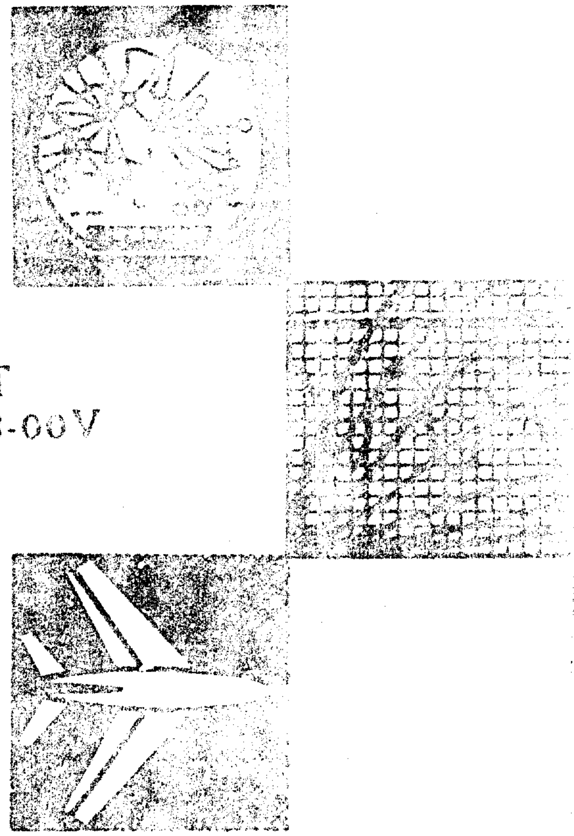
REPORT NO. RD-64-46



FINAL REPORT
Project No. 421-013-00V

EVALUATION OF TAXIWAY CENTERLINE LIGHTING

MARCH 1964

FEDERAL AVIATION AGENCY
Systems Research & Development Service
EVALUATION DIVISION
Atlantic City, New Jersey

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FINAL REPORT

EVALUATION OF TAXIWAY CENTERLINE LIGHTING

PROJECT NO. 421-013-00V
REPORT NO. RD-64-46

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This report is approved for submission to the Director, Systems Research and Development Service. The conclusions and recommendations are those of the Evaluation Division. This report does not necessarily reflect FAA policy in all respects and it does not, in itself, constitute a standard, specification or regulation.

H. V. Hermansen
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March 1964

FEDERAL AVIATION AGENCY
Systems Research and Development Service
Evaluation Division
National Aviation Facilities Experimental Center
Atlantic City, New Jersey

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EVALUATION OF TAXIWAY CENTERLINE LIGHTING by Robert F. Gates, Final Report, Mar. 1964
63 pp., incl. 31 illus., plus 5 appendices (18 pp., incl. 5 illus.)
(Project No. 421-013-00V, Report No. RD-64-46)

ABSTRACT

A project was undertaken at the Federal Aviation Agency's National Aviation Facilities Experimental Center, Atlantic City, New Jersey, to determine the suitability of taxiway centerline lighting toward establishing new configuration and design criteria for airport taxiway lighting. The report reviews the taxiing problem during low visibility conditions. In accomplishing the project, comparisons were made among the standard blue taxiway edge lighting, taxiway edge reflective markers, and taxiway centerline lighting. Adequacy of new fixtures, 180 cycle regulators and a control system for taxiway centerline lighting was also evaluated.

A specially prepared Mylar film was used in simulating taxiway centerline light visibilities (TCLV) of 1500, 600 and 200 feet on straight and curved taxiways of differing radii. Photometric and environmental tests were conducted over a period of approximately a year and a half on four types of fixtures.

It was concluded that taxiway centerline lighting was a significant improvement over conventional edge lighting and that aircraft could accurately taxi in visibilities as low as 200 feet over a taxiway centerline lighting system. None of the fixtures withstood the environment encountered. Taxiway edge reflectors showed promise but further development was recommended. No problems were encountered with the 180-cycle regulators and control system. It was recommended that a Selection Memorandum for taxiway centerline lighting be prepared by applying the results of this evaluation to fixture configuration and spacing. Green was recommended as the color for taxiway centerline lighting to differentiate between it and the white runway centerline lighting.

INTRODUCTION

Purpose

The purpose of this project was to determine the suitability of taxiway centerline lighting for low visibility operations by comparing taxiway centerline lighting, edge lighting, edge reflectors, and combinations thereof. At the same time, the adequacy of a 180 cycle regulator and control for taxiway lighting was to be determined.

Background

Blue lights, outlining the edges of taxiways, are used internationally for lighting taxiways. As taxiways at major terminals increase in number and complexity, pilots voice numerous complaints concerning the "sea of blue" appearance of the edge lights. Complex taxiway intersections and large ramp areas are particularly confusing because of the extremely poor guidance provided by the edge lighting. Poor guidance results in slow taxiing speeds and less efficient use of airports during low visibility conditions.

Green taxiway centerline lights have been in use at London Airport for several years. These lights are used in a dual role. First, they are used by the pilot as a means of keeping the aircraft near the taxiway centerline. Second, they are used by the ground controller as a means of routing aircraft, i.e., the pilot taxis his aircraft along the lighted path. Switches in the Aerodrome Control Room allow the ground controller to set up the taxi route he desires the aircraft to follow. Pilots using London Airport have found this system of taxiway lighting to be very effective.

