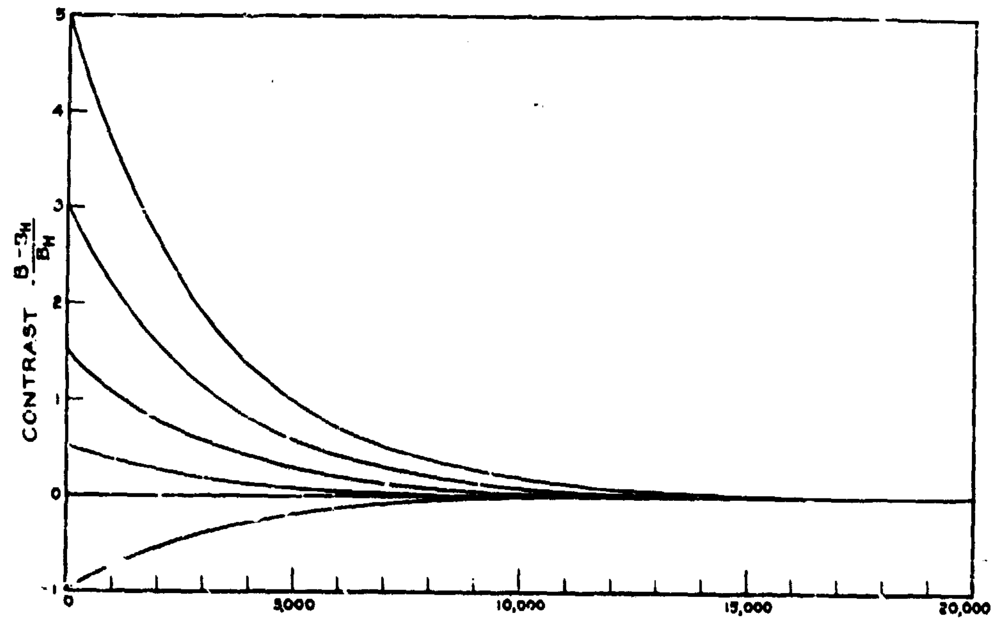


FIGURE 3. Variation of apparent contrast with distance for targets seen against a background of horizon sky on a day when the meteorological range is 12,000 yards.

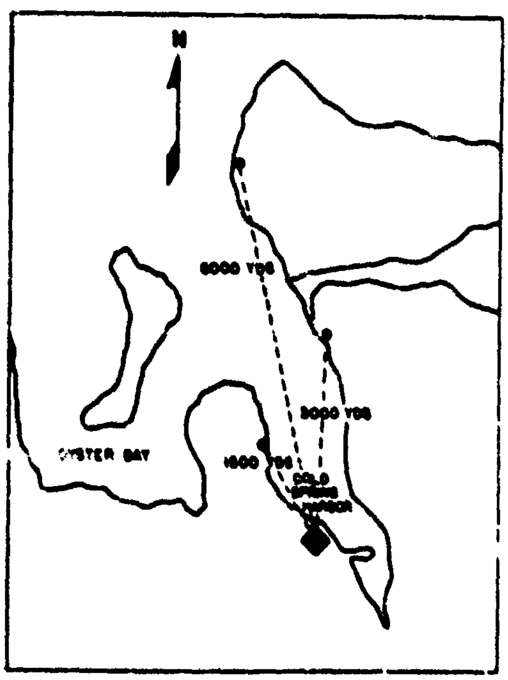


FIGURE 4. Sketch of Cold Spring Harbor, Long Island, showing the location of targets.

By substitution, equation (7) takes on the form

$$C_R = C_0 e^{-\sigma R}. \qquad (14)$$

Similarly, equation (11) becomes

$$C_R = C_0 T^R. \qquad (15)$$

Equation (14) states that the apparent contrast of any target, bright or dark, is exponentially attenuated with distance. This is illustrated in Figure 3, which shows the contrast attenuation with distance for both black and white targets on a day when the meteorological range (Section 2.2.5) is 12,000 yards; a bright target, having inherent contrast greater than unity, is visible at greater distance than the darkest dark target of equal size.

Experimental Verification of the Theory

The Tiffany Foundation, under contract OEMsr-597, performed experiments designed to test the theory developed above. A series of black and white targets was set up on the shores of Cold Spring Harbor at the locations shown in Figure 4. These were billboard-type structures, carefully placed so that the angle of incidence of the sunlight was the same on each and adjusted in size so that every target subtended the same angle at the observing sta-

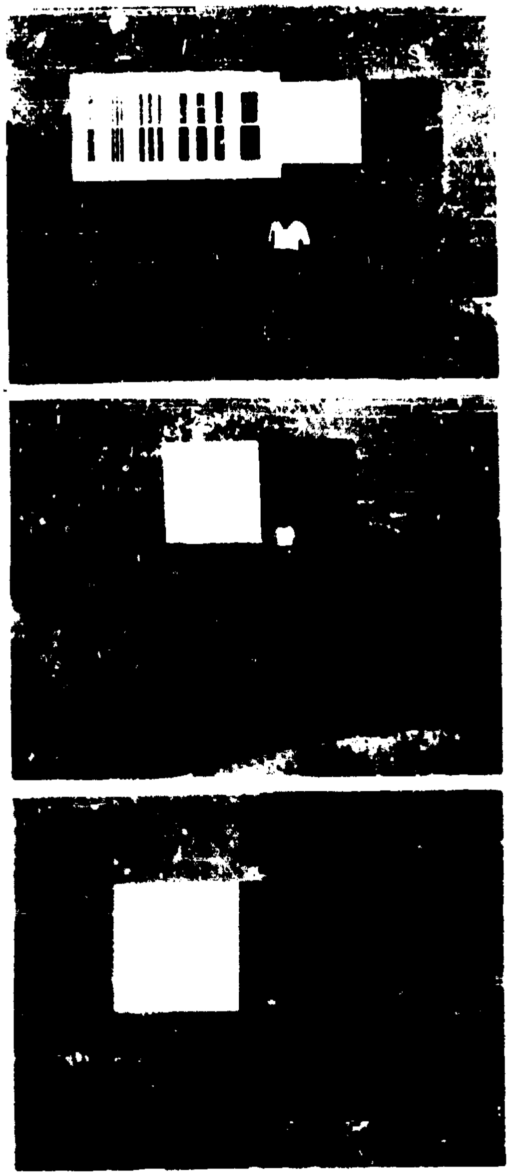


FIGURE 5. Billboard-type targets used by the Tiffany Foundation.

tion on the Tiffany beach. Photographs of these targets are shown in Figure 5. The apparent contrast of the targets relative to the horizon sky was measured by means of a telephotometer along the sight paths indicated by broken lines in Figure 4. Meteorological data of the conventional type were taken at the time of each experiment; and, in addition, the transmission of the atmosphere over a 1,000-yard path across Cold Spring Harbor was determined by means of a Bureau of Standards transmissometer.

The simplest type of telephotometer used to measure the apparent contrast of the targets was the long-focus camera shown in Figure 6. A lens having a focal length of 10 feet was used in order to obtain an image of the distant billboard suffi-

FIGURE 6. Long-focus camera used as a telephotometer.

ciently large to permit reliable density measurements to be made with the microdensitometer described in Section 5.3.1. A photographic gray scale, mounted a few feet in front of the camera, provided sensitometric calibration on each negative.

Photographs of the three targets on a clear day are shown in Figure 7. The clearness of the atmosphere on this occasion can be judged by the fact that hills in Connecticut, 50 miles distant, are clearly shown in the third picture. The negatives from which these pictures were made were measured with the microdensitometer, and the contrast of the target relative to the sky above the Connecticut hills was determined by the usual methods of photographic photometry.[28] Figure 8 is a semilogarithmic plot of apparent target contrast as a function of range. In making this plot, no distinction has been made between positive and negative values of contrast. It will be noted that the three points representing the black targets fall along a straight

FIGURE 7. Photographs of the billboard targets made with the long-focus camera.

line which, when extrapolated to zero range, passes through a contrast of approximately minus 1. The atmospheric attenuation coefficient β was computed from the slope of this line. The meteorological range (Section 2.2.5) that corresponds to this value of β is 47.3 miles.

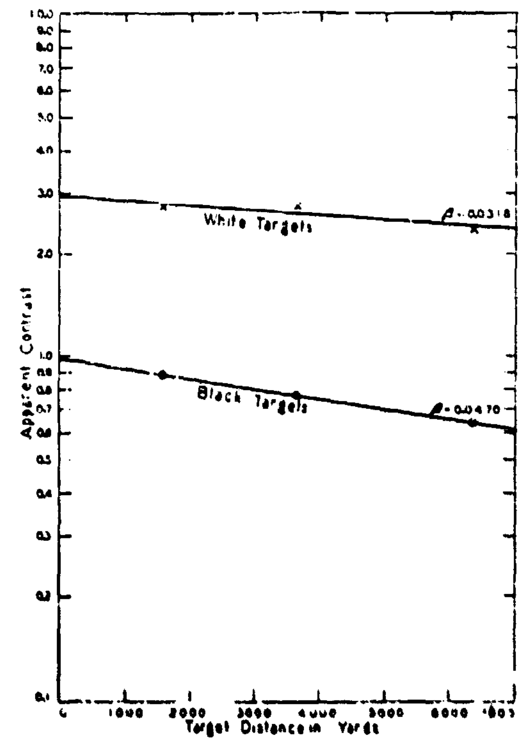


FIGURE 8. Plot showing the variation with distance of the apparent contrast of the billboard targets as shown in Figure 7.

The same contrast scale has been used for both negative and positive contrasts. From the slope of the line drawn through the black target points, β = [illegible] per thousand yards.
Time: [illegible] a.m. to [illegible] a.m.
Sky: Clear, light [illegible] over Connecticut
Estimated visibility: [illegible] miles
Atmospheric pressure: [illegible] millibars
Temperature: [illegible] degrees F.
Dew point: [illegible] degrees F.
Relative humidity: [illegible] per cent
Wind: NW [illegible] miles per hour

The points representing the contrast of the white targets cannot be fitted by a straight line. Random scattering of white target points was observed in most of the experiments, but no systematic trend was noted. The scattering of these points appears to result from differences in the lighting of the targets. Even on seemingly clear days traces of cloud formation at very high altitudes often cause the illumination over the surface of the earth to vary slightly, and these variations cause considerable uncertainty in the inherent contrast of a white target against a background of horizon sky. Most targets of naval or military interest are of low reflectance,

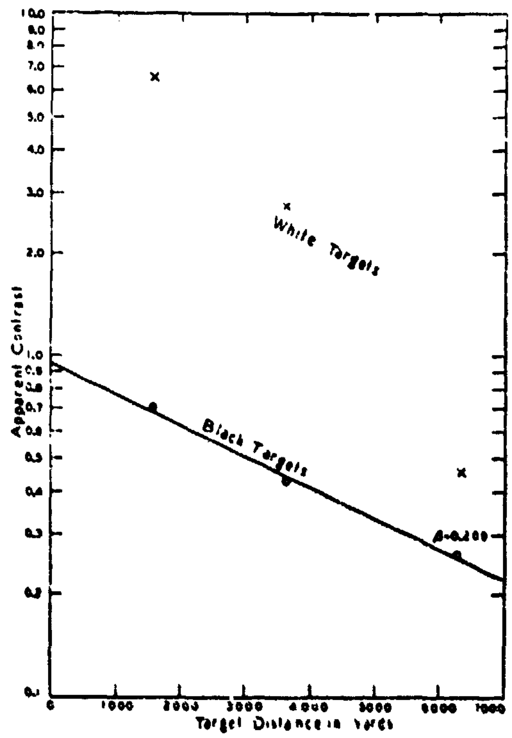


FIGURE 9. Plot showing variation with distance of the contrast of the billboard targets on a day when the Connecticut shore (12 miles distant) was not visible.

From the slope of the line representing the black targets $\beta = 0.200$ per thousand yards.
Time: 10:00 a.m. to 11:00 a.m.
Sky: 7/10 cirrus [illegible]
Ceiling: [illegible] feet
Estimated visibility: Between 3 and 12 miles.
Atmospheric pressure: 1011.0 millibars.
Temperature: [illegible] degrees F.
Dew point: [illegible] degrees F.
Relative humidity: [illegible] per cent.
Wind: NW light.

so that small variations in illumination do not greatly alter their inherent contrast. In the limiting case of a completely black target, illumination differences have no effect. For this reason, meteorologists specify black targets for use in estimating the daylight visual range (Section 2.2.5).

These same effects are to be noted in Figure 9, which represents a corresponding experiment conducted on a hazy day when the visibility was greater than three and less than twelve miles. The meteorological range computed from the value of β was 10.6 miles for the black targets. Little reliability can be placed upon the points representing the white targets, but the trend of the data indicates the general validity of the principle that the apparent contrast of all targets changes exponentially with distance.

The results obtained with the photographic telephotometer were duplicated, but not improved, by experiments conducted with several other types of telephotometers housed in a small temporary laboratory building (Figure 10) on the shore of Cold

FIGURE 10. This temporary building on the shore of Cold Spring Harbor was used to house the telephotometer.

Telescope can be seen protruding from building under rain shield (left front). Building was called "Celestes Lodge."

Spring Harbor. The design of a telephotometer suitable for measuring the apparent contrast of the targets is not easy, if the size of the most distant board is held within practical limits. A telescope objective, 6 inches in diameter and 4 meters in focal length, was used to form an image of the targets. Careful external and internal baffling was used in the telescope, and the stray light in the system was found to be exceedingly small. During preliminary experiments, the photometric measurements were made with a Macbeth illuminometer mounted on the telescope to form a Maxwellian view device. The precision of such a telephotometer cannot be made high because of the small relative aperture of the objective. Subsequently, a Photovolt electronic photometer was used. A satisfactory compromise between sensitivity and stability could not be found, and finally the a-c photoelectric telephotometer shown in Figure 11 was built.[26]

FIGURE 11. Photograph of the a-c telephotometer used by the Tiffany Foundation for measuring the apparent brightness of the billboard targets. This instrument was housed in Celotex Lodge (Figure 10).

2.2.4 Two Misconceptions

Two apparenty nonexistent "effects" are often mentioned in the literature of meteorology. These are known as the *ground-glass plate effect*[129] and the *edge effect*;[129] they refer to loss of sharp detail by *low-angle scattering* and *diffraction of light around the target* respectively. Neither is based upon sound theoretical reasoning, and neither has been demonstrated experimentally. Both effects are the result of attempts to explain certain *visual impressions* in terms of the scattering properties of the atmosphere. Actually, these illusions are natural consequences of the mechanism of human vision, and are dealt with properly in the next three chapters of this volume.

The ground-glass plate effect was explored photographically with the long-focus camera (Figure 6) at the Tiffany Foundation. Photographs of the resolving power targets shown on the left in Figure 5 (top) were photographed in both clear and foggy weather. When the contrast (gamma) of the photograph was made equal to $e^{\beta N}$ as determined from transmissometer readings, the targets were resolved equally well in all photographs. The experiment was repeated using natural objects as targets, and the same conclusion was reached. No fine details were obliterated by the haze. The meteorologist may safely consider that *the ground-glass plate effect does not exist*.

The *edge effect* was explored with the a-c photoelectric telephotometer (Figure 11) at the Tiffany Foundation. This instrument was used to compare the apparent brightness of several black targets visible against a background of horizon sky. The angular size of the targets ranged from 0.8 minute to more than 1 degree. No difference in the apparent brightness of the targets was found. This conclusion is supported by the electromagnetic theory of light. Inasmuch as all the targets are large compared with the wavelength of light, diffraction around them would not be expected to increase their apparent brightness. The meteorologist may safely consider that *the edge effect does not exist*.

2.2.5 Meteorological Range

The optical effect of the atmosphere is usually reported by meteorologists in terms of the *daylight visual range* or *visibility*. By international agreement, the daylight visual range is the distance at which a large dark object on the horizon is just recognizable against the sky background. The relationship between the daylight visual range and β has not yet been established by international agreement, but it is standard practice at the Naval Research Laboratory and elsewhere to assume that an object subtending a large angle at the eye can be recognized in the daytime when its brightness differs from that of its sky background by as much as 2 per cent. The contrast of a black target is by definition -1. If -1 is substituted for C_0, and -0.02 for C, equation (14) can be written

$$\ln \frac{1}{0.02} = \beta v = 3.912, \qquad (16)$$

where N has been replaced by the symbol v. The distance v will henceforth be referred to as the *meteorological range*. It is, by definition that horizontal distance for which the transmittance of the atmosphere $e^{-\beta v}$ is 2 per cent.

It must be borne in mind that the daylight visual range refers to the distance at which large black objects can just be recognized against a bright daytime sky. By a *large object* is meant an object so large that the angle it subtends at the eye of the observer is sufficiently great so that a greater angle would not increase the reported value of daylight visual range. The visibility marks available to a practicing meteorologist are rarely of sufficient angular size. In other words, the daylight visual range is seldom so short that a *large* object, such as a house or a tree, subtends a sufficiently large visual angle. As a result, the *visibility* reported by meteorologists is usually somewhat less than the meteorological range defined by equation (16). A Civil Aeronautic Administration report[25a] presents results which indicate that *visibility as ordinarily reported averages to be three-quarters of the meteorological range.*

Under homogeneous lighting conditions, the meteorological range is the same in all directions. This is implied by equation (16), inasmuch as v depends only on the nondirectional quantity β. The extent to which the apparent brightness of a distant object differs from its inherent brightness depends upon the bearing of the object relative to the sun, as shown by equation (4). This equation involves the scattering coefficient σ, the magnitude of which depends upon the direction in which the scattering takes place. However, the variation of apparent contrast with distance is independent of σ, as shown by equation (14). This is a valuable consequence of the definition of contrast.

2.2.6 Directional Variation of the Daylight Visual Range

Under nonhomogeneous lighting conditions the daylight visual range may not be the same in all directions. The variation may be caused by banks of clouds or smoke on the horizon; or it may be due to inhomogeneities in the atmosphere along the line of sight. The latter may be caused by temperature variations, such as those encountered when the line of sight passes over both land and water, or by local banks of haze or fog. There may be local variations in the luminous density due to differing reflectivities of the natural terrains along the line of sight, or to cloud shadows.

When the daylight visual range is to be predicted from values of β measured by an instrument such as the Bureau of Standards transmissometer, it may be necessary to allow for directional variations. When interest in this problem was expressed by the Navy Bureau of Aeronautics, the following possible procedure for making such allowances was suggested.

Let it be assumed from equation (16) and the subsequent discussion that the daylight visual range s is inversely proportional to β,

$$s = \frac{K}{\beta}, \tag{17}$$

where K is a constant. Combining equations (6) and (17)

$$s = \frac{KB_H}{\sigma q}. \tag{18}$$

Let directions 1 and 2 be denoted by subscripts. Then,

$$s_1 = \frac{KB_1}{\sigma_1 q},$$

and

$$s_2 = \frac{KB_2}{\sigma_2 q}.$$

By division

$$\frac{s_1}{s_2} = \frac{B_1}{B_2} \cdot \frac{\sigma_2}{\sigma_1}. \tag{19}$$

But under homogeneous lighting conditions $s_1 = s_2$. Hence,

$$\frac{B_1}{B_2} = \frac{\sigma_1}{\sigma_2}. \tag{20}$$

Assuming equation (19) to apply under the nonhomogeneous lighting condition, then by the substitution of equation (20) in equation (19)

$$\frac{s_1}{s_2} = \frac{B_1}{B_2} \cdot \frac{B_2'}{B_1'}, \tag{21}$$

where the primed quantities refer to normal homogeneous conditions.

In order to measure the quantities involved in equation (21), a horizon-scanning photometer was built by the research laboratories of the Interchemical Corporation under contract OEMsr-697.[m] This instrument, shown in Figures 12 and 13, was developed to permit the brightness of a 4-degree zone above the horizon to be measured in any desired direction. Values of B_2'/B_1' can be obtained with this instrument, and expressed in the form of polar curves, from which the ratio s_1/s_2 for any existing nonhomogeneous conditions could be computed by means of equation (21) from measured values of B_1, B_2.

For example, consider Figure 14, which shows a polar plot of horizon brightness as measured by the horizon-scanning photometer. The dotted curve indicates the brightness of the horizon sky under homogeneous conditions. The solid curve represents an occasion when the northeast horizon appeared abnormally bright. Let it be required to predict the daylight visual range at an azimuth of 40 degrees

FIGURE 12. Photograph of horizon scanning photometer (rear view).

The diffusing globe mounted on the top of the photometer was used to measure the luminous density (q).

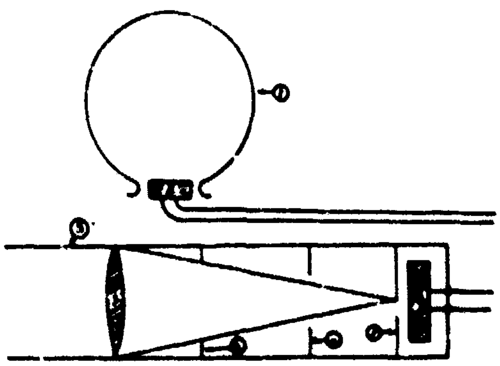


FIGURE 13. Schematic diagram of the horizon scanning photometer.

Diffusing globe (1) and photocell (2) were used to measure the luminous density (q). Lens (3) imaged the sky just above the horizon on stop (7). A photocell (4) received the light which passed through the stop. A sunshade (5) and baffles (6) reduced stray light.

(measured clockwise from the north) by means of equation (21). Let this direction (shown by the dashed line in Figure 14) be referred to as direction 1, and let direction 2 be any direction for which the solid curve has normal shape. Since, in this case, the normal and abnormal curves coincide except in the northeast, equation (21) becomes

$$s_1 = \frac{B_1}{B_1'} s_2.$$

Substituting values from Figure 14,

$$s_1 = \frac{7\,660}{3{,}660} \cdot 22 = 47 \text{ miles.}$$

At the request of the Navy, the horizon-scanning photometer was turned over to the Aircraft Camouflage Sub-Section, Tactical Test, Naval Air Station, Patuxent River, Maryland. No experimental test of equation (21) is known to have been made.

2.2.7 Backgrounds Other Than the Horizon Sky

Throughout the foregoing discussion, the target has been assumed to be viewed against a background of horizon sky. Under some circumstances, the target may be seen against other backgrounds.

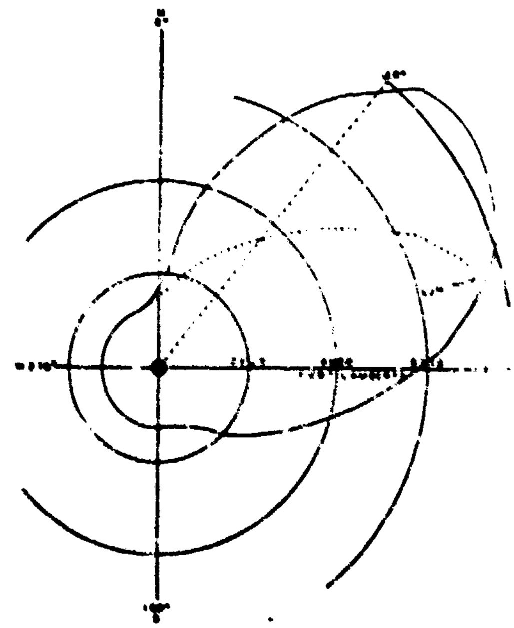


FIGURE 14. Polar plot of the brightness of the horizon sky measured by the horizon scanning photometer at the Naval Air Station, Patuxent River, Maryland.

[illegible] sun elevation [illegible] degrees [illegible] visibility [illegible] miles. The broken curved line [illegible] the brightness of the horizon sky [illegible]

For convenience, consideration of the apparent contrast of a target under such circumstances will be deferred until the visibility of objects viewed downward along slant paths has been discussed (Section 2.3.7).

2.3 THE VISIBILITY OF OBJECTS VIEWED DOWNWARD ALONG A SLANT PATH

An aerial observer views any object on the ground along a slant path throughout which the scattering coefficients β and σ vary with altitude. If the stratification of the atmosphere is continuous, these coefficients vary regularly and in a readily predictable manner, but such a condition is rare. Usually the atmosphere is composed of optically dissimilar strata, the boundaries of which are often sharply defined and within which β and σ vary with altitude. A method for solving practical visibility problems involving any set of atmospheric conditions which may exist is described in Chapter 5. However, the case of an atmosphere having continuous, regular optical stratification must be discussed first in order to provide a basis for treating the case of discontinuous stratification.

2.3.1 The Differential Equation

Along slant paths, the fundamental scattering processes are the same as along horizontal paths of sight. The differential equation corresponding to equation (1) is

$$\frac{dt}{dr} = -\beta_y t + \sigma_y q_y, \qquad (22)$$

where the meaning of the symbols is shown by Figure 15. The subscript y is used to indicate that the scattering coefficients β and σ and the luminous density q are functions of the altitude coordinate y.

An attempt was made to use the spectrograph (Section 3.4.1) to explore the variation of luminous density with altitude, but no variation was detected up to the highest altitude attained (15,000 feet). A similar lack of variation was found on other occasions when the illumination on a horizontal plane was measured at altitudes up to 18,000 feet. During all these flights, the solar altitude was in the neighborhood of 30 degrees. From these experiments, it is believed that ordinarily the variation of q with altitude is insignificant.[e] If q is regarded as a constant, equation (22) can be solved by direct integration, provided a simple functional relationship exists between β_y and y and between σ_y and y.

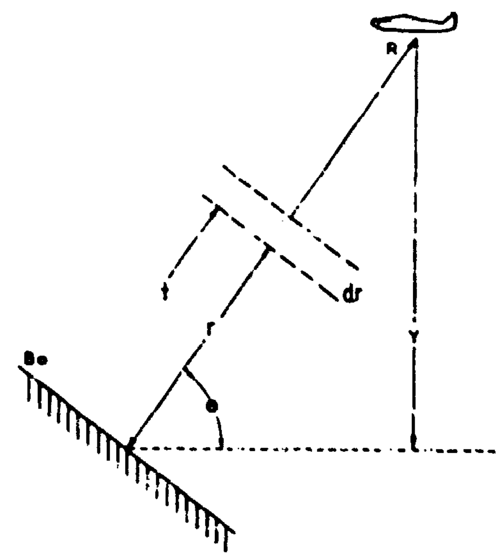


FIGURE 15. See text for explanation.

2.3.2 The Standard Atmosphere

Meteorologists sometimes refer to a *standard atmosphere* in which the temperature-lapse rate within

TABLE 1

Altitude (feet)	Pressure of mercury (inches)	Altitude (feet)	Pressure of mercury (inches)
1,000	31.02	14,000	17.58
0	29.92	15,000	16.88
1,000	28.86	16,000	16.22
2,000	27.82	17,000	15.57
3,000	26.82	18,000	14.94
4,000	25.84	19,000	14.34
5,000	24.90	20,000	13.75
6,000	23.98	22,000	12.64
7,000	23.09	24,000	11.60
8,000	22.22	26,000	10.63
9,000	21.38	28,000	9.72
10,000	20.58	30,000	[illegible]
11,000	19.79	35,000	7.04
12,000	19.03	40,000	5.54
13,000	18.29	50,000	3.42

the troposphere is 6 F per thousand feet of altitude. The variation of pressure with altitude is given in Table 1.[27]

[e] This approximation cannot always be made. For example, just after sunset the luminous density is much greater at high altitudes than it is near the ground. The exact range of solar altitudes within which the variation of q with altitude may be neglected is not known. Any extension of the research described in this volume should include an investigation of this matter.

From the standpoint of visibility, the refracting, scattering, and absorbing properties of the atmosphere determine its effectiveness in screening targets. It is beyond the scope of this report to discuss the deleterious effect on image quality sometimes produced by local variations in the refractive index of the air along the line of sight, but it is a well-known physical principle that the refractive index of a gas is proportional to its density. Similarly, the absorbing and scattering properties of a gas are proportional to its density, that is, to the number of molecules per unit volume. Therefore, the data shown in Table 1 have been converted into the relative number of molecules per unit volume, account having been taken of the effect of the temperature-lapse rate by means of the equation of state of a perfect gas. The result is shown in Table 2.

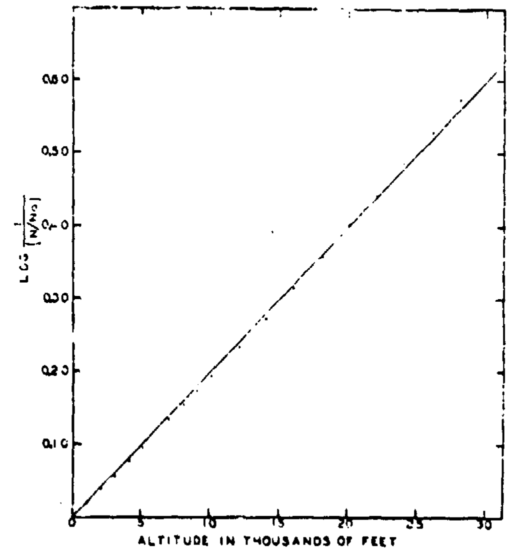


FIGURE 16. Variation with altitude of relative density of scattering particles.

Points represent optical standard atmosphere defined by Table 2. These data have been approximated by the straight line. Slope: 2 100.

TABLE 2

Altitude (feet)	Relative number of molecules per unit volume
0	1.000
1,000	0.956
2,000	0.918
3,000	0.878
4,000	0.841
5,000	0.804
6,000	0.770
7,000	0.736
8,000	0.703
9,000	0.672
10,000	0.642
12,000	0.586
14,000	0.531
16,000	0.485
18,000	0.440
20,000	0.399
22,000	0.361
24,000	0.326
26,000	0.295
28,000	0.270
30,000	0.233

The atmosphere may contain, besides air, microscopic water droplets, dust, rain, snow, smoke, etc. Water particles and dust are usually homogeneously distributed except for stratification. Let the *optical standard atmosphere* be defined as a homogeneous atmosphere in which the water particles, dust particles, and air molecules are subject to continuous vertical stratification at the rate implied by Table 2.

An analytic expression for the data in Table 2 is required before differential equation (22) can be solved. Figure 16 shows a semilogarithmic plot of the relative number of particles per unit volume as a function of altitude. Within the range of altitude represented, the data may be approximated by a straight line, the equation of which is

$$\frac{N_y}{N_0} = e^{-y/21{,}700}. \tag{23}$$

Accordingly, let

$$\beta_y = \beta_0 e^{-y/21{,}700} \text{ and } \sigma_y = \sigma_0 e^{-y/21{,}700}, \tag{24}$$

where y is to be expressed in feet. Along any slant path making an angle θ with the horizontal

$$y = r \sin \theta. \tag{25}$$

After combination with equations (24) and (25), equation (22) becomes:

$$\frac{dB}{dr} = -\beta_0 B e^{-r \sin\theta/21{,}700} + \sigma_0 \rho e^{-r \sin\theta/21{,}700}. \tag{26}$$

4.3.3 Optical Slant Range

Equation (26) can now be integrated directly:

$$\int_{B_0}^{B_R} \frac{dB}{\sigma_0 \rho - \beta_0 B} = \int_0^R e^{-r \sin\theta/21{,}700}\, dr. \tag{27}$$

whence

$$\frac{\sigma_0 q - \beta B_R}{\sigma_0 q - \beta B_0} = e^{-\beta \bar{R}}, \tag{28}$$

where

$$\bar{R} = \frac{21{,}700}{\sin\theta}\left[1 - e^{-R \sin\theta / 21{,}700}\right]. \tag{29}$$

The quantity $\bar{R}$ will henceforth be referred to as the *optical slant range*. Physically, it is the path length within a homogeneous atmosphere, having no lapse rate or pressure gradient, along which light would encounter the same number of particles actually encountered along the path of length R within the standard atmosphere. In other words, $\bar{R}$ is that horizontal distance which contains as much *air* as does the slant distance R.

2.3.4 Variation of Apparent Brightness Along Slant Paths

Equation (28) can be written in a form similar to equation (4):

$$B_R = \left(\frac{\sigma_0 q}{\beta_0}\right)\left(1 - e^{-\beta \bar{R}}\right) + B_0 e^{-\beta \bar{R}}. \tag{30}$$

For the special case of $\theta = 0$, $\bar{R} = R = X$, and equation (30) reduces to equation (4). The factor

$$\frac{\sigma_0 q}{\beta_0} = \frac{\sigma q}{\beta} = B_H. \tag{31}$$

By extension, when $\theta \neq 0$ the factor

$$\frac{\sigma_0 q}{\beta_0} = B_H', \tag{32}$$

where B_H' is the brightness of the horizon sky in the particular directions indicated by the arrows m and n in Figure 17. In these directions, the brightness of the horizon is determined by space light scattered at the same angle from the rays of the sun as the space light scattered in the direction of the aerial observer. Under most circumstances, directions m and n can be found and B_H' measured directly. However, when the observer is nearly "in the sun" as seen from the target, the cone produced by rotating his line of sight about the direction of the rays of the sun will not intersect the horizontal plane. In this case, resort must be had to special photometric equipment for determining $\sigma_0 q / \beta_0$.

Optical Equilibrium

Equation (26) indicates that when $\beta_0 t = \sigma_0 q$, $dt/dr = 0$. Thus, a condition of optical equilibrium (Section 2.2.1) exists along slant paths in the sense that any object whose inherent brightness equals $\sigma_0 q/\beta_0$ appears equally bright when viewed from any distance. Equation (32) indicates that objects having the brightness of the horizon sky in the m and n directions (Figure 17) fulfill the conditions

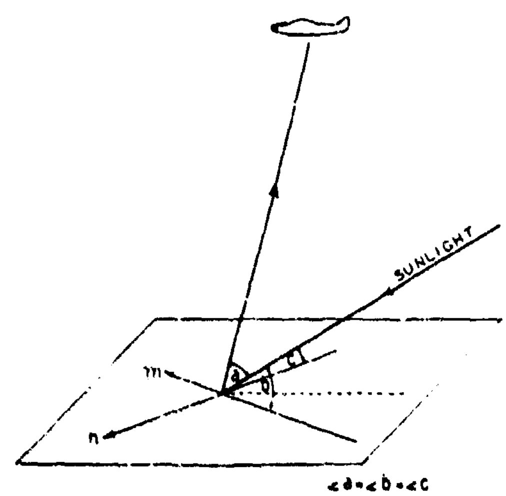


Figure 17. Arrows m and n indicate the directions in which the brightness of the horizon sky is determined by light scattered from the rays of the sun at the same angle as light scattered toward the aerial observer.

for equilibrium. The apparent brightness of darker objects increases with distance, while that of brighter objects decreases. In the limit, the apparent brightness of all objects on the ground approaches the equilibrium value asymptotically. Thus, when an observer aloft cannot see the ground because of haze, the apparent brightness of the earth is the same as the brightness of the horizon sky seen by an observer on the ground looking in the m or n directions. A measurement of the apparent brightness of the earth by such an aerial observer may be taken as the value of $\sigma_0 q/\beta_0$.

The Attenuation of Brightness Differences

An important consequence of equations (4) and (30) is the theorem that along either slant paths or horizontal paths brightness differences are exponentially attenuated. That is to say, if the target and its background have inherent brightnesses B_0 and B_0'

respectively, so that the difference in their brightnesses $\Delta B_0 = B_0 - B_0'$, then from equation (30) their apparent brightness difference at range R is given by

$$\Delta B_R = \Delta B_0 e^{-\beta R}. \tag{33}$$

2.3.5 Variation of Apparent Contrast Along Slant Paths

The variation of apparent contrast along slant paths is more complex than along horizontal paths. This complexity arises because the apparent brightness of the background is a function of R. Let the inherent contrast between the target and its background be defined by

$$C_0 = \frac{\Delta B_0}{B_0} \tag{34}$$

and the apparent contrast at range R by

$$C_R = \frac{\Delta B_R}{B_R}. \tag{35}$$

If equations (30), (33), and (34) are substituted in equation (35), the law of contrast attenuation along slant paths is found to be

$$C_R = \frac{C_0}{1 + \frac{B_H'}{B_0}\left(e^{\beta R} - 1\right)}. \tag{36}$$

2.3.6 The Sky-Ground Ratio

The quantity B_H'/B_0 has been called the *sky-ground ratio*. On a uniformly overcast day when the earth is covered with snow, $B_H' = B_0$, and the sky-ground ratio is unity. Equation (36) then reduces to

$$C_R = C_0 e^{-\beta R} \tag{37}$$

along any line of sight, vertical, slant, or horizontal. Under other circumstances, the sky-ground ratio provides a means by which the law of contrast attenuation along slant paths can be adjusted for the effect of lighting conditions, ground reflectance, and the orientation of the line of sight with respect to the sun.

Typical values of the sky-ground ratio for a slant path such as that shown in Figure 15 are given in Table 3.

TABLE 3

Sky condition	Ground condition	Sky-Ground ratio
Overcast	Fresh snow	1
Overcast	Desert	7
Overcast	Forest	25
Clear	Fresh snow	0.2
Clear	Desert	1.4
Clear	Forest	5

2.3.7 Horizontal Sight Paths

Along the horizontal paths of sight discussed earlier in this chapter, the background of the target was assumed to be the horizon sky. In such a case B_0 and B_H' are identical, and therefore, since $\bar{R} = R = X$, equation (36) reduces to equation (14). However, under some circumstances, the target may be viewed against a background other than the sky. For example, a ship at sea may be seen against a background formed by a distant land mass, or the "target" may be a numeral painted on the side of a ship. In such a case, the apparent contrast can be calculated by means of equation (36), if the sky-ground ratio is replaced by the ratio of the brightness of the horizon sky in the direction of observation to the inherent brightness of the background of the target.

2.3.8 The Visibility of Military and Naval Targets

Targets of military and naval interest ordinarily subtend a very small angle at the eye of the observer when they are viewed at limiting range. In such cases, the limiting range of visibility is governed not only by the condition of the atmosphere, but also by the angular size and effective contrast of the target. The following chapter presents data on the perceptual capacity of the human observer under virtually all circumstances encountered outdoors. The manner in which this information can be combined with the laws of contrast attenuation by the atmosphere will be treated in Chapter 4 for the case of targets viewed along a horizontal path, and in Chapter 5 for the case of targets viewed downward along a slant path.

Chapter 3

PERCEPTUAL CAPACITY OF THE HUMAN OBSERVER

3.1 INTRODUCTION

The visibility of targets is influenced not only by such physical factors as were discussed in the preceding chapter, but also by certain physiological factors. These include the effective brightness and color contrasts of the target against its background, the size and shape of the target, the brightness level to which the eyes of the observer are adapted, and the conditions and technique of observing.

Previous investigations have seldom included the entire useful range of any one of these factors and have never undertaken to include the combined effect of all of them. Consequently, existing experimental data have rarely been applicable to the visibility problems encountered in naval and military operations.

From the outset of the visibility program conducted under the supervision of Section 16.3, NDRC, it was the basic plan to investigate the various factors one by one over their entire ranges in such a manner that the final data could be used to predict the visibility of naval and military targets. The investigation of the physiological factors was divided into two basic programs, one concerned with the influence of brightness contrast[26,a] and the other with the influence of color contrast.

The Louis Comfort Tiffany Foundation, of Oyster Bay, New York, was requested under Contract OEMsr-507, to conduct an extensive investigation of the influence on visibility of the brightness contrast of targets of all sizes and shapes, at all brightness levels encountered outdoors, day or night. This research is described in OSRD Report No. 6401, entitled, *Visibility of Targets*.[26]

The influence of color contrast was investigated by the Eastman Kodak Company, Rochester, New York, under Contract OEMsr-1070, and the results are to be found in OSRD Report No. 4541, *Influence of Color Contrast on Visual Acuity*.[27] As shown therein, it is possible to evaluate any color contrast in terms of a brightness contrast yielding the same visual acuity. This makes it possible to combine the influences of color contrast and brightness contrast in such a way that the visual capacities of a typical human observer can be expressed quantitatively.

3.2 INFLUENCE OF BRIGHTNESS CONTRAST ON VISIBILITY

The key to a method for investigating the influence of brightness contrast on the visibility of targets was given by a preliminary experiment in which the visibility of the silhouettes of typical naval vessels and aircraft was compared with the visibility of circular spots. This experiment indicated that, ordinarily, uniform targets of equal area and equal apparent contrast are equally visible regardless of their shape.[a] Accordingly, a fundamental investigation of the visibility of circular targets was first undertaken.

3.2.1 The Visibility of Circular Targets

The major portion of the Tiffany investigation was devoted to the determination of the contrast of circular targets of selected diameters which were just visible against uniform backgrounds having various brightnesses from 10^{-6} to 100 foot-lamberts. The target diameters subtended angles from 0.6 to 400 minutes at the eyes of the observers; and targets both brighter and darker than their backgrounds were used.

Preliminary Experiments

The Tiffany Foundation was forewarned by the published results of earlier investigators to expect the reproducibility of visual experiments to be highly erratic. For this reason, their first experiments were designed to yield results of the highest possible precision in order to determine the general nature of visual functions.

The Eight-Position Method. A circular spot of a given size was produced by projection at any one of eight equally spaced positions around a clearly visible orientation spot located at the center of the screen. The circumference of the *spot track* thus formed was such that a straight line of equal length would have subtended an angle of approximately 15 degrees at the eyes of the observers. The target was projected for 6 seconds, during which time the observers were notified by the sound of the buzzer that

[a] See Section 3.2.10 for a quantitative discussion of the effect of target shape.

the target was present. The 6-second searching time was considered to correspond to a scanning rate of 2.5 degrees per second, a value consistent with the reported practice of lookouts aboard German submarines. It was sufficiently short that, with ten observers, a large enough number of observations could be taken to permit the liminal contrast of the target to be determined with a high degree of reliability. Ordinarily, a total of 2,880 observations were made in determining each datum point.

Final Experiments

Later in the war, after the subject of search had become a major interest of the Operations Research Group, COMINCH, U. S. Navy, it was no longer necessary or desirable to make any assumption concerning the rate of search to be employed by an observer in the field. Moreover, it was found that no simple relation exists between the diameter of the spot track and the effect of the time allowed for search. For these reasons it is felt that the results of the preliminary experiments are of little practical importance other than to illustrate the general shape of the visibility curves and to demonstrate that highly reproducible visual experiments are possible.

The Single-Position Method. The final experiments were designed to determine the upper limit of visibility (lower limit of just-visible contrast), the time for observation being such that a longer period produced no lower value of liminal contrast. For targets of low contrast seen at high levels of adaptation brightness, the time required to attain ultimate scores was found to be impracticably long. When, however, the target was confined to a single fixed position and the observer was required to report only whether or not the target was visible, maximum scores could be obtained with reasonably short observation times. The target was frequently absent, so that mere guessing was discouraged and allowance for its influence could be based on the erroneous reports of the presence of the target.

The results of the preliminary 8-position experiments served as a valuable guide in selecting the key points required to produce the final curves. This was fortunate, since the single-position experiments could not be conducted as rapidly as had the 8-position ones. Most of the experiments with large targets at high-brightness levels were repeated with the single-position method, and a representative selection of experiments for smaller targets and lower brightnesses was also repeated. The precision of the results obtained with the single-position method was inferior to that of the 8-position method. Consequently, the curves representing the single-position results were drawn with spacings and slopes similar to those of the curves representing the results of the 8-position experiments.

The equality of visibility for equal light and dark contrasts was demonstrated by experiments with the 8-position method. The influence of target shape on

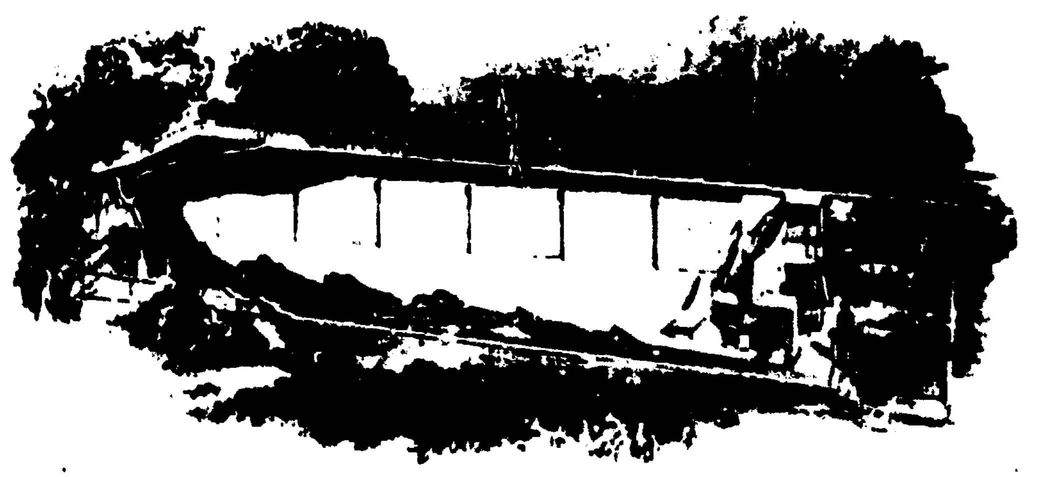


Figure 1. Observation room at Tiffany Foundation

FIGURE 2. Control and recording chamber.

visibility was determined for various brightnesses, contrasts, and target shapes by the single-position method.

3.2.2 Apparatus

Certain functional requirements governed the arrangements of the apparatus used by Tiffany. These were:

1. Simultaneous but independent observation by as many as 10 observers.
2. Presentation of the target at frequent and regular intervals.
3. Use of the psychophysical method of constant stimuli.
4. Photometric measurements based exclusively on the use of standard lamps and the inverse square law.

Observation Room

The observations were made in a room 63 feet long, 12 feet wide, and 10 feet high. This room, a sketch of which is shown in Figure 1, was constructed of plywood panels inside a room at the Tiffany Foundation. A large control and recording chamber (Figure 2) was situated at one end of the observation room. Ten upholstered theatre seats were located just inside the observation room, five on and five under a balcony which extended across the control-room end of the observation room, as shown in Figure 3.

The floors, walls, ceilings, and all the furnishings and accessories within the observation room had flat white finishes. The side panels of the room, each 10 feet square, were arranged as louvers, opposite pairs converging toward the front of the room, as shown in Figures 4a and 4b. The front wall, 10 feet square, was smooth and unobstructed and had, during most of the experiments, only one small hole in the center through which light for the fixation spot was admitted. About 6 feet were available beyond the front wall of the observation room and this space was occupied by apparatus during experiments with very small targets.

Illumination Arrangements

Hidden from the observers, in troffers behind the front edges of the side panels were five banks of

FIGURE 3. Photograph of observers in stations, and projection lens.

lamps on each side of the room (see Figure 4b). These lamps illuminated the room quite uniformly, especially the front wall, which served as the field of observation (see Figure 5). Part or all of the lamps in each troffer could be operated, in order to produce several levels of illumination in the room and on the observation screen. For moderate and high levels, general service bulbs of various wattages were installed as shown in Figure 6.

In all cases, the arrangement of lamps was intended to produce a gradual gradation of brightness from a maximum at the screen to approximately 10 per cent of the maximum near the observers. A telephotometer was used to insure that the desired pattern of brightness was attained and maintained throughout the program. For experiments with targets brighter than their background, the brightness relative to that of the screen was approximately 95 per cent for the first panel, 75 to 85 per cent for the second panel, 60 to 70 per cent for the third panel, 45 to 50 per cent for the fourth panel, 25 to 30 per cent for the fifth panel, and 8 to 15 per cent for the sixth panel.

To achieve low levels of illumination, small bulbs were placed inside light-tight brass tubes, each containing several plates of ground glass through which the light had to pass. (See Figure 7.) The luminous output of these units was adjustable by varying the distance from the bulbs to the first ground glass, by varying the number and separation of the plates, and by placing opaque annular diaphragms between the bulb and the first ground glass. These diaphragms had holes of various diameters, to reduce the amount of light incident upon and transmitted by the layers of ground glass.

For the observation of targets darker than their background, part or all of the illumination of the surrounding screen was by projection, as described in Section 3.2.3. In the majority of these experiments, the gradation of brightness from the front to

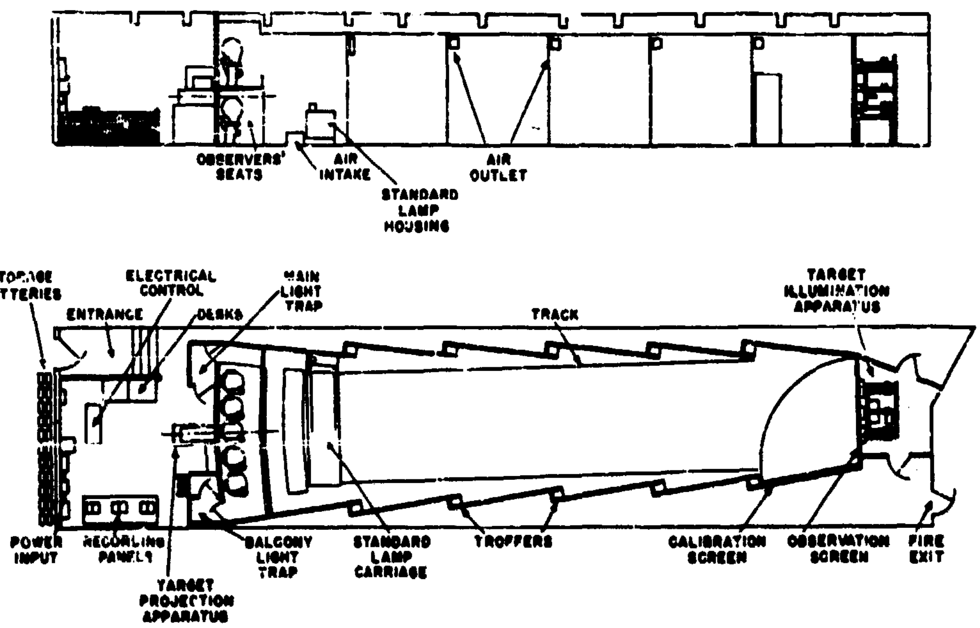


FIGURE 4. Top view elevation of observation room; bottom view plan of observation room.

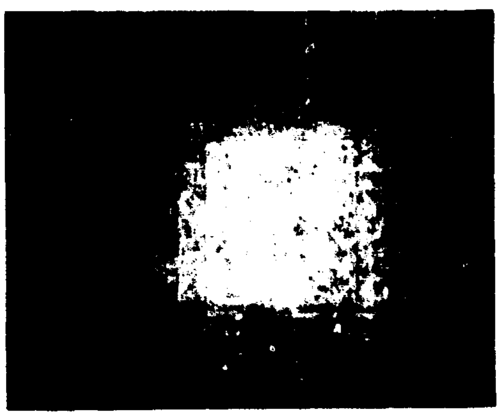


FIGURE 5. Photograph of observation room from observers' seats. Note circular target at center of screen.

the rear panels was similar to that for experiments with targets brighter than their background.

3.2.3 Projection Equipment

All the targets were produced by projection of additional light on the screen. A single lantern-slide projector (Figure 8) was used for targets brighter than their surroundings (Arrangements I to IV). Additional projectors were used in Arrangements V and VI for targets darker than their backgrounds. Arrangement VII was used to project targets in a single position on the center of the screen.

Arrangement I. This was used for experiments with highest background brightness when the great-

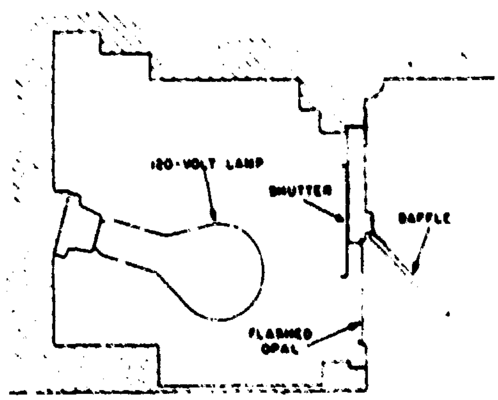


FIGURE 6. Cross section of troffers of observation room, with lamp arranged for moderate and high brightness experiments.

est projector output was required. Several interchangeable metal plates with single round holes of various diameters (in the focal plane of the projector) produced targets subtending 3.60, 9.68, 18.2, 55.2, and 121 minutes at the eyes of the observers. An achromatic prism larger than the aperture, with an angle of about 4.5 degrees, was mounted in front

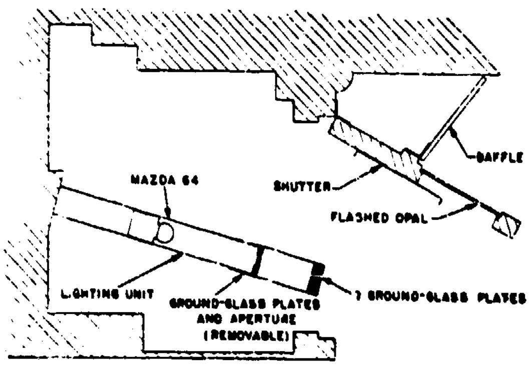


FIGURE 7. Cross section of troffer and lighting unit for low brightness experiments.

of the projector lens. By rotating this prism (Figure 9), the target could be made to appear at any one of eight equiangular positions, each 32 inches from the center of the observation screen. A set of eight electric contacts was provided, one of which completed a circuit to indicate the position of the target.

The contrast of the projected bright target was governed by filters placed between the condenser lens and the target aperture, as shown in Figure 8. Four filters mounted in a circular disk (Figure 10) could be interposed, one at a time, to achieve transmissions of 1.000 (empty aperture), 0.762, 0.540, 0.372, and 0.235. The location of the filter disk, and consequently the contrast, was indicated electrically by an 8-point switch, shown in Figure 10. An opaque plate (Figure 11) served as a shutter to prevent the projection of the image while its position and contrast were being changed. An electric contact closed a circuit so that a buzzer sounded whenever the shutter was open. The duration of each presentation of the target was 6 seconds, with a 6-second interval between.

Arrangement II. This was used for experiments at intermediate brightnesses (Figure 12). The maximum contrast was governed by neutral absorbing filters inserted between the condenser and the contrast-filter disk in Arrangement I. These *range filters* were selected for each experiment according to the results of a preliminary series of observations. Once selected, they were unchanged throughout each experiment. The spectral transmittances of typical range filters are shown in Figure 13.

Arrangement III. This was used in one experiment with small targets on the highest background brightness, for which additional light was provided by a spherical mirror placed behind the projection lamp in Arrangement II (Figure 14).

Arrangement IV. This was used in all experiments with low levels of adaptation and targets brighter than their backgrounds. This arrangement (Figure 15) was the same as II, with the addition of a ... of ground-glass plates one-half inch from the target

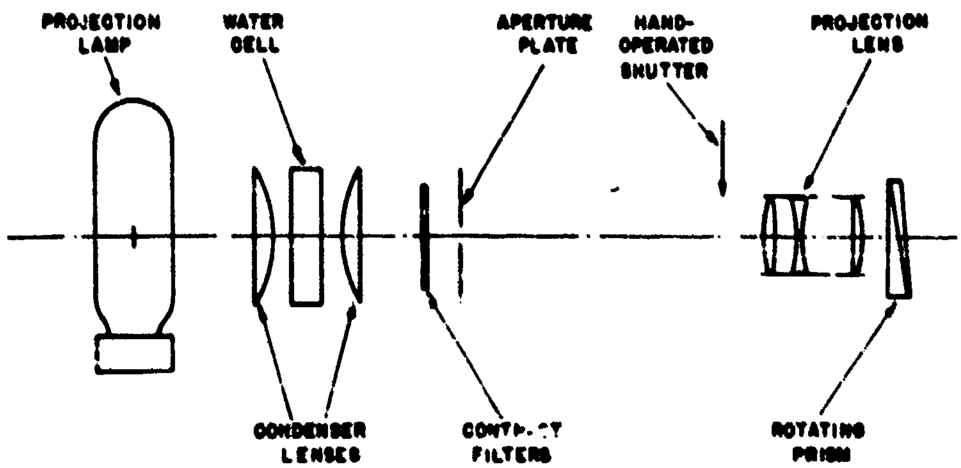


FIGURE 8. Projector Arrangement I, for targets lighter than background, with highest background brightness.

aperture on the side toward the condenser lens. This diffusing glass reduced nonselectively the flux projected by the system and will be called the *secondary source* of the projection system in the discussion which follows.

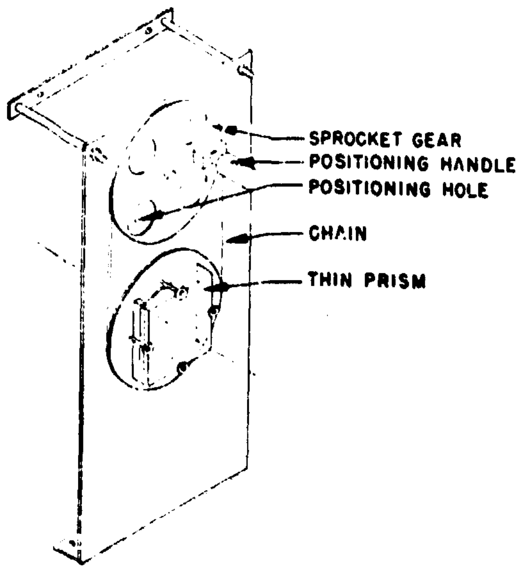


FIGURE 9. Mechanism for rotating prism.

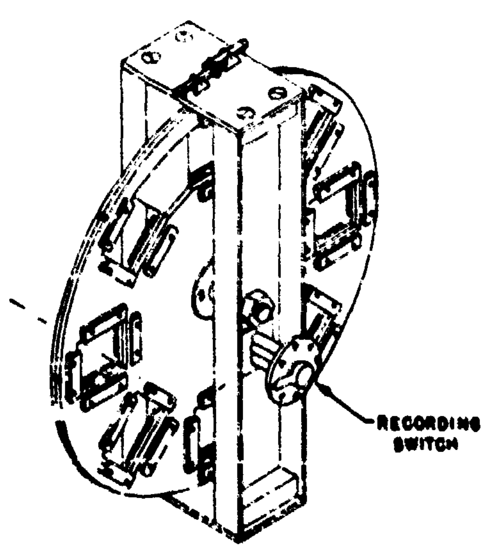


FIGURE 10. Control filter disk with indicating switch.

Arrangement V. For the production of targets darker than their backgrounds, a pair of projectors (Figures 16 and 17) was used. The second projector was necessary to equalize the light projected on the screen surrounding the target, at all contrasts. The target was projected by placing one of several glass plates in the focal plane of projector A, each plate bearing an opaque circular spot. The projected diameters of these spots subtended angles of 5.01, 9.55, 18.9, 55.5, and 114 minutes at the eyes of the observers. To procure projection at eight points on the screen, the plateholder was supported on pins set in two sprocket gears as shown in Figure 18; the position of the target was indicated by the same electric arrangement as was used for the bright targets. Projector B illuminated the entire screen uniformly.

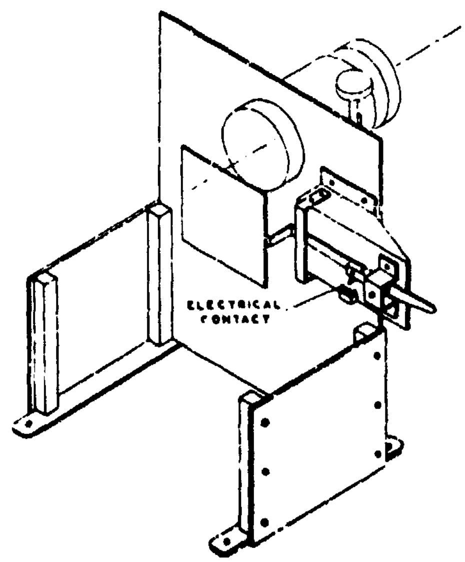


FIGURE 11. Shutter and buzzer signal switch.

A filter disk with six apertures, shown in Figure 19, was mounted with its axis of rotation midway between the two projectors. An empty aperture, four filters, and an opaque plate gave transmittances of 1.000, 0.760, 0.595, 0.382, 0.231, and 0.000. Complementary transmittances were placed diametrically, the opaque plate opposite the empty aperture, filter 0.760 opposite 0.231, 0.595 opposite 0.382. Consequently, five contrasts ranging from a maximum down to 23.1 per cent of the maximum were obtained by successively placing the five apertures (other than the opaque plate) next to the condenser lenses of the projector.

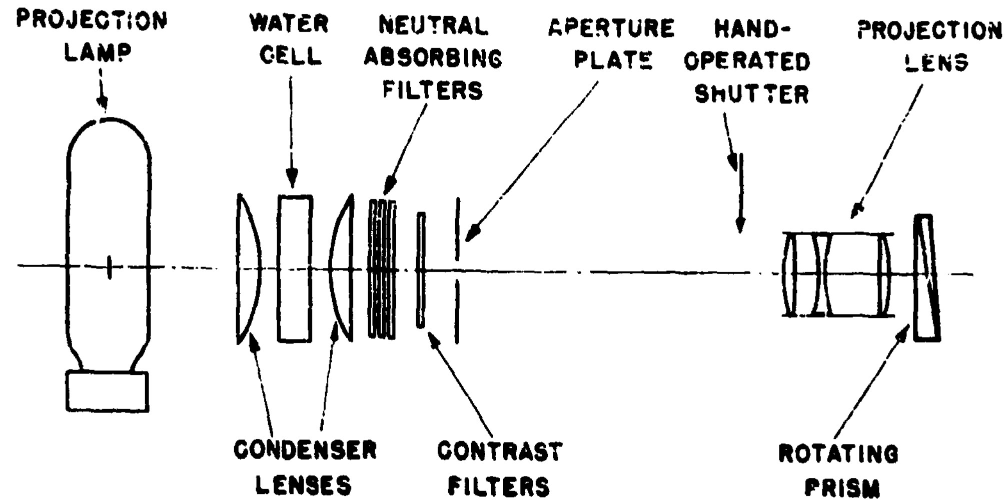


FIGURE 12. Projector Arrangement II, for intermediate background brightnesses.

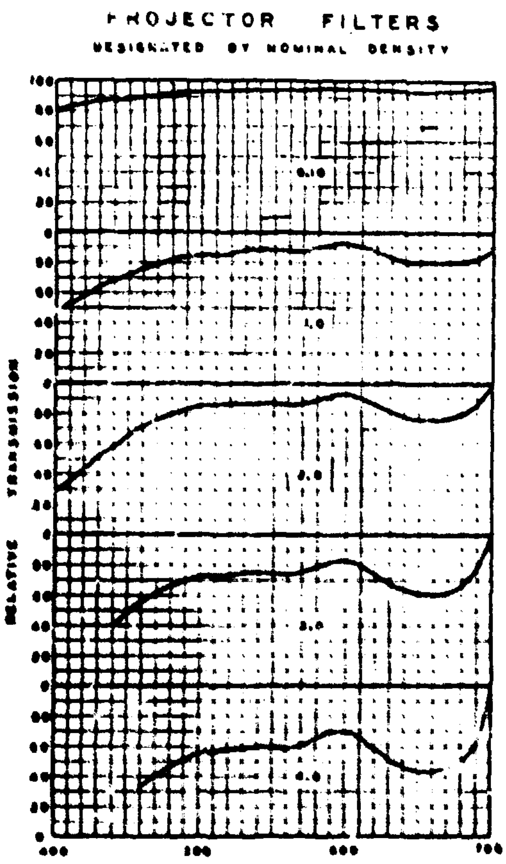


Figure 13. Spectral transmittance curves for typical range filters used in projectors. Numerals on curves indicate the nominal density of each filter.

In this fashion, the total brightness of the surrounding screen was maintained approximately the same for all contrasts, which were indicated electrically by a switch similar to that shown in Figure 10. For most experiments, part of the illumination of the screen was provided by lighting units located in the troffers behind the side-wall panels. The target and compensating projecters were extinguished while the location and contrast of the target were being changed.

Arrangement VI. A third "masking" projector (Figure 20) was employed to avoid considerable changes of screen brightness in the intervals between presentations. This projector illuminated the screen uniformly while the others were extinguished. By the use of auxiliary filters each projector was adjusted so that the brightness of the screen was nearly constant throughout each experiment.

Arrangement VII. A "fade-in-and-out" shutter (Figure 21) was used to avoid sudden flashes when the target projector was extinguished and the screen illuminated by the masking projector. An auxiliary projector (Figure 22) was employed for illuminating the first panels of the observation room in some experiments, to reduce the contrast between the dark side walls and the front wall when the illumination of the latter was provided mostly or entirely by the projectors.

Projector Arrangements IV and V were also used for projecting silhouettes of a German Mavis-class destroyer and a German Heinkel 111 bomber. These

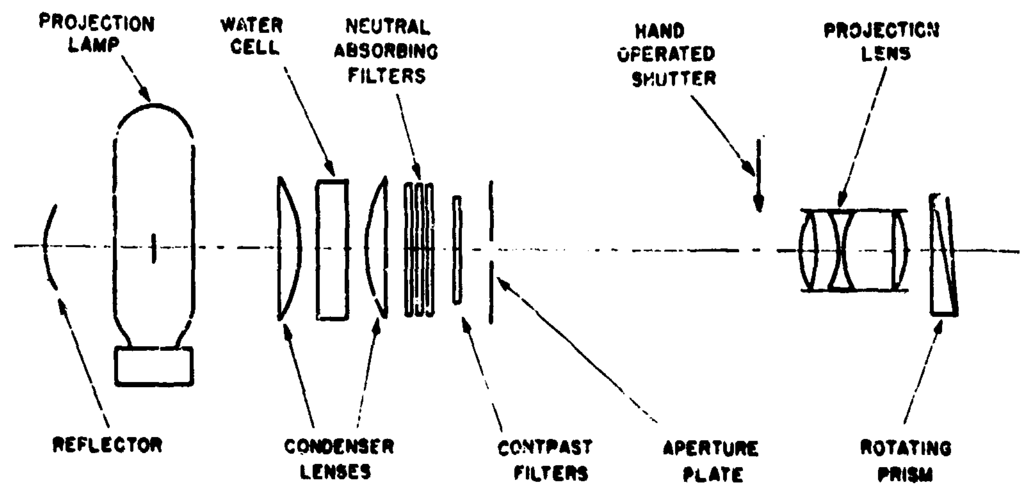


FIGURE 14. Projector Arrangement III, for small targets brighter than the brightest background.

tests verified the substantial equivalence of visibility of such silhouettes with circular targets of the same area and contrast against the background.

Arrangement VIII. To project a fixed central spot, the target was the image of a round hole in an aperture plate, the hole centered on the axis of the projector, as shown in Figure 23. The neutral absorbing filters were selected for each experiment so that, at maximum contrast, the target was barely perceptible to all observers. Four lower degrees of contrast were obtained from the filter disk shown in Figure 19. An opaque plate over one of the apertures of this disk was used to prevent the projection of the target in frequent instances, so that the proportion of guessing in responses could be determined.

Small-Target Presentation. An essentially different arrangement of equipment was used for experiments with very small targets subtending 0.6 minute. Projected targets of this size did not have suitably sharp definition, nor could their contrasts be measured with sufficient accuracy. For these experiments, eight small holes were drilled in the front wall of the observation room. Short lengths of glass rods, 3 millimeters in diameter, were pushed through these holes until their ends were flush with the inside surface of the wall. The ends of the glass rods

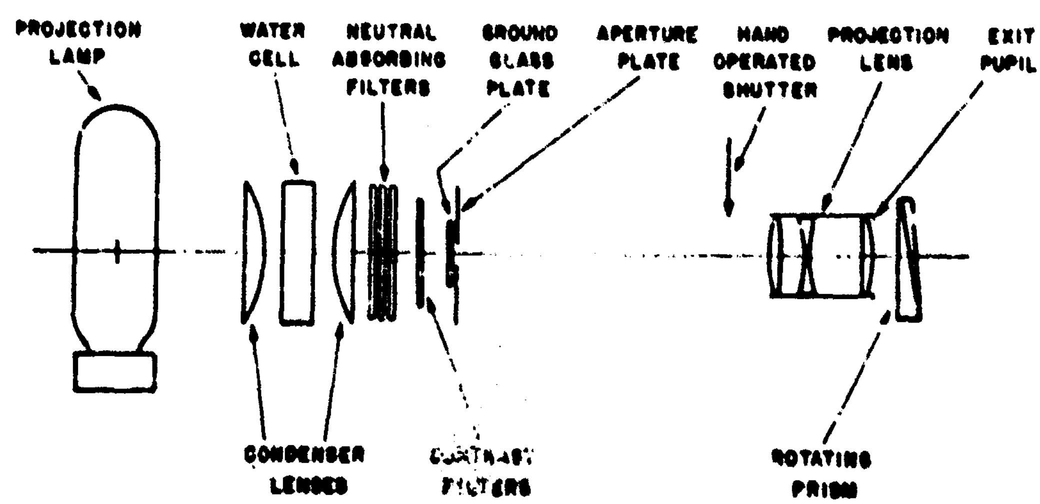


FIGURE 15. Projector Arrangement IV, for targets lighter than background, with backgrounds of low brightness.

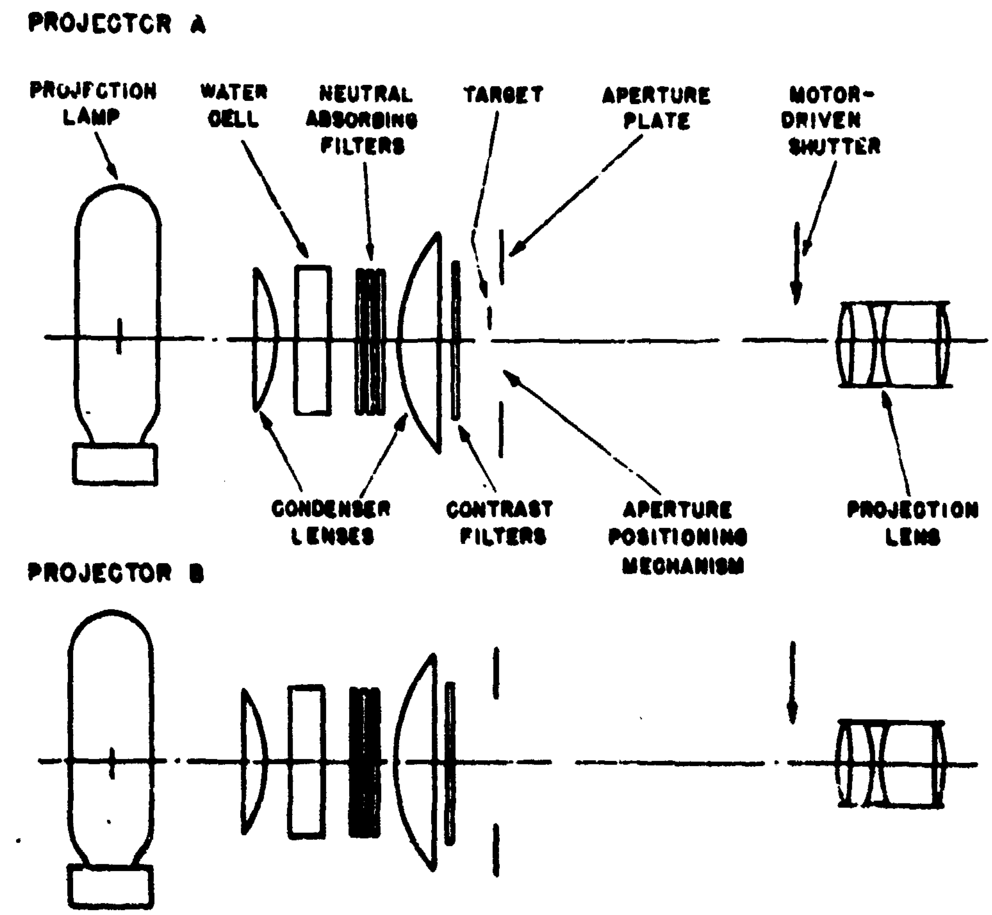


Figure 16. Projector Arrangement V, for targets darker than background.

were polished flat, and at a point approximately 0.01 inch from the outside end of each rod an opal glass plate was placed which was illuminated by two systems of lamps, shown in Figure 24. The oblique illumination of the opal plate by the pair of Mazda Number 34 lamps was adjusted so that, with the observation screen at the desired brightness, the glass rod was invisible even when viewed from a very short distance.

For bright targets, these matching lamps were on at all times. The projection lamp of each unit furnished the increment of illumination which determined the contrast of the target. Only one of these "increment lamps" was operated at a time, so that the brightness of only one of the glass rods differed from the brightness of the screen. Negative contrasts (dark targets) were produced by operating all of the "increment lamps," and by adjusting the total illumination of the opal glass so that the glass rods were invisible when all lamps in each unit were operated. The contrast of the dark target thus produced was controlled by the illumination of the opal glass due to the "increment lamp." The illumination provided by this lamp could be changed by varying its distance from the opal glass and by the use of absorbing filters between the lamp and the opal glass.

Orientation Spots

For the 8-position target experiments, a red spot 1 inch in diameter was always visible at the center of the observation screen, serving to orient the observers during experiments with dark backgrounds.

The spot, of adjustable intensity, shone through a red filter and a hole in the wall, as already mentioned. Red was considered to have the least influence of all colors on adaptation and was most easily distinguishable from the achromatic target at all adaptation levels. The brightness of the orientation spot was adjusted for each experiment so that it was only bright enough to be visible with certainty to all observers.

During the single-position experiments, the diameters of the projected targets were 0.7, 2.0, 3.88, 11.75, 27.88, and 83 inches. The location of the target was indicated by four orientation spots. These were placed in groups of four, above, below, and at either side of the target. Within each group, the spots were arranged in a straight line from the center of the projection screen at distances of 17, 23, 29, and 56 inches, respectively. This made possible the selection of any four equidistant spots, so that in any one experiment the spots were more than 14 and less than 17 inches from the edge of the target. Poorer results were obtained when greater and lesser separations were tried.

These orientation spots consisted of glass rods, 3 millimeters in diameter, inserted in holes in the screen and lighted from behind. Their brightnesses were adjusted for each experiment so that they were noticeable but not disturbing.

3.2.3 Recording Apparatus

Indicators. Each observer was provided with an indicator mounted in the right armrest of her seat. The indicator (Figure 25) consisted of a large handle which the observer turned until it pointed in the direction corresponding to the position in which the

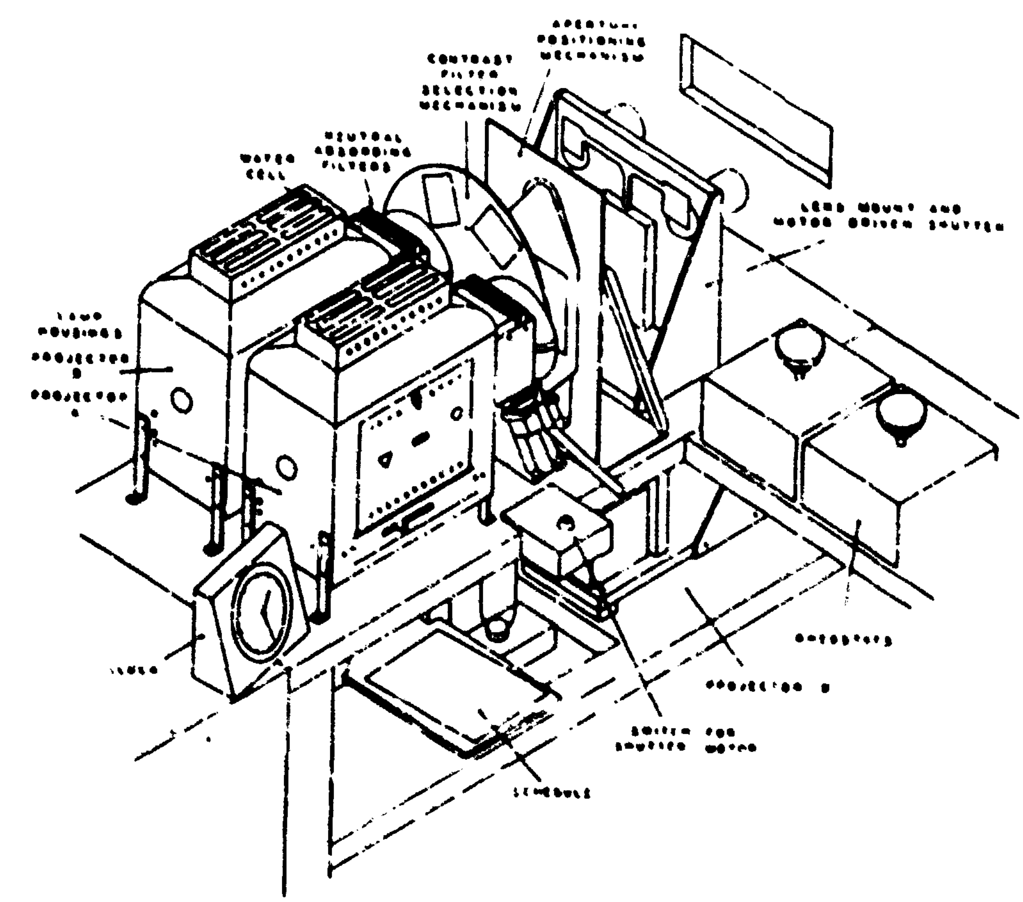


FIGURE 17. Projectors (Arrangements V, VI, and VII) assembled for projection of targets darker than background.

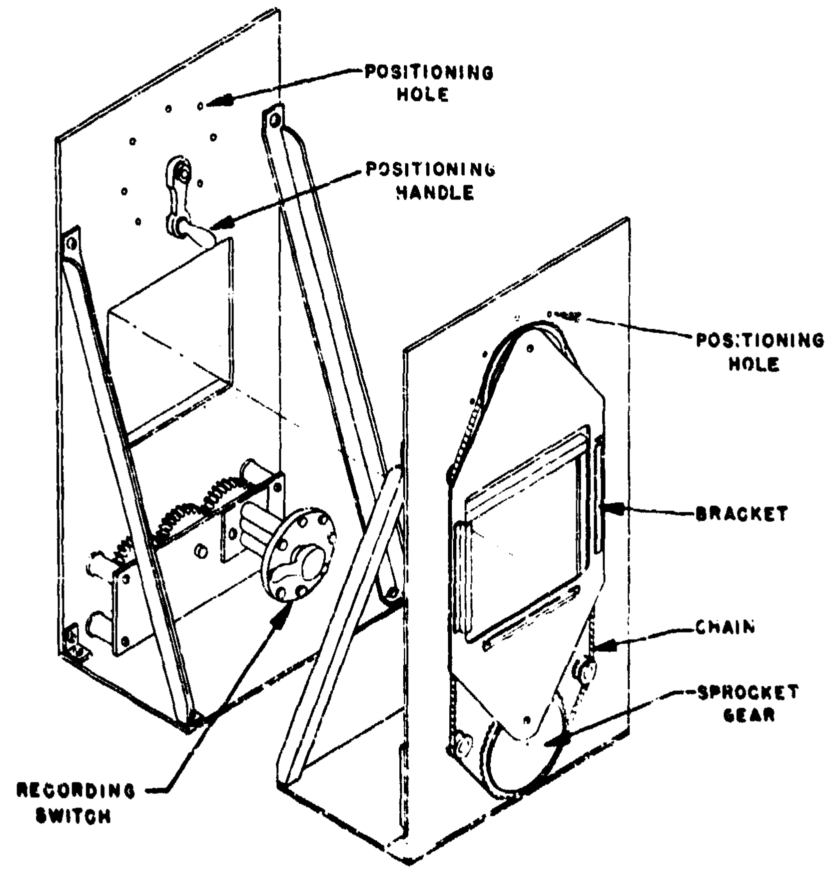


FIGURE 18. Mechanism for locating opaque spot in Projector A in eight eccentric positions. Two views, showing parallel displacement mechanism, positioning handle and indicating switch.

target was judged to be. Roundheaded tacks driven into the arm of the seat just outside the path of the handle guided the observer in tactually locating the switch point in the dark without visual distraction. The handle rotated the contact bar of a 16-point selector switch, which contained dead points separating the eight possible target positions, so there could be no ambiguity concerning the indication by the observer. The handle rotated freely in either direction, and the switch was silent to prevent an observer from getting clues from clicks of neighboring switches.

Recording Boxes. Indicator points were connected to miniature neon-discharge lamps located in three duplicate recording boxes in the control room. There were 96 lamps in each box in a rectangular array of 12 rows of 8 lamps each. Five of the lamps in the top row were connected to the five switches of the filter disk of the projector; these indicated the contrast of the target for each observation. The second row of lamps was connected to the switches of the target-position mechanism and indicated the actual position of the target. Each remaining row of lamps was connected to the indicator switch of one observer, showing that observer's judgment as to the location of the target.

The lamps were separated by sheet-metal partitions, forming a rectangular grid and covered with a sheet-metal plate with a 1/4-inch hole located over the center of each bulb. Above this metal plate, a piece of plate glass, flush with the top of the table containing the recording box, carried guides against which a sheet of thin paper could be accurately positioned. A separate sheet of paper was placed on the glass for each presentation of the target. The record assistant marked the paper above each glowing lamp (Figure 26). The duplicate recording boxes provided facilities for relief of the recording assistant and were spares in case any of the neon lamps failed.

The recording sheets were numbered consecutively. For analysis, they were sorted according to contrast, indicated by the position of the mark in the first row, and the number of correct judgments for each observer was counted for that contrast. Incorrect judgments were indicated by marks in columns other than the one marked in the second row. In experiments with fixed central targets, the handle was placed at one position (Figure 25) when the target was seen and in another when not.

3.2.4 Observers

SELECTION OF OBSERVERS

Very careful consideration was given to the selection of observers. Although it was necessary to have observers with vision as good as that of naval lookouts, the use of young men of service age was inadvisable. The number of suitable males available was limited, and there could be no assurance of their continued availability for the duration of the program. Since there is no evidence of a correlation of visual acuity with sex, young women were employed as observers. Also, although observations did not occupy all of the working hours and although assistance was needed in many technical tasks connected with the project, it was impracticable to

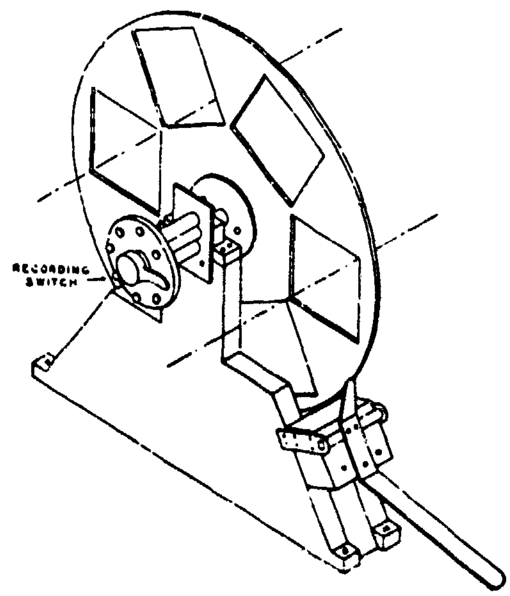


FIGURE 19. Mechanism for placing complementary filters in projectors of Arrangement V.

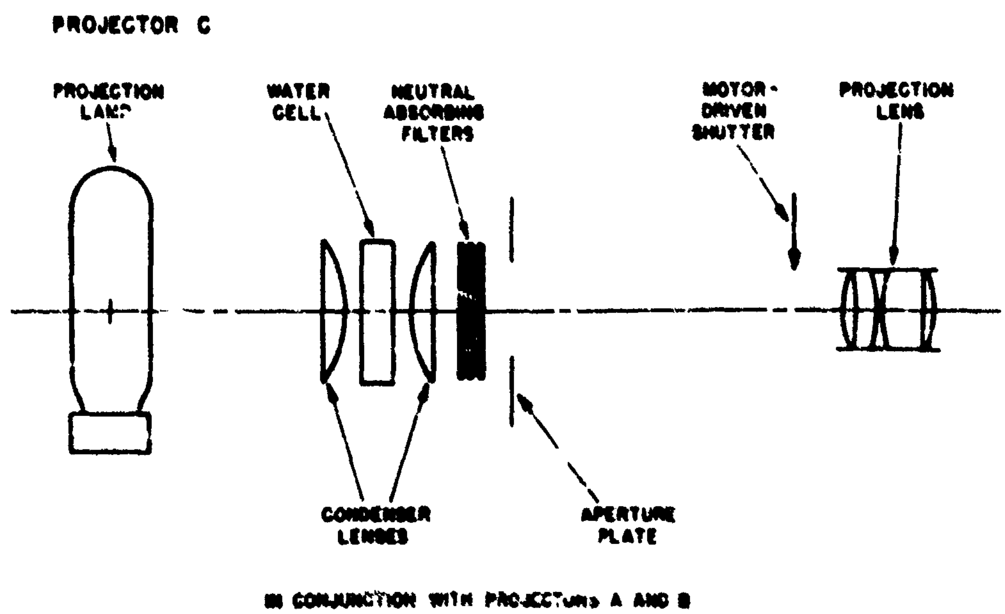


FIGURE 20. Projector Arrangement VI for projecting an equivalent background during the period for changing position and contrast in Arrangement V.

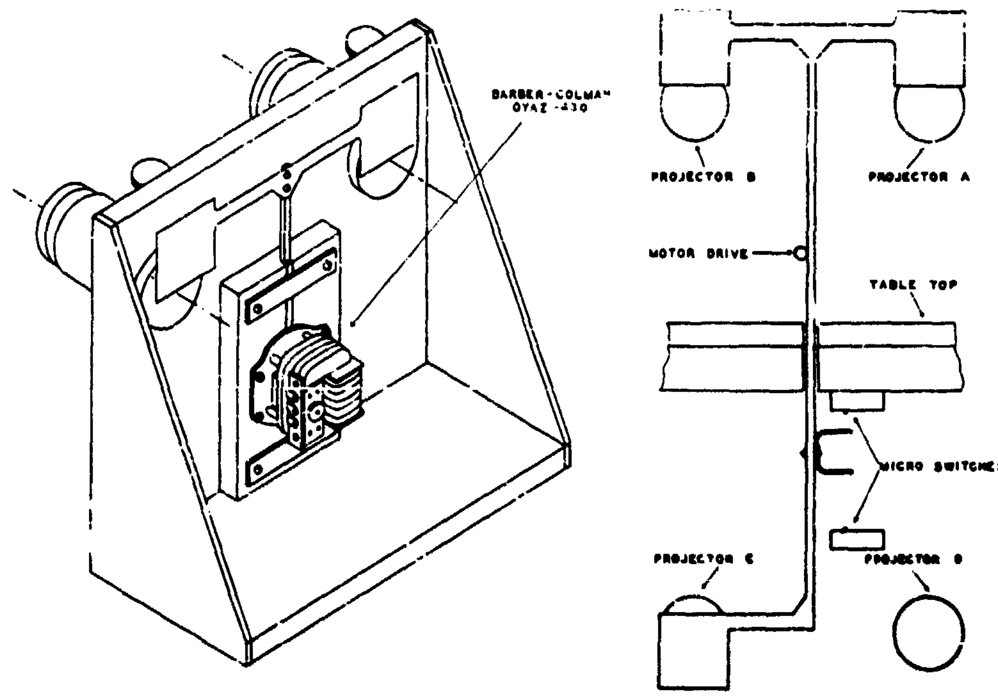


FIGURE 21. Motor-driven shutter for alternating Projector Arrangements V and VI.

