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CAMOUFLAGE OF SEA-SEARCH AIRCRAFT

(The Yehudi Project)

Prepared by

The Louis Comfort Tiffany Foundation

Oyster Bay, Long Island, N. Y.

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It is a matter of established policy within the OSRD organization to use a short code name or symbol when referring to classified projects in unclassified correspondence. "YEHUDI" was selected as the code name for this project. For the benefit of those unfamiliar with this neologism, Yehudi symbolizes, in contemporary slang, "the little man who wasn't there."

CAMOUFLAGE OF SEA-SEARCH AIRCRAFT

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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 thirty seconds of flying time.

FOREWORD

This project was undertaken at the request of Brigadier General Harold M. McClelland, then Director of Technical Services of the Army Air Forces. It was first discussed with General McClelland, informally, on September 17, 1942, in a conference arranged by Dr. E. L. Bowles of the Office of the Secretary of War, at which Dr. A. C. Hardy (Chief) and Dr. S. Q. Duntley (Technical Aide) represented the Camouflage Section of the NDRC.

The problem posed by General McClelland was the suppositious case of a sea-search aircraft which detects the presence of a surfaced submarine in the daytime by radar at such a range that the aircraft would presumably not have been sighted by the submarine. It was hoped that some appropriate camouflage measure might enable the aircraft to approach as close as two miles before being sighted by the watch on the deck of the submarine. Such an approach would ordinarily enable the aircraft to release its depth charges before the submarine could execute a crash dive.

General McClelland was informed that even a white airplane will ordinarily be seen as a dark silhouette against a sky background. He was also informed 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. General McClelland indicated that the plane could be ordered to fly any required tactical course; and he suggested that it be assumed, as a basis of calculation, that the airplane can be held on 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 could be made to match ordinary sky backgrounds with a power consumption of less than 500 watts. The conference adjourned after General McClelland had been assured that the Camouflage Section would make arrangements for an experimental determination of the possibilities of this camouflage measure.

The investigation of the principles underlying this camouflage measure was immediately assigned to the Tiffany Foundation at Oyster Bay, New York, where an OSRD contract for camouflage field studies was already in force. To demonstrate the principle, a black-painted board 2 inches wide was equipped with flash-light bulbs at intervals of 4 inches along its face. This board was mounted in a horizontal position on a roof where, when observed against the sky from a distance of 900 feet, it represented, approximately to scale, the appearance of a wing-section of a sea-search aircraft as seen from a submarine two miles away. On September 26, 1942, a demonstration was arranged for General McClelland, who was accompanied by Generals Larson and Williams. The demonstration was quite successful in that, whereas the simulated wing-section was plainly silhouetted against the sky before the lights were turned on, it

vanished when the lights were adjusted to the proper intensity.

Immediately following this demonstration, a conference was held to consider the next step in the program. It was generally agreed that, whereas a full-scale demonstration was desirable, the use of an actual bomber in this connection would be fraught with many difficulties. It was finally decided that the next step should be to construct a silhouette representing the head-on aspect of a Liberator; to equip this silhouette with lights; and to suspend it from towers that would be erected on the top of a hill on the Tiffany estate. Maps of the region indicated that, by observing the silhouette from the shore on the opposite side of Oyster Bay, a visual range of two nautical miles could be secured over the water. General McClelland, on his return to Washington from this demonstration and conference, initiated a formal request for the project, which was assigned A/N Project Control Number AC-45.

By the end of January, the two steel towers had been erected, a plywood silhouette had been constructed, and several acres of woodland had been cleared to provide an unobstructed view from the observation point. The proper distribution and color of the lamps had been explored, both theoretically and experimentally; and engineering data had been secured on the amount of power required to match the brightness of any sky background. A number of demonstrations were then arranged for members of the Armed Forces and for NDRC personnel, the most successful of which was held on the afternoon of February 19, 1943. In the unusually clear atmosphere then prevailing, the full-scale model and the supporting towers stood out sharply against the sky background. However, when the lights on the silhouette were turned on, the model became invis-

ible to the observers at the Observation Post, two miles distant. Since the model with its wingspread of 110 feet occupied more than half the space between the two steel towers, the observers had the special advantage of knowing exactly where to look. Nevertheless they were unable to detect even the barest outline of the silhouette, although they could discern the one-inch steel cables that acted as guy-wires for the support of the towers.

At this stage, General McClelland issued orders that a Liberator be equipped with this camouflage measure at Wright Field. No further work appeared necessary at the Tiffany Foundation, but the equipment was kept intact for several months on the chance that unforeseen difficulties might be encountered in the course of the Army project. No such difficulties arose, however, and several flights were made at Wright Field during the month of May. The first flights were not successful demonstrations because of misalignment of the lamps. This was corrected; and a successful flight was made on a day when the sky was overcast. Later, on a clear day, the demonstration was not so successful because the lights did not match the blue of the sky. This difficulty was traced to the use of color filters whose spectral transmission characteristics were unlike those of the color filters used in the Tiffany experiments. Unfortunately, the airplane was damaged in landing after this flight; and it was sent to the hangar for repairs and for the installation of some newly developed anti-submarine devices. Although the Army's sea-search activities were turned over to the Navy in their entirety while the plane was still grounded, it is understood that the Army intends to investigate whether this camouflage measure has other fields of application.

Just prior to the time that sea-search activities came under the exclusive cognizance of the Navy, the Anti-Submarine Development Detachment, Air Forces, U. S. Atlantic Fleet, at the Naval Air Station, Quonset Point, Rhode Island, requested the advice of this Section on the design of appropriate camouflage measures for seaplanes of the PBM type. These plans were later modified to apply to the TBF type.

A TBF was equipped at the Naval Air Station during January, 1944, and a number of successful trial flights were made. In these flights, two identical planes flying side by side approached the observers over a pre-determined course. Although the conventional TBF was spotted at twelve miles, the Yehudi plane closed the range to three thousand yards before being observed. On the basis of these tests and the recommendation of ASDEVLANT, COMAIRLANT has ordered that a squadron of Avenger Torpedo planes (TBF) be equipped with Yehudi camouflage. Concurrently, the Navy Department has requested this Section to attempt a further reduction of the effective range of this camouflage measure for use in connection with a project of higher classification than that of this report.

Project AC-45, under which this program was initiated, has now been cancelled, inasmuch as the Navy now has cognizance over sea-search. This foreword introduces the report of the Tiffany Foundation on its activities under the original Army project control number.

Cambridge, Massachusetts
May 24, 1944.

Arthur C. Hardy,
Chief, NDRC Section 16.3.

I. PRELIMINARY EXPERIMENT

Pursuant to instructions issued by the Chief of Section 16.3 of the NDRC, the staff of the Tiffany Foundation started work, on the morning of September 18, 1942, on an experimental test 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, 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 pre-focused bulb operated at 2.4 volts and 0.5 amperes. Each bulb was fitted in 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 candlepower. This left a horizontal strip 1/4 inch

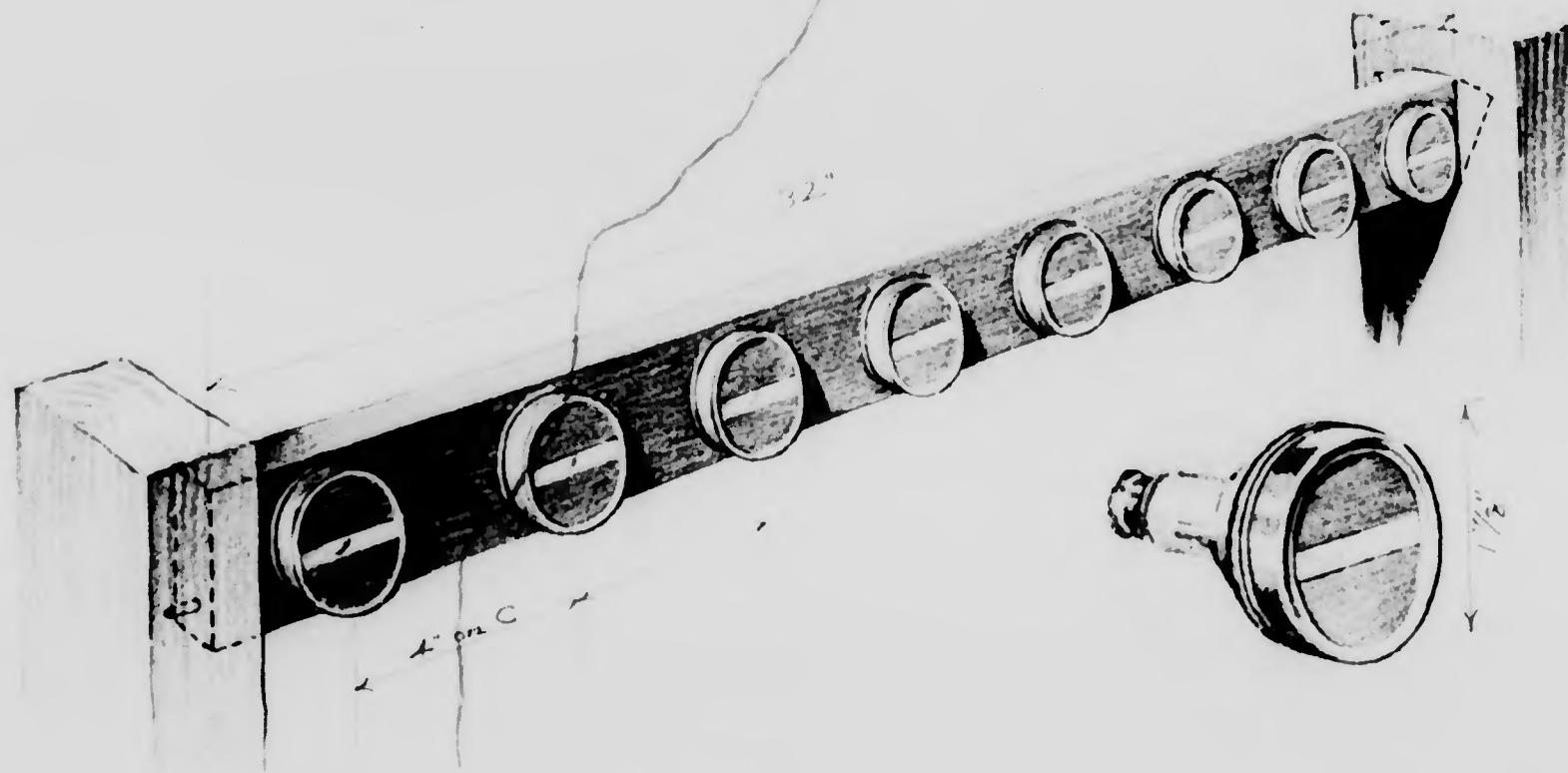


Figure 2 - Details of experiment designed to demonstrate the Yehudi principle.

wide by 1 3/4 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.

Demonstration of the Principle

A demonstration of the Yehudi principle was arranged at the Foundation for Brigadier Generals McClelland, Williams, and Larson on September 26, 1942. The "model" was fixed horizontally between two vertical supports, which were mounted on the roof of the studio building 50 feet above the ground level. The model 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. See Figure 3.

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 north sky. When the lamps were switched on, the model 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



Figure 3 - General view of experiment on roof as seen from observing station 900 feet distant.

to be erected on the estate, and to observe the effectiveness of the Yehudi principle from an observing station two nautical miles distant.