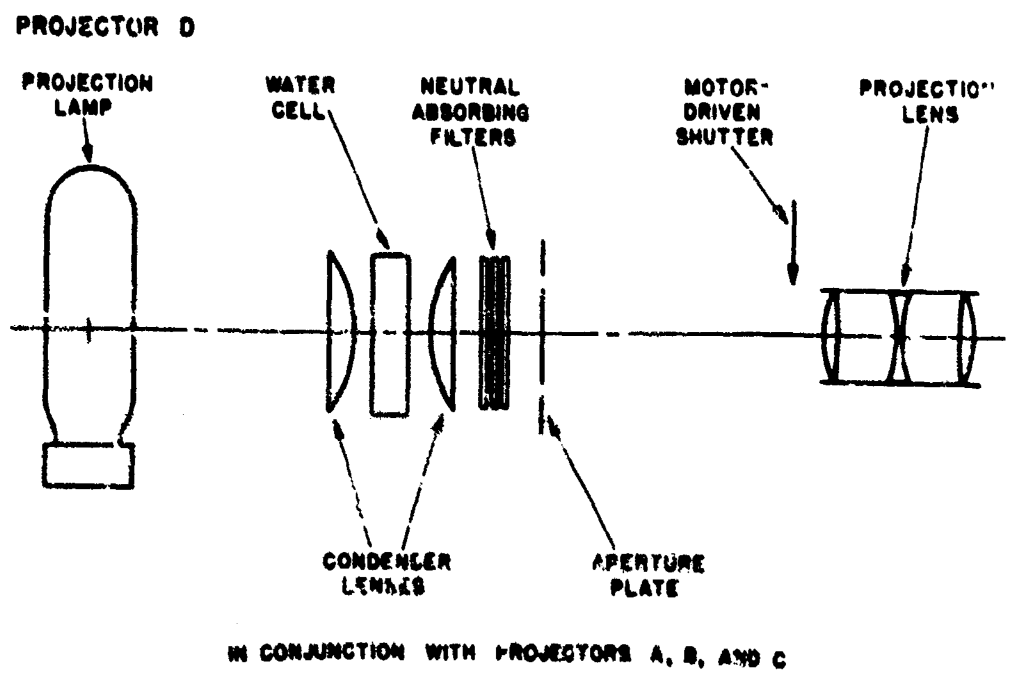


FIGURE 22. Projector Arrangement VII for illuminating floor panels of observation room.

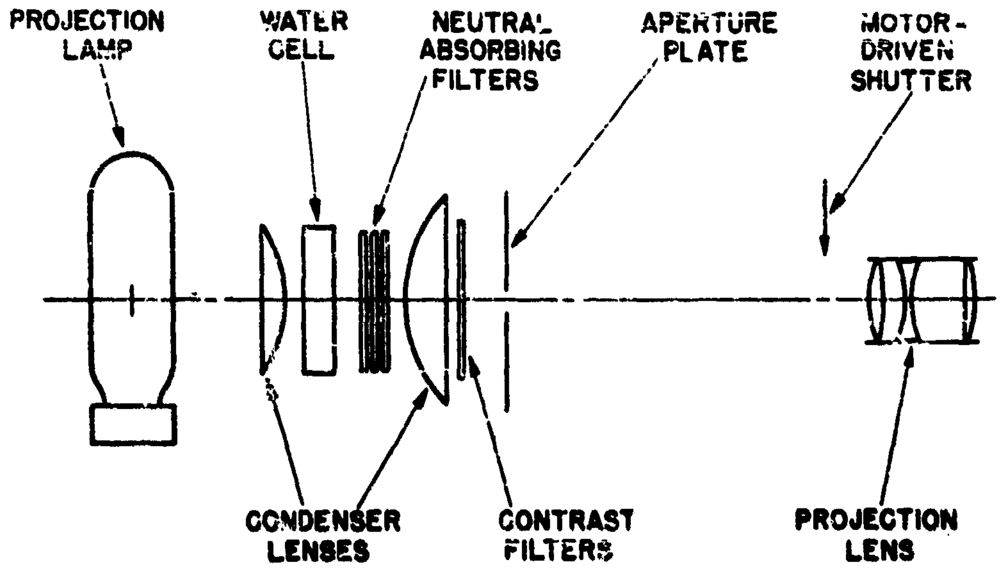


FIGURE 23. Projector Arrangement VIII, for the projection of a fixed central spot.

specify women with technical or scientific training. College graduates with promising personalities and good academic records were selected. Almost without exception these young ladies proved adaptable and useful also as computers and technical assistants. All observers were citizens of the United States.

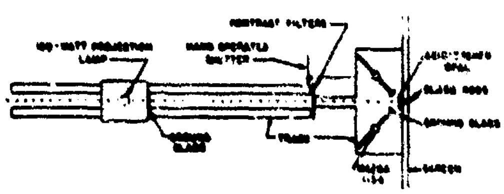


FIGURE 24. Illumination arrangement for glass-rod targets.

VISUAL REQUIREMENTS

Visual acuity better than 20-20, without glasses, was required of all observers. Although complete ophthalmic examination of the conventional type was given each observer, no significant correlation was found between the conventional data and the results of the visibility tests which are the principal subject of this chapter.

LIVING ARRANGEMENTS

Since it was necessary for the observers to reside at the Foundation, prior experience with dormitory

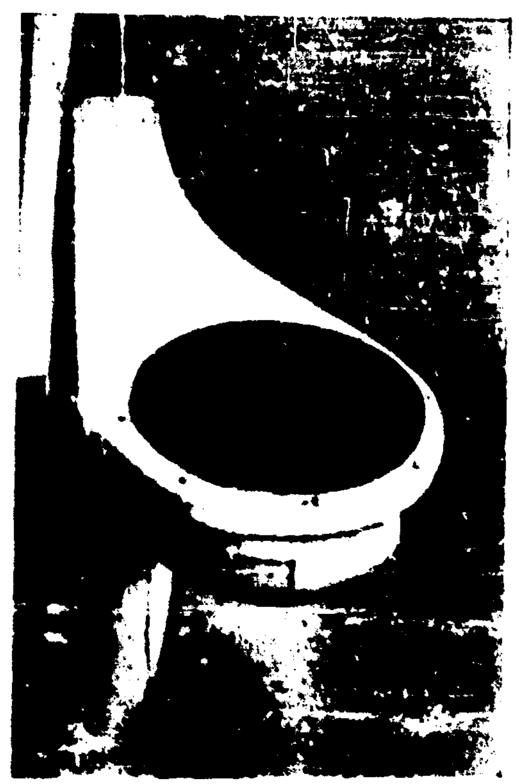


FIGURE 25. Indicator switch at observer's seat.

Figure 26. Recording table and method of use.

life was considered in the selection of the observers. Although not explicitly recognized when the program was planned, it became evident that the isolated, almost cloistered, life of the observers and the academic atmosphere maintained in the laboratory contributed in large measure to the success of the program. The observers promptly settled down to the routine with quite stable levels of visual attainment, and it was possible to verify results even after a lapse of many months.

Motivation

The task of observing targets of liminal size and contrast every day for months in the same surroundings and frequently in nearly total darkness was very monotonous and exacting. Without a high degree of motivation, the observers probably could not have continued the task with a stable level of attainment. The motivation was to a large extent self-created and consisted of a lively interest in the results of the daily experiments. The observers assisted and took much of the responsibility for the tabulation and analysis of the results. Consequently, each observer was continually aware of her attainment relative to the other observers and to the average of the group. Although no emphasis was placed on competition, each observer took some interest in maintaining, if not improving, the standard of her results relative to the results of the group. After the first week or so, each observer reached her ultimate level of attainment and subsequently maintained that level with remarkable consistency. The consistency of the individual observers fully justifies the procedure, which permitted them to have knowledge of their own results.

The observers were impressed by the interest shown by official visitors who indicated the need for the information expected to result from the research. Several naval officers talked to the group of observers and other assistants, and this testimony concerning the immediate practical importance of this research resulted in marked revival in the interest and morale of the group. The presence in the staff of several wives and fiancées of overseas servicemen served to sustain the patriotic motivation during the long and tedious months required for the investigation of the tremendous range of visual conditions of importance to the Services.

During a delay in the program (caused by installation of a new heating system in the building), five members of the group were transferred for a month to the laboratories of the Eastman Kodak Company in Rochester. These girls served as observers in the related investigation of the effect of color contrast on visibility (Section 3.3). They returned to the Tiffany Foundation with a new understanding of their part in war research and helped infuse new enthusiasm in the larger group.

Constancy of Personnel

The staff of observers suffered some losses and required some replacements during the 16 months in which the final data were obtained. These changes were not numerous, however, and the average of the results from the group did not exhibit serious changes as a result of the changes in personnel. The group of observers was so nearly homogeneous that the average of the results for the group was not changed appreciably by occasional absences of one or two observers. The reader can demonstrate this to his own satisfaction by omitting the data for one or two observers from any experiment.

Use of Nontechnical Personnel in Scientific Research

Although the equipment was designed and the procedures developed under the direction of a number of scientists and engineers employed by the Tiffany Foundation at various times, the conduct of the experiments was the direct responsibility of recent college graduates. Most of the experimental procedures and analyses were performed by the observers and additional women assistants, few of whom had any technical training. The use of this very low ratio of staff members with technical training to those without was an interesting and, on the whole, successful experiment.

Training of Observers

The observers were required to indicate a definite judgment about every presentation of the target, regardless of difficulty or consciousness of failure. Each observer was told, and learned also by experience, that such judgments were correct much more frequently than she suspected. Consequently, the observers gradually developed an attentive, but quite detached, attitude in which they searched diligently but were not discouraged when the target seemed to be hopelessly invisible. They based their indications on the slightest suspicion.

Obviously, some experience was required to convince each observer of the efficacy of this attitude, and considerable practice was needed to develop it fully. Consequently, the liminal contrast for a new observer, initially much greater than those of experienced observers, decreased rapidly during the first week or two of service. Therefore, results furnished by new observers were not used until they became stable. The necessity and adequacy of training, consisting of at least 18 practice sessions with a variety of target sizes and background brightness, were established by an investigation conducted at the beginning of the program. The training procedure consisted of letting the new observer work with the group, showing her how her scores compared with her impressions and with the scores of her companions, and calling her attention to improvement of her scores relative to those of the group as she learned and cultivated the detached, confident attitude. This attitude was encouraged solely because it gave the most reproducible results, and to this feature of the procedures may be attributed the high degree of self-consistency of the final results, as indicated by the closeness with which the experimental points fit smooth and regularly spaced curves.

Although the observations required great effort and concentration during the first practice sessions, experience yielded stable and efficient performance with a minimum of strain. Conversation and reception of radio programs were permitted during the observations and appeared to promote, rather than interfere with consistent observation. Experienced psychophysicists expect to get the most consistent results from practiced observers who make their judgments automatically without full conscious awareness of the process.

[illegible] Experimental Procedure

Study of previous investigations and experience during preliminary experiments indicated that much [illegible] uncertainty of data on visual acuity and visibility could be attributed to inaccurate photometry. Inadequate methods of photometry have been tolerated in many previous investigations because of a belief that the observations were not sufficiently reproducible or self-consistent to necessitate very accurate photometry. Adoption of the methods of observation described above and the use of a large homogeneous group of observers secured a degree of observational reproducibility and accuracy never before imagined possible in visibility experiments. Consequently, conventional methods of photometry, especially for the measurement of low contrast and low brightness, were found to result in errors which were serious in comparison with the precision of the visibility observations. Irregularities in the curves representing the results (of liminal contrast versus adaptation brightness), many times larger than the probable error of the observations, were finally proved to be consequences of inaccurate photometry. The methods of projection and of photometry were completely revised before the final set of experiments was undertaken, so that the accuracy of photometric specification is equal or superior to the accuracy of the observational means.

Photometric Procedures

All of the photometric procedures used in this research were based on the use of standard lamps and the inverse square law of illumination. A Macbeth illuminometer[36] was employed as a comparison device, but no reliance was placed on its calibration and its scale was used only to determine the ratio of nearly equal brightnesses. A photocell photometer was used only in the study of the uniformity of illumination of small portions of the screen. The Macbeth illuminometer was fitted with a telescopic attachment for studies of the uniformity of brightness over larger areas of the screen, walls, floor, and ceiling. In all cases, however, absolute values of brightness were determined by setting up an equivalent brightness by use of a standard lamp at a measured distance from a standard reflecting surface.

In some cases the standard lamp could not produce a sufficiently high or low brightness, and in these cases different filters had to be used in the illuminometer during photometric matching of the screen and the test plate. The transmittances of these filters were calibrated in the illuminometer by direct application of the inverse square law, using the standard lamp and test plate.

Standard Lamps. Three sets of three standard lamps (approximately 1,600, 300, and 20 candle power) were used during the program. Four of these lamps were calibrated at the beginning of the experiments by the Electrical Testing Laboratories, 2 East End Avenue, New York, and were used only for periodic recalibration of other lamps, which were used as working standards in the routine photometry. The working standards were calibrated by moving them to such distances from a test plate that they produced the same brightness as the reference standard lamps at known distances. Similarly, the brightness of the projection screen for various experimental arrangements was determined by producing an equal brightness with a working standard lamp at a measured distance from a test plate of known reflectance. Each set of standard lamps was enclosed in a boxlike carriage (Figures 3, 27, and 28) which could be moved on a track to any desired distance from the standard test plate. The interior of the carriage was painted black and was provided with several baffles which eliminated stray light. The lamps were operated from storage batteries and at the voltage specified by the Electrical Testing Laboratories.

The Test Plate. Since there was no direct way of determining the reflectance of the projection screen (front wall of the observation room), a standard test surface was illuminated by the standard lamps (Figure 28). The brightness of this surface was computed on the basis of its distance from the standard lamp and its reflectance. The test plate was a piece of opal glass, 8 inches in diameter, with an acid-etched surface. This was supplied by the Electrical Testing Laboratories, which certified the reflectance for normally incident illumination. The brightness of this surface was constant within 0.2 per cent for all angles of observation within 15 degrees of the normal, and the plate was never used at greater angles. The test plate was mounted in the center of a large black screen in order to minimize re-illumination by light reflected from the white walls of the observation room.

For measurements of brightness of 0.1 foot-lamberts and greater the Macbeth illuminometer was provided with a telescopic attachment (Figure 29). This consisted of a lens mounted in a tube so that an image of an area 4 inches in diameter, at a distance of 60 feet, was imaged sharply in the comparison field of the illuminometer. Some light from other areas of the projection screen also contributed to the brightness of the photometric field of the illuminometer because of lens flare and internal reflections in the telescopic tube. This stray light was reduced, but not completely eliminated, by installation of baffles in the telescope.

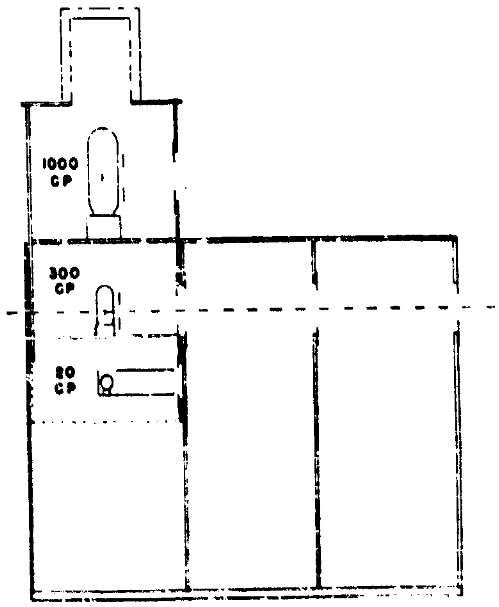


FIGURE 27. Housing for three standard lamps.

During calibrations, the telescope was used in exactly the same manner as for measurement of the brightness of the projection screen. Since the test plate used with the standard lamps was only 8 inches in diameter and was mounted in the center of a black screen, no appreciable stray light was present during calibration. Consequently, an error was caused by the stray light which was present during the determination of screen brightness. This error was evaluated by experiment and found to be 1.5 per cent of the brightness of the surrounding screen. There was no appreciable stray light during measurement of the projected light targets because the surrounding screen was dark during these measurements. Consequently, no correction was needed in the determination of the brightness increments of bright targets.

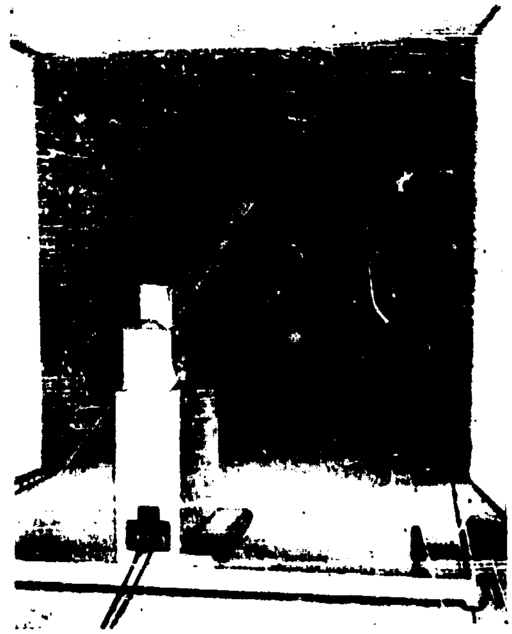


FIGURE 28. Photograph of arrangement of standard lamps, test plate, and black background for photometry of observation room.

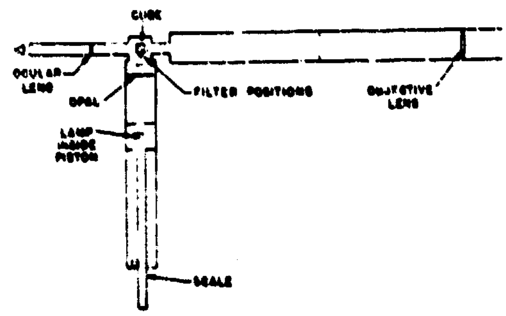


FIGURE 29. Telephotometer for photometry of projected targets and studies of uniformity of brightness of observation room.

Low-Level Photometry. Special methods were devised for the accurate determination of screen brightnesses below 0.1 foot-lambert. These consisted of measuring the brightness of the ground glass of the troffer lighting units as shown in Figure 30, and the brightness of the opal glass plate in Projector Arrangement IV (Figure 15), as seen through the lens. Factors were determined by which the brightness of each source could be multiplied in order to compute the brightness produced on the screen. These factors were determined at intermediate levels of screen brightness for which direct photometry was satisfactory, and the arrangements of the sources were kept strictly unchanged for lower levels for which the indirect photometry was applied.

A psychometric determination of a low-level brightness match provided an independent verification of the foregoing method. For this test, a gray disk (diameter 36 inches) was mounted in the center of the white front wall of the observation room to form a photometric field. When the room was illuminated with the troffer lamps, the gray disk ap-

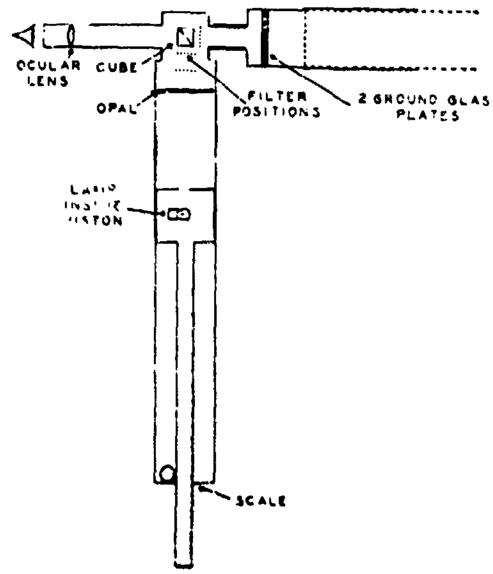


FIGURE 30. Macbeth illuminometer arranged for photometry of low-level troffer lighting-units.

peared darker than the surrounding white screen. Additional light was put on the disk alone by use of Projector Arrangement IV. Two slightly different degrees of illumination were provided by the projector. In one case, the disk was just brighter and in the other it was just darker than the surrounding white screen.

These increments of illumination were projected on the gray disk 64 times each in a random order. The observers were asked to indicate for each presentation whether they judged the disk to be brighter or darker than the surrounding screen. The proportions of judgments "brighter" were plotted against a quantity proportional to the brightness of the disk. This quantity was the brightness of the secondary source of the projection system, which was sufficiently brighter than the disk itself so that direct photometry was feasible for all adaptation levels at which the disk was used. The factor of proportionality between the brightness of the secondary source and the brightness of the disk was determined at an intermediate level for which direct photometry was adequate. The brightness of the screen during the psychometric comparisons with the disk was considered to be the brightness of the disk interpolated so as to correspond to 50 per cent judgment of "brighter." The brightness of the screen determined in this way confirmed the value computed by applying the experimental factors to the brightness of the lamp units in the troffers.

Contrast Determination. In order to determine contrasts with the greatest accuracy, only the maximum increment of brightness was measured directly. The four smaller contrasts used in each experiment were computed by multiplying the maximum contrast by the transmittances of the filters through which the incremental light was projected. The transmittances of these filters were measured in the projector system at levels of brightness most favorable for accurate photometry. Consequently, the products of these transmittances by the maximum contrast in any experiment were more accurate than direct measurements of the reduced contrasts.

Similarly, the brightness increments of the targets projected in experiments at low levels of adaptation were determined by direct photometry with *all* filters removed. The measured value was then multiplied by the transmittance of the filter combination used to determine the limen.

Measurement of Filters. The transmittance of each filter combination was determined by measurements at high-brightness levels. For these measurements and for the measurement of the contrast-control filters, ground-glass plates were inserted in the projector between the filters and the projection lens. Various numbers of ground-glass plates were used in different instances to provide a brightness level favorable for accurate photometry. The brightness of the foremost of these plates, as seen through the lens, was measured by use of the telephotometer and the standard-lamp method of evaluating each brightness setting. The brightness of the foremost ground-glass plate was measured with and without the filter in the projector. The ratio of the brightnesses was taken as the effective transmittance of the filter.

Uniformity of the Screen. Very slight variations of the observed contrast, depending on the target position and location of the observer, were caused by the slightly glossy surface of the screen. These variations were measured with the telephotometer. A method was evolved which permitted this second-order effect to be allowed for in interpreting the data.

The effect of various target sizes on the projected brightness was also studied, and there was found to be no significant difference. The distribution of brightness over the area of the larger targets was studied and found to be quite uniform. The effective area of the smallest targets was determined by measurement of the total flux in the image. The angles subtended by the smallest targets were computed from these results to compensate for imperfect image projection and for stray light at the edges of the image.

Photometry of Small Targets. A lens was used, as shown in Figure 31A, to image the ends of the glass rods in the field of the Macbeth illuminometer, for routine measurements of their brightnesses. The effects of minute imperfections on the ends of the glass rods, and of the holes through which they were mounted, were evaluated by use of the flux photometer shown in Figure 31B. The end of each glass rod and its immediate surroundings were imaged in the aperture of the cavity. The interior of the cavity was whitened, and the brightness of the portion of the interior viewed through the photometer was proportional to the flux entering the cavity. The average brightness of each glass rod was taken to be the brightness of a large uniform surface which produced the same reading in the flux photometer, multiplied by the ratio of the area of the opening of the photometer cavity to the area of the image of the end of the glass rod focused in the aperture of the cavity.

Computation of Contrast. In all cases, contrast was computed by dividing the difference of brightness between the target and background by the brightness of the background. Targets brighter than their backgrounds, therefore, had contrasts ranging from zero to infinity, while targets darker than their backgrounds had contrasts ranging from zero to one. Since the difference of brightness was produced by projection, this increment was measured directly. This avoided the gross errors which result from subtracting two nearly equal quantities, both of which

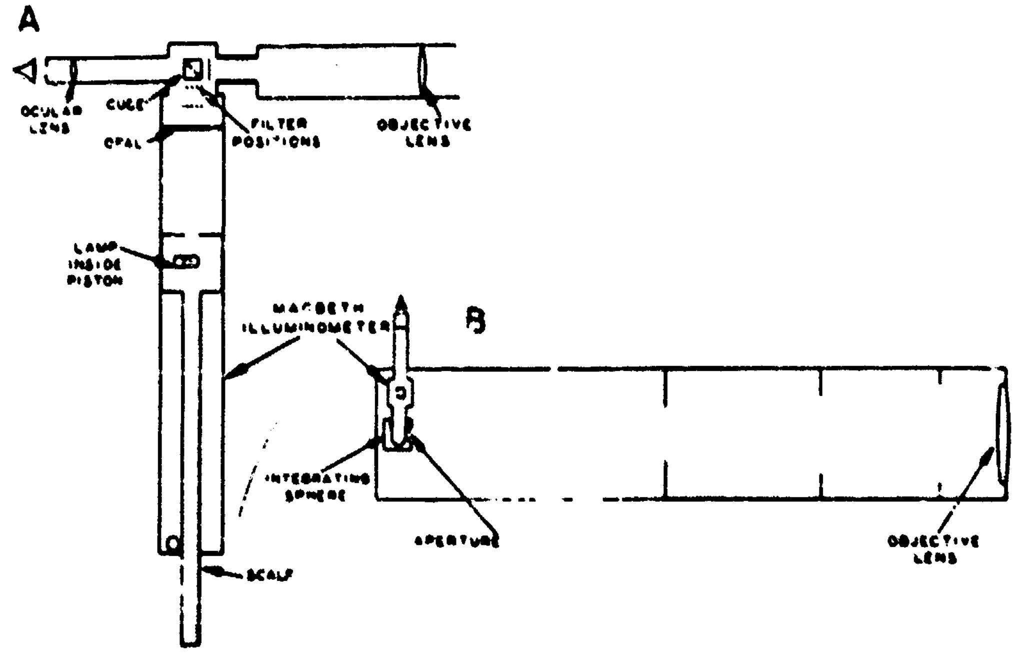


FIGURE 31. (A) Macbeth illuminometer arranged for routine photometry of glass-rod targets. (B) Macbeth illuminometer arranged for evaluating average brightness of glass-rod targets.

would be subject to errors comparable in magnitude to their difference.

3.2.8 Psychometric Procedure

CRITERION OF VISIBILITY

The basic experimental task was to determine the contrast which produced a standard degree of visibility for each size of target and brightness of background. The standard degree of visibility, or criterion for identification of the contrast just visible, was that for which the location or presence of the target was reported correctly just 50 per cent of the time, due allowance being made for accidentally correct or chance reports. For example, when there were eight possible positions of the target, coincidence of random guesses would be expected to yield one correct report out of every eight responses. The criterion of visibility adopted in this investigation required half of the remaining 87½ per cent of reports to be correct. These, in addition to the 12½ per cent attributed to chance, correspond to 56¼ per cent correct responses, which was the score employed for the determination of liminal contrasts throughout this investigation.

This degree of success corresponds to a very low degree of self-assurance but gives the most accurate and statistically reliable determination of the dependence of visibility on contrast and adaptation brightness. Liminal contrasts, or target sizes, determined by use of this criterion in the unstrained conditions of the laboratory, may or may not be less than the contrasts and sizes of targets sighted under the conditions of discomfort and violent disturbance but extremely great motivation of naval lookouts. It can be safely assumed, however, that any change of contrast or background brightness will produce a change of range of detection accurately proportional to the change of range predicted on the basis of the laboratory data. The use of the criterion of visibility and conditions of observation which yield the most accurately consistent laboratory data is, therefore, justified and necessary.

TARGET PRESENTATION

Each experiment used a single size of target and a single brightness of background. The target was exhibited with five different contrasts, the ratios of which are specified in Section 3.2.3. It suffices here to mention that these fixed ratios, with the mini[illegible] approximately [illegible] of the maximum, were found suitable for the determination of adequate psychometric curves for all target sizes and at all levels of adaptation. For each size of target and background brightness, a short preliminary series of observations was made to confirm or correct the choice of the maximum contrast. The requirement on this adjustment was that the most sensitive observers should correctly report the location of the target for less than 56 per cent of the presentations at lowest contrast, and that the least sensitive observers should correctly report the location of the target for more than 56 per cent of the presentations at highest contrast. For groups of nearly equally sensitive observers, the target was reported correctly for 92 to 97 per cent of the presentations at maximum contrast and for 13 to 22 per cent at lowest contrast.

Order of Presentation. The five contrasts were presented in random order. The order for each experiment was governed by a schedule prepared in advance by recording the order in which numbered cards occurred in a shuffled deck. This deck consisted of 16 sets of 5 cards, each numbered from 1 to 5. Preparation of the schedule from this deck assured that each contrast would be presented 16 times during each group of 80 presentations. This deck was reshuffled after the schedule for each 80 observations had been copied.

For the 8-position experiments, the position of the target was also governed by a prearranged schedule determined by means of five shuffled decks of 64 cards each. One of the five decks was assigned to each contrast, and within each deck the cards were marked "North," "Northeast," "East," et cetera. Whenever a given contrast was called for by the deck of cards described in the preceding paragraph, the top card was taken from one of the five position-indicating decks. Thus targets having each of the five contrasts were presented in each of the eight positions eight times. This series of presentations constituted one experiment. In order to provide rest periods, each series of 320 observations was divided into four groups of 80 observations each.

Rest Periods. Rest periods were scheduled throughout each experiment. In the case of the 8-position tests, the regular schedule included rests of 5 minutes' duration, with the observers remaining in the observation room, between the first and sec-

[illegible] between the third and fourth quarter of the experiment. A rest of at least 10 minutes outside the room was allowed at the end of the second quarter, followed by 10 minutes' adaptation in the room before the third group of observations was commenced. The observers were adapted for 5 minutes before beginning each group of observations at 10 and 100 foot-lamberts. For experiments in which the brightness of the background was 10^{-2} foot-lambert or lower, the observers wore standard Navy dark-adaptation red goggles during their rest period outside the observation room. The schedule was flexible within limits which assured adequate rest and adaptation. The normal duration of a group of 80 observations (16 minutes) was sometimes lengthened by delays for adjustment of voltage or other contingencies. Since these delays gave the observers some unscheduled rest, their scheduled rest periods in such cases might be reduced slightly. The total duration of the first or third quarters, plus the ensuing rest in the observation room, was never less than 21 minutes, however, and the rest period after these quarters was never less than 2 minutes. Occasionally the available time was used to better advantage by running the first half of an experiment before a meal and the second half afterwards. Sometimes, by common consent, the observers remained in the observation room between halves, so as to save the time required for re-adaptation. The time at which each portion of the experiment was begun and finished was recorded.

Sequence of Operations. Each presentation of the target involved a series of operations. During the interval between presentations, the filter wheel was rotated so as to place in the projector the filter specified by the schedule. The operator watched the second hand of an electric clock and at the appropriate instant opened the shutter. This operation caused a buzzer to sound as long as the shutter remained open, informing the observers that the target was on the screen. At the end of the exposure, the operator closed the shutter and adjusted the filter wheel and target position for the next presentation.

Recording of Data. During each presentation of the target the observers indicated their judgments of the location of the target by turning their switches to the corresponding positions. The recording assistant placed a tissue sheet, numbered according to the serial number of the presentation, on the recording box and marked around each lighted lamp with a pencil, thus recording the actual contrast and position of the target and the judgments of the observers.

Analysis of the Data

Eight-Position Experiments. When an experiment was complete, the 320 record sheets were sorted according to contrast. The number of correct judgments was counted for each observer and for each contrast. The proportion of correct responses was computed by dividing the number of correct responses by the total number of presentations. These proportions were computed for each observer and for the group as a whole. From the proportions of correct judgments at the 5 degrees of contrast, it was possible to plot psychometric functions for the several observers and for the group of observers as a whole. The limen for any observer was the value of contrast corresponding to 36 correct responses in a series of 64 presentations, a proportion of 0.5625. The limens were computed by the Urban constant process,[28] rather than by graphical or linear interpolation, in order to employ all of the observational data rather than only those for the two contrasts yielding most nearly liminal responses.

Single-Position Experiments. In the single-position experiments, the liminal contrast was determined by interpolation between the scores for the contrasts actually used. It was that contrast for which each observer reported the presence of the target correctly in 50 per cent of the instances, due allowance being made for guessing. Guessing that a target was present, even though not visible, was discouraged by the knowledge that in frequent instances no target was projected. The residual effects of guesswork were at least partially compensated by dividing the incorrect scores for all contrasts by the fraction of target absences which were correctly reported as such. The proportion of correct responses was consequently reduced by this compensation. The consistency of the results was improved because the amount of guessing by each observer fluctuated much more violently from day to day than the adjusted scores for the several contrasts.

The single-position experiments usually received about 2[illegible] observations. Greater numbers of observations would be expected to improve the precision of the results, but in most cases they could not be

[illegible]

Each of the single position experiments included equal numbers of presentations for two quite different observation times. These two sets of presentations were intermingled in random order, so that the effects of fatigue would be equalized. The results for the two sets were compared, and their approximate equality was taken as proof that both observation times were sufficient. The results for the two sets were averaged to obtain the final values.

Record of Research

The determination of liminal contrast for each target size and field brightness was considered a separate experiment to which at least one full observation period was devoted. Separate reports of procedure, photometric data, and observational results were prepared for each experiment, and the complete record is a document of more than 2,700 pages, describing over 200 separate experiments. A complete copy of the record is included in the microfilm supplement to this volume.[7] The report of each experiment contains a tabular summary which includes the proportion of the responses correct for each observer and each contrast; the liminal contrasts for each observer computed by the Urban method; the liminal contrasts for the group, computed as the arithmetic mean of the liminal contrasts for the individual observers; and the standard deviation of the liminal contrast for the group. Table 1 is an example of such a summary.

3.3 Summary of Results

Eight-Position Experiments

The liminal contrasts of round targets brighter than their backgrounds, when the targets could appear in any one of eight positions, are shown in Figure 32. The observation time was 6 seconds in

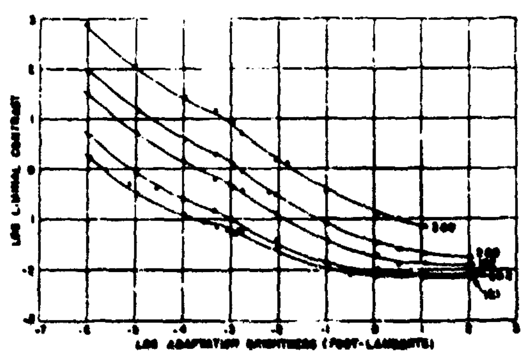


Figure 32. Liminal contrasts for round targets brighter than their backgrounds.

Eight-positions. 6 seconds observation time. Angular subtense of diameter is shown (in minutes) at right of each curve.

all cases represented on this diagram. Each curve represents the data for a single target size, the angular subtense of which is indicated to the right of the curve, in minutes of visual angle. The brightness of the background, expressed in foot-lamberts, is represented on a logarithmic scale (base 10) along

Table 1. Psychometric data for a typical 8-position experiment.

Target circular; brighter than background; subtense 121 minutes; background brightness 118 foot-lamberts. Arithmetic mean = [illegible]; standard deviation = [illegible]

[illegible] No.	Observer	0.00291	0.00461	Contrasts 0.00670	0.00945	0.0124	Contrast limen
1	CCC	0.167	0.251	0.444	0.878	0.981	[illegible]
2	MJH	0.167	0.226	0.447	0.781	0.984	[illegible]
3	KSK	0.128	0.241	0.480	0.937	1.00	[illegible]
4	MC	0.167	0.261	0.473	0.841	0.962	0.00796
6	ITR	0.264	0.278	0.573	0.894	1.00	[illegible]
7	MRR	0.167	0.234	0.340	0.780	[illegible]	[illegible]
8	VRM	0.167	0.433	[illegible]	0.797	[illegible]	[illegible]
9	ELC	0.167	0.141	0.270	0.872	[illegible]	[illegible]
10	SR	0.121	0.203	0.226	0.781	[illegible]	[illegible]

the horizontal axis. The contrast required for 50 per cent (above chance) frequency of correct reports by the group of observers is shown on a vertical logarithmic scale.

A greater number of experiments is indicated in the neighborhood of 0.001 foot-lambert than at any other adaptation level. These were obtained in order to verify the existence of the discontinuity of slope indicated by the curves. This discontinuity is attributed to the change from rod-vision, which is most effective at low levels of adaptation, to cone-vision, which is effective at high levels.

Repeated Experiments. Seven open circles shown in Figure 32 indicate the results of experiments which were repeated during the series of dark-target experiments. In these check experiments, the bright targets were produced by Projector Arrangement V, with which at least part of the background brightness is produced by the projectors. These check experiments served, therefore, to prove the equivalence of the observing conditions used for bright and dark targets. They also indicate the consistency of the observers over a span of many months. There is one check point for each of the four upper curves, and three points on the lowest curve. The point on the curve for 18.2 minutes is at exactly 0.001 foot-lambert and is so nearly coincident with one of the original points that it may not be visible in the reproduction of Figure 32.

Dark Targets. The liminal contrasts of round targets darker than their backgrounds are indicated by the experiment points shown in Figure 33. These experiments were exactly comparable with those for the bright targets. The curves shown in Figure 33 were interpolated from Figure 32 for bright targets having the same sizes as the targets used in the dark-target experiments. The closeness with which the curves fit the experimental points is an indication of the equivalence of light and dark contrasts in visibility phenomena.

Single-Position Experiments

Figure 34 shows the results for light targets which were presented in only one location on the screen and which were observed for as long as was required under each set of conditions in order to obtain the highest possible frequency of correct responses. As mentioned in preceding sections, the precision of the results was lower than in the eight-position experiments. In order to avoid confusion, the experimental points are shown for only the largest and smallest targets. Data for all of the targets for all adaptation levels are given in Table 2.

Table 2. Minimal contrasts for visibility; circular targets brighter than their background.

Visual angle (min of arc)	Adaptation brightness (foot-lamberts)	Liminal contrast (arith. mean)
360.	71.90	0.003024
121.	70.81	0.002533
18.2	71.36	0.003448
9.68	74.78	0.008658
0.595	71.42	0.4755
360.	10.58	0.003511
121.	11.08	0.003089
3.60	11.06	0.02759
0.595	10.82	0.8804
360.	0.8808	0.002490
121.	0.9968	0.003620
55.2	0.8850	0.003664
18.2	[illegible]	0.006081
3.60	[illegible]	0.04745
0.595	1.0[illegible]	1.835
360.	[illegible]	0.006051
121	[illegible]	0.006152
55.2	0.1014	0.008707
18.2	0.1038	0.01070
9.68	0.09492	0.02129
0.595	0.09669	1.658
360.	0.01308	0.008265
121.	0.01323	0.01590
55.2	0.01384	0.03050
18.2	0.01348	0.04764
9.68	0.01260	0.08422
3.60	0.01298	0.4135
0.595	0.01278	13.67
360	0.001128	0.02770
121.	0.001152	0.04355
55.2	0.001192	0.07080
18.2	0.001194	0.2212
9.68	0.001114	[illegible]
3.60	0.001084	3.918
0.595	0.001146	127.2
360	0.0001058	[illegible]
121	0.0001073	[illegible]
9.68	0.0001170	[illegible]
0.595	0.0001104	570.8
360.	[illegible]	0.1423
121	0.00001083	[illegible]
18.2	0.00001043	[illegible]
0.595	0.00001002	[illegible]

Although the magnitudes of the liminal contrasts were determined more accurately by the single-position, long-observation technique, the shapes of the curves were determined with greater precision with the eight-position method. Consequently, curves having shapes as similar as possible to those in Figure 32 have been fitted to the single-position results and are shown in Figure 34. Also, it was [illegible] experiments with targets darker than their backgrounds, because the precision of the results would have been insufficient to detect any differences

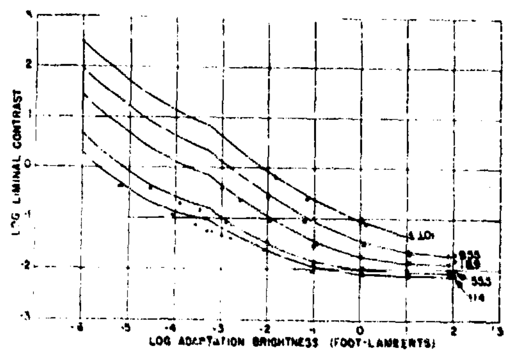


FIGURE 33. Liminal contrasts for round targets darker than their backgrounds are shown by indicated points.

Curves show liminal contrasts for bright targets of same size, interpolated from Figure 32.

[illegible] posi-tion method.

The dependence on contrast of the visual angle subtended by a barely visible circular object is shown in Figure 35. The several curves are for different levels of adaptation, which are specified in foot-lamberts at the lower ends of the curves. These curves were obtained from Figure 34 by graphical interpolation and therefore indicate the minimum target subtense visible when the location of the target is known exactly and when the time of search is essentially unlimited. *The curves in Figure 35 are given in tabular form in Appendix A; values from this table should be used for all calculations.*

3.2.10 The Effect of Target Shape

The effect of the shape of the target on the liminal contrast was studied with the single-position method. By these experiments, the liminal contrasts

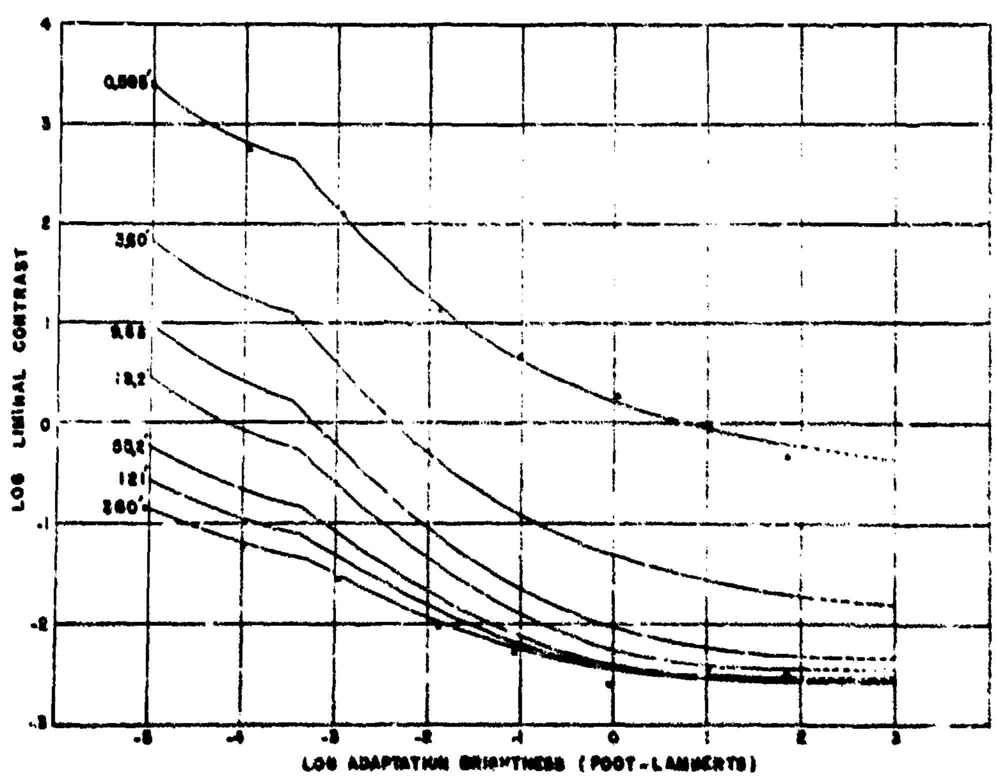


FIGURE 34. Liminal contrasts for round targets brighter than their backgrounds.

Single position, with sufficient time to attain maximum frequency of correct reports. Experimental points are shown for largest and smallest targets. Data for all targets are presented in Table 2.

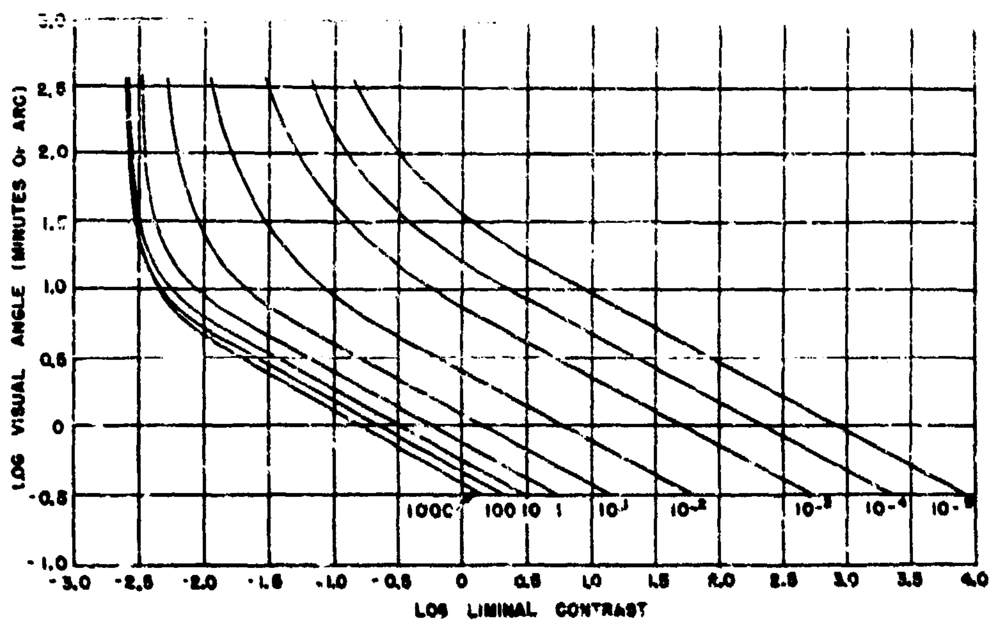


FIGURE 35. Angular subtense of just visible circles as function of contrast, for various background brightnesses. (See Appendix A for a tabular summary of this figure.)

of squares and circles having the same area were found to be equal. Rectangles of various shapes and sizes were then studied. The ratio of the liminal contrast of a rectangle to the liminal contrast of a square or circle having the same area (for the same background brightness) is called the *form factor*. The form factor is always unity or greater. Experimentally determined form factors are shown by points in Figure 36 for a background brightness of 10 foot-lamberts and in Figure 37 for an eye adapted to 10^{-3} foot-lambert.

FORM FACTOR THEORY

The curves in Figures 36 and 37 represent the variation of form factor with angular area predicted on theoretical grounds that may be summarized[29] thus.

The liminal contrast of a rectangle is the geometric mean of the liminal contrasts of squares having sides equal in visual target subtense to the sides of the rectangle.

It is to be noted that the side of a square of equal area subtends 0.886 times the angle subtended by the diameter of a circle. Since the liminal contrasts of a square and circle of equal area are equal, the liminal contrast of a square is indicated in Figure 35 by the abscissa of the curve for the appropriate adaptation level for the ordinate obtained by adding 0.052 to the logarithm of the angle subtended by the side of the square. Consequently, the predicted liminal contrast of a rectangle is indicated on the logarithmic abscissa scale of Figure 35 by the midpoint between the abscissas corresponding to the angular subtenses of the sides, that is, at ordinates equal to 0.052 plus the logarithms of the visual angle (minutes) subtended by the sides.

5.3 INFLUENCE OF COLOR CONTRAST ON VISIBILITY

In the hope of discovering a direct correlation between the effects on visibility produced by color contrast and brightness contrast, the Eastman Kodak Company was asked to study the visual acuity of a homogeneous group of observers to whom both colored targets and gray targets were presented. In these experiments, the acuity obtained with any color contrast was specified by the brightness contrast which produced the same acuity. The utility of this mode of specification arises from the fact that it is nearly independent of differences among normal observers, shape of target, and adaptation level (at least between 10^{-2} and 100 foot-lamberts).

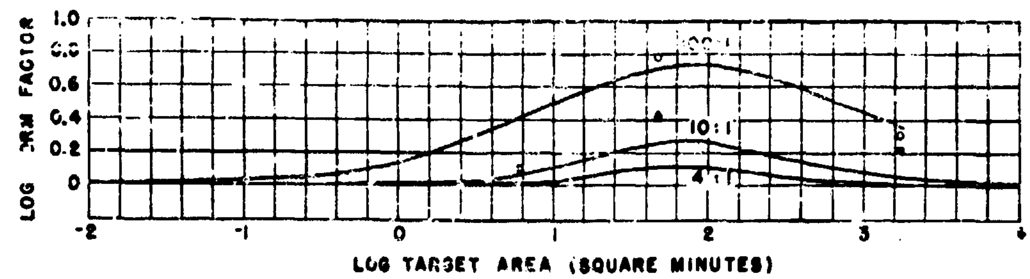


FIGURE 36. Form factors for rectangles.

Circles, 100:1, triangles, 10:1, squares, 4:1. Brightness of background: 10 foot-lamberts. Curves represent theoretical variation of form factor with size.

By specifying the influence of chromatic contrast on acuity and visibility in terms of the equivalent achromatic contrast, the results reported earlier in this chapter can be extended to include the general case of combined chromatic and brightness contrast, presumably for all levels of adaptation.[b]

3.3.1 Earlier Investigations

Earlier studies of the influence of color on the perception of form have been fragmentary and almost entirely qualitative. The essential phenomena have all been described previously but without quantitative specification. Langley (1889)[29] proposed a method of heterochromatic photometry based on the fact (or assumption) that visual acuity is a function of brightness only, regardless of the color of the light. The validity of this method was tested and confirmed by Bender (1919),[30] who determined spectral luminosity curves for several observers and compared these with the curves obtained for the same observers by flicker photometry. In these experiments a Snellen-type vision test chart was illuminated with monochromatic light, the intensity of which was varied until a standard value of acuity was obtained. Brightness contrast alone, albeit with highly chromatic light, was involved in these experiments.

Acuity with patterns involving chromatic differences was indirectly studied by Lehmann (1904),[31] Benussi and Liel (1904),[32] Liebmann (1927),[33] and Koffka and Harrower (1931).[34] None of these studies was quantitative, but the evidence was conclusive that chromaticity difference alone produces very little visibility in the absence of brightness differences. Liebmann reported that forms are difficult to perceive when the brightnesses of the figure and ground are equated, although color differences themselves are seen most clearly under these circumstances. Koffka and Harrower studied this apparent anomaly, confirmed the difficulty of perceiving forms consisting of colors different from but equated in brightness to their backgrounds, and reported a difference in this respect between the colors akin to blue and colors akin to red. Thus the Liebmann

[b] This investigation was not intended to explore the effects of visual angle, adaptation, and contrast on the recognition of colors as such.

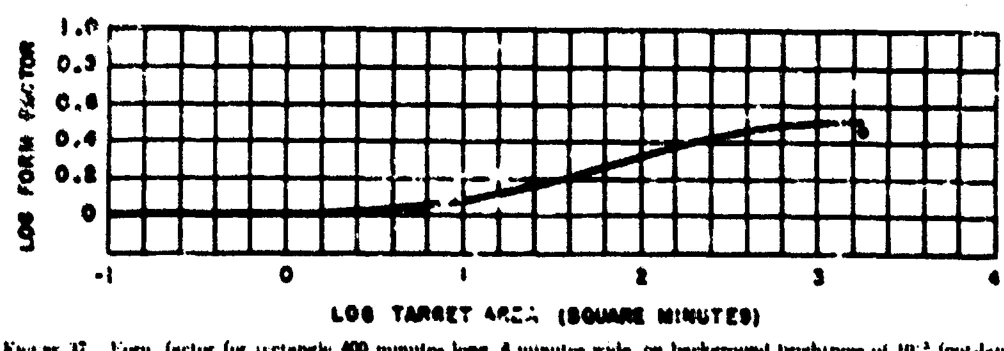


FIGURE 37. Form factor for rectangle 400 minutes long, 4 minutes wide, on background brightness of 10^{-3} foot-lambert. Curve shows theoretical variation.

effect was most complete, that is, the figures were least visible for blue, green, and violet figures on equally bright, nearly neutral grounds. Conversely, red, red-purple, and orange figures were seen most easily on equiluminous backgrounds. Present indications are that this difference is attributable to the much higher purities of obtainable red, red-purple, and orange colorants compared to the purities of moderately bright blue, green, and violet materials. The disturbing influence of this circumstance can best be detected and eliminated by quantitative specification of the colors employed. This is one of the objectives of the present investigation. Liebmann, and Koffka and Harrower relied on verbal descriptions of the subjects' perceptions, which, although interesting and instructive, are not useful as a basis for estimating the effect of chromatic contrast on visual acuity.

Acuity was studied with Landolt ring test patterns made from Ostwald colored papers by Hartinger and Schubert (1940)[35] and Schaefer, Kliefoth, and von Wolff (1943).[36] The avowed purpose of these investigations was to determine the influence of colored spectacles on visibility and acuity for patterns containing chromatic contrasts. No effort was made to eliminate brightness contrasts, and it is not clear from the accounts whether the brightness difference was eliminated in a single instance. The colors were specified only in terms of the Ostwald notations of the papers used, and specifications of the influence of the spectacle glasses on the colors were confined to their effects in changing brightness contrasts. Little can be gleaned from these experiments as reported beyond the fact that brightness contrasts exert a predominating influence on acuity even when combined with considerable chromatic contrast.

A report by Langstroth, et al. (1943),[37] *Visibility of Targets in Relation to Night Screening* (where *screening* denotes concealment) presents the results of tests with large targets (53 minutes minimum visual angle), low levels of brightness (none greater than 1 foot-lambert), in which simple judgments of disappearance were reported. The results for gray on gray indicate a contrast limen of less than 1 per cent for large targets when the brightness is 1 foot-lambert or greater. The contrast limen is reported to increase from 1 to 10 per cent when the brightness is decreased from 10^{-1} to 10^{-3} foot-lambert. The limen for dark on light is reported to be the same as for light on dark. Contrast limen is found to be nearly independent of size for all targets subtending 1 degree or more but increases very sharply with decrease in size when the target subtends less than one-half degree. This effect is much less for brightnesses greater than 0.1 foot-lambert than for lower brightnesses. Results of observations on the visibility of colored targets at night are all explained on the basis of the Purkinje shift of the luminosity curve. The *brightness contrast* is computed on the basis of physical rather than psychophysical data. These facts indicate that the possibility of contributions of chromatic contrast to visibility was not considered, and the report yields no information on the relative importance of chromatic contrast as compared to brightness contrast in determining visibility or acuity.

3.3.3 New Results

The following diagrams (Figures 39 to 41) show for each specified condition of observation the achromatic brightness contrast which would be necessary in order to yield the same visual acuity or visibility as any selected color contrast. These diagrams consist of "contours" in the standard chromaticity diagrams. Along each contour the equally effective achromatic contrast is constant. Such contours are shown for equivalent achromatic contrasts (e.a.c.) of 5, 10, 15, 20, and 25 per cent. In some cases these contours are incomplete, and in others fragments of contours for higher e.a.c. are shown. These diagrams are the results of conscientious efforts to establish and represent the facts correctly, but in the last analysis the diagrams are based largely on personal judgment concerning the significance of the experimental data.

The actual data[72] are very erratic and conflict in many details with these diagrams. Reasonable representations of the results cannot be obtained by any strictly objective or statistical treatment of the experimental data. Fluctuating motivation and occasional indispositions of the observers contributed to the irregularity of the data and have been taken into consideration in manners and extents which no statistical treatment of the data would permit.

Gamut of the Data

For chromaticities beyond the domain enclosed by the contours, estimates may be made by extra-

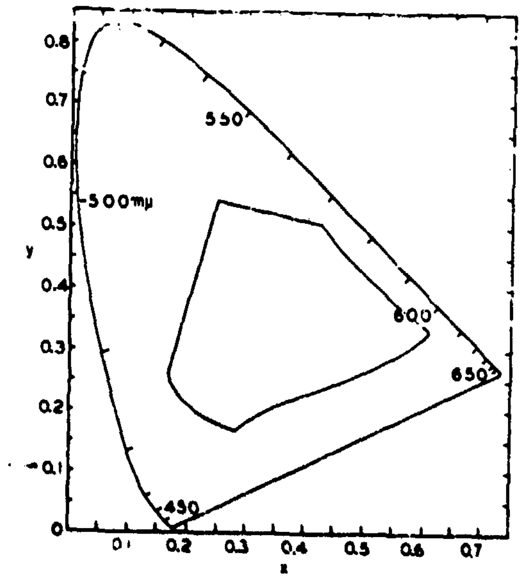


FIGURE 38. Standard I.C.I. chromaticity diagram.

Inner curve indicates the gamut of colors obtainable by a typical process of color printing. Most colors of nature lie within this gamut.

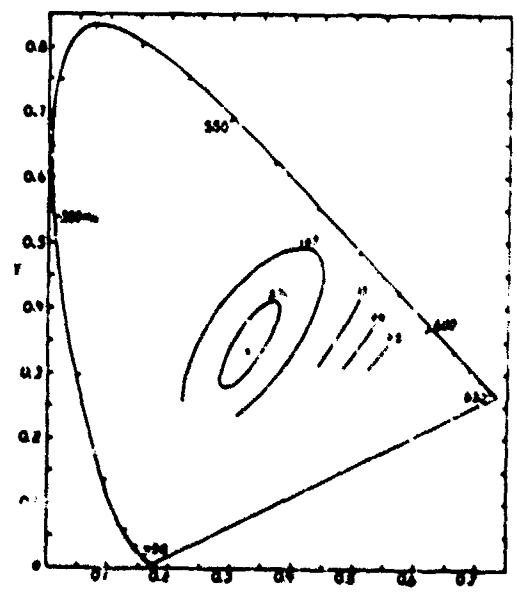


FIGURE 39. I.C.I. chromaticity diagram.

Contours indicate values of equivalent achromatic contrast of equiluminous colors on neutral background. The neutral point is indicated by a cross.

polation, but considerable uncertainty must be attributed to such values. Extrapolation is especially unreliable when acuity is in question, because the effects of chromatic aberration of the eye become serious for chromaticities beyond the range covered by the contours. Such extreme chromaticities, however, are rarely encountered in field conditions. An idea of the gamut of colors covered by the e.a.c. contours can be gained by comparing them with Figure 38, which shows the extreme range of colors obtainable by a modern process of color printing. More extreme chromaticities are seldom found in nature.

COMPARISON OF EXPERIMENTAL PROCEDURES

Figures 39 through 41 are all based on tests of visual acuity, requiring reports of the location of

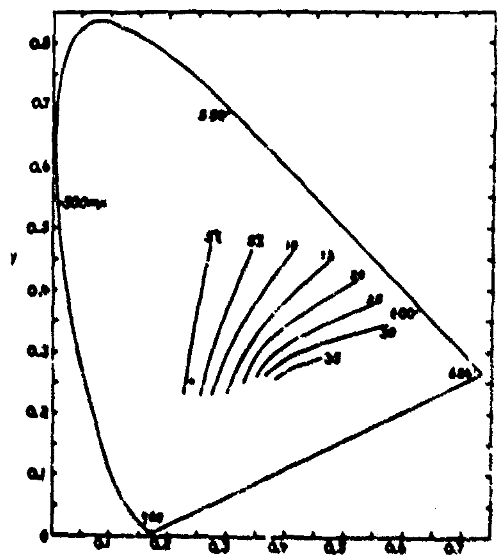


FIGURE 41. I.C.I. chromaticity diagram.

Contours indicate values of equivalent achromatic contrast of equiluminous colors on "sky blue" background (Munsell PB ...). Cross indicates the color of the background.

the gap in a Landolt broken-circle test pattern. Experiments designed to compare the results obtained with Landolt rings and with circular spots (which might appear in any one of eight eccentric positions) were performed very early in the investigation. Figure 43 shows as functions of excitation purity, for various dominant (and complementary) wavelengths, the e.a.c. of colors approximately equal in brightness to their immediate achromatic surround, based on the detection of the presence of a small spot. Figure 44 shows similar results obtained under the same conditions with Landolt

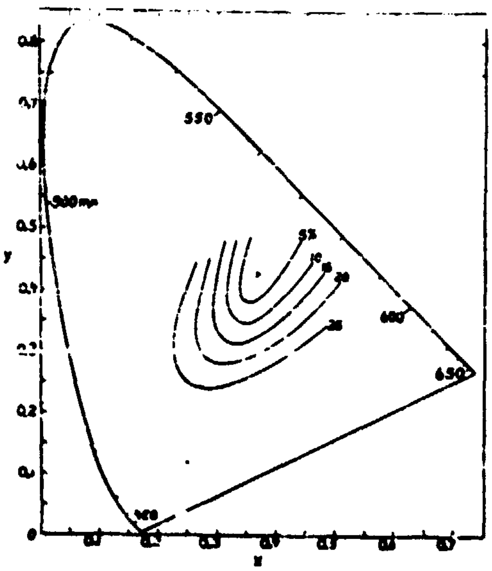


FIGURE 41. I.C.I. chromaticity diagram

Contours indicate values of equivalent achromatic contrast of equiluminous colors on "foliage green" background (Munsell GY 3/4). Cross indicates the color of the background.

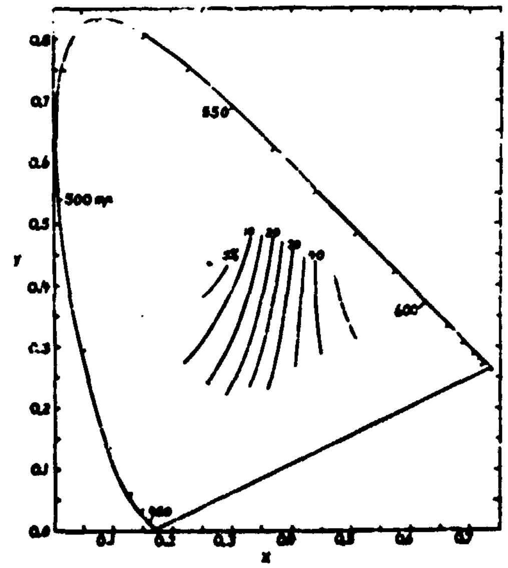


FIGURE 42. I.C.I. chromaticity diagram

Contours indicate values of equivalent achromatic contrast of equiluminous colors on green background (Munsell, G 5/4). Cross indicates the color of the background.

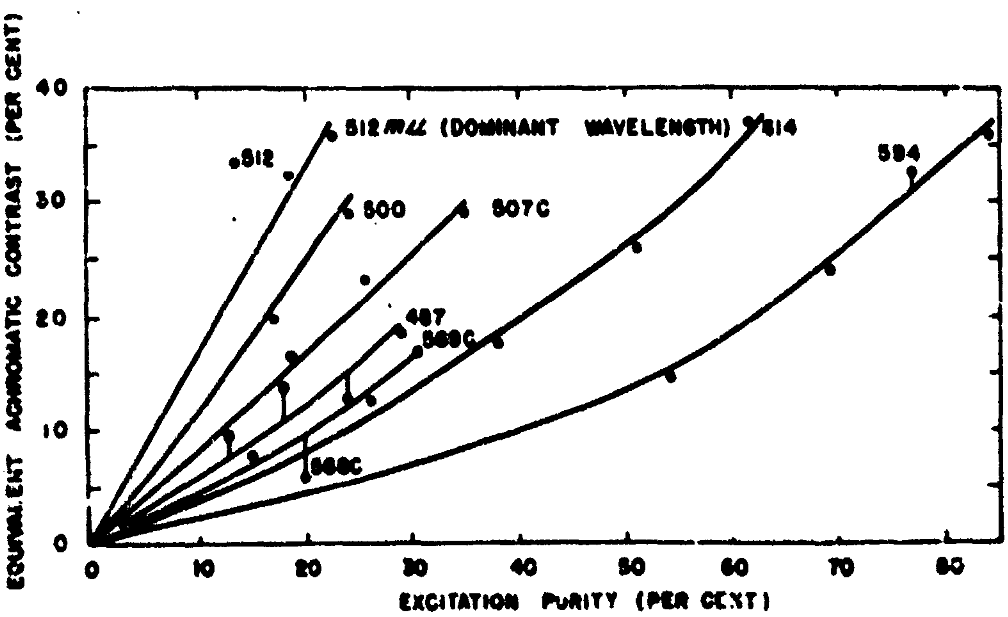


FIGURE 43. Equivalent achromatic contrast of colors approximately equal in brightness to their achromatic surround based on the detection of the presence of a small spot

(Illuminant: tungsten lamp, color temperature [illegible] degrees K)

rings. Figure 44 was derived from Figure 43 by plotting the purities corresponding to the indicated values of e.a.c. for the several dominant wavelengths. Figure 46 was derived in a similar manner from Figure 45.

The general trends of the results indicated for

... Figures 43 and 44 are the same as shown in Figures 45 and 46 for Landolt rings. The most notable exception is indicated by the curves for

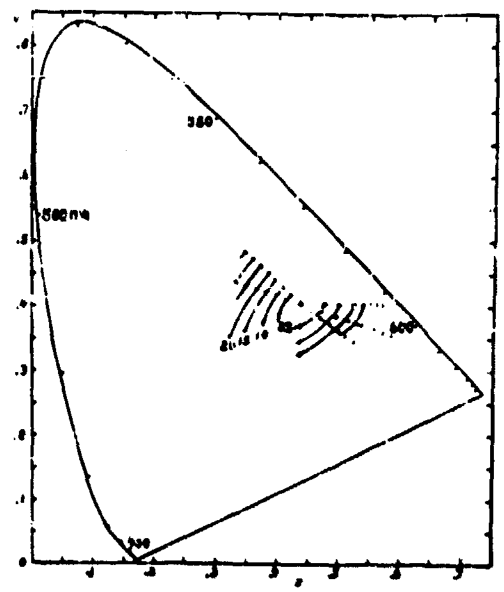


FIGURE 44. Data from Figure 43 plotted on the I.C.I. chromaticity diagram.

dominant wavelength 612 millimicrons, in Figures 43 and 45. The failure of the curve in Figure 45 to rise as sharply for high purities as the corresponding curve in Figure 43 is attributed to the effects of chromatic aberration in the refracting media of the observers' eyes.

This conclusion was confirmed by the conscious reactions of the observers, who reported the red to be very prominent, so that the spots were easy to find, but "fuzzy," so that the gap in the Landolt ring was detected with difficulty. Similar reports were made in the case of blue, blue-purple, and red-purple rings of high purity, the last being particularly exasperating on the strong green (G5/8) background. Despite the consistency of these reports, all of which were unsolicited and many of which were independent, little evidence of the effect can be found in the quantitative results. Nevertheless, it is concluded that although e.a.c. for colors of moderate purity on an achromatic background is essentially the same whether determined by the visibility of spots or the Landolt ring acuity test, chromatic aberration in the eye interferes with acuity more seriously than with visibility, especially for red and blue colors of high purity.

Combined Contrasts

Many observations were made with spots and Landolt rings differing from their backgrounds in luminous reflectance as well as chromaticity. Efforts to deduce a general rule for calculating the effectiveness of combined brightness and chromatic contrasts were largely frustrated by the frequency of erratic and unreproducible data. Figure 47 represents an effort to test the formula which appears to

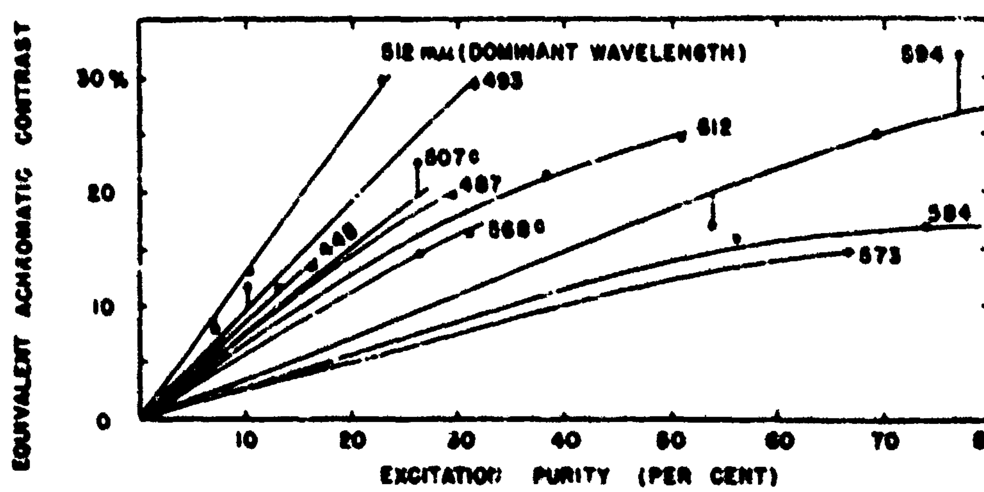


FIGURE 45. Equivalent achromatic contrast of colors approximately equal in brightness to their achromatic surround, based on observations of the orientation of Landolt rings.

Illuminant: tungsten lamp; color temperature 2800 degrees K.

[illegible] large discrepancies from the formula have been noted, these discrepancies have not revealed any regularities which might suggest useful modifications of th formula. This formula is also the simplest approximation suggested by current devel-

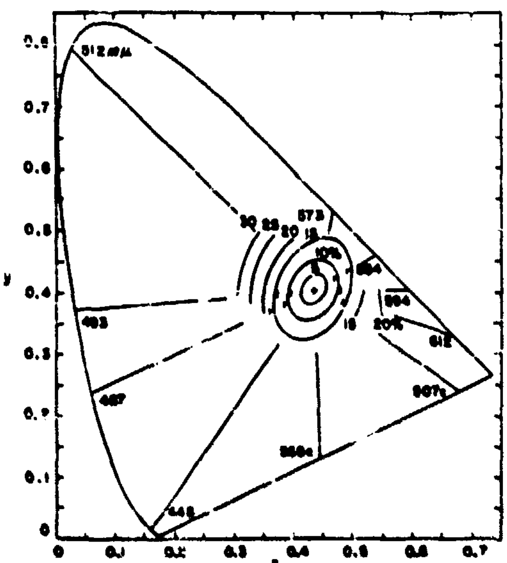


FIGURE 46. Data from Figure 45 plotted on the I.C.I. chromaticity diagram.

opment and theory of the metrics of the color domain (MacAdam, 1944).[31] Consequently, although its validity cannot be considered proved, and modifications will probably be found necessary in the future, the following formula is the best that can be given at present:

$$C_R = [C_b^2 + C_c^2]^{1/2} \qquad (1)$$

In this formula, C_R is the resultant, equivalent, achromatic contrast of a chromatic contrast combined with a brightness contrast, C_b is the brightness contrast, and C_c is the chromatic component of the contrast. The chromatic component (C_c) of the contrast should be determined from the most appropriate diagram, Figure 39, 40, 41, or 42, depending on the background color. Since each background color appears to introduce peculiarities into the shapes of the contours, no generalization seems permissible concerning the shapes of the contours for backgrounds appreciably different from those represented in Figures 39, 40, 41, and 42. In default [illegible] be based on the present diagrams in cases of necessity, but accuracy should not be expected when considerable extrapolation has been employed.

A few series of observations have been performed in order to test the formula for the resultant equivalent achromatic contrast of colors seen against chromatic backgrounds. The results were not very accurate but were not inconsistent with the formula, which appears to be satisfactory for estimates and approximations.

Constancy of E.A.C. at Various Adaptation Levels

Experimental Procedure. Four gray and four chromatic papers were selected which, in the form of Landolt rings (gap 0.7 minute) on a neutral (N5/), gave scores between 30 and 80 per cent for four of the five observers for both 35 foot-lamberts of artificial daylight quality and 26 foot-lamberts of 3000° K color temperature. Landolt rings were

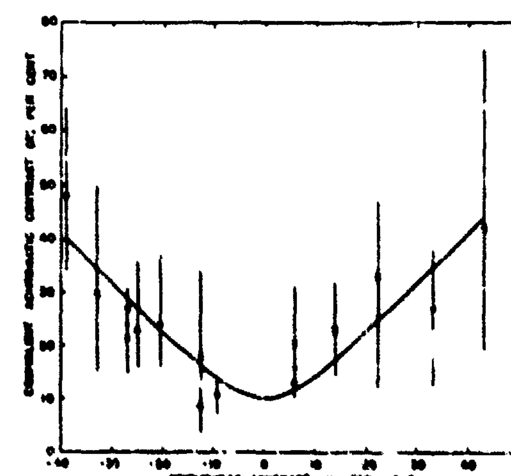


FIGURE 47. A study of combined chromatic and luminance contrasts. Curve represents equation (1).

Vertical lines represent the spread of the data. Target: neutral Landolt ring on sky blue background (Munsell: PB 5/). Brightness contrast: 10 per cent.

cut [illegible] on these same papers, with gaps subtending 0.7, 1.0, 1.4, 2.8, and 5.6 minutes. Using the 0.7-minute gap size for control tests during the same session, observations were made with the 1.0-minute gap for several reduced levels of illumination until a brightness level was found for which the gray rings (1.0-minute gaps) were reported exactly about as often as ... the smaller ... (0.7-minute gap) of the same papers at the higher levels. This procedure was followed for each of the available ring sizes.

Results. The equivalent achromatic contrasts of the colors were found to be the same for all brightness levels between 0.01 and 26 foot-lamberts. Since there are no essential differences between the results with daylight and ordinary, artificial light, the constancy of c.a.c. is not attributable to the Purkinje effect.

Implications. The primary purpose of the test of the constancy of e.a.c. with adaptation level was to extend the applicability of the diagrams (Figures 39 to 41) to all photopic levels (above 1 foot-lambert). This purpose was fully accomplished by the test. The failure to find any evidence for decrease of e.a.c. for levels definitely below photopic is surprising and indicates that the disappearance of color sensation at low levels may not imply a radical change of function but merely a decrease of differential sensitivity similar to, and apparently proportional to, the decrease of sensitivity to brightness differences.

Brightness differences are appreciable at very low levels only because there is no limit to the corresponding contrasts. Color difference, the appreciation of which is implicitly required for the recognition of any color as distinct from neutral, is, on the other hand fundamentally limited, and for levels at which the equivalent achromatic contrast cannot be appreciated it is reasonable to expect that a color will be indistinguishable from neutral. Therefore, no extraneous explanatory principle or hypothetical duality of retinal function is required for the explanation of the disappearance of color sensation at low levels. The persistence of the sensation of red at levels for which all other colors are indistinguishable from gray can be attributed directly to the equivalent achromatic contrast of red on gray which, for all levels of adaptation, is far greater than for any other color.

3.3.3 Observation Room

Observations were conducted in a room 30 feet long, 15 feet wide, 8 feet high, consisting of sheetrock on a temporary wood frame. The entire interior —walls, ceiling, and floor—was sprayed with flat white paint. The appearance of the room from the observers' stations is shown in Figures 48 and 49.

Lighting Arrangements. The room was lighted with lamps placed in two banks on each of the side walls, 10 and 20 feet from the front wall. The sockets for the lamps were mounted in sheet-metal ducts which were connected to an exhaust fan. The lamps

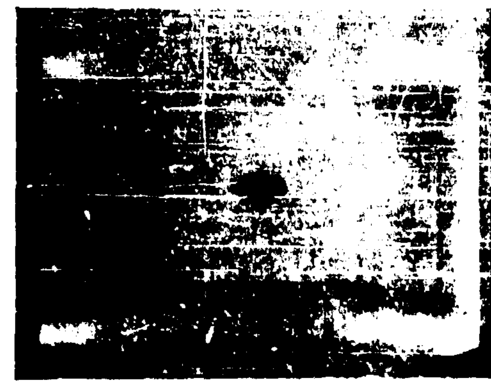


FIGURE 48. Observation room as seen from observers' seats. Landolt ring appears on dark background. Shutters are open.

extended into the room through 3-inch diameter holes cut in the sheetrock, which produced a draft around the necks of the lamps and facilitated the removal of the air heated by contact with the lamps. Seven lamps could be mounted in each of the four

FIGURE 49. Troffer lighting-units as seen from observers' seats.

banks. Lamps from 15 to 1,000 watts were used. Separate switches were provided for each lamp, so that they could be operated in any and all combinations. For very low levels of illumination, 15-watt lamps were located deep in the ventilating ducts and the holes in the wall were reduced by opaque blue glass from broken 1,000-watt GE Mazda Photo Blue bulbs were also placed in the small holes to obtain the same quality of light at extremely low levels as at high levels. Two types of lamps and the arrangement for low-level tests are shown in Figure 50, which also shows the arrangement of the baffles which concealed the lamps from the observers and increased the diffusion of the light in the room.

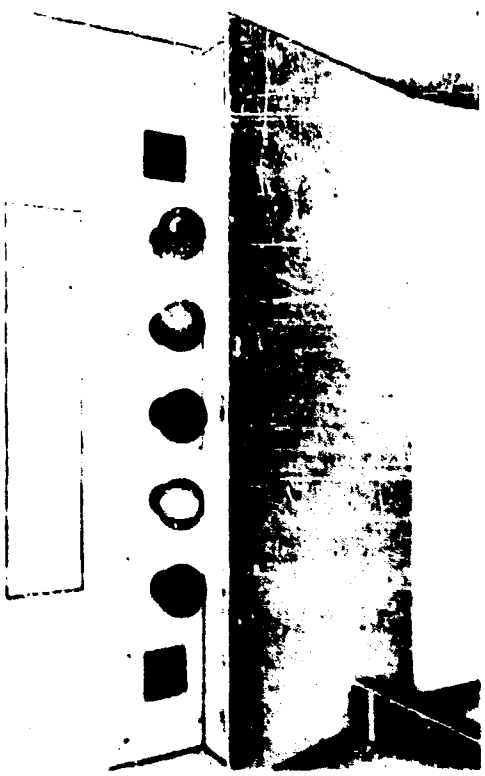


FIGURE 50 Interior view of troffer unit.

A ramp separated the observers' stations from the remainder of the room as shown in Figure 51. The observers normally removed their shoes before entering the room and wore cotton boot-socks which were laundered regularly to prevent the floor from getting dirty. The entire room was repainted on three different occasions when the floor became appreciably darker than the walls and ceiling. When freshly painted, the front wall, including the two diagonal panels in the front corners, had less than 3 per cent variation of brightness. The center of the ceiling and floor, from the front wall to 15 feet brightness to the front wall. The brightness of the side walls, and the floor and ceiling near the walls, varied as shown in Figures 48 and 49, but no variation greater than 50 per cent from the brightness of the front wall was discovered forward of the edge of the baffles which hid the lamp banks nearest the observers.

Presentation of Test Pattern

The test pattern consisted of Munsell colored papers cut with punch and die and mounted with tacky rubber cement on paper-covered synthane disks which could be removed and interchanged rapidly in the center of a steel plate. This steel plate was also covered with a Munsell paper to provide the surrounding color. Figure 52 shows the rear view of this apparatus and several of the synthane disks covered with a Munsell light gray paper. The target shown in the instrument in Figures 48, 49, and 53 is mounted on a Munsell medium gray paper, which is also shown covering the large steel plate. A flat ring which covers the edge of the steel plate to hide any imperfections in the plate or the edge of the cover paper is painted light gray (about 30 per cent reflectance) and can be seen in Figures 48, 49, and 53. This shade of gray reduces the severe contrast between the cover of the steel plate and the white wall of the observation room. The fanlike shutters, which can be seen in Figures 48 and 49 and partly in Figure 53, are painted with this same light gray to reduce after-image effects.

The steel plate, which carries the large surrounding paper and supports the synthane disk, is mounted in a ball bearing 12 inches in diameter which is attached to the hinged rectangle shown in Figures 52 and 53. A self-starting 75-rpm synchronous motor is also mounted on the rectangle and rotates the steel plate by means of a belt and pulley. Around the circumference of the bearing are mounted eight microswitches, which can be seen in Figure 52. These are normally closed-circuit but open-circuit when a short cam surface (which can be seen under the roller of the left switch in Figure 52), attached to the rotating plate, actuates the switches. The power to the 75-rpm motor passes through one of the eight switches, which is selected by an [illegible]-point switch, the knob of which is shown set into the shelf below the apparatus in Figures 52 and 53. A cam, mounted on the same shaft as this

Figure 51. Observers at their stations in the observation room.

commutator, opens the fanlike shutters symmetrically through the action of the roller and gears shown in the upper center of Figures 32 and 33. The cam and commutator are continuously rotated, one revolution every 20 seconds. The shutters are held open for 10 seconds and remain fully closed for 5 seconds. Power is supplied to the lower motor, through the commutator and microswitches, only during the 5-second period while the shutters are fully closed. This is sufficient for one complete revolution of the steel plate, which begins to rotate as soon as the shutters are completely closed and stops when the selected microswitch is opened. The position at which the plate stops is, therefore, determined by the position to which the selector switch has previously been placed.

This switch is operated manually according to a prearranged schedule but is changed only when the shutters are opened, that is, when no power is available to drive the plate. The neon-discharge lamp, mounted just behind the selector switch, glows as long as the shutters are closed. The operator refrains from changing the selector switch during this period. When the random schedule calls for the same location of the plate twice in succession, the power from the commutator is fed to an already open microswitch and the plate remains stationary. Since the commutator supplies power for rotation of the plate only while the shutters are closed, the observers never see the pattern in motion, but it is exhibited every 20 seconds for a full 10-second observation. The synthane disks, carrying patterns of various shapes, sizes, and colors, can be changed while the steel plate is rotating without interrupting the periodicity of presentations. For convenience, each synthane disk was left in place for 10 successive presentations at random orientations.

The selector switch is combined with a punch which cuts a small hole in a strip of 16-mm. un-[illegible], cine positive film and advances the film one frame for each operation of the switch. The orientation of the switch is indicated by the location of the hole within the frame of the film. Errors of reading the pre-arranged schedule are indicated by this device, and the punched film record is used as a master against which similar punched film records of the responses of the observers are compared was provided for each observer.

Landolt rings were cut out of the Munsell papers with a punch press. Die sets were procured to cut rings having the following dimensions.

Outside diameter	2.8 in.	1.40	0.70	0.50	0.35	0.25
Inside diameter	1.68	0.84	0.42	0.30	0.21	0.15
Width of gap	0.56	0.28	0.14	0.10	0.07	0.05
Subtense of gap (at 30 feet)	5.6 min.	2.8	1.4	1.0	0.7	0.5

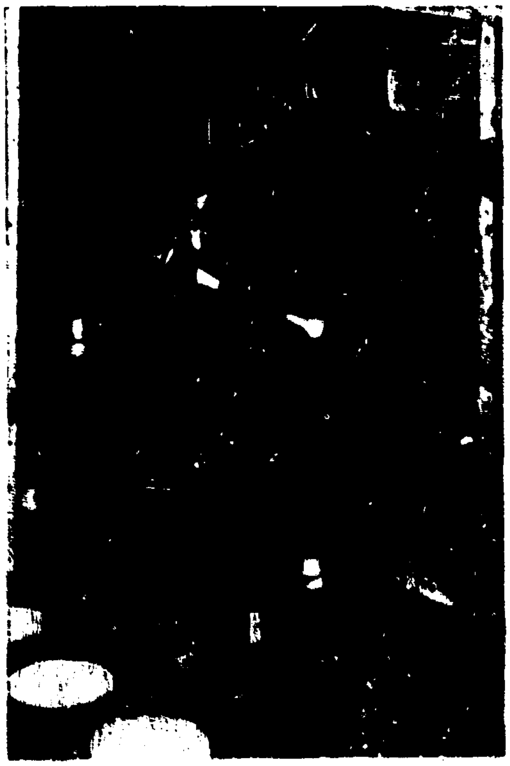


Figure 52. Rear view of the apparatus used to present the targets.

Figure 53. Target presentation apparatus with hinged test-plate lowered.

A small punch was made for cutting small circular disks from Munsell papers, with the diameters 0.090, 0.075, and 0.060 inch, subtending at 30 feet 0.9, 0.75 and 0.6 minute respectively. Munsell papers were coated with a tacky rubber cement before the rings or disks were punched out. The rings and disks could be stored in a notebook and removed by peeling from the page. They could then be mounted on the paper-covered synthane disks by simple pressure (with a clean pressure pad and avoiding abrasion). The rubber cement remained tacky and adhesive after several dozen transfers. Razor blades were used to peel the ring or disk from the surface to which it was attached. Cotton

Figure 54. Revolving punch at observer's seat. Record consisted of holes in 16-millimeter movie film.

gloves and tweezers were used in handling larger [illegible] papers.

The 1.4-inch diameter Landolt ring shown in Figures 48, 49, and 53 is much larger than necessary for successful response but was installed so that the pattern could be seen clearly in the photographs. With such a great contrast as this, the smallest ring (0.25-inch diameter) would be seen correctly in a significant fraction of the observations by practiced observers.

Munsell papers were used because of the predominant role of brightness contrast in visual acuity. Numerous sets of Munsell papers are available which have approximately the same luminous reflectance in daylight and in the artificial daylight employed in the experiments. The use of such sets makes possible the separate study of the influences of chromatic and brightness contrasts preparatory to study of the effectiveness of chromatic contrasts unrestricted to brightness equality.

3.3.2 Procedure

For convenience of notation and record, the eight possible orientations of the test pattern were numbered consecutively, clockwise as viewed by the observers, beginning with one at the top. The observers made no use of these numbers and were required merely to turn indicators on their recording punches to positions corresponding to their impressions of the location of the gap in the ring (or the solid dot in visibility tests). A schedule was prepared in advance of each test period, listing the target arrangements, sequence and repetition of the tests, and the random orientations of the pattern, designated numerically. As many as 12 different patterns were used in one test session. Each was exhibited 10 successive times, in random orientations, and the entire schedule was repeated, often with reversed or otherwise changed order of presentation of the various patterns. Patterns consisting of various contrasts of gray on gray were usually included among the color contrast patterns to check on the level of performance of the observers and to accumulate a sufficient mass of data on achromatic contrasts in order to furnish satisfactory psychometric curves to be used as the basis for interpretation of the data for color contrasts.