II. 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

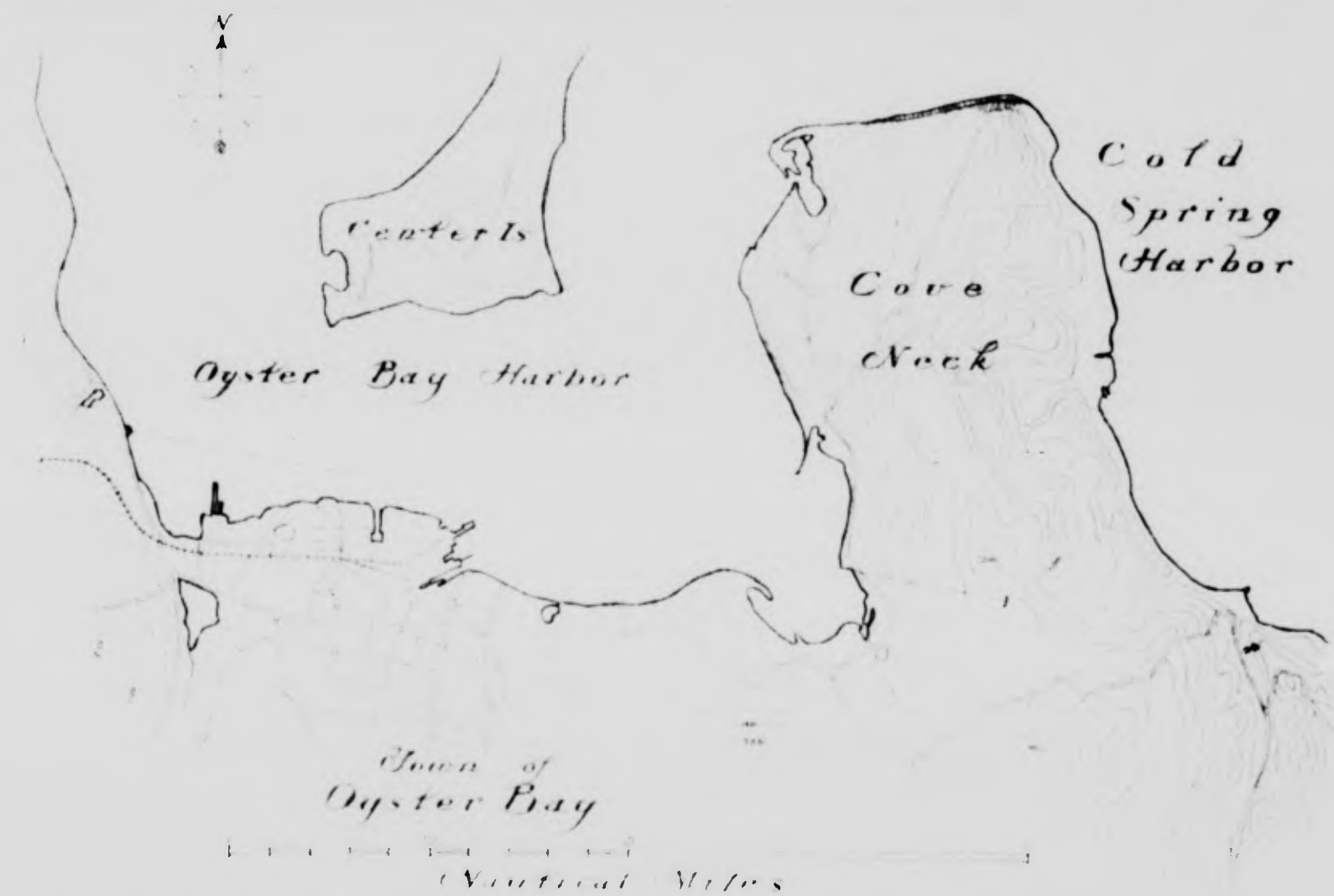


Figure 4 - Map of Oyster Bay and vicinity. The dashed line indicates the 13,000-foot range from the observing station on the left to the hilltop station on the right.



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Figure 4 - 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.



Figure 5 - Aerial view of Oyster Bay looking toward the east. The observing station is on the shore road, center foreground, and the hilltop station is directly above on the crest of the first ridge.

shore of Oyster Bay from a point approximately 13,000 feet distant. Such a range would be about 85 percent over water with the eastern sky as background. The viewing station selected was a semi-circular parking area on the shore road a few feet above the water at high tide. See Figure 4.

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 station was arranged by installation of a private telephone line. An aerial view of the range is shown in Figure 5.

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 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 6.

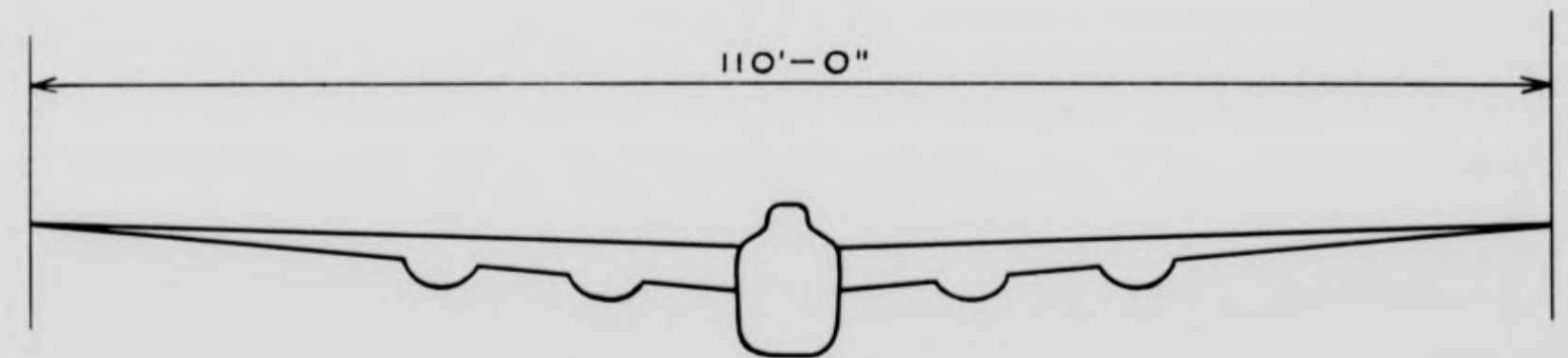


Figure 6 - Silhouette of Liberator in head-on aspect.



Figure 7 - Close-up view of suspended silhouette.

The first model, built by a local carpenter, was constructed of plywood, reinforced to provide sufficient rigidity. Since its overall length of 110 feet was too great for fabrication as a single unit, it was made in six sections and assembled at the hilltop.

This model was short lived, due to a defective suspension cable; and it was not found expedient to repair it. A theatrical scene maker was then engaged, and a new model was built in four sections with some minor changes in design.

Method of Suspension

Two steel towers 100 feet high were erected 200 feet apart, and the model was supported on a 1/2-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



Figure 8 - Rigging layout for the suspension of the full scale model.

level. A view of the elevated silhouette is shown in Figure 7. 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.

Arrangement and Control of Lights

It had previously been calculated that 500 watts of power would suffice for this experiment. Special lamps were supplied by Mr. K. D. Scott of the Lamp Division of 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 AC generator of 500 watts capacity. The in-

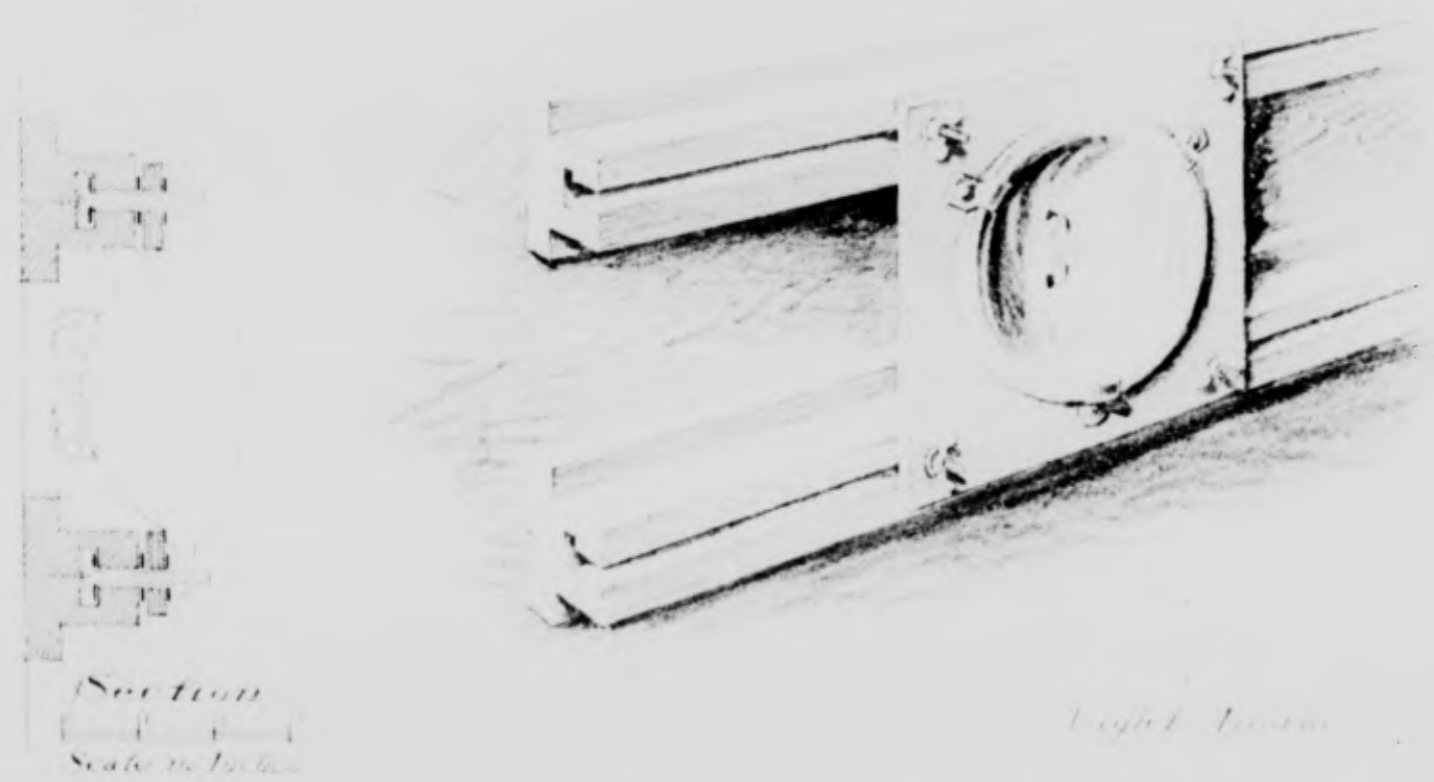


Figure 9 - Lamp details and method of mounting.

tensity 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 tungsten light to light of 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 9. 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 V. The arrangement shown in Figure 10 is one of several used during these experiments. Although determined somewhat empirically, it is a close approximation to the theoretical spacing.



Figure 10 - Dimension drawing showing the location of the lamps.

III. 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, the only adjustments that could be made were overall ad-

justments by means of the guy ropes. The necessary instructions were relayed by telephone from the observers' station. When the best overall setting had been obtained, a twelve 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 9. 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.

During the month of February, 1943, several demonstrations were made for Army and Navy personnel. The most successful demonstration was made on the afternoon of February 19, 1943, 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 experi-

ments 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 300 feet of the station. The observation station is depicted in Figure 11.



Figure 11 - 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 hilltop terminates in the box on the pole

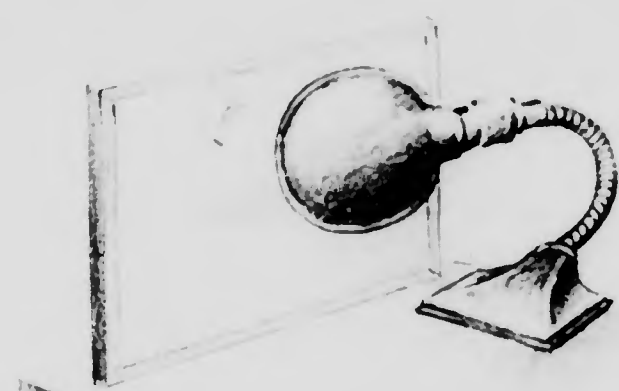


Figure 12 - Oil painting of Liberator (B-24) used to demonstrate the Yehudi principle.

IV. 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 a thin sheet metal, a photograph of which is shown in Figure 12. 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 painting to cover the holes as shown in Figure 13a. 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.