With the shutters closed, the observers settled in their seats in the observing room. The first disk was placed in the apparatus and the selector switch and master punch was placed at the first number appearing in the schedule, opposite the number of the disk. When the power switch was closed, the plate and pattern rotated to and stopped at the selected orientation, and shortly thereafter the shutters opened, exhibiting the pattern to the observers. As soon as the shutters opened, the operator changed the selector switch to the position indicated by the next number in the schedule opposite the number of the disk being exhibited. The discharge in the neon warning lamp ceased as soon as the shutter opened, indicating to the operator the proper time for change of the selector switch. Ten seconds after the shutters reached their maximum opening they began to close. As soon as they were fully closed, a buzzer sounded briefly in the observation room, the neon warning lamp glowed, and the disk carrying the pattern rotated to the new position. At the sound of the buzzer, the observers recorded their judgment of the observation just completed. They were at liberty to turn the indicators of their recorders at any time during the observation period and to change their indications to correspond with revised judgment as much as they cared. Only their final judgment was recorded at the sound of the buzzer, each operator deliberately pressing on the dial of her recorder. The operator waited before changing the selector switch again until the neon lamp was extinguished, indicating that the shutters were open again and the motor circuit was dead. As soon as the switch was set to the indicated location, the operator checked off each digit in the schedule to avoid duplications and omissions.

When all the digits in a row had been checked off, the selector switch was next set to the position indicated by the first number of the next row. When the shutters subsequently closed, the first synthane plate was removed from the recess in the steel plate, and the one listed next on the schedule was inserted. This change could be made during the 5 seconds in which the shutters were closed without interrupting the rhythm of the observations or interfering with the functioning of the rotating mechanism. In this way, as many as 12 patterns were exhibited without interruption 10 times each, in random but recorded orientations, in a period of 40 minutes. During this period, the observers operated their recorders once for each observation, and the complete record of the 120 judgments of each observer was obtained on a [illegible], of 16-mm film, 36 inches long.

Each pattern was shown 20 or 30 times, the second and third repetitions of the complete schedule following rest periods of 15 minutes. Many patterns and certain achromatic contrasts were repeated every session for weeks as common denominators for all of the tests with chromatic contrast.

When each schedule was completed the master record was compared with the schedule. Division lines were drawn between the tape records of the groups made up of 10 positions of each pattern. The notation of each pattern was transcribed on the corresponding portion of the master tape, and the tape record made by each observer was compared with the master.

3.3.5 Observers

Difficulty was experienced in obtaining suitable observers for this program. More or less extensive data were obtained with 27 individuals, all of whom had normal color vision, as indicated by the Ishihara test. Of the 14 whose data are sufficiently complete to warrant inclusion in our results, three wore glasses continually while observing. Since the objective was to evaluate only the relative contributions of chromatic and brightness contrast to acuity, observers with glasses were tolerated.

Group I consisted of five high school students, ages 17 to 19, who served after school hours and on Saturdays and holidays. Special check tests were devised and used to make sure that the results were not affected by communication of test information among observers.

Group II consisted of five employees of the Tiffany Foundation who had been trained and used there in similar tests already described. The maximum age of these observers was 25 years; all were recent college graduates, four majors in psychology and one major in history but none had any appreciable preparation in any of the physical sciences. This group of observers was far superior to any others used in this program.

This superiority was not in degree of acuity, but in stability, reproducibility, and immunity to boredom and the varieties of misbehavior which all of the other groups exhibited occasionally. This is attributed to the intellectual curiosity and academic background of the girls, who were interested in the technique and day-to-day trends of the results. Judging from the experience gained in this project, there is no adequate substitute for this background and attitude in extensive tests of visual acuity.

The last four observers (Group III) used to complete the program were also recent college or junior [illegible] similar in background to Group II, this group was much less stable, probably because of distraction of interest and energies by after-hours activities.

3.3.6 Summary of Results

Conclusion 1. For moderate achromatic and chromatic contrasts, acuity appears to depend on contrast in the same manner as visibility. Therefore, data obtained with test objects convenient for experimentation (such as the Landolt ring, employed in most of the present investigation) may be applied to other shapes by the determination of empirical conversion factors, using for these tests any convenient but definitely specified contrasts of object against background. If these conversion factors are determined by field tests, their application renders the laboratory data useful under those field conditions. Fundamental data of such intricate phenomena as are the subject of this report cannot be obtained by actual field experiments because of uncontrollable variations of essential conditions, distraction of attention, and interruptions and delays due to weather and unfavorable circumstances.

Conclusion 2. For high, increasing chromatic contrasts, acuity appears to increase less rapidly than visibility. This is believed to be a consequence of chromatic aberration in the eye but is not likely to be of importance in long-distance observations, since even the colors of highly chromatic signal flags are considerably desaturated by atmospheric haze. The magnitude of this desaturation can be computed for any specified set of conditions. The resultant acuity will depend on the decreased contrast, but the contribution of the decreased chromatic contrast can usually be estimated from the attached diagrams because the chromatic contrast is less than the limiting value above which the chromatic aberration of the eye becomes important.

Conclusion 3. The colors of figures yielding constant acuity against an equally bright background of approximately daylight quality are represented by a smooth closed curve around the point representing the color of the background in the standard diagram for representing colors. Such curves are presented for colors giving the same acuities as achromatic brightness contrasts of 5, 10, 15, 20, and 25 per cent.

Conclusion 4. For combined chromatic and brightness contrasts, the acuity appears to be approxigiven by equation (1),

$$C_0 = (C_b^2 + C_c^2)^{1/2},$$

when C_b is the brightness contrast, and C_c is the achromatic brightness contrast equivalent to the chromatic component of the contrast, as determined by interpolation in the diagrams. The chromatic components of contrasts encountered under field conditions are rarely over 25 per cent. On the other hand, appreciable color contrasts are almost invariably combined with brightness contrasts greater than 25 per cent. Therefore, the visibility of objects and acuity for identification of detail are primarily dependent on brightness contrast under most field conditions. When brightness contrasts are limited, as in the case of signal flags or panels, color differences may increase acuity and visibility, if chromaticity contrast can be introduced without equivalent sacrifice of brightness contrasts. The diagrams given for several different background colors may be employed in conjunction with the formula given in the first sentence of this paragraph for design and estimation of the effectiveness of any specified color combinations under any specified conditions.

Conclusion 5. The effectiveness of chromatic contrast in acuity and visibility appears to be proportional to the effectiveness of brightness contrast when brightness decreases from 100 foot-lamberts to 10^{-2} foot-lambert. As the adaptation level decreases, greater and greater visual angles and contrasts are necessary to make any perception of the contrast possible. Sufficient increase of brightness contrast is always possible, but if the contrast is purely chromatic, with brightness contrast excluded, there exists a level of adaptation below which the perception of contrast is impossible even for large visual angles, because chromatic contrasts are fundamentally limited. If exceedingly severe glare is encountered, in which brightness contrasts of less than 30 per cent cannot be perceived, it may be expected that chromatic contrasts (the effectiveness of which cannot exceed some such limit) will not be perceptible and otherwise highly chromatic stimuli, such as green, blue, or yellow signals, may not be distinguishable from white and may be reported as colorless. Such conditions have not been tested experimentally.

Conclusion 6. At or near the limit of visibility, the hues of chromatic targets are not perceptible, even though the object may be seen in an appreciable [illegible] This is particularly true of violet, blue, green, and yellow stimuli. Orange and red-purple, as well as red, appear reddish or brownish under these circumstances.

Conclusion 7. When responses are forced for every observation, significant percentages of correct responses are recorded for nearly visible targets even when the observer is firmly convinced that the object or detail is hopelessly invisible.

3.4 PERCEPTION WITHOUT AWARENESS

The statements of Conclusion 7 are true both for spots and for gaps of Landolt rings, for achromatic and chromatic contrasts alike, and for all observers. Lythgoe[38] reported the same phenomena. He wrote:

> In general, the subject is unaware of the sort of results he is getting. At the flat portions of the top of the curve he finds the task none too easy: it is quite an effort to read the test object. At the bottom of the curve, he has no idea that he is getting any right answers at all and yet he is getting more than the expected value due to guesswork. Inexperienced subjects find it difficult to force themselves to give an answer at each exposure of the test object. The remarkable fact is that with very small test objects when the subject is under the impression that he is guessing, actually he is returning more than one in eight correct answers. In one series of experiments, we made the size of the test object very small indeed and in this case the number of (correct) answers returned was not significantly greater than would be expected from pure guesses.

In another part of his report, Lythgoe describes a quantitative test of this phenomenon and writes:

> It is as though the eye and the subject's answer formed part of a purely physical process, the readings getting worse as the conditions are made more difficult. Existing at the same time is a spectator of the process—the subject's awareness. In our experiments, the subject was invited to express his views on the accuracy of the working of the physical process. Judged by objective standards, his awareness saw little of the game. *When the subjects were quite certain they were wrong, actually they were giving thirty per cent correct answers.*

Experience in the present investigation has borne this out in very striking fashion. In all cases when liminal results (50 per cent correct) were being obtained, the observers experienced such difficulty that they were almost always unconscious of seeing the gap or spot. The rare perceptions of the orientation of the target were so fleeting and nonrepeatable that verification was impossible, and there was no alternative to indicating the orientation thus so vaguely perceived. In the remaining cases, the observers had no awareness of seeing any persistent irregularity which might indicate the proper orientation, though they looked as carefully and as long as they could. The indications seemed to be pure guesses, literally forced by the requirements of the mechanisms, yet when they followed conscientious observation they were correct more often than can be accounted for by chance.

4.4.4 Lookout Procedure

Since the phenomenon of perception without awareness is not dependent on the particular form or color of the test object or on the procedure of the experiment, it may be of general occurrence. Because of its possible bearing on the procedures employed by lookouts, this point was emphasized to the Army-Navy-OSRD [ANOSRD] Vision Committee at one of its first meetings. It is evident from the data that if use is made of the phenomenon described above distant objects may be detectable and identifiable at distances as much as 50 per cent greater than at present (see Section 4.4.1). This conclusion is based on the assumption that the observer is required to be certain before he reports or identifies a strange object. In practice, an approaching plane might be reported 50 per cent sooner and identification of type may be possible at 50 per cent greater range than at present, reducing the hazards of destroying friendly planes or of permitting hostile planes to approach dangerously close. Also, search for survivors may be subject to improvement corresponding to as much as 50 per cent increase of radius of visibility and appreciable increase of the efficiency of searching within the present limits of visibility.

A Suggested Technique

It was suggested to the ANOSRD Vision Committee that such improvements might be obtained by providing at least three observers *to scan the same sector simultaneously*. These lookouts probably should not collaborate, but each might report immediately (possibly by some remote indicator device) to a central station his estimate of the azimuth, range (and altitude of aircraft), and character (that is, ship or plane) of each thing that he thinks he saw, however fleeting or vague and unverified the impression may have been. The central station might relay such reports to higher authorities only if two or more corroborating reports are received. This procedure would eliminate almost all false reports but a [illegible] change for the advantage of 50 per cent or greater increase of range of vision. Of course, every lookout might also be furnished with the present means of reporting immediately any object which he sees or identifies positively. Positive reports could be distinguished clearly from [illegible]inal reports and relayed (or perhaps transmitted from the lookout by more direct channels), even in the improbable event that they are not immediately corroborated.

Thorough trial and modification by careful experimentation would undoubtedly be necessary to perfect a technique of this general character, but the probable advantages may be sufficiently important to justify the effort. This method may not be feasible on any except large units, because the present number of lookouts would probably need to be tripled to provide coverage without widening the sector of any one lookout. The change of attitude required to report all "hunches" immediately and as accurately as possible without waiting for self-confirmation may be so great that many experienced lookouts may be unsuitable and the training of new personnel for such duty may have to be considered. Such training would cultivate a very attentive, careful attitude *completely free of inhibitions regarding false alarms*. The essence of the method is in the fact that when an observer concentrates and reports all possibly significant impressions a considerable fraction of his "false alarms" prove to have foundation, and when confirmed by an independent report of another similar observer the probability of correctness approaches certainty. A triple coincidence should be more reliable than a "positive" report by a single observer and may extend the range of visibility and time available for countermeasures 50 per cent or more

No word has been received that the suggested technique was tried by Navy lookouts, but it is understood that recent editions of the *Manual for Lookout Instructors* advocate the reporting of "hunches."

4.5 PRACTICAL VISIBILITY PROBLEMS

Before the results of the extensive experimental programs described in this chapter can be used in the solution of practical visibility problems, means must be provided for combining these data with information regarding the optical state of the atmosphere. Nomographic charts for this purpose are presented in the two following chapters.

Chapter 4

THE VISIBILITY OF NAVAL TARGETS

INTRODUCTION

The limiting range at which a ship at sea, a low-flying aircraft, or a shoreline may be sighted can be predicted from the principles and data which have been presented in the two preceding chapters. Such a prediction, however, requires tedious computations, impractical under operational conditions. It is the purpose of this chapter to show how the computations can be avoided by the use of simple nomographic charts and to illustrate the use of such charts in predicting the limiting range at which any specified target will be just visible.

4.1 THE NATURE OF THE PROBLEM

Previous chapters have shown that the visibility of a uniform target depends upon the apparent contrast between the target and its background, the angular size of the target, its shape, and the perceptual capacity of the observer at the level of brightness to which his eyes are adapted. Both the apparent contrast and the angular size of a target vary with target distance, but in accordance with different laws. For example, at a distance of X yards, a circular target of area A square feet subtends an angle α given by

$$\alpha = \frac{1293\sqrt{A}}{X} \text{ minutes of arc.} \tag{1}$$

The apparent contrast C_X of any target at distance X is related to its inherent contrast C_0 by the relation

$$C_X = C_0 e^{-3.912X/v}, \tag{2}$$

where v is the meteorological range. Because the perceptual capacity of a human observer depends simultaneously upon both α and C_X, in the manner shown by Figure 35, Chapter 3, any calculation intended to determine the range at which a target can just be sighted must consist of a series of successive approximations. In other words, the answer must be found by bracketing. The procedure is illustrated by the following example.

Illustrative Example

Let it be required to find the distance at which a uniform circular target having a projected area of 100 square feet and a brightness of 10 foot-lamberts will be liminally visible on a day when the meteorological range is 20,000 yards, assuming the target to be viewed along a homogeneous, horizontal path against a uniform background of horizon sky, the brightness of which is 1,000 foot-lamberts. The inherent contrast of the target is

$$C_0 = \frac{10 - 1000}{1000} = -0.990.$$

This value indicates that, to an observer close aboard, the target appears as a nearly black silhouette.

Since the meteorological range is 20,000 yards, it may be assumed that a very large black object would be liminally visible at approximately that range. However, at 20,000 yards the angle subtended by the target is shown by equation (1) to be only 0.646 minutes. Referring to Figure 35, Chapter 3, or Appendix A, the liminal contrast for a target of this angular size is -0.355. However, from the definition of meteorological range, the apparent contrast of the target is -0.020. Hence, the target is invisible at 20,000 yards.

Although the liminal target distance is now known to be less than 20,000 yards, its actual value must be found by trial and error. Assume the target to be at 10,000 yards. At this distance it subtends an angle of 1.292 minutes, and its apparent contrast is shown by equation (2) to be -0.145. From Figure 35, Chapter 3, or Appendix A, the liminal contrast for a target of this angular size is -0.0966. Since the magnitude of the apparent contrast exceeds the magnitude of the liminal contrast, the target can be seen at 10,000 yards and beyond.

In order to bracket the answer in a systematic manner, let equation (2) be used to find the distance at which the apparent contrast is -0.0966. This is found to be 11,930 yards. At this distance the target subtends an angle of 1.083 minutes, and the corresponding liminal contrast is -0.134. Since this

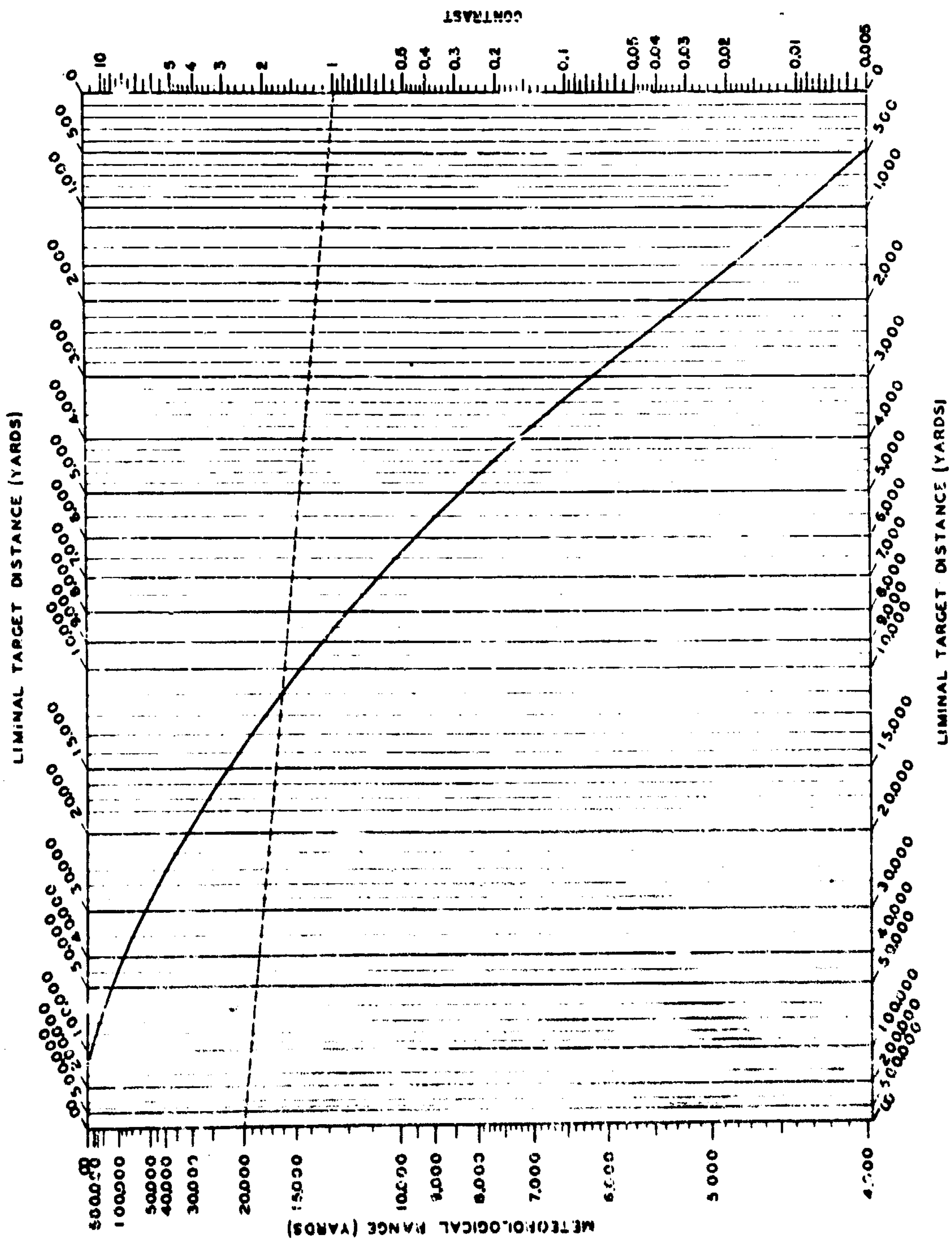


FIGURE 1. Nomographic visibility chart.

Curved line represents data from Figure 35 for uniform, circular target 100 square feet in area when $B_H = 1{,}000$ foot-lamberts.

exceeds the apparent contrast in magnitude, the target is not visible.

It is evident that the distance at which the target is liminally visible has been bracketed. If the bracketing process is continued, the answer finally attained is 11,000 yards.

The foregoing calculation is obviously too cumbersome, too time consuming, too subject to error to be practical for routine use. Fortunately, the calculation can be avoided completely by the use of nomographic charts.

4.3 THE NOMOGRAPHIC METHOD

Figure 1 shows a nomographic chart capable of making simultaneous allowances for the variations of a and C_R with target distance. The curved line which crosses the center of the figure represents data from Figure 35, Chapter 3. Specifically, it represents the limiting perceptual capacity of a typical observer whose eyes are adapted to full daytime sky brightness when the target is uniform, circular, and 100 square feet in area. A target of any other area could be represented by a different curve, and subsequent nomographic charts in this volume contain a family of curves corresponding to a billionfold range of areas.

Illustrative Example

To illustrate the use of the nomographic visibility chart, let the example of the preceding section be solved by means of Figure 1. Lay a straightedge across the chart in such a manner that it connects 20,000 yards on the meteorological range scale with 0.99 on the contrast scale. (The dashed line in Figure 1 indicates the position of the straightedge.) From the point where the curve is intersected by the straightedge, move straight up or straight down to the target distance scale. The answer, 11,000 yards, read from this scale, agrees with that previously obtained by bracketing.

4.3.1 Special Cases

Fog

The scales of meteorological range and liminal target distance on the nomographic visibility chart shown in Figure 1 may be multiplied by any factor, provided the value of area assigned to the curve is multiplied by the *square* of the factor. This convenient property of the charts enables them to be used for problems involving [illegible] cal range.

For example, let the scales of meteorological range and liminal target distance in Figure 1 be multiplied by 1/10, so that the former covers values down to 400 yards and the numbered divisions of the latter begin with 50 yards and end with 70,000. The curved line, which formerly applied to a target 100 square feet in area, now applies to a target whose area is 1 square foot. Thus, as indicated by the dashed line, a circular target 1 square foot in area and having an inherent contrast of ± 0.99 is liminally visible at 1,100 yards on a day when the meteorological range is 2,000 yards. Obviously, if Figure 1 bore a curve corresponding to a target area of 10,000 square feet on the basis of the scales as originally numbered, the curve would apply to a target 100 square feet in area when the chart is used in the manner just described.

Targets of Very Large Area

In dealing with targets of very large area or targets visible at very long distances, the range and distance scales of the visibility charts may advantageously be multiplied by 10. If this is done in Figure 1, the curved line then applies to targets 10,000 square feet in area, and the dashed line indicates that such a target will be liminally visible at 110,000 yards on a day when the meteorological range is 200,000 yards, provided the inherent contrast of the target is ± 0.99.

Exact Values of Target Area

Since the factor by which the scales are multiplied may have *any* value, the curved line in Figure 1 can be made to apply to *any* area.

For example, let it be required to find the liminal target distance for a target whose area is 64 square feet, assuming, as before, that the inherent contrast of the target is ± 0.99 and the meteorological range is 20,000 yards. Since the area represented by the curve must be multiplied by 0.64, the range and distance scales are to be multiplied by 0.80. This means that the division marked 20,000 yards on the meteorological range scale corresponds with a meteorological range of 16,000 yards. A meteorological range of 20,000 yards is therefore represented by the division numbered 25,000. If this point is connected by a straightedge (not shown) to 0.99 on the contrast scale, the intersection of the curve and

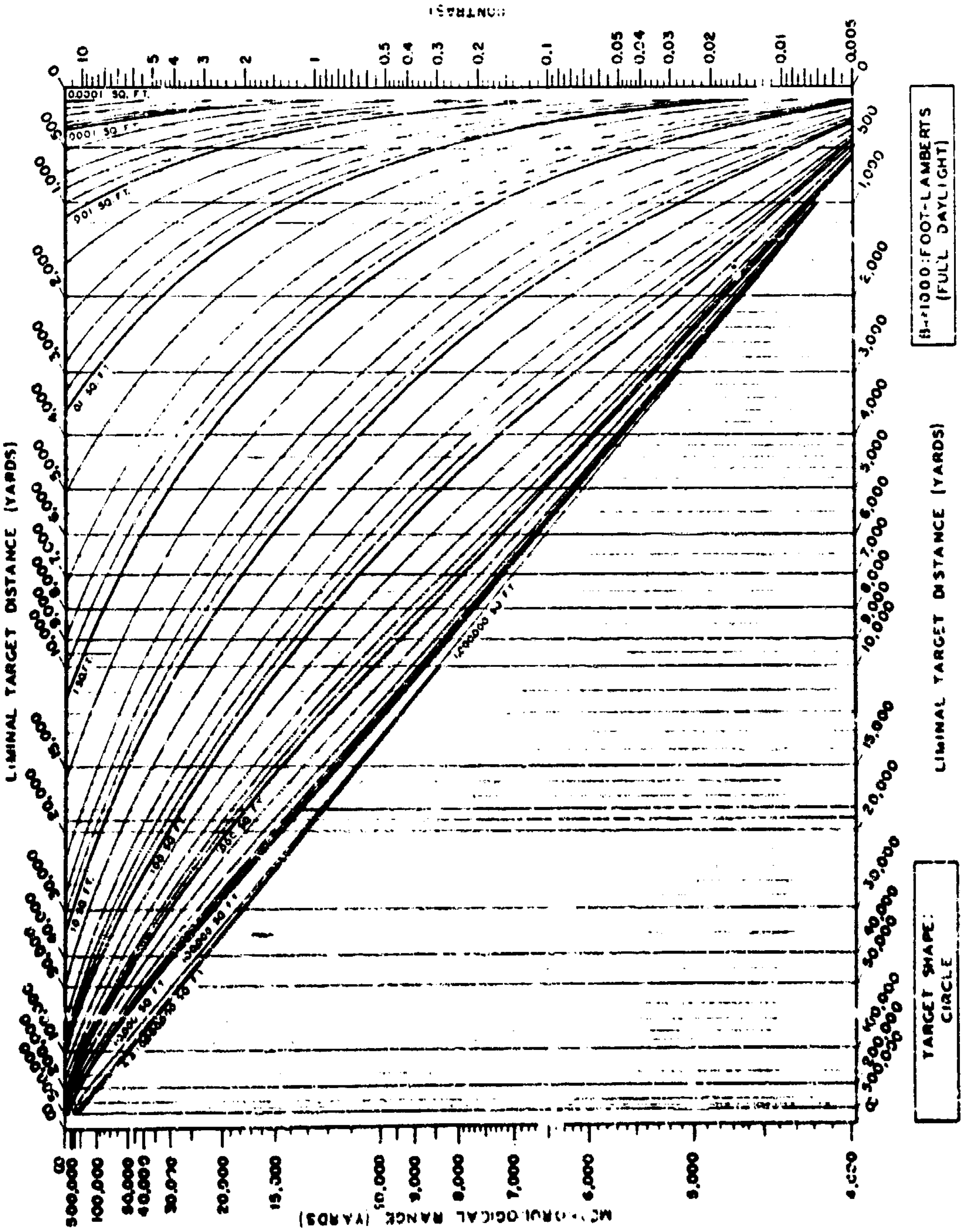

LIMINAL TARGET DISTANCE (YARDS)
LIMINAL TARGET DISTANCE (YARDS)
(FULL DAYLIGHT)
TARGET SHAPE: CIRCLE

FIGURE 2

[illegible] indicates 12,400 on the scale of target distance. After multiplying by the scale factor 0.80, the liminal target distance is found to be 9,920 yards.

The family of curves, each representing a target of different area, which appear on all the nomographic charts presented later in this volume are intended to make unnecessary the type of calculation just described. However, for the construction of tables, or for special computations requiring great precision, the method described in this section should be used.

4.3.2 Other Uses of the Nomograph

THE DETERMINATION OF LIMINAL CONTRAST

The nomographic visibility chart may be considered as a special plot of the liminal contrast data given in Figure 35, Chapter 3.

For example, let it be required to find the liminal apparent contrast of a target 100 square feet in area and 10,000 yards from the observer. Place a straightedge across Figure 1 in such a manner that it connects the infinity point at the top of the meteorological range scale with the intersection of the curve and the vertical line representing 10,000 yards. The straightedge then intersects the contrast scale at $\pm$ 0.097, the value of liminal contrast for a target of this angular subtense. This implies that all liminally visible uniform circular targets subtending the same angle at the observer's eye are represented by a straight line connecting the infinity point on the meteorological range scale with the point representing the liminal contrast.

Precise Values of Liminal Contrast. The curved line on Figure 1 was constructed by marking the point of intersection of each vertical target-distance line with a straightedge connecting the infinity point on the meteorological range scale with the appropriate value of liminal contrast. Before this could be done, a table showing the values of liminal contrast for each intersection was prepared from very large-scale plots of Figure 35, Chapter 3. This table gives the values of liminal contrast more precisely than they can be read from either Figure 35, Chapter 3, or Figure 1. *Tables of this type for all the visibility charts in this volume are given in the microfilm supplement,*[39] *and should be consulted together with Appendix A whenever new tables or new charts are prepared.*

THE DETERMINATION OF APPARENT CONTRAST

The nomographic visibility chart can be used to solve equation (2). For example, let it be required to find the apparent contrast of a target of inherent contrast [illegible] 0.99 when it is 10,000 yards from the observer on a day when the meteorological range is 20,000 yards. Place a straightedge across Figure 1 in the position shown by the dotted line. Place the point of a pencil at the intersection of the straightedge with the vertical target-distance line for 10,000 yards. Rotate the straightedge until it passes through the infinity point at the top of the meteorological range scale. The straightedge now intersects the contrast scale at $\pm$ 0.145, the apparent contrast of the target.

Obviously, this technique can be employed to solve for any of the four quantities in equation (2).

Structure of the Nomograph. A mathematical discussion of the nomographic charts is included in the microfilm supplement.[39]

4.3.3 Nomographic Charts for Circular Targets

More than a million observations of uniform, circular targets were made by a homogeneous group of observers at the Tiffany Foundation (Chapter 3). The observing conditions, covering the entire gamut of brightness conditions from the brightest day to the darkest night, were carefully controlled and accurately measured. No visibility experiment of comparable magnitude or thoroughness has ever been reported; the Tiffany data are believed to possess far greater reliability than any other visual data. It is appropriate, therefore, to present these data in the form of nomographic charts similar to Figure 1. A set of such charts is presented in Figures 2 through 10. These charts cover adaptation brightnesses B_H from 10^{-5} foot-lambert to 1,000 foot-lamberts in decimal steps.

Each of the nine figures (Figure 2 through 10) is a nomographic visibility chart for uniform circular targets seen against a uniform background of horizon sky having the brightness B_H indicated at the lower right corner of the diagram. Descriptive phrases such as *overcast day* or *quarter moon*, have been added to serve as a rough guide in selecting the proper chart for use in a given problem.

These charts possess reliability of a very high order when used to predict the distances at which a

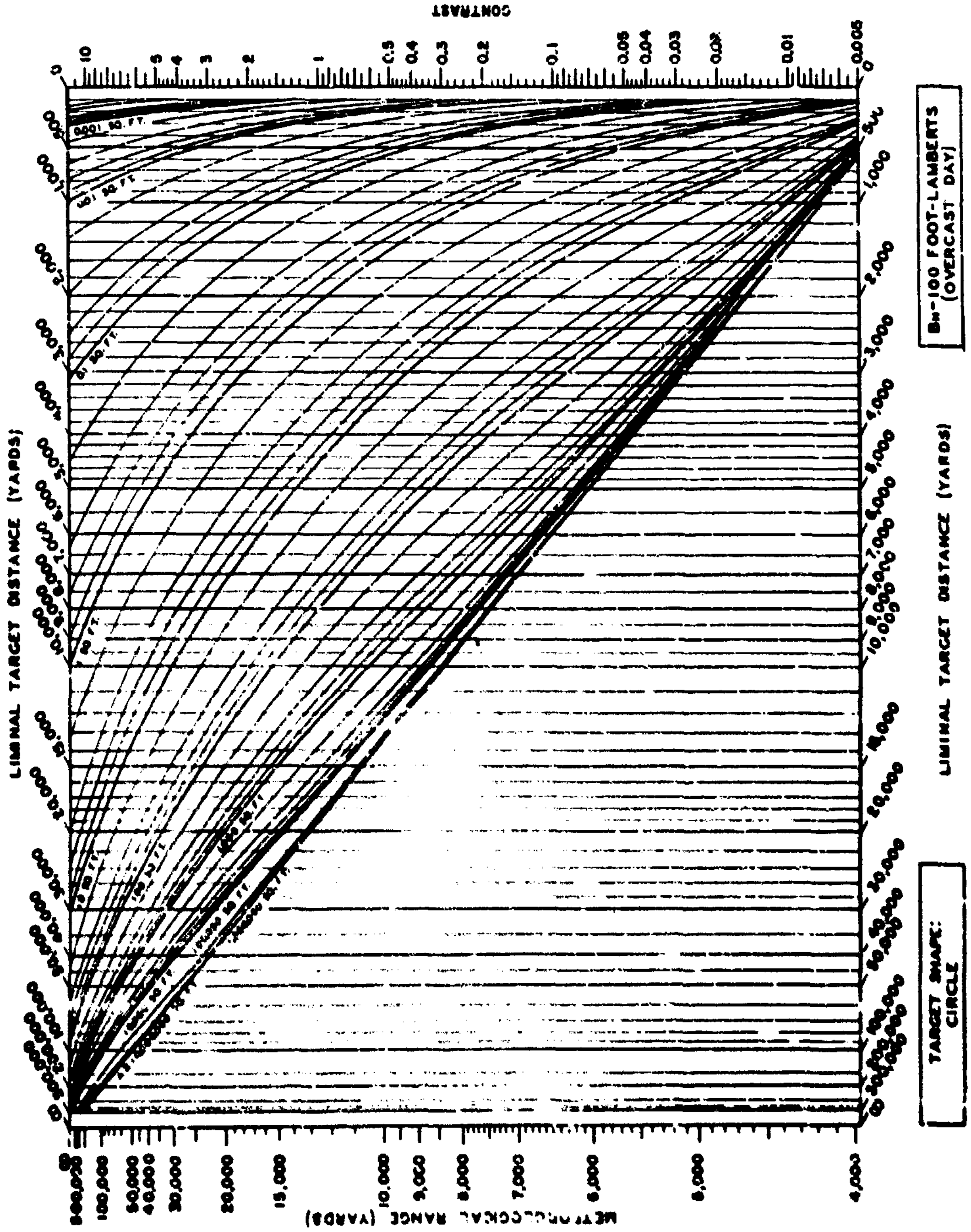

CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
BH=100 FOOT-LAMBERTS (OVERCAST DAY)
TARGET SHAPE: CIRCLE

Figure 3

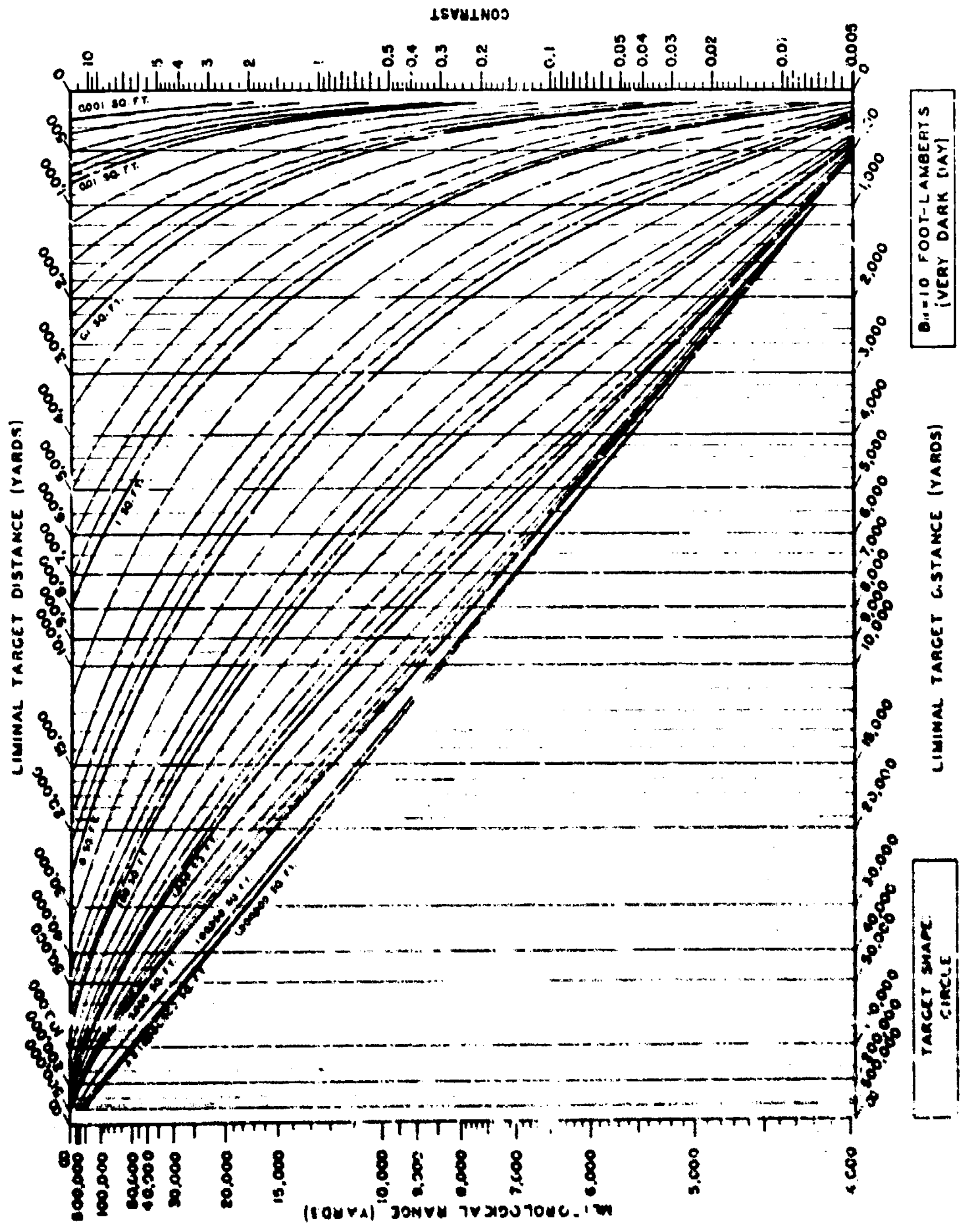

CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
B = 10 FOOT-LAMBERTS (VERY DARK DAY)
TARGET SHAPE CIRCLE

FIGURE [illegible]

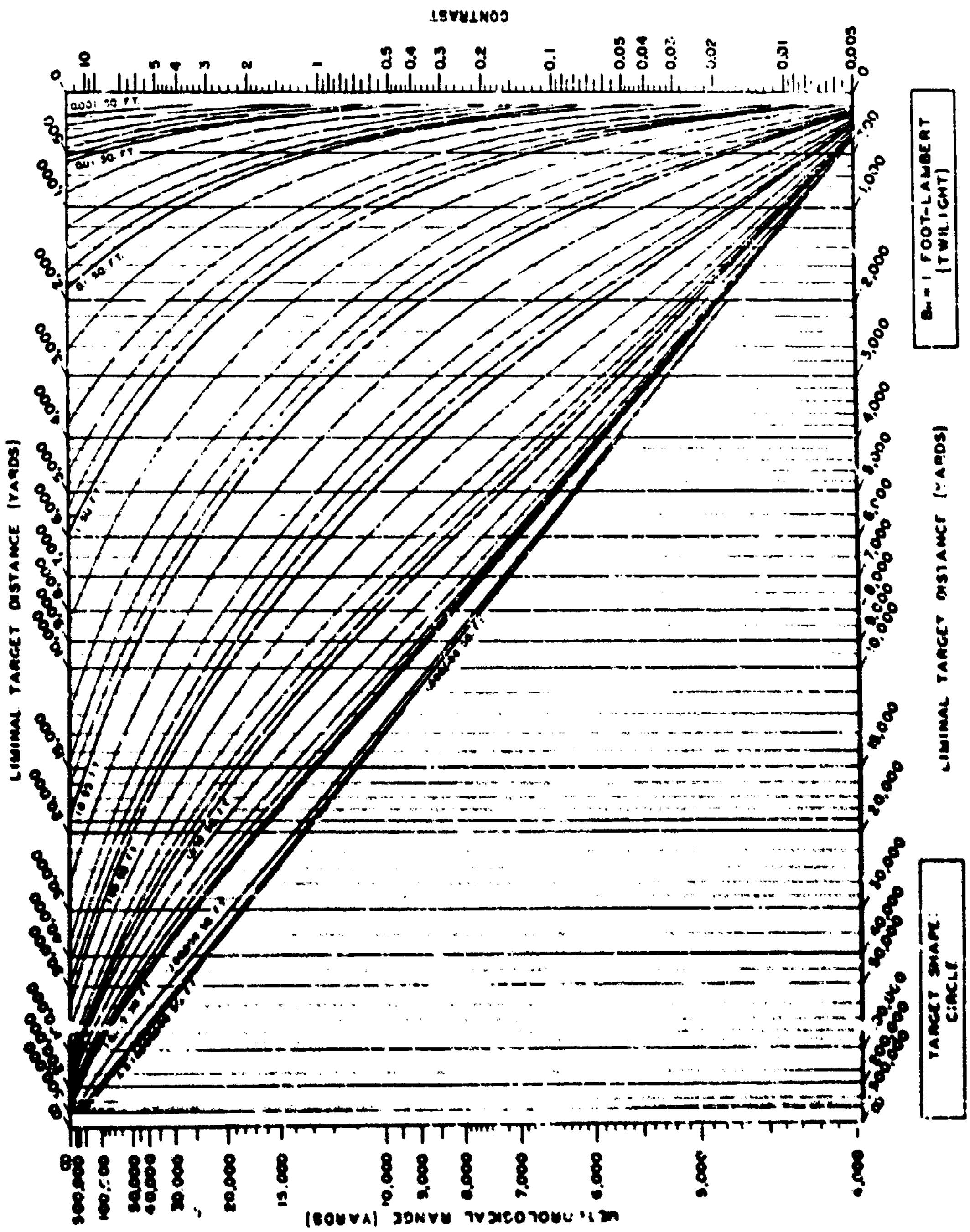

CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
B_0 = 1 FOOT-LAMBERT (TWILIGHT)
TARGET SHAPE: CIRCLE

FIGURE 5

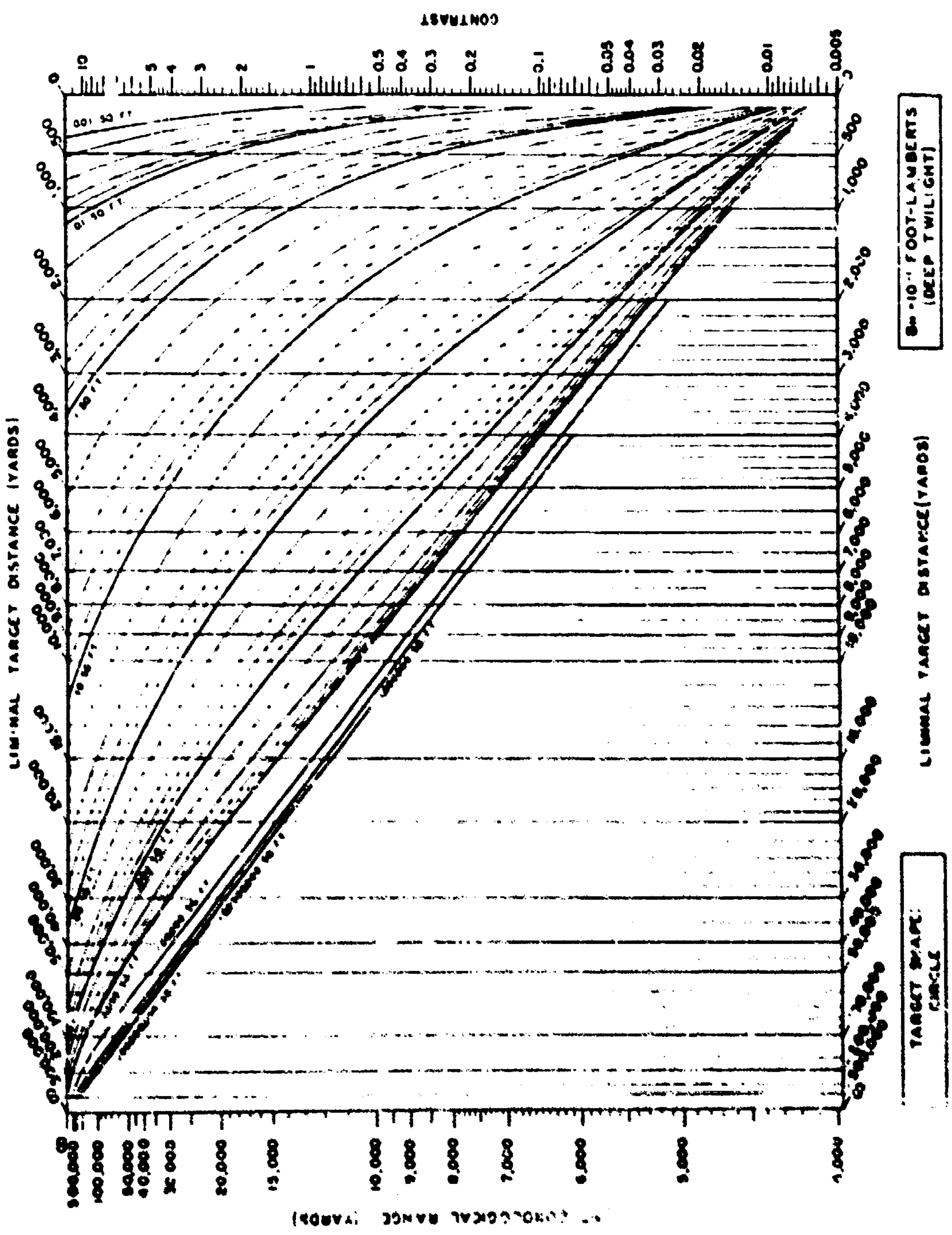

CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
(DEEP TWILIGHT)
TARGET SHAPE: CIRCLE

FIGURE 6

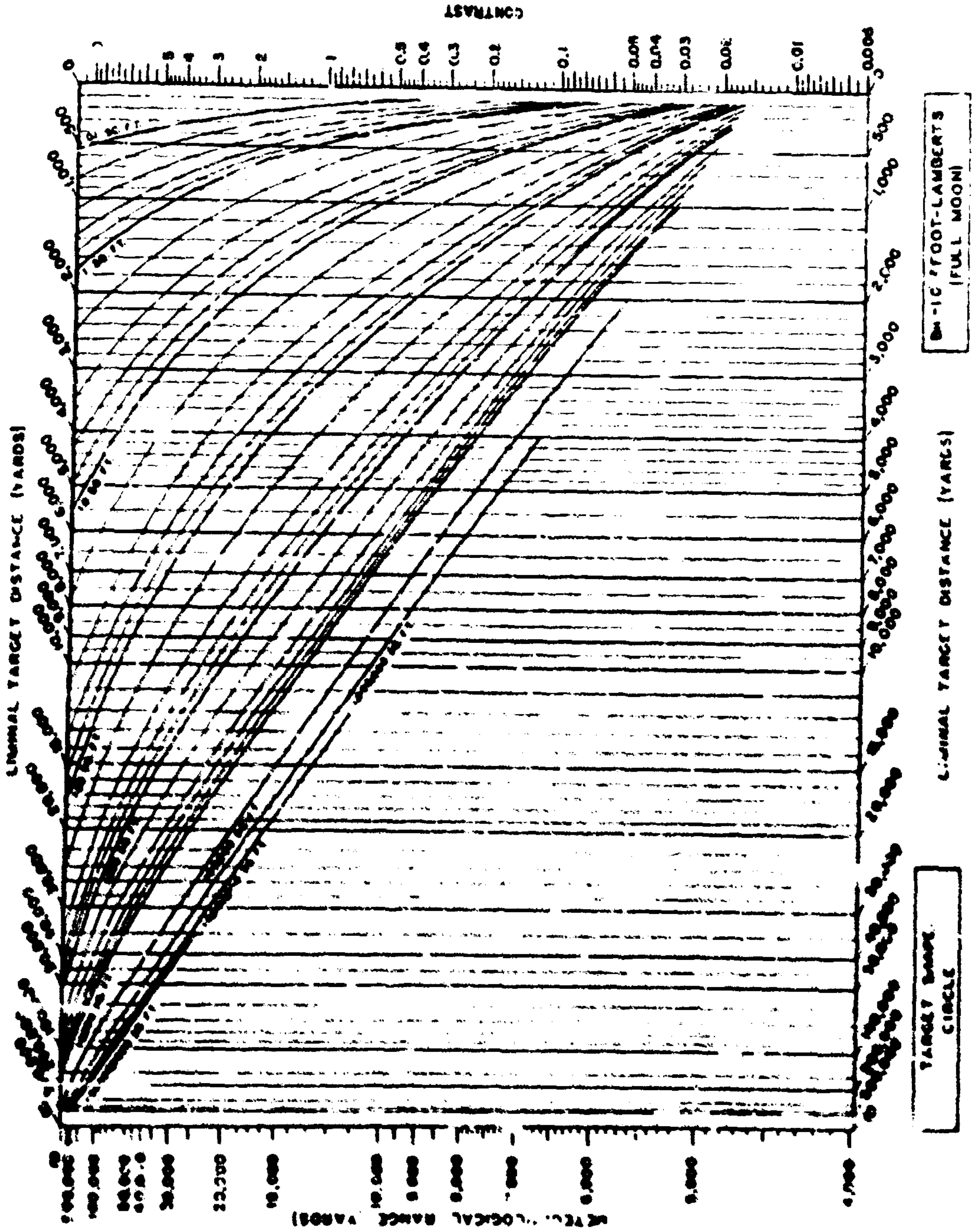
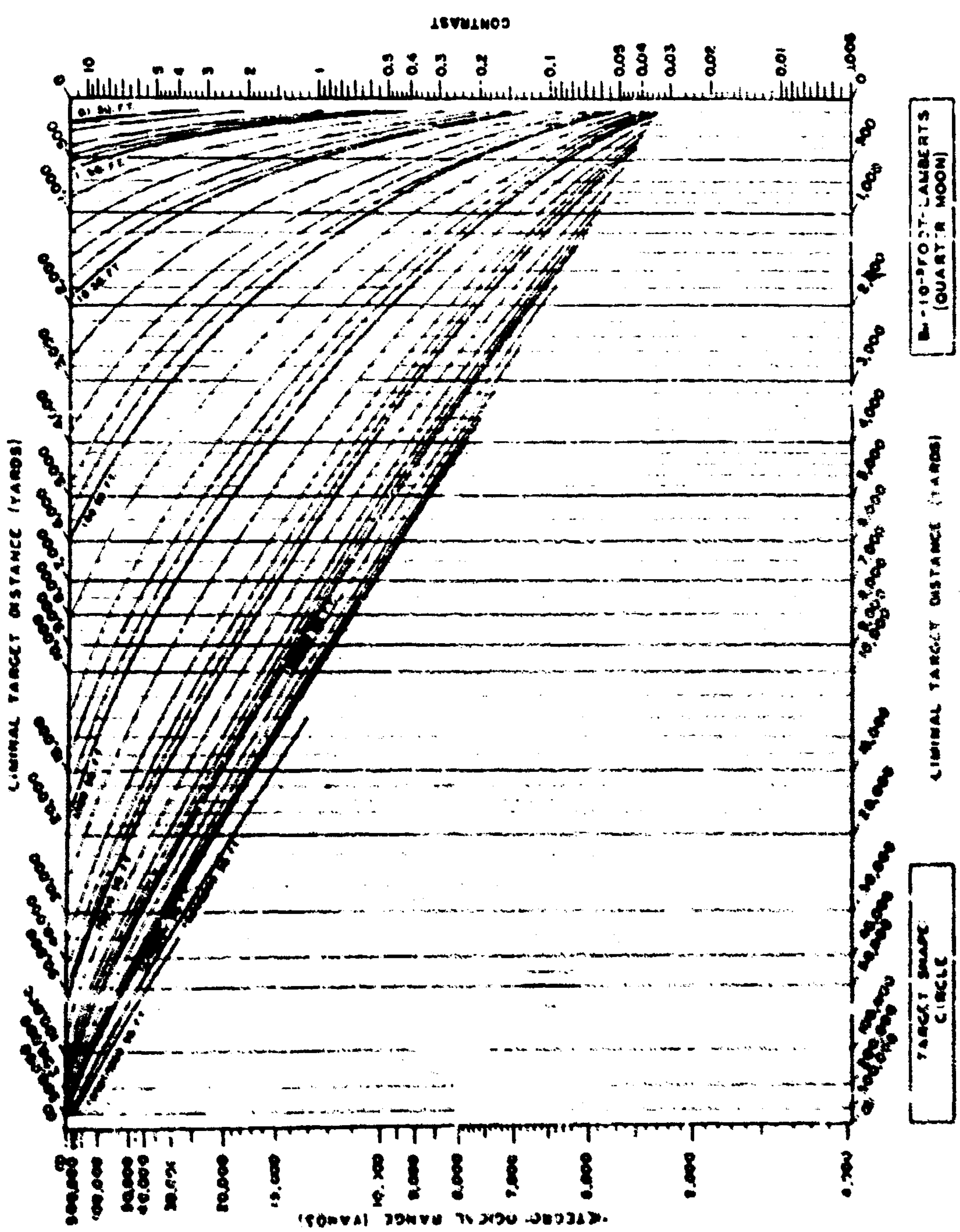


FIGURE 7



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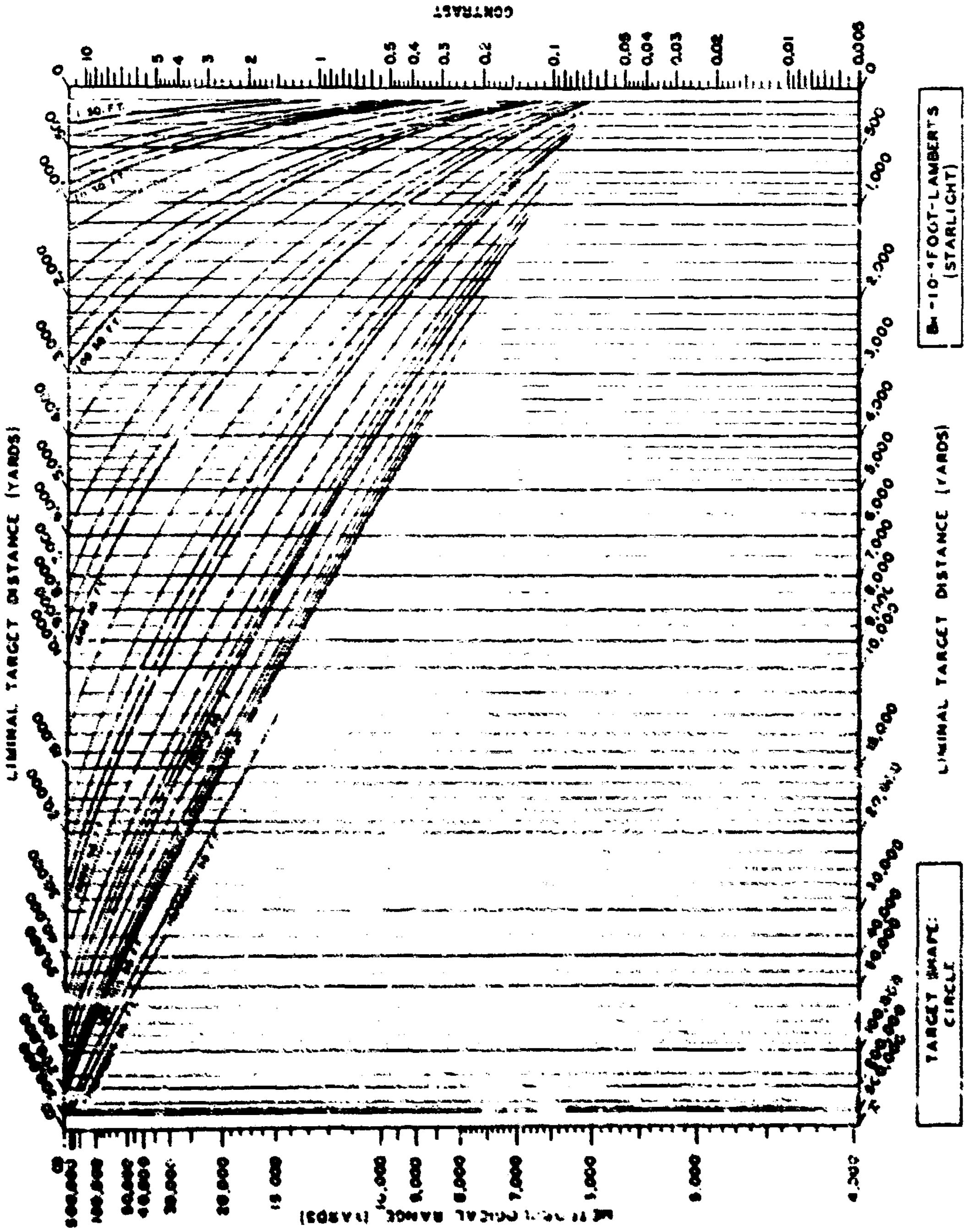
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
LIMINAL TARGET DISTANCE (YARDS)
B=10^-4 FOOT-LAMBERTS (STARLIGHT)
TARGET SHAPE: CIRCLE

FIGURE 9

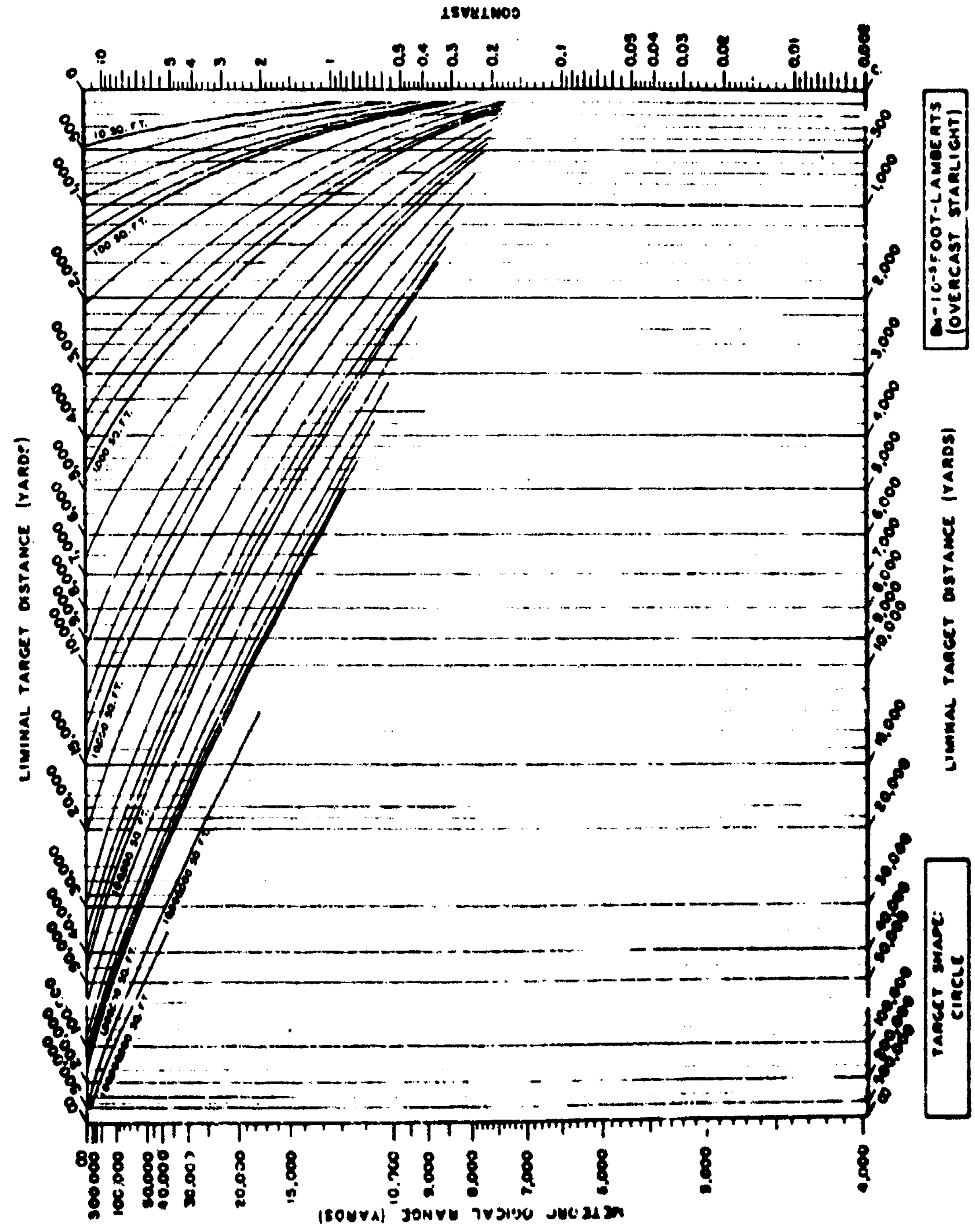
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
OVERCAST STARLIGHT
TARGET SHAPE: CIRCLE

FIGURE 10

[illegible] when viewed along a homogeneous, horizontal sight path against a uniform background of horizon sky. The use of the visibility charts (and modifications of them) for the solution of problems of increased complexity and greater realism is described in later sections of this chapter. In such cases, the reliability of the predicted values of liminal target distance depends upon the accuracy with which the conditions assumed by the user of the charts agree with the actual conditions.

4.4 THE SIGNIFICANCE OF LIMINAL TARGET DISTANCE

When used in the manner described in the foregoing section, the nomographic visibility charts predict the distance at which the target will be liminally visible. It was explained in Chapter 3 that a target is liminally visible when an observer who is forced to judge whether the target is present or absent is as likely to be right in his judgment as he is likely to be wrong, correction having been made for chance. Unfortunately, the observer is quite unaware that half his answers are right. He has no confidence that he has seen the target. *The probability of an observer voluntarily reporting the presence of a liminally visible target is nearly zero.*

4.4.1 The Sighting Range

At some range less than the liminal distance, the observer becomes conscious of seeing the target. The Tiffany observers became convinced that the threshold of confidence usually coincides with a 90-10 chance of making a correct report. They also discovered that *in terms of contrast* the slope of the psychometric function is nearly independent of adaptation level and target size. The slope is such that *if a given target is liminally visible, a similar target having double the contrast will be seen with threshold confidence.*

The approximate range at which a target will be seen with threshold confidence can be predicted from the nomographic visibility charts by dividing the inherent contrast of the target by two before entering the data on the chart. For example, if, in Figure 1, the dashed line connected 20,000 yards on the meteorological range scale with 0.50 on the contrast scale, a target distance of 9,260 yards would be indicated. At approximately this distance, [illegible] the *sighting range*, the target would be seen with threshold confidence. Nomographic charts have been drawn to indicate the liminal target distance rather than the sighting range, because the former quantity has a precise physical significance not shared by the latter.

4.5 VISIBILITY OF NONCIRCULAR UNIFORM TARGETS

One of the first experiments performed by the Tiffany Foundation compared the visibility of the silhouette of a ship with that of a circular target having the same area. The experiment was repeated, using the silhouette of an airplane. These experiments suggested that uniform targets of equal area and equal apparent contrast are equally visible, regardless of their shape. Later experiments showed, however, that in certain extreme cases a correction for target shape is required. Indeed, as shown by Figure 36, Chapter 3, the liminal contrast of a uniform rectangular target, having a length 100 times its width and subtending a solid angle of 100 square minutes, has been found to be more than six times greater than the liminal contrast of a square or circular target of the same area. *The visibility of a uniform target of any shape is never greater than the visibility of a uniform circular target of the same area and apparent contrast.*

Visibility Charts for Rectangular Targets

Each of the sixteen figures (Figure 11 through 26) is a nomographic visibility chart for uniform rectangular targets seen against a uniform background of horizon sky having the brightness B_H indicated at the lower right corner of the diagram. The side-to-side ratio of the rectangle to which a chart applies is indicated at the lower left corner of the diagram.

Because the form factors for rectangles reported in Section 3.2.9 depend upon the angular size of the target and therefore upon its distance, special visibility charts are required for rectangular targets. Such charts are presented in Figures 11 through 26. They have been produced by applying the appropriate values of form factor to the data from which Figures 2 through 10 were plotted. The visibility of a rectangular target of side-to-side ratio for which no chart is given can be inferred by finding the re-

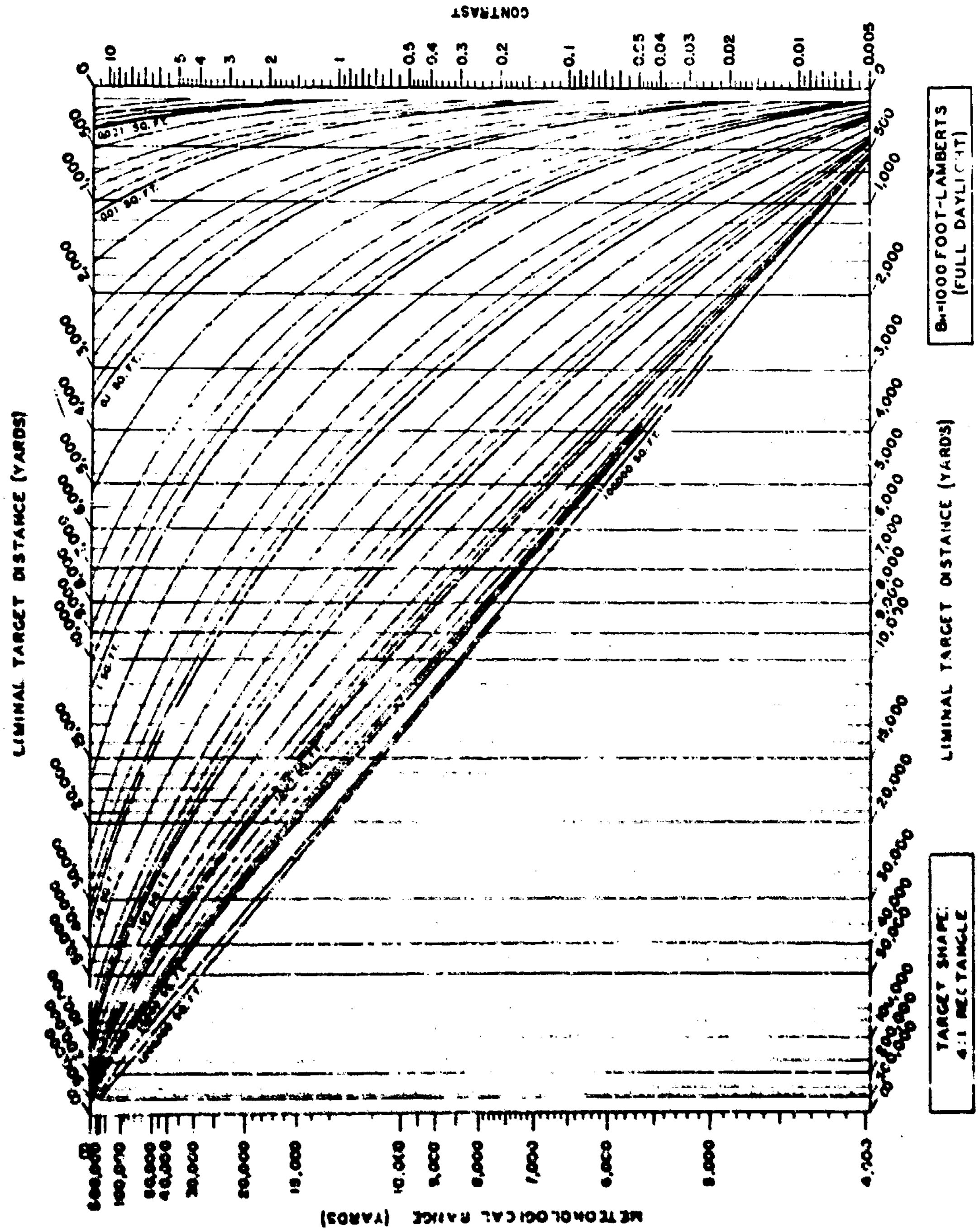
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
B=1000 FOOT-LAMBERTS (FULL DAYLIGHT)
TARGET SHAPE: 4:1 RECTANGLE

FIGURE 11

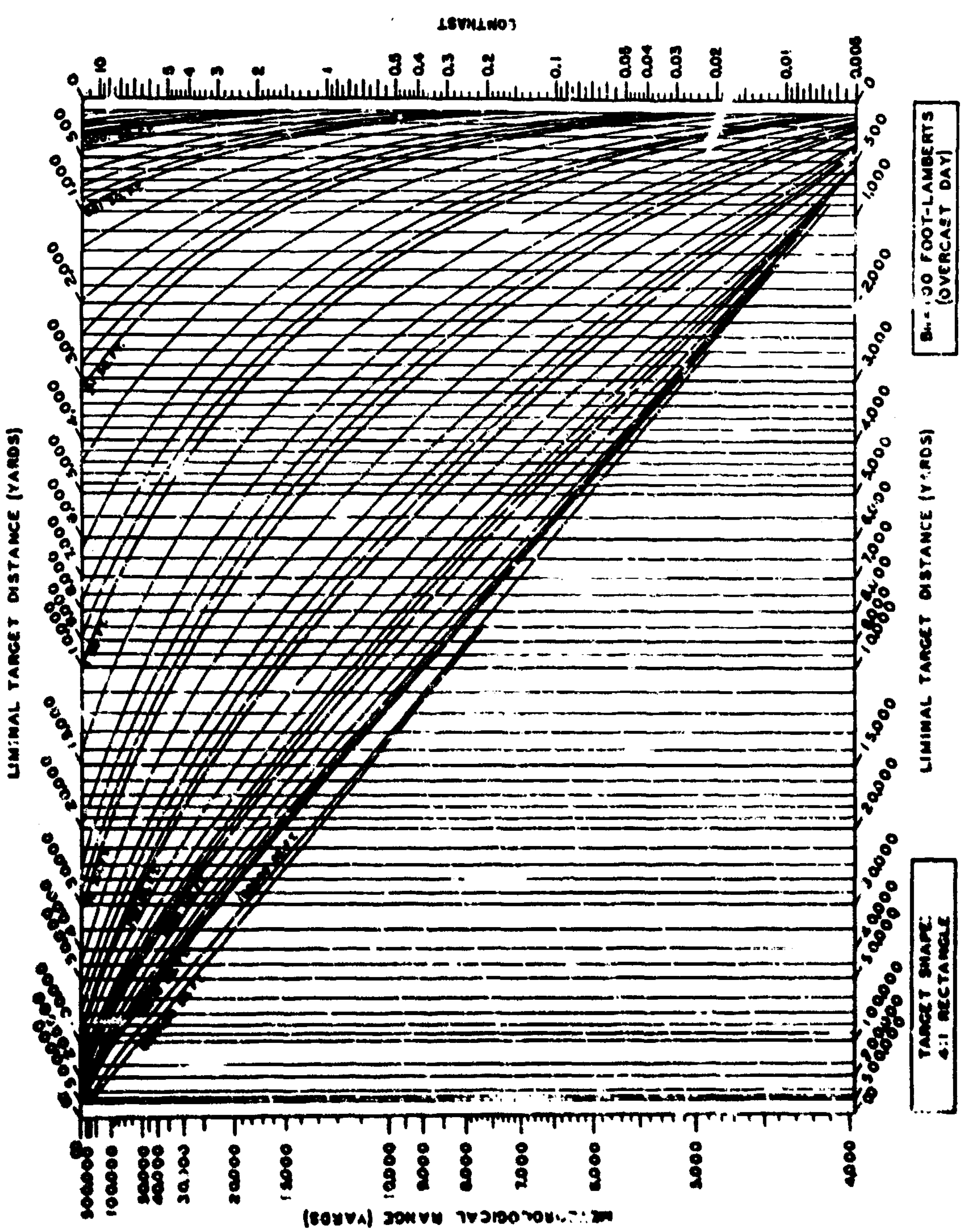

FIGURE 12

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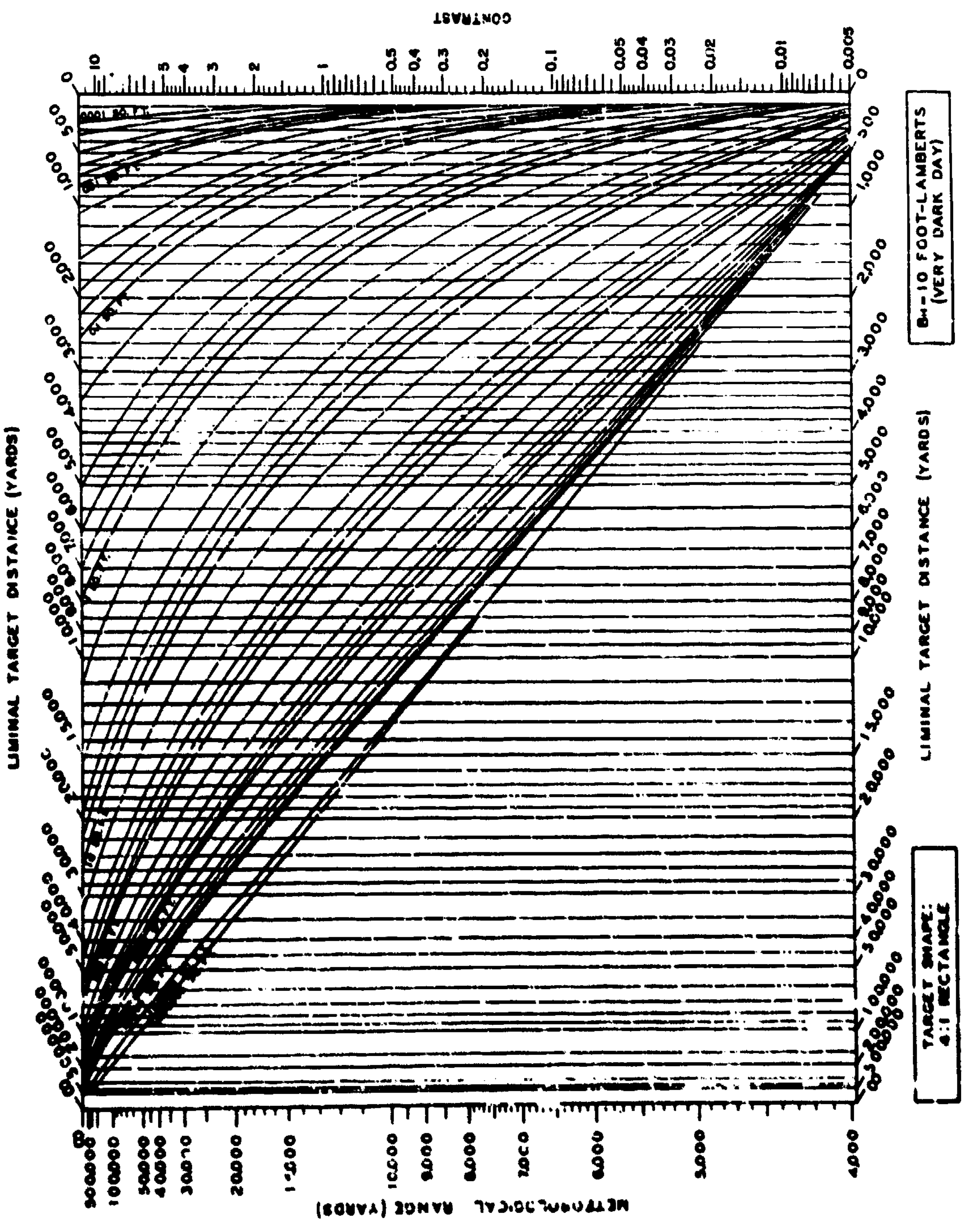
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
BH-10 FOOT-LAMBERTS (VERY DARK DAY)
TARGET SHAPE: 4:1 RECTANGLE

FIGURE 13

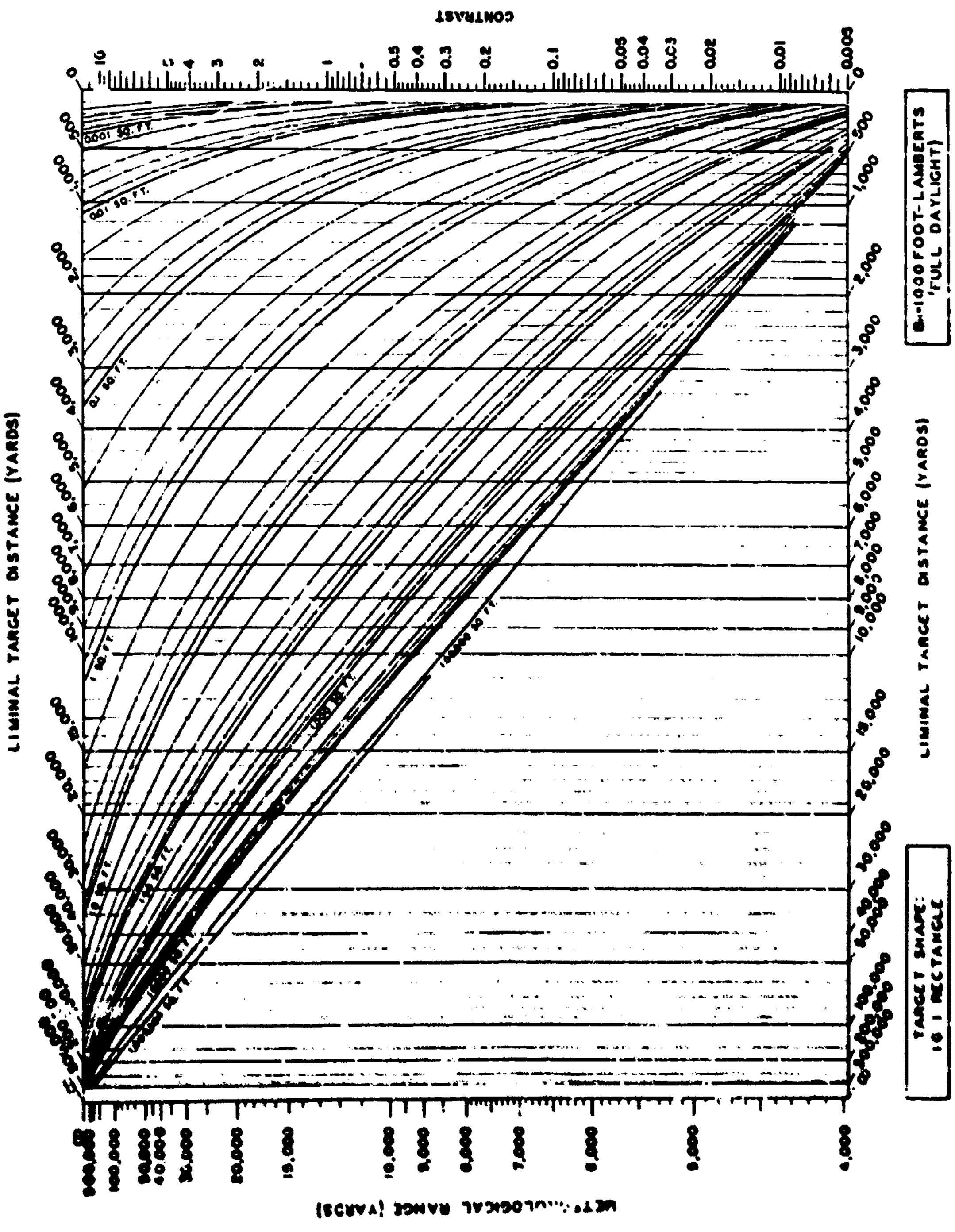
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
B=1000 FOOT-LAMBERTS (FULL DAYLIGHT)
TARGET SHAPE: 16:1 RECTANGLE

Figure 11

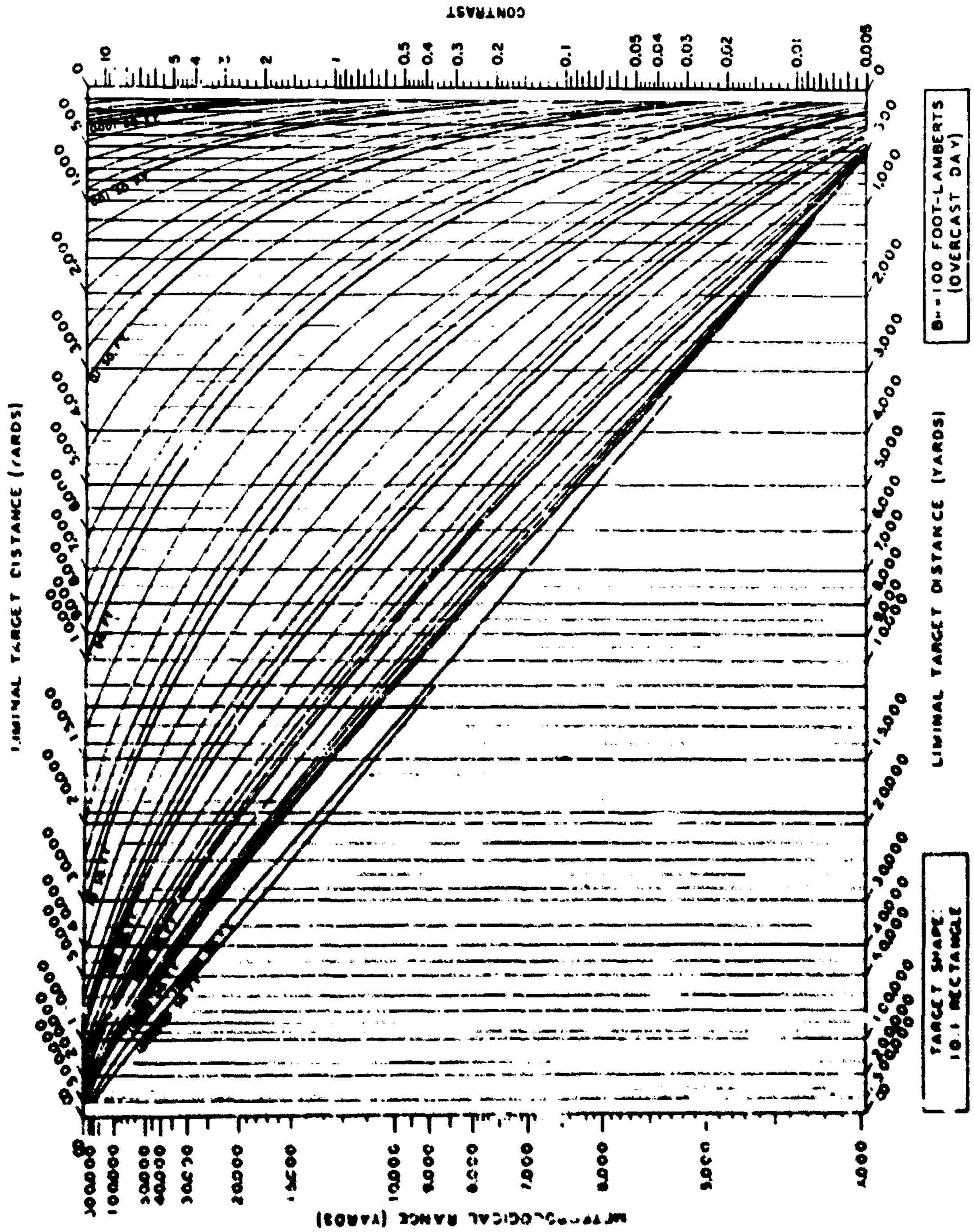
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
B = 100 FOOT-LAMBERTS (OVERCAST DAY)
TARGET SHAPE: 10:1 RECTANGLE
METEOROLOGICAL RANGE (YARDS)

FIGURE 15

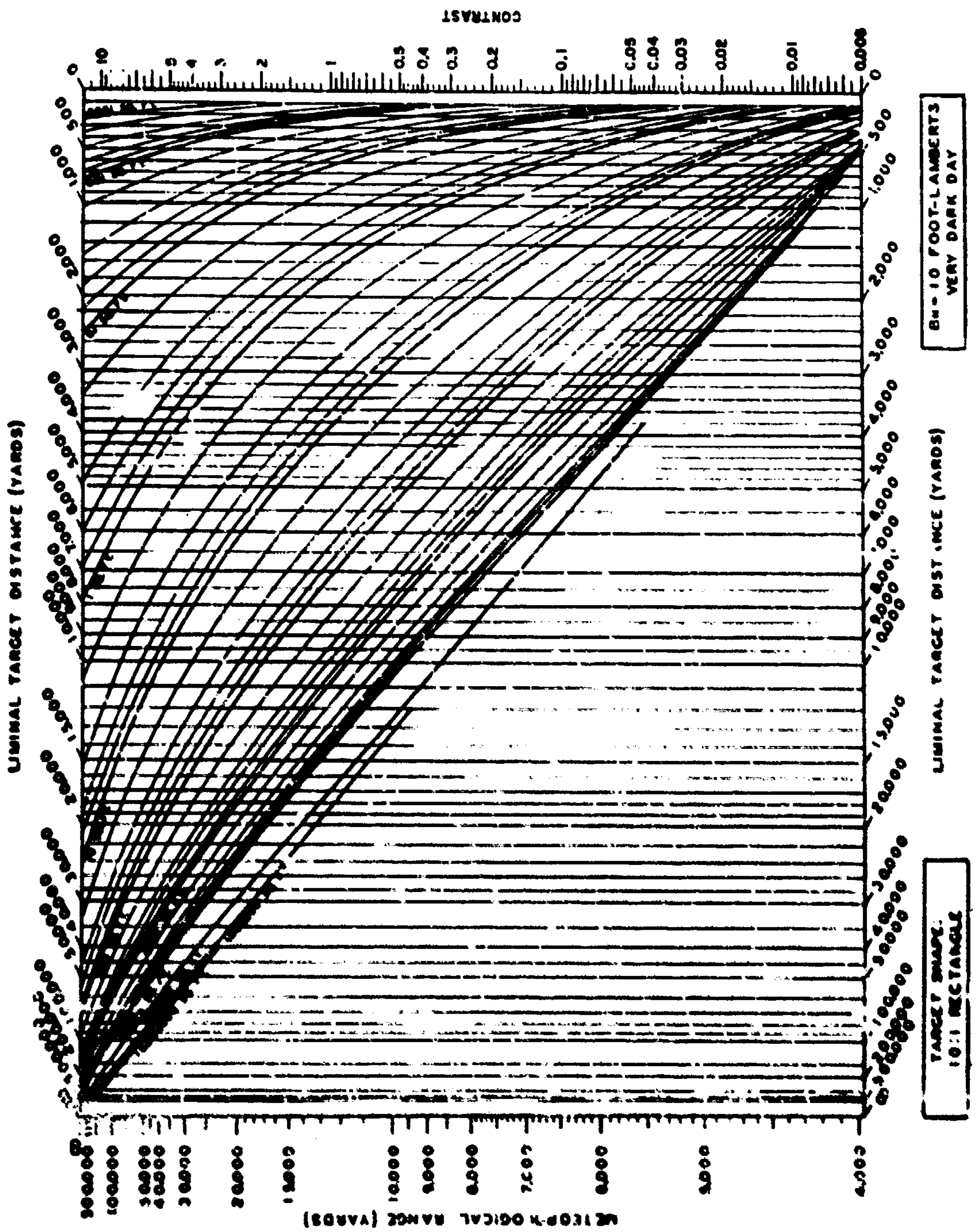
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
Bt = 10 FOOT-LAMBERTS
VERY DARK DAY
TARGET SHAPE:
10:1 RECTANGLE