(a)
Desk lamp positioned behind the painting to illuminate the holes in the silhouette.

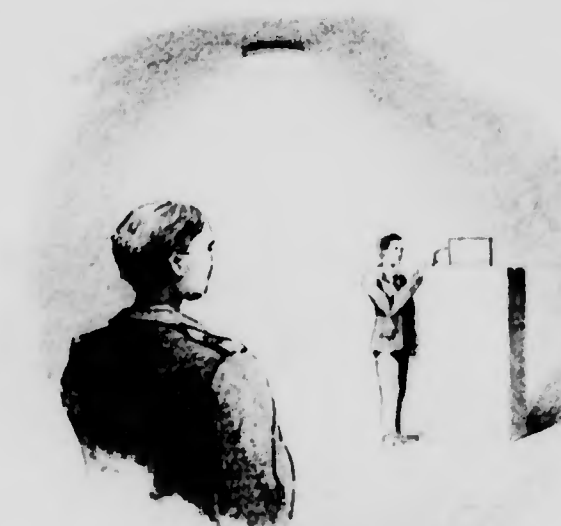


Figure 13
(b)
Observer viewing the painting at a distance of 30 feet (scale distance of 2 miles).


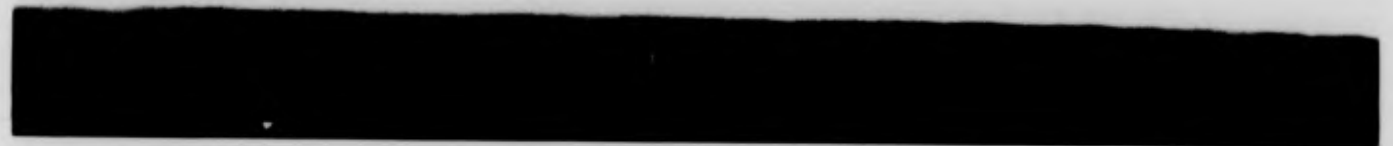



Figure 14 - Photograph taken with lens having resolving power of human eye. When viewed at 14 feet, this photograph shows the appearance of a Liberator at two statute miles.

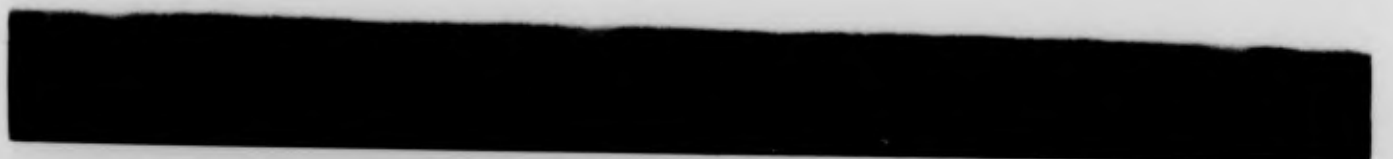


Figure 15 - Photograph taken under the same conditions as Figure 14, with Yehudi camouflage applied. Note that, although the arrangement of lights is not perfect, the Liberator becomes invisible well within the proper viewing distance of 14 feet.

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 13b. An attempt to illustrate this demonstration by photographic means is shown in Figures 14 and 15. 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 14 is a photograph made under these conditions before the desk lamp was turned on; Figure 15 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 630 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 drawing need be no more than a black paper silhouette 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 under-wing 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 under-wing 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 V.

V. TACTICAL AND TECHNICAL ASPECTS

This report is concerned with one specific tactical use of the Yehudi principle; and it is not within the province of the report to consider other possible tactical aspects. The technical information that follows is supplied 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.

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 x 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 candlepower of 100,000 would fulfill the requirements. If 20 lights of equal intensity are to be employed,

each should have a beam candlepower 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 x 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 2000/20 = 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° , the solid angle is

$$S = 2\pi(1 - \cos 5^\circ) = 0.0239 \text{ steradians.}$$

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° in the vertical plane and 10° in the horizontal plane represents a solid angle of $10/57.3 \times 8/57.3 = 0.0244$ steradians.

Practical Power Requirements

It was tacitly assumed in the foregoing that lamps can be obtained whose intensity is uniform within the beam and is zero outside the beam. Lamps having this 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. 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. The mounting of the filament is exceedingly sturdy 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 envelopes 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.

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

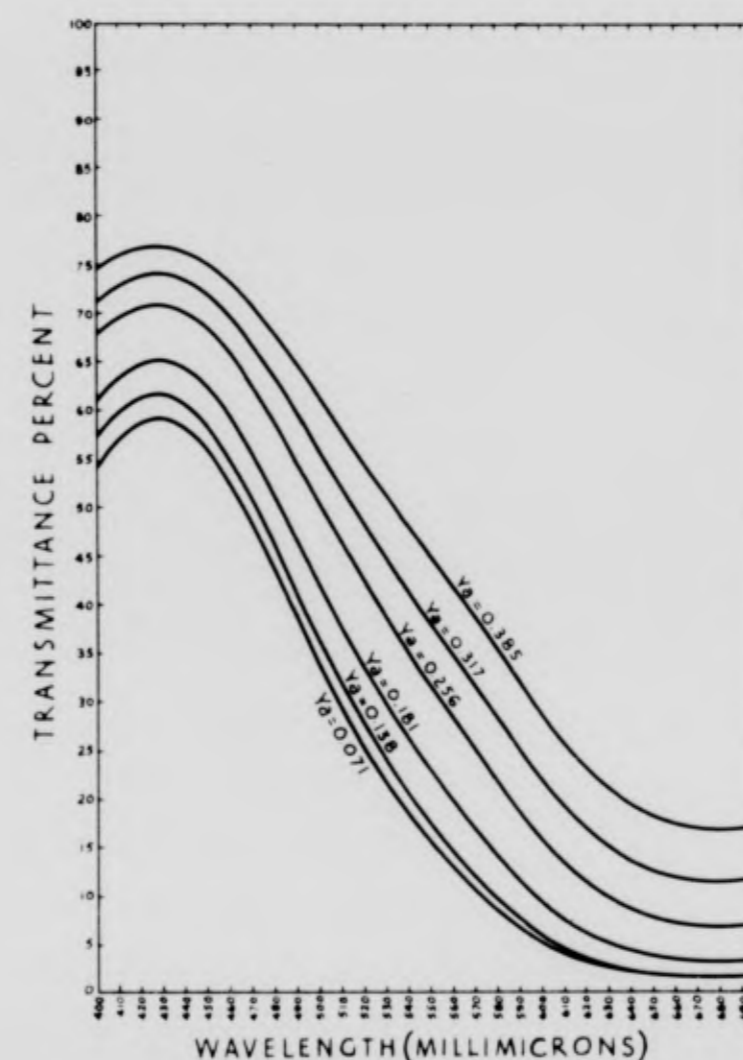


Figure 16 - Spectral transmittance curves of 6 different thicknesses of transparent iron blue lacquer films applied to glass filters.

the color temperature of a blue sky may exceed $20,000^\circ\text{K}$. 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 16 shows the spectral transmittance curves

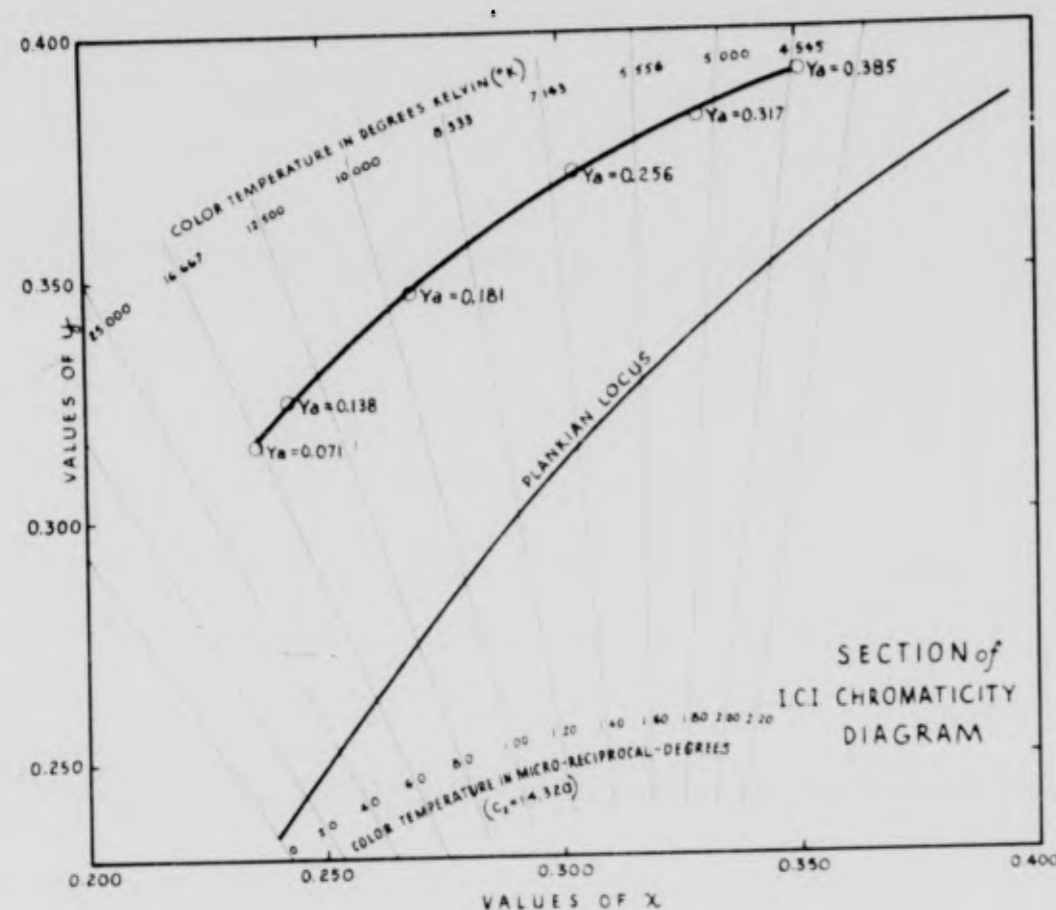


Figure 17 - Section of standard I. C. I. Chromaticity diagram showing the efficiency of the 6 filters whose spectral transmittance curves appear in Figure 16. The values of Y_a give the integrated transmittance for illuminant A, a tungsten source at 2848°K.

of typical filters produced by this method. The performance and efficiency of these filters is indicated in Figure 17.

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 counter-measure.

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 con-

ducted in the vision range of the Tiffany Foundation. Observers viewed a uniformly illuminated white screen on which was mounted a black disc with a small central hole. It was found that, by properly adjusting the intensity of a lamp mounted behind the central hole in the black disc, the disc 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 disc. 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 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 18. 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 IV of this