FIGURE 16

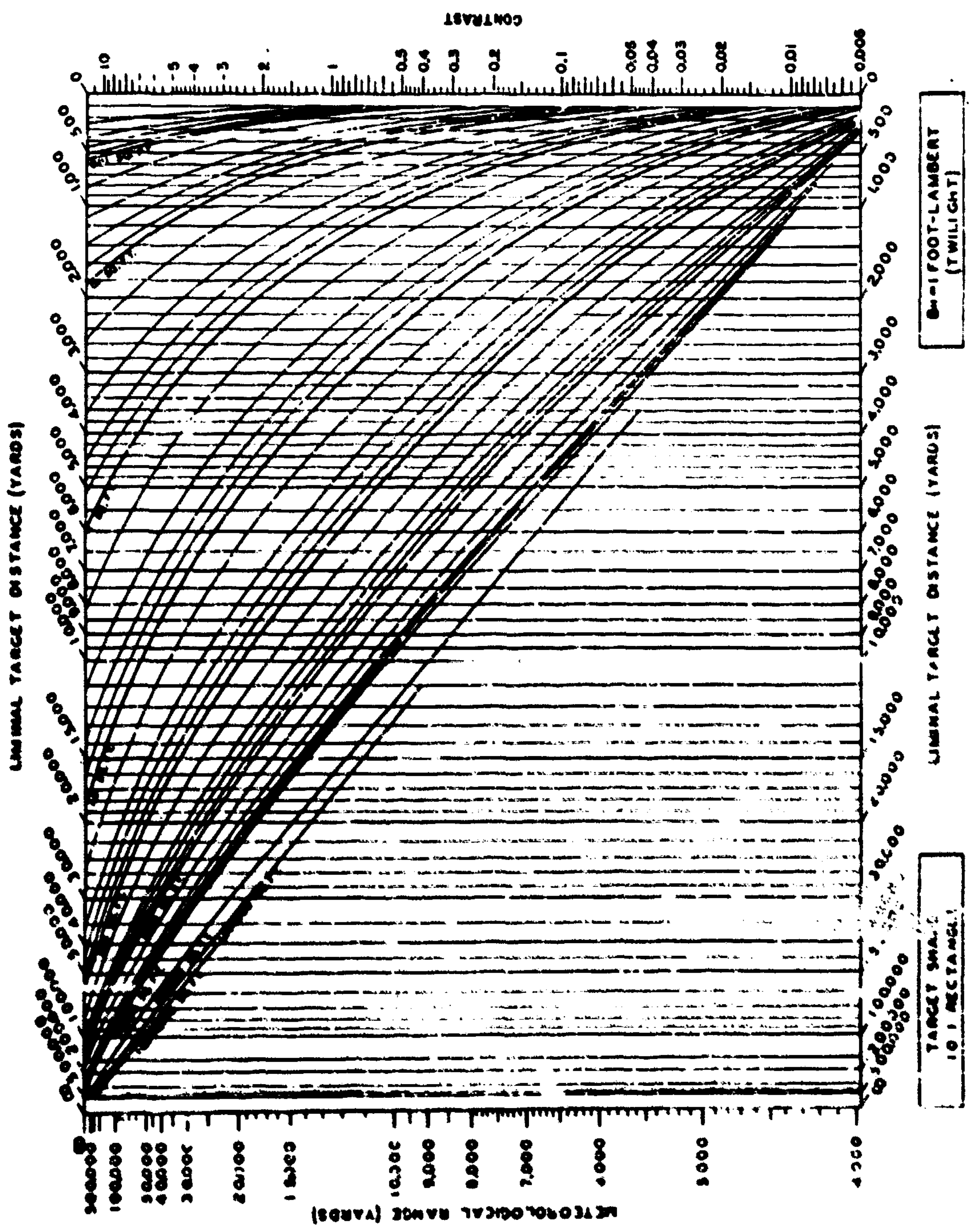
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
B=1 FOOT-LAMBERT (TWILIGHT)
TARGET SHAPE 10:1 RECTANGLE

FIGURE 17

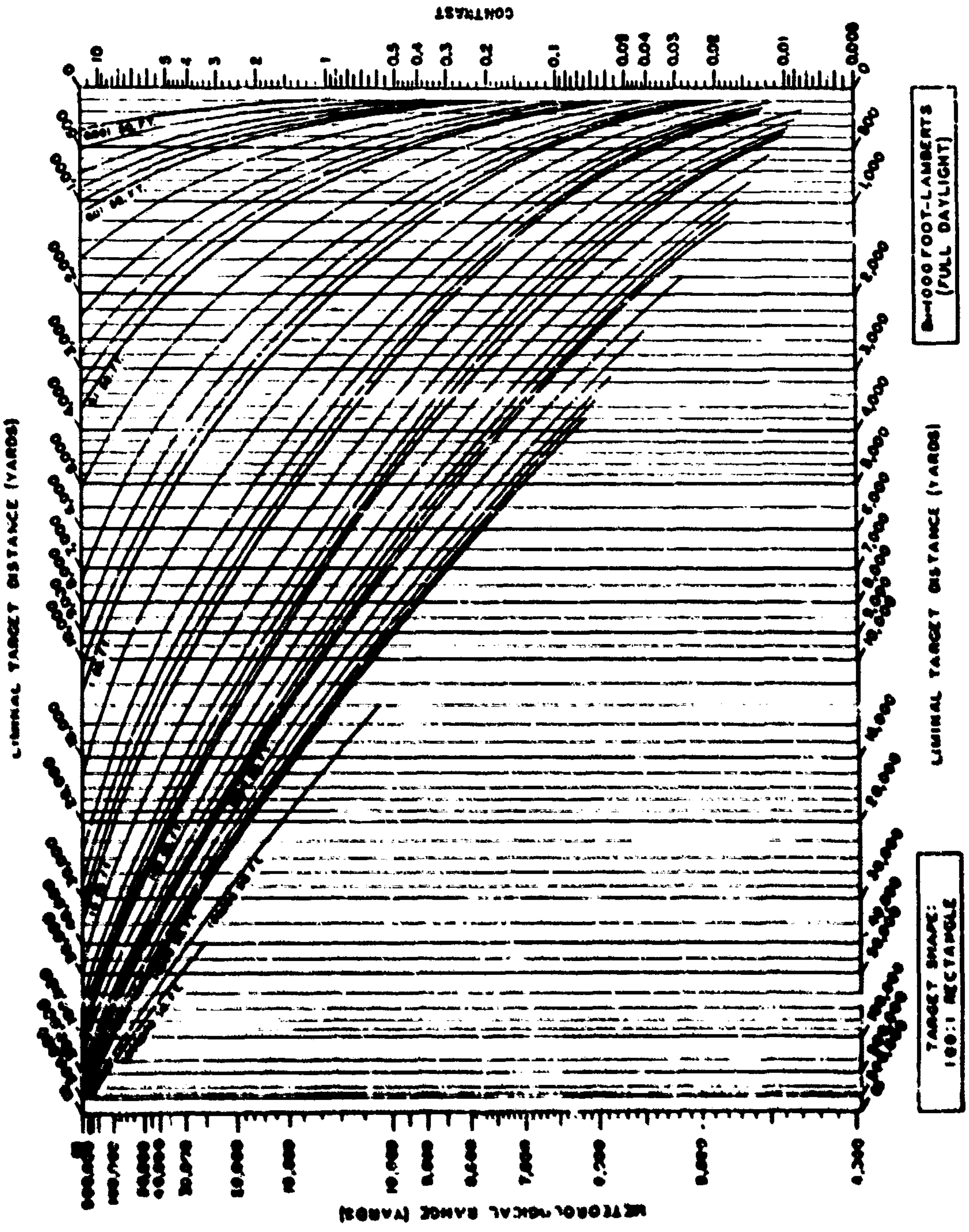
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
B=1000 FOOT-LAMBERTS (FULL DAYLIGHT)
TARGET SHAPE: 100:1 RECTANGLE

FIGURE 15

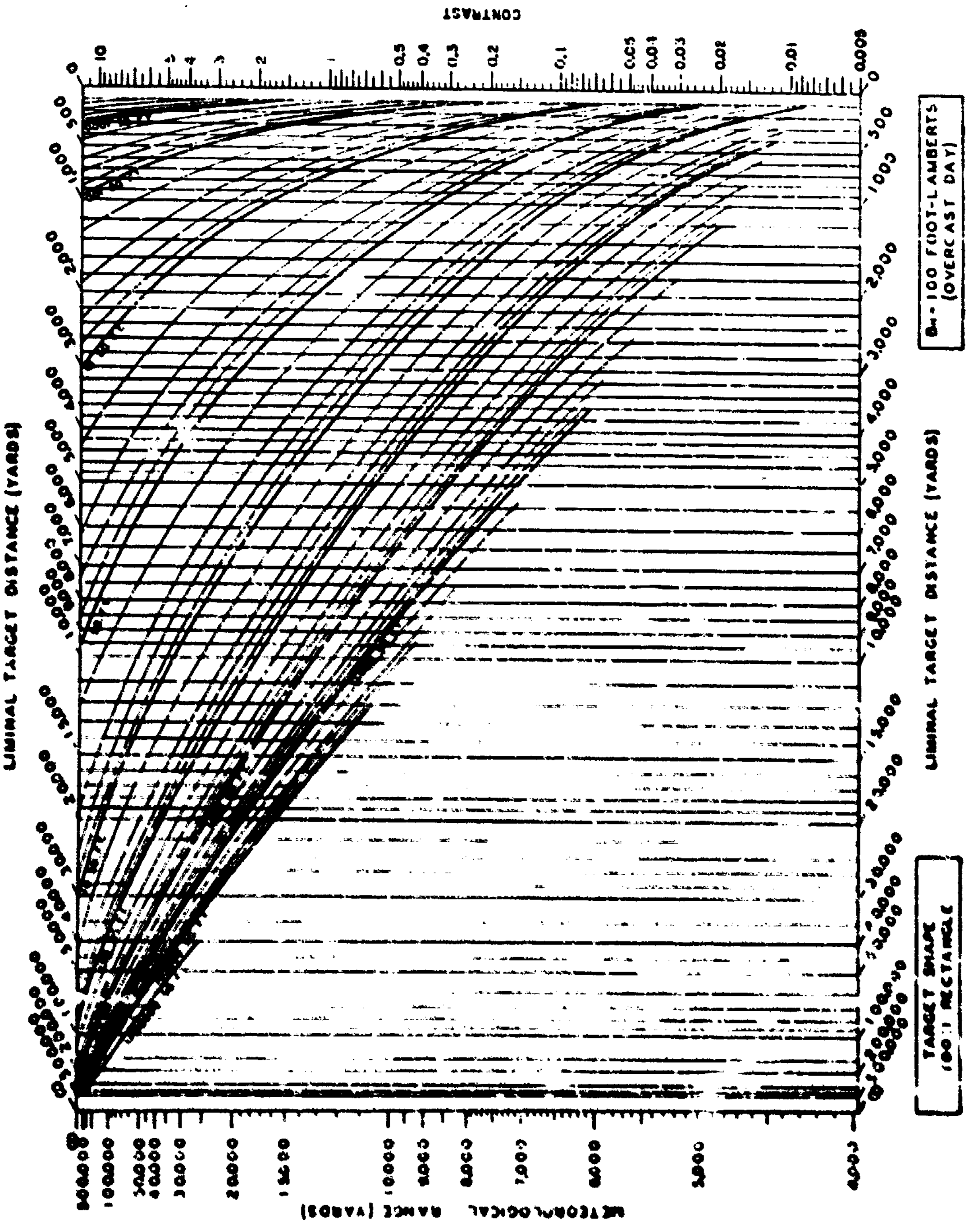
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
B₀ - 100 FOOT-LAMBERTS (OVERCAST DAY)

Figure 19

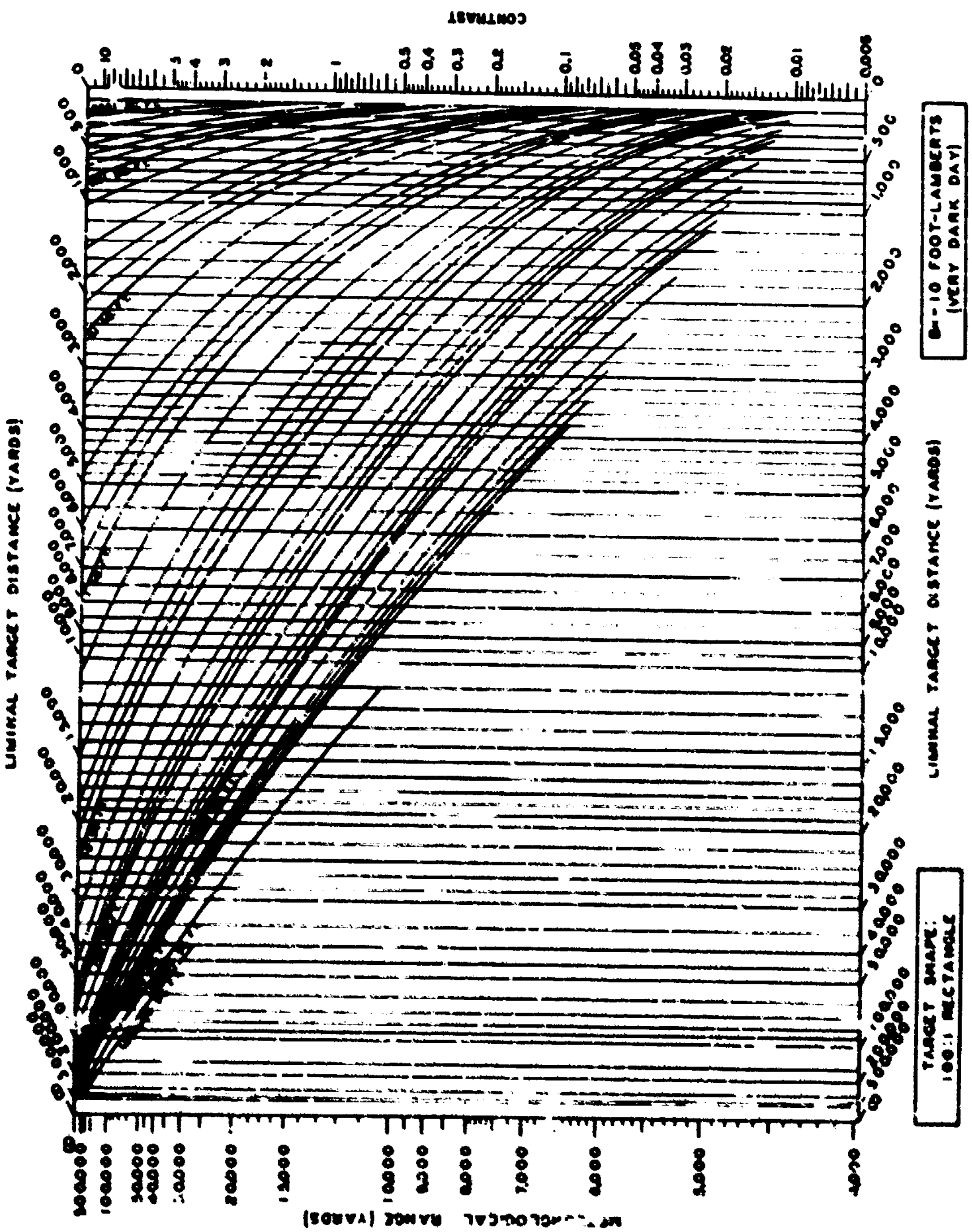
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
B = 10 FOOT-LAMBERTS
(VERY DARK DAY)
TARGET SHAPE:
100:1 RECTANGLE

FIGURE 28

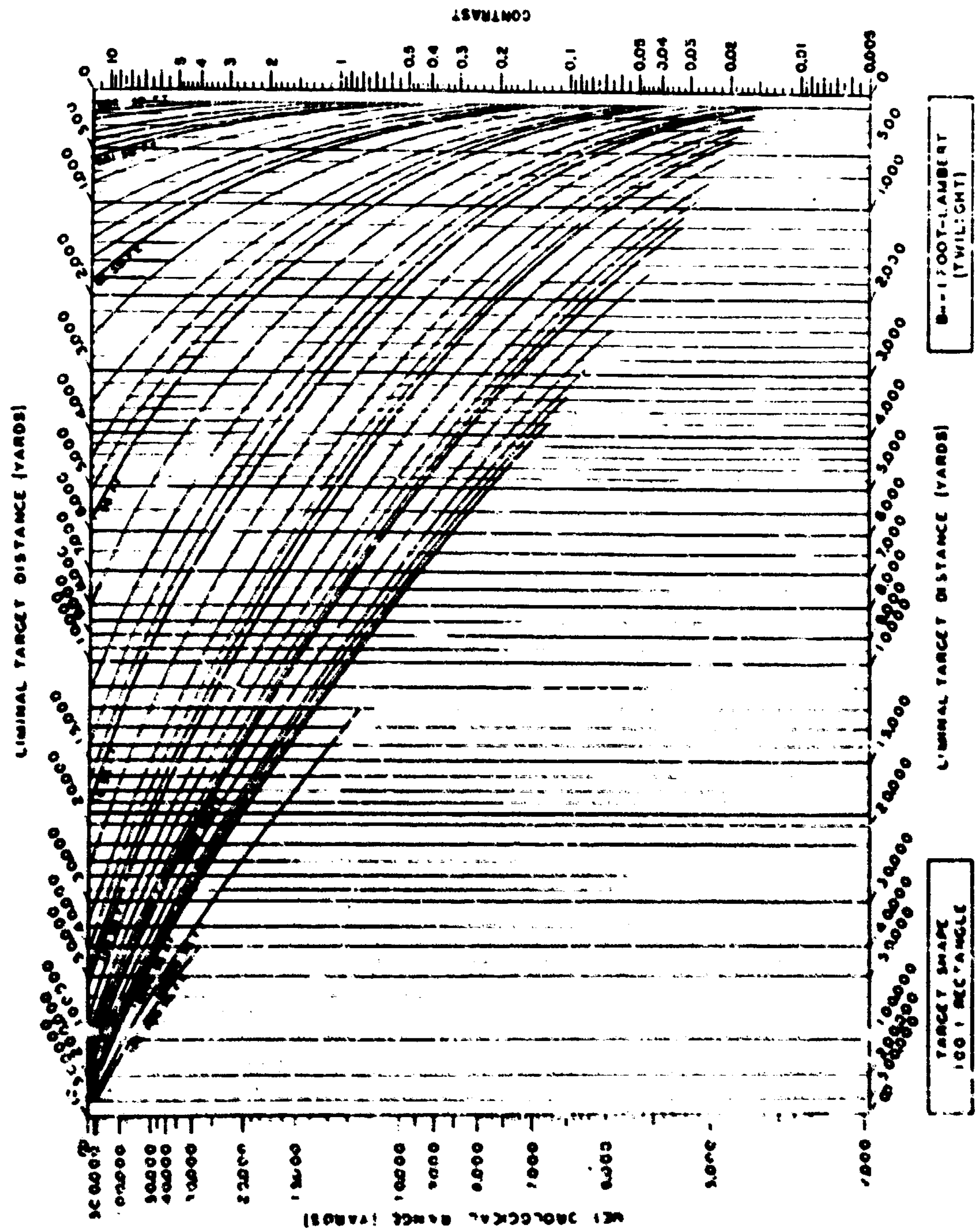

FIGURE 21

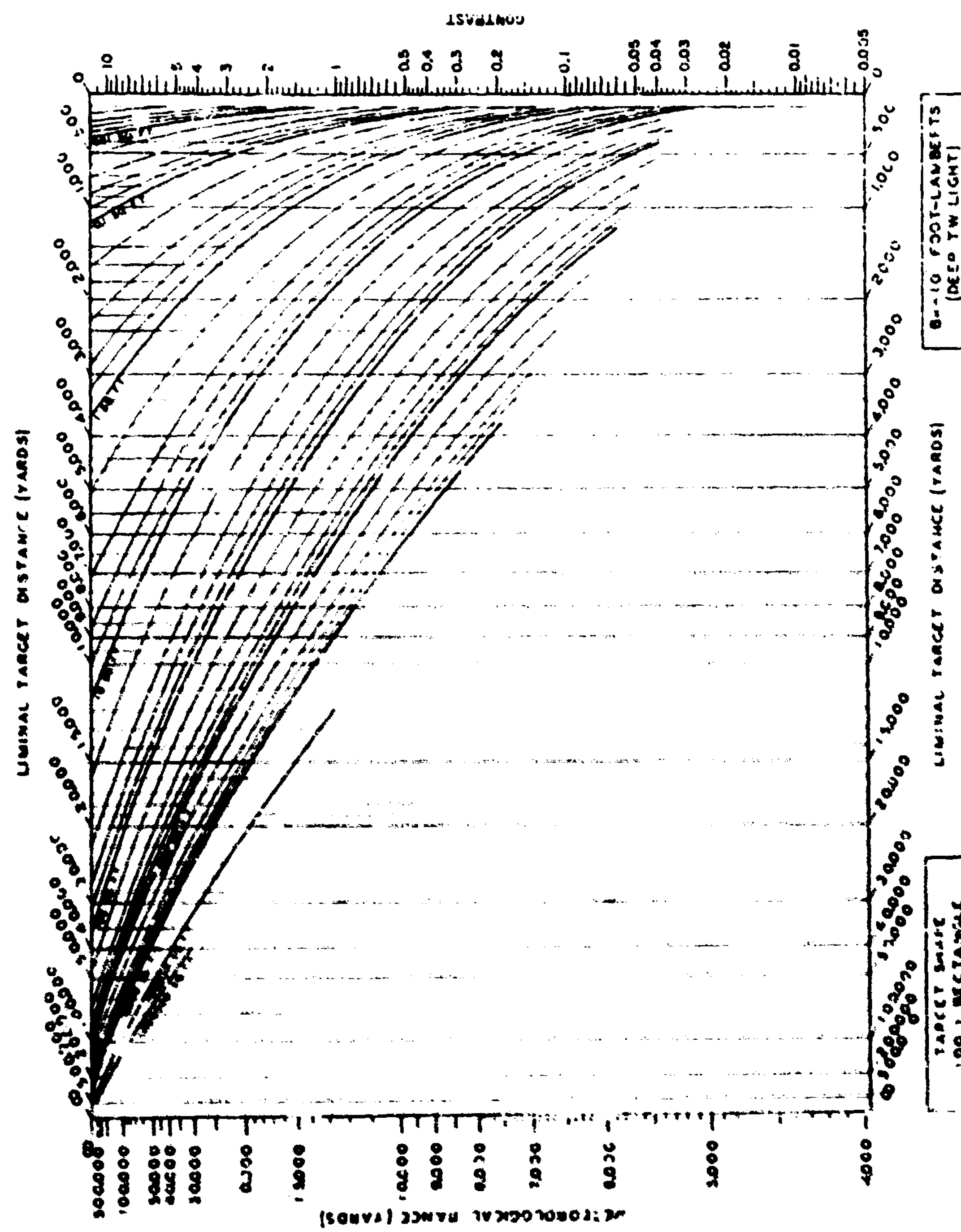
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
TARGET SHAPE 100:1 RECTANGLE

FIGURE 22

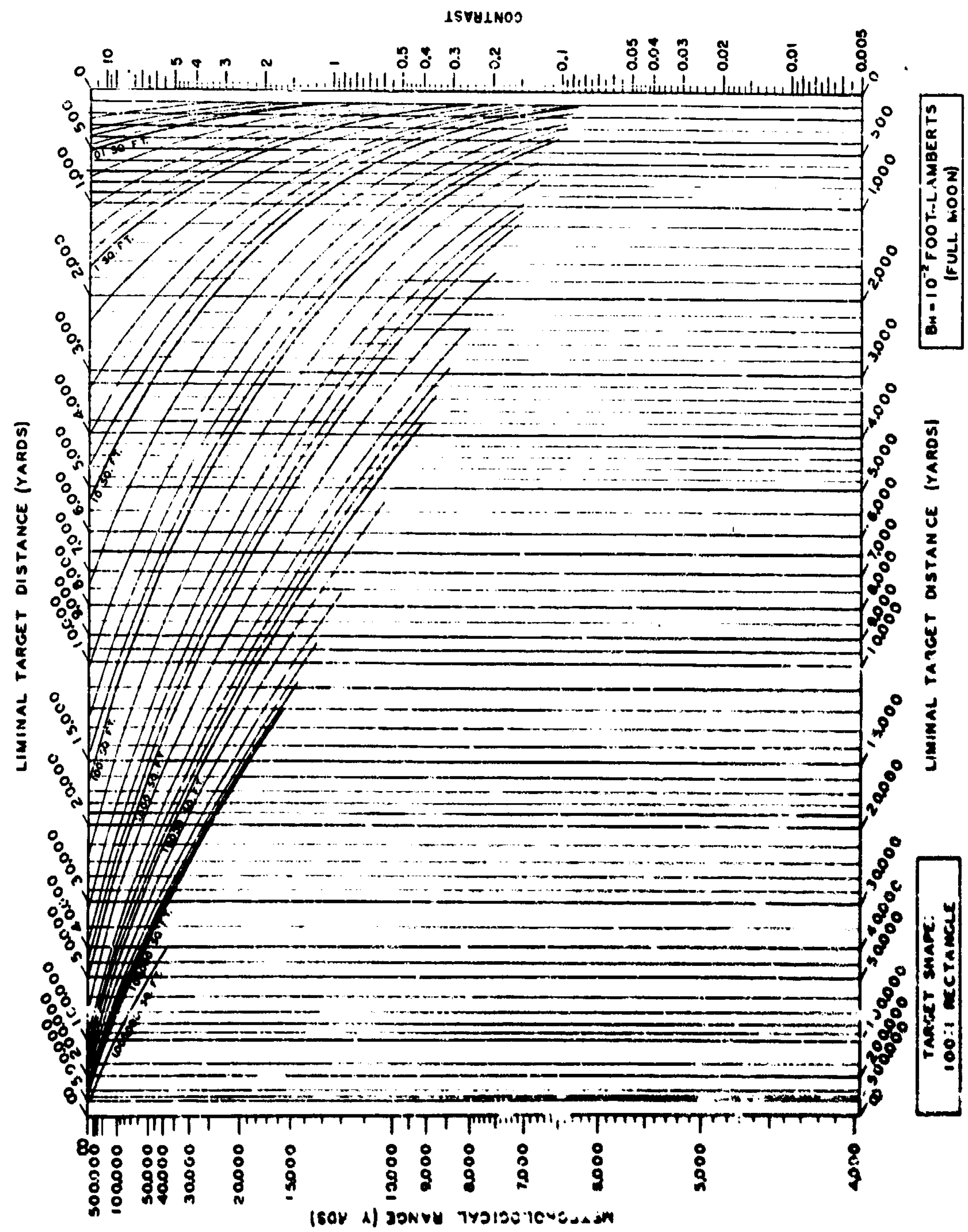
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
LIMINAL TARGET DISTANCE (YARDS)
BH = 10^-2 FOOT-LAMBERTS (FULL MOON)
TARGET SHAPE: 100:1 RECTANGLE

FIGURE 23

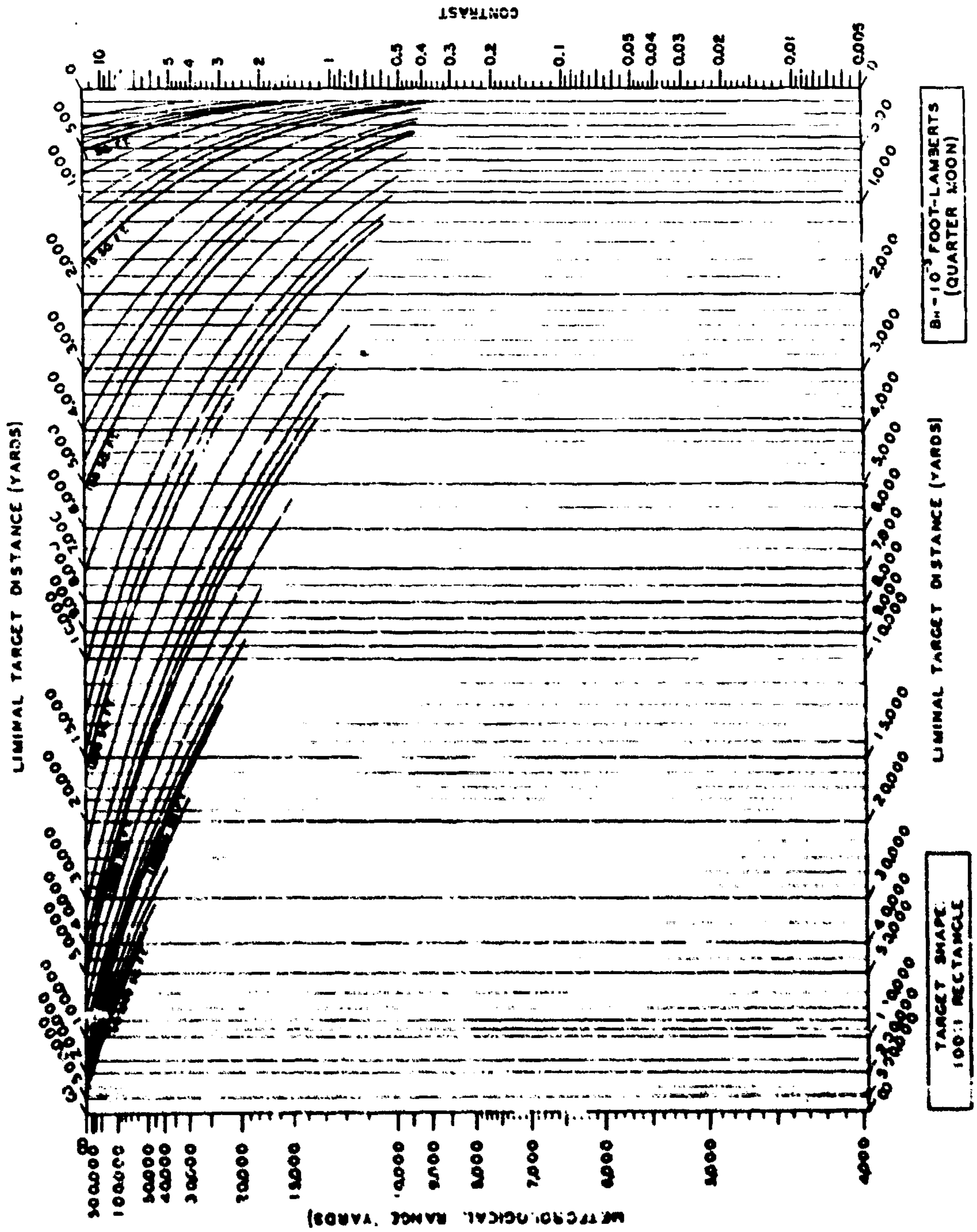
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
$B_H = 10^{-3}$ FOOT-LAMBERTS (QUARTER MOON)
TARGET SHAPE 100:1 RECTANGLE

FIGURE 24

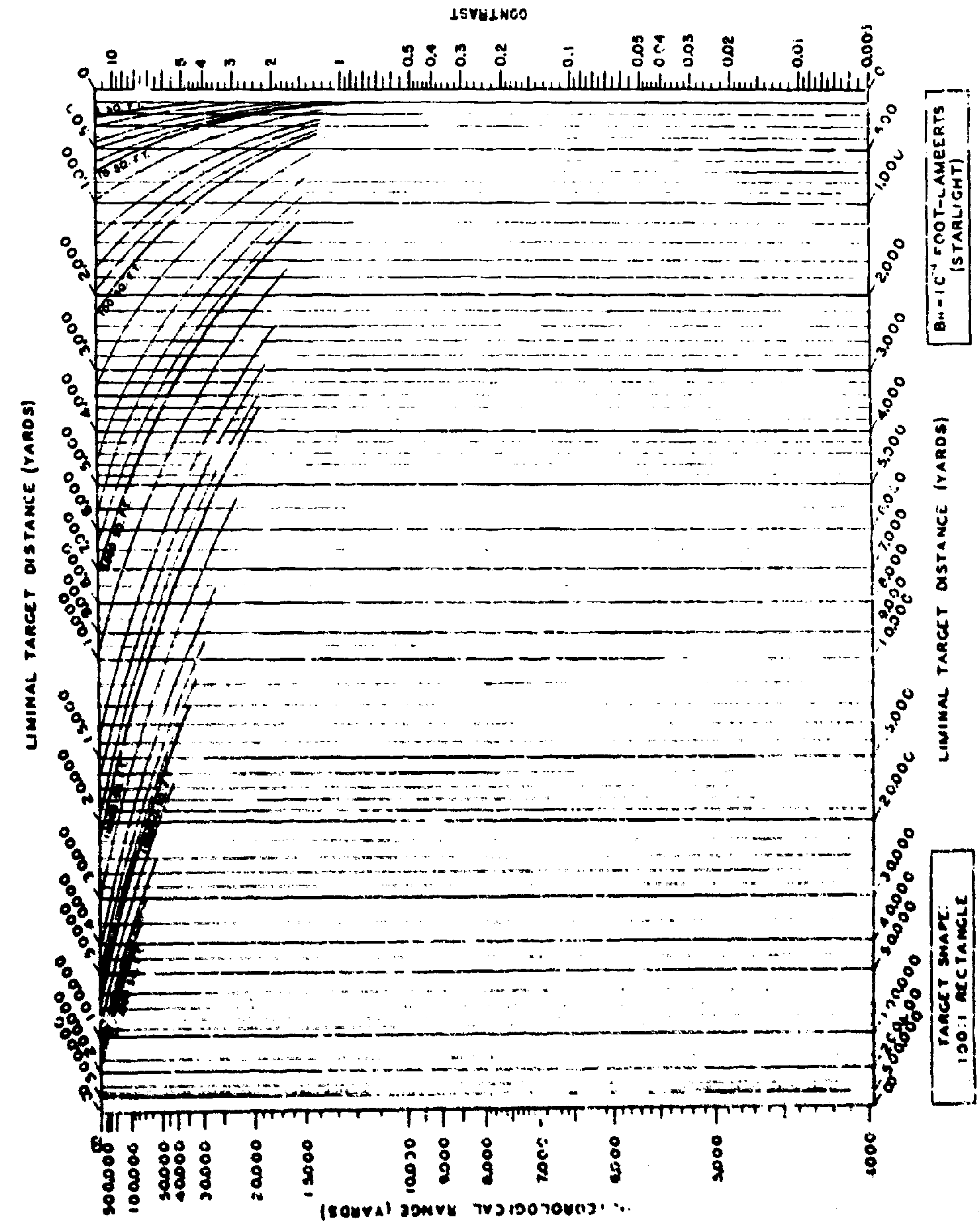
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
LIMINAL TARGET DISTANCE (YARDS)
TARGET SHAPE: 100:1 RECTANGLE
(STARLIGHT)
RANGE (YARDS)

FIGURE 25

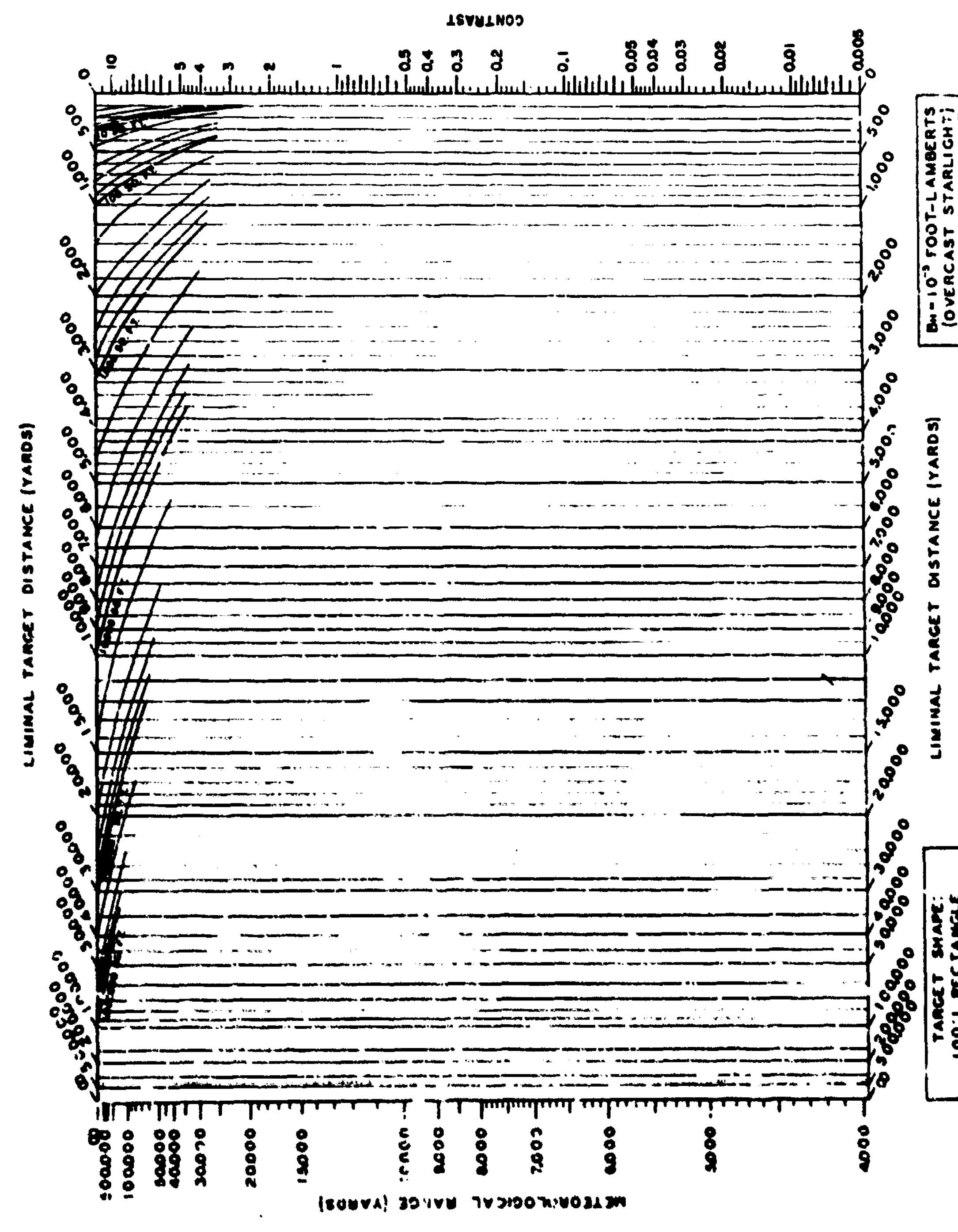
CONTRAST
LIMINAL TARGET DISTANCE (YARDS)
METEOROLOGICAL RANGE (YARDS)
$B_H = 10^{-3}$ FOOT-LAMBERTS (OVERCAST STARLIGHT)
TARGET SHAPE: 100:1 RECTANGLE

FIGURE 26

and a less extreme case. For example, the visibility of a 7:1 rectangle is intermediate between the visibility of the corresponding 10:1 and 4:1 rectangles for which charts are given. The visibility of uniform targets of irregular shape is usually identical with the visibility of the uniform rectangular target that they most closely resemble. This rule does not apply to a hollow rectangle or to an annulus. Such a target should be treated in the manner described in Section 4.9.

4.6 BACKGROUNDS OTHER THAN THE SKY

It was shown in Section 2.3.7 that, in the case of targets viewed against backgrounds other than the sky, the apparent contrast at distance X of a target seen against any background is related to the inherent target contrast by the expression

$$C_x = \frac{C_0}{1 + \frac{B_H}{B_0}\left(e^{3.912X/v} - 1\right)}, \tag{3}$$

where B_H/B_0 is the ratio of the brightness of the horizon sky in the direction of the target to the brightness of the background of the target and v is the meteorological range. B_H/B_0 is a limiting case of the *sky-ground ratio* discussed in Section 2.3.6.

4.6.1 Visibility Charts for Any Background

The nomographic visibility chart shown in Figure 27 is identical with Figure 1 except that a sky-ground ratio scale has been added along the inside left margin, and the contrast scale has been moved to the center of the figure.

To illustrate the manner of using this chart, let the numerical example of Section 4.3 be re-solved for the case of a target viewed against a background having a brightness of 200 foot-lamberts. Since the brightness of the horizon sky was assumed to be 1,000 foot-lamberts, the sky-ground ratio is 5.0. The inherent contrast of the target against its background is

$$C_0 = \frac{10 - 200}{200} = -0.95.$$

Place a straightedge across the chart in such a manner as to connect 5.0 on the sky-ground ratio scale with ± 0.95 on the contrast scale. The position ... as shown by the dotted line in Figure 27. Place the point of a pencil at the intersection of this line with the right-hand vertical boundary of the chart. Rotate the straightedge until it connects this point with 20,000 yards on the meteorological range scale as shown by the dashed line. From the intersection of the dashed line and the curve, proceed vertically to a reading of 6,900 yards on the scale of liminal target distance.

A complete set of charts similar to Figure 27 is presented in Chapter 5 for dealing with problems of visibility downward along slant paths. Figure 6 corresponds with Figure 27. Figures 6 to 30 should be used for the solution of problems of the type illustrated in this section.

4.6.2 Uncertain Adaptation

Whenever a target is viewed against a background limited in angular extent and differing in brightness from the major portion of the field of view, uncertainty exists concerning the effective level of brightness to which the eyes of the observer are adapted. When the background of the target appears dark, the liminal target distance may be less than would be predicted by assuming the observer to be adapted to the brightness of the major portion of the field of view.

When the background of the target appears bright, the true liminal target distance may exceed the predicted value. This is illustrated by a ship seen as a silhouette against the moon. In this case, a first-order correction can be applied by using a nomographic visibility chart based upon the apparent brightness of the moon rather than upon the brightness of the night sky.

4.7 THE VISIBILITY OF SIGNAL LIGHTS

The illumination on the pupil of an observer's eye produced by a distant point source of intensity I_0 is given by

$$E_X = \frac{I_0}{X^2} e^{-3.912X/v}, \tag{4}$$

where v is the meteorological range. This relation is valid only when X is so great that the light may be considered a "point source" in the sense that the product of target area and liminal contrast is constant.

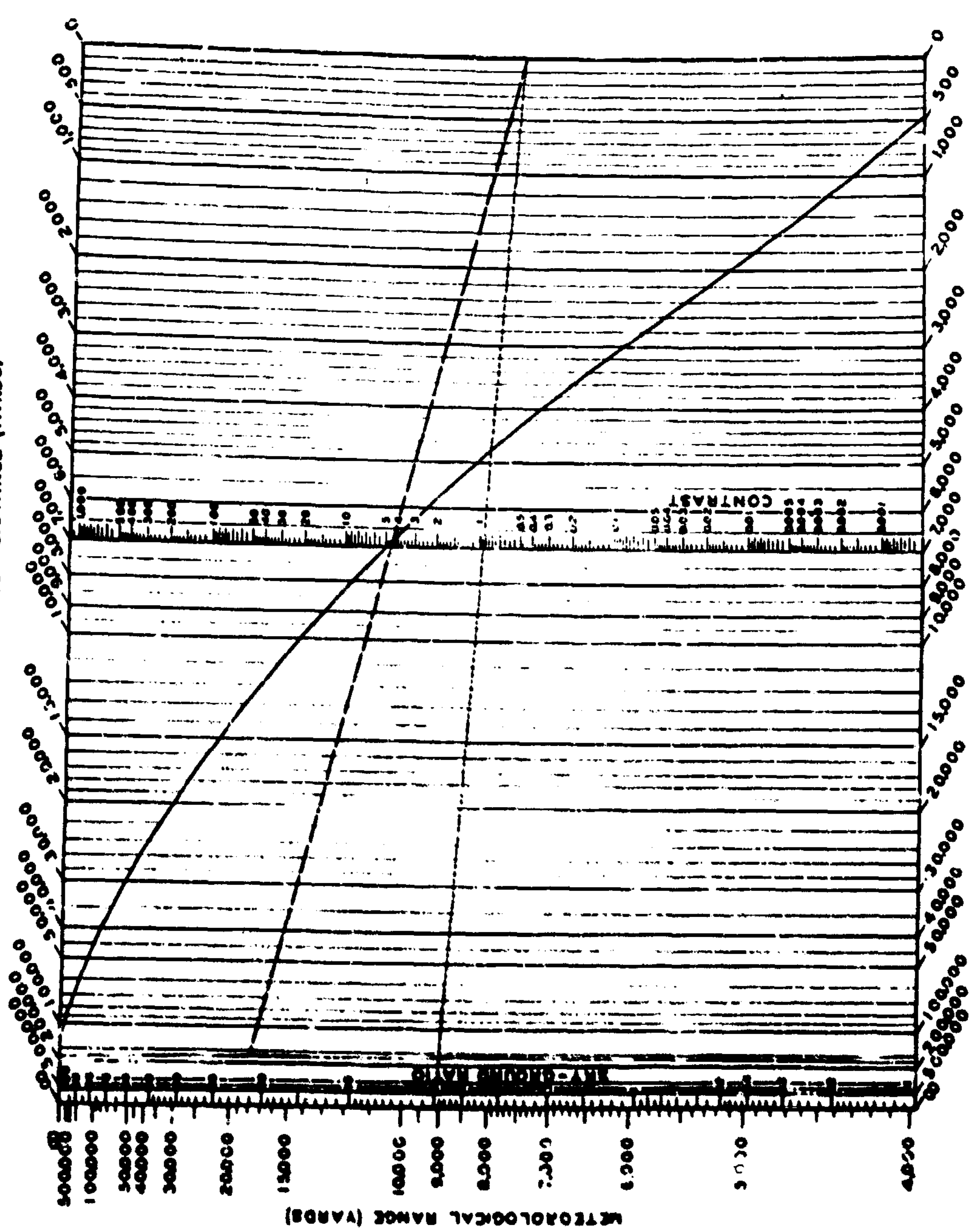

FIGURE 27. Nomographic visibility chart of the type used when the target is seen against a background other than the horizon sky. *The original of this figure is a photostat which shows numerous distortions and must not, therefore, be used in the solution of problems.*

Curved line represents data from Figure 25 for uniform, circular target 100 square feet in area when B_H = 1,000 foot-lamberts.

4.7.1 Maximum Angular Size of a Point Source

The curves of Figure 35, Chapter 3, are straight lines for small values of angular target size. The slope of these straight lines is $-\frac{1}{2}$, as would be expected from equation (4). Obviously, the maximum angular size of target for which equation (4) is valid is indicated by the point at which the curves in Figure 35 of Chapter 3 depart from a straight line. Table 1 has been obtained by inspection of a large-scale plot of that figure.

TABLE 1

Adaptation brightness (foot-lamberts)	Maximum angular size (min of arc)
1,000	0.708
100	0.708
10	0.750
1	0.891
10^{-1}	1.30
10^{-2}	2.82
10^{-3}	6.68
10^{-4}	8.55
10^{-5}	15.0

From this table, the range beyond which equation (4) applies to a searchlight of area A can be found by solving equation (1). For example, on a night when the sky brightness is 10^{-3} foot-lambert, a signal light having an area of 1 square foot may be considered as a point source beyond

$$X = \frac{1293\sqrt{1}}{6.68} = 194 \text{ yards.}$$

4.7.2 A Nomographic Visibility Chart for Signal Lights

Figure 28 is a visibility chart for predicting the range at which signal lamps or other point sources will be liminally visible. The chart is similar to the foregoing visibility charts in this volume, except that the contrast scale has been replaced by a scale of intensity. Each curve represents a decimal value of adaptation brightness.

As an example of a use of this chart, let it be required to determine the intensity of a signal lamp liminally visible at 10,000 yards on a foggy night when the sky brightness is 10^{-3} foot-lambert and the meteorological range is 5,000 yards. Place a straightedge across the chart so that it connects 5,000 yards of the meteorological range scale with the intersection of the 10,000 yards distance ordinate and the curve representing an adaptation level of 10^{-3} foot-lambert. The intersection of the straightedge with the intensity scale of the chart indicates the required liminal intensity of the signal lamp to be 2,500 candles.

4.8 VISIBILITY THROUGH BINOCULARS

The distance at which a specified target is liminally visible through perfect binoculars can be found from the nomographic visibility charts by multiplying the area of the target by the square of the magnifying power of the binoculars before entering the data on the chart. For example, suppose a pair of perfect 7-power glasses is used by the observer in the example of Section 4.3. Since the area of the target is 100 square feet, the area used in entering the chart is 4,900 square feet and the resulting liminal target distance is 22,500 yards. The liminal target distance for the unaided eye was shown in Section 4.3 to be 11,000 yards. It will be noted that, although 7-power glasses were used, the liminal target distance was increased by but a factor of 2. Only when the meteorological range is infinite do perfect binoculars having a magnifying power M permit objects to be seen M times as far as they can be seen by the naked eye.[40]

The foregoing discussion applies to *perfect* binoculars, by which is meant an instrument whose only effect is to increase the apparent angular size of the target. Actually, even the best binoculars fall somewhat short of the ideal, so that the liminal target distance predicted by means of the visibility charts should be considered as a limiting value, never exceeded but often approached by observers using real binoculars.

4.9 THE VISIBILITY OF NONUNIFORM TARGETS

A ship or a plane is usually seen as a nonuniform target, because of its complex three-dimensional shape. Even if the target is painted uniformly, illumination differences produce a pattern of highlights and shadows. Although countershading is sometimes employed to lessen the internal contrast of the pattern, it is seldom possible to compensate fully for the differences in illumination. The dis-

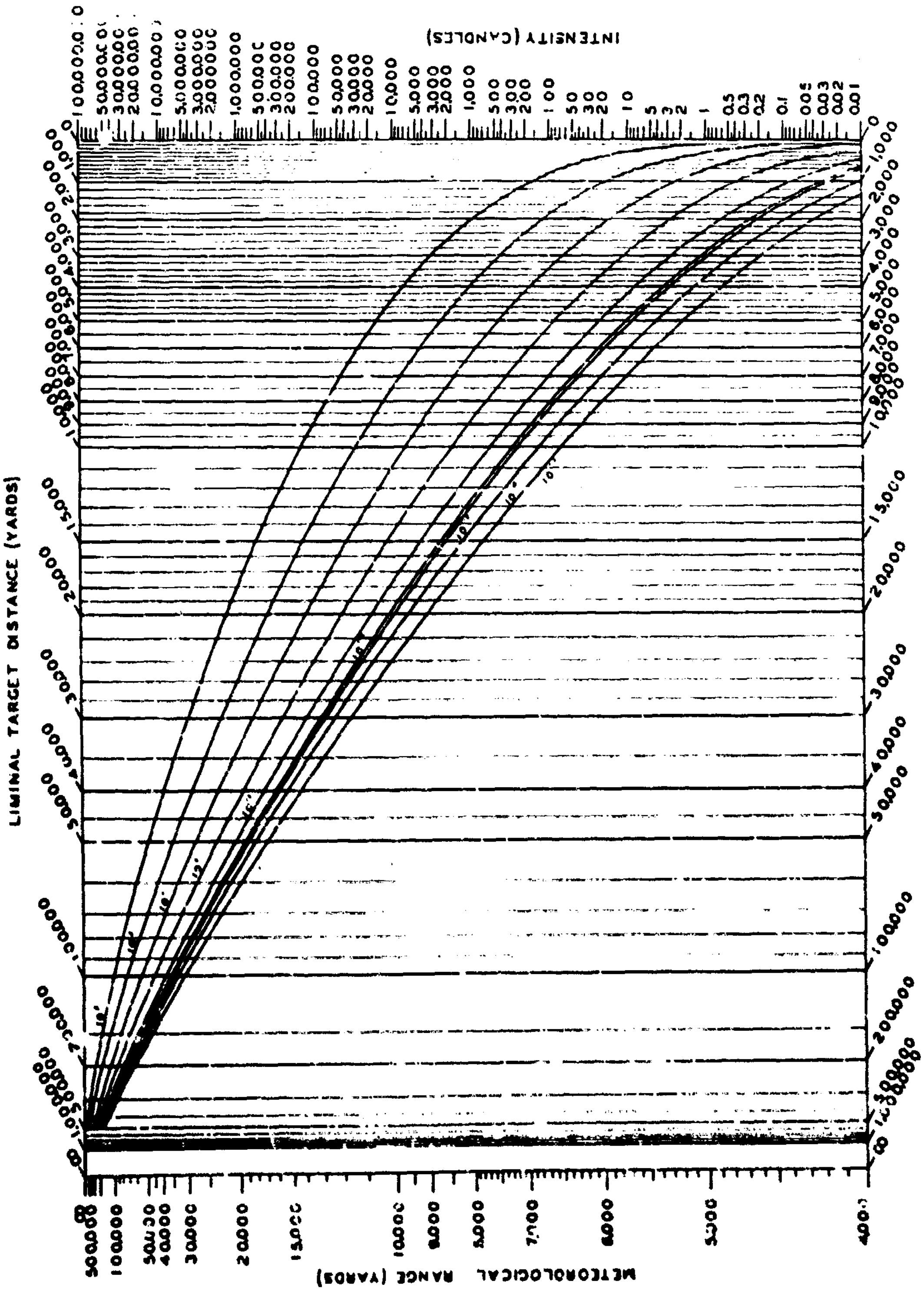

FIGURE [illegible]. Nomographic visibility chart for signal lights.
Each curved line corresponds to a [illegible] value of adaptation luminance (B_0). The value of B_0 expressed in foot-lamberts appears on each curve.

visible can be predicted from nomographic visibility charts only if an effective value of inherent contrast can be found and only if this value is nearly independent of liminal target distance.

Two approaches were made to this problem. (1) Studies were begun by the Tiffany Foundation intended to disclose the basic principles governing the relation between the size, shape, and brightness of the components of a pattern and its effective contrast. (2) The visibility of a photographic model of a cruiser (Figure 29) was compared with the visibility of a uniform target of equal projected area. Neither of these experiments was completed, but the fragmentary results suggest certain practical rules which will be summarized in the following sections.

FIGURE 29. Photograph of a 20-foot model of a cruiser.

4.9.1 The Visibility of Naval Targets in Clear Weather

Nearly all naval targets present patterns characterized by high, inherent, internal contrasts. Under most situations their inherent integrated contrasts are also high. In very clear weather such a target subtends but a small angle when it is liminally visible. In this case, the liminal target distance can be found from the nomographic visibility charts by using the inherent integrated contrast as the value of effective inherent contrast.

Under certain circumstances of lighting and observation, the inherent integrated contrast may approach zero. When this occurs, the effective inherent contrast must have some value substantially greater than zero, inasmuch as zero effective contrast implies that the target is invisible regardless of how close it may be. During the Tiffany experiments it was found that when the inherent integrated contrast of the cruiser model was zero, it was liminally visible at the same distance as a uniform target of the same projected area having an inherent contrast on this result are probably unwarranted, but the experiment proved that, for the cruiser model tested, the *effective inherent contrast should be taken as equal to the inherent integrated contrast or unity, whichever is greater.* It is probable that this rule applies to most naval targets under most circumstances of observation. However, in the case of skillfully camouflaged targets viewed under the most favorable circumstances, the minimum value of effective inherent contrast may be substantially less than unity. Experiments with models of all types of naval targets should be conducted in a visibility theater, in order to determine for each the minimum value of effective inherent contrast.

4.9.2 The Visibility of Naval Targets in Foggy Weather

It remains to be determined whether or not the effective inherent contrast of a target having zero inherent integrated contrast is independent of liminal target distance. The experiment described in the preceding section tested only the clear-weather case. Had time permitted before the expiration of the Tiffany contract, the experiment would have been repeated using a series of photographic models having successively lower contrasts, and the liminal target distances so obtained would have been compared with liminal target distances predicted by the nomographic visibility charts using a fixed value (unity) of effective inherent contrast. It is recommended that such an experiment be performed and, if agreement is found, no special corrections are necessary when the nomographic visibility charts are used to predict the visibility of naval targets in foggy weather.

4.9.3 The Effect of Color

It was shown in Chapter 3 that the equivalent achromatic contrast (C_c) of even the most garish color contrast seldom exceeds 0.5, and that the resultant equivalent achromatic contrast (C_s) of a color contrast combined with a brightness contrast (C_b) is given by equation (1) of Chapter 2.

$$C_s = (C_b^2 + C_c^2)^{1/2}.$$

As shown in Section 4.9.1, the effective inherent contrast of a typical naval target is usually unity or greater because of the pattern formed by the high-

[illegible] added, the effective inherent contrast is increased by only 12 per cent:

$$C_0 = (1.00^2 + 0.50^2)^{1/2} = 1.12.$$

It will be seen from the nomographic visibility charts that this increase in contrast produces only a small change in liminal target distance. For example, on a day when the meteorological range is 20 miles, a target having an area of 100 square feet and a contrast of 1.00 is liminally visible at 14,000 yards. A similar target having a contrast of 1.12 is liminally visible at 14,600 yards.

Ships and planes are seldom painted highly chromatic colors. Ordinarily the maximum color contrast encountered in time of war is represented by a gray ship seen against a sky-blue background or by the reverse, a blue ship seen against a gray background. Figures 39 and 40, Chapter 3, show that in neither case does the equivalent achromatic contrast exceed 0.12. The corresponding increase in effective inherent contrast is only 0.7 per cent:

$$C_0 = (1.00^2 + 0.12^2)^{1/2} = 1.007.$$

The effect on the liminal target distance of so small an increase in contrast is negligible. Ordinarily, *the color of a naval target does not affect the distance at which it is liminally visible.* This statement has no bearing upon the noticeability of a readily visible target.

4.10 THE MEASUREMENT OF CONTRAST

The effective inherent contrast of a ship or a plane has been shown to be equal to the inherent integrated contrast of the target until this quantity falls below some minimum value which depends upon the nature of the target and the lighting conditions. It is necessary, therefore, to provide means for measuring the integrated contrast of a target and for specifying the nature of the lighting conditions.

4.10.1 Maxwellian View Photometers

Clerk Maxwell proposed a photometer in which a lens is used to form an image of the target on the pupil of the observer's eye. The lens then appears uniformly bright; its brightness, apart from light losses in the lens itself, equals the integrated brightness of the target. Most visual photometers can be modified for use as Maxwellian view devices. Al- [illegible] Stiles-Crawford effect,[41] their results are usually sufficiently reliable for use in visibility calculations.

A convenient Maxwellian-type photometer can be produced by fastening a short-focus photographic objective ($f = 2$ inches) to the front end of the drawtube of a Luckiesh-Taylor brightness meter.[42] The quality of the photometric field can be improved by cementing a tiny positive lens to the front (inner) end of the ocular tube.

When a Maxwellian view photometer is used for the determination of the integrated contrast of a ship or plane, allowance must be made for the fact that the target does not fill the field of view of the photometer precisely. One method for making such allowances will be described in the next section.

4.10.2 An Integrating Contrast Photometer for the Study of Models

A recording photoelectric photometer for studying the integrated contrast of model ships and model planes was built and used by the Tiffany Foundation to measure models of submarines supplied by the Bureau of Ships and models of aircraft supplied by the Bureau of Aeronautics.[44] Thereafter, the instrument was moved to the U. S. Naval Air Station at Patuxent River, Maryland, where it is in use by Navy personnel.

Comparative studies of the integrated contrast of different camouflage designs can be made very quickly with this instrument, the polar curves of integrated contrast drawn by the photometer indicating the directions in which the target is least likely to be visible.

The High Hill Project

In order to provide the photometer with an unobstructed view of the horizon, the Tiffany Foundation erected a 50-foot tower atop High Hill, South Huntington, Long Island. This site, only a short distance from the Tiffany estate, is the highest point on Long Island. The tower, shown in Figure 30, elevated the apparatus above the tree tops. The photometer was mounted on the roof of the inclosure which housed the recording apparatus at the top of the tower.

Figure 31 shows the photometer assembly before it was mounted in the tower. The model C is mounted on the outer end of an 8-foot arm E, designed to be rotated by the vertical shaft F. Two identical photo-

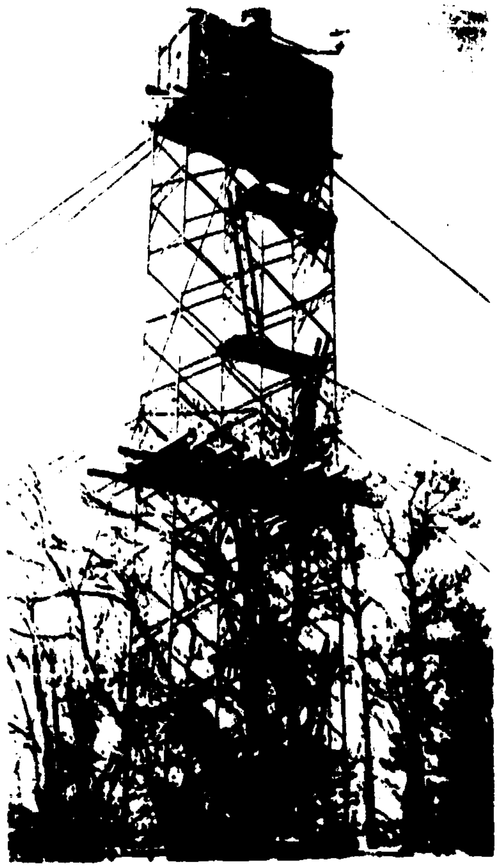

FIGURE 30. Tower on High Hill, South Huntington, Long Island.

From [illegible] the integrating contrast photometer [illegible] and an unobstructed view of the horizon. A model of a submarine is in place at the end of the photometer arm.

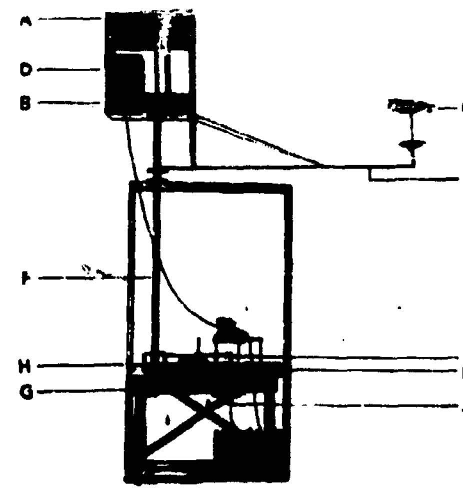

FIGURE 31. Integrating contrast photometer before being mounted in the tower.

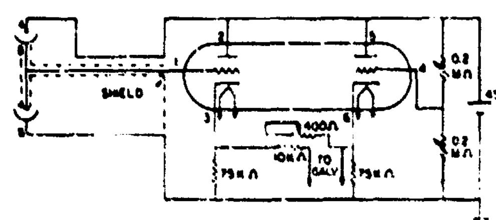

FIGURE 32. Circuit diagram of the integrating contrast photometer.

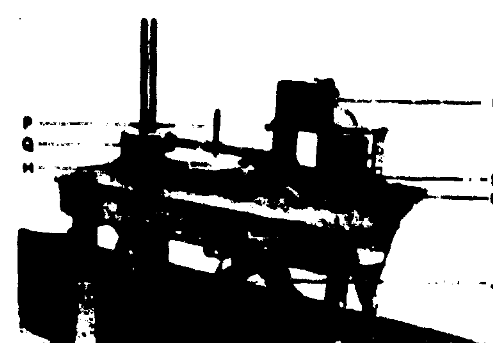

FIGURE 33. Control desk and recording mechanism of the integrating contrast photometer.

electric photometers, *A* and *B*, are supported and rotated by the same shaft. The field of view of the lower photometer *B* includes the model, but that of the upper photometer *A* does not. A vacuum-tube bridge circuit (Figure 32), housed in box *D*, is used to compare the photocell currents from the two photometers. A shutter in photometer *A*, operated by control *J*, adjusts the amount of light entering the top photometer until it equals the light entering photometer *B*. This condition is indicated by a zero (center) reading of the light-beam galvanometer *K* on the operator's table. The setting of the shutter is indicated by recording pen *P* on polar graph paper attached to turntable *H*, which is geared to shaft *F*. The photometers, model and graph paper are rotated simultaneously by crank *G*. A close-up view of the control desk and recording mechanism is shown in Figure 33.

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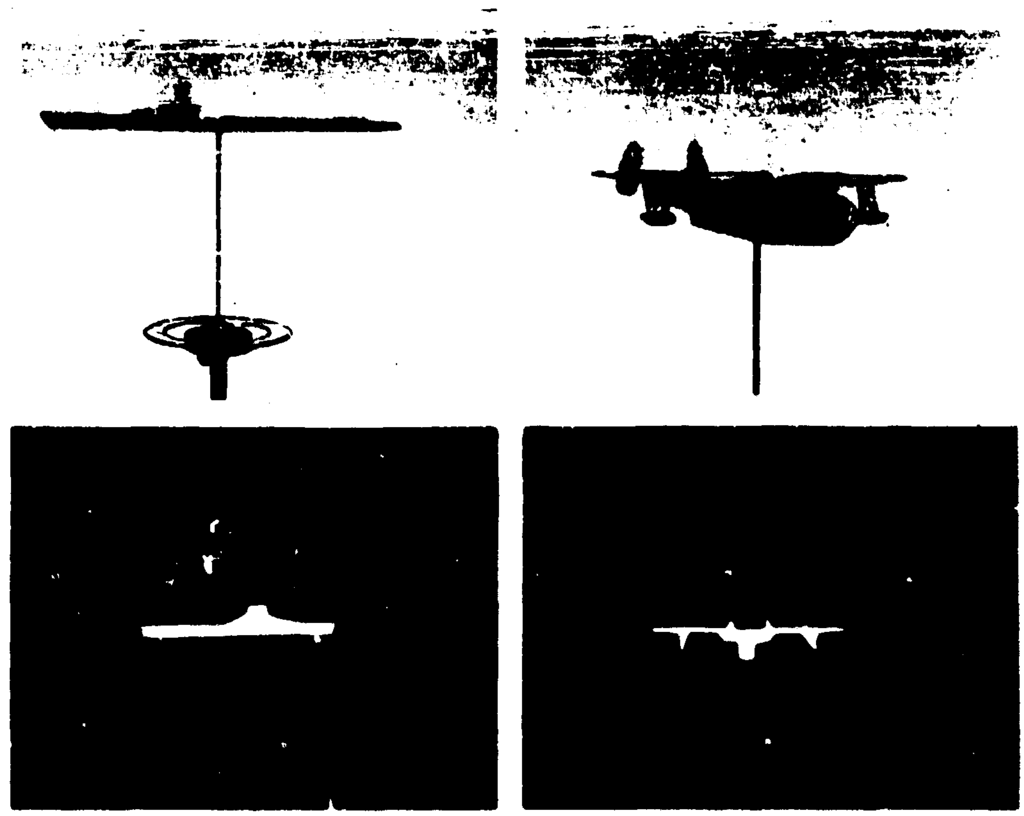

FIGURE 34. Photographs of typical models tested with the integrating contrast photometer. Metal masks of the type shown below each photograph are [illegible] the fields of view of the photometers.

CORRECTION FOR EXTRANEOUS BACKGROUND

The fields of view of both photometers are controlled by identical metal masks cut to match the shape of the targets as closely as possible. Two such masks are shown in Figure 34. The areas of the masks and of the image of the model are determined by exposing a photographic plate behind the mask and measuring the areas on the resulting picture. A correction for the extraneous background surrounding the image is made in the following manner.

Let K = the ratio of the light received by photometer B to the light received by photometer A;

B_H = the brightness of the horizon sky;

B_M = the average brightness of the model;

A_s = the area of the image of the field stop in the plane of the model;

A_M = the projected area of the model.

Then

$$K = \frac{B_M A_M + (A_s - A_M) B_H}{A_s B_H}. \qquad (5)$$

The integrated contrast of the model is

$$C = \frac{B_M - B_H}{B_H}. \qquad (6)$$

Combining equations (5) and (6):

$$C = (K - 1)\frac{A_s}{A_M}. \qquad (7)$$

MODEL STUDIES

A typical polar curve of integrated contrast of the model airplane shown in Figure 34 is shown in Figure 35. Similar curves for model aircraft and model submarines will be found in OSRD Report No. 6533.[13]

The integrating contrast photometer can also be used to determine the reflectance required if a uniform surface perpendicular to the line of sight at the model is to have a contrast against the sky equal

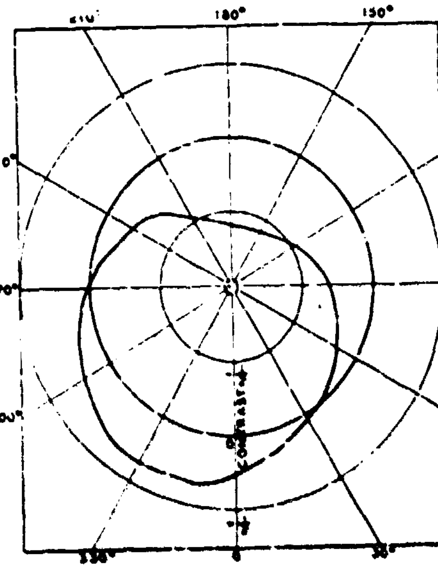

FIGURE 35. Typical polar curve of integrated inherent contrast for the model airplane shown in Figure 34.

to the integrated contrast of the target. This has been called the *average reflectance* $\bar{\rho}$ of the model. It is related to the average brightness of the model by the relation

$$\bar{B}_M = \bar{\rho}\, E. \tag{8}$$

where E is the illumination on a plane perpendicular to the line of sight at the model.

E can be measured in the following manner. Let the model be replaced by any uniform flat gray surface of reflectance ρ. This surface should be large enough to fill the field of view of photometer B and should be mounted perpendicular to the line of sight. Let the ratio of the light entering photometer B to the light entering photometer A be designated by K'. Then

$$K' = \rho E / B_H. \tag{9}$$

Equations (7), (8), and (9) can be combined to show that the average reflectance of a model is related to its integrated contrast by the relation

$$\bar{\rho} = \frac{\rho}{K'}\,(C + 1). \tag{10}$$

A simple, rugged contrast photometer for field use was constructed by the Eastman Kodak Company under Contract OEMsr-1070 (Figure 36). The instrument consists of a gray plastic case pierced by a central hole through which the background can be viewed. A circular, transparent absorbing wedge, contained within the case, covers this hole. In use,

FIGURE 36. A contrast photometer for field use. With this instrument the integrated contrast of any target can be determined if the average reflectance of the target is known.

the photometer is held with its surface perpendicular to the line of sight as shown in Figure 37. The wedge is then rotated by the thumbs of the operator until the hole appears to be as bright as the surface of the case. The integrated contrast of any target of average reflectance $\bar{\rho}$ is related to the scale reading of the photometer (H) by the relation

$$C = \frac{2.5\,\bar{\rho} - H}{H}. \tag{11}$$

A small nomographic chart representing equation (11) may be mounted on the back of the photometer to facilitate its use in the field. One of these instruments was turned over to the Navy for use in the Pacific.

FIGURE 37. Contrast photometer in use.

Glare from the sky is eliminated by means of special goggles which limit the operator's field of view to the surface of the photometer.

4.10.4 The Sun-Ratio

The integrated contrast of a ship or a plane depends on the nature of the lighting conditions, for these determine the pattern of highlights and shadows. The most widely used index of the lighting conditions is called the *sun-ratio*. It is, by definition, the ratio of the illumination on a vertical surface facing the sun to the illumination on a vertical surface facing away from the sun. The sun-ratio varies from unity on a uniformly overcast day to 30 or more near sunrise or sunset in clear weather.

Figure 38 shows one of several types of sun-ratio meters which were built or tested.[a] An earlier model of this instrument was used by the Tiffany Foundation in conjunction with the integrating contrast photometer on High Hill, the shapes of the polar curves depending upon the value of sun-ratio.

4.11 A CONTEMPLATED HANDBOOK OF VISIBILITY

At the outset of its research on the visibility of targets, Section 16.3 was asked by the Navy to prepare a handbook of visibility suitable for use under operational conditions by nonspecialized personnel. Considerable thought was given to the preparation of such a volume, and a draft was begun by the section chief. However, the requisite experimental data did not become available in time for the manuscript to be completed.

The handbook of visibility, as planned, would have been limited to the visibility of naval targets along horizontal paths of sight. It would have contained, in concise form, much of the information to be found in this chapter, together with nomographic visibility charts for circular targets (Figures 2 through 10). The principal feature, however, was intended to be a large number of worked examples, illustrated by sketches or photographs and based upon practical problems submitted by Navy liaison officers. These problems, typical of situations encountered under operational conditions, would have been implemented by special charts and tables de-

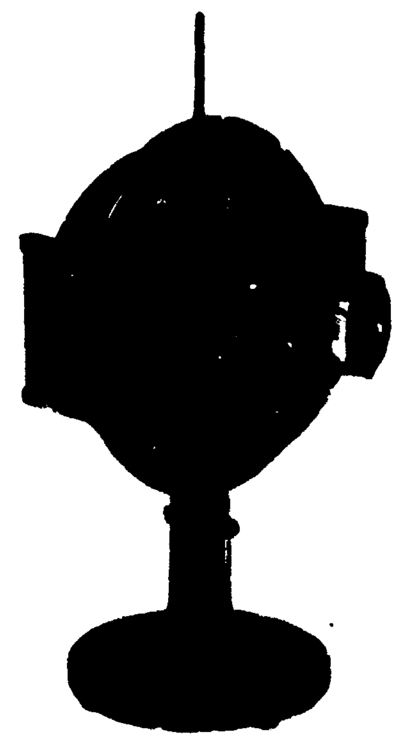

FIGURE 38. Sun-ratio meter.

[illegible]

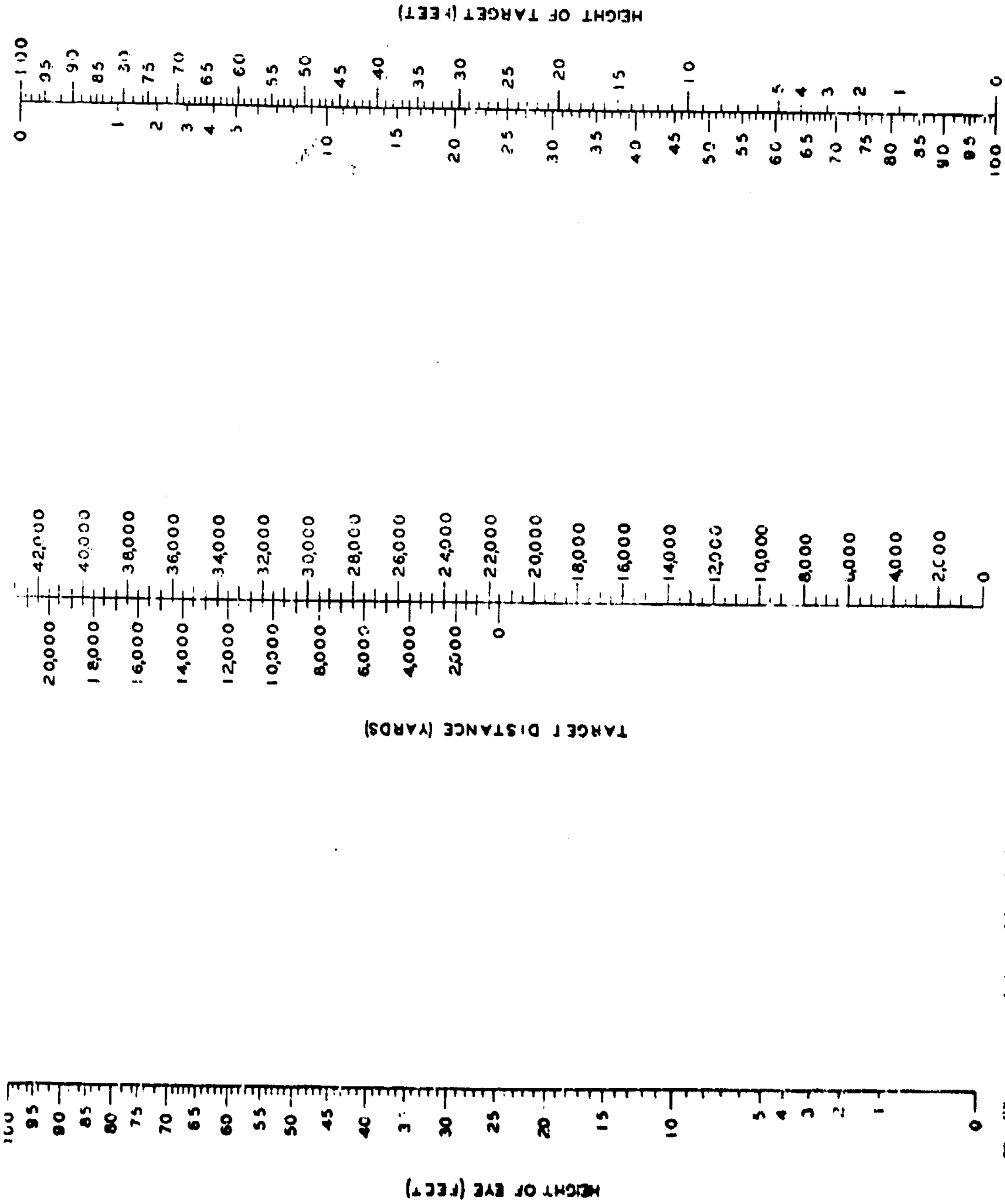

FIGURE 38. The nomograph is used by placing a straight edge across the chart in such a manner that it joins the appropriate points on the three vertical lines. (See text.)

signed to facilitate the calculations. Figure 39 shows an example of one of the charts prepared for the handbook. This nomograph indicates, for any height of the observer above the sea, the height of target which will be seen in line with the horizon. This chart involves no trigonometric approximation, and, therefore values obtained with it take precedence over those obtained by means of Bowditch's rule.[44]

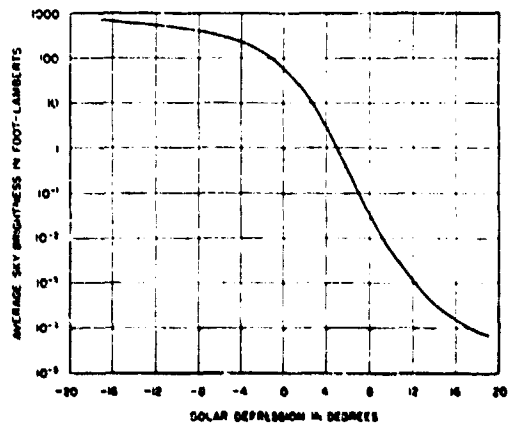

FIGURE 40. Plot of value of sky brightness as a function of solar depression compiled from data published by the staff of the U. S. Weather Bureau. Moderate overcast may be allowed for by lowering the value of sky brightness by a factor of 10.

For targets more distant than the horizon, use the right-hand (outside) scale marked *Height of Target* and the right-hand scale marked *Target Distance*. In the case of targets which are between the observer and the horizon, use the left-hand (inside) scale marked *Height of Target* and the left-hand scale marked *Target Distance*.

Another example of the charts planned for the handbook of visibility is shown in Figure 40. Compiled from data published by the staff of the U. S. Weather Bureau,[52,53] this figure indicates average values of sky brightness as a function of solar altitude. It is intended to serve as a guide in selecting the appropriate value of adaptation brightness (B_H) during sunrise or sunset, when the brightness of the sky undergoes a millionfold change of brightness within a few minutes. The value of solar altitude at any time, date, and location can be computed from standard navigation tables.

4.12 VISIBILITY UNDER OPERATIONAL CONDITIONS

In predicting the visibility of naval targets from the visibility charts contained in this chapter, it should be borne in mind that the data represent the performance of excellent observers under nearly ideal observing conditions. Because of fatigue, discomfort, distraction, and the necessity for search, it is to be expected that, in most instances, actual sightings at sea will occur at ranges somewhat less than those indicated by the charts. On the other hand, the atmosphere is sometimes so inhomogeneous that the actual sighting range may exceed the range indicated by the charts. Experience in the use of the nomographs is the best guide to the allowances that should be made for departures from the conditions upon which the charts are based. Under no circumstances should the visibility charts contained in this chapter be used to predict the ability of aviators to see objects on the ground. This problem is dealt with in the following chapter.

Chapter 8

VISIBILITY FROM AIRCRAFT

8.1 INTRODUCTION

THE MINIMUM contrast required to make an object on the ground visible from the air can be predicted by methods similar to those presented in the preceding chapter. However, along any slant path, the changes of atmospheric conditions with altitude must be taken into account. This may be accomplished by means of the nomographic visibility charts presented in this chapter.

8.2 STRATIFICATION OF THE ATMOSPHERE

Airmen view the earth along slant paths throughout which the scattering and absorbing particles vary in number and kind. The idealized case of a homogeneous atmosphere exhibiting regular, continuous stratification was discussed in Chapter 2, wherein it was shown that the law of contrast attenuation along slant paths in such an *optical standard atmosphere* could be expressed in a simple form [equation (36), Chapter 2] in terms of the *optical slant range* $\bar{R}$. This distance is related to the actual slant range R by equation (29) of Chapter 2. Figures 1, 2, and 3 are plots of this equation for various values of θ, the angle between the line of sight and the horizontal. Values of true altitude are indicated by the family of dashed curves. These figures have been called *optical slant-range diagrams*.

8.2.1 Discontinuous Stratification

GROUND HAZE

The curves in Figures 1, 2, and 3 apply only when no optically dissimilar strata are present. Ordinarily, however, the air near the ground contains dust, smoke, and large water particles not found at higher altitudes. This condition is frequently called *ground haze*. In clear weather, this layer often has a sharply defined upper boundary, above which the atmosphere contains very little condensed water. Above the boundary, the meteorological range is often several times as great as within the ground haze.

Graphical Representation. Figure 4 illustrates how the discontinuity in meteorological range can be represented on Figure 3. For simplicity, Figure 4 shows only the curve for $\theta = 25$ degrees in Figure 3. Let it be assumed that the upper boundary of the ground haze is at an altitude of 5,000 feet and that the meteorological range is five times greater above the boundary than below it. Beginning at the point corresponding to an altitude of 5,000 feet, a new curve has been drawn having five times the slope of the original curve. The relation between $\bar{R}$ and R is then represented by the accentuated curve; it follows the normal curve up to altitude 5,000 feet and the steeper curve thereafter.

Diffuse Boundaries. If the boundary of the ground haze is gradual rather than sharp, the accentuated curve in Figure 4 may be rounded off to avoid the abrupt change in slope.

The character and altitude of the boundary can be observed easily from a plane climbing or descending through it. In many cases the pilot can also make an estimate of the ratio of the meteorological range above and below the boundary. Proficiency in describing the stratification of the atmosphere is acquired very quickly by any flyer, once he understands what to look for. Moreover, stratification may be correlated with other meteorological conditions, and experience may enable very intelligent guesses to be made by an observer on the ground. Statistical information concerning the frequency of occurrence of common stratification conditions in a given locality can be accumulated in the same manner as other meteorological data.

CEILINGS

Experience in drawing curves of modified slope on the optical slant-range diagram is quickly acquired with practice. Freehand curves are usually as precise as are warranted by the estimates of the ratio of meteorological ranges within the strata. Often, straight lines are sufficient approximations for curves of very great or very small slopes. An example of the latter is the *ceiling*. This is an opaque cloud deck within which the meteorological range is very short. Usually, the lower boundary of the cloud layer is sharply defined; it can be represented

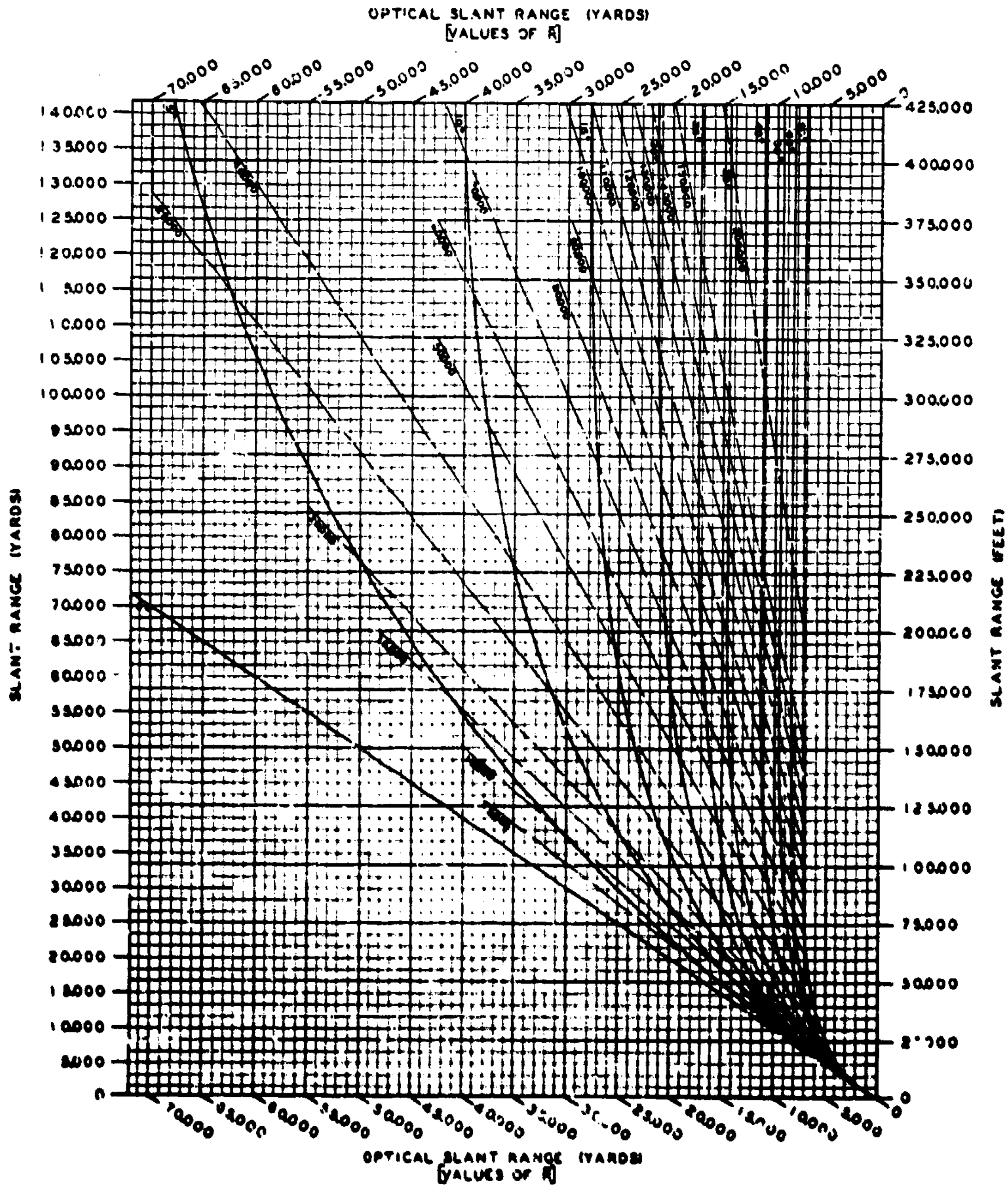

FIGURE 1. Optical slant-range diagram for the optical standard atmosphere

Solid curves represent the relation between $\bar{R}$ and R for various sight path elevation angles θ. Broken lines represent loci of equal altitude, expressed in feet.