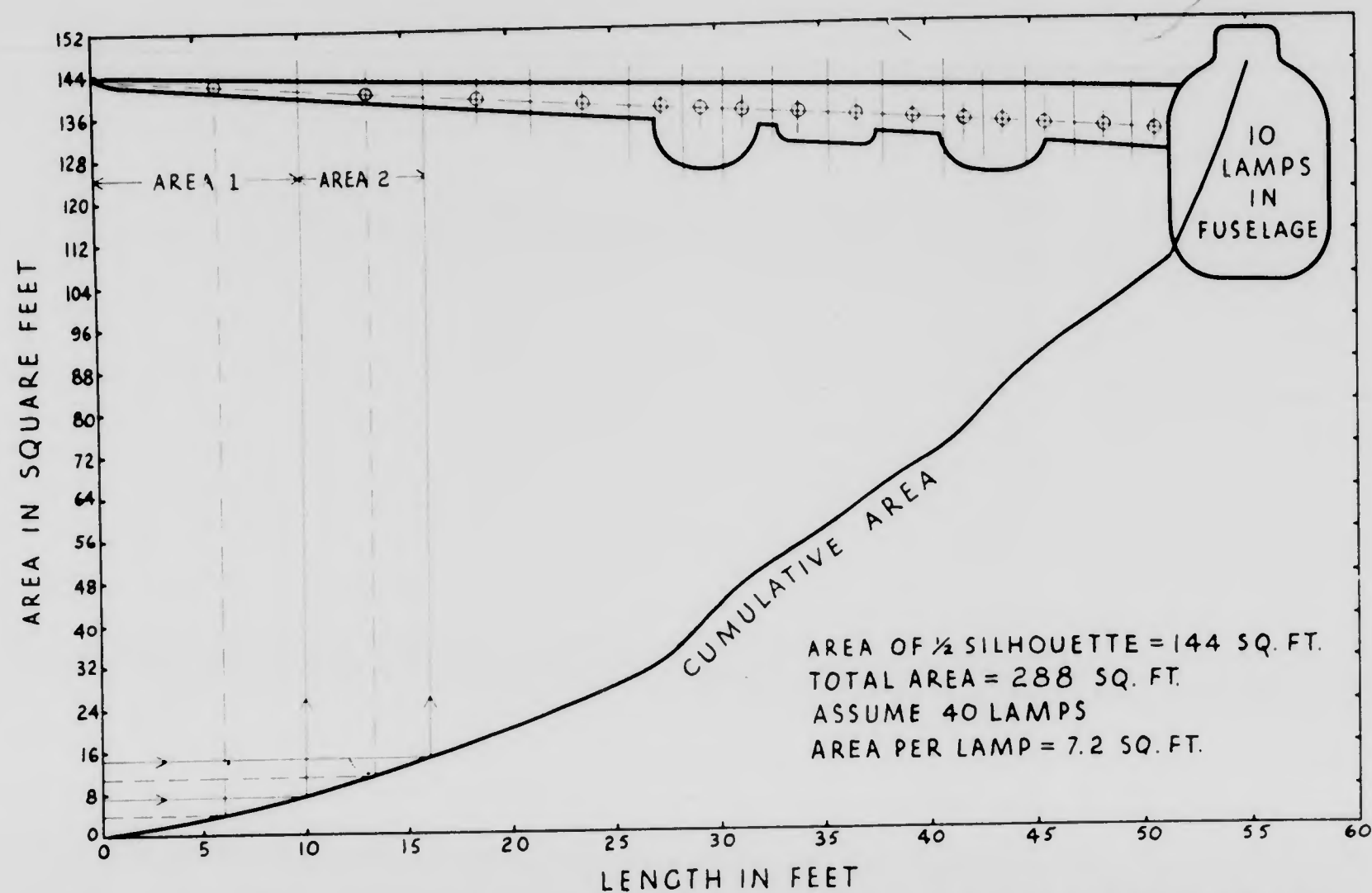


Figure 18 - The spacing of the lamps can be determined theoretically by dividing the total area into elemental areas equal in number to the number of lamps to be used on this half of the plane. From the standpoint of horizontal spacing, the lamps should be placed at the center of each elemental area as shown.

report. For example, it has been found by this method that although lamps suspended on brackets beneath the wing function properly near the wing tips, they should be mounted nearer the center of the section wherever the wing section is thick. See

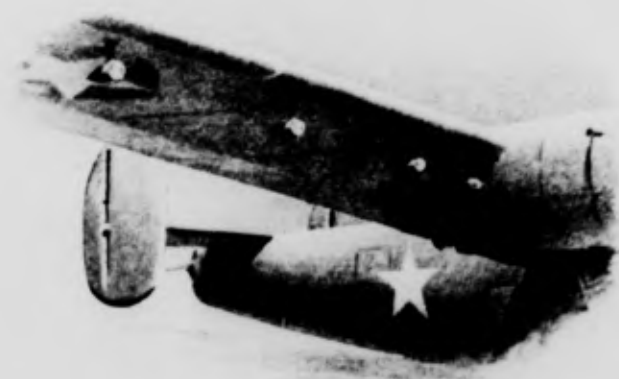


Figure 19 - Lamps suspended on brackets beneath outer wing.



Figure 20 - Lamps mounted in leading edge of inboard wing.

Figures 19 and 20. 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.

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 non-rigid structure. There are many possible procedures, and an outline of one will suggest many variations. If a level air field 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 by the method used in aligning automobile headlights, but this method is not sufficiently critical for the final adjustment.

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 21. One of

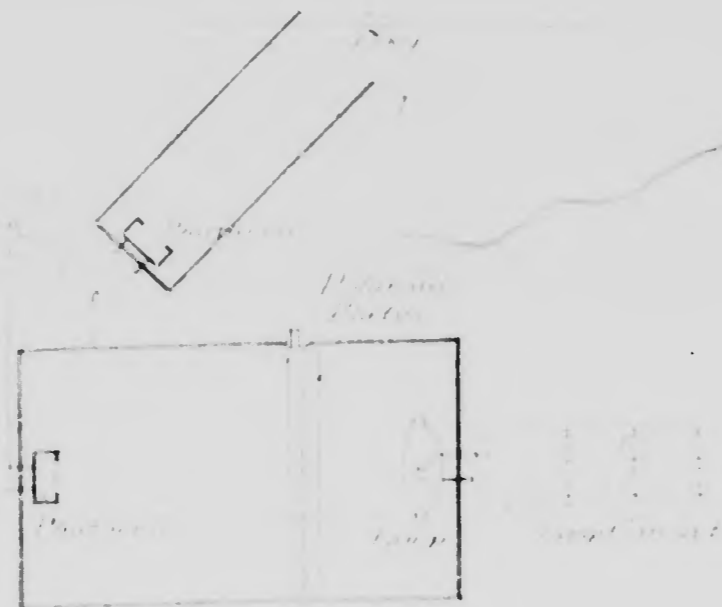
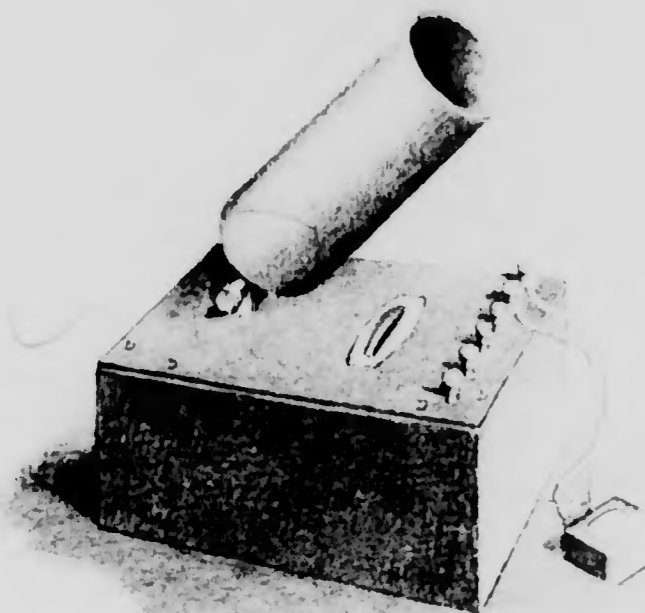