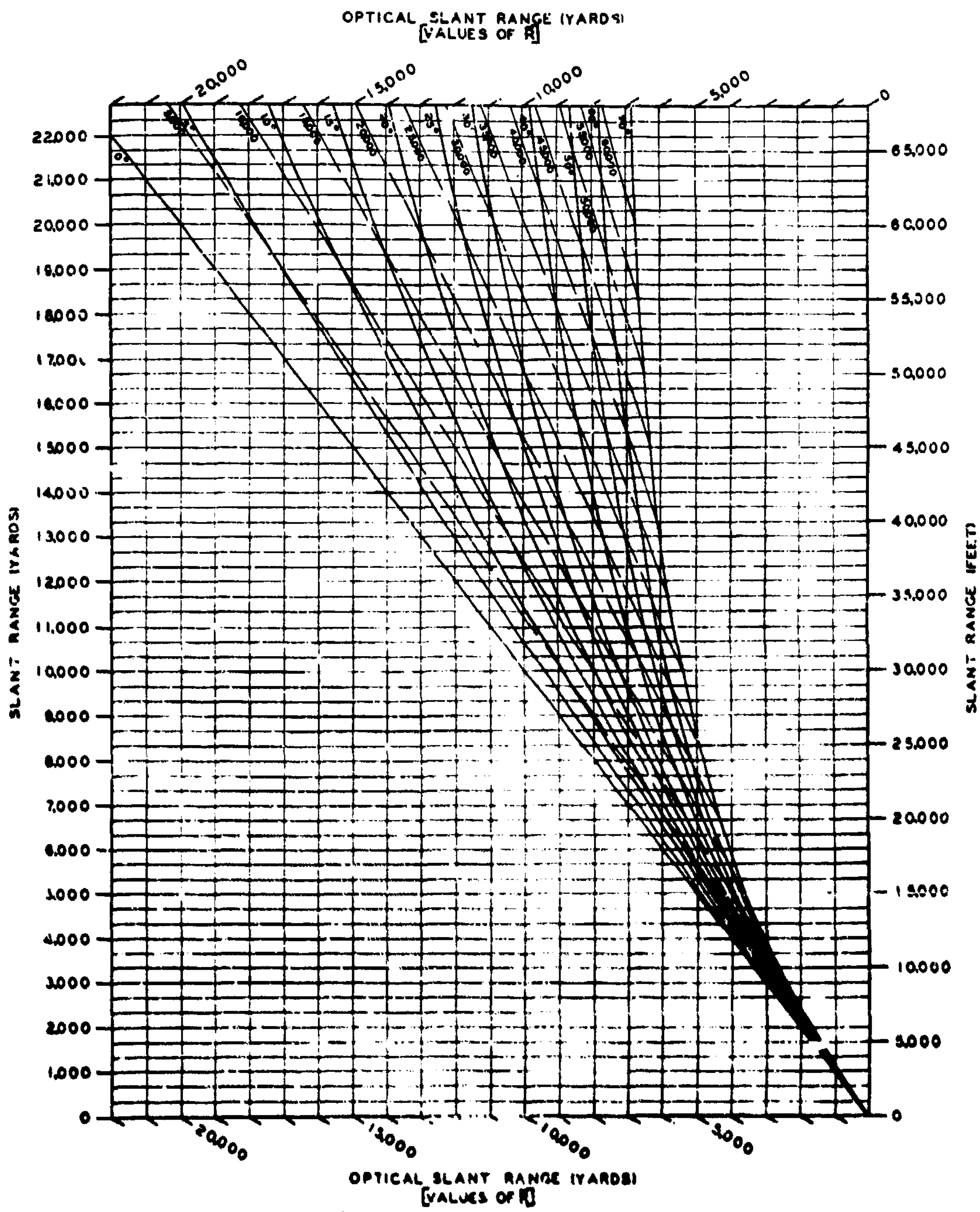

FIGURE 2. Optical slant-range diagram similar to Figure 1, but adapted to the solution of problems involving shorter slant ranges.

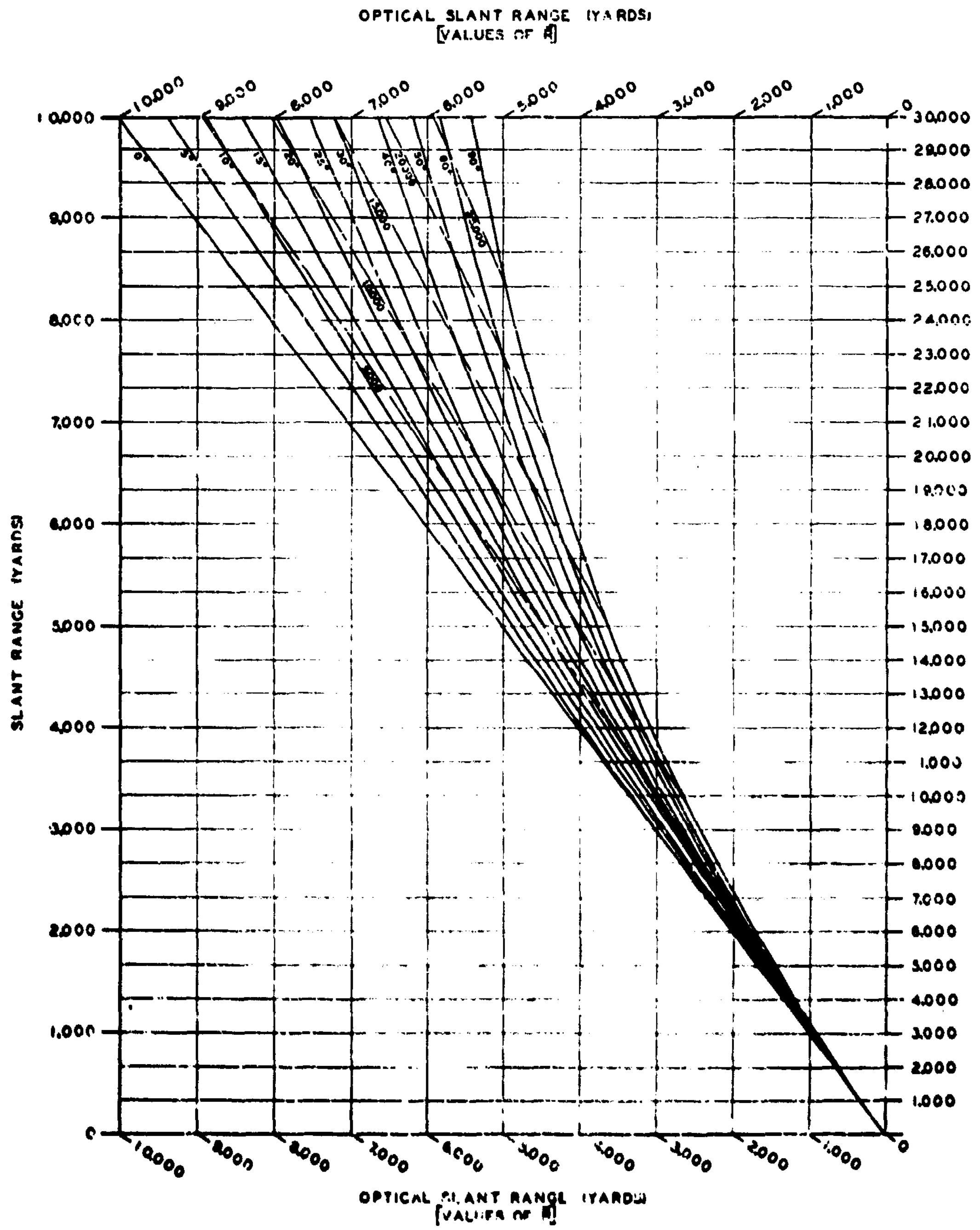

FIGURE 3. Optical slant-range diagram similar to Figures 1 and 2, but adapted to the solution of problems involving still shorter slant ranges.

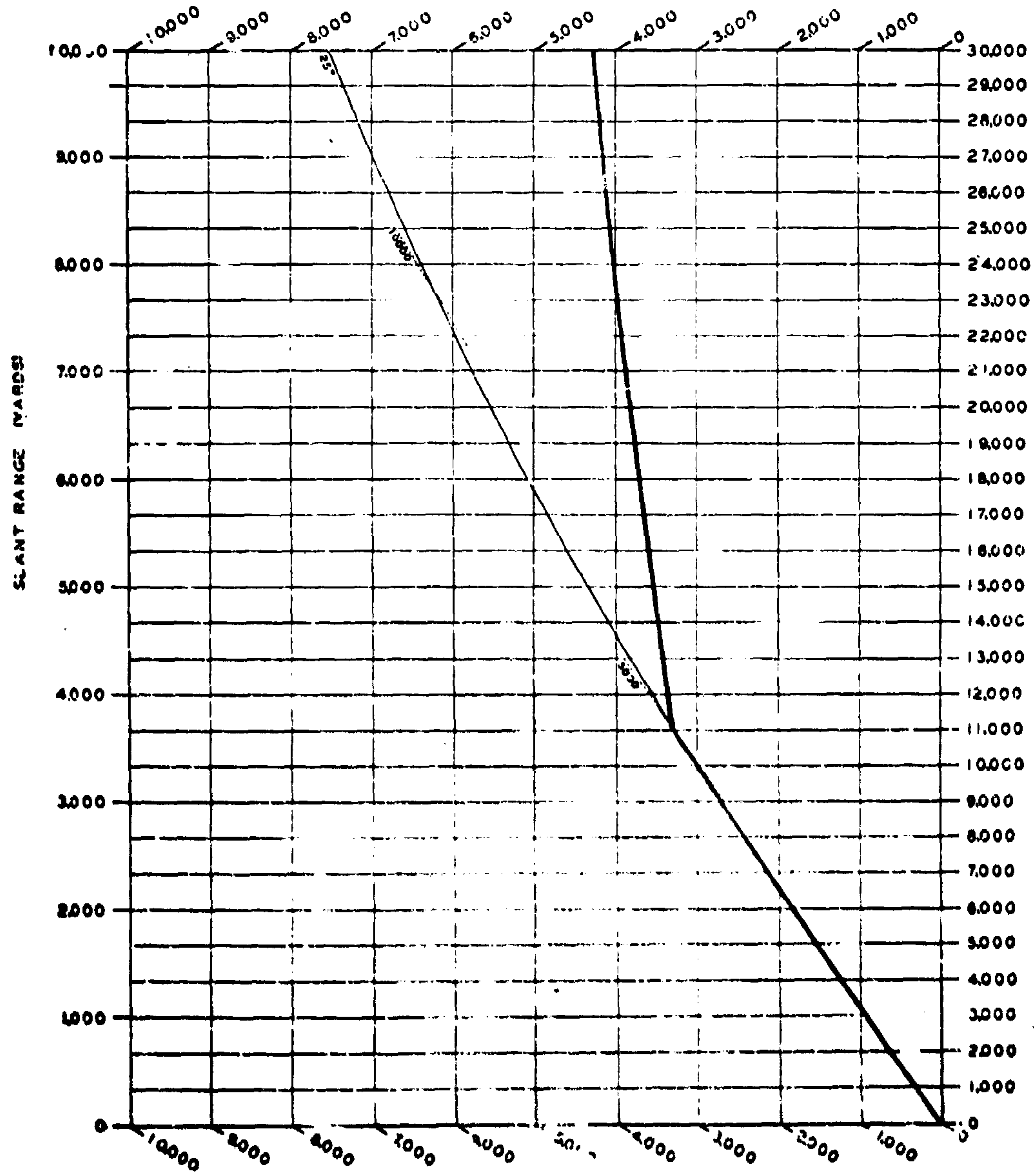

FIGURE 4. Optical slant-range diagram for $\theta = 25$ degrees. (Not intended for use in solving problems.)

Accentuated curve shows relation between $\bar{R}$ and R when the ground haze has a sharp upper boundary at 6,300 feet, above which the meteorological range is five times greater than it is below the boundary.

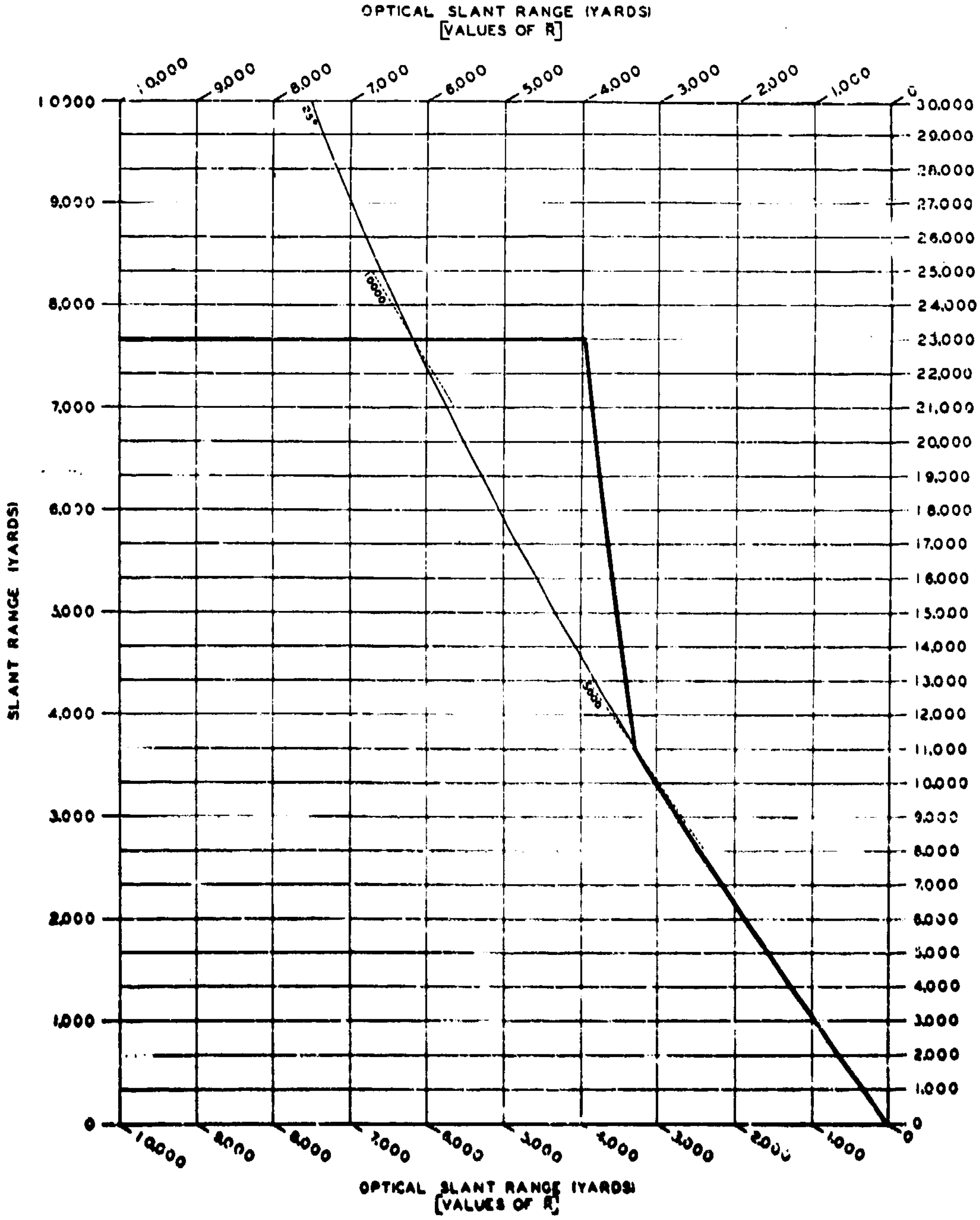

FIGURE 5. Optical slant-range diagram similar to Figure 4 except for a ceiling at 10,000 feet. (Not intended for use in solving problems.)

[illegible] straight line passing through the point on the standard curve which corresponds to the altitude of the ceiling (Figure 5).

Ceiling Zero. Even when the ceiling is at ground level the nomographic visibility charts contained in this chapter can be used to predict the visibility of objects along slant paths. However, it should be noted that the relation between $\bar{R}$ and R within the haze blanket is given by the printed curves on the optical slant-range diagram rather than by a horizontal line. *The slope of the curves on the optical slant-range diagram does not depend upon the magnitude of the meteorological range.* The slope of hand-drawn sections is governed by the *ratio* of the meteorological ranges above and below the stratum boundary. When fog extends to the ground, the limitation it imposes on liminal target distance is taken into account by the value of meteorological range entered on the nomographic visibility charts, the relation between $\bar{R}$ and R being expressed by the printed curves on the optical slant-range diagram.

5.3 NOMOGRAPHIC METHODS

The concept of optical slant range enables nomographic visibility charts of the type discussed in Section 4.6.1 to be used to predict the visibility of objects along slant paths. The nomographic chart shown in Figure 19 is constructed around contrast reduction equation (3), Chapter 4. This equation is of the same form as equation (36), Chapter 2, which expresses the law of contrast attenuation along slant paths in terms of the optical slant range. Figure 19 can be adapted for use in predicting visibility from aircraft by changing the legend of the scale marked "Liminal Target Distance" to read "Values of $\bar{R}$."

5.3.1 Visibility Charts for Aerial Use

A series of nomographic visibility charts for circular and rectangular targets at decimal levels of adaptation brightness are presented in Figures 6 through 30. Each of the twenty-five figures (Figures 6 through 30) is a nomographic visibility chart for uniform circular or rectangular targets seen by an observer whose eyes are adapted to the value of brightness indicated at the lower right corner of the diagram. The shape of target to which a chart ap- [illegible] gram. When used in the manner described in following text, these charts enable the visibility of targets on the ground to be predicted.

The assumed value of adaptation brightness (B_H) is indicated at the lower right corner of each chart. The descriptive phrases, such as *Full Daylight* or *Quarter Moon*, are intended to serve as a rough guide in selecting the proper chart for solving a particular problem. In making the selection, however, it should be borne in mind that the level of brightness to which an aerial observer's eyes are adapted depends upon the average reflectance of the terrain at which he is looking. Therefore, the descriptive phrases are applicable only to circumstances when the sky-ground ratio is approximately unity, or when there is sufficient haze to make the apparent brightness of the earth approach the equilibrium value (Section 2.3.4). Otherwise, a chart for a lower or higher value of B_H should be used. For example, on a very clear but overcast day, Figure 7 should be used to predict the visibility of circular objects on a large field of snow, but Figure 8 should be used to predict the visibility of such objects in a verdant landscape for which the sky-ground ratio is 10.

Projected Target Area

Before the visibility of an object on the surface of the earth can be predicted, its *projected area* must be determined. For example, the projected area of a flat, level surface is simply its true area multiplied by the sine of θ. In the case of targets that are not flat, level surfaces, the projected area can be determined graphically by techniques known to every draftsman. The projected areas of existing structures can be determined from properly made oblique aerial photographs.

Effect of the Atmosphere. Because the atmosphere along the line of sight is stratified, the slant range ordinarily exceeds the optical slant range. Therefore, the target actually subtends a smaller angle at the observer's eye than if it were at distance $\bar{R}$. From the standpoint of the user of the nomographic visibility charts, *the atmosphere is equivalent to an optical system producing demagnification.*

It was suggested in Section 4.8 that the magnifying effect of binoculars can be allowed for by entering an increased value of target area into the nomographic visibility charts. Similarly the "demagnifying" effect of the atmosphere along slant paths can

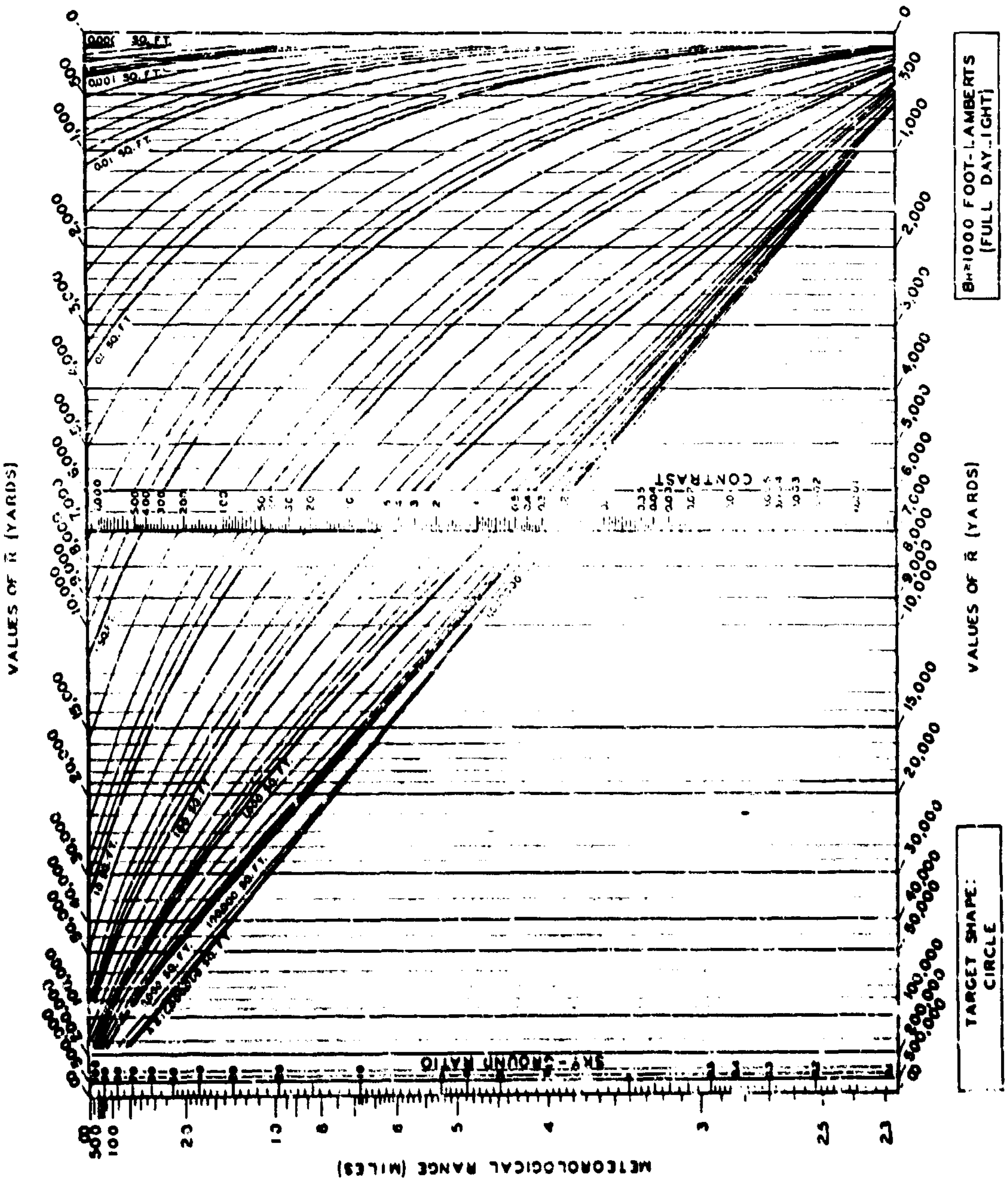
VALUES OF R̄ (YARDS)
B=1000 FOOT-LAMBERTS (FULL DAYLIGHT)
TARGET SHAPE: CIRCLE
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)

Figure 6

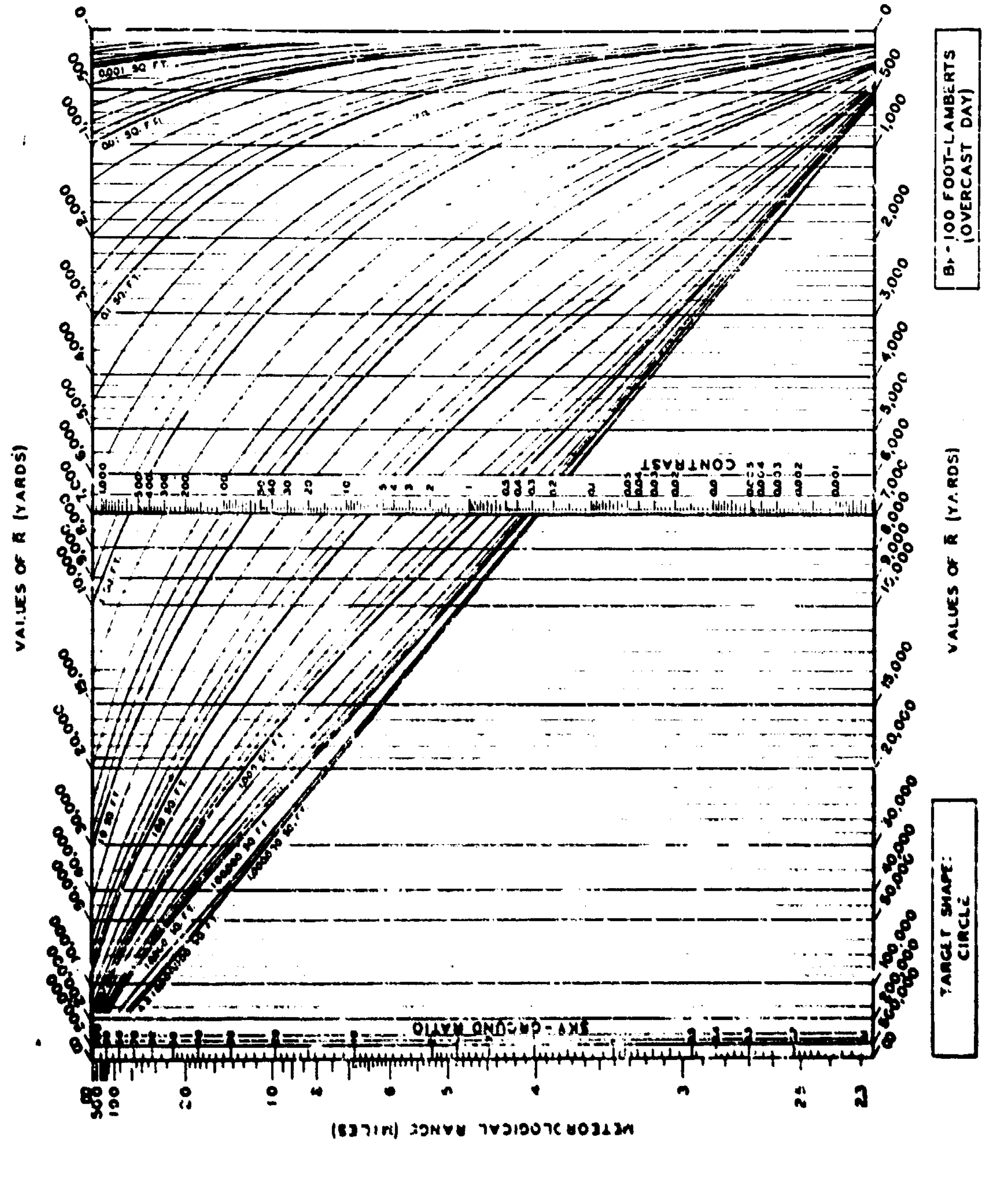
VALUES OF R̄ (YARDS)
B = 100 FOOT-LAMBERTS (OVERCAST DAY)
TARGET SHAPE: CIRCLE
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)

FIGURE 7

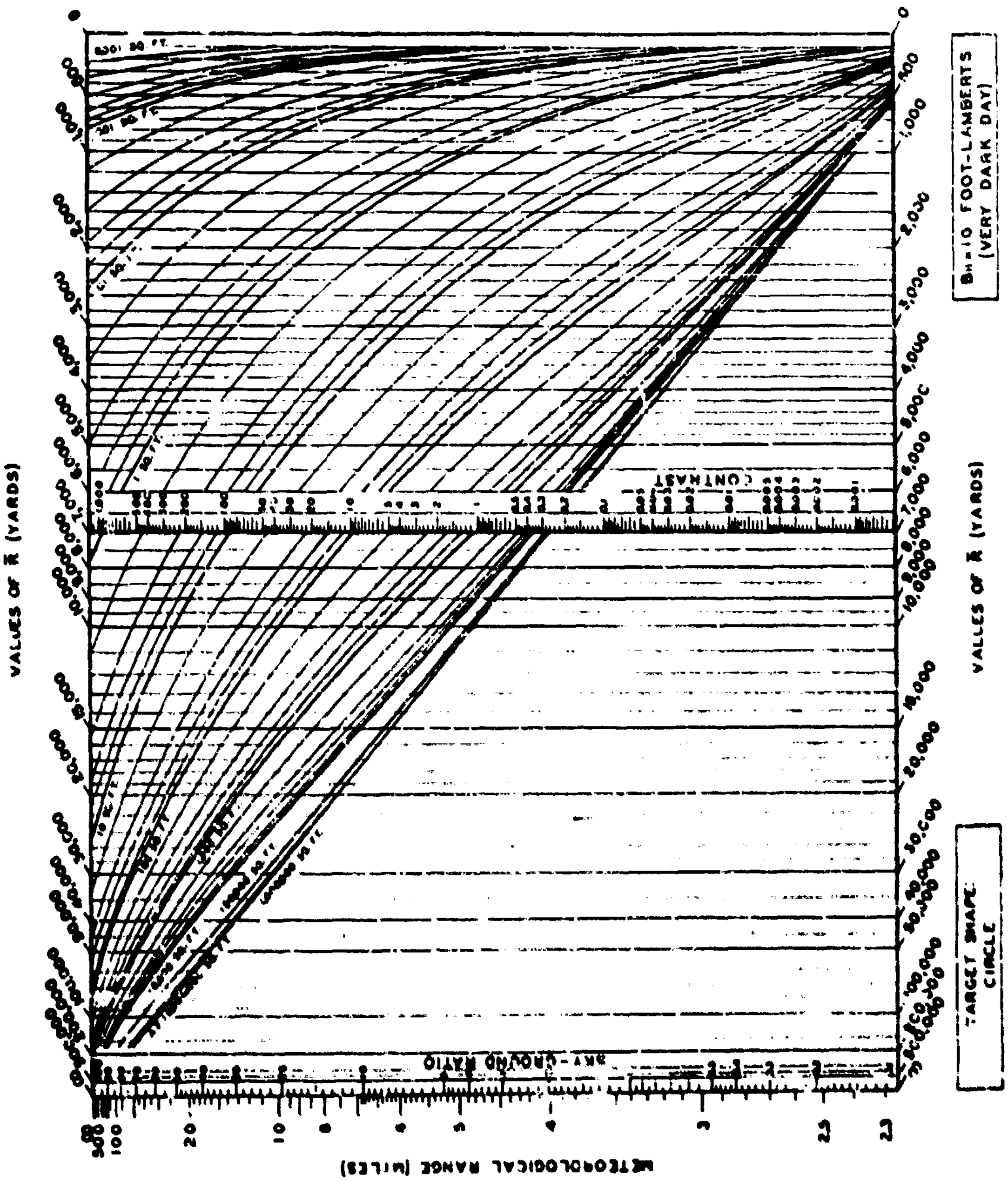
BH=10 FOOT-LAMBERTS (VERY DARK DAY)
VALUES OF R̄ (YARDS)
TARGET SHAPE: CIRCLE
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)

FIGURE 8

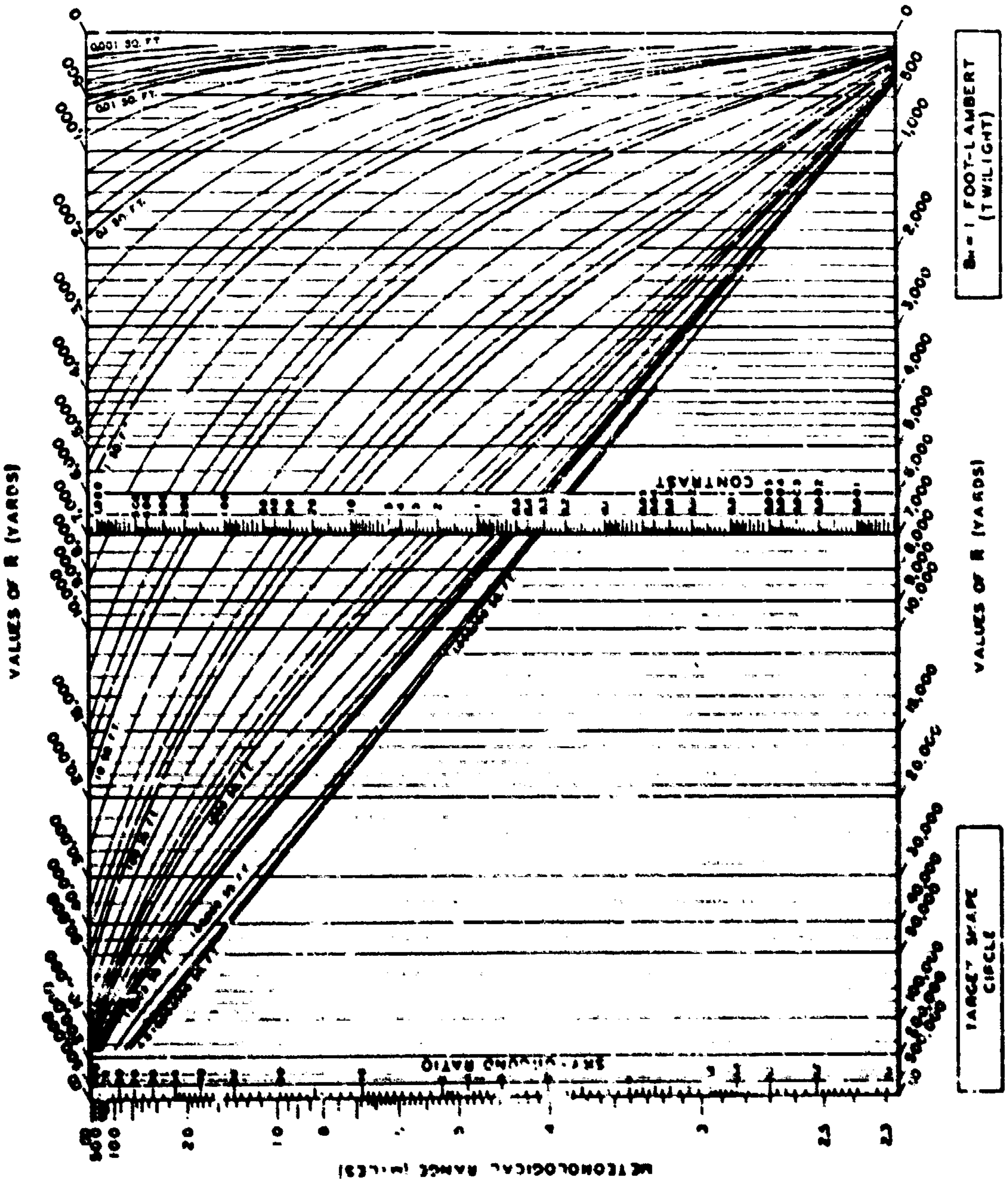
VALUES OF R (YARDS)
VALUES OF R (YARDS)
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)
B = 1 FOOT-LAMBERT (TWILIGHT)
TARGET SHAPE CIRCLE

FIGURE 9

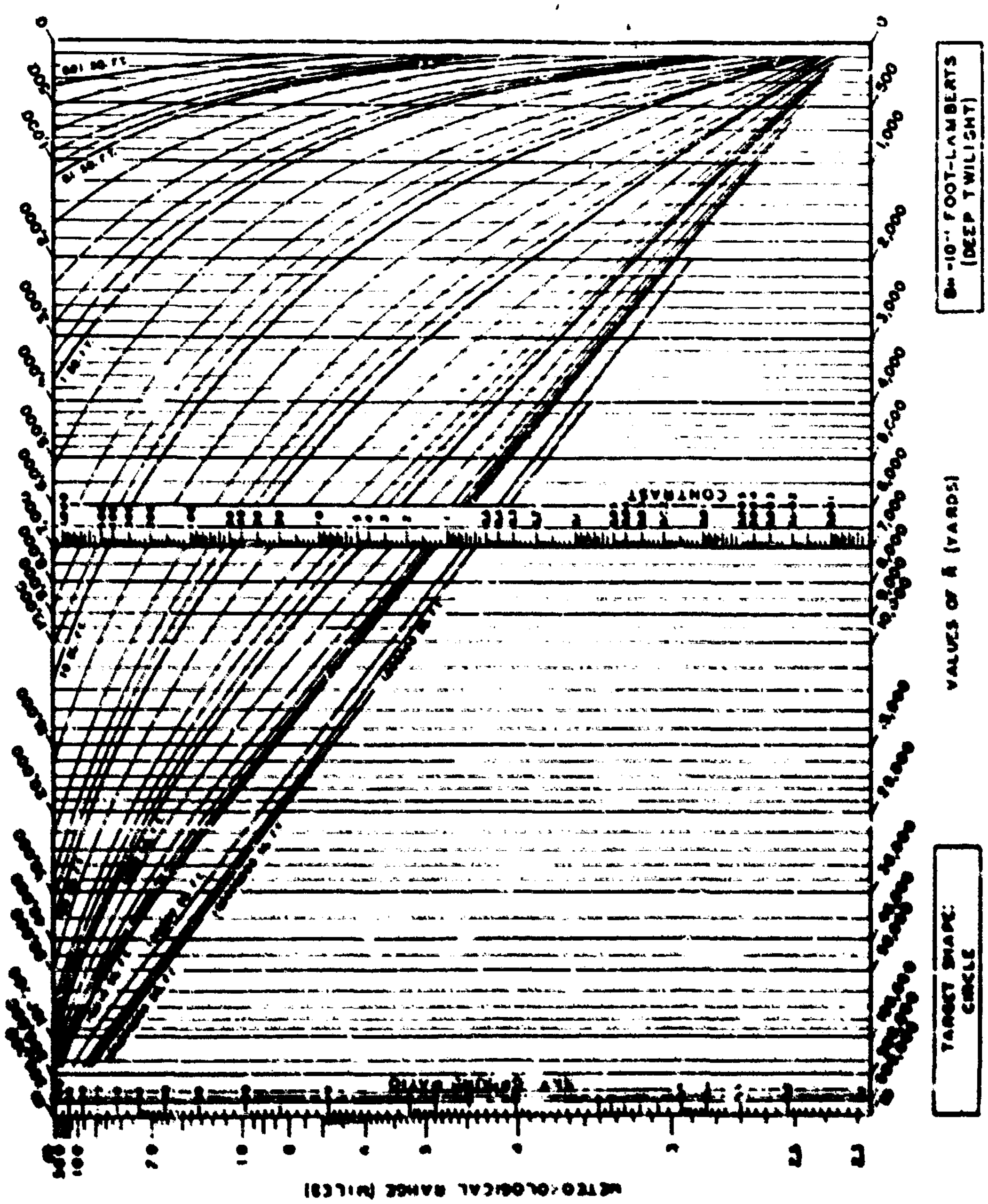
VALUES OF R (YARDS)
B = 10^-4 FOOT-LAMBERTS (DEEP TWILIGHT)
CONTRAST
TARGET SHAPE: CIRCLE
METEOROLOGICAL RANGE (MILES)

Figure 10

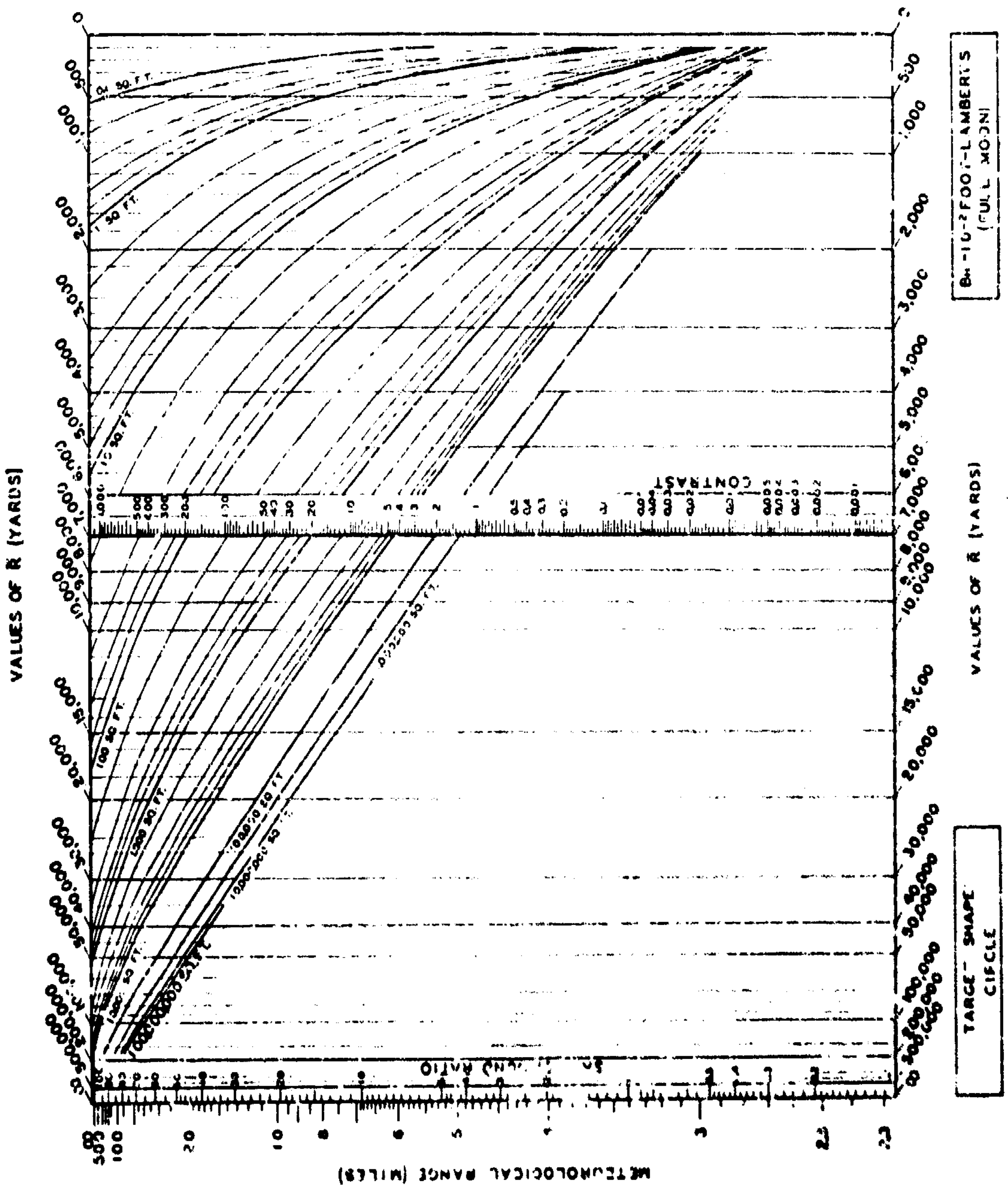
VALUES OF R̄ (YARDS)
VALUES OF R̄ (YARDS)
METEOROLOGICAL RANGE (MILES)
CONTRAST
TARGET SHAPE
CIRCLE
(FULL MOON)

FIGURE [illegible]

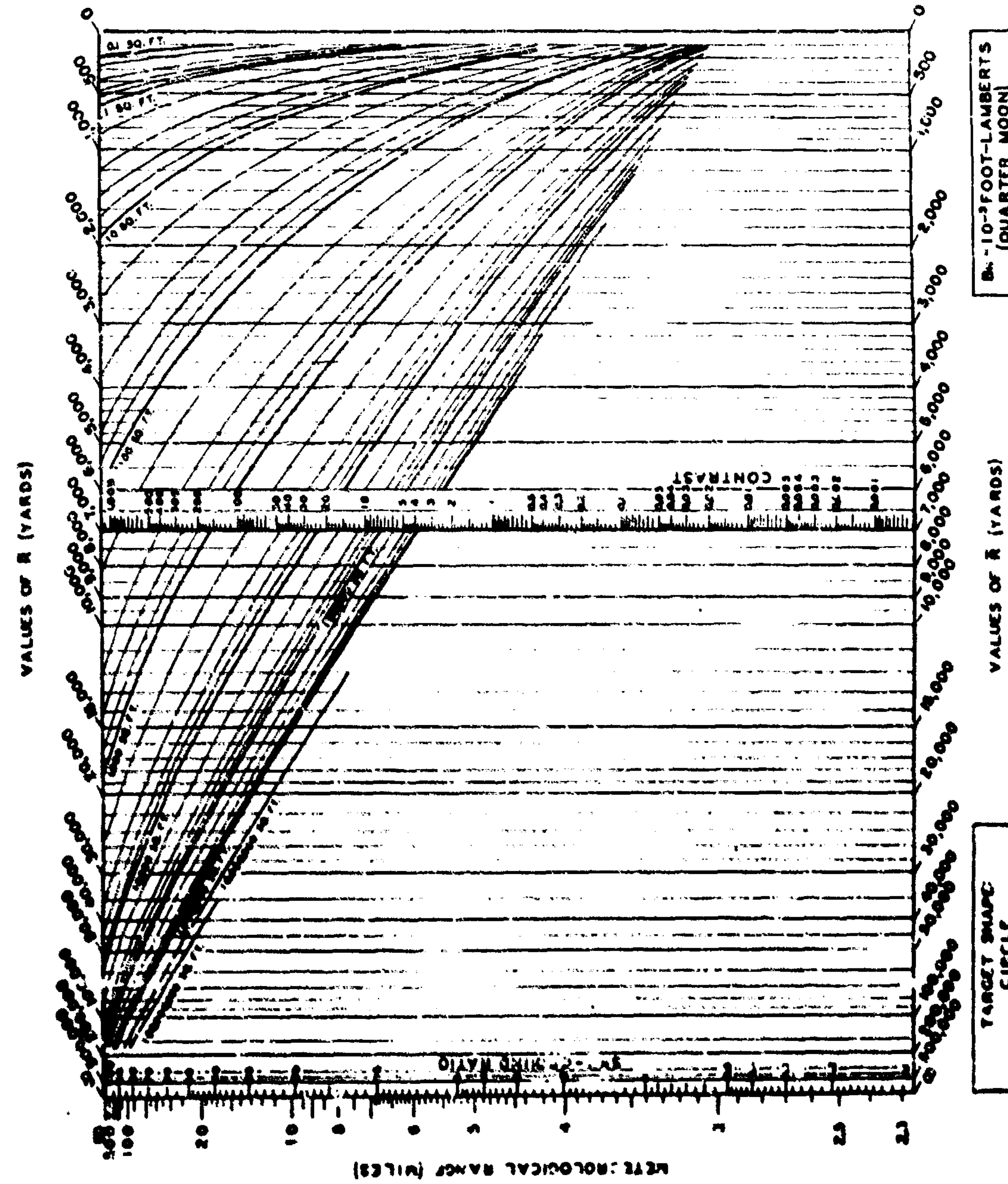
VALUES OF R (YARDS)
CONTRAST
METEOROLOGICAL RANGE (MILES)
B = 10⁻³ FOOT-LAMBERTS (QUARTER MOON)
TARGET SHAPE CIRCLE

FIGURE 12

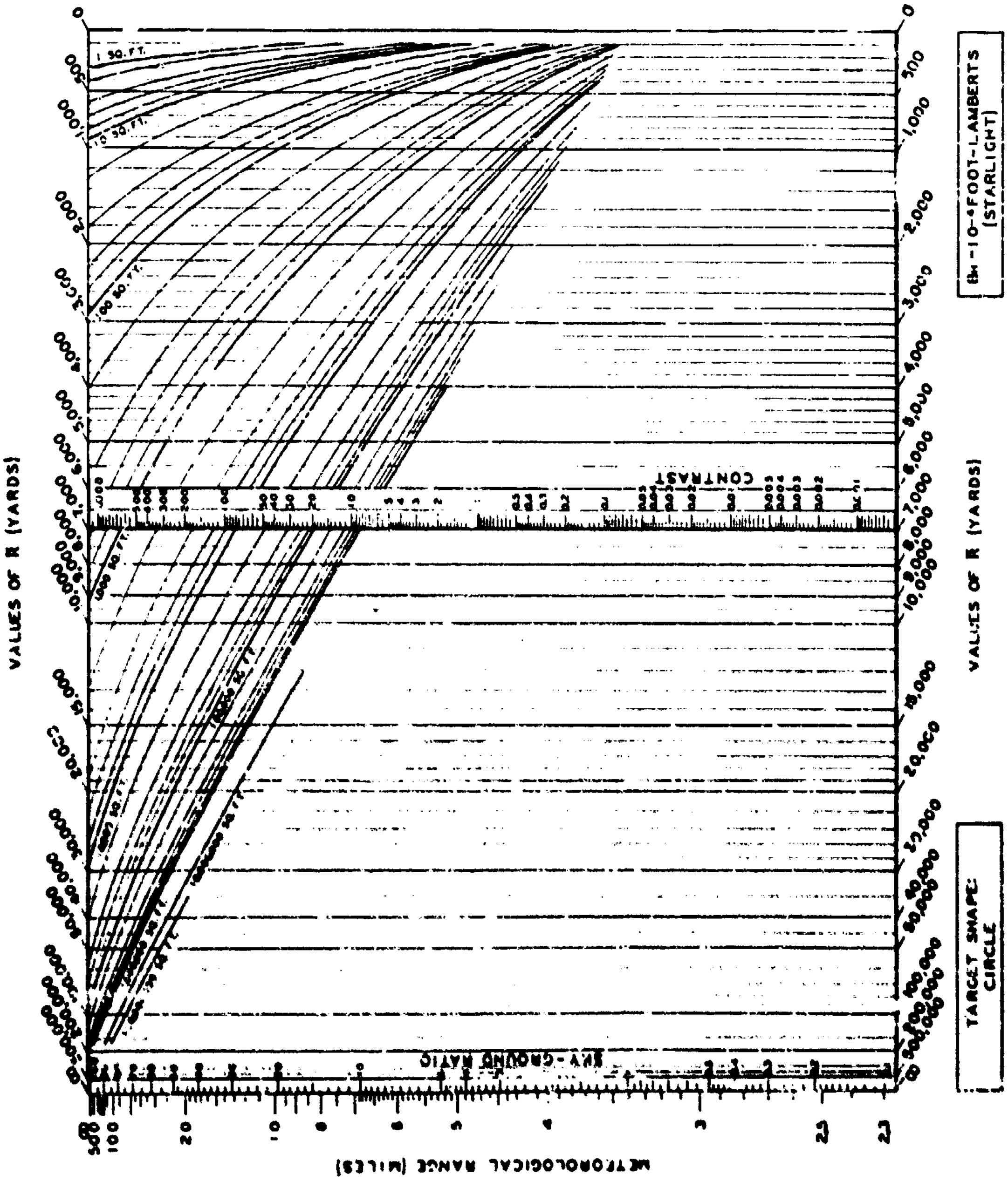
VALUES OF R (YARDS)
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)
B = 10^-4 FOOT-LAMBERTS (STARLIGHT)
TARGET SHAPE: CIRCLE

FIGURE 13

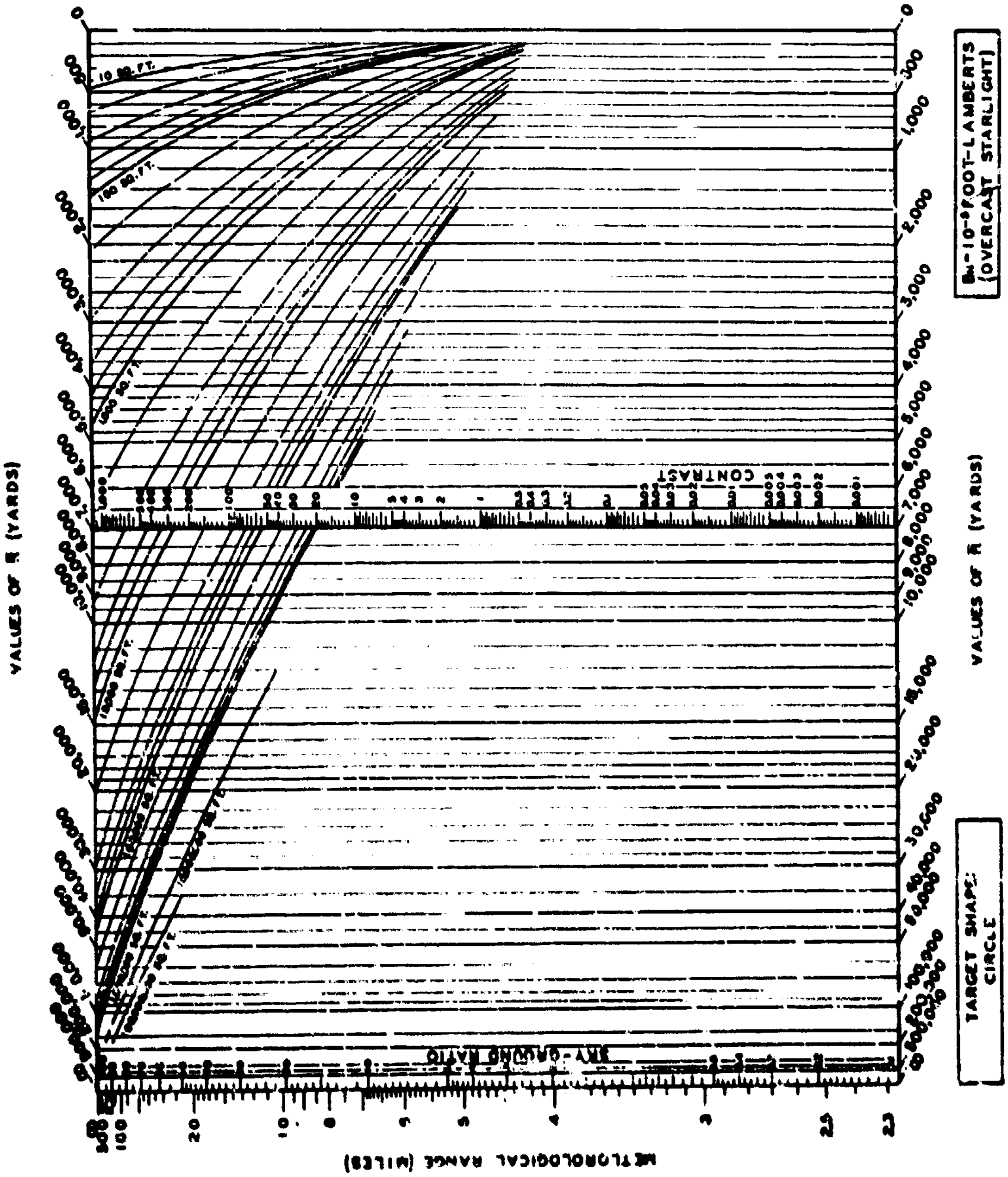
VALUES OF R (YARDS)
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)
VALUES OF R (YARDS)
B = 10^-9 FOOT-LAMBERTS (OVERCAST STARLIGHT)
TARGET SHAPE: CIRCLE

FIGURE 14

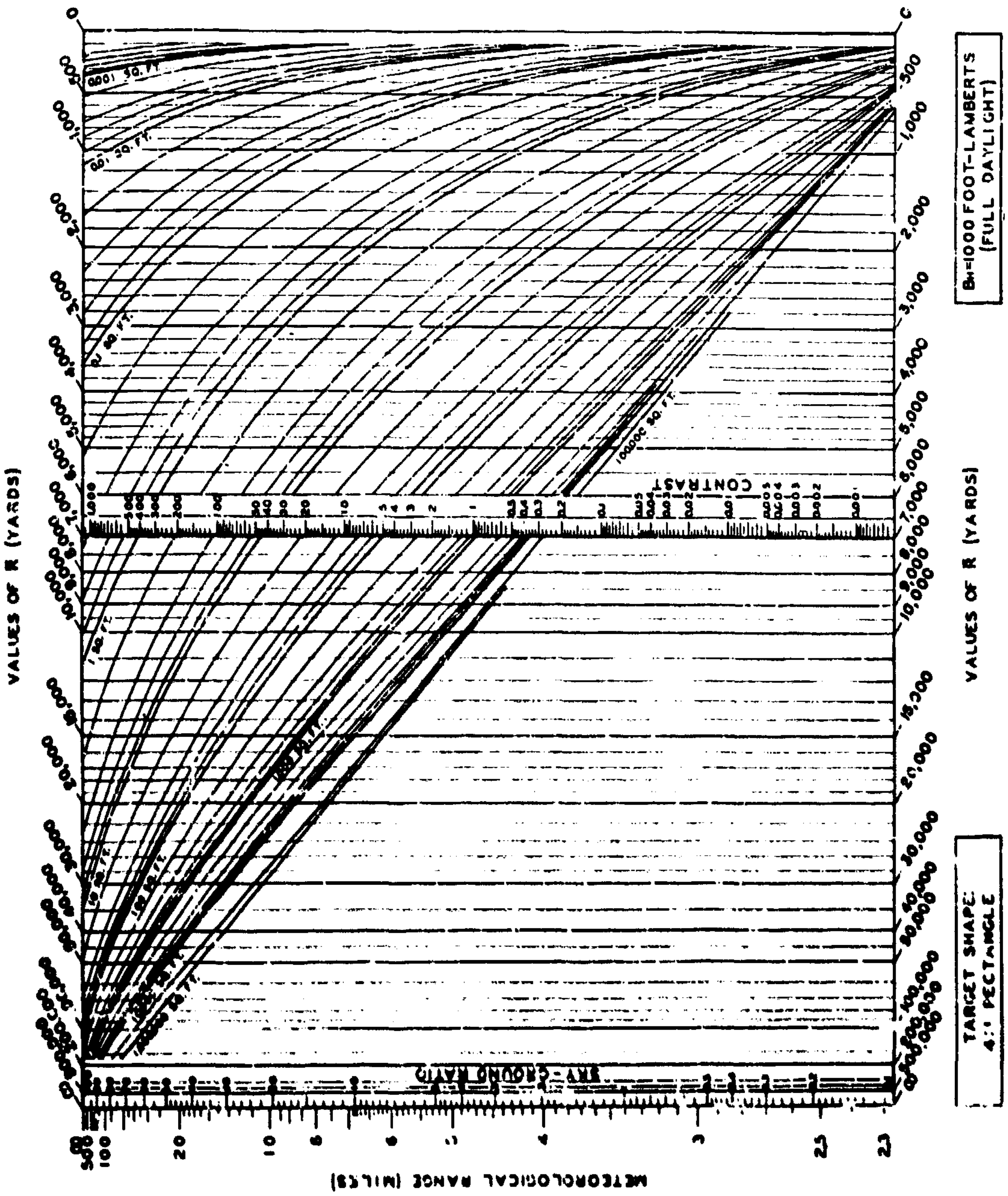
VALUES OF R (YARDS)
B=1000 FOOT-LAMBERTS (FULL DAYLIGHT)
CONTRAST
TARGET SHAPE: 4:1 RECTANGLE
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)

FIGURE 15

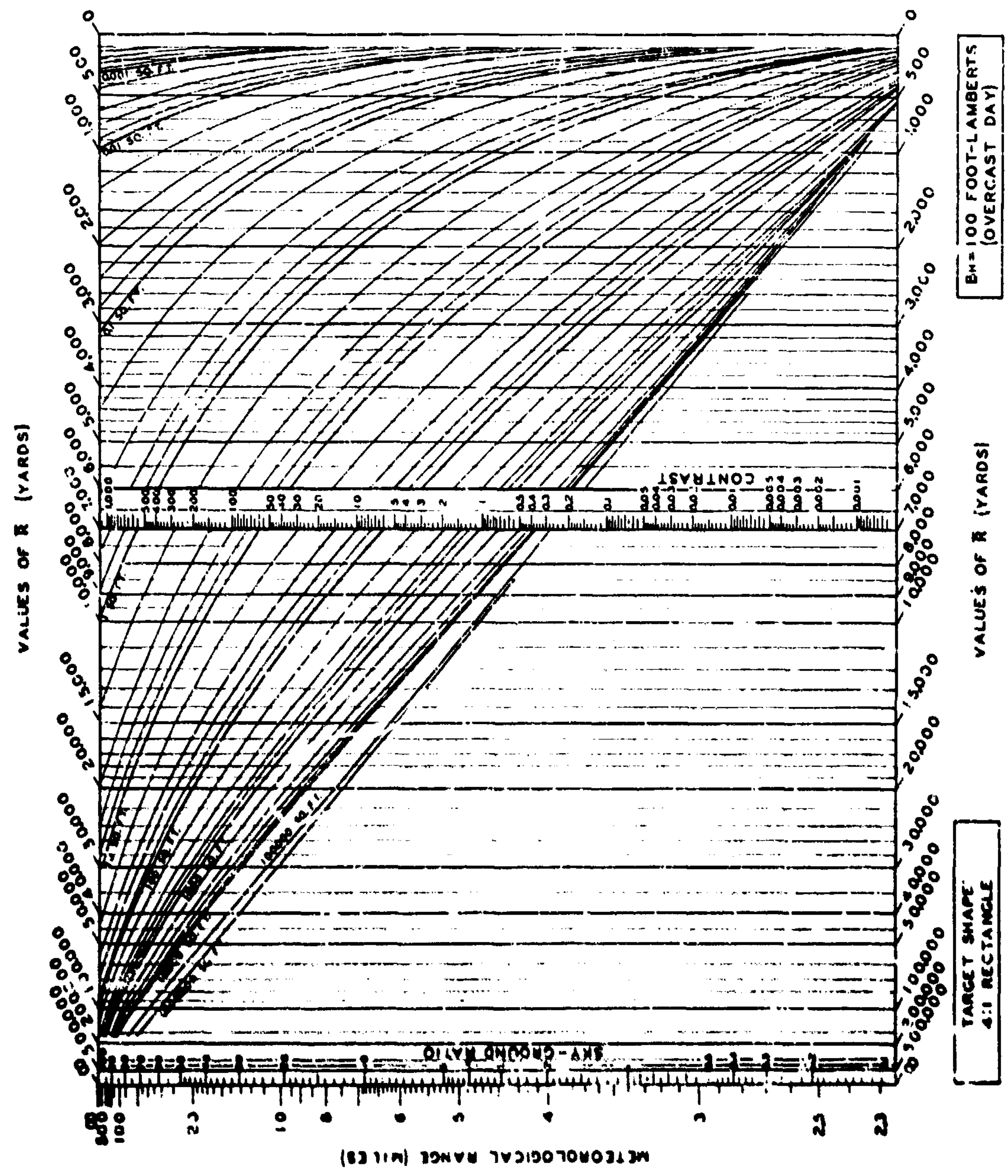
VALUES OF R (YARDS)
VALUES OF R (YARDS)
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)
BH=100 FOOT-LAMBERTS (OVERCAST DAY)
TARGET SHAPE 4:1 RECTANGLE

FIGURE 16

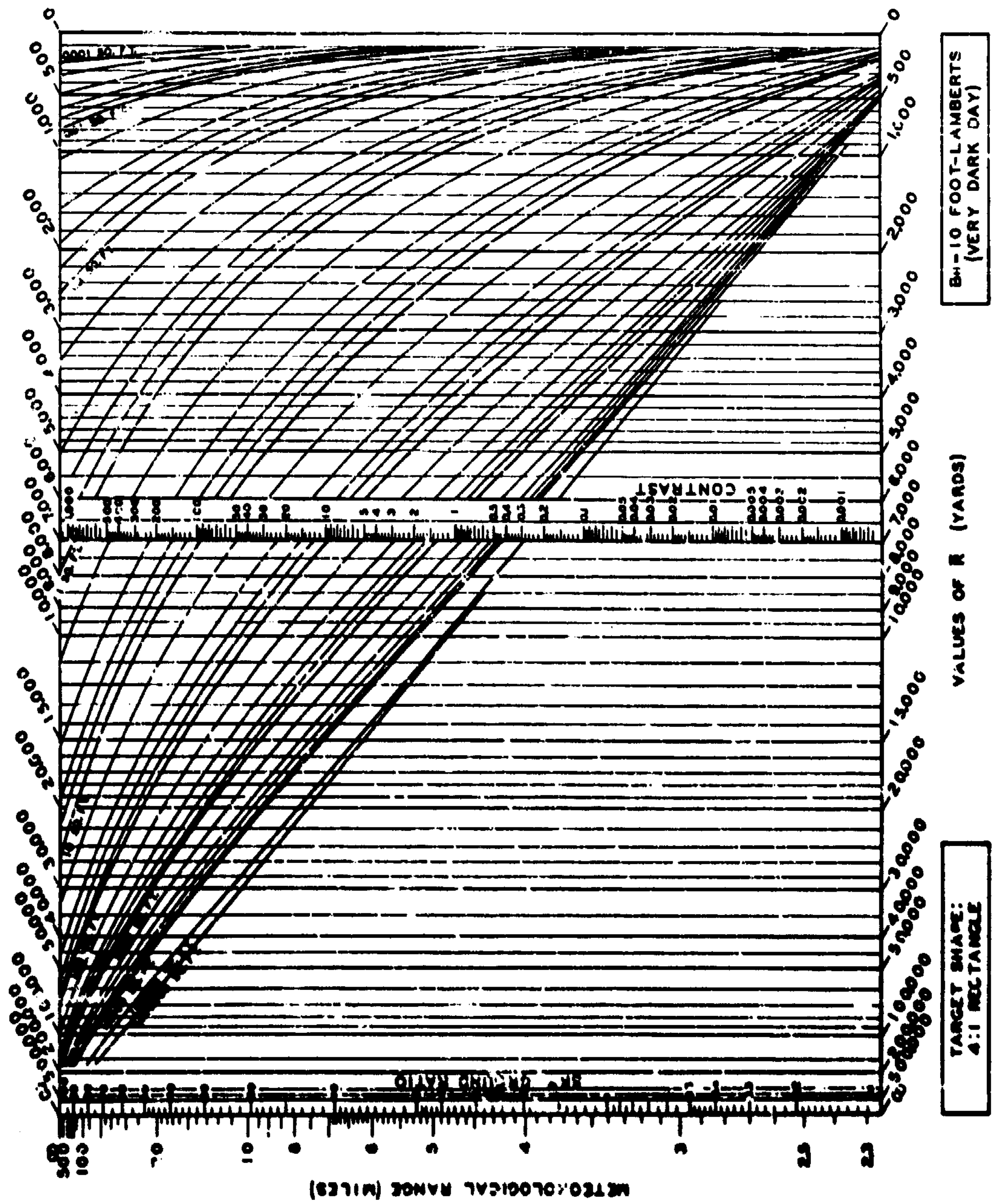
VALUES OF R (YARDS)
B = 10 FOOT-LAMBERTS (VERY DARK DAY)
TARGET SHAPE: 4:1 RECTANGLE
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)

Figure 17

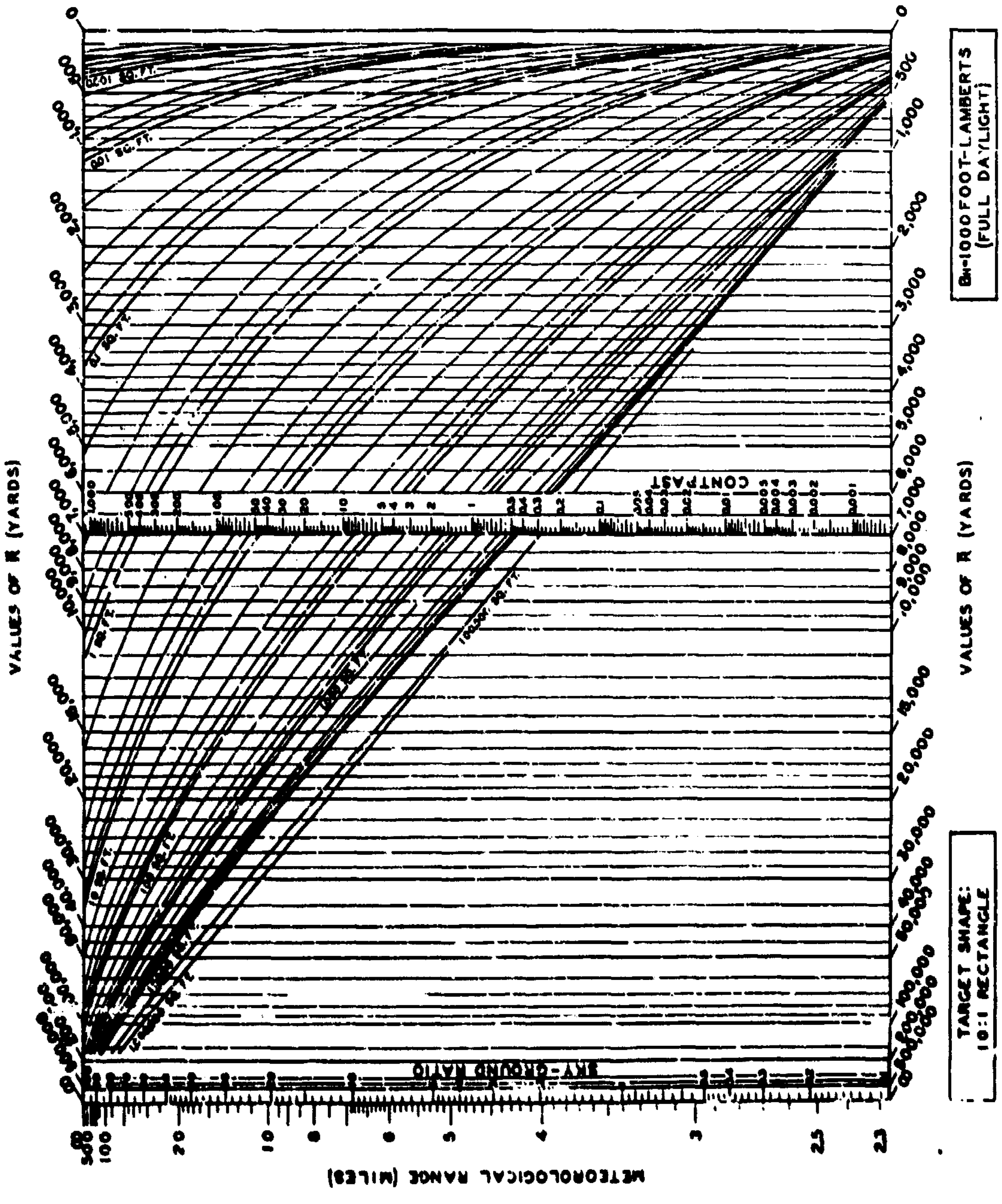
VALUES OF R (YARDS)
METEOROLOGICAL RANGE (MILES)
CONTRAST
SKY-GROUND RATIO
BH=1000 FOOT-LAMBERTS (FULL DAYLIGHT)
TARGET SHAPE: 10:1 RECTANGLE

FIGURE 18

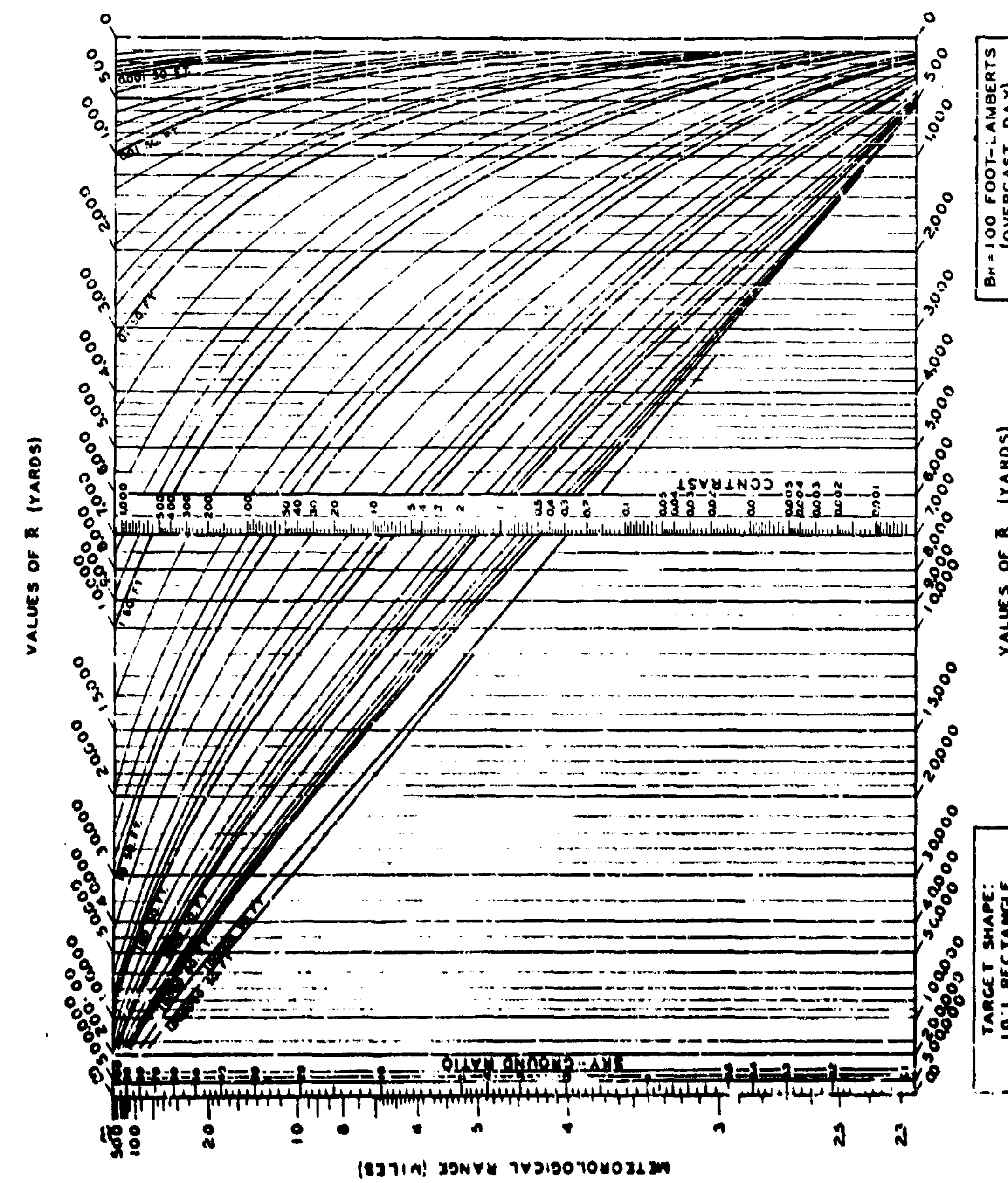
VALUES OF R̄ (YARDS)
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)
BH = 100 FOOT-LAMBERTS (OVERCAST DAY)
TARGET SHAPE: 10:1 RECTANGLE

FIGURE 19

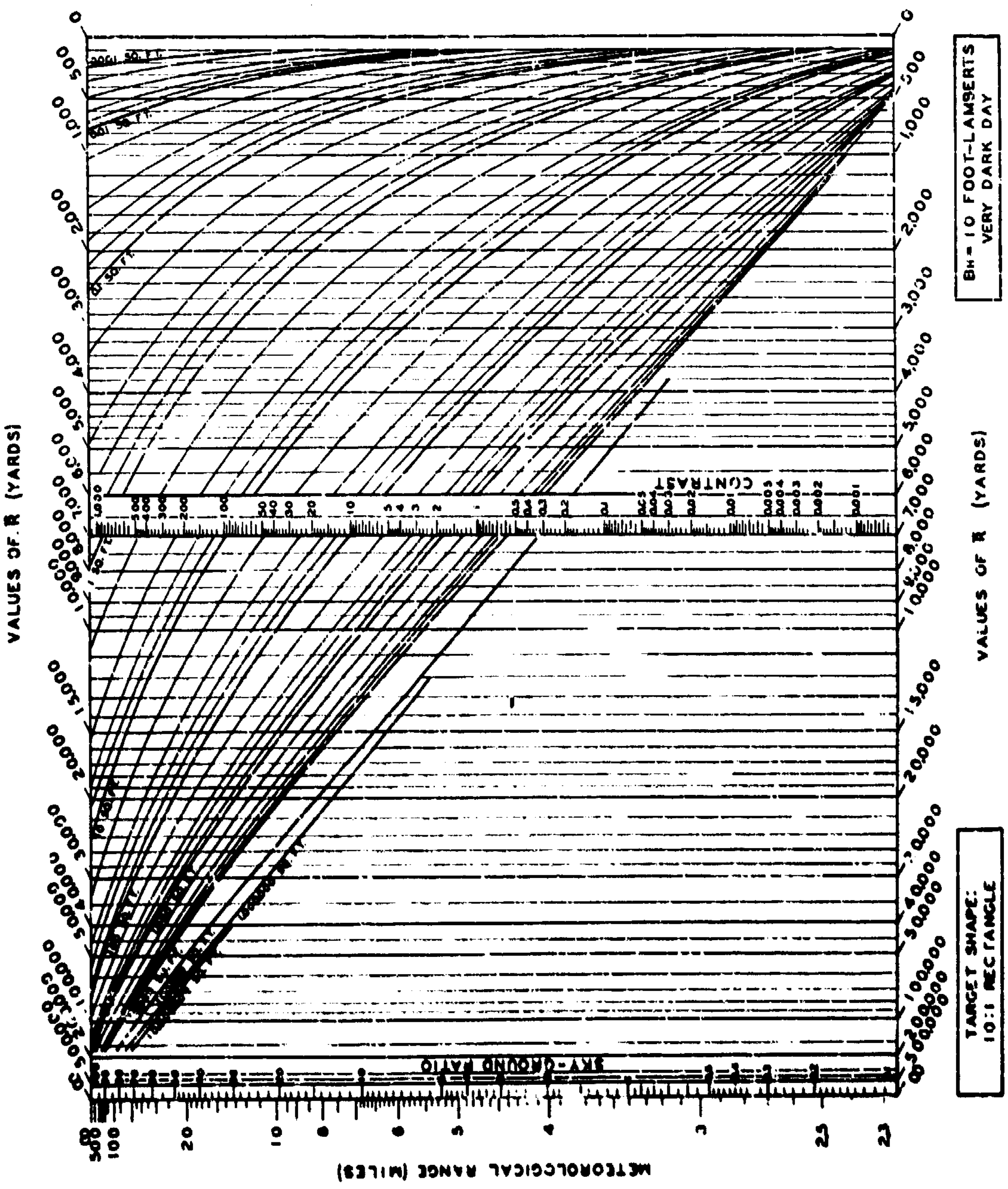
VALUES OF R (YARDS)
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)
BH = 10 FOOT-LAMBERTS
VERY DARK DAY
TARGET SHAPE:
10:1 RECTANGLE

FIGURE 20

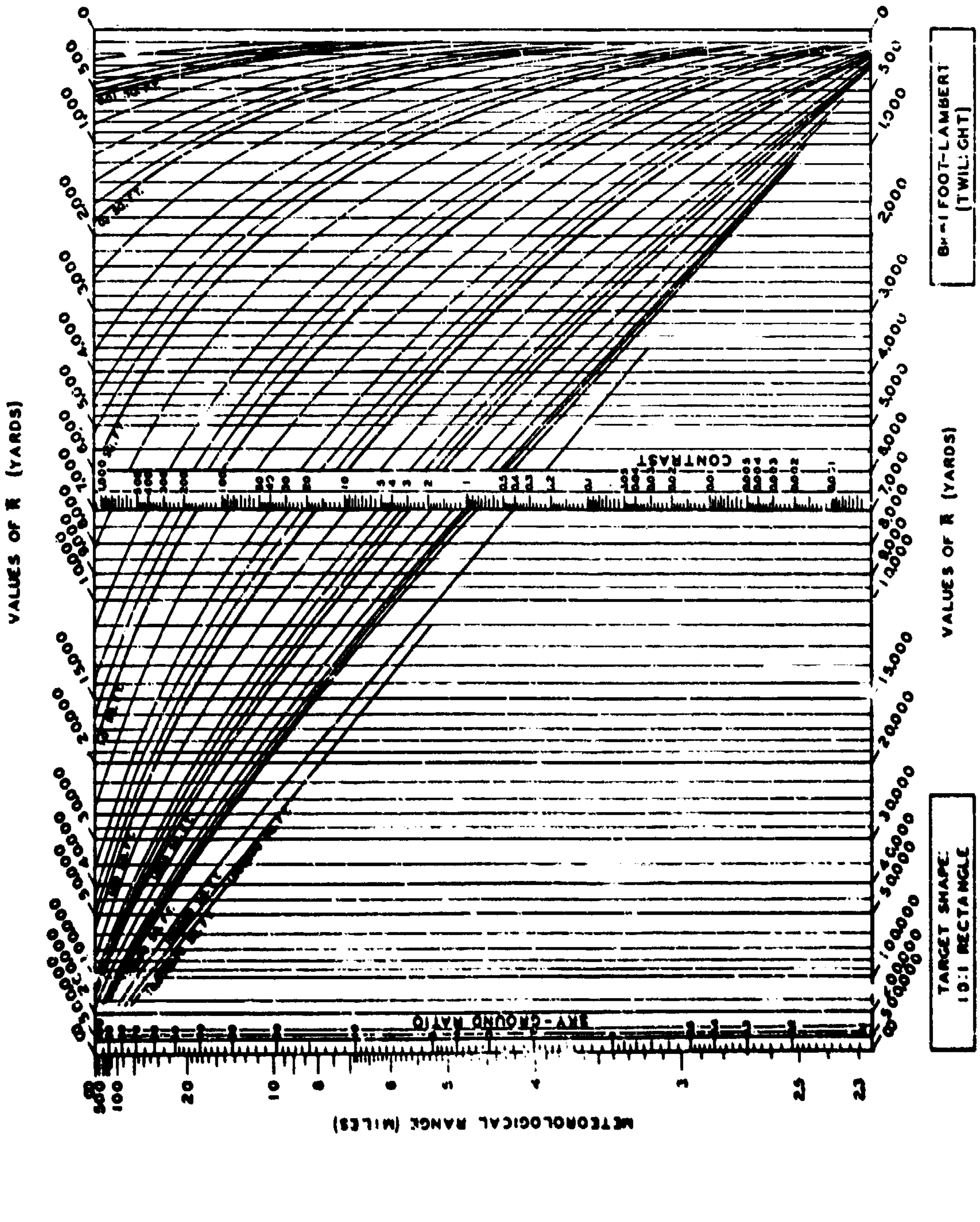
VALUES OF R (YARDS)
FOOT-LAMBERT
(TWILIGHT)
TARGET SHAPE:
10:1 RECTANGLE
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)

FIGURE 21

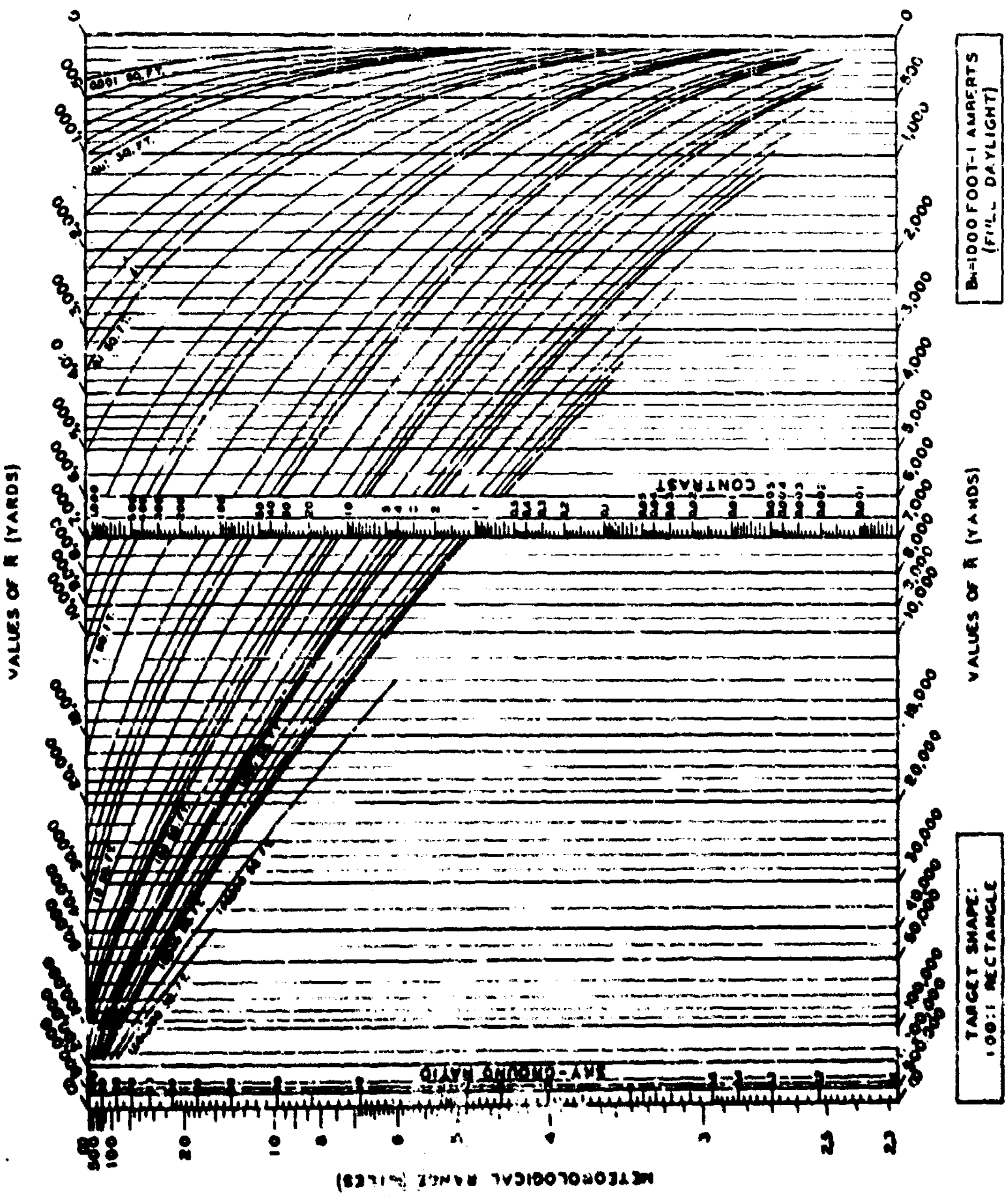

FIGURE 22

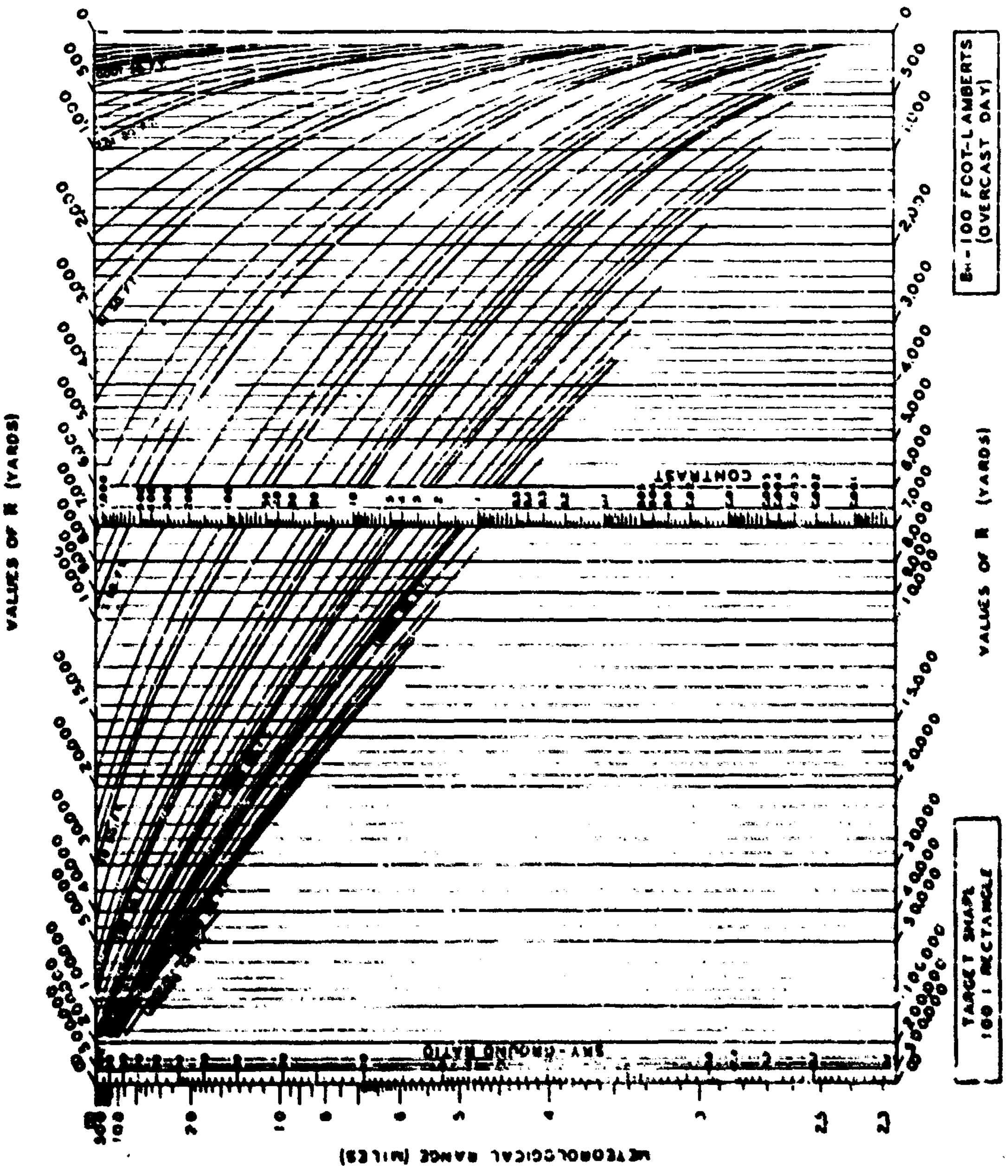
VALUES OF R (YARDS)
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)
B_H - 100 FOOT-LAMBERTS (OVERCAST DAY)
TARGET SHAPE 100:1 RECTANGLE
VALUES OF R (YARDS)

FIGURE 22

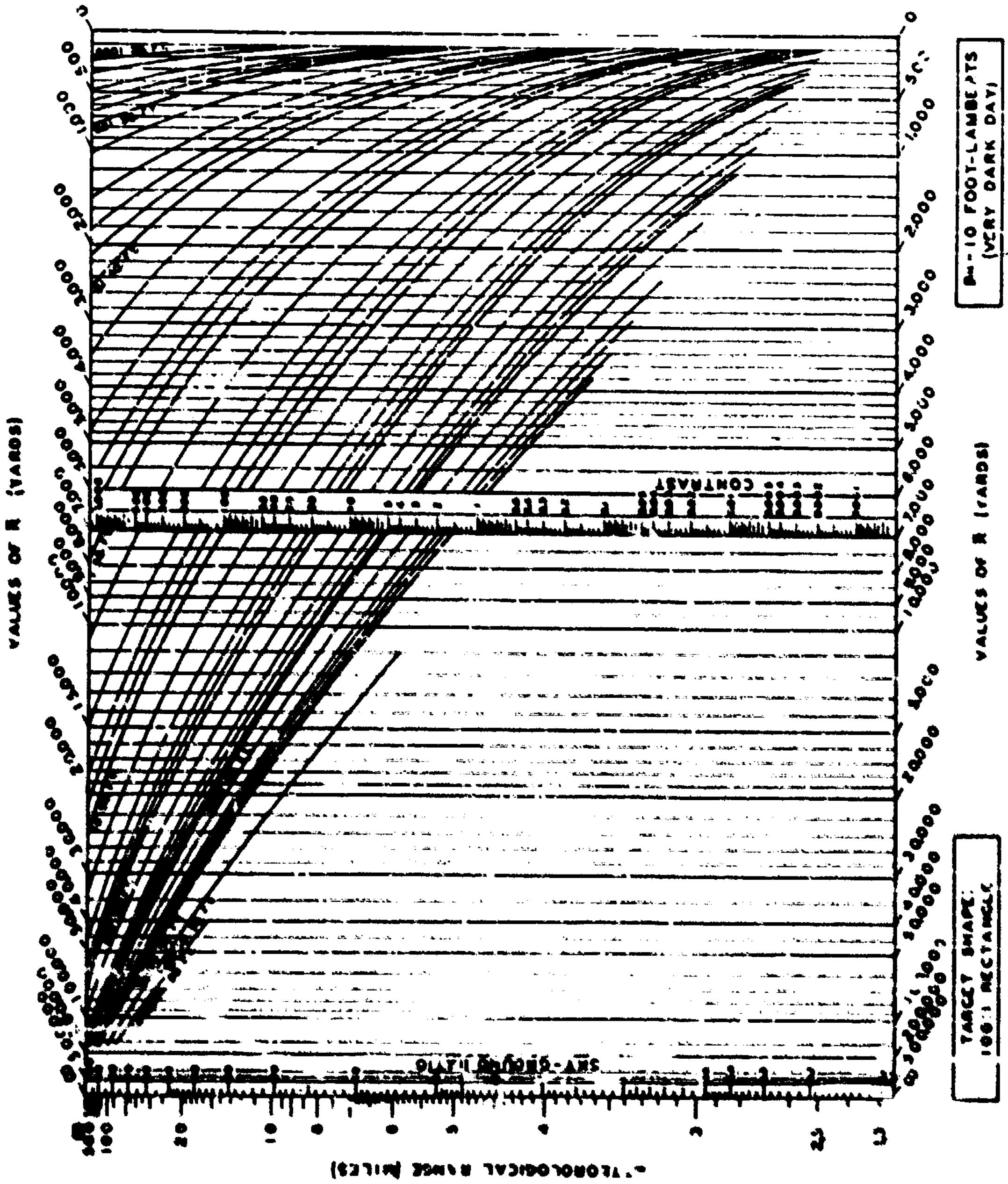
B = 10 FOOT-LAMBERTS
(VERY DARK DAY)
VALUES OF R (YARDS)
CONTRAST
SKY-GROUND RATIO
TARGET SHAPE:
100:1 RECTANGLE
VALUES OF R (YARDS)

FIGURE 24

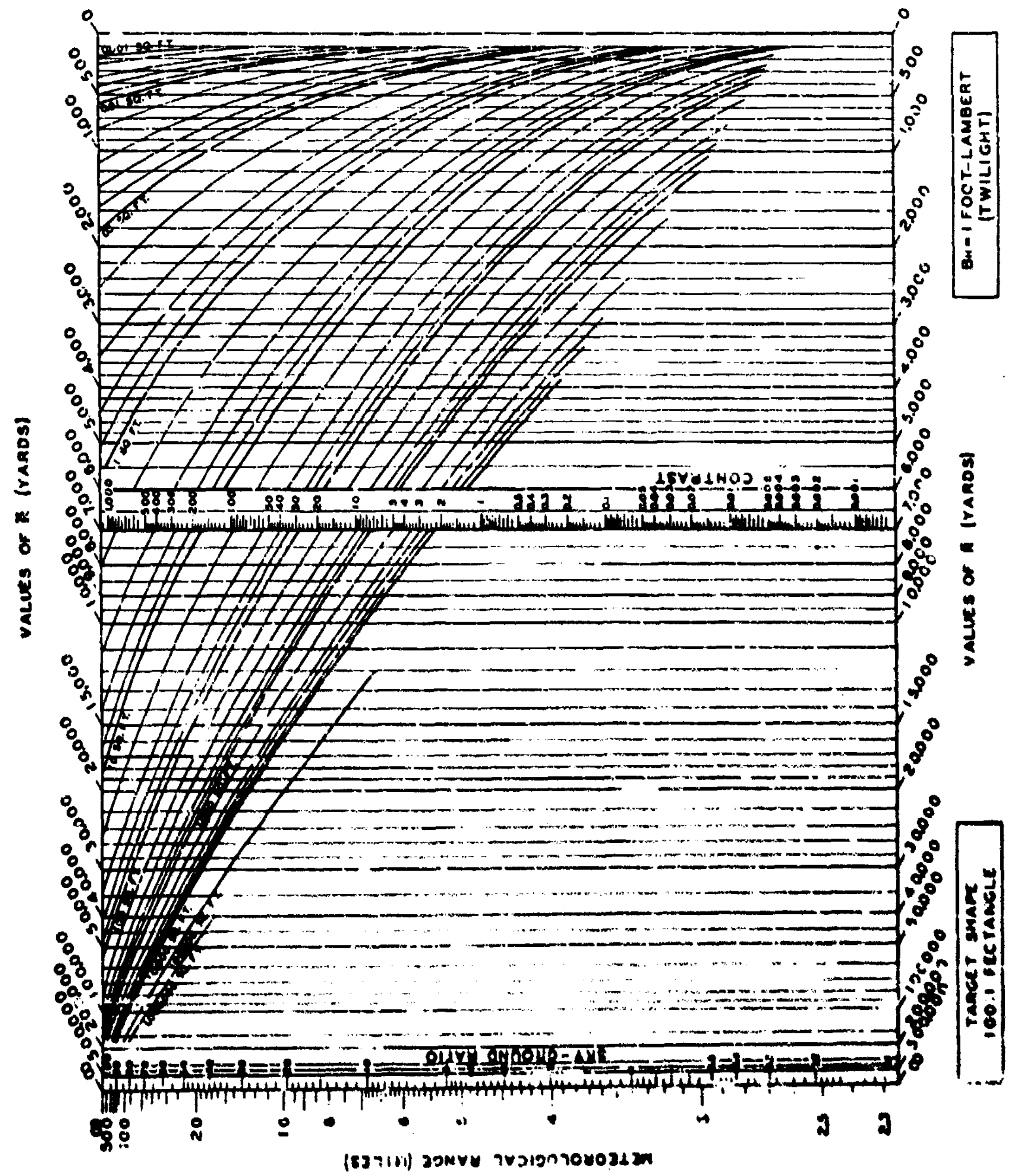
VALUES OF R (YARDS)
BH = 1 FOOT-LAMBERT (TWILIGHT)
TARGET SHAPE 100:1 RECTANGLE
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)

Figure 25

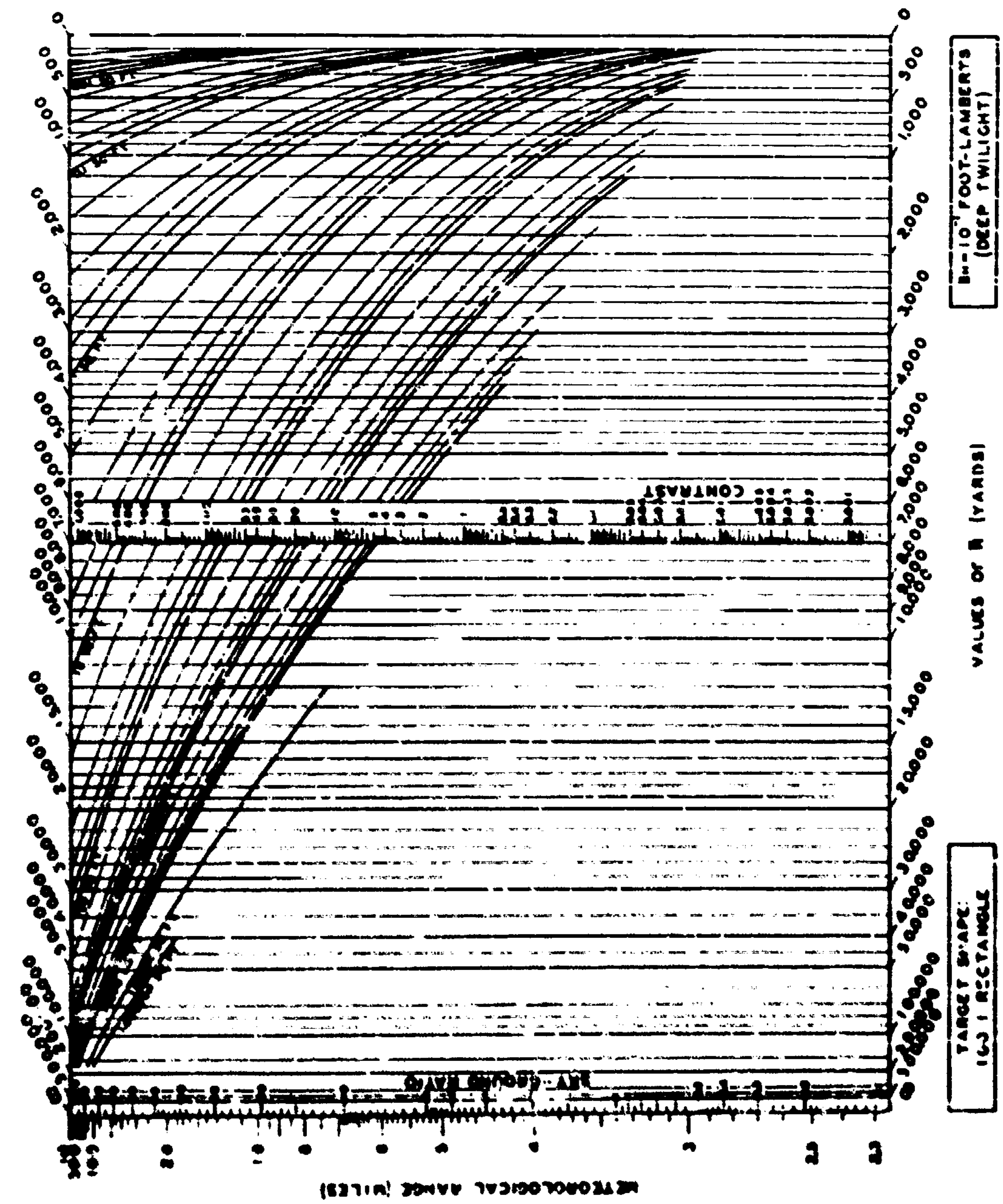
VALUES OF R (YARDS)
CONTRAST
METEOROLOGICAL RANGE (MILES)
SKY-GROUND RATIO
(DEEP TWILIGHT)
TARGET SHAPE
VALUES OF R (YARDS)

FIGURE [illegible]

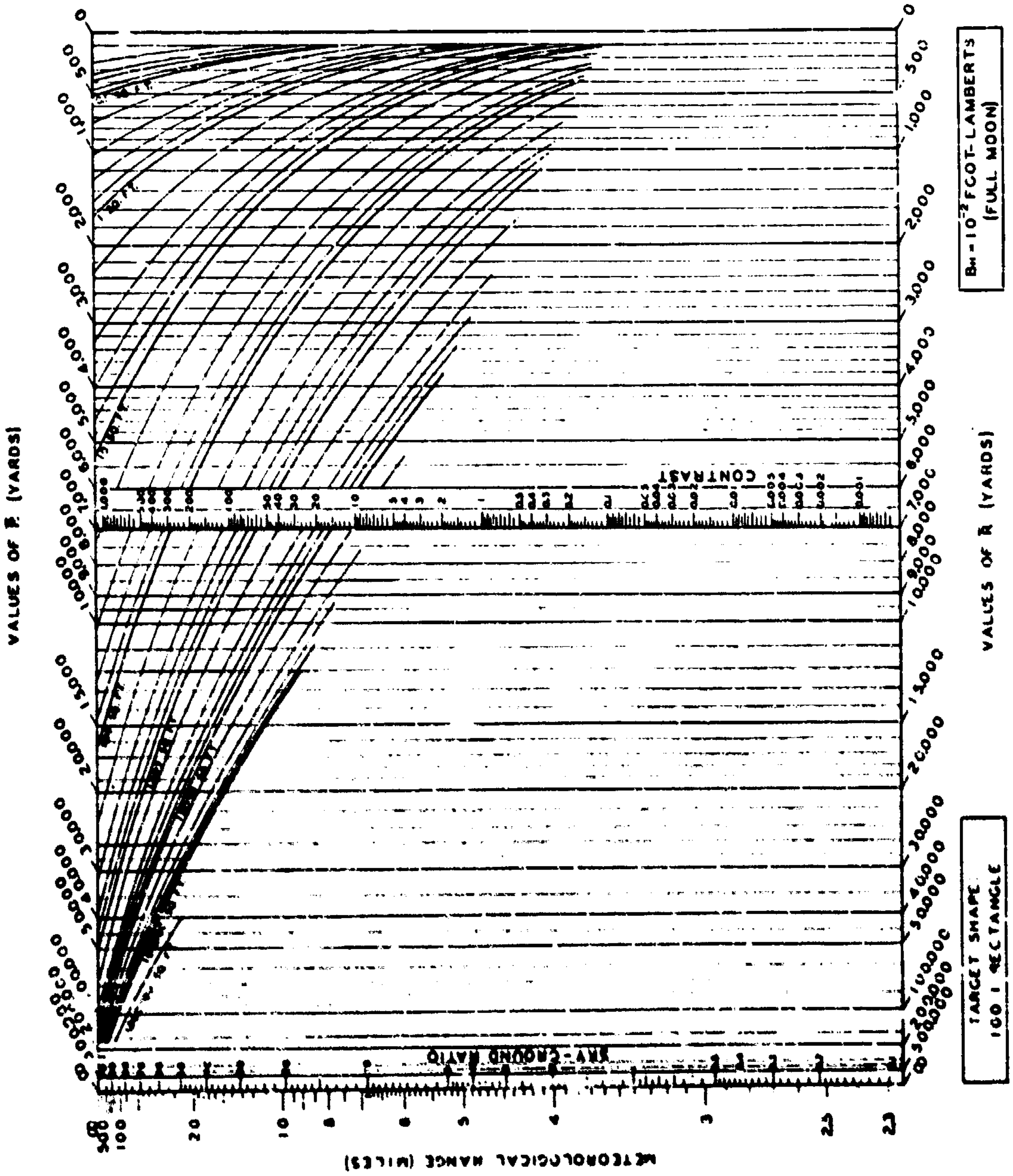
VALUES OF R (YARDS)
Bн = 10⁻² FOOT-LAMBERTS (FULL MOON)
CONTRAST
SKY-GROUND RATIO
TARGET SHAPE 100:1 RECTANGLE
METEOROLOGICAL RANGE (MILES)
VALUES OF R (YARDS)

FIGURE 27

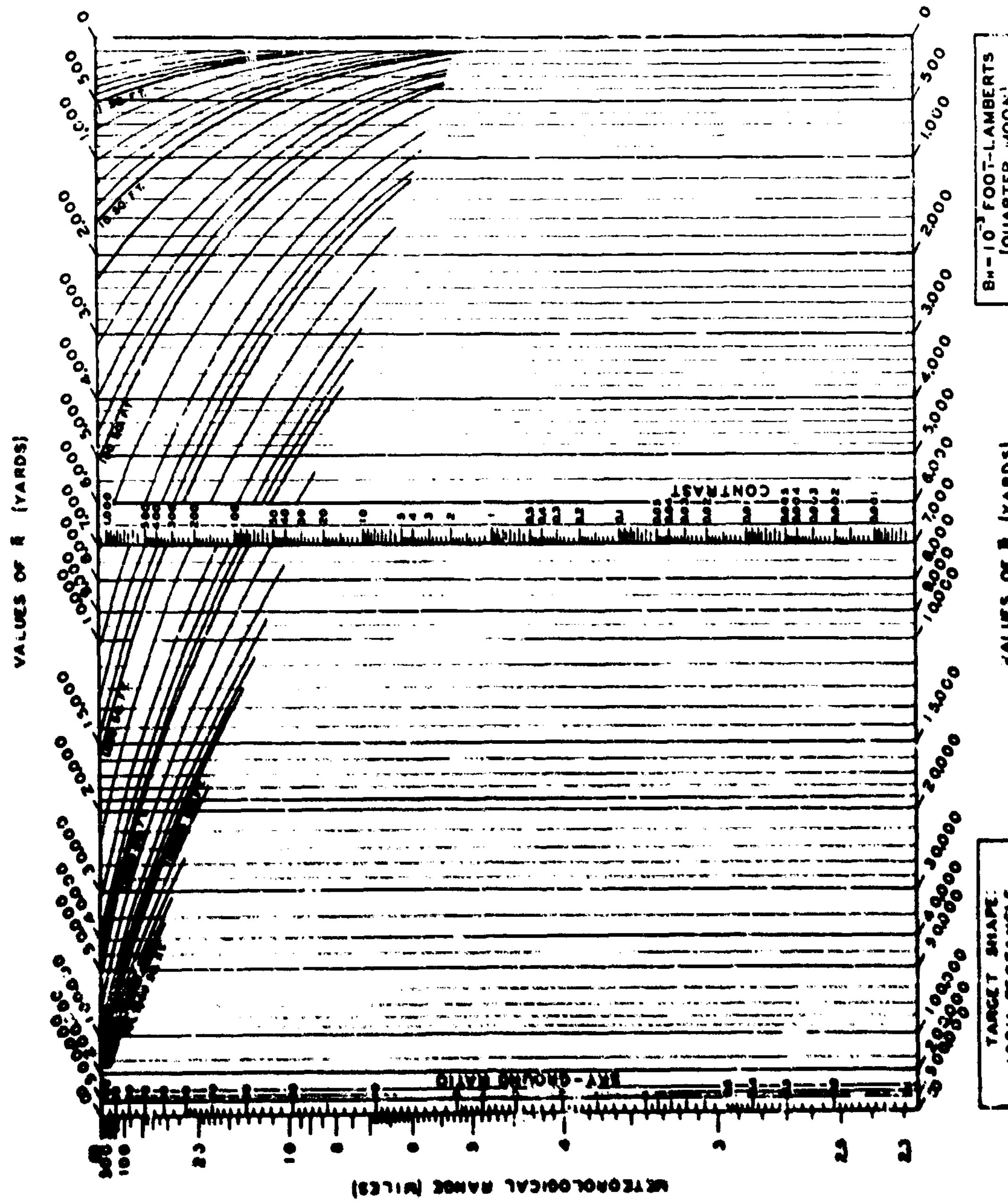
VALUES OF R (YARDS)
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)
B = 10^-3 FOOT-LAMBERTS (QUARTER MOON)
TARGET SHAPE: 12:1 RECTANGLE

FIGURE 26

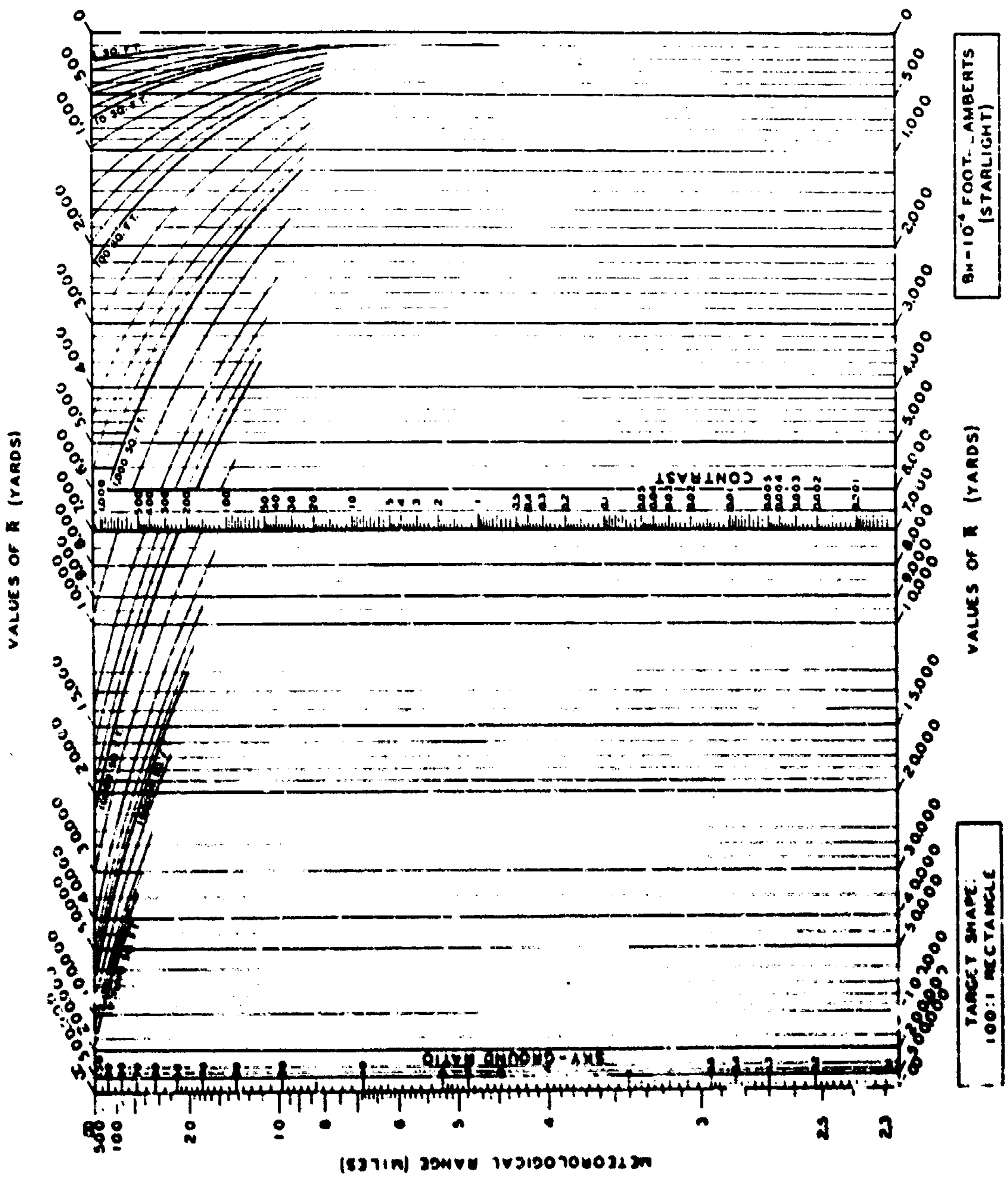
VALUES OF R (YARDS)
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)
TARGET SHAPE: 100:1 RECTANGLE
(STARLIGHT)

FIGURE 29

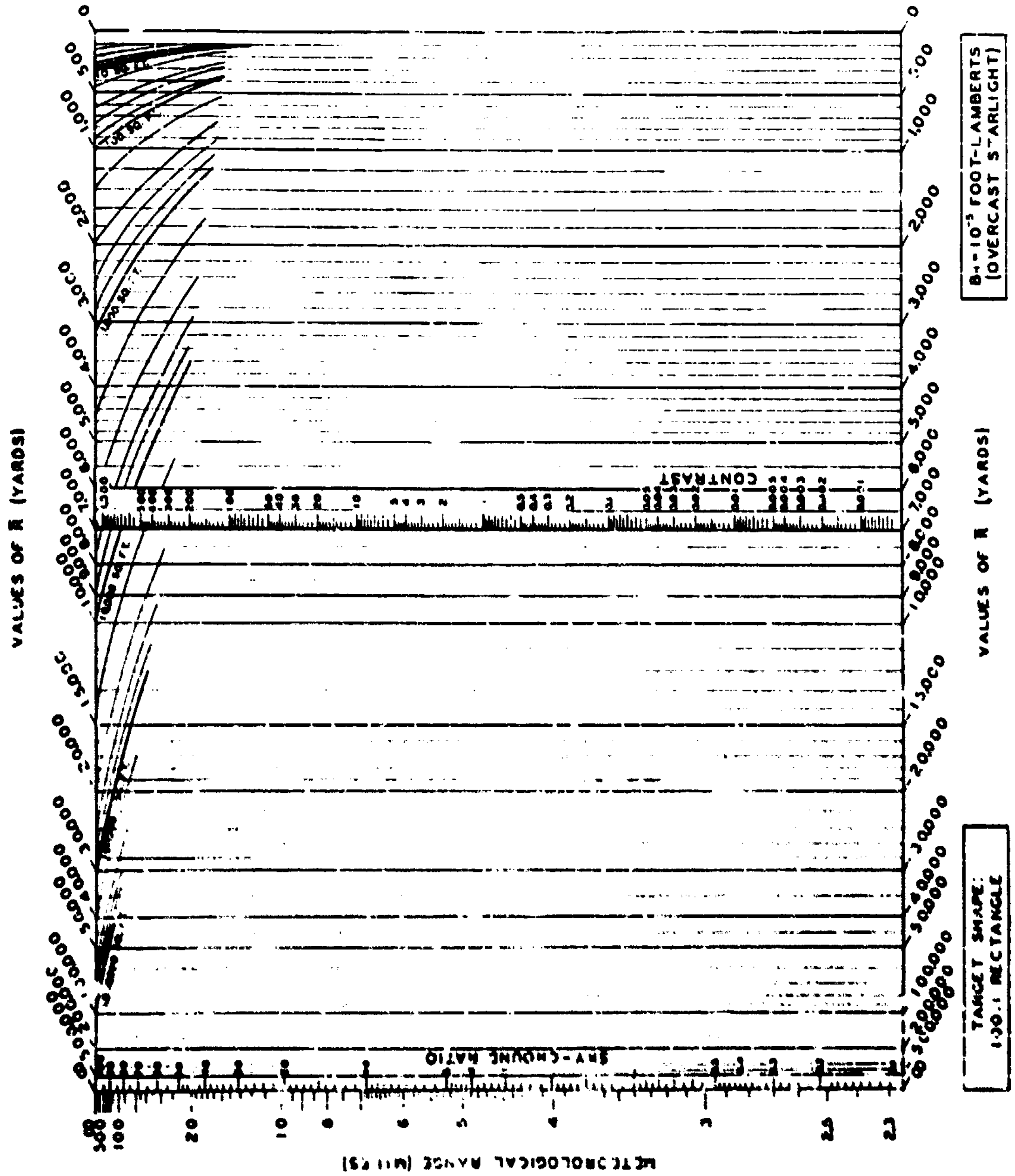
VALUES OF R (YARDS)
CONTRAST
SKY-GROUND RATIO
METEOROLOGICAL RANGE (MILES)
VALUES OF R (YARDS)

FIGURE 20

a reduced value of target area.

The reduced or *effective projected target area* $\bar{A}$ is related to the *projected target area* A by the expression:

$$\bar{A} = \left(\frac{\bar{R}}{R}\right)^2 A \qquad (1)$$

A nomographic chart embodying this relation is shown in Figure 31.

5.4 THE REFLECTANCE OF NATURAL TERRAINS

Natural terrains form the background for most objects seen from aloft. Protective concealment has been attained when, to enemy eyes, the object is indistinguishable from the surrounding terrain. The design of camouflage by engineering methods must, therefore, be based upon knowledge of those optical properties of natural terrains which determine the appearance of the earth from aloft. The experiments described in this section provide some of the required information.

5.4.1 The Spectrogeograph

A specially constructed spectrograph adapted for aerial use was required for the study of the optical properties of natural terrains. Under the provisions of contract OEMsr-717, the Eastman Kodak Company undertook "the design and construction of an instrument and the development of techniques for its use in measuring the quantity and spectral quality of radiant energy from natural daytime sources reaching an aeroplane during flight." The instrument (see Figure 4, Chapter 1) was called a *spectrogeograph* at the outset of the program, when it was thought that it would embody the principle of the well-known spectroheliograph. The name was retained as a code word for use in unclassified correspondence after the spectroheliograph principle had been abandoned.[11]

The spectrogeograph is essentially a photographic spectroradiometer capable of measuring the spectral distribution of radiant energy reaching an airplane from the ground or from the sky. The spectral reflectance of natural terrains can be determined by comparison of the energy received from any terrain with that received from gray panels of several this limited sense, the spectrogeograph may be considered to be an aerial spectrophotometer.

Prior Art

Two previous investigations contributed to the design of the spectrogeograph:

1. A four-lens aerial camera in which various filters were tested for their effect in reducing haze in aerial photographs is described in a monograph on the theory of photography, Number 4, from the Research Laboratories of the Eastman Kodak Company. The title of this monograph is *Aerial Haze and Its Effect on Photography from the Air.*[25]

Photographs were taken from the air with this camera at Rochester, New York, and at Langley Field, Virginia, in 1918 and 1919. The method consisted essentially in photographing three test objects (a black, a gray, and a white canvas, each 60x60 feet, of known reflectance) spread upon level ground. Four lenses, each of 10-inch focal length, were located in a single lens board. The plate holder carried four 4x5-inch plates. Provision was made in each lens barrel for the insertion of color filters. The camera thus served as an abridged photographic spectrophotometer, since the filters chosen were such as to divide the spectrum into sharp intervals of known limits. The reduction of contrast between the images of the targets, when photographed on various days, at various altitudes and with various degrees of haze, was determined by photographic photometry.

2. An aerial spectrograph was employed for a similar purpose by R. Schimpf and C. Aschenbrenner in 1934 and 1939. Their investigation was described in the *Zeitschrift fur angewandte Photographie,*[26] Vol. II, pp. 41–51 (1940). The spectrograph consisted of a direct-vision Amici prism between collimator and objective lenses. A collector lens was placed directly below the spectrograph slit and an image of the ground was focused on the prism (Figure 32). A step wedge was placed in contact with the slit so that the spectrum was divided into seven intensity bands for calibration purposes. The exposure time was standardized at 5 seconds, with the result that the image of a long strip of terrain swept across the prism during the exposure. The spectrogram obtained with this arrangement is, of course, that of the average illumination from a very large area. Neutral-density filters were used in front of the collector lens to reduce all exposures

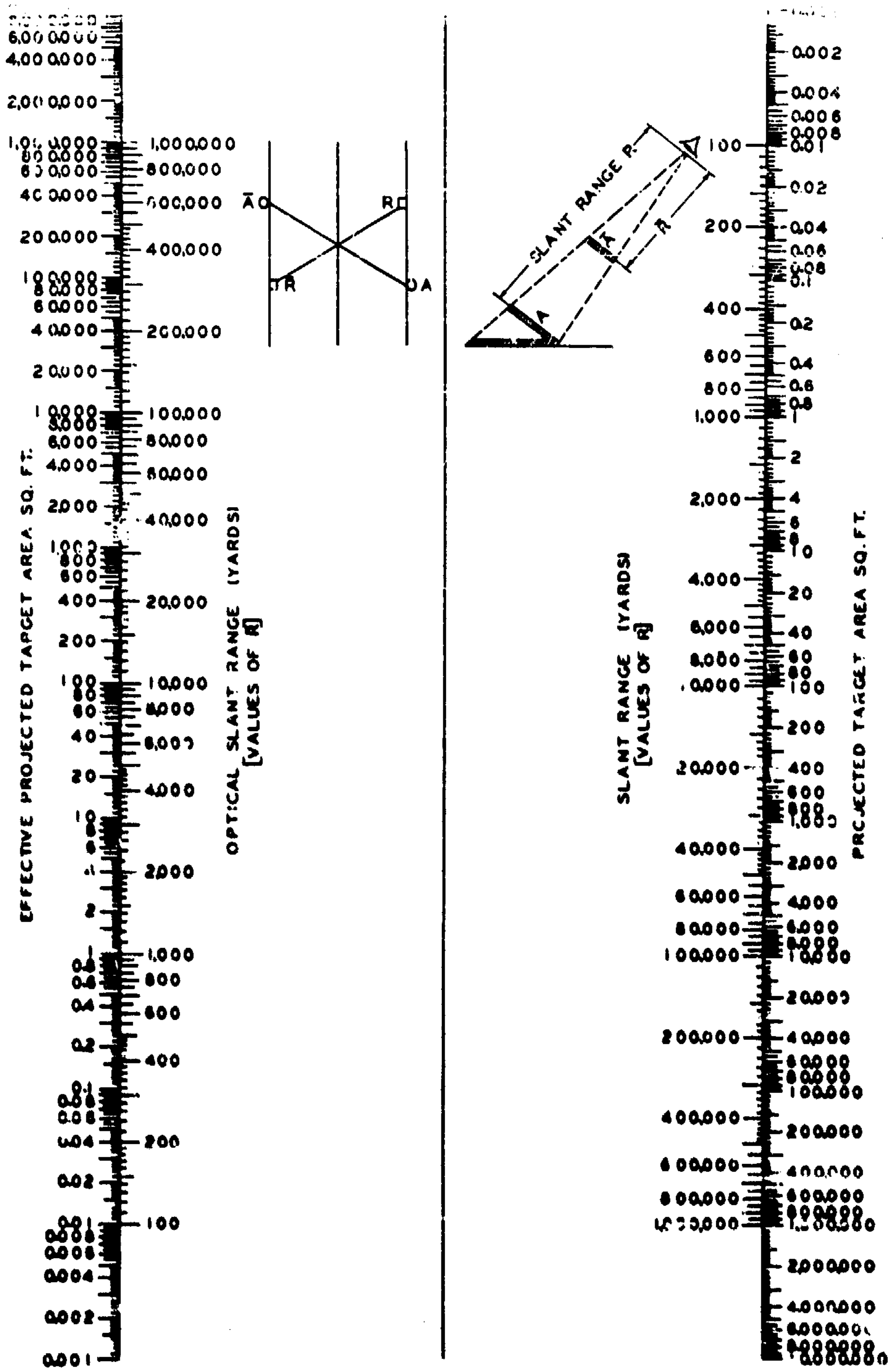

FIGURE 31. Nomographic chart for determining the effective projected area of a target. This nomograph represents equation (1).

was mounted directly on the floor boards of the airplane, so that in normal straight flight the exposure was vertically downward.

Three terrains of typical nature and sufficient expanse and uniformity were selected in the vicinity of Berlin, namely, a meadow, a forest, and a lake. Immediately prior to each flight, a comparison-reflecting surface lying horizontally on the runway

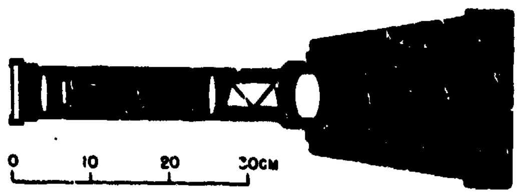

FIGURE 32. Schimpf and Aschenbrenner aerial spectrograph.

was photographed from a height of 2.5 meters. The several terrains were then photographed from altitudes of 100, 1,000, and 2,000 meters. The spectral reflectances of the terrains were then deduced from the densities of the spectrograms of the comparison surface and the terrains.

Strip-Camera Principle

The spectrogeograph had its inception when an instrument modeled on the principle of the spectroheliograph was conceived. In the first conception (see Figure 33), an objective lens was to form an image of the ground on the slit of a spectrograph. At a selected wavelength in the focal plane of the spectrograph, a second slit was to be located in front of a moving strip of film. The rate of movement of this film was to be synchronized with the rate of movement of the image of the ground, so that a continuous strip photograph of the ground would be produced by light of substantially a single wavelength. The location of the slit in the focal plane was to be adjustable. With an instrument of this kind, each wavelength region would require a separate flight over the target. Since daylight changes continually, there could be no assurance that the results for the several wavelengths, recorded during successive passages over the terrain, were comparable.

Such an instrument might be useful for studies in which only one wavelength region need be con-

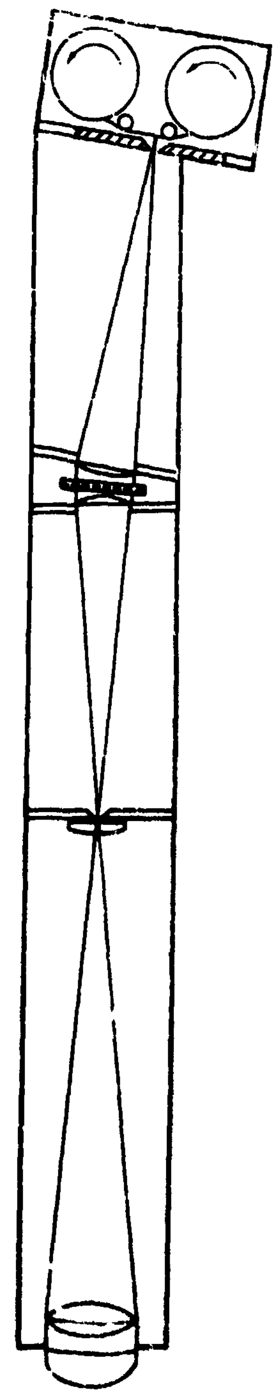

FIGURE 33. Moving-film type of spectrograph.

[illegible] flage, but experience with aerial strip cameras does not encourage the use of this method for photographic photometry, which imposes the most severe requirements of uniformity and reproducibility of exposure. Consequently, an alternative to the strip-camera principle was sought.

Image Stabilization by Optical Means

Refraction in a thick, rotating glass plate has been used in high-speed motion picture photography by synchronizing, during a sufficient exposure time, the motion of the refracted image with film moving continuously at a high speed. The converse of this principle was finally applied in the spectrogeograph. The refraction in the glass block produces a displacement equal and opposite to the rate of motion of the image of the ground in the focal plane of an aerial camera objective. In this way the image is held stationary upon the slit of the spectrogeograph during an exposure time three or four times as great as would be obtained in a strip camera with the same slit width. The film is stationary during the exposure, no slit is used in the focal plane of the spectrograph, and a complete spectrogram of a strip of the image is obtained in a single exposure.

The two principal problems in connection with this arrangement are the synchronization of the block with the movement of the image formed by the objective lens and the identification of the strip actually analyzed in the spectrogram. Even if a spectrogram were taken during each quarter revolution of the stabilizer block, transverse strips of the ground would be missed, the width of which would be at least twice the width of the strips analyzed. It is, therefore, necessary to aim as well as to synchronize the spectrogeograph.

Target Identification

An identification camera is necessary to identify accurately the portion of the terrain analyzed by the spectrograph. Use of a separate identification camera was considered when the stationary-film type of spectrogeograph was being designed. The identification camera could be synchronized electrically with the opening of the spectrograph slit. Such an arrangement would have considerably simplified the construction and operation of the spectrogeograph. The idea was rejected, however, because of alleged installation limitations and because vibration of the plane might disturb the parallelism of [illegible] and introduce errors into the identification of the portion of the image analyzed.

In the first attempt to design a built-in identification camera, a mirror was placed in the spectrogeograph to reflect the light onto the identification camera. This mirror was to be hinged and the plan was to rotate it automatically out of the axis of the spectrogeograph, preliminary to the spectrum analysis. Because of the mechanical difficulties of moving this large mirror rapidly without causing vibrations which would disturb the spectrogeograph during the exposure, other types of identification were investigated.

A stationary mirror was finally used in the spectrogeograph. This arrangement utilizes the fact that the airplane is moving at a relatively constant speed toward the selected target. Although the identification camera and the spectrograph slit occupy different portions of the focal plane of the objective, a photograph of the target which is subsequently analyzed by the spectrograph is obtained by synchronizing the time lapse between the identification and spectrum exposures with the time of transit of the crosswire in the sight.

The spectrogeograph automatically takes two identification pictures for each spectrogram. One of these pictures is taken at a time when the selected target is certainly imaged in the identification camera, and the other is taken simultaneously with the opening of the slit of the spectrograph. These identification pictures overlap and can be assembled as a composite picture. It is a simple matter of geometric construction to identify exactly the target analyzed, which appears in the composite picture at a position known in relation to crossmarks in the second identification picture (Figure 34). The spectrogram of the target indicated in Figure 34 is shown in Figure 35.

Description of the Instrument

The spectrogeograph consists of a [illegible]-inch, $f/6$ aerial objective lens, an optical device which stabilizes a portion of the image on the slit of a grating spectrograph, an identification camera, and a sight mechanism. The image stabilizer is driven by an adjustable governor-controlled motor (Figure 36), and it is coupled to the sight with which the synchronization of the image and stabilizer speeds is verified and the desired target selected. Electric circuits, which are controlled chiefly by the sight mech-

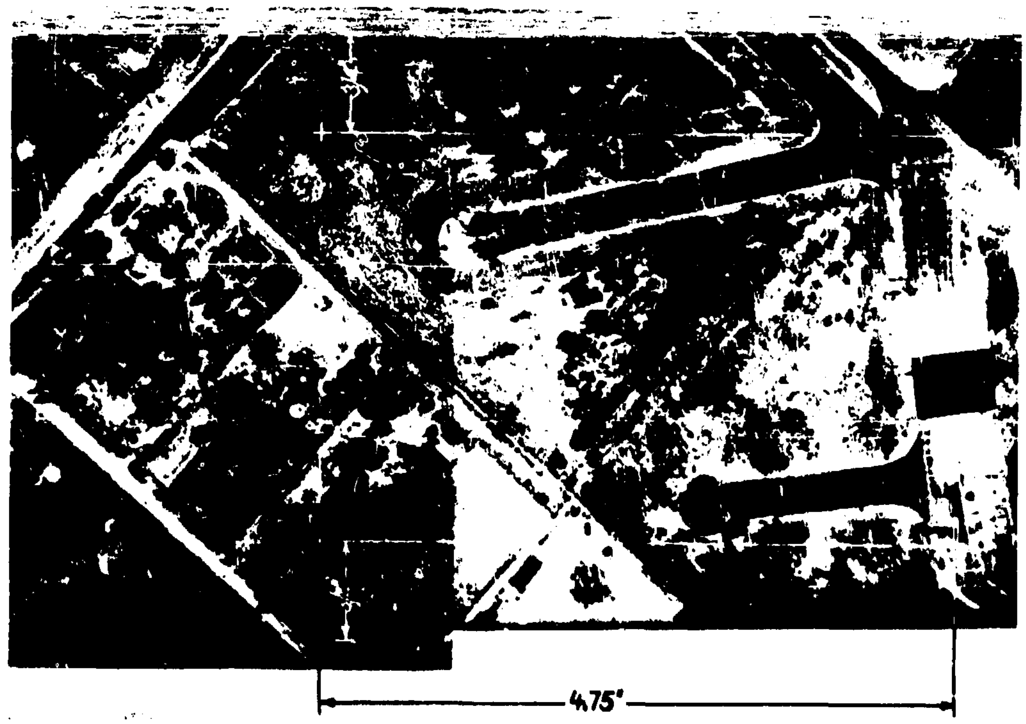

FIGURE 34. Composite identification picture.

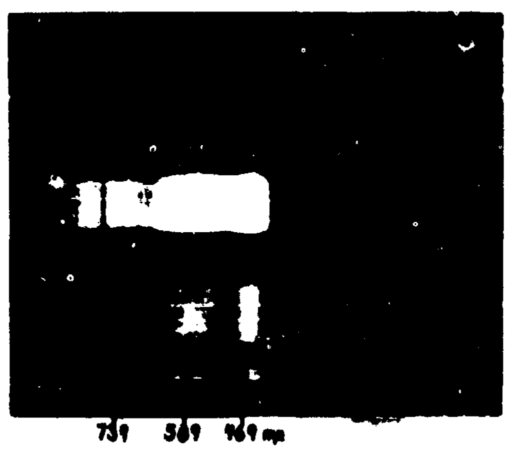

FIGURE 35. Spectrogram corresponding to Figure 34.

anism, actuate the shutters of the identification and spectrum cameras and initiate the transport of the film after each exposure.

Optical System. The optical system is shown in Figure 37. The 24-inch objective lens is provided with an iris diaphragm, for control of exposure. A graduated knob controlling the aperture is located on the right side of the casting below the sight (Figure 4, Chapter 1).

The optical stabilizer device, which holds the image of the ground stationary upon the spectrographic slit during the exposure, consists of a glass block having polished plane parallel surfaces (Figure 38). This block is mounted so as to rotate in front of the spectrograph slit. The rotation is about an axis parallel to the length of the slit. When this block is rotated at the proper speed, the refractive displacements of rays passing through it compensate for the motion of the image of the ground in the focal plane of the 24-inch aerial objective lens. The provisions for synchronizing the speed of rotation of this block with the velocity of the image of the ground formed by the objective will be described subsequently.

The Spectrograph. The spectrograph proper (Figure 39), consists of a slit 3 inches long, collimator and camera lenses each of 15-inch focal length and 3-inch diameter, and a Wood, first-order replica

plane grating [illegible]
4-inch square area.

The film is held in the focal plane of the spectrograph in the film magazine of a K-24 automatic

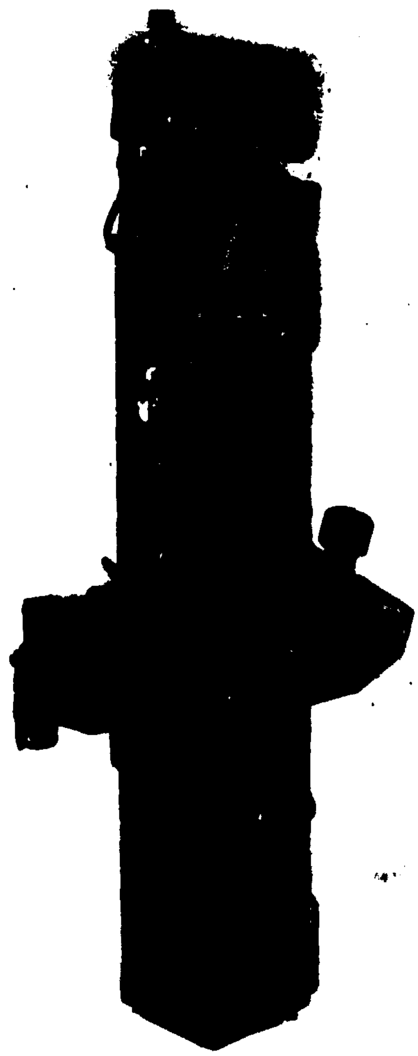

Figure 36. Photograph of left side of spectrograph, showing governor-controlled motor, identification and spectrum cameras, sky periscope, sky and practice control lever, coincidence control lever, and periscope shutter lever.

aerial camera, the mechanism of which provides high-speed automatic film changes. The focal-plane shutter curtain belonging to this mechanism has been removed, and the spectrograph exposure is con-

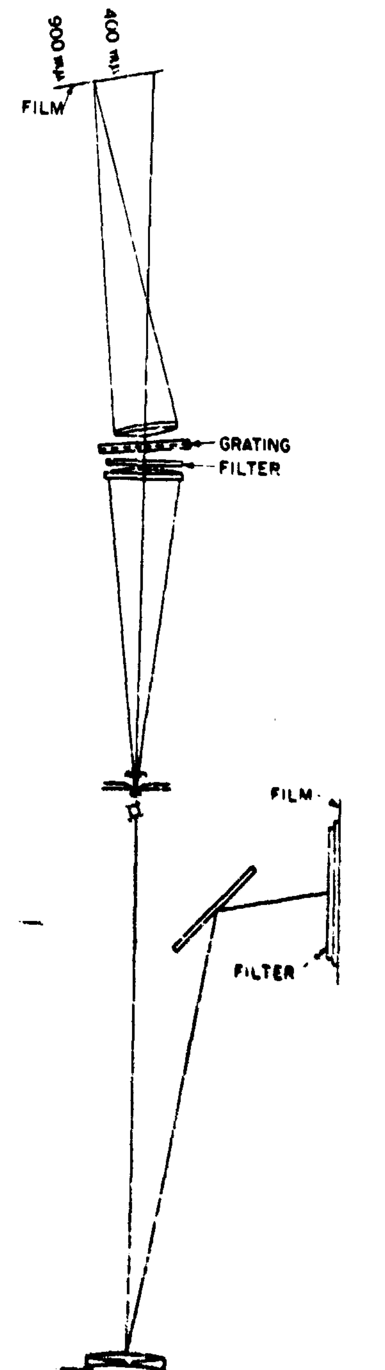

Figure 37. Sketch of basic optical system of spectrograph.

40).

This vane is opened by a solenoid when the image is first synchronized on the slit, remains open as long as the image is held stationary on the slit, and closes again before the block rotates beyond the extreme position for synchronization. The block is mounted in a metal cylinder with apertures cut

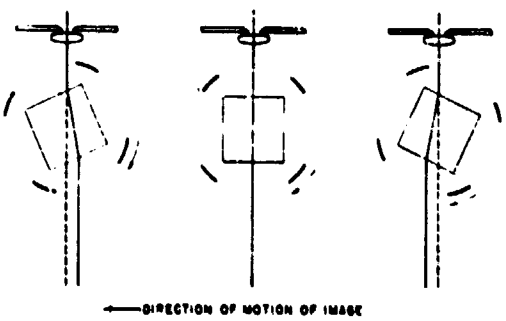

Figure 38. Cross sections of stabilizer block and cylindrical apertures in relation to slit for successive positions of the block.

away opposite each of the faces (Figure 41). The remaining portions of the cylinder prevent light from entering or leaving the block at angles in excess of those for which accurate stabilization is obtained. The slit-vane opens and closes while two successive opaque portions of this cylinder are in front of the slit. Consequently, the edges of the apertures of the cylinder actually control the exposure; the slit-vane merely confines the exposure to one of these apertures.

Identification Photographs. Identification photographs of the ground are made by reflection of a portion of the image formed by the objective lens into a second K-24 automatic camera. The exposure of the film in this camera is controlled by the focal-plane shutter which is a standard part of the mechanism. The film is held accurately in the focal plane by being pressed against a clear glass plate through which the light must pass. Opaque crosses engraved on this pressure plate produce the identification marks in the pictures. A Wratten No. 12 haze filter is cemented onto the front surface of the pressure plate of this camera.

The identification camera photographs a portion of the ground ahead of the section imaged on the spectrograph slit. The central ray recorded in the identification photograph is therefore inclined forward of the vertical. Consequently, the identification camera must photograph the target imaged on the spectrographic slit prior to the exposure in the spectrograph. The necessary interval depends upon the

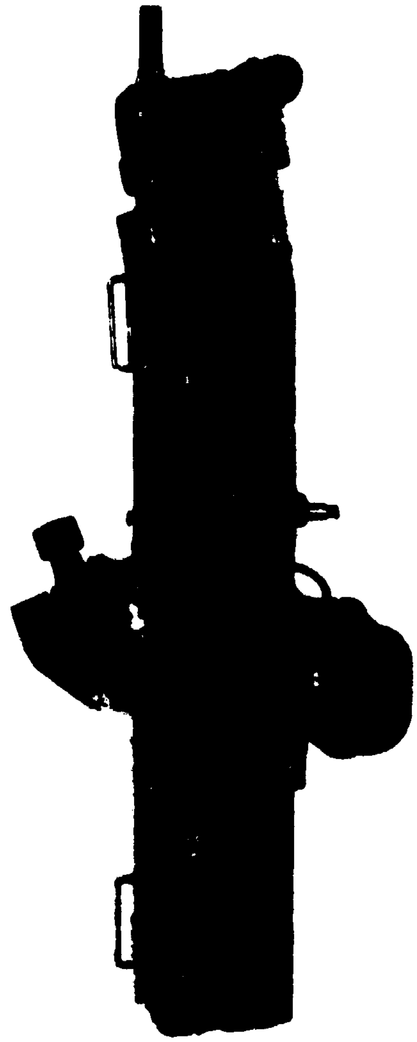

Figure 39. Photograph of interior of spectrograph.

speed of the image in the focal plane and is controlled by the same synchronization device that controls the speed of rotation of the stabilizer block. This synchronization apparatus is part of the sight mechanism.

The Sight. The sight (Figure 42) is built as an integral part of the spectrograph [illegible] carried across the focal plane of the sight in a frame which travels at a speed proportional to the rate of rotation of the stabilizer block. When the crosswire remains coincident with the image of a target, that

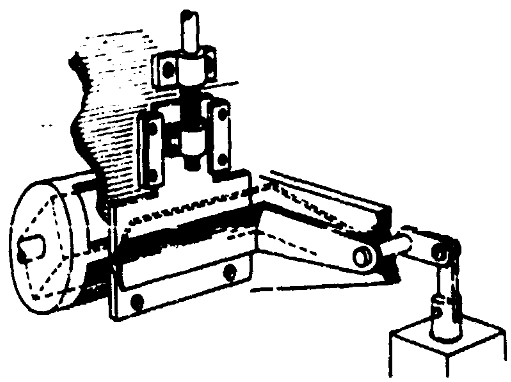

FIGURE 40. Perspective view of vane and slit.

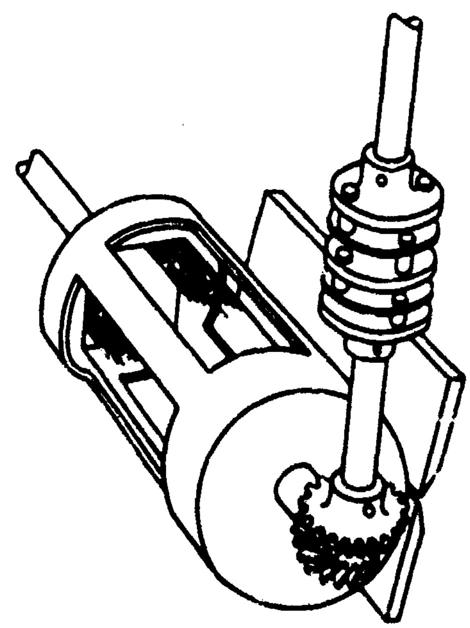

FIGURE 41. Perspective view of stabilizer block, cylinder, and coupling between block and sight mechanism.

target is focused upon the spectrograph slit and its image remains stationary while one face of the stabilizer block rotates past the slit. The speed of a governor-controlled motor, which drives the stabilizer block as well as the crosswire, is adjusted by

[illegible] the sight-wire remains fixed on the image of the ground. The motor rotates the block continually, but the crosswire in the sight moves only when a clutch is engaged.

When the target selected for spectral analysis appears in the sight and coincides with the crosswire in its initial position, the operator presses a handle.

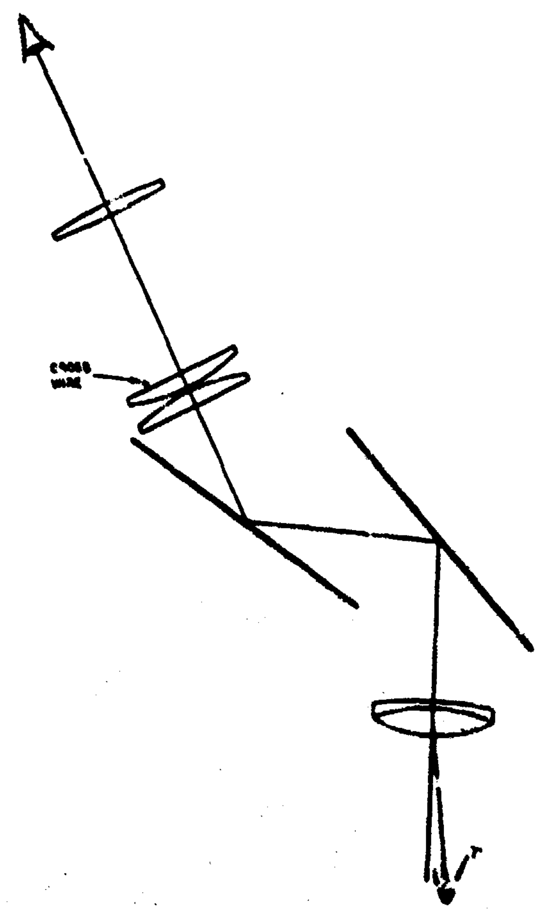

FIGURE 42. Optical system of sight.

This engages the clutch, and the crosswire moves, remaining coincident with the image of the target. When the crosswire reaches a position corresponding to the first position of the stabilizer block in which the target is imaged on the slit, an electric contact on the frame which carries the crosswire closes a circuit through a solenoid which opens the vane above the slit, thus exposing the spectrogram. The speed of the crosswire can be varied by [illegible] over a 16:1 speed ratio. This range of speeds enables the image of the ground to be stabilized at all altitudes between 1,000 and 16,000 feet, provided the spectrogeograph is flown at a ground speed of 150 miles per hour. The image may be stabilized at higher altitudes if the ground speed of the airplane is increased.

The width of the spectrograph slit is changed from 0.05 inch to 0.15 inch when the gear ratio is changed from low to high. This is accomplished with a lead screw which is coupled to the gear-shift lever (Figure 43). This arrangement partially compensates for the change of exposure time, which is directly proportional to the time of rotation of the stabilizer block. The use of the narrow slit for high altitudes also makes possible the analysis of a smaller area. The change of spectral resolution corresponding to this change of slit width is not important in the analysis of the spectrally continuous energy distributions which are observed from aircraft.

[illegible] already been mentioned which may be turned to a position so as to reflect light from the top of the airplane into the spectrograph slit. Light from the sky is brought to this mirror by a periscope system (Figure 44), which is designed specifically for installation in a B-17 Flying Fortress.

A flat, opal-glass cap is provided for the top of the periscope tube. The light transmitted by the periscope from this opal glass is representative of the illumination on a horizontal plane. Compensation for the selective absorption of this opal glass and of the other optical elements of the periscope must be accomplished by the calibration procedures.

A pair of adjustable mirrors is also mounted in an accessory which may be placed on top of the periscope (Figure 45). The light from any region of the sky can be analyzed by this mirror system by orienting it with respect to the direction of flight of the airplane and by adjusting the mirrors to reflect light from various vertical angles into the periscope.

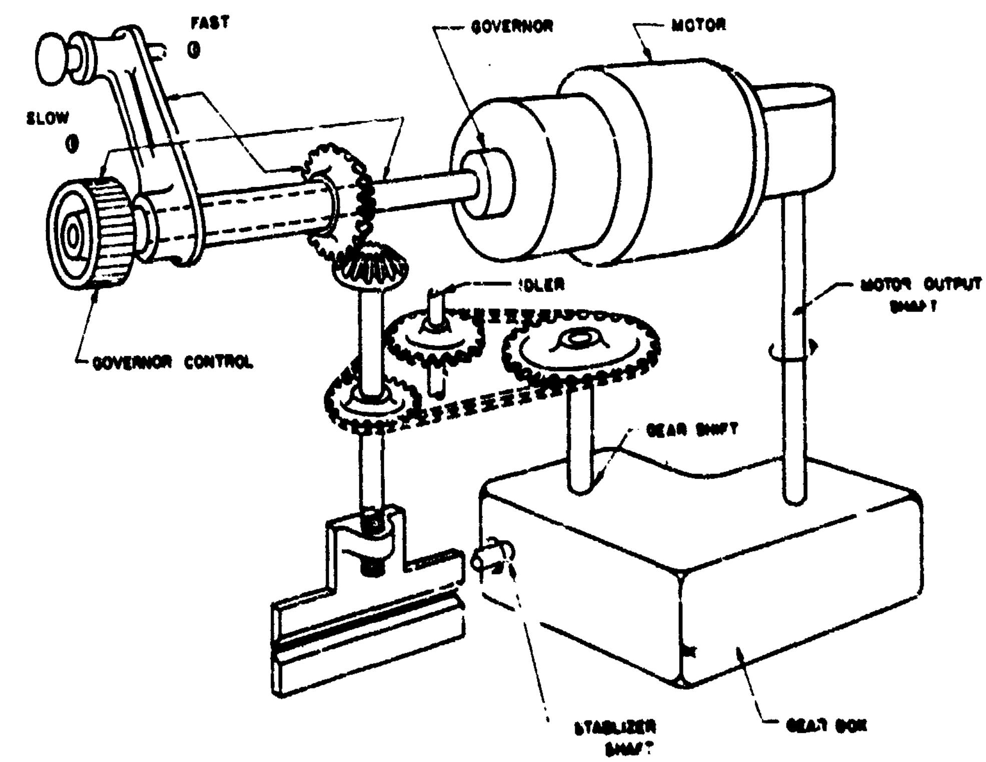

FIGURE 43. Perspective view of coupling between gear shift and lead-screw controlling slit width.

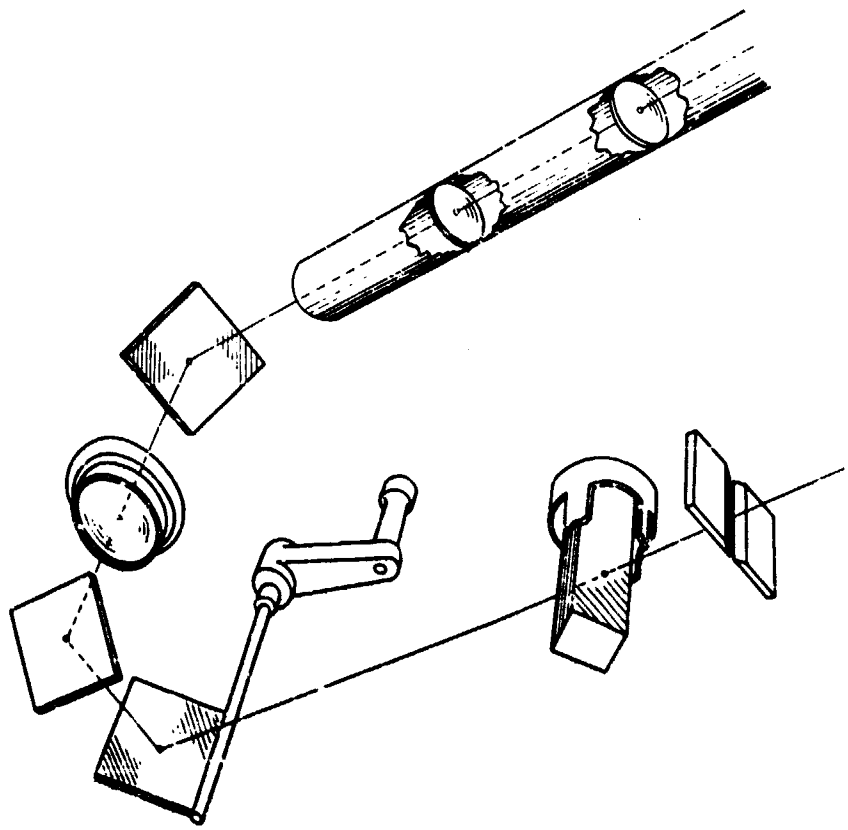

FIGURE 44. Perspective sketch of periscope system.

Oblique Terrestrial Mirror System. A large adjustable mirror system is provided for the investigation of the spectral distribution of energy received from the ground at oblique angles (Figure 46). This system can be placed in front of the objective lens of the spectrogeograph. With this mirror system, the spectral distribution of the energy from targets as far as 65 degrees from the vertical can be analyzed. These oblique angles are perpendicular to the direction of the flight of the airplane, so that flight paths can be laid out and specific target areas investigated.

INSTALLATION OF THE SPECTROGEOGRAPH

The spectrogeograph was designed to be flown in a B-17 aircraft partly because of advice from liaison officers that this type of airplane was more likely to be available than any other type large enough to contain the instrument and partly because the B-17 has a removable hatch in the top of the fuselage directly over the camera station. This permits the periscope of the spectrogeograph to protrude above the airplane when light received from above is to be measured.

Figure 47 shows the spectrogeograph installed in the camera pit of the B-17F (F-9) airplane (Army 229801) in which it was flown during the experiments in Florida and California. The instrument and its mounting frames weigh approximately 250 pounds. The main frames are welded steel parallelograms which are bolted to the standard camera supports in the B 17 and clamped to the floor-support metals at the rear of the camera pit. The spectrogeograph, in a modified A-8 ring mount, is bolted to the tops of the frames. The mounting is so designed that the instrument is offset toward the tail of the ship in order to give the sight system a sufficient forward view. This has the additional advantage of transferring at least one-third of the weight of the installation to the floor structure. The mount-

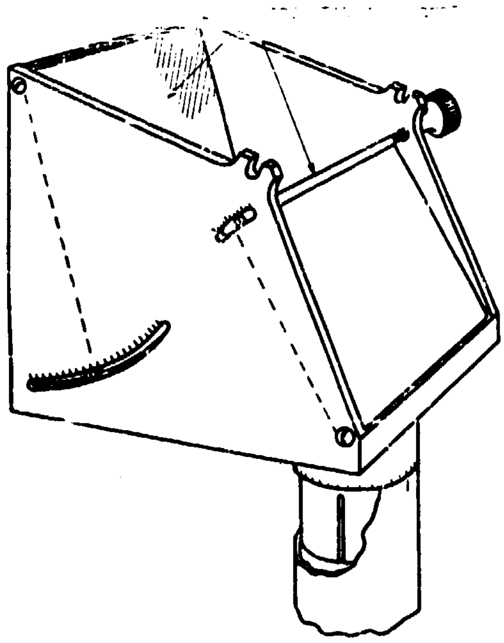

Figure 45. Perspective sketch of sky-scanning mirror system.

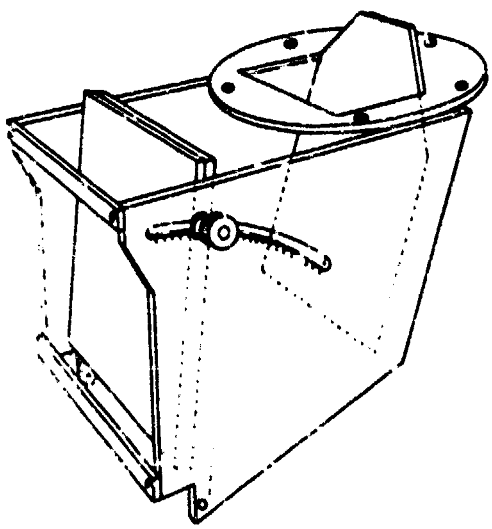

Figure 46. Perspective sketch of large mirror system for oblique terrestrial analyses.

ing is relatively free from sidesway, but this effect is further eliminated by auxiliary welded steel frames, triangular in shape, which are bolted to the sides of the main frames and rest on the floor at the

[illegible]
frames, clearly shown in Figure 47, serve to transfer most of the weight of the spectrogeograph to the floor in case of hard landings.

Calibration and Use

The spectrogeograph is not an easy instrument to use. Technical skill of a high order and meticulous attention to detail are required, not only at the time of the flight but later in the laboratory.

Figure 47. Spectrogeograph installed in camera pit (radio room) of a B-17 airplane.

Periscope protrudes through open hatch in roof directly above camera station. (Photograph by Photo Technical Unit, AAFTAC, Orlando, Florida.)

Useful results can be obtained only if the experiments are planned and the findings interpreted by a scientist thoroughly versed in the physical principles involved.

In an effort to preserve the experience gained by Section 16.3 of NDRC and its contractor, the Tiffany Foundation has prepared a report entitled *Calibration and Use of the Spectrogeograph*, which is intended to serve as an instruction manual for subsequent users of the instrument, as well as a record of the procedure by which the data were obtained.[13]

A special photographic film was required to permit the spectrum to be photographed without serious overexposure or underexposure at any wavelength between 420 and 900 millimicrons. After many experiments, a double-coated film was chosen. This consists of an infrared-sensitive emulsion coated on a supersensitive panchromatic film. The spectral sensitivity of this material is shown in Figure 48. This curve was determined from exposures made in the spectrogeograph. The density-versus-exposure gradient of this film is very different for the infrared than for the visible portion of the spectrum, and this fact complicates sensitometry, especially near the extreme red end of the panchromatic sensitivity.

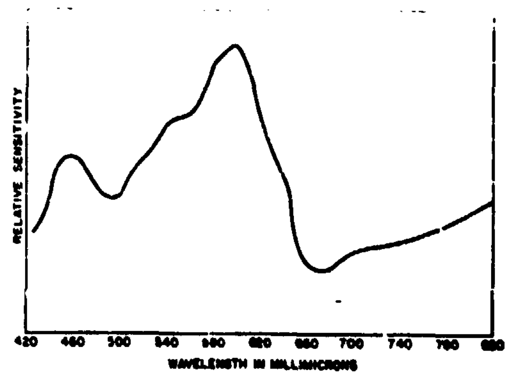

Figure 48. Spectral sensitivity of double-coated, panchromatic, infrared film.

Densitometer

Measurement of the densities of the numerous calibration films and of all of the aerial spectrum analyses represent a formidable task. A photoelectric densitometer is provided to facilitate this work (Figure 49), which is designed to measure the densities of very small areas and to locate the film very accurately in the measurement beam. Accurate location of the film is necessary so that the portion of the film corresponding to the selected target can

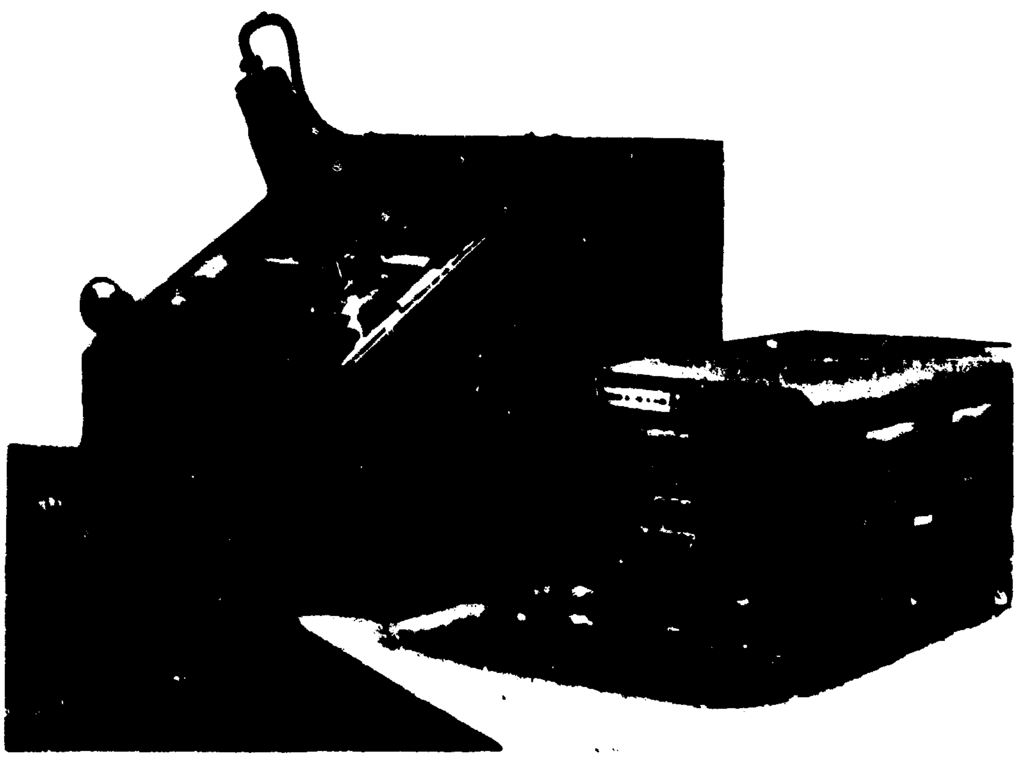

Figure 49. Densitometer and power amplifier.

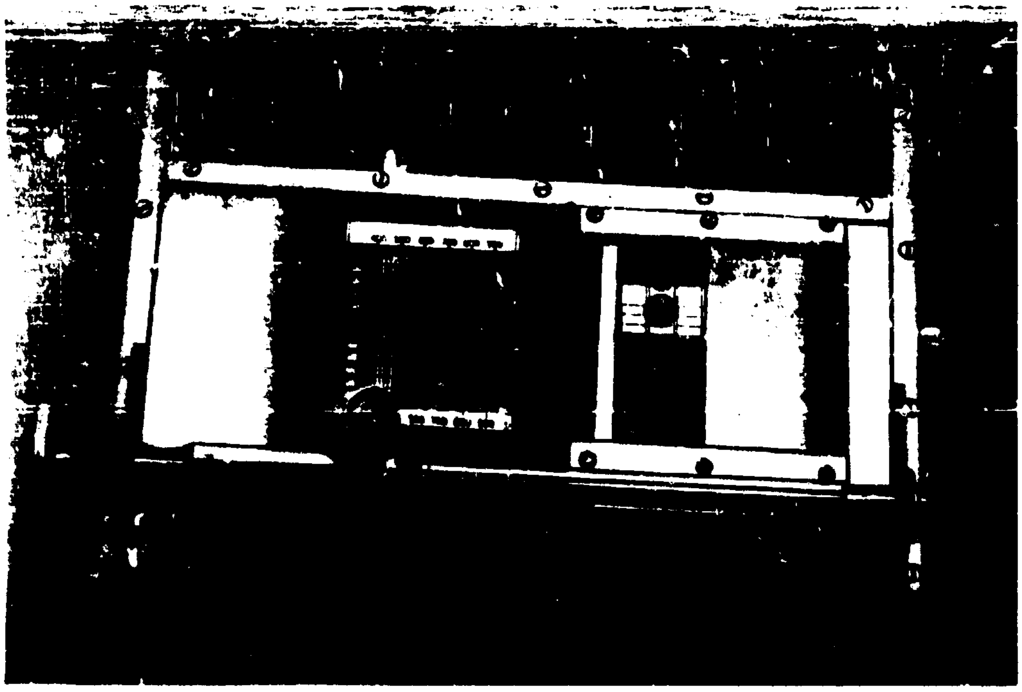

FIGURE 50. Mechanical stage and reticle of densitometer.

be measured with certainty, and so that the wavelengths corresponding to the measured densities can be assigned positively. The film is placed on a mechanical stage which has independent rack and pinion movement in vertical and horizontal directions. This mechanical stage also carries a glass pattern which indicates wavelengths and slit positions by perpendicular lines (Figure 50). When the vertical reticle line corresponding to the desired wavelength is coincident with an indicator fixed to the base of the densitometer, the light beam passes through the portion of the spectrogram exposed by that wavelength. The stage may then be racked vertically until the horizontal reticle line corresponding to the position of the target on the slit is also over the fixed indicator. As soon as this process is complete, the density of the image of the target for the desired wavelength is automatically indicated by the densitometer scale.

The densitometer consists essentially of a neon crater-discharge lamp located in a tube above the spectrogram; a 16-mm, 0.20 N.A. microscope objective located in the bottom of the lamp tube so that a reduced image of the discharge crater is formed on the spectrogram; a circular wedge of continuously varying optical density located directly under the spectrogram; a pair of condenser lenses which refocus the image of the crater in a 918 photocell; a second crater-discharge lamp which throws a comparison beam into the photocell; an amplifier; and a motor which is controlled by the output of the amplifier and rotates the optical wedge to the balancing position (Figure 51).

The crater-discharge lamps are excited with 60-cycle current and biased with sufficient d-c voltage so that they are not extinguished. The flux from these lamps fluctuates very nearly sinusoidally; the fluctuations of the two lamps are exactly out of phase. The photocell is illuminated with a combination of the light from the two lamps. When the optical wedge is at the balanced position, the peaks of the fluctuations of the photocell illumination originating in one of the lamps just compensate for the troughs of the illumination from the second lamp, and the 60-cycle component of the photocell current is eliminated. However, if the wedge is not exactly at balance, the fluctuations from one of the lamps predominate and the resultant 60-cycle fluc-

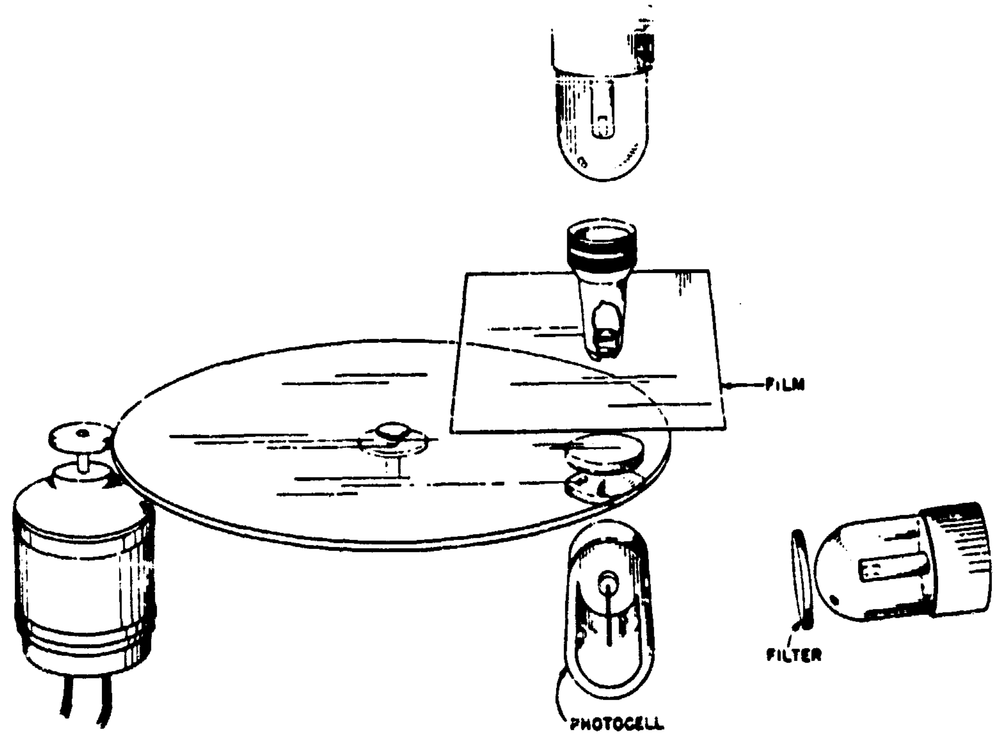

FIGURE 51. Schematic diagram of densitometer.

tuations of the photocell current are amplified. The output of the amplifier passes through the two shading-coils of a Barber-Colman motor (Figure 52). The phase of the fluctuations and therefore the direction of the rotation of the motor depend upon which of the lamps is more strongly illuminating the photocell. The connections are arranged so that the wedge rotates in the direction which equalizes the flux reaching the photocell from the two lamps. When the balance is attained, the motor stops for lack of 60-cycle current in the shading-coils, and the density of the sample is indicated by the location of a density scale marked along the rim of the wedge.[42-47]

The section of the film measured by this densitometer is a circle 0.03 inch in diameter. The photocell sensitivity extends through the visible and the infrared to 1.1 microns, with maxima near 0.45 and 0.8 microns and with a minimum near 0.5 microns. The wavelength centroid of the energy measured by the densitometer appears to be at about 0.7 micron, although the effective sensitivity corresponds to many neon lines scattered over a very wide wavelength range. The densitometer is calibrated to indicate densities of photographic film equal to those indicated by visual densitometers. However, it cannot be expected to indicate visual densities for materials which are appreciably different from gray photographic silver deposits in either spectral or diffusing characteristics. Some photographic developers produce stained images of a character which would be measured incorrectly, but use of the developer and procedure recommended in this report[18] will produce deposits which can be measured accurately with the densitometer described.

The densitometer was shipped throughout the country by air and railroad and functioned satisfactorily and consistently with only minor adjustments and replacements.

[illegible] Data from the Spectrogeograph

Two kinds of information obtainable with the spectrogeograph are useful in the design of camouflage by engineering methods, data concerning the optical properties of the atmosphere along slant

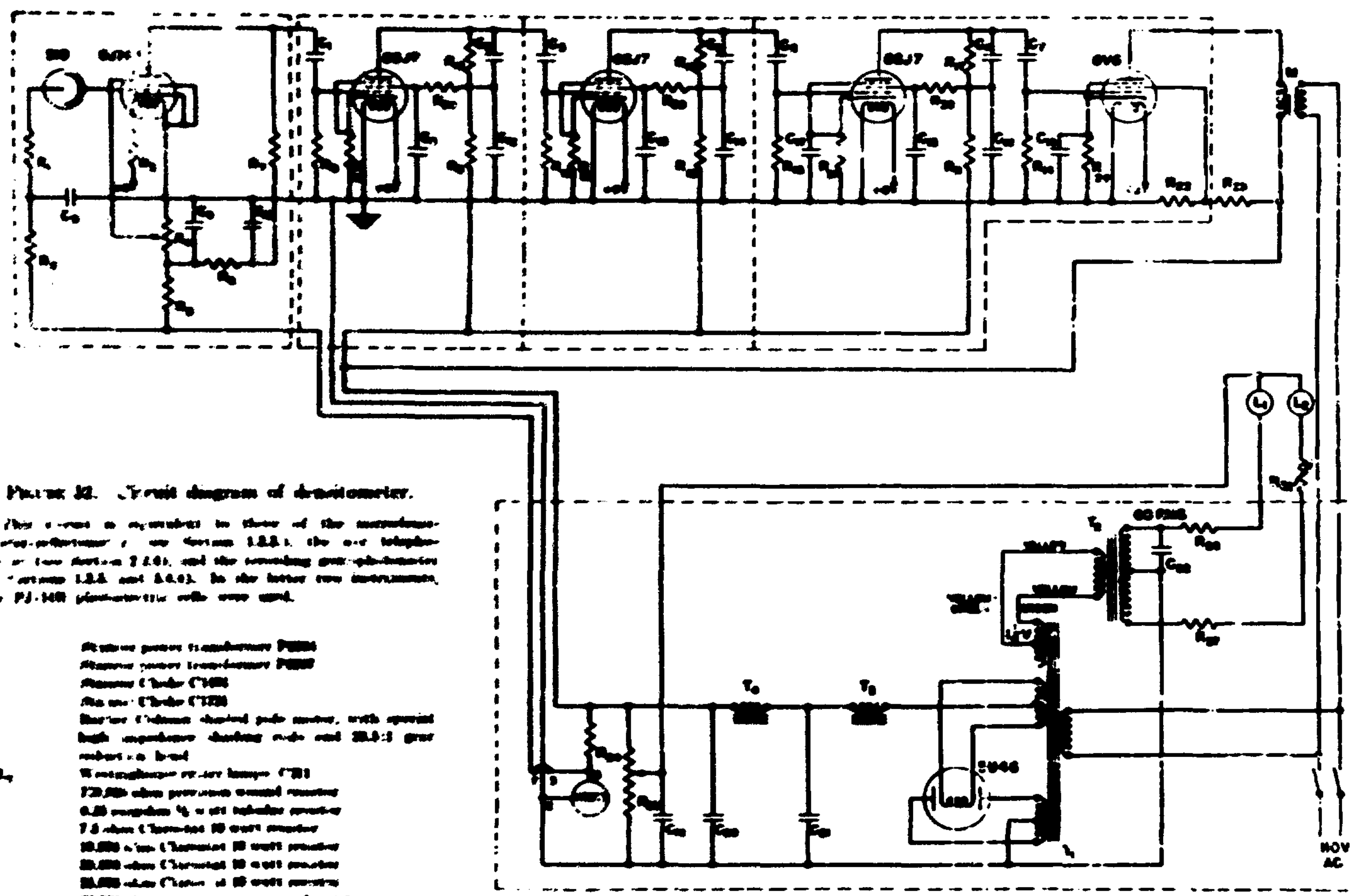

FIGURE 32. Circuit diagram of densitometer.