Figure 21 - Photoelectric device used in the Tiffany experiments for matching the sky background.

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 of the light beam. It can be shown that the greatest 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 $\frac{36}{(f/\text{-number})^2}$ 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 nine-fold 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.

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 under-surfaces with a highly reflecting paint, since these surfaces receive very little illumination by reflection from the water 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.

The Effect of Cross Winds

During discussions of this project with Service personnel, attention has often been called to the fact that, when cross winds are encountered, aircraft would not ordinarily present their head-on aspect during an approach. Thus, even if the spread of the beams were 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 22 shows the silhouette of a Liberator

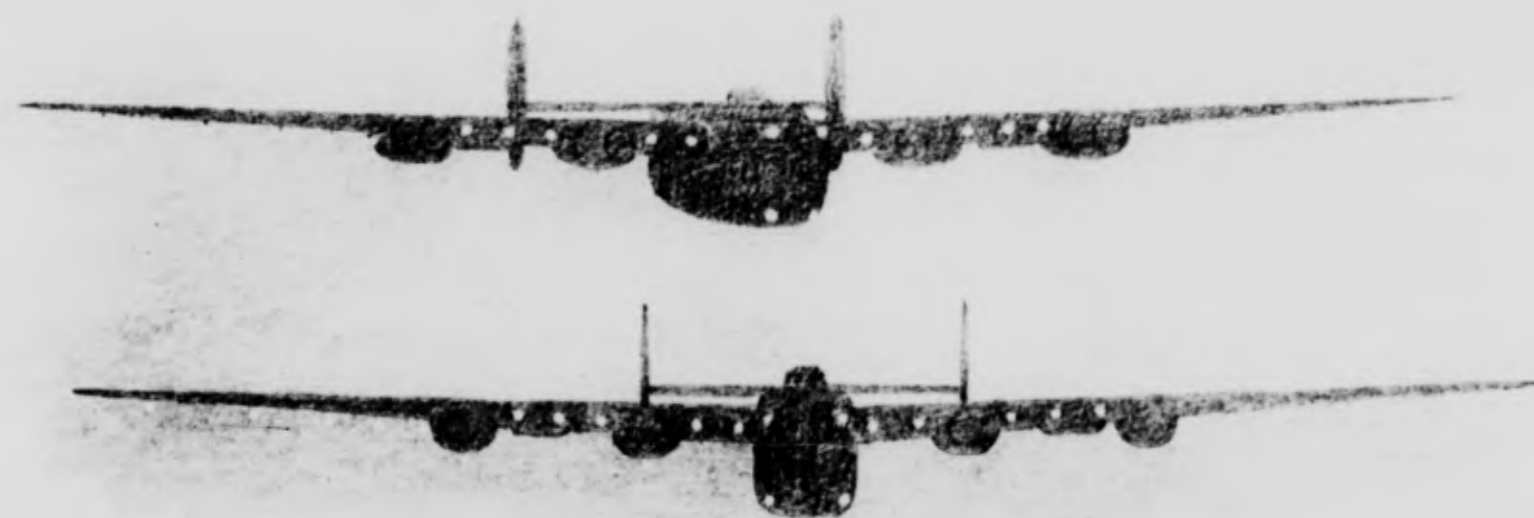


Figure 22 - (Above) Silhouette of Liberator viewed from the left at an angle of 20°. (Below) Head-on silhouette.

(B-24) at a heading of 20° in comparison with one 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 23.

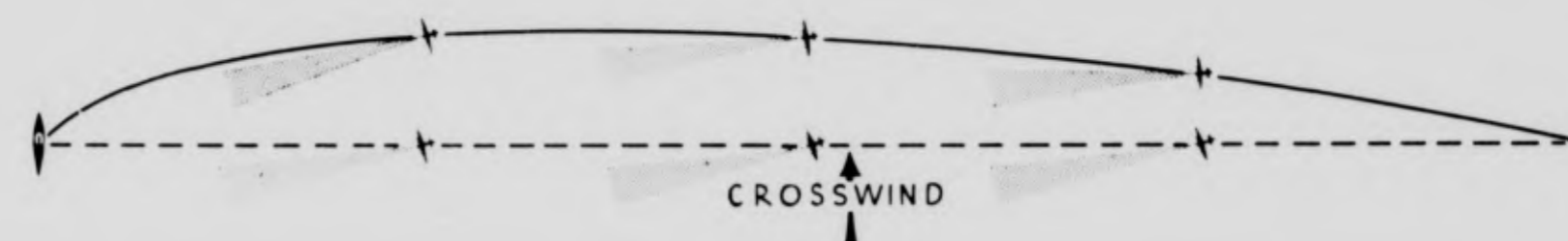


Figure 23 - Diagram showing the curved flight course that results when the light beams are held on the target during an approach with a strong cross wind. This curve was plotted for the case of a cross wind whose velocity is one-fifth of the air speed of the plane.

The Effectiveness of Enemy Counter-Measures

The only effective optical counter-measure suggested thus far is the use of binoculars. Theoretically, if there were no atmosphere, a perfect pair of 8-power glasses would increase by 8-fold 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 re-

quire that enemy look-outs 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.