This circuit is equivalent to those of the [illegible]-reflectometer (see Section [illegible]), the [illegible] telephotometer (see Section [illegible]), and the recording gust-photometer (see Sections [illegible] and [illegible]). In the latter two instruments, type PJ-100 photoelectric cells were used.

T_1	Stancor power transformer P[illegible]
T_2	Stancor power transformer P[illegible]
T_3	Stancor Choke C[illegible]
T_4	Stancor Choke C[illegible]
M	Barber-Colman shaded pole motor, with special high impedance shading coils and [illegible] gear reduction head
L_1, L_2	Westinghouse meter lamps [illegible]
R_1	[illegible] ohm precision wound resistor
R_2	0.25 megohm ½ watt tubular resistor
R_3	7.5 ohm Clarostat 10 watt resistor
R_4	10,000 ohm Clarostat 10 watt resistor
R_5	[illegible] ohm Clarostat 10 watt resistor
R_6	[illegible] ohm Clarostat 10 watt resistor
R_7	[illegible] ohm precision wire wound resistor
R_8	1,000,000 ohm precision wire wound resistor
[illegible]	[illegible] ohm ½ watt tubular resistor
[illegible]	0.5 megohm ½ watt tubular resistor
[illegible]	1.5 megohm ½ watt tubular resistor
[illegible]	0.25 megohm ½ watt tubular resistor
[illegible]	1,000 ohm ½ watt tubular resistor
[illegible]	1,000 ohm ½ watt tubular resistor
[illegible]	[illegible] ohm Clarostat 10 watt resistor
[illegible]	7,000 ohm Clarostat 10 watt resistor
[illegible]	10,000 ohm Clarostat 10 ohm resistor
[illegible]	25,000 ohm Clarostat 20 watt resistor
[illegible]	15,000 ohm Clarostat 10 watt resistor
[illegible]	12,000 ohm Clarostat 10 watt resistor
[illegible]	2.2 megohm ½ watt tubular resistor
[illegible]	1.0 megohm ½ watt tubular resistor
[illegible]	7,300 ohm wire wound tubular resistor
C_1	0.02 mfd paper condenser
C_2, C_3, C_5	0.01 mfd paper condenser
C_4, C_6	0.002 mfd paper condenser
C_7	0.001 mfd paper condenser
C_8 to $C_{[illegible]}$	10 mfd 400-v electrolytic condenser
[illegible]	20 mfd 100-v electrolytic condenser
[illegible]	40 mfd 450-v electrolytic condenser
[illegible]	0.25 mfd 200-v electrolytic condenser

terrains

Atmospheric Data

Repeated attempts were made to obtain observations suitable for testing the theory and assumptions underlying the optical slant-range diagram discussed in Section 5.2. For a variety of reasons, such data were never secured. Faulty calibration procedures

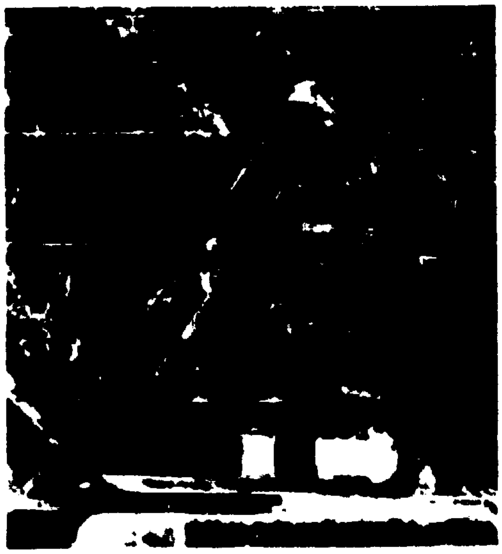

Figure 53. Aerial photograph of 5-step gray scale used at Orlando, Florida.

and/or mechanical failures of the K-24 cameras spoiled each attempt during the flights in Florida and California. These troubles were subsequently eliminated and, after very thorough preparations, several flights were made at Bedford, Massachusetts, through the courtesy of NDRC Section 16.1, during a two-week period. On every one of these flights, the visibility over the target was so poor that no usable photographs could be made.

Reflectance Data

The simplest and most accurate method for evaluating the reflectance of a terrestrial object involves a direct comparison of the light reflected by the terrain with that reflected by each of a series of large horizontal gray panels (a *gray scale*) laid nearby. The spectral reflectance of each panel of the gray scale can be determined in the laboratory by means of a *spectrophotometer*.

of painted panels of Celotex (Figure 53) was used for this type of experiment during a series of flights from the airbase at Orlando, Florida. On a day when the sky was completely free from clouds so that the gray scale and the surrounding countryside were lighted uniformly, the spectrogeograph was flown at constant altitude over the gray scale and over a variety of nearby terrains. After development, the spectrograms were measured with the densitometer described in Section 5.4.1. At a selected wavelength, the value of density corresponding to each step on the gray scale was plotted against the known spectral reflectance of the panel (Figure 54), and the reflectances of nearby terrains were read directly from this curve. This process was repeated at many wavelengths throughout the spectrum, and

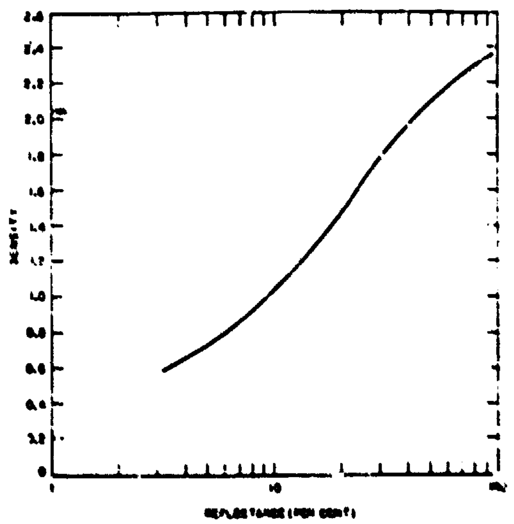

Figure 54. Typical plot of density of spectrogram vs. reflectance of gray scale at wavelength 520 millimicrons.

the resulting spectrophotometric curves of the terrains were plotted. Figure 55 shows a typical curve obtained in this manner. Other examples will be found in Figures 1 and 12 of OSRD Report No. 6554.[11] This report, ***Reflectance of Natural Terrains***, presents all the spectrophotometric and spectroradiometric data obtained by the Tiffany Foundation in Florida and California; a copy of the report will be found in the microfilm supplement to this volume. The results of a colorimetric analysis of some of the [illegible] in Table 1.

An alternative procedure, involving only two panels of known reflectance, was also used in Florida

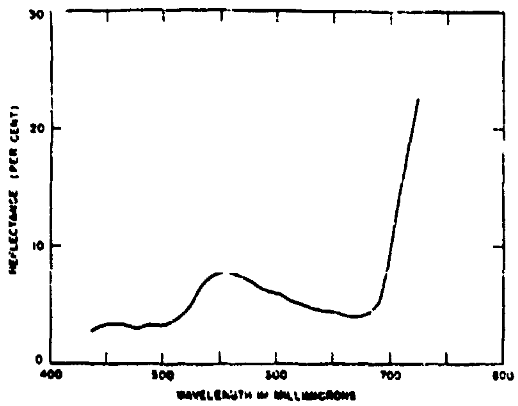

FIGURE 55. Spectral reflectance of green field.

and in California for measuring the reflectance of natural terrains. On theoretical grounds, only two known panels are needed if the spectrogeograph is calibrated independently.[48] Techniques for calibrating the instrument are discussed in detail in OSRD Report No. 6555,[13] and the data in all except Figures 1, 12, and 29 of OSRD Report No. 6554[11] were obtained in this manner.

[illegible] of underwater terrains was studied with the spectrogeograph in quest of data which subsequently provided a basis for improved methods of aerial photographic reconnaissance for ocean shoals. This work was undertaken at the request of the Navy following the landings at Tarawa. Shoal waters off Dania, Florida, were specified by the Navy's liaison officer to this research. Buoys (Figures 56 and 57)

FIGURE 56. Floating buoy, number 4, being launched. Ten such buoys were anchored off the beach at Dania, Florida.

were anchored at intervals along a line perpendicular to the beach in order to provide positive identification of the water depths. Samples of the bottom were collected for spectrophotometric study. Two

TABLE 1. Color of natural terrains. (ICI illuminant C, standard observer, and coordinate system.)[50]

No. of fig. OSRD Report No. 6554	Subject	Y	x	y	Dominant wavelength (mμ)	Excitation purity (per cent)
1	Large maple tree (1)	[illegible]	0.378	[illegible]	570.4	[illegible]
	Citrus tree (2)	0.0877	0.357	[illegible]	572.9	[illegible]
2	Dark green field	[illegible]	[illegible]	0.370	573.7	[illegible]
5	Green field with soil showing	[illegible]	[illegible]	[illegible]	[illegible]	18.1
6	Light green tree (1)	[illegible]	[illegible]	[illegible]	[illegible]	20.0
9	Yellow-green vegetation (1)	0.107	[illegible]	0.410	570.9	[illegible]
10	Tree shadow on brown soil (2)	0.0128	[illegible]	[illegible]	[illegible]	4.7
12	Asphalt paving (1)	[illegible]	[illegible]	[illegible]	[illegible]	9.9
	Ground with little vegetation (2)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Sandy soil (3)	0.103	[illegible]	[illegible]	[illegible]	18.7
13	Mud (2)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14	Pond	0.0142	0.277	[illegible]	477.5	[illegible]
15	Red soil in Californ[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
17	Dry wash	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
18	Light red ground (1)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20	Yellow sand dune (2)	[illegible]	[illegible]	0.373	[illegible]	[illegible]
21	Salt flats	0.197	[illegible]	[illegible]	[illegible]	10.7
22	Dark brown sand in dry wash	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
24	Light sand on slope of volcano (1)	[illegible]	[illegible]	[illegible]	[illegible]	21.7
	Dark volcanic rock (2)	[illegible]	[illegible]	[illegible]	[illegible]	4.1
28	Desert during green season	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

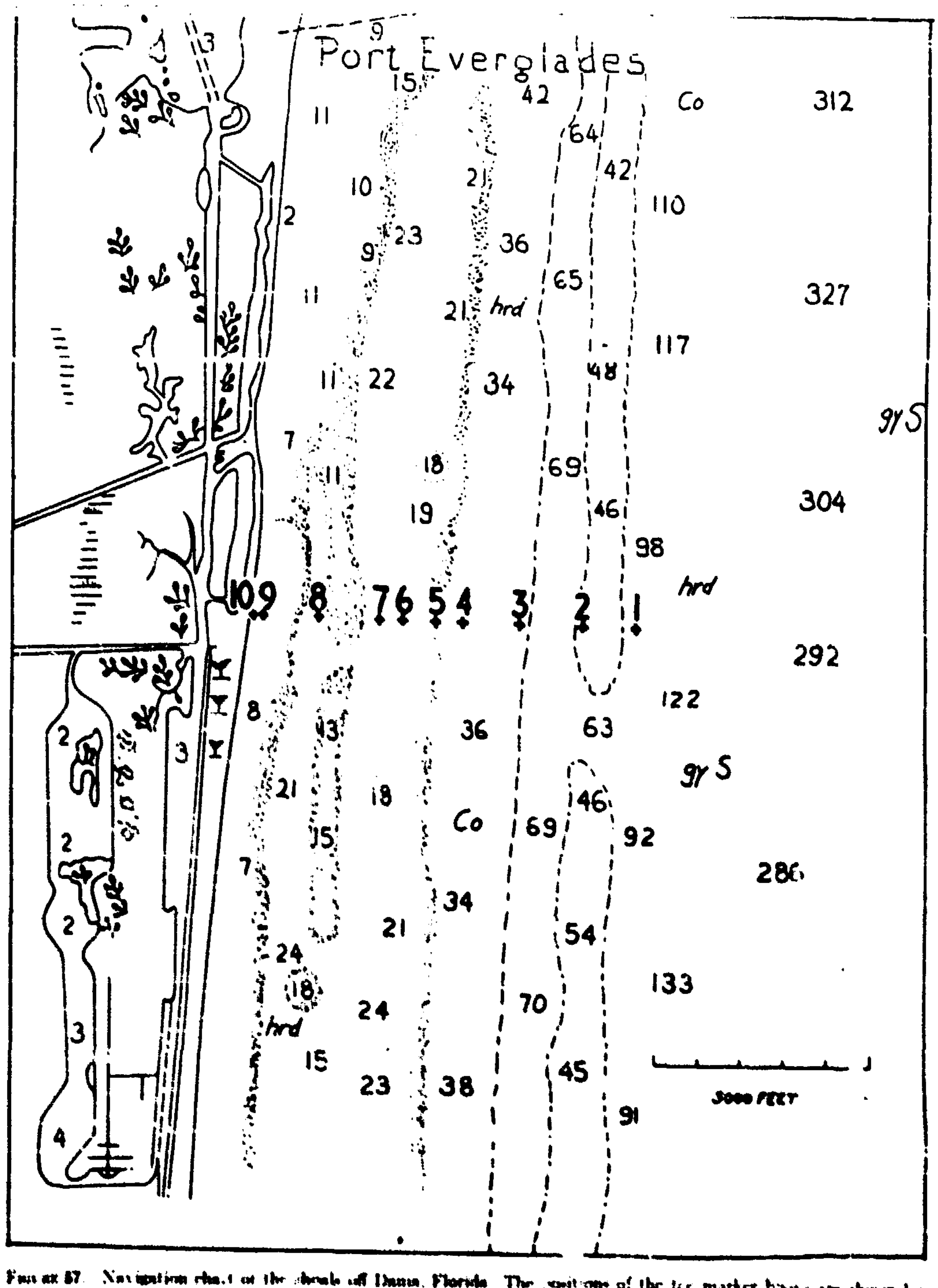

Figure 87. Navigation chart of the shoals off Dania, Florida. The positions of the ten marker buoys are shown by numbered crosses.

beach, and the spectrogeograph was flown over the shoals. Figure 58 shows the resulting spectroradiometric curves.[15]

Because color-changes with depth are partially masked by light reflected from the surface of the sea, the experiment was repeated with the spectro-

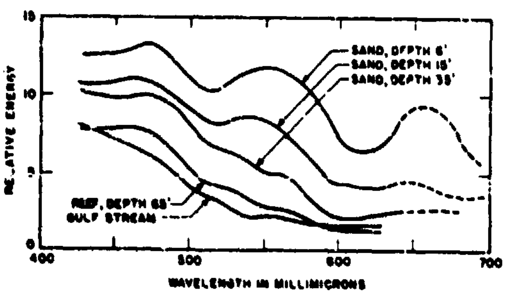

FIGURE 58. Spectroradiometric curves of the light reaching the spectrogeograph 4,000 feet above the shoal waters off Dania, Florida.

geograph mounted in a glass-bottomed boat (Figures 59 and 60). The resulting spectroradiometric curves are shown in Figure 61. The relation between water depth and color, as computed by standard procedures from the curves of Figures 58 and 61, is shown in Figure 62. Here the loci of the colors seen from

FIGURE 60. Spectrogeograph mounted in glass-bottomed boat.

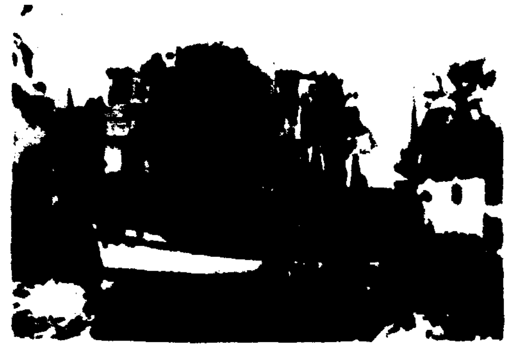

FIGURE 59. Glass-bottomed boat in which spectrogeograph was mounted

the air and from the glass-bottomed boat are shown on the standard I.C.I. chromaticity diagram.

It is clear from Figures 58 and 61 that greatest variations of reflectance with respect to depth occur in the spectral region from 540 to 570 millimicrons. The data and this conclusion were made known to the Navy through the office of the Coordinator of

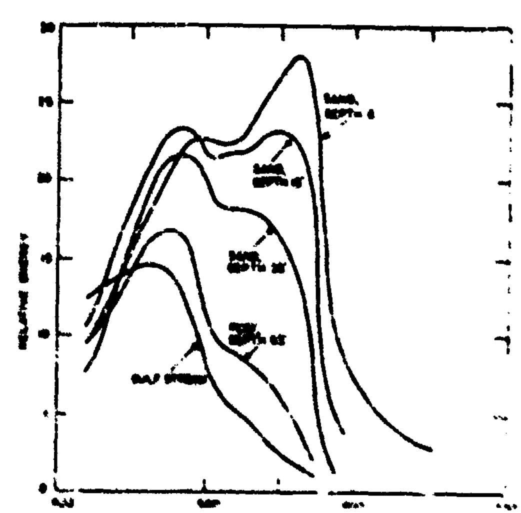

FIGURE 61. Spectroradiometric curves of the light reaching the spectrogeograph in the glass-bottomed boat from the shoals off Dania, Florida.

techniques for photographing ocean shoals were improved as a result of this information.

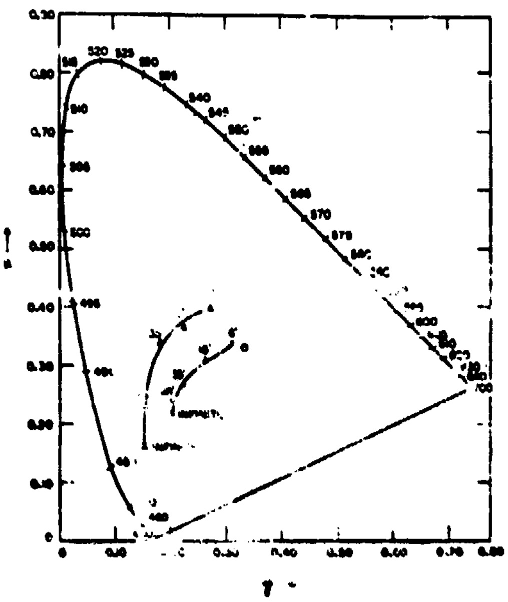

FIGURE 62. Standard I.C.I. chromaticity diagram showing the loci of the colors of the ocean shoals as seen from the air and from the glass-bottomed boat.

8.4.3 Texture

The spectral reflectance of a forest (or a tree) differs from that of a leaf partly because of the dark shadow pockets in which some of the light is trapped, and partly because of the interreflections between the leaves. This is illustrated in Figure 63, which shows the spectral reflectance of a tree as measured from aloft by the spectrogeograph, and the spectral reflectance of a leaf as measured by a spectrophotometer. These curves differ because of the *texture* of the tree.

Camoufleurs have long recognized the necessity of simulating the effects of natural texture. Nets festooned with colored garlands [illegible] for this purpose. Similarly, tufts of dyed fibers, chicken feathers, stone chippings, and many other "rough" materials have been employed. Research early in the war by the Passive Defense Project showed that the principal optical properties of a textured surface depend very little upon the size of the texturing elements but are controlled by the sharpness of the angles formed by adjacent struc- [illegible] the surface.[10]

TEXTURE-SIMULATING PAINT

Paint having a microscopically jagged surface (Section 1.3.3) was developed by the Interchemical Corporation under contract OEMsr-697, supervised by Section 16.3 of NDRC. Notable success was achieved in preparing a paint which simulated the texture *and gloss* characteristics of the wintertime deciduous forest, but attempts to make a corresponding paint [illegible] green forest were only

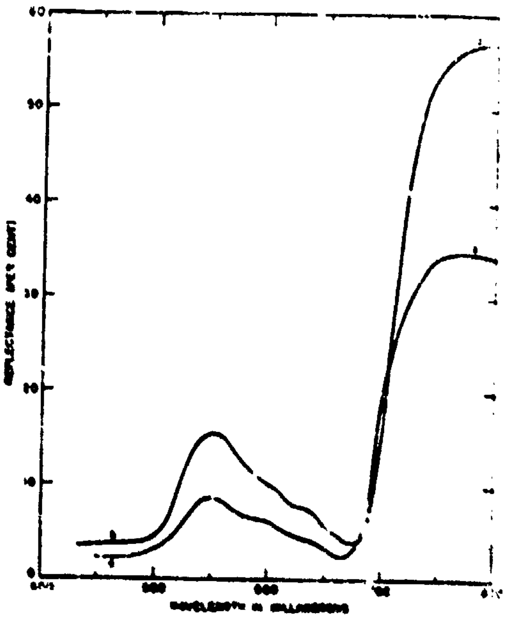

FIGURE 63. Spectrophotometric curves. (a) of a maple tree as measured from aloft by the spectrogeograph, and (b) of a single leaf as measured in the laboratory by a spectrophotometer.

partially successful. Moreover, no blue, yellow, or green pigments were found which have the proper optical and chemical properties and adequate permanence in sunlight. Because this development came [illegible] the need for defensive camouflage was diminishing [illegible] texture-simulating paints [illegible] interrupted and no service [illegible] of them is known to have been made.

8.4.4 Gloss

Artificial texture seldom matches its natural surroundings from all points of view [illegible] when viewed up-sun. This is caused by a difference in *gloss* or *goniorefle tance* between the camouflage and the natural terrain

Research on the gloss characteristics of naturally and artificially textured surfaces was conducted by the Passive Defense Project before World War II. These studies showed the characteristic differences illustrated by the curves in Figure 64 to be responsible for the visibility of flat surfaces coated with conventional matte paint when viewed up-sun.

GONIOPHOTOMETRY

The instrument used by the Passive Defense Project in its gloss studies was the photoelectric goniophotometer in the Illuminating Engineering Laboratories of the Massachusetts Institute of Technology.[19] In this instrument, a sample approximately 3 inches in diameter is illuminated at any selected angle of incidence by substantially collimated light. A photoelectric cell, carried by a movable arm pivoted about the center of the sample, measures the light reflected in various directions. A polar plot of the photocell readings produces a goniophotometric curve of the type shown in Figure 64. Research was handicapped by the slowness of the instrument; several hours were required to obtain and plot the data for each curve.

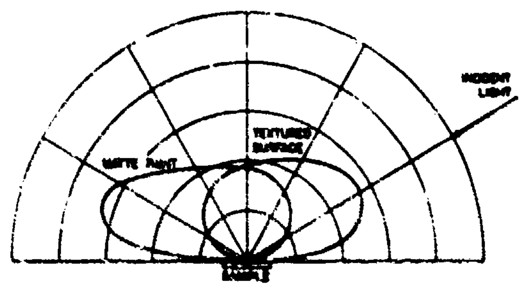

FIGURE 64. Goniophotometric curves (flux vs. angle) illustrating the characteristic difference between a matte surfaced paint and a textured surface.

Automatic Recording Goniophotometer. An automatic recording goniophotometer was designed and partially constructed by the Passive Defense Project. The instrument was subsequently completed by the electronics staff of the Research Laboratories of the Interchemical Corporation under contract OEMsr-697, and turned over to the Materials Laboratory of the Engineer Board, Corps of Engineers, in Figure 3, Chapter 1, a complete curve can be drawn in less than five minutes. The main frame of this instrument was cast from patterns loaned by the Massachusetts Institute of Technology and is thus identical with the frame of their goniophotometer. The photometric system is essentially identical with that of the densitometers described in Sections 1.3.3 and 5.4.1 of this volume. Details of the electrical and optical system will be found in OSRD Report No. 6556,[84] a copy of which appears in the microfilm supplement. It may be noted, however, that the source spread was made ½ degree in order to simulate the geometry of sunlight. The sensitivity of the instrument depends upon the receiver spread. When this is made as great as is recommended by the American Society for Testing Materials, the instrument is so sensitive that a reflectance of 0.001 relative to a perfect mirror can be made full-scale on the recording paper. The instrument will then balance to within less than 1 per cent. This high sensitivity is required in order to measure the goniorefletance of dark, textured surfaces. Some typical curves made by the recording goniophotometer are shown in Figures 65 and 66.

GONIOPHOTOMETRY FROM THE AIR

Provision has been made for adapting the spectrograph to gonio-spectrophotometric measurements of terrestrial targets by means of the mirror system shown in Figure 46. The target must be a uniform area of considerable extent (¼- to ½-mile square) in order to allow for uncertainties in the attitude of the airplane at the instant of exposure.

The best flight plan for such an experiment is believed to consist of a pattern of four courses, 90 degrees apart, forming a square centered on the target and so oriented that two sides of the square are cross-sun; the remaining courses being up-sun and down-sun respectively. A series of square courses of various sizes and altitudes enable goniophotometric curves in the plane of incidence and perpendicular to it to be determined. The square courses should be corrected continuously for the apparent motion of the sun. This is accomplished very easily if the aircraft is equipped with photoelectric solar navigation equipment. Otherwise, the correction can be accomplished by carefully corrected compass bearings. A technique for navigation by compass during such experiments was worked out by the Army during the flights at Orlando, Florida, and it

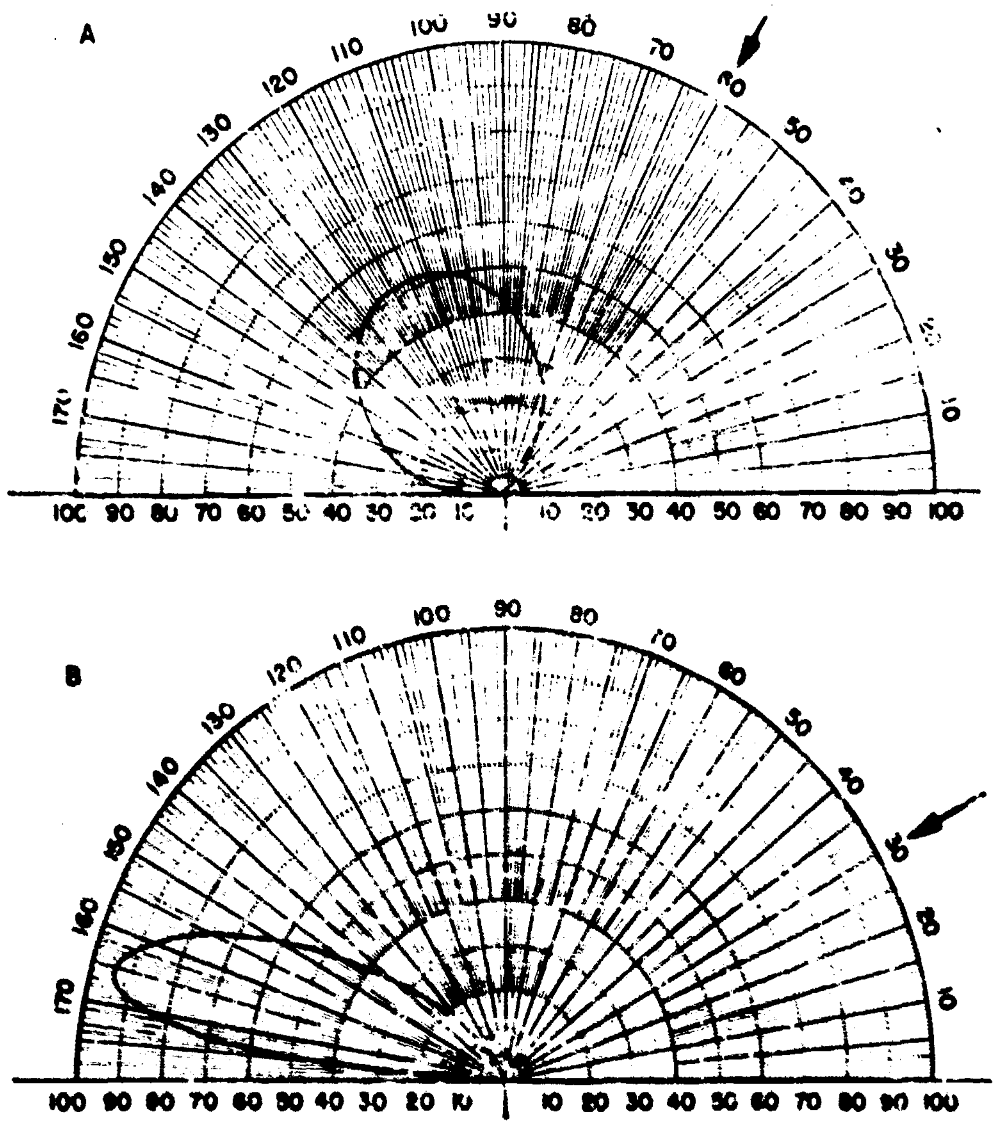

FIGURE 66. Typical curves drawn by the recording goniophotometer.

(a) [illegible] paint, incident angle [illegible] degrees, [illegible] (b) [illegible] paint, incident angle [illegible] degrees, no filter, stop ½ inch by 1 inches.

is discussed in detail in OSRD Report No. 6555.[?] Adverse weather conditions and technical difficulties frustrated both of the two attempts by the Tiffany Foundation to conduct an aerial goniophotometric experiment.

Camouflage, to be effective from all points of view, must match its surroundings goniophotometrically. After a sufficient body of data concerning the goniophotometric properties of natural and artificial terrains have been collected with the spectrogoniograph, the gloss characteristics required of satisfactory camouflage materials can be specified in terms of the readings of a laboratory goniophotometer.

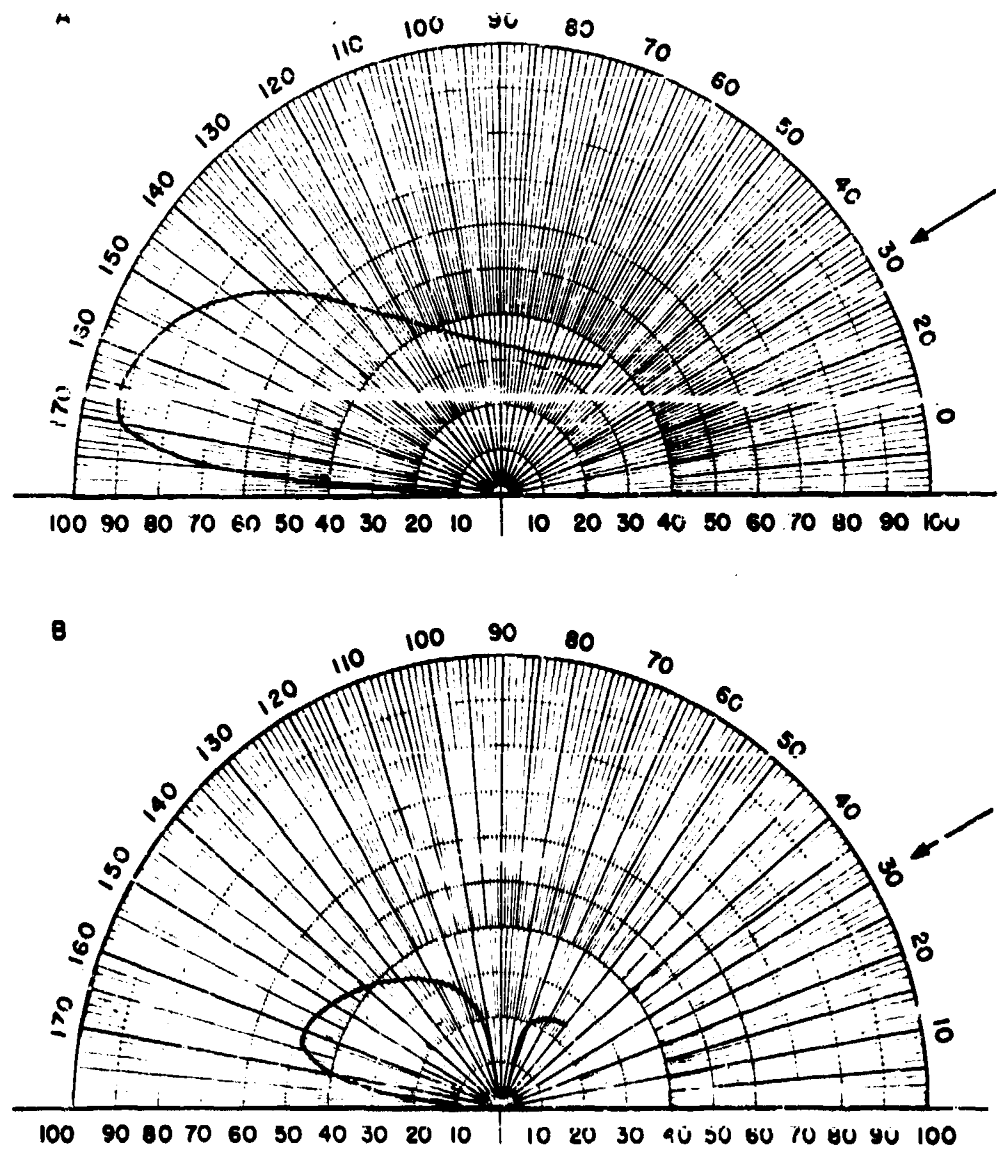

FIGURE 66. Typical curves drawn by a recording goniophotometer.

(a) emery paper, incident angle 60 degrees, no filter, no stop; (b) burlap, incident angle 60 degrees, no filter, stop ½ inch by 2 inches.

5.5 CAMOUFLAGE ENGINEERING

The ultimate goal of the spectrogeograph program as originally conceived was the establishment of engineering procedure capable of predicting the allowable differences in reflectance between a camouflaged object and its surroundings. There is almost no limit to the perfection with which it is possible to match natural terrain with artificial construction. However, the cost involved and the labor required increase so sharply as perfection is approached that, of necessity, camouflage measures far short of perfection must be adopted. Indeed, the economic factors are so critical that a slight relaxation in the [illegible] thousands of dollars in the cost of a camouflage treatment. However, such a relaxation of requirements based upon guesswork may prove costly, for obviously camouflage is valueless unless it fulfills its purpose. The spectrogeograph program was undertaken in the hope of providing an engineering basis for camouflage design which would avoid costly empirical mistakes, while taking full advantage of the permissible tolerances afforded by the veiling blanket of atmospheric haze and the distance of the enemy. It is hoped and believed that the concepts, data, and nomographic charts contained in this volume fulfill the basic requirements and make camouflage engineering a reality.

5.5.1 A Typical Problem

As an example of a typical camouflage engineering problem, consider the requirements to be met by the camouflage for a building having a flat, rectangular roof 100x400 feet, situated among dense deciduous trees, with the long dimension of the roof in the east-to-west direction. Let it be assumed that, according to military advice, attack is most likely to occur during midmorning hours in clear weather by bombers flying from the east at an altitude of 25,000 feet. Let it be assumed further that the camouflage will have served its purpose if the target is invisible, despite identifying landmarks, until the plane is so nearly over the target that bombs cannot be dropped on it.

The minimum distance from which a successful bombing run can be made depends on the characteristics of the bombsight, the ground speed of the plane, and its altitude. For the purposes of this example, let it be assumed that, for a successful attack, the target must be visible to the bombardier when he looks along a sight path corresponding to $\theta = 40$ degrees, as shown in Figure 67. If, at this *critical point*, the target is only liminally visible, the camouflage will have fulfilled its purpose and full advantage will have been taken of the available tolerances.

Preliminary Calculations

Before the nomographic visibility charts can be used, the following preliminary calculations are required:

Slant-Range. At the critical point the slant-range R must be calculated. The value is expressed as

$$R = \frac{25{,}000}{\sin 40^\circ} = 39{,}000 \text{ feet} = 13{,}000 \text{ yards.}$$

This value can also be obtained from the optical slant-range diagram (Figure 2) by noting the intersection of the solid curve for $\theta = 40$ degrees with the dashed curve for altitude 25,000 feet.

Optical Slant-R[illegible] [illegible] the optical standard atmosphere is assumed, the optical slant-range $\bar{R}$ is shown by Figure 2 to be 7,690 yards; if nonstandard atmospheric conditions are expected to prevail, a corrected value of $\bar{R}$ can be found by the procedures described in Section 5.2.1.

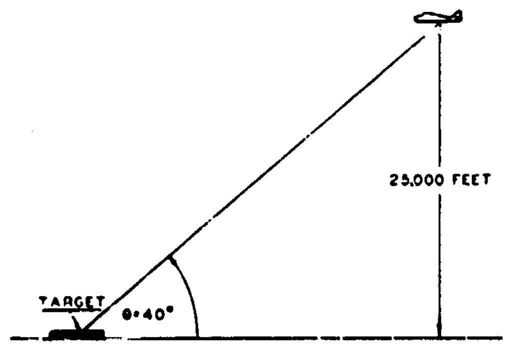

Figure 67. Bomber at the critical point in its approach to the target under conditions assumed in Section 5.5.1.

Projected Target Area. The projected area of the target is:

$$A = 100 \times 400 \times \sin 40^\circ = 25{,}700 \text{ square feet.}$$

Effective Projected Target Area. The appropriate value of effective projected target area $\bar{A}$ can now be found with the aid of the nomographic chart shown in Figure 31, or by substitution in equation (1),

$$\bar{A} = \left(\frac{7{,}690}{12{,}970}\right)^2 (25{,}700) = 9{,}060 \text{ square feet.}$$

Meteorological Data

In addition to $\bar{R}$ and $\bar{A}$, values of the sky-ground ratio and of the meteorological range must be had before the nomographic visibility charts can be used.

The Sky-Ground Ratio. If the reflectance Y of the terrain surrounding the target is known from measurements made with the spectrogeograph or by some equivalent method, the brightness of the ground can be found by multiplying Y by the illumination on a horizontal plane at ground level. A variety of visual and photoelectric illumination meters (ilstruments are also capable of measuring the brightness of the horizon sky in the directions m and n shown in Figure 17, Chapter 2. The sky-ground ratio can then be found by dividing the brightness of the sky by the brightness of the ground.

For the purposes of the present example, let it be assumed that the required measurements have been made and that a sky-ground ratio of 4.0 has been found for the conditions under which concealment is desired.

The Meteorological Range. A photoelectric *transmissometer* for measuring the meteorological range has been devised by the U. S. Bureau of Standards,[25] and it is understood that a number of these instruments are in use throughout the country. A variety of other instruments for measuring v have been described in the literature.[12] When instrumentation is not available, the *visibility* (Section 2.2.5) can be estimated by eye in the manner customarily employed by meteorologists. Such visibility estimates are usually included in aircraft weather reports. As pointed out in Section 2.2.5, the meteorological range should be taken as 4/3 times the *visibility*.

Use of the Visibility Charts

Selection of the Proper Chart. The selection of the proper visibility chart for use in a given problem is governed by the level of brightness to which the eyes of the observer are adapted and by the shape of the target. In the present example, full daylight brightnesses are involved. Since the sky-ground ratio is 4, the ground is one-quarter as bright as the sky in the directions m and n (Figure 17, Chapter 2). However, as seen from above, the apparent brightness of the landscape is increased by space light, so that a nomographic visibility chart for full daylight ($B_H \geq$ 1,000 foot-lamberts) should be used.

Since the roof of the target is a rectangle 400x 100 feet, its side-to-side ratio is 4:1 when viewed vertically downward. Because of the foreshortening due to the oblique angle of view ($\theta = 40$ degrees) from the critical point, the effective side-to-side ratio of the target is reduced to 2.5:1. As explained in Section 4.5.1, the best answer will be intermediate between the values given by Figures 6 and 15. Since, however, these values differ only by the order of 5 per cent, the shape of the target is unimportant in comparison with other factors and either chart may be used. Since no target is more visible than a circular target (Figure 6) is preferable. However, no generalization should be drawn from the foregoing example concerning the importance of target shape its effect should be considered in connection with every problem. For example, had the long dimension of the building been in the north-to-south direction, the shape of the target would produce a four times greater effect than in the case considered above.

Procedure. The effective projected area $\bar{A}$ of the target and the optical slant-range $\bar{R}$ at which it must be liminally visible determine a point on the nomographic visibility chart. This *target point* is indicated by the letter T on Figure 68. Place a straightedge across the chart in such a manner as to connect the appropriate value on the meteorological range scale with T. The position of the straightedge is shown by the dashed line on Figure 68, for the case of a meteorological range of 10 miles. Place the point of a pencil at the intersection of the dashed line and the right-hand vertical boundary of the chart. Rotate the straightedge about this point until it passes through the appropriate value on the sky-ground ratio scale. This position of the straightedge is indicated by the dotted line in Figure 68, for the case of a sky-ground ratio of 4. Read the value of liminal contrast C_0 from the contrast scale at the middle of the diagram. In this case, $C_0 = 0.079$.

The Role of Atmospheric Haze

The value of contrast, which will make the target liminally visible from the critical point, depends upon the value of meteorological range. This relation is illustrated by Table 2. It will be noted that when the air is exceptionally clear ($v \to \infty$) the target is visible unless its contrast is less than 0.014.

TABLE 2

Meteorological range (miles)	Liminal contrast
∞	0.014
50	0.020
20	0.035
10	0.079
8	0.122
6	0.25
4	1.01
2	4.10

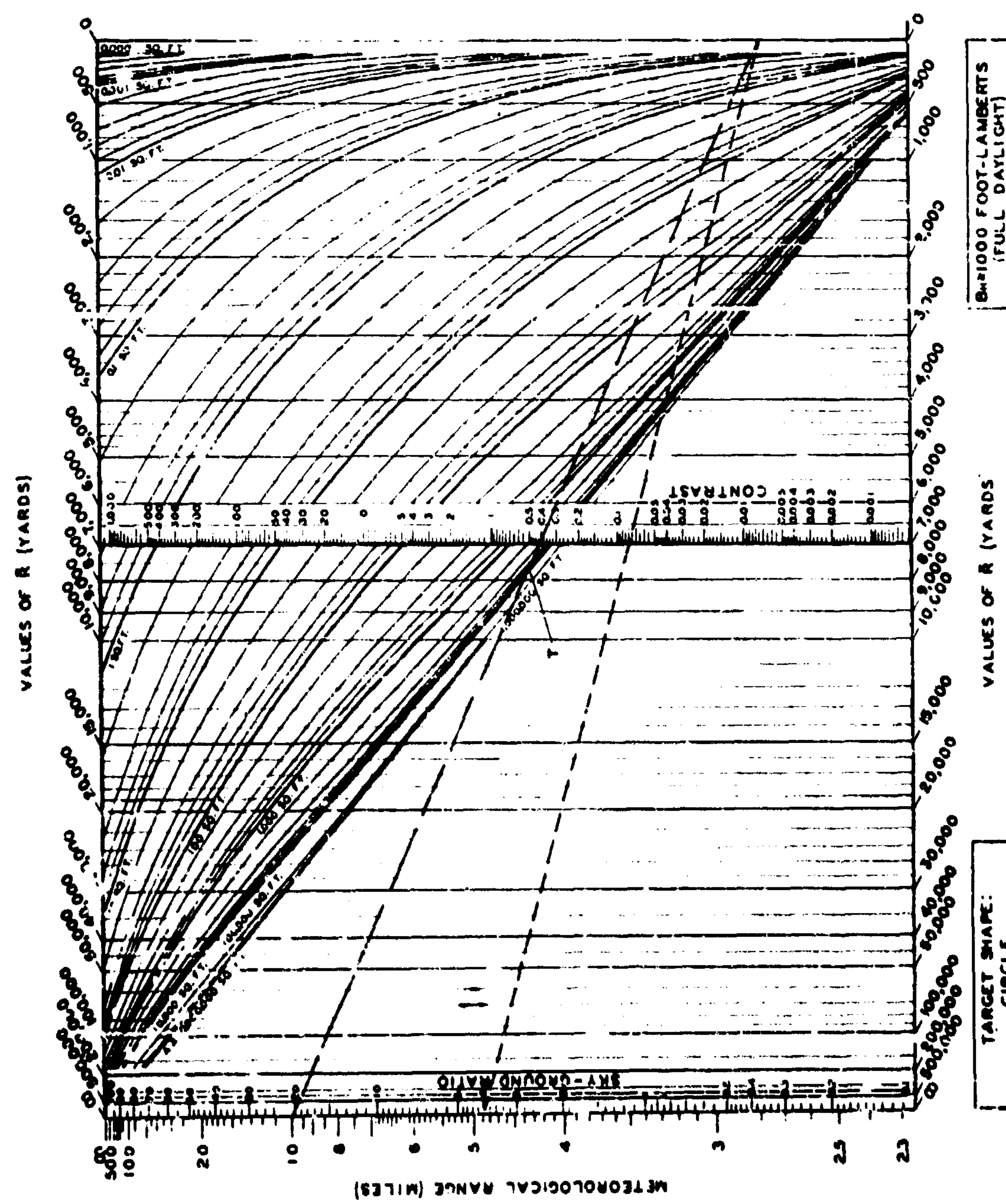

FIG. 98. Nomographic visibility chart illustrating method of solution of typical camouflage engineering problem (see Section 55.1). The symbol T indicates the *target point*. (The original of this figure is a photostat which shows serious distortion and this figure must not, therefore, be used in the solution of problems. It is intended only to illustrate the manner of using Figure 6.)

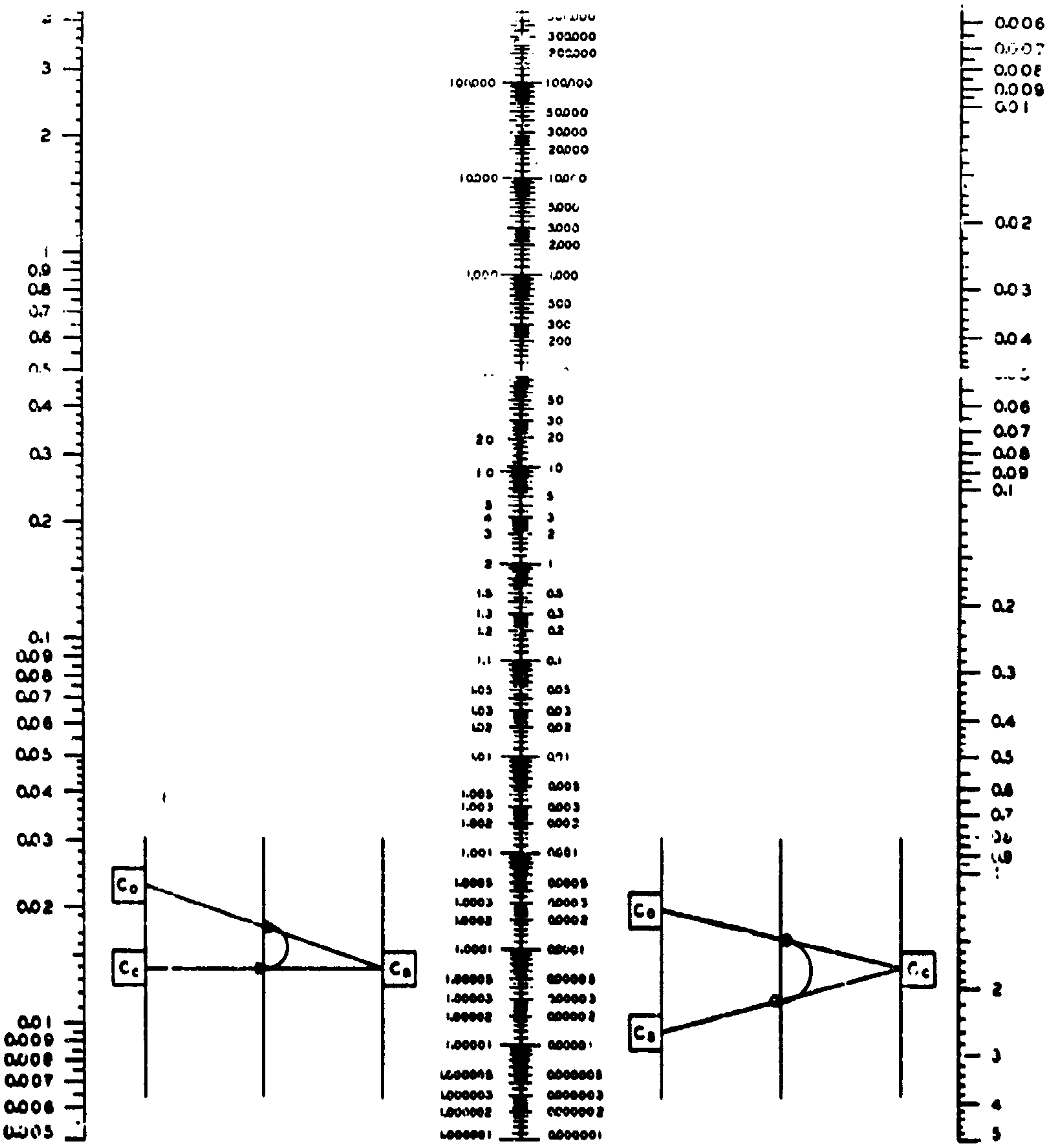

FIGURE 69. Nomographic chart representing equation (1) Chapter 3.

When equivalent achromatic contrast (C_0) and brightness contrast (C_B) are known, color contrast (C_C) may be found by using chart as shown in left-hand key diagram. When C_0 and C_C are known, C_B may be found by using chart as shown in right-hand key diagram. When brightness contrast and color contrast are known, equivalent achromatic contrast can be found by using chart in either manner.

Such a low value of contrast can be attained only with great difficulty, and the maintenance of such perfect camouflage is almost impossible because of fading and/or change in the natural background. In other words, in the case of so large a target the camoufleur must depend upon haze to conceal the target.

Tone-Down. When the meteorological range is less quired to make the target visible from the critical point. A white roof, which may be several times as bright as the surrounding terrain, will be plainly visible, but a roof that is darker than its surroundings will not be seen by the enemy no matter how black it may be. Therefore, an application of black paint, tar, or other black material to the roof will provide camouflage during hazy weather. This camouflage measure is known as *tone-down*.

Color Contrasts. Although color contrasts have little effect on the visibility of naval targets (Section 4.9.3), they are often not negligible in the case of objects on the ground, where the brightness differences may be small.

If the neutral point, represented by the cross in Figure 39, Chapter 3, is plotted on Figure 41, Chapter 3, it will be seen that an equivalent achromatic contrast of 0.12 is produced by the color contrast of a black roof in green surroundings. Table 2 indicates that this contrast will render the target visible from the critical point whenever the meteorological range v exceeds 8 miles. This value of v has been called the *tone-down limit*.

Whenever the meteorological range exceeds the tone-down limit for the target, colored camouflage must be used to achieve concealment.

5.5.2 Camouflage Design

After tables similar to Table 2 have been prepared for various values of sky-ground ratio, the type of camouflage to be used can be chosen on the basis of a compromise involving cost, frequency of occurrence of the various types of weather, and the military or economic value of the target. If the tone-

may be made between brightness contrast and color contrast. This choice will be governed by the cost, the availability, and the permanence of the camouflage materials rather than by any optical principles.

To aid the camoufleur in computing resultant achromatic contrast from the brightness contrast and the equivalent achromatic contrast, a convenient nomographic representation of equation (1), Chapter 3, is presented in Figure 69.

After the reflectances of camouflaged objects as measured from the air with the spectrogeograph have been correlated with spectrophotometric and goniophotometric properties of the camouflage materials as measured in the laboratory, suitable materials can be selected. Special flights with the spectrogeograph are required only when the natural terrain surrounding the target has not previously been catalogued. However, the spectrogeograph may be used whenever the importance of a target warrants a final check on the performance of the completed camouflage installation or when the visibility of an object on the ground is to be studied.

5.6 PEACETIME APPLICATIONS

The foregoing discussion of the visibility of objects on the ground has been written from the point of view of the camoufleur. However, the methods and data presented in this volume make possible the prediction of the visibility of landmarks, landing fields, and hazards to aerial navigation. It is expected that the principles discussed herein will find valuable peacetime applications in military, naval, commercial, and private aviation.

Chapter 6

CAMOUFLAGE OF SEA-SEARCH AIRCRAFT

6.1 INTRODUCTION

When the menace of German submarines to Allied Atlantic shipping constituted one of the major problems of World War II, the Camouflage Section of NDRC was requested by the Director of Technical Services of the Army Air Forces to devise a method of camouflage which would enable a radar-equipped sea-search aircraft to approach a surfaced submarine within 30 seconds of flying time, before the aircraft became visible to members of the U-boat crew. Such an approach would ordinarily enable the aircraft to release its depth charges before the submarine could execute a crash dive.

The Director of Technical Services was informed that even a white airplane will ordinarily be seen as a dark silhouette against a sky background, and that, although the plane might be rendered invisible by floodlighting, the amount of power required would be prohibitive. It was indicated, however, that if the plane could always approach the submarine in such a manner as to present the same head-on aspect, concealment might be possible by placing lights along the leading edge of the wings and in the fuselage section. It is known from data on the visual acuity of the human eye that, at a distance of two miles, individual lights are indistinguishable as such, if their spacing is less than about four feet. If, by means of suitable reflectors, the light from each lamp is confined to a narrow beam visible only from the deck of the submarine, the most economical use of power is achieved. The Director stated that the plane could be flown on any required tactical course and, as a basis for calculation, it could be assumed to hold a course toward the submarine with a deviation of less than 3 degrees. It was calculated, on this basis, that even a bomber as large as a Liberator (Figure 1) could be made to match ordinary sky backgrounds with a power consumption of less than 500 watts.

[a] In classified correspondence, this project was referred to by the code name *Yehudi*. For the benefit of those unfamiliar with this neologism, Yehudi symbolizes in contemporary slang "the little man who wasn't there."

6.2 PRELIMINARY EXPERIMENT

Pursuant to instructions issued by the Chief of Section 16.3 of NDRC, the staff of the Tiffany Foundation started work on an experimental test[10] of a new camouflage principle by which a black silhouette can be rendered invisible to an observer through the use of lamps adjusted to the proper intensity and directed toward the observer. For this experiment,[b] a black-painted board 2 inches wide by 32 inches long was provided at 4-inch intervals with lamp and reflector units taken from hand flashlight assemblies, as shown in Figure 2. Each unit was composed of a prefocused bulb operated at 2.4 volts and 0.5 amperes with a parabolic reflector giving a beam-spread of about 2 degrees. The plain glass lens of each reflector unit was opaqued over the greater part of its area to reduce its candle power. This left a horizontal strip ¼ inch wide by 1¾ inches long, which was covered with a paint film composed of a transparent blue pigment dispersed in linseed oil. This film converted the spectral energy distribution of the tungsten lamps to approximately that of daylight. A rheostat was used to adjust the intensity of the lamps to a brightness-match with the sky background.

6.2.1 Demonstration of the Principle

A demonstration of the Yehudi principle was arranged for Service representatives. The model was fixed horizontally between two vertical supports, which were mounted on the roof of the studio building 50 feet above the ground, and was so adjusted that the beams of the lamps converged at a point 900 feet distant. The viewing range lay in a north-south direction with the observation point at the southern end.

In this demonstration, held on a clear day between 10:30 A.M. and 12:30 P.M. Eastern war time, the model was boldly silhouetted against the northern sky. When the lamps were switched on, the model

[b] Sections 6.2 through 6.6.9 are reproduced from OSRD Report No. [illegible], *Camouflage of Sea-Search Aircraft (The Yehudi Project)*,[10] by the Louis Comfort Tiffany Foundation, Oyster Bay, New York, June 1, 1944, under Contract No. OEMsr-807.

FIGURE 1. Artist's conception of a Liberator (B-24) camouflaged for sea-search in accordance with the Yehudi principle.

In this application, lights of the sealed-beam type are shown mounted in the leading edges of the wings, in brackets beneath the wings, and in brackets around the fuselage.

The tests described in this report show that, when treated with this camouflage measure, a Liberator (B-24) can be rendered invisible, even under perfect weather conditions, at ranges as short as 30 seconds of flying time.

FIGURE 2. Details of experiment designed to demonstrate the Yehudi principle.

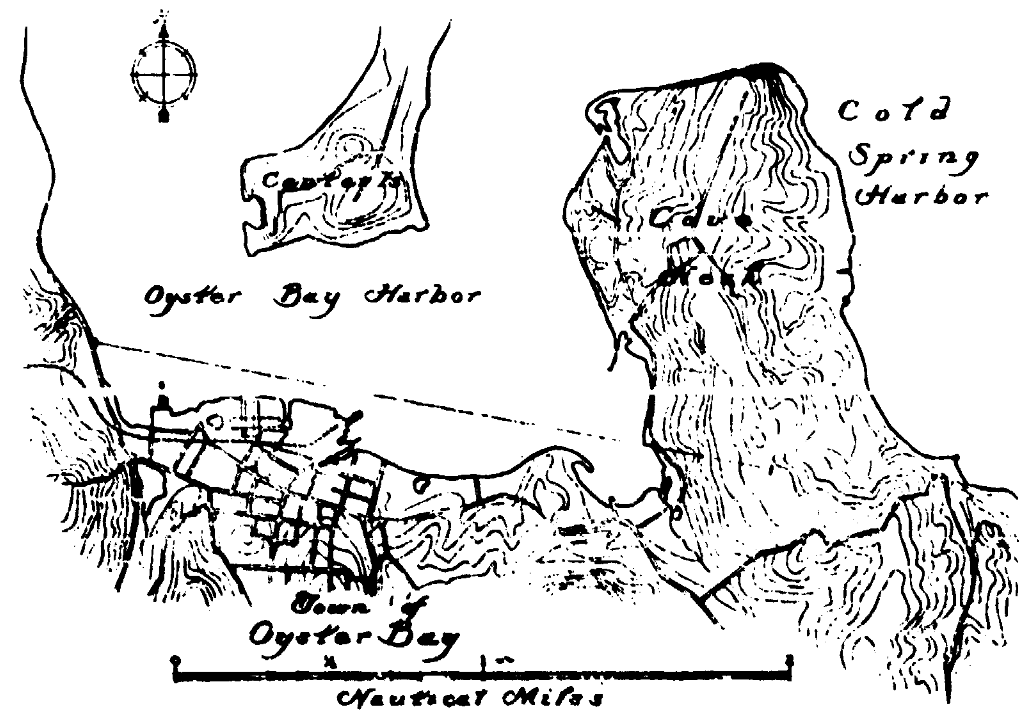

FIGURE 3. Map of Oyster Bay and vicinity.
The dashed line indicates the 13,000-foot range from the observing station on the left to the hilltop station on the right.

became invisible, even though the vertical supports served to fix its location. Light clouds appeared in the sky during the period of the demonstration, and appropriate adjustments were made in the lamp current to maintain a brightness-match. The effect of operating the lamps above and below the best value for the existing sky brightness was also demonstrated. It was noted that enough reserve power was available to match the brightness of a white card exposed in full sunlight behind the model. As a result of this demonstration, a decision was made to construct a full-scale silhouette of a Liberator (B-24), to suspend it from steel towers to be erected on the estate, and to observe the effectiveness of the Yehudi principle from an observing station two nautical miles distant.

6.2 FULL-SCALE SILHOUETTE OF LIBERATOR

The choice of a site for testing the full-scale model was dictated, primarily, by the following considerations: (1) the necessity of securing the large-scale experiment against unauthorized observation, (2) the desirability of making observations over water, and (3) the requirement that the model be elevated as high as possible. A study of the terrain in the Oyster Bay region revealed that a ridge 180 feet high on the Tiffany property would provide adequate height and that the model should be visible from the shore of Oyster Bay from a point approximately 13,000 feet distant. Such a range would be about 85 per cent over water, with the eastern sky as background. The viewing station selected was a semicircular parking area on the shore road a few feet above the water at high tide (Figure 3).

The ridge on which the towers were to be erected was accessible by a dirt road but was heavily wooded. To provide an unobstructed view of the silhouette from the viewing station, it was necessary to clear several acres of trees and underbrush. Communication between the hilltop station and the shore telephone line.

6.3.1 The Silhouette

Only the head-on aspect of a Liberator was involved in this experiment, and the first step was to reproduce the corresponding silhouette. Manufacturer's drawings were not readily available for this purpose, but the necessary data were obtained from

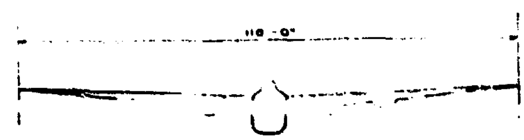

FIGURE 4. Silhouette of Liberator in head-on aspect.

a photograph of a wind-tunnel model supplied by Wright Field. Additional details were obtained from an actual photograph of a Liberator taken on the ground. The silhouette drawing used is reproduced in Figure 4.

A model was constructed of plywood and reinforced to provide sufficient rigidity.

Two steel towers, 100 feet high, were erected 260 feet apart, and the model was supported on a ½-inch steel cable between them. This cable was attached to winches at the base of each tower; and the model was raised from its resting place in cradles on the ground to an elevation of 85 feet above the ground by simultaneous operation of the two winches. Guy wires were rigged to steady the model in the elevated position. The upper half of the steel towers was painted white to reduce the contrast when seen against the sky. When in the elevated position, the model was 235 feet above sea level. A view of the elevated silhouette is shown in Figure 5 and the rigging layout in Figure 6. It is of interest that, on the occasion of its first elevation, the approach of a four-motored bomber was reported by the local volunteer airplane spotters several miles away.

6.3.2 Arrangement and Control of Lights

It had been calculated previously that 500 watts of power would suffice for this experiment. Special

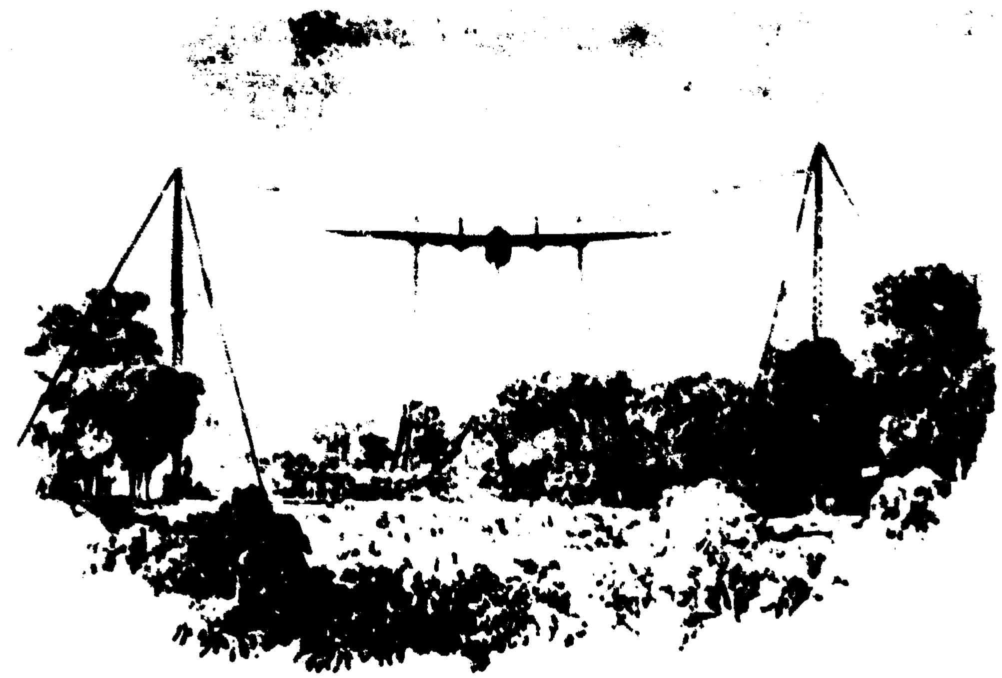

FIGURE 5. Close-up view of suspended silhouette.

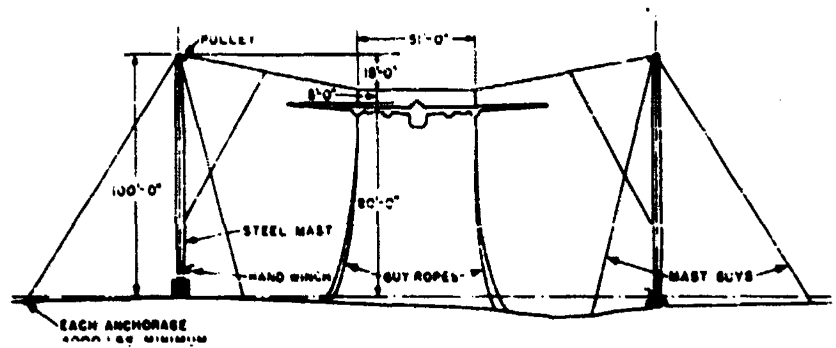

Figure 6. Rigging layout for the suspension of the full-scale model.

lamps were supplied by the General Electric Company, Cleveland, Ohio. These lamps were of the sealed-beam type, 4 inches in diameter, with a single-coil filament operating at 6.5 volts and 1.7 amperes. They had a beam-spread of 3 degrees in the horizontal plane and 6 degrees in the vertical plane. The lamps were wired two in series, with pairs in parallel, and were operated from the 18-volt secondary of a transformer supplied from a portable 110-volt a-c generator of 500 watts capacity. The intensity of the lamps was adjusted by means of a Variac in the primary circuit of the transformer, a voltmeter across the secondary circuit being used for reference. The clear glass face of each lamp was coated with a transparent paint containing iron-blue (red shade) to correct the light to daylight quality.

The lamps were mounted in adjustable wooden frames which were clamped to tracks mounted on the face of the silhouette as shown in Figure 7. These tracks permitted easy adjustment of lamp positions.

The method by which the proper spacing of the lamps can be calculated is discussed in Section 6.6. The arrangement shown in Figure 8 is one of several

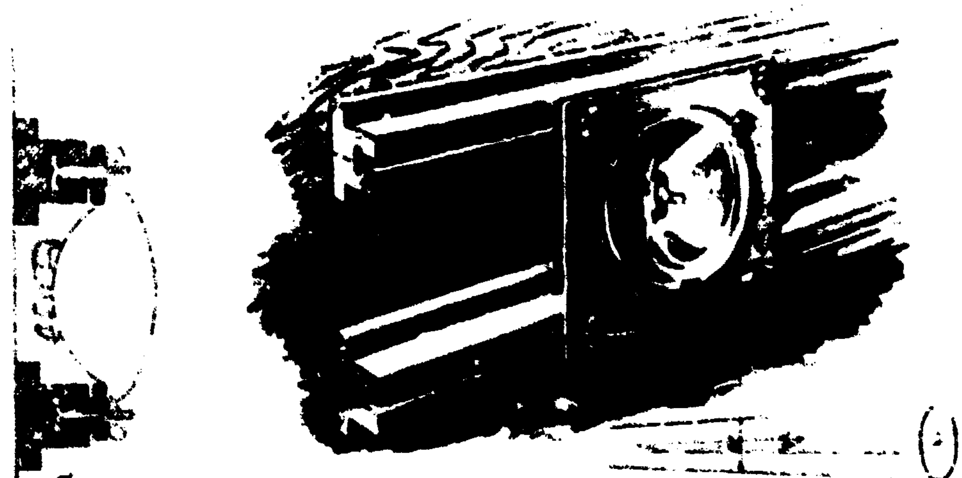

Figure 7. Lamp details and method of mounting.

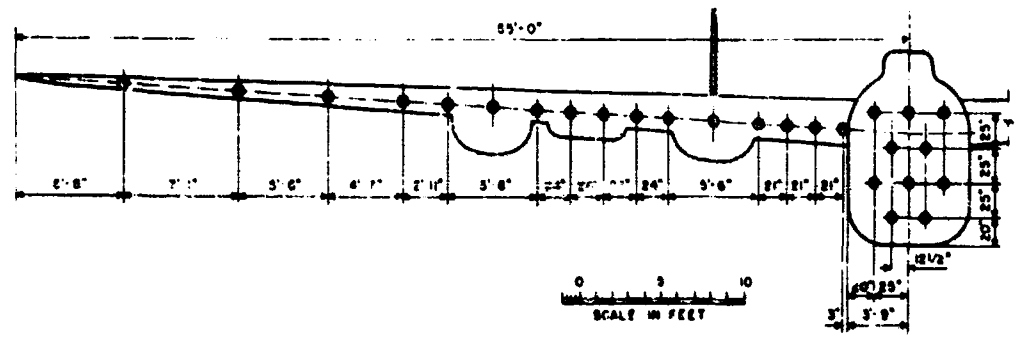

FIGURE 8. Dimension drawing showing the location of the lamps.

used during these experiments. Although determined somewhat empirically, it is a close approximation to the theoretical spacing.

8.3 EXPERIMENTS WITH THE FULL-SCALE MODEL

Because of the narrow beams of the lamps, the lamp alignment was correspondingly critical. With the model in the elevated position, only overall adjustments could be made and these were by use of the guy ropes. The necessary instructions were relayed by telephone from the observers' station. When the best overall setting had been obtained, a 12-power telescope was used to inspect the alignment of individual lamps. The model was then lowered and the individual lamp mounts were adjusted by means of the thumb screws shown in Figure 7. The voltage across the lamps was then regulated on the basis of information from the observers' station until the minimum visibility was obtained. This voltage was found not to be especially critical.

The experiments necessary for the determination of the proper spacing of the lamps and the necessary range of intensity and color were performed during the winter of 1943. During the greater portion of this period, the visibility was less than 2 miles; and clear weather was usually attended by winds of high velocity. Since the silhouette was located on the top of a ridge and presented approximately 300 square feet of surface area, even winds of moderate velocity made elevation of the model a precarious undertaking.

The most successful demonstration was made in the presence of four qualified observers. The visibility was so high on this occasion that the 1-inch cables supporting the towers could be discerned without difficulty from the observing station. Nevertheless, all observers agreed that the silhouette was completely invisible when the lamps were adjusted to the proper intensity.

Mention should be made of the assistance rendered by the Police Department of Oyster Bay in connection with these experiments and demonstrations. Patrol cars, furnished whenever requested, prevented automobiles from slowing down or stopping near the observation station. Because of the narrow horizontal beam-spread of the lamps (3 degrees), the alternate appearance and disappearance of the silhouette during demonstrations could be witnessed only from points along the shore road within [illegible] feet of the station. The observation station is depicted in Figure 9.

8.4 APPLICATION TO OTHER TYPES OF PLANES

While the work on the full-scale model was in progress, a need arose for portable equipment suitable for demonstrations of the Yehudi principle at several conferences in Washington. This need was finally met by an oil painting on thin sheet-metal, a photograph of which is shown in Figure 10. The black silhouette of a Liberator (B-24) was 3.75 inches long in the painting. Hence, when viewed from a distance of 30 feet, the silhouette subtended the same angle as a Liberator at two statute miles.

Small holes were drilled through the painting at points corresponding to the positions of the lights that had been calculated for the Liberator. A strip of onionskin paper was attached to the back of the

FIGURE 9. Observation station of the viewing range during demonstration of the full-scale model.
The silhouette is visible above the ridge, slightly to the left of the most distant boat. The telephone connection with the [illegible] [illegible] in the tent on the pole.

painting to cover the holes, as shown in Figure 11A. With a desk lamp placed behind the painting, the light issuing from the holes closely simulated the appearance of the lamps of the full-scale model. The intensity of the light issuing from the holes was adjusted to the required level by varying the distance of the desk lamp from the back of the painting.

Unless marked differences in color were present, the black silhouette could be made to disappear completely when the painting was viewed from the scale distance in the manner depicted in Figure 11B. An attempt to illustrate this demonstration by photographic means is shown in Figures 12 and 13. These illustrations were reproduced from unretouched negatives made with an ordinary view camera, a small stop in front of the lens being used to reduce its resolving power to correspondence with that of the human eye. Figure 12 is a photograph

FIGURE 11. Oil painting of Liberator (B-24) used to demonstrate the Yehudi principle.

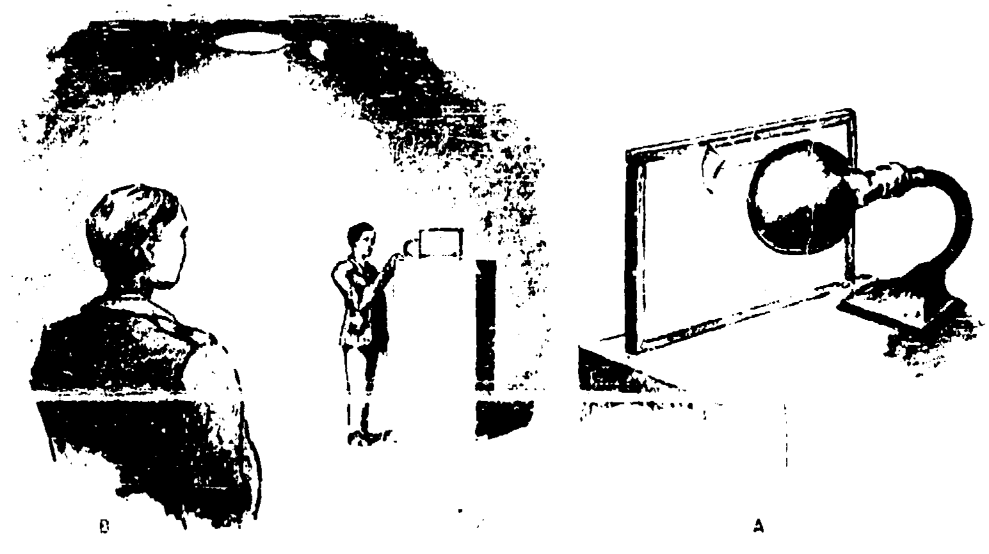

FIGURE 11. (a) Desk lamp positioned behind the painting to illuminate the holes in the silhouette. (b) Observer viewing the painting at a distance of 30 feet (scale distance of 2 miles).

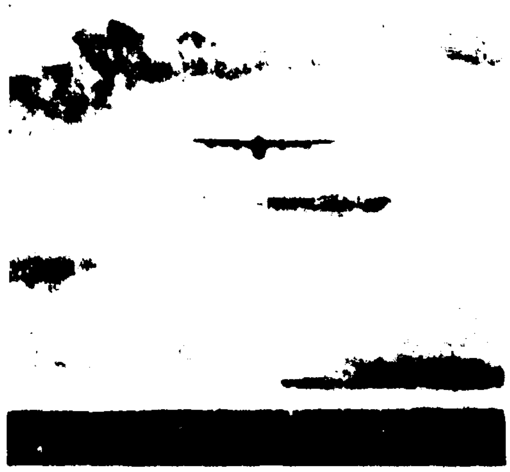

FIGURE 12. Photograph taken with lens having resolving power of human eye.

When viewed at 11 feet, this photograph shows the appearance of a Liberator at 2 statute miles.

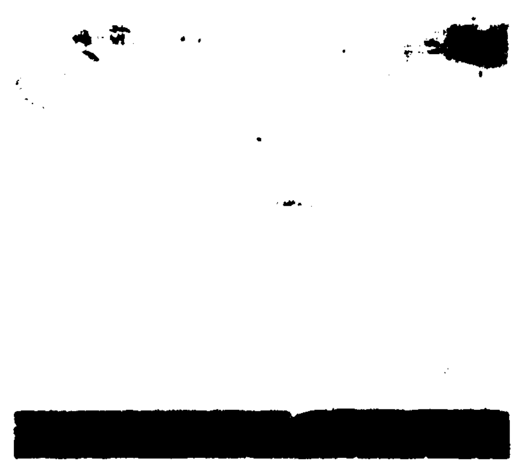

FIGURE 13. Photograph taken under the same conditions as Figure 12, with Yehudi camouflage applied.

Note that although the arrangement of lights is not perfect, the Liberator [illegible] well [illegible] distance of 11½ feet.

made under these conditions before the desk lamp was turned on; Figure 13 is a photograph made under identical conditions after the desk lamp had been turned on. When these photographs are viewed from the normal reading distance (10 inches), they represent the appearance of a Liberator only 880 feet away.

It was subsequently found that the illusion created is almost as realistic when a simple drawing is substituted for the colored oil painting. In fact, the houette pasted on a large piece of white cardboard. This simplified technique has been used on several occasions to test the effect of modifying the lamp positions. For example, before an actual installation was made on a Liberator at Wright Field, it was proposed that the lamps be mounted on brackets beneath the wings instead of in the leading edge of the wings. When a drawing of this arrangement had been made, it was seen at once that although the underwing brackets would be satisfactory where the wing is thin, they would not properly camouflage the thicker portions of the wing structure. A new drawing, in which only the lamps near the wing tips were mounted on underwing brackets, showed that such an installation should be satisfactory.

This technique is applicable to any type of plane and eliminates the necessity for constructing a model. Because atmospheric haze is absent, a design that performs satisfactorily at reduced scale can be expected to perform even more satisfactorily at full scale. Although this technique may be used for empirical determinations of lamp distribution, more direct methods will be discussed in Section 6.6.

6.6 TACTICAL AND TECHNICAL ASPECTS

The foregoing sections of this report are concerned with one specific tactical use of the Yehudi principle. The technical information that follows is supplied, however, because of other possible tactical uses. An attempt has been made to arrange the subject matter of this section in the sequence that is normally employed in completing a camouflage design based on the Yehudi principle.

6.6.1 Theoretical Power Requirements

Assume a black aircraft to be viewed against a sky background of brightness B (candles per square foot). If the area of the silhouette (in square feet) is A, the equivalent intensity of the part of the sky obscured by the silhouette is BA (candles). Thus, if the sky has a brightness of 500 candles per square foot (500π foot-lamberts), and the area of the silhouette is 200 square feet, the intensity of the portion of the sky obscured by the aircraft is $500 \times 200 = 100{,}000$ candles. Apart from the fact that a single source does not provide the proper distribution of intensity, a searchlight with a beam candle power of 100,000 would fulfill the requirements. If 20 lamps were used, each lamp should have a beam candle power of 5,000 candles.

If the solid angle of the cone of light from each lamp is represented by S, the amount of flux associated with a total beam candlepower BA is BAS (lumens), assuming the intensity to be uniform within the beam. Thus, if the total beam candlepower required is 100,000, and the solid angle is 0.02 steradians, the number of lumens required is $100{,}000 \times 0.02 = 2{,}000$ lumens. The luminous efficiency of tungsten lamps of the sealed-beam type is of the order of 20 lumens per watt at their normal operating temperature. This means that 2,000 lumens can be supplied with a power expenditure of $2{,}000/20 = 100$ watts.

Generalizing, the amount of power that is theoretically required by a Yehudi installation is given by the following equation:

$$P = \frac{BAS}{LT}$$

where P is the power requirement in watts,
- B is the brightness of the sky in candles per square foot,
- A is the area of the silhouette in square feet,
- S is the solid angle in steradians,
- L is the efficiency of the lamps in lumens per watt, and
- T is the transmission factor of the color-correcting filters.

The solid angle of a circular cone is related to the half-plane angle by the equation $S = 2\pi(1 - \cos\theta)$. Thus, for a circular cone whose plane angle is 10 degrees, the solid angle is

$$S = 2\pi(1 - \cos 5 \text{ degrees}) = 0.0239 \text{ steradians.}$$

The shape of the filament commonly employed in lamps of the sealed-beam type is such that the cone of light is nearly rectangular in cross section. The solid angle of such a beam can be computed with sufficient accuracy in terms of the product of the two plane angles in radian measure; thus, a rectangular cone subtending 8 degrees in the vertical plane and 10 degrees in the horizontal plane represents a solid angle of $10/57.3 \times 8/57.3 = 0.0244$ steradians.

6.6.2 Practical Power Requirements

It was tacitly assumed in the foregoing that lamps can be obtained whose intensity is uniform within ing the distribution of intensity are impossible of attainment, but lamp manufacturers are usually willing to supply data from which the applicability of their products for this purpose can be determined. Ordinarily, the catalogue description of sealed-beam lamps indicates the rated power input and the corresponding candlepower in the center of the beam.

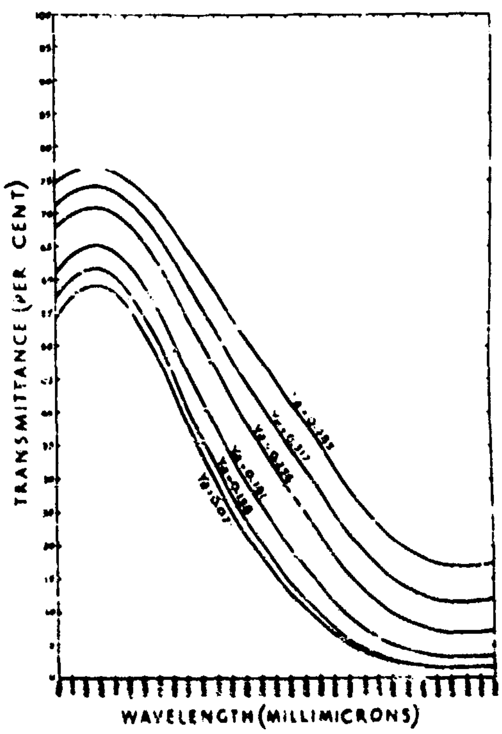

FIGURE 14. Spectral transmittance curves of 6 different thicknesses of transparent, iron-blue, lacquer films applied to glass filters.

Information concerning the solid angle of the beam and the criterion used in specifying the solid angle is frequently lacking. On inquiry, however, manufacturers are usually willing to state the angular distribution of intensity; and it is common practice to define the spread of the beam in terms of the horizontal and vertical angles at which the intensity becomes some stated fraction of the intensity in the center of the beam.

Emphasis has been placed on the sealed-beam type of lamp because it is so eminently suited for use in this connection. The reflector is of excellent quality and is made in a variety of standard sizes and avoids the focusing difficulties associated with the old-fashioned type of headlamp with separate bulb and reflector. Although departure from one of the standard sizes is not justified unless purchase in considerable quantity is contemplated, special filaments can readily be incorporated in the standard envelopes. Because the volume of the envelope is so much greater than that of the old fashioned headlight bulb, many of the former limitations on filament construction are removed. The manufacturers of sealed-beam lamps have now had sufficient manufacturing experience with this type of unit to be able to design and produce, literally overnight, special lamps meeting specified requirements.

6.6.3 Color Correction

Even when the candlepower of the Yehudi lamps is correctly adjusted for an intensity match with the sky, the airplane may be visible by virtue of a color difference. The color of a white cloud in direct sunlight is in the neighborhood of 5500° K, an overcast sky has a color temperature approximating 6500° K, and the color temperature of a blue sky may exceed 20000° K. Since tungsten lamps normally have a color temperature in the vicinity of 3000° K, it is common practice to increase their color temperature by the use of filters. As a matter of convenience and expediency, the filters used in the later experiments were made by coating glass plates with a film of clear lacquer containing a transparent iron-blue pigment (red shade). Figure 14 shows the spectral transmittance curves of typical filters produced by this method. The performance and efficiency of these filters is indicated in Figure 15.

Since the amount of light absorbed by the filter increases with the amount of color correction effected, it is in the interest of power conservation to make no greater correction than is required for satisfactory performance. Presumably, filters made of colored glass or of colored plastic might be specified for a large-scale installation, and it should be noted that many blue glasses and blue plastics transmit freely at the long wavelength end of the spectrum. When used with incandescent lamps, this high red transmittance would make red goggles an effective countermeasure.

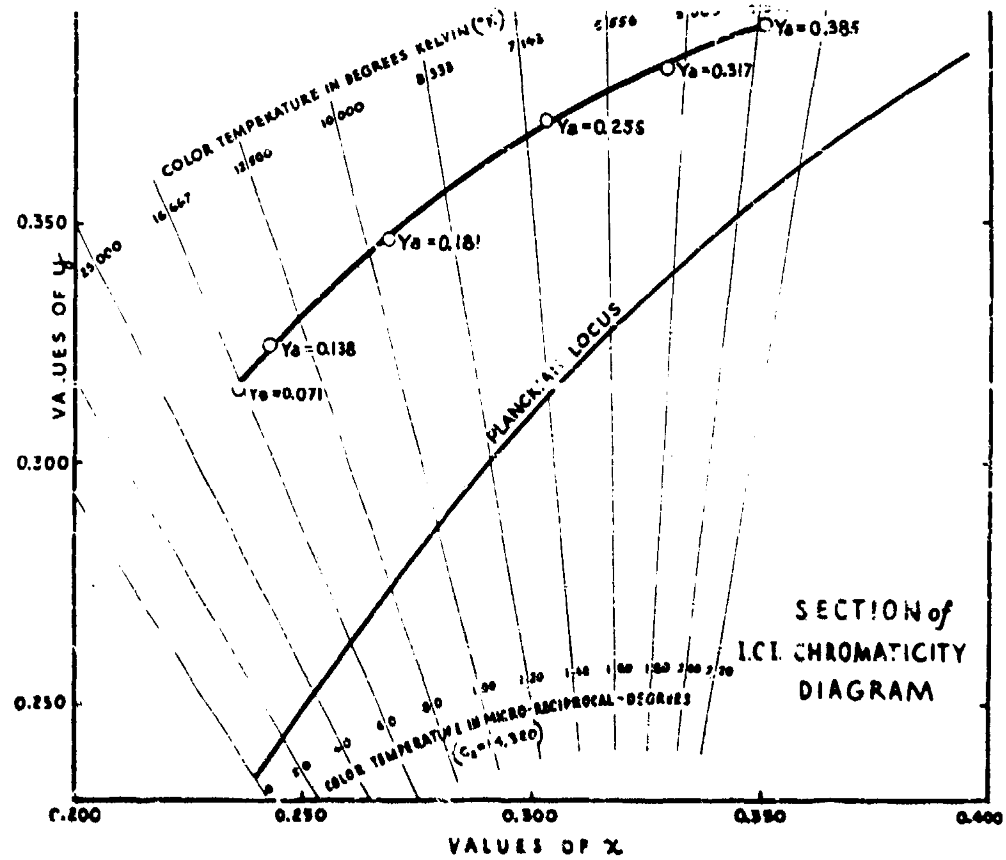

FIGURE 15. Section of standard ICI chromaticity diagram[32,33] showing the efficiency of the 6 filters whose spectral transmittance curves appear in Figure 14.

The values of Y_a give the integrated transmittance for illuminant A, = tungsten source at 2848 degrees K.

6.6.4 Number and Distribution of Lamps

The resolving power of the human eye for two light sources of equal intensity is ordinarily assumed to be one minute of arc. To make certain that this value is of the correct order of magnitude under these special conditions, the following experiment was conducted in the vision range of the Tiffany Foundation. Observers viewed a uniformly illuminated white screen on which a black disk with a small central hole was mounted. It was found that, by properly adjusting the intensity of a lamp mounted behind the central hole in the black disk, the disk became invisible when it subtended an angle of less than 1.4 minutes at the eye of the observer. Photometric measurements confirmed that the candlepower supplied by the small lamp corresponded to the candlepower of the area of the screen obscured by the black disk. This experiment indicates that even in a perfectly clear atmosphere, a black circular area 4.92 feet in diameter should be completely obscured at a distance of two nautical miles under the best conditions of observation when a source of the proper intensity is mounted at the center of the area. Subsequent experiments with the full-scale model were in accord with this calculation when applied to the fuselage section, but a greater spacing was found to be permissible along the thin sections of the wings.

Within the limitations set by the resolving power of the eye, there is considerable latitude in the choice of number and distribution of the lamps. For example, if the spacing of the lamps is to be uniform, lamps of various candlepowers could be used. Such

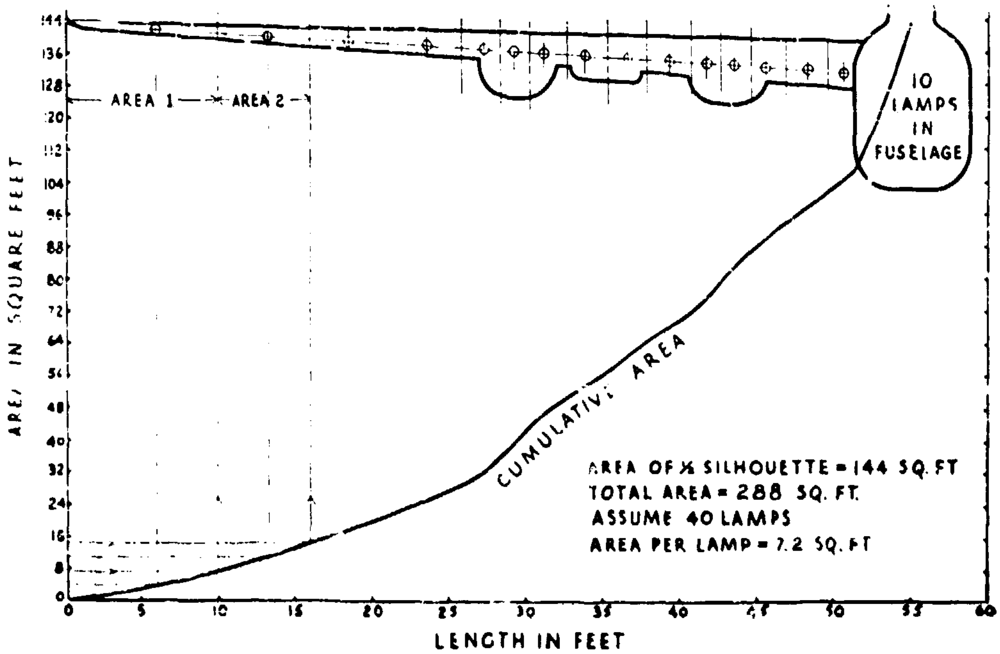

FIGURE 16. The spacing of the lamps can be determined theoretically by dividing the total area into elemental areas equal in number to the number of lamps to be used on this half of the plane. From the standpoint of horizontal spacing, the lamps should be placed at the center of each elemental area as shown.

an installation is impractical from many standpoints, and an equivalent result is secured by employing lamps of equal intensity with appropriate spacing. A method for determining the appropriate spacing is illustrated in Figure 16. Structural considerations often preclude the mounting of lamps in the calculated locations, but minor displacements of the lamps are usually permissible, as can be demonstrated by the method outlined in Section 6.5 of this report. For example, it has been found by this method that although lamps suspended on brackets beneath the wing function properly near the wing

FIGURE 17. Lamps suspended on brackets beneath outer wing.

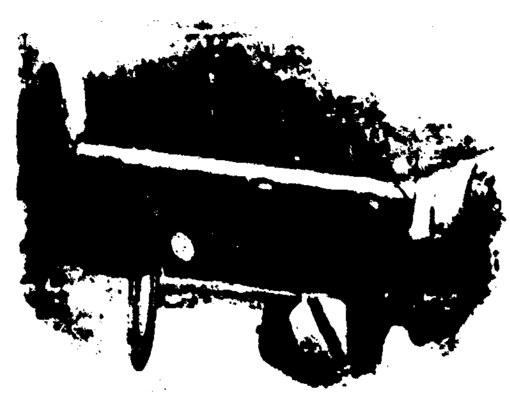

FIGURE 18. Lamps mounted in leading edge of inboard wing.

the section wherever the wing section is thick. (See Figures 17 and 18.) In the fuselage section and around the motor cowlings, aerodynamic considerations may require that two or more lamps be replaced by a single unit of correspondingly greater intensity.

6.6.5 Alignment of Lamps

The alignment of the lamps on an actual airplane should present none of the difficulties encountered in the final adjustments that were necessary on an elevated nonrigid structure. There are many possible procedures, and an outline of one will suggest many variations. If a level airfield a mile or more in length is available, the airplane may be stationed at one end with its tail elevated on jacks to the proper attitude. By lighting one lamp at a time, an observer at the opposite end of the field can indicate the necessary adjustments. Portable radio equipment is useful in this connection. When all the lamps are in approximate alignment, a delicate test for horizontal adjustment can be made by noting whether all lamps remain equally bright when viewed from positions at equal lateral distances from the axis. The corresponding test for vertical adjustment can be made by raising or lowering the tail of the plane. Some time might be saved in the above procedure by making a preliminary adjustment

headlights, but this method is not sufficiently critical for the final adjustment.

6.6.6 Method of Controlling Intensity

Throughout the experiments herein reported, photoelectric equipment has been used as a guide in controlling the intensity of the lights. Two photocells of the photronic type were employed in the bridge-type circuit shown in Figure 19. One of the cells is illuminated by the sky background and the other by an auxiliary lamp in the main lamp circuit. With this arrangement, a zero center milliammeter gives no deflection when the two cells are equally illuminated. A Polaroid shutter is provided between the auxiliary lamp and the photocell to adjust the zero position of the meter after the proper intensity has been found for one condition. Subsequent changes in sky brightness, as observed by the sky photocell, can be compensated by adjusting the rheostat in the lamp circuit until the meter again reads zero. Such a manual control contemplates that some member of the crew will maintain this adjustment prior to and during the attack. Full automatic control is possible by the use of a suitable servo-mechanism.

Because of local variations in the brightness of the sky, the field of view of the sky photocell should theoretically be restricted to the angular divergence

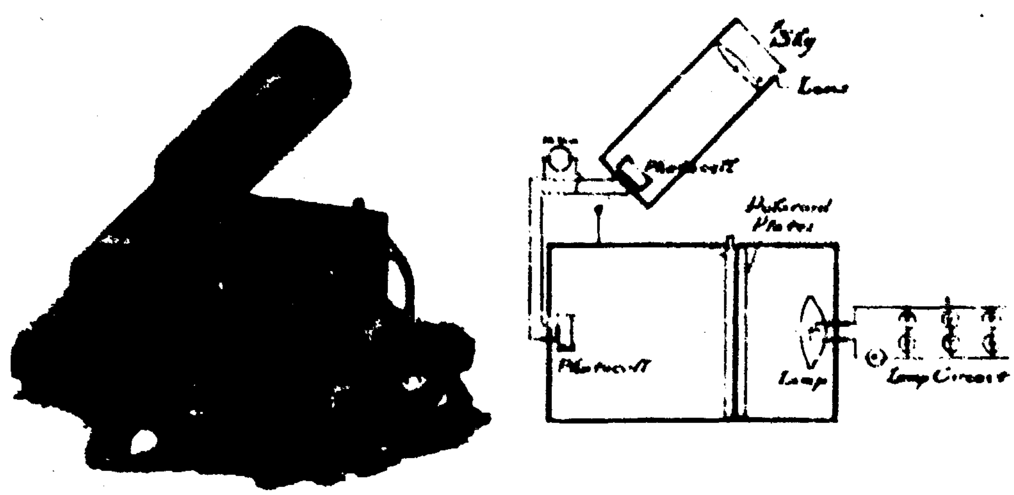

Figure 19. Photoelectric device used in the Tiffany experiments for matching the sky background.

quantity of flux is received by the photocell when the limitation of its field of view is accomplished by mounting an aperture identical in size with the photocell window at such a distance from the cell that the desired field of view is obtained. A greater quantity of flux and a resulting increase in the sensitivity of the control system can be achieved by replacing the front aperture with a lens having its focal point at the cell. When this is done, the field of view is independent of the lens diameter, and a gain of $36/(f\text{-number})^2$ in sensitivity is secured. Suitable lenses having a relative aperture of $f/2$ are marketed as reading glasses. With such an $f/2$ lens, a ninefold gain in flux results. When a collection lens is not used, the photoelectric control is forced to operate near its threshold sensitivity on dark days.

6.6.7 Color of Paint

A black silhouette was used throughout the experiments described in this report because the intensity required to match the sky background is then independent of the illumination falling on the face of the silhouette. In an actual installation, the portions of the airplane that an enemy observer can see during a tactical approach may advantageously, from the standpoint of power requirements, be painted some other color. There is little benefit to be gained from painting the undersurfaces with a highly reflecting paint, since these surfaces receive and by scattering in the intervening atmosphere, but considerable saving in power can be effected by using a more highly reflecting paint on the vertical and top surfaces. However, the control of the lighting equipment is then more complicated, because the illumination of the vertical surfaces varies enormously with the angle at which sunlight strikes them.

If the important areas visible to an enemy observer are painted a dark, saturated blue, it should be possible to reduce the power requirements somewhat without necessitating a more complicated control mechanism. In this case, the light reflected from such surfaces will be predominantly blue; and blue light has little effect on luminosity. Blue light does increase the color temperature considerably, and the greatest increase would occur on sunny days when the sky background is most likely to be at the high color temperature of blue sky.

6.6.8 The Effect of Crosswinds

During discussions of this project with Service personnel, attention has often been called to the fact that, when crosswinds are encountered, aircraft would not ordinarily present their head-on aspect during an approach. Thus, even if the spread of the beams was great enough to include the target, the match with the sky would be imperfect because of the change in size and shape of the silhouette. Figure 20 shows the silhouette of a Liberator (B-24)

FIGURE 20. (Above) Silhouette of Liberator viewed from the left at an angle of 20 degrees. (Below) Head-on silhouette.

viewed head-on. Obviously, an installation of lights intended to camouflage over so wide an arc would require that lamps be mounted along the sides of the fuselage. Such complications are avoided if pilots are instructed to "home" on the target. In this case, the approach will be along the slightly curved course illustrated in Figure 21.

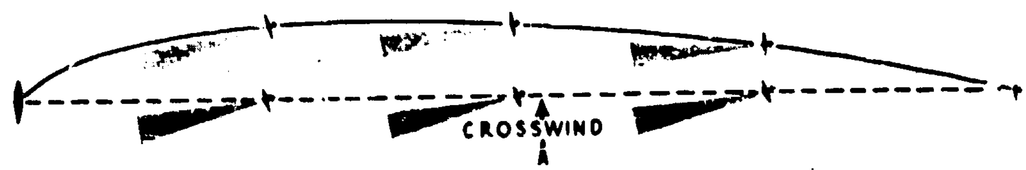

FIGURE 21. Diagram showing the curved flight course that results when the light beams are held on the target during an approach with a strong crosswind.

This curve was plotted for the case of a crosswind whose velocity is one-fifth of the air speed of the plane.

6.6.9 The Effectiveness of Enemy Countermeasures

The only effective optical countermeasure suggested thus far is the use of binoculars. Theoretically, if there were no atmosphere, a perfect pair of 8-power glasses would increase by eightfold the effective range of the Yehudi camouflage. Because light is always scattered to some extent by the atmosphere, the effectiveness of binoculars is always less than the theoretical value. Furthermore, the field of view of such binoculars is scarcely more than 5 degrees, which greatly increases the difficulty of search. At the time this project was started, it was understood that the Germans were using three observers on the decks of their submarines, each being assigned to search the sky through an arc of 120 degrees. It was stated as part of the original project assignment that the use of this camouflage measure would be fully justified if its only result was to require that enemy lookouts use binoculars continuously.

The use of color filters by enemy observers would, of course, be futile unless there is a marked spectral dissimilarity between the lights and the natural background which they attempt to simulate. Under certain special conditions, polarizing devices would increase the visibility of the camouflaged airplane, but these special conditions do not often occur. Sea-search planes equipped with Yehudi camouflage can be detected by enemy radar if the enemy is willing, or finds it necessary, to sacrifice radar silence.

AIRCRAFT

In 1943, the Aircraft Anti-Submarine Warfare Development Detachment of the Air Force, U. S. Atlantic Fleet [ASDevLant] stationed at the Naval Air Station, Quonset Point, Rhode Island, requested the aid of Section 16.3 of NDRC in connection with Yehudi camouflage. They wished to install lamps on their patrol aircraft similar to those designed for the B-24 but intended for continuous use while flying in clear weather under blue skies. For this purpose, the Navy requested a much greater horizontal beam-spread and the ability to match sky brightnesses up to 1,500 foot-lamberts. Such a design was produced for the PBM flying boat. Later, a second design was undertaken at the Navy's request which provided for intermittent operation with a beam-spread limited to 9 degrees and the matching of sky brightnesses up to 2,000 foot-lamberts. Although special sealed-beam lamps and the necessary housings were devised, no installation was made on a PBM.

In the same year, the ASDevLant Group at the Naval Air Station, Quonset Point, Rhode Island, requested aid in designing Yehudi camouflage for a TBF torpedo bomber. Such a design was made, and advice was given on several incidental problems. Navy photographs of the completed installation are shown in Figures 22 and 23. The first flight test occasioned favorable reaction. Further test flights resulted in improvements in the adjustment of the equipment and in techniques for its use. It is understood that under conditions such that an uncamouflaged plane was visible at about 12 miles, the plane equipped with Yehudi camouflage could approach to within 3,000 yards without detection, even when its approximate location was indicated by an accompanying uncamouflaged plane.

On the basis of the recommendations in a report

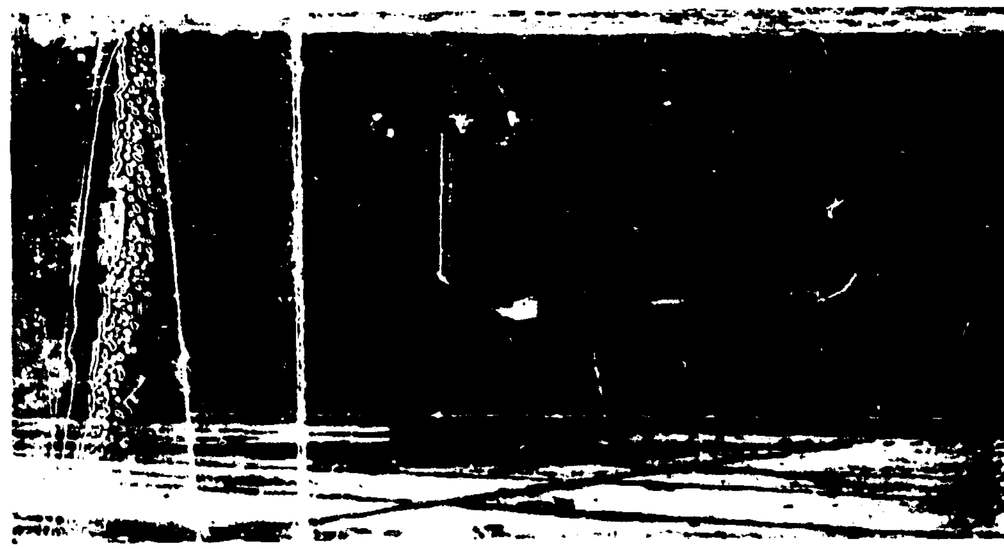

Figure 22. TBF torpedo bomber equipped with Yehudi camouflage designed to conceal the aircraft from visual detection by an observer at the target until the range has been closed to 1.5 miles.

In Navy tests, the camouflage fulfilled this requirement even on days so clear that the plane was visible at 12 miles when the Yehudi lamps were not lighted.

Figure 23. Side view of the TBF torpedo bomber shown in Figure 22.

The Yehudi lamps are mounted in housings protruding from the leading edge of the wing, and on tapered mounts on the motor cowling.

issued by AirDevLant Command that ordered the installation of Yehudi camouflage on an operative squadron of TBF aircraft. Concurrently, the Naval Air Station at Patuxent River, Maryland, was asked to make the necessary changes in the engineering drawings of the TBF so that Yehudi camouflage could be factory installed. So far as is known, neither of these projects was completed.

MISSILES

During 1944, the Special Designs Section of the Navy Bureau of Aeronautics requested the technical assistance of Section 16.3 of NDRC in the design of Yehudi camouflage for an LBT-1 Glomb. Because production of the Glomb had already begun, the Section was requested to devise Yehudi gear in the form of attachments which might be installed in the field, and which would enable this guided missile to approach its target within 6 seconds of flying time before becoming visible. Structural and aerodynamic difficulties made this problem appear impossible of solution.

On November 1, 1944, the production of LBT-1 Glombs was discontinued and the Section was asked about the feasibility of installing Yehudi camouflage on the LBE-1 Glomb then under development by Pratt, Read & Company, Inc., Deep River, Connecticut. After a preliminary investigation had disclosed that the technical difficulties encountered in the LBT-1 were not present in the new LBE-1, the Navy requested the Section to supervise the engineering and installation at the factory of Yehudi camouflage on an experimental LBE-1. This request was formalized by A/N Project Control No. NA-188. In response thereto, an OSRD contr— (OEMsr-1450) was placed with Pratt, Read & Company Inc. for the mechanical design of the lighting being constructed by them under their contract wi the Navy. The electronics staff of the Research La oratories of the Interchemical Corporation, Ne York, was requested under Contract No. OEMs 697 to design, construct, and install an automat photoelectric control system which would make ma ual adjustment of the intensity of the Yehudi lam during flight unnecessary. This equipment was bu (Figure 24) and field-tested at full scale on t premises of the Louis Comfort Tiffany Foundatio

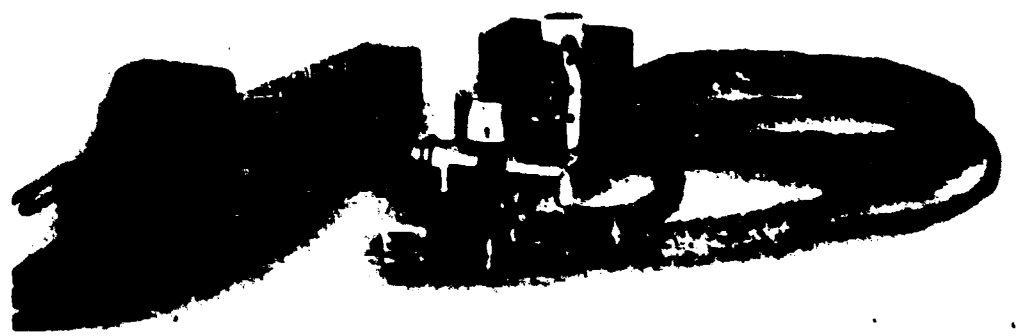

FIGURE 24. Automatic photoelectric current control for Yehudi lamps.

This equipment was built under contract OEMsr-697 for use on LBE-1 Glombs and is described in OSRD Report No. 6556. Two photocells (center), on long shielded cables, monitor one of the Yehudi lamps and the sky behind the plane respectively. [illegible] currents are compared by the [illegible] bridge (center) and a relay control unit controls servomotor (left) which drives the special [illegible] rheostat.

Oyster Bay, New York where an OSRD contra (OEMsr-597) for camouflage field studies was force. A description of the control equipment ap pears in OSRD Report No. 6556.[30]

The work by Pratt, Read & Company Inc. was in terrupted on several occasions by changing requir ments imposed by the Navy, including a change the method of intelligence by which the Glomb caused to home on its target. At the time of t Japanese surrender, the engineering had been com pleted, and a special wing bearing the Yehudi lam nearly constructed. The Navy subsequently cancel its contract with Pratt, Read & Company In thereby making it impossible for the contractor complete the subject work of Contract No. OEMs 1450. At the request of the Bureau of Ships, t apparatus constructed by the Interchemical Corp ration and by Pratt, Read & Company Inc. w transferred to the Navy.

ANTISEARCHLIGHT CAMOUFLAGE FOR AIRCRAF

7.1 INTRODUCTION

During 1942, the camouflage officer at Eglin Field, Florida, visited the headquarters of Section 16.3 of NDRC to discuss the application of various camouflage measures to Army aircraft. During the discussion, it was reported that the matte black finish used for antisearchlight camouflage was not effective, and that its roughness resulted in a decrease in the airspeed.

7.2 COFFIN PAINT

The development of an improved type of matte black finish was referred to the Research Laboratories of the Interchemical Corporation, already operating under an OSRD contract (OEMsr-697) supervised by this section. In less than two weeks, the contractor had produced a novel type of finish in which, by the use of a suitable plastic, the small particles of carbon black are formed into agglomerates of sufficient size to impart the necessary optical roughness to the surface, the function of the plastic being somewhat similar to that of the molasses in a popcorn ball. Since the plastic is transparent in ordinary vehicles, this finish, although smooth by ordinary criteria, is extremely matte, and has a diffuse reflectance of only 2.2 per cent. Samples of this finish were sent to the Army Air Forces Proving Ground Command at Eglin Field for flight tests.

The results of the Eglin Field tests of this *coffin paint*, as the material came to be called, indicated no significant improvement in concealment, the observers reporting that aircraft camouflaged with this material "looked white in a searchlight beam." They were, in fact, almost indistinguishable from planes camouflaged with the standard Army matte black finish, which has a diffuse reflectance in the neighborhood of 5 per cent. It was concluded from these tests that, since a reduction from 5 per cent to 2.2 per cent had produced only slight improvement, a much greater reduction would be necessary before concealment in a searchlight beam could be achieved. This conclusion was borne out by the results obtained concurrently at the tion in a laboratory study on the gets.

The possibility of further reduct low diffuse reflectance of coffin pai Of the light reflected by coffin pa the 2.2 per cent is reflected at tl paint without entering the body of all. Hence, a more complete absor the black pigment itself would reflectance of the paint film signi

7.3 GLOSSY BLACK PA

In view of the experience witl appeared that the only hope of plane invisible in searchlight bean sibility of altering the *geometric* the reflected light. Whereas an airc coffin paint is almost equally vi direction when caught in the beam. *glossy black* paint might make an from some directions at the expen somewhat more visible in others. in which it is visible should happ military importance, the advantag ible under all other circumstance great.

The Interchemical Corporation fore, to produce a glossy black fi having the lowest possible diffuse meant a dispersion of carbon bla vehicle without extenders or fillers material developed is described b 7.5, and its development has been by the contractor.[1]

7.3.1 Preliminary Tests at Mo

A sample of the new material to the Tiffany Foundation for fiel identical 16-inch models of a B- obtained and painted in the new paint, and with the standard Ar The models were suspended from

Chapter 6. Automobile spotlights and battery-powered searchlights were used to view the models.

From the moment of the first comparison, it was plainly evident that the new camouflage was vastly superior to the matte finish. Indeed, under many circumstances, the glossy plane could not be seen at all. The appearance of the models is illustrated in Figures 1 to 4. These photographs, made as illustrations for this report at a later date, were produced with the arrangement of lights, cameras, and models shown in Figure 5.

Figures 1 through 4 show the models as they appeared to an observer stationed at or near the lights. On the side of the model opposite from the lights, there is a point (or points) from which light specularly reflected by the Black Widow finish renders the plane visible, as shown in Figure 6. However, in the case of a moving airplane, the point from which it is visible is moving also, at *double* the ground speed of the plane. An observer, therefore, is afforded only a fleeting glimpse of the plane. The shortness of the time interval during which the plane is visible is important, for it makes the target nearly impossible to follow with searchlights or guns.

7.2.2 Flight Tests by the Army

After the successful experiments at model scale, samples of the glossy black finish were sent to Eglin Field for flight test. The Army* report which was issued subsequently describes the results as follows:

> On most occasions the invisibility of the subject black camouflage with searchlights full on the airplane is amazing. The standard daytime camouflage is visible as a silvery airplane during the entire traverse across the searchlights. The standard dull black camouflage is almost always as visible, but does not shine as brightly. The subject black camouflage is invisible most of the time.

Optically controlled searchlights were said to be quite unable to find and hold the airplane at all, and the effectiveness of radar-controlled searchlights was reduced about 50 per cent. Even when the test plane was held in the beam of a radar-controlled searchlight, 8-power night binoculars enabled only the insignia and the revolving propellers to be distinguished. These results were not wholly unex-

* *Final Report on Test of Glossy Paint for Night Camouflage*, Serial No. 3-43-11?, AAF ... Project No. (3?-1) 17, Proof Department, Army Air Forces Proving Ground Command, Eglin Field, Florida.

diffuse reflectance in the ne... cent.

THE PROCUREMENT PROBLEM

In view of the favorable ... Forces Proving Ground, it se... extensive tests and demonstr... ducted, and that such tests ... the glossy black finish than ... tories of the Interchemical ... able to produce with their ... Arrangements were made, th... & Wiborg Corporation, Cincin... Chemical Works, St. Louis, a... Company, Philadelphia, to ... identical in formulation with ... the Eglin Field tests. These ... available under the trade ... Mallo Black, and Rhoco Bl... establishing three sources of ... could be procured by the Ar... waiting for a specification to ...

7.2.3 ...doption by th...

The contemplated tests were ... cause the Chief of the Army ... that all night fighters be provi... camouflage. The Section imme... Army Air Forces Materiel ... Field concerning all pertinent ... opment, and the regular Army ... dures were instituted.

At this time, the code name ... ect, was adopted in recogniti... fighter, which was the first t... given this antisearchlight prot...

7.2.4 Inquiries from ...

The London Mission of the ... informed of the progress of t... as a result, cables from Brit... more information concerning ... finish, primarily in connection ... operations based in England. ... essary information could not ... in correspondence or reports, ... to the War Department that ... Miscellaneous Section, Proving ...

Chapter 6. Automobile spotlights and battery-powered searchlights were used to view the models.

From the moment of the first comparison, it was plainly evident that the new camouflage was vastly superior to the matte finish. Indeed, under many circumstances, the glossy plane could not be seen at all. The appearance of the models is illustrated in Figures 1 to 4. These photographs, made as illustrations for this report at a later date, were produced with the arrangement of lights, cameras, and models shown in Figure 5.

Figures 1 through 4 show the models as they appeared to an observer stationed at or near the lights. On the side of the model opposite from the lights, there is a point (or points) from which light specularly reflected by the Black Widow finish renders the plane visible, as shown in Figure 6. However, in the case of a moving airplane, the point from which it is visible is moving also, at *double* the ground speed of the plane. An observer, therefore, is afforded only a fleeting glimpse of the plane. The shortness of the time interval during which the plane is visible is important, for it makes the target nearly impossible to follow with searchlights or guns.

7.3.2 Flight Tests by the Army

After the successful experiments at model scale, samples of the glossy black finish were sent to Eglin Field for flight test. The Army* report which was issued subsequently describes the results as follows:

> On most occasions the invisibility of the subject black camouflage with searchlights full on the airplane is amazing. The standard daytime camouflage is visible as a silvery airplane during the entire traverse across the searchlights. The standard dull black camouflage is almost always as visible, but does not shine as brightly. The subject black camouflage is invisible most of the time.

Optically controlled searchlights were said to be quite unable to find and hold the airplane at all, and the effectiveness of radar-controlled searchlights was reduced about 50 per cent. Even when the test plane was held in the beam of a radar-controlled searchlight, 8-power night binoculars enabled only the insignia and the revolving propellers to be distinguished. These results were not wholly unexpected, in view of the low ... diffuse reflectance in the neighborhood of 0.1 per cent.

The Procurement Problem

In view of the favorable report from the Air Forces Proving Ground, it seemed likely that more extensive tests and demonstrations would be conducted, and that such tests would require more of the glossy black finish than the Research Laboratories of the Interchemical Corporation would be able to produce with their small-scale equipment. Arrangements were made, therefore, with the Ault & Wiborg Corporation, Cincinnati, the Mallinckrodt Chemical Works, St. Louis, and the Rohm & Haas Company, Philadelphia, to compound materials identical in formulation with the material used in the Eglin Field tests. These materials were made available under the trade names of Wiblack, Mallo Black, and Rhoco Black respectively. By establishing three sources of supply, the material could be procured by the Army or Navy without waiting for a specification to be prepared.

7.3.3 Adoption by the Army

The contemplated tests were never conducted because the Chief of the Army Air Forces ordered that all night fighters be provided with this type of camouflage. The Section immediately informed the Army Air Forces Materiel Command at Wright Field concerning all pertinent details of this development, and the regular Army procurement procedures were instituted.

At this time, the code name, Black Widow Project, was adopted in recognition of the P-61 night fighter, which was the first type of aircraft to be given this antisearchlight protection.

7.3.4 Inquiries from Britain

The London Mission of the OSRD had been kept informed of the progress of this development, and, as a result, cables from Britain began to request more information concerning the antisearchlight finish, primarily in connection with night-bombing operations based in England. Inasmuch as the necessary information could not be readily embodied in correspondence or reports, the Section suggested to the War Department that the Assistant Chief, Miscellaneous Section, Proving Ground Command,

* *Final Report on Test of Glossy Paint for Night Camouflage*, Serial No. 3-43-114 AAF Bd Project No. (M-1) 17, Proof Department, Army Air Forces Proving Ground Command, Eglin Field, Florida.

FIGURES 1 through 4. Photographs of models of B-24 aircraft as seen against the night sky when fully illuminated [illegible] the model on the right has the Black Widow finish.

FIGURE 1

FIGURE 2

CONFIDENTIAL

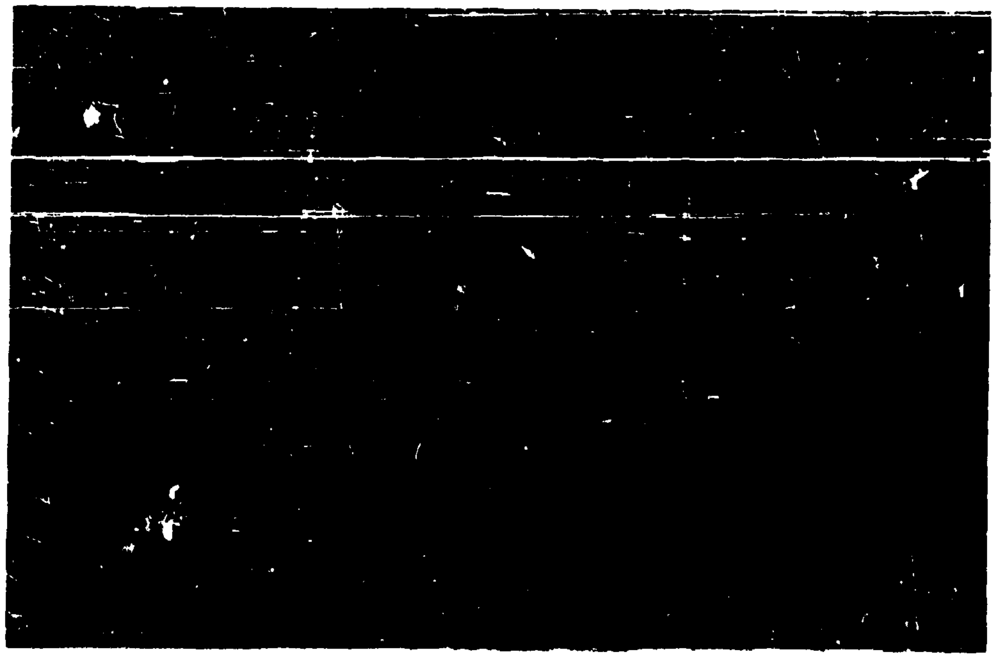

FIGURE 3

FIGURE 4

CONFIDENTIAL

Figure 5. Arrangement of camera, lights, and model aircraft used to secure photographs shown in Figures 1, 2, 3, 4 and 7.

be sent to England on a special mission to acquaint both the AAF and the RAF with this new camouflage measure.

This was done, and during the four months he was there, the application of this finish on a large number of aircraft was supervised, a routine schedule for refinishing was established, and arrangements for suitable production facilities in the United Kingdom were made.

7.3.3 Use over Germany

Memorandum Report No. 283 from the Air Technical Section, Headquarters, European Theater of Operations, subject, *Application and Observation of Antisearchlight Camouflage in E.T.O.*, contains the first indication of the effectiveness of this antisearchlight camouflage under combat conditions. Although only relatively few bombers had been refinished at the time that this report was issued, there had been enough instances of effective protection against enemy searchlights to enable the report to take cognizance of the improvement in the morale of squadrons using Black Widow finish.

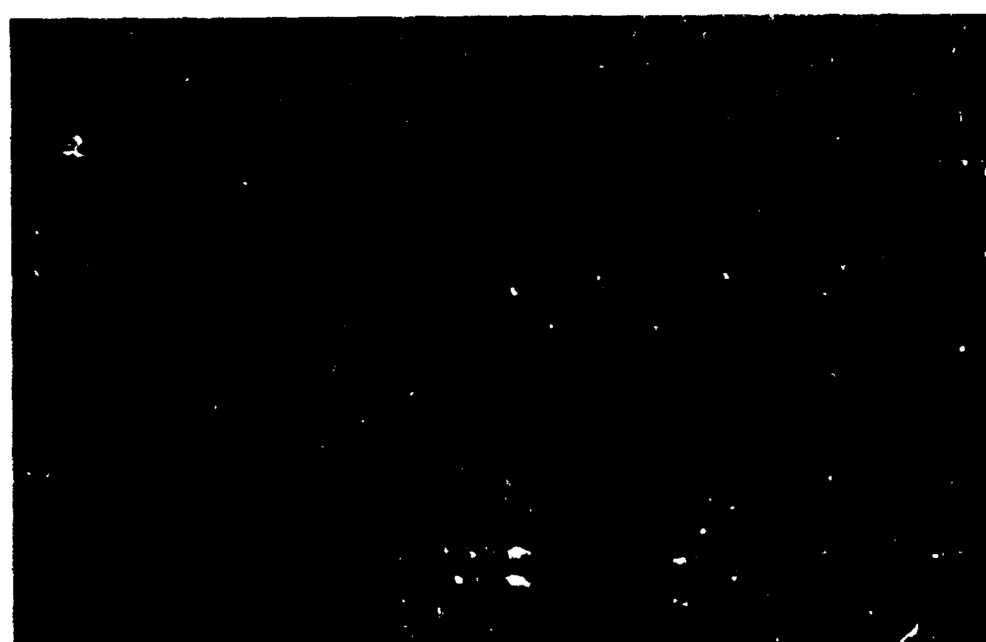

Figure 6. Photograph of models of B-24 aircraft showing light reflected specularly by Black Widow finish (model on right) when the plane is between the observer and the searchlights. In the case of a moving plane, any observer sees this condition only for an instant.

7.3.5 Inquiries from the Pacific

U. S. Air Forces stationed in the Pacific theaters, on receipt of the report from Eglin Field mentioned above, requested technical assistance in connection with this new antisearchlight camouflage. A considerable quantity of this paint, procured under specifications prepared by Wright Field, was shipped to the various theaters, and the camouflage officer was sent to the central and south Pacific areas shortly after his return from England. He was assisted by civilian members of the Office of Field Service. In this way, all Air Forces involved in the war with Japan were apprised of the value of this camouflage measure and were given assistance in the application and maintenance of the finish.

Because the operational conditions in the Pacific theater are so unlike those that exist in Europe, the effectiveness of this antisearchlight measure was subjected anew to field tests over searchlight batteries manned by veteran crews in one of the active theaters. These tests brought out advantages which had not been realized previously, and suggested new tactics which had not been employed formerly. The results of these tests are to be found in *Memorandum Report on Antisearchlight Camouflage*, Operations Analysis Section, Headquarters, Far Eastern Air Forces, the classification of which is higher than that of this report.

7.4 OPTICAL BEHAVIOR OF THE BLACK WIDOW FINISH

An aircraft camouflaged with Black Widow finish has a diffuse reflectance of approximately 0.1 per cent, so that in a searchlight beam it appears about 1/1000 as bright as would a white-painted ship. To this diffusely reflected light is added the contribution due to all of the tiny virtual images of the searchlights formed by the mirror-like surface of the paint.

If aircraft were geometrically simple shapes, such as planes, cylinders, or spheres, it would be an easy matter to calculate the size of the virtual images of the searchlights. Since most aircraft surfaces are convex, the virtual images are generally small, located within the ship, and visible over a wide range of directions. The brightness of each image is approximately 1 per cent of the brightness of the searchlight itself, neglecting the attenuation due to atmospheric haze between the light and the plane.

When the plane is considered as a visual target, the inherent integrated contrast of the plane will be zero if the total light reflected toward the observer equals the total light which the observer would have received from the part of the sky which the plane obstructs. Because the space behind the plane is lighted by the searchlight beam the obstructed light may exceed the amount received normally from the night sky. Therefore, zero reflected light from the plane is not the condition for minimum visibility.

No opportunity was found during the war to measure the quantities of light involved in an actual service test. However, the reports from the Services indicate that the Black Widow finish affords more perfect concealment for the planes caught in searchlight beams than was originally expected. This success may be explained if, by chance, the condition for zero inherent integrated contrast is met by a plane of conventional shape treated with Black Widow finish.

7.5 FORMULATION OF THE BLACK WIDOW FINISH

Black Widow finish may be prepared and used in a variety of forms, such as lacquer, fast-drying enamel and enamel of medium drying rate. The type of finish which should be chosen for use in any one location depends upon such factors as the shelter afforded, the time available before the aircraft must be returned to service, the atmospheric conditions, and the finishing equipment installed.

The drying of lacquer depends almost entirely on the evaporation of the solvents in the lacquer, while the drying of enamel is related not only to the evaporation of the solvents in it but also, as in ordinary paints, to the oxidation of some of the resinous constituents in the binder, which converts them into tough, insoluble films. Lacquers dry dust-free much more rapidly than enamels and therefore do not require as much shelter during application as enamels. In general, the desired coverage may be obtained in fewer coats with enamel than with lacquer, which contains less solids. Also, enamel yields a somewhat higher gloss than lacquer, because the more rapid evaporation of solvents, characteristic of the lacquer form, tends to impart to the surface a mild unevenness called orange-peel. Except in aggravated or neglected cases, however, this orange peel does not detract from the performance of Black Widow lacquer as a camouflage finish compared to Black Widow enamel.

In preliminary discussion with the Army Air Forces Proving Ground Command, Eglin Field, Florida, a preference was expressed for the synthetic enamel type of formulation, which promised to be the easier material to apply to aircraft previously finished with Air Corps camouflage materials. For this reason the enamel type of Black Widow finish was the first supplied. Subsequent events suggested that Black Widow finish might not be applied to any considerable extent in modification centers as a repaint job, but would find its greatest use in production as the original finish, where rapid drying is of paramount importance to permit further work on the plane as soon after painting as possible. When Black Widow finish is shipped for application elsewhere, the greater storage stability of lacquers as compared with enamels, particularly for Pacific areas with their considerable transit times, further recommended the lacquer type. In addition, since painting facilities are often crude and time is of vital importance in advanced theaters, the lacquer type will be in much greater demand. Both forms, however, receive attention here.

Like all coating compositions, Black Widow finish consists of pigment, vehicle, and solvent. Carbon black alone seems permissible as the pigment, and the desired results, will be obtained only from the best lacquer grades of carbon black, selling in the neighborhood of 50 cents and more per pound. The gas blacks generally used for compounding rubber, in news ink, and in paints are not suitable. Further, the carbon black chosen must be very well dispersed by one of several highly efficient methods known to the art, for any clumps of undispersed black will mar the final finish and disturb the desired low-diffuse reflectance.

For Black Widow lacquer, the vehicle generally consists of a mixture of suitable grades of nitrocellulose and one or more synthetic resins. In the case of Black Widow enamel, the binder in the vehicle is made up of one or more resins, chosen to give in combination the desired ultimate properties in the film. To accelerate the air-drying of the enamel coat, conventional metallic driers are added.

Sufficient solvents and diluents are present or added to the coating compositions to convert them to the proper consistency for the selected method of application.

7.5.1 Typical Formulations

The composition of typical formulations is as follows:

Typical Black Widow Lacquer

Ingredients	Parts by Weight	
Carbon black (high color)	5.0	
Nitrocellulose (low viscosity)	40.0	
Alkyd resin (nonoxidizing type)	45.0	
Plasticizer	10.0	
Solids		100.0
Volatile lacquer solvent and diluent		225.0
Total		325.0

For spraying, thin 3 parts above with 2 parts of lacquer thinner.

Typical Black Widow Enamel

Ingredients	Parts by Weight	
Carbon black (high color)	6.5	
Alkyd resin (oxidizing type)	84.5	
Mixed drier solution	9.0	
Solids		100.0
Volatile solvent		90.0
Total		190.0

For spraying, thin 2 parts above with 1 part of enamel thinner.

7.6 APPLICATION OF BLACK WIDOW FINISH

In the application of either the lacquer or the enamel type of Black Widow finish, standard industrial painting procedure is followed. No special techniques are required. The lacquer or enamel, as the case may be, is thinned to the proper consistency for spraying and applied by means of the spraying facilities with which Air Corps service installations are equipped.

When a repaint job over other camouflage is necessary, it is not possible to avoid the sanding of the previous paint since conventional camouflage finishes are comparatively very rough and porous and are not adapted to receive a glossy top coat. The old surface is first sanded smooth with No. 320 or No. 400 abrasive paper and water. The scum which is left after the water sanding is carefully wiped away. The Black Widow finish is then applied by standard spraying methods.

On jobs old or new, Black Widow finish need not be applied to the entire fuselage. The gloss black is sprayed on all under surfaces and carried three-quarters of the way up the sides. When viewed from below or from any low lateral position, only an-broken glossy black surfaces should present themselves.

The top insigne is left undisturbed. The identification insignia on the bottom are completely covered. The side insigne is usually dulled by fogging with gray paint or by a light pass of the Black Widow finish.

Detailed instructions for the application of this paint are contained in Headquarters Army Air Forces Technical Order 0–7–1–1, which also gives some information as to coverage and procurement.

Like all lacquers and enamels, Black Widow finish gradually shows the normal cumulative effects of weathering. After the equivalent of a two-week exposure in Florida, the spectral reflectance of the cleaned surface is found to increase to a value of about 0.5 per cent (after the gentle removal of the scum collected in this period). Conditions on an airfield and in flight are more rigorous than standard Florida exposure, for the clouds of abrasive dust stirred up by propellers on the ground and caked in wet weather on the aircraft surfaces, and the cor-

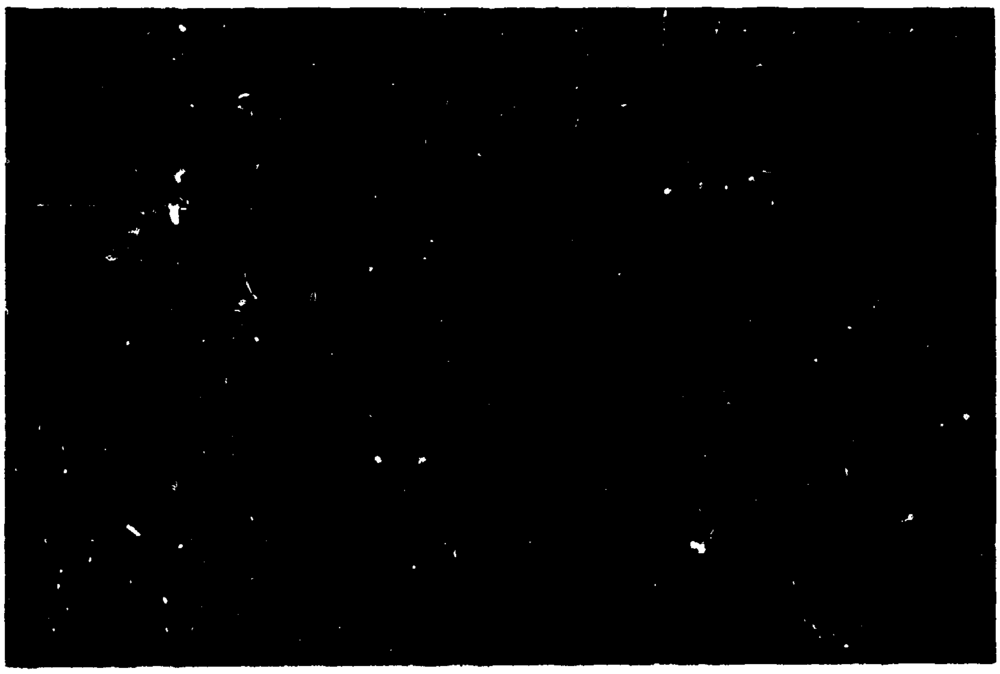

FIGURE 7. Photograph identical with Figure 3 except that the Black Widow finish on the model on the right has been splashed with mud, thus giving parts of the plane a high diffuse reflectance. This illustrates the importance of keeping the Black Widow finish clean and glossy. Maintenance procedures are discussed in Section 7.7

7.7 MAINTENANCE OF THE BLACK WIDOW FINISH

The most important attribute of Black Widow finish is, of course, its exceptionally low diffuse reflectance (Figure 7). With reasonable care in the selection of raw materials, as outlined in the preceding section, the diffuse reflectance is readily kept at a value of 0.15 per cent or lower. Since information concerning methods of maintaining Black Widow finish does not appear in practicable form elsewhere, it is included in the following paragraphs.

rosive gases eliminated in proximity to gun mountings, hasten the destruction of the desirable low reflectance. It was therefore considered essential that methods for the maintenance of the low reflectance of Black Widow finish be investigated.

Based upon a long series of experiments with various polishes, waxes, and rejuvenating coats, a set of maintenance recommendations was formulated for maintenance installations offering moderately complete facilities and ample time for the necessary operations:

1. On a fresh surface, whether of the enamel or

lacquer type, all additional treatment results only in a finish of increased reflectance and should therefore be avoided.

2. For a fresh finish which has become dusty or is covered only superficially with dirt, the best procedure for restoring the original low reflectance consists of washing away the foreign material with a mild detergent or soap containing a minimum of alkali.

3. A mildly weathered surface may be brought back to a satisfactory low level of reflectance with an extremely mild abrasive. In the case of a lacquer finish, the reflectance may be still further reduced by application thereafter of a waxy compound with a soft cloth, while care is taken not to leave any whitened areas of excess wax. Enamel finishes, however, are in general softer than typical lacquers, which makes waxing of the enamel undesirable because it introduces fresh scratches.

4. When a finish has become badly abraded but still consists of a continuous unbroken film, whether of lacquer or of enamel, it is first cleaned of all dirt, dust and other foreign materials by washing with a mild soap and water or by cleaning with a very mild abrasive, and the entire surface is then rejuvenated by application of a very thin coat of enamel. This new coat may be applied with a cloth soaked with diluted enamel. A diluted lacquer composition is not suitable for this purpose because, when used, it will dissolve the lacquer coat previously applied to give a finish of considerably increased reflectance. On enamel, it is much more difficult to apply than a rejuvenating enamel finish. A second, additional rejuvenation coat may be applied after weathering of the rejuvenated finish.

5. If the lacquer or enamel finish is broken, burned, or so badly marred that it gives unsatisfactory results when treated according to the procedures outlined above, another full finishing coat, comparable in thickness to those which preceded it, is required. To reproduce the original reflectance characteristics, the surface to be recoated should be smooth, which often necessitates preliminary sanding followed by washing. The use of lacquer over enamel or enamel over lacquer for this additional full coat is to be avoided, as the resultant film will show poor adhesion to and (in the case of lacquer over enamel) will lift the coats below.

In combat theaters, however, the necessary equipment and time for the execution of the recommendations above are not always available. In these instances, emergency measures must be adopted for the rejuvenation of the surfaces which are encrusted with mud or marred by muzzle blast and engine exhaust. Under these conditions, the aircraft is first washed thoroughly with water from a steam jenny. The temperature and pressure of the water used are adjusted to cope with the mud crusts. Soap may be added to the water to assist in its detergent action. Any dull spots which remain after the washing has been completed are then polished with wax free of abrasive. If wax polish is not available, the dull spot may be wiped with lubricating oil or hydraulic fluid. Such treatments may not, of course, reduce the non-specular reflectance to the desired low value but have been found in practice to serve adequately under the circumstances.

7.8 OPERATIONAL RESULTS

Numerous informal reports of the successful operational use of Black Widow camouflage reached Section headquarters. In the opinion of the Section, the evolution of this camouflage measure was its most important contribution to the war effort. If commonly quoted figures regarding the cost of a bomber and its crew are multiplied by the number of bombers which appear to have been saved, the total expenditures by the Camouflage Section are dwarfed to the point of insignificance. After taking account of the saving in the lives of bomber crews and of the possible increase in bombing efficiency which resulted from the use of the Black Widow finish, Section 16.3 of NDRC has come to feel a deep sense of pride in the development of this camouflage measure.

APPENDIX A

Values of the liminal contrast of circular targets as read from a large-scale plot of Figure 35, Chapter 3. The various values of the angular subtense of the target were chosen to facilitate the preparation of the nomographic visibility charts.

Angular subtense of target (minutes)	LIMINAL CONTRAST (FOOT-LAMBERTS)								
	1,000	100	10	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
358.9	0.00272	0.00272	0.00277	0.00334	0.00534		0.0303	0.0624	0.136
340.4	0.00272	0.00272	0.00277	0.00334	0.00536	0.0112	0.0308	0.0637	0.140
340.0	0.00272	0.00272	0.00277	0.00334	0.00537	0.0112	0.0308	0.0638	0.140
323.0	0.00272	0.00272	0.00277	0.00335	0.00539	0.0114	0.0314	0.0652	0.144
302.6	0.00272	0.00272	0.00277	0.00335	0.00542	0.0116	0.0320	0.0664	0.147
293.6	0.00272	0.00272	0.00277	0.00335	0.00544	0.0117	0.0325	0.0678	0.151
291.8	0.00272	0.00272	0.00277	0.00335	0.00544	0.0117	0.0326	0.0679	0.152
280.9	0.00272	0.00272	0.00278	0.00335	0.00547	0.0119	0.0330	0.0690	0.155
269.2	0.00272	0.00272	0.00278	0.00335	0.00556	0.0120	0.0335	0.0703	0.159
258.4	0.00272	0.00272	0.00278	0.00335	0.00553	0.0121	0.0340	0.0716	0.164
255.3	0.00272	0.00272	0.00278	0.00335	0.00553	0.0122	0.0341	0.0720	0.164
234.9	0.00272	0.00272	0.00278	0.00336	0.00558	0.0124	0.0352	0.0748	0.172
226.9	0.00272	0.00272	0.00278	0.00336	0.00562	0.0126	0.0356	0.0760	0.176
215.3	0.00272	0.00272	0.00278	0.00336	0.00565	0.0128	0.0364	0.0780	0.182
204.3	0.00272	0.00272	0.00279	0.00336	0.00569	0.0129	0.0370	0.0800	0.188
198.8	0.00272	0.00272	0.00279	0.00337	0.00570	0.0130	0.0376	0.0811	0.191
185.7	0.00272	0.00272	0.00279	0.00338	0.00575	0.0133	0.0386	0.0840	0.200
184.6	0.00272	0.00272	0.00279	0.00338	0.00577	0.0133	0.0386	0.0842	0.201
172.3	0.00273	0.00273	0.00279	0.00339	0.00581	0.0136	0.0398	0.0875	0.210
170.2	0.00273	0.00273	0.00279	0.00339	0.00582	0.0136	0.0401	0.0880	0.212
161.5	0.00273	0.00273	0.00279	0.00340	0.00588	0.0138	0.0410	0.0907	0.220
157.1	0.00273	0.00273	0.00279	0.00340	0.00589	0.0140	0.0415	0.0922	0.224
152.0	0.00274	0.00274	0.00279	0.00340	0.00593	0.0141	0.0422	0.0940	0.230
145.9	0.00274	0.00274	0.00279	0.00341	0.00596	0.0143	0.0430	0.0963	0.237
143.6	0.00274	0.00274	0.00279	0.00341	0.00597	0.0144	0.0434	0.0973	0.240
138.2	0.00274	0.00274	0.00279	0.00342	0.00603	0.0146	0.0446	0.101	0.250
136.0	0.00274	0.00274	0.00280	0.00342	0.00605	0.0146	0.0446	0.101	0.250
129.2	0.00275	0.00275	0.00280	0.00343	0.00608	0.0149	0.0459	0.104	0.259
127.7	0.00275	0.00275	0.00280	0.00343	0.00608	0.0150	0.0461	0.104	0.263
120.1	0.00275	0.00275	0.00280	0.00344	0.00615	0.0153	0.0476	0.109	0.274
117.5	0.00276	0.00276	0.00280	0.00345	0.00617	0.0154	0.0482	0.110	0.280
113.5	0.00276	0.00276	0.00280	0.00345	0.00621	0.0156	0.0493	0.113	0.287
107.7	0.00276	0.00276	0.00281	0.00347	0.00627	0.0159	0.0508	0.118	0.301
107.5	0.00277	0.00277	0.00281	0.00347	0.00627	0.0160	0.0508	0.118	0.301
102.1	0.00277	0.00277	0.00281	0.00348	0.00634	0.0163	0.0523	0.122	0.315
99.38	0.00277	0.00277	0.00281	0.00349	0.00638	0.0165	0.0530	0.125	0.323
97.26	0.00277	0.00277	0.00281	0.00349	0.00639	0.0166	0.0540	0.127	0.328
92.84	0.00278	0.00278	0.00282	0.00351	0.00646	0.0169	0.0554	0.131	0.343
92.29	0.00278	0.00278	0.00282	0.00351	0.00646	0.0169	0.0562	0.132	0.344
88.80	0.00278	0.00278	0.00282	0.00352	0.00652	0.0172	0.0572	0.136	0.356
86.[illegible]	0.00278	0.00278	0.00283	0.00352	0.00656	0.0175	0.0581	0.139	0.366
85.10	0.00278	0.00278	0.00283	0.00352	0.00659	0.0176	0.0586	0.140	0.371
81.70	0.00279	0.00279	0.00283	0.00353	0.00664	0.0179	0.0605	0.145	0.386
80.75	0.00279	0.00279	0.00284	0.00355	0.00667	0.0180	0.0607	0.146	0.389
76.00	0.00279	0.00279	0.00284	0.00358	[illegible]	0.0184	0.0632	0.151	[illegible]
74.28	0.00279	0.00279	0.00284	0.00358	0.00679	0.0187	0.0645	0.157	0.422
71.78	0.00280	0.00280	0.00285	0.00360	0.00685	0.0190	0.0658	0.162	0.436
68.08	0.00280	0.00280	0.00286	0.00361	0.00698	0.0194	0.0684	0.169	0.462
68.00	0.00280	0.00280	0.00286	0.00361	0.00698	0.0195	0.0686	0.170	0.462
64.60	0.00281	0.00281	0.00286	0.00365	0.00705	0.0200	0.0710	0.177	[illegible]
62.85	0.00281	0.00281	0.00287	0.00366	0.00710	0.0202	0.0725	0.182	0.501
58.73	0.00282	0.00282	0.00289	0.00369	0.00724	0.0209	0.0764	0.194	0.537
58.36	0.00282	0.00282	0.00289	0.00369	0.00725	0.0210	0.0767	0.194	0.541
54.47	0.00284	0.00284	0.00290	0.00374	0.00741	0.0218	0.0809	0.208	0.583

Angular subtense of target (minutes)	LIMINAL CONTRAST (FOOT-LAMBERTS)								
	1,000	100	10	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
53.83	0.00284	0.00284	0.00290	0.00374	0.00743	0.0220	0.0818	0.216	0.591
51.06	0.00285	0.00285	0.00292	0.00378	0.00756	0.0225	0.0850	0.222	0.627
49.69	0.00286	0.00286	0.00293	0.00380	0.00763	0.0229	0.0874	0.228	0.649
48.06	0.00286	0.00286	0.00294	0.00382	0.00771	0.0233	0.0897	0.236	0.673
46.14	0.00287	0.00287	0.00295	0.00385	0.00782	0.0238	0.0926	0.246	0.708
45.39	0.00288	0.00288	0.00296	0.00386	0.00785	0.0240	0.0940	0.250	0.721
43.07	0.00290	0.00290	0.00298	0.00390	0.00802	0.0247	0.0982	0.265	0.767
43.00	0.00290	0.00290	0.00298	0.00390	0.00802	0.0249	0.0984	0.265	0.768
40.85	0.00292	0.00292	0.00301	0.00394	0.00815	0.0256	0.103	0.280	0.818
40.38	0.00292	0.00292	0.00301	0.00395	0.00820	0.0258	0.104	0.283	0.831
38.00	0.00294	0.00294	0.00304	0.00402	0.00840	0.0267	0.110	0.293	0.896
37.14	0.00295	0.00295	0.00305	0.00404	0.00845	0.0271	0.112	0.312	0.925
36.91	0.00295	0.00295	0.00306	0.00405	0.00848	0.0272	0.113	0.314	0.930
35.89	0.00296	0.00296	0.00307	0.00407	0.00857	0.0277	0.116	0.324	0.937
34.04	0.00299	0.00299	0.00310	0.00413	0.00876	0.0286	0.122	0.344	1.04
34.00	0.00299	0.00299	0.00310	0.00413	0.00881	0.0287	0.122	0.345	1.04
32.30	0.00302	0.00302	0.00313	0.00420	0.00895	0.0297	0.128	0.367	1.12
31.42	0.00304	0.00304	0.00314	0.00422	0.00904	0.0302	0.131	0.380	1.16
30.76	0.00305	0.00305	0.00316	0.00425	0.00913	0.0306	0.134	0.389	1.20
29.36	0.00307	0.00307	0.00320	0.00432	0.00933	0.0316	0.141	0.412	1.28
29.18	0.00308	0.00308	0.00321	0.00432	0.00934	0.0317	0.142	0.416	1.30
28.71	0.00309	0.00309	0.00321	0.00434	0.00942	0.0321	0.144	0.425	1.33
28.09	0.00310	0.00310	0.00323	0.00438	0.00954	0.0326	0.148	0.436	1.37
27.23	0.00312	0.00312	0.00327	0.00442	0.00966	0.0332	0.153	0.454	1.44
26.92	0.00313	0.00313	0.00327	0.00444	0.00970	0.0335	0.154	0.460	1.46
25.84	0.00316	0.00316	0.00330	0.00452	0.00991	0.0346	0.161	0.486	1.56
25.59	0.00316	0.00316	0.00331	0.00453	0.00991	0.0348	0.163	0.494	1.58
24.03	0.00321	0.00321	0.00337	0.00462	0.0103	0.0364	0.175	0.537	1.74
23.49	0.00323	0.00323	0.00340	0.00469	0.0104	0.0371	0.179	0.555	1.80
22.69	0.00326	0.00326	0.00344	0.00474	0.0106	0.0381	0.186	0.581	1.91
21.53	0.00330	0.00330	0.00350	0.00485	0.0110	0.0397	0.198	0.625	2.07
21.50	0.00330	0.00330	0.00350	0.00486	0.0110	0.0398	0.199	0.628	2.09
20.43	0.00335	0.00335	0.00357	0.00499	0.0113	0.0414	0.211	0.676	2.27
19.88	0.00337	0.00337	0.00361	0.00506	0.0115	0.0423	0.218	0.703	2.38
18.57	0.00344	0.00344	0.00371	0.00524	0.0120	0.0449	0.237	0.731	2.68
18.46	0.00345	0.00345	0.00371	0.00526	0.0120	0.0452	0.239	0.787	2.71
17.23	0.00352	0.00352	0.00383	0.00547	0.0126	0.0470	0.262	0.877	3.08
17.02	0.00354	0.00354	0.00386	0.00551	0.0127	0.0485	0.266	0.891	3.15
16.15	0.00360	0.00360	0.00395	0.00569	0.0132	0.0508	0.286	0.972	3.44
15.71	0.00364	0.00361	0.00401	0.00581	0.0135	0.0522	0.297	1.02	3.64
15.20	0.00368	0.00368	0.00409	0.00593	0.0138	0.0540	0.312	1.08	3.89
14.59	0.00374	0.00370	0.00417	0.00611	0.0143	0.0562	0.330	1.15	4.21
14.30	0.00376	0.00372	0.00420	0.00618	0.0144	0.0571	0.337	1.19	4.34
13.62	0.00384	0.00382	0.00434	0.00643	0.0151	0.0604	0.365	1.30	4.83
13.60	0.00384	0.00382	0.00436	0.00644	0.0152	0.0605	0.366	1.30	4.84
12.92	0.00392	0.00391	0.00449	0.00668	0.0158	0.0639	0.393	1.43	5.36
12.77	0.00394	0.00394	0.00453	0.00678	0.0160	0.0649	0.401	1.46	5.47
12.09	0.00406	0.00407	0.00473	0.00713	0.0170	0.0696	0.439	1.64	6.18
11.75	0.00410	0.00412	0.00481	0.00726	0.0172	0.0713	0.455	1.71	6.47
11.67	0.00411	0.00413	0.00484	0.00733	0.0174	0.0719	0.460	1.73	6.52
11.35	0.00417	0.00419	0.00493	0.00750	0.0179	0.0742	0.480	1.82	6.93
10.77	0.00430	0.00434	0.00518	0.00791	0.0189	0.0794	0.522	2.03	7.73
10.75	0.00430	0.00436	0.00520	0.00792	0.0189	0.0796	0.524	2.03	7.71
10.21	0.00443	0.00450	0.00542	0.00836	0.0200	0.0847	0.569	2.24	8.55
9.938	0.00451	0.00460	0.00558	0.00861	0.0206	0.0879	0.593	2.37	9.01
9.726	0.00456	0.00468	0.00572	0.00883	0.0212	0.0904	0.616	2.47	9.45
9.284	0.00470	0.00485	0.00598	0.00931	0.0224	0.0965	0.667	2.71	10.3
9.229	0.00472	0.00489	0.00603	0.00940	0.0226	0.0969	0.674	2.74	10.5
9.078	0.00478	0.00494	0.00612	0.00954	0.0231	0.0988	0.692	2.82	10.8

Angular subtense of target (minutes)	LIMINAL CONTRAST (FOOT-LAMBERTS)								
	1,000	100	10	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
8.880	0.00485	0.00506	0.00629	0.00984	0.0237	0.102	0.720	2.95	11.4
8.613	0.00496	0.00519	0.00649	0.0103	0.0248	0.107	0.758	3.13	12.0
8.510	0.00500	0.00525	0.00659	0.0104	0.0251	0.108	0.774	3.21	12.3
8.170	0.00518	0.00544	0.00696	0.0110	0.0266	0.116	0.828	3.49	13.4
8.075	0.00522	0.00552	0.00703	0.0112	0.0272	0.117	0.852	3.55	13.6
7.600	0.00550	0.00589	0.00763	0.0122	0.0298	0.129	0.956	4.[illegible]	15.5
7.[illegible]	0.00562	0.00605	0.00787	0.0126	0.0309	0.132	0.995	4.20	16.[illegible]
7.178	0.00579	0.00627	0.00824	0.0133	0.0327	0.140	1.06	4.49	17.3
6.808	0.00611	0.00673	0.00891	0.0145	0.0358	0.153	1.19	5.00	19.2
6.800	0.00611	0.00675	0.00892	0.0146	0.0359	0.154	1.19	5.01	19.3
6.460	0.00646	0.00720	0.00962	0.0158	0.0393	0.167	1.31	5.55	21.4
6.290	0.00657	0.00745	0.0100	0.0166	0.0413	0.175	1.38	5.82	22.6
5.873	0.00721	0.00824	0.0113	0.0188	0.0438	0.197	1.57	6.68	25.9
5.836	0.00728	0.00828	0.0113	0.0190	0.0472	0.199	1.66	6.76	26.2
5.447	0.00794	0.00923	0.0127	0.0216	0.0534	0.226	1.83	7.78	30.0
5.383	0.00807	0.00943	0.0130	0.0220	0.0546	0.230	1.88	7.97	30.7
5.106	0.00869	0.0102	0.0143	0.0243	0.0603	0.254	2.07	8.83	34.2
4.969	0.00906	0.0107	0.0149	0.0256	0.0639	0.268	2.19	9.35	36.1
4.806	0.00955	0.0114	0.0159	0.0275	0.0681	0.286	2.34	9.98	38.6
4.614	0.0101	0.0123	0.0171	0.0297	0.0736	0.309	2.55	10.80	41.9
4.539	0.0104	0.0126	0.0175	0.0307	0.0759	0.319	2.63	11.2	43.2
4.307	0.0114	0.0137	0.0193	0.0339	0.0840	0.354	2.93	12.4	47.9
4.300	0.0115	0.0138	0.0194	0.0339	0.0845	0.355	2.94	12.4	48.2
4.085	0.0124	0.0151	0.0213	0.0375	0.0933	0.391	3.26	13.8	53.5
4.038	0.0127	0.0154	0.0217	0.0383	0.0948	0.402	3.33	14.1	54.4
3.800	0.0140	0.0172	0.0244	0.0432	0.107	0.451	3.74	16.0	61.7
3.714	0.0146	0.0179	0.0255	0.0450	0.112	0.470	3.93	16.8	64.4
3.691	0.0148	0.0182	0.0257	0.0455	0.113	0.479	4.00	17.0	65.1
3.589	0.0156	0.0191	0.0272	0.0480	0.119	0.502	4.21	18.0	69.1
3.404	0.0171	0.0211	0.0301	0.0531	0.132	0.560	4.67	20.0	77.0
3.400	0.0171	0.0211	0.0302	0.0533	0.133	0.560	4.70	20.6	77.4
3.230	0.0187	0.0232	0.0333	0.0580	0.147	0.617	5.19	22.2	85.4
3.142	0.0196	0.0243	0.0350	0.0622	0.154	0.653	5.47	23.3	89.6
3.076	0.0203	0.0253	0.0364	0.0645	0.161	0.678	5.72	24.4	94.1
2.936	0.0221	0.0276	0.0397	0.0706	0.177	0.746	6.27	26.9	103
2.918	0.0222	0.0277	0.0403	0.0716	0.178	0.752	6.35	27.2	104
2.871	0.0229	0.0287	0.0414	0.0736	0.184	0.776	6.55	28.0	108
2.809	0.0237	0.0298	0.0432	0.0770	0.192	0.814	6.84	29.2	113
2.723	0.0251	0.0316	0.0461	0.0818	0.204	0.863	7.26	31.3	120
2.[illegible]	0.0257	0.0322	0.0471	0.0838	0.207	0.886	7.40	31.9	122
2.584	0.0277	0.0348	0.0508	0.0910	0.226	0.964	8.13	34.8	133
2.553	0.0283	0.0355	0.0519	0.0920	0.231	0.977	8.30	35.4	136
2.403	0.0313	0.0398	0.0583	0.104	0.260	1.11	9.34	40.0	154
2.349	0.0328	0.0413	0.0607	0.109	0.272	1.18	9.75	42.0	161
2.260	0.0350	0.0442	0.0652	0.116	0.291	1.25	10.5	44.9	173
2.153	0.0384	0.0488	0.0718	0.129	0.321	1.38	11.7	49.9	192.0
2.150	0.0384	0.0480	0.0721	0.130	0.322	1.39	11.7	50.0	193.0
2.043	0.0423	0.0538	0.0794	0.143	0.355	1.53	12.9	55.5	213
1.968	0.0444	0.0566	0.0838	0.150	0.370	1.61	13.6	58.3	225
1.857	0.0502	0.0644	0.0954	0.171	0.430	1.85	15.6	66.7	258
1.816	0.0509	0.0653	0.0964	0.173	0.432	1.88	15.8	67.6	261.0
1.723	0.0574	0.0749	0.110	0.198	0.496	2.15	18.1	77.0	299
1.702	0.0588	0.0757	0.113	0.202	0.507	2.20	18.5	79.4	306
1.615	0.0643	0.0840	0.125	0.224	0.562	2.44	20.6	88.1	340.0
1.571	0.0680	0.0882	0.132	0.236	0.594	2.59	21.8	93.3	361
1.520	0.0720	0.0944	0.14[illegible]	0.251	0.633	2.77	23.3	100.[illegible]	386
1.459	0.0776	0.101	0.152	0.272	0.68[illegible]	2.99	25.2	108	[illegible]
1.430	0.0796	0.105	0.157	0.281	0.7[illegible]	3.09	26.1	112	432
1.362	0.0877	0.116	0.174	0.311	0.7[illegible]	3.43	28.9	124	479

Angular subtense of target (minutes)	LIMINAL CONTRAST (FOOT-LAMBERTS)								
	1,000	100	10	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
1.360	0.0881	0.116	0.175	0.312	0.785	3.45	29.0	125.	480.
1.292	0.0966	0.128	0.193	0.345	0.868	3.82	32.2	138.	535.
1.277	0.0986	0.131	0.197	0.352	0.885	3.90	32.9		544
1.201	0.110	0.148	0.222	0.395	0.995	4.45	37.1		617.
1.175	0.115	0.151	0.232	0.413	1.05	4.58	38.7		643.
1.167	0.117	0.155	0.234	0.419	1.06	4.63	39.3		652.
1.135	0.123	0.164	0.248	0.442	1.12	4.91	41.4		687.
1.077	0.135	0.182	0.274	0.491	1.24	5.48	46.6		766.
1.075	0.136	0.182	0.275	0.492	1.25	5.50	46.2		770
1.021	0.149	0.200	0.304	0.542	1.38	6.09	51.3		851.
0.9938	0.157	0.210	0.319	0.572	1.45	6.41	53.6		893.
0.9726	0.162	0.219	0.333	0.596	1.52	6.67	59.1		941.
0.9284	0.177	0.239	0.364	0.652	1.66	7.33	61.6		1030.
0.9229	0.180	0.242	0.368	0.662	1.68	7.41	62.4		1042.
0.9078	0.185	0.250	0.381	0.682	1.74	7.66	69.5		1080.
0.8880	0.192	0.260	0.395	0.714	1.82	7.98	67.4		1130.
0.8613	0.203	0.277	0.420	0.758	1.93	8.40	71.2		
0.8510	0.209	0.284	0.432	0.776	1.98	8.70	73.3		
0.8170	0.225	0.306	0.463	0.841	2.14	9.44	79.4		1330
0.8075	0.232	0.313	0.476	0.859	2.26	9.60	81.3		
0.7600	0.258	0.352	0.538	0.967	2.48	11.0	92.0		
0.7428	0.271	0.367	0.562	1.01	2.61	11.5	96.2		
0.7178	0.290	0.392	0.598	1.08	2.79	12.4	104		
0.6808	0.325	0.434	0.664	1.20	3.10	13.8	116		
0.6800	0.322	0.436	0.667	1.22	3.12		116.		
0.6400	0.355	0.480	0.740	1.34	3.43		129		
0.6285	0.374	0.512	0.783	1.41	3.64		136.		
0.5973	0.429	0.582	0.898	1.61	4.16				
0.5836	0.432	0.586	0.912	1.64	4.21				
0.5447	0.497	0.676	1.04	1.88	4.82				
0.5383	0.507	0.692	1.07	1.92	4.96				
0.5106	0.562	0.766	1.19	2.14	5.45				
0.4969	0.596	0.807	1.26	2.26	5.77				
0.4806	0.637	0.871	1.34	2.42	6.16				
0.4614	0.687	0.935	1.46	2.62	6.68				
0.4539	0.714	0.975	1.50	2.71	6.92				
0.4307	0.787	1.08	1.67	3.01	7.67				
0.4300	0.793	1.08	1.68	3.01	7.74				
0.4085	0.881	1.20	1.85	3.34	8.52				
0.4038	0.902	1.23	1.90	3.42	8.70				
0.3800	1.02	1.38	2.14	3.85	9.86				
0.3714	1.06	1.44	2.24	[illegible]	10.1				
0.3691	1.08	1.46	2.27	4.09	10.5				
0.3589	1.14	1.55	2.40	4.32	11.1				
0.3401	1.28	1.73	2.68	4.82	12.4				
0.3400	1.28	1.73	2.68	4.83	12.4				
0.3230	1.40	1.91	2.96	5.31	13.7				
0.3142	1.49	2.02	3.14	5.62					
0.3076	1.55	2.11	3.26	5.85					
0.2936	1.70	2.32	3.58	6.43					
0.2918	1.73	2.33	3.63	6.53					
0.2871	1.77	2.42	3.76	[illegible]					
0.2809	1.86	2.54	3.91	7.02					
0.2723	1.99	2.69	4.17	7.50	19.3				
0.2602	2.03	2.78	4.27	7.67					
0.2584	2.10	2.98	4.63	8.32					
0.2553	2.25	3.07	4.71	8.55					
0.2403	2.52	3.43	5.36	9.55					
0.2349	2.66	3.62	5.60	10.0					

Angular subtense of target (minutes)	LIMINAL CONTRAST (FOOT-LAMBERTS) 1,000	100	10	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
0.2269	2.86	3.88	6.01	10.8					
0.2153	3.16	4.28	6.68	12.0					
0.2150	3.19	4.32	6.68	12.0					
0.2043	3.53	4.78	7.40	13.3					
0.1988	3.72	5.04	7.81	14.1					
0.1857	4.26	5.76	8.97						
0.1846	4.32	5.82	9.66						
0.1723	4.96	6.67	10.3						
0.1702	5.08	6.86	10.6						
0.1615	5.62	7.62	11.9						
0.1571	5.96	8.04	12.5						
0.1520	6.38	8.61	13.4						
0.1459	6.91	9.31	14.5						
0.1436	7.14	9.66							
0.1362	7.74	10.7							
0.1360	7.75	10.7							
0.1292	8.83	11.9							

GLOSSARY

AAFTAC. Army Air Forces Tactical Air Center.

ACHROMATIC COLOR. White, gray, or black.

AD HOC COMMITTEE. A fact-finding committee whose existence terminated automatically after its report had been made.

ADAPTATION. Process by which the eye achieves optimum perceptual capacity for a given set of lighting conditions.

ADAPTATION LEVEL. The brightness of a uniform field of view to which the eye attains a given state of adaptation.

APPARENT CONTRAST. The contrast of an object as it appears to a distant observer.

ASDEVLANT. Anti-Submarine Development Detachment, Air Force, U. S. Atlantic Fleet.

AVERAGE REFLECTANCE. The reflectance of a uniform surface perpendicular to the line of sight at the target having a contrast against the sky equal to the integrated contrast of the target.

β. Atmospheric attenuation coefficient. (Typical unit: reciprocal meters.)

BLACK WIDOW FINISH. Antisearchlight camouflage for aircraft described in Chapter 7. (Origin of code name: first used on P61, Black Widow nightfighters.)

BOWDITCH'S RULE. "The distance from an observer to the horizon, expressed in miles, equals the square root of 3/2 the height of the observer's eye above the sea measured in feet."

$$\left[D = \sqrt{\frac{3}{2}H}\right].$$

(This rule is based upon trigonometric approximations which render its predictions inaccurate except for small values of H.)

BUAER. Bureau of Aeronautics, U. S. Navy.

BUORD. Bureau of Ordnance, U. S. Navy.

BUSHIPS. Bureau of Ships, U. S. Navy.

CHROMATIC COLOR. A color other than white, gray, or black.

CHROMATIC CONTRAST. Color contrast.

CHROMATICITY. Those properties of a color described by its dominant wavelength and purity.

COFFIN PAINT. Matte black paint of exceptionally low diffuse reflectance, developed under Contract OEMsr-997. (Origin of name: A substitute for "coffin paper" produced originally for coffin manufacturers but used as an antireflection lining for high-grade optical instruments.)

COLOR CONTRAST. Departure in chromaticity of a target from its background.

CONTAINED SHADOW. A black area within the outline of a ship or plane produced by the shadow of some overhanging structure.

CONTRAST. The fractional difference in brightness between an object and its background.

COUNTER SHADING. A method of camouflage painting whereby the reflectance is graded in a manner inversely related to the illumination of the surface. In general, dark paint is used on upper surfaces and light paint is used on under surfaces.

CRITICAL POINT. The point of closest approach along the path of flight of a bomber to its target at which the bombardier must be able to see the target in order to drop the bomb on it.

DAYLIGHT VISUAL RANGE. That distance at which a large dark object on the horizon is just recognizable against the sky background.

DEMAGNIFICATION. A reduction in the apparent size of objects. (Example: The effect of a telescope looked through in reverse direction.)

DENSITOMETER. Apparatus for measuring the transmittance or "density" of a photographic film.

DENSITY (PHOTOGRAPHIC). A measure of the blackness of a photographic film. (Quantitative definition: Density = $\log_{10}$ 1/transmittance.)

DENSITY (PHYSICAL). Mass per unit volume. (Typical unit: kilograms per cubic meter.)

DESATURATION. Reduction in purity.

DIFFUSE REFLECTION. Light reflected in all directions (as by a sheet of blotting paper).

DOMINANT WAVELENGTH (OF A COLOR). The wavelength of that monochromatic light which, when mixed in proper proportion with white light, will match the chromaticity of the sample.

E A C. Equivalent achromatic contrast.

EFFECTIVE INHERENT CONTRAST. The inherent contrast of a uniform target of the same size and shape as a given nonuniform target having the same liminal target distance.

EFFECTIVE PROJECTED TARGET AREA. (See Section [illegible].)

EQUIVALENT ACHROMATIC CONTRAST. That brightness contrast which produces the same acuity as a color contrast (see Section 3.3).

MATTING AGENT. A material added to paint in order to produce a matte surface. (Example: asbestine.)

Foot-lambert. A unit of brightness. One foot-lambert is the brightness of a perfectly diffusing surface emitting or reflecting one lumen per square foot.

Form Factor. The ratio of the liminal contrast of a noncircular target to the liminal contrast of a circular target of equal area.

Glomb. A bomb-carrying, remote-control glider.

Goniophotometer. A laboratory instrument for measuring the reflectance of materials for any angle of incidence and observation.

Goniophotometric Curve. A plot of the readings of a goniophotometer over a range of angles of incidence or observation.

Gonioreflectance. The reflecting properties of a surface as defined by a goniophotometric curve.

Gray Scale. A graded series of gray panels of known reflectance.

Haze Box. A viewing device capable of simulating the effect of atmospheric haze.

High Level. Photopic brightness level.

I.C.I. International Commission on Illumination.

Illumination Ratio. Term sometimes used as a synonym for sun-ratio.

Infrared. In this volume the term "infrared" has been used to denote that portion of the electromagnetic spectrum having wavelengths longer than visible light, but short enough to be detected by infrared Aero film (700 to 950 millimicrons).

Inherent Contrast. The contrast of an object as seen nearby.

Inherent Integrated Contrast. Integrated contrast of a target seen nearby.

Inherent Internal Contrast. Internal contrast of a target as seen nearby.

Integrated Contrast. An average of the internal contrasts of a patterned target weighted in accordance with the area of the pattern elements.

Internal Contrast. Contrast between parts of a patterned target.

Ishihara Test. A common test for color blindness.

J.O.S.A. Journal of the Optical Society of America.

Landolt Ring. A broken ring pattern.

Lapse Rate. The variation of temperature with altitude.

LBE. Glide bomb Pratt-Read ("Glomb").

LBT. Glide bomb Taylorcraft ("Glomb").

Liberator. Four-motored U.S. bomber (Army: B-24. Navy: PB4Y).

Liminal Contrast. Value of contrast for which the probability of an observer making a correct response is 50 per cent greater than chance.

Liminal Target Distance. That distance at which a target is visually detectable with a probability 50 per cent greater than chance.

Low Level. Scotopic brightness level.

Meteorological Range. That horizontal distance for which the transmittance of the atmosphere is 2 per cent (see Section 22.5).

Microdensitometer. Apparatus for measuring the density of very small areas of a photographic film.

Monochromatic Light. A narrow band from the visible spectrum within which the range of wavelength is so small that the physical phenomena under consideration show no significant wavelength dependence.

Munsell Paper. Special colored papers sold by the Munsell Color Company, Baltimore, Maryland, for use as color standards.

Nomographic Charts. (Synonym: alignment charts). Charts in which the relation between three or more variables are expressed by a series of scales and lines so arranged that an unknown value of one of the variables can be determined from known values of the others by establishing one or more straight lines across the chart.

Optical Equilibrium. (See Section 22.1.)

Optical Slant Range. (See Section 22.3.)

Optically Homogeneous Atmosphere. An atmosphere wherein β, σ, and ρ have the same values at all points along the line of sight.

Ostwald Paper. Papers the colors of which were specified in the Ostwald color notation.

PBM. Patrol bomber Martin.

P.D.P. Passive Defense Project, Work Projects Administration, Project No. 22292.

Photopic. Pertaining to the properties of the human eye when adapted to full daytime levels of brightness.

Purity (of a Color). A measure of the proportion in which white light and monochromatic light of the dominant wavelength must be mixed in order to match the chromaticity of the color. Achromatic [illegible] purity. Monochromatic light is considered 100 per cent pure.

Purkinje Effect. Shift in the spectral sensitivity of the human eye at reduced levels of brightness. (See "Principles of Optics," Hardy and Perrin, p. [illegible].)

η Luminous density (see Section 23.2). (Typical unit: [illegible] per cubic meter.)

Reflectance. Ratio of the light reflected by an object to the light incident upon it.

Sky-Ground Ratio. The ratio of the brightness of the sky in particular directions (see Figure 17, Chapter 2) to the brightness of the ground (see Section 2.3.5).

Slant Range. The distance from an aircraft to its target along a slanting path of sight.

Snellen-type. Typical test chart used by oculists.

Solar Altitude. The angular elevation of the sun above the horizon.

Solar Depression. The negative of solar altitude. After sunset, values of solar depression are positive, since solar altitude assumes negative values.

Spectral Reflectance. Reflectance in terms of monochromatic light.

Specular Reflection. The mirror-like reflection from a smooth surface.

Spectrograph. A spectrograph for aerial use in determining the reflectance of natural terrains and the optical properties of the atmosphere (see Chapter 6).

Spectrophotometer. Laboratory instrument for measuring the reflectance of materials, wave length by wave length.

Spot Track. Imaginary circle of fixed diameter around which targets were presented by projection during the disposition experiments at the Tiffany Foundation.

Standard Atmosphere. (See Section 2.3.2.)

Sun-Ratio. The ratio of the illumination on a vertical surface facing the sun to the illumination on a vertical surface facing away from the sun.

Target Point. The point on a nomographic visibility chart which is determined by the effective projected target area and the optical slant range from the target to the critical point.

Telephotometer. A photometer for measuring the apparent brightness of distant objects.

Tone Down. Camouflage accomplished by giving the target a dark color.

Tone Down Limit. The greatest value of meteorological range for which a target can be concealed from an observer at the critical point by tone down measures.

Transmissometer. An apparatus for measuring the transmittance of the atmosphere.

Transmittance. Ratio of the light transmitted by an object to the light incident upon it.

Troffer. A trough containing lamps.

Variac. Trade name for an auto-transformer having an adjustable voltage output.

"Visibility." See Section 2.2.5.

Yehudi. Code name for use in unclassified correspondence concerning the camouflage of aircraft by means of beams of light projected into the eyes of the enemy.

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CONTRACT NUMBERS, CONTRACTORS, AND SUBJECTS OF CONTRACTS FOR SECTION 16.3

Contract No.	*Contractor*	*Subject*
OEMsr-551	Harvard University, Cambridge, Massachusetts	". . . studies and investigations in connection with the extraction of chlorophyll from plant sources and its use as a pigment. . . ."
OEMsr-597	Trustees of the Louis Comfort Tiffany Foundation, Oyster Bay, Long Island, New York	". . . perform certain camouflage field studies. . . ."
OEMsr-697	Interchemical Corporation, New York, New York	". . . studies and investigations of characteristics of camouflage paints, develop noncritical substitutes, improve and simplify procedure in field practice, and develop and construct such special apparatus as may be requested by the Contracting Officer or an authorized representative, for use in camouflage field studies. . . ."
OEMsr-717	Eastman Kodak Company, Rochester, New York	". . . studies and experimental investigations in connection with the design and construction of an instrument and the development of techniques for its use in measuring the quantity and spectral quality of radiant energy from natural daytime sources reaching an aeroplane during flight. . . ."
OEMsr-726	American Cyanamid Company, 30 Rockefeller Plaza, New York, New York	". . . studies and experimental investigations in connection with the camouflaging of stationary or slowly moving bodies of water by thin surface films. . . ."
OEMsr-1020	Cornell University, Ithaca, New York	". . . studies, experimental investigations, and field tests in connection with the uses of plants and plant materials in camouflage. . . ."
OEMsr-1070	Eastman Kodak Company, Rochester, New York	". . . conduct a quantitative study of the effect on visibility of differences in chromaticity. . . ."
OEMsr-1459	Pratt, Read & Company, Inc., Deep River, Connecticut	". . . studies and experimental investigations in connection with the design and installation on a Navy LBE aircraft of special camouflage equipment. . . ."

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Office of the Executive Secretary, OSRD, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Subject*
	Army Projects
AC-45	Development of Equipment for Rendering an Aircraft Less Visible to an Observer on the Surface of the Earth
CE-24	Fundamental Optics
CE-25	Paints and Pigments
CE-26	Color Transients
	Navy Projects
NA-188	Yehudi
NS-147	Ship Camouflage

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INDEX

The subject indexes of all STR volumes are combined in a master index printed in a separate volume. For access to the index volume consult the Army or Navy Agency listed on the reverse of the half-title page.

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Research and development activity of Committee on Camouflage is presented with primary consideration given to protection of offensive weapons. Development of chlorophyll paint, color transients, water surface camouflage, camouflage paint, camouflage detection, ship camouflage, " Yehudi Project" , and visibility of targets are discussed. " Yehudi" project involves installation of headlights along front of airplane which renders the aircraft invisible. " Black Widow" is a paint which makes an airplane invisible in a searchlight beam.

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DIVISION: ~~Military Operations (24)~~ 3

SECTION: Strategy and ~~Tactics (6)~~ 18

SUBJECT HEADINGS: Camouflage (21315); Paints, Camouflage (68742.82); Ships - Camouflage (86193.8); Visibility - Effect of color contrast (97160)

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