Because of the favorable results obtained with green taxiway centerline lighting at London Airport, Annex 14 to the Convention on International Civil Aviation, an International Civil Aviation Organization (ICAO) publication, was amended in September of 1958 to include green taxiway centerline lighting as a standard alternative method of lighting taxiways along with blue edge lighting.

The taxiway centerline fixtures used at London Airport protrude one inch above the surface. This height causes an undesirable roughness problem, particularly with small aircraft, which may be the primary reason why taxiway centerline lighting was not investigated earlier in the United States.

The development of a low profile, easily installed, pancake type lighting fixture paved the way for an evaluation of taxiway centerline lighting in the United States. This work was performed at NAFEC and preliminary results obtained in the project were used to determine the United States Position for the United States Delegation to the Seventh Air Ground Aids Division Meeting of ICAO at Montreal, November 13 to December 14, 1962. Reflective edge markers of a type used by the United States Air Force were also evaluated in the program at NAFEC. Reflective edge markers have the particular advantages of being relatively inexpensive, easy to install, and without a power requirement.

The evaluation of taxiway lighting was continued through the winter of 1962-1963 to obtain data on four types of fixtures used at NAFEC in the taxiway centerline lighting evaluation program.

Equipment Description

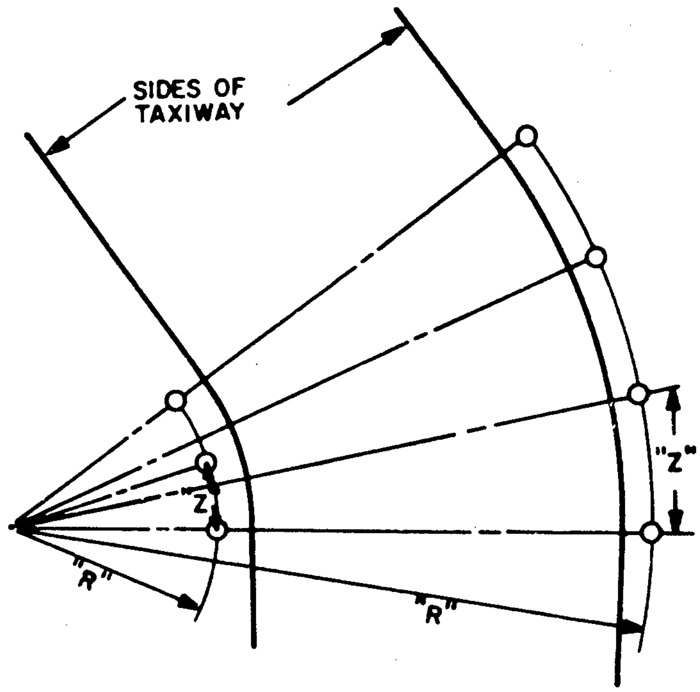
Taxiway Configurations: All fixtures installed in the centerline of taxiways and runways at NAFEC for this evaluation were spaced 25 feet apart on straight sections and large radius curves, and 12-1/2 feet apart on short radius curves. Installations on Runways 17-35 and 8-26 were considered to be part of the taxiway system since the runways were to be used as taxiways to and from active runways. Fixture spacings for the taxiway test were set at 12-1/2, 25, 50 and 100 feet; the larger spacings were obtained by masking the light output from fixtures not contributing to the desired interval.

Blue taxiway edge lighting had been previously installed at NAFEC in accordance with National Standard AGA-NS8 with spacings of 200 feet on long straight sections and spacings as shown in Figure 1 on curved sections.

The taxiway and runway widths in the evaluation were:

Taxiways E and G	50 feet wide
Taxiway B	75 feet wide
Runway 17-35	150 feet wide
Runway 8-26	150 feet wide

The distance from the taxiway centerline lights to the edge of the pavement was in excess of 25 feet except on the curved portion at the intersection of Taxiways E and G where the distance was 19 feet.



RADIUS "R" IN FEET	LIGHT SPACING "Z" IN FEET	RADIUS "R" IN FEET	LIGHT SPACING "Z" IN FEET
15	20	300	80
25	27	400	95
50	35	500	110
75	40	600	130
100	50	700	145
150	55	800	165
200	60	900	185
250	70	1000	200 MAX.

NOTES: 1. FOR RADII NOT LISTED, "Z" SPACING SHALL BE DETERMINED BY LINEAR INTERPOLATION.
2. "Z" IS THE CHORD LENGTH.

FIG. 1 NATIONAL STANDARD REQUIREMENTS FOR TAXIWAY EDGE LIGHT SPACING ON CURVED SECTIONS

Figure 2 shows the location and radii of taxiway curves evaluated in this program. The centerline lighting, shown by the dashed line, was divided into eleven segments. Three of these segments (I, J, and K) were used only in the configuration and color tests. The other segments (A through H) were used for tests on spacing of fixtures as well as for configuration and color tests. Segments A through D used the same fixtures as segments E through H; however, the effective spacing between the lights in segments E through H was changed by masking one or both sides of the selected fixtures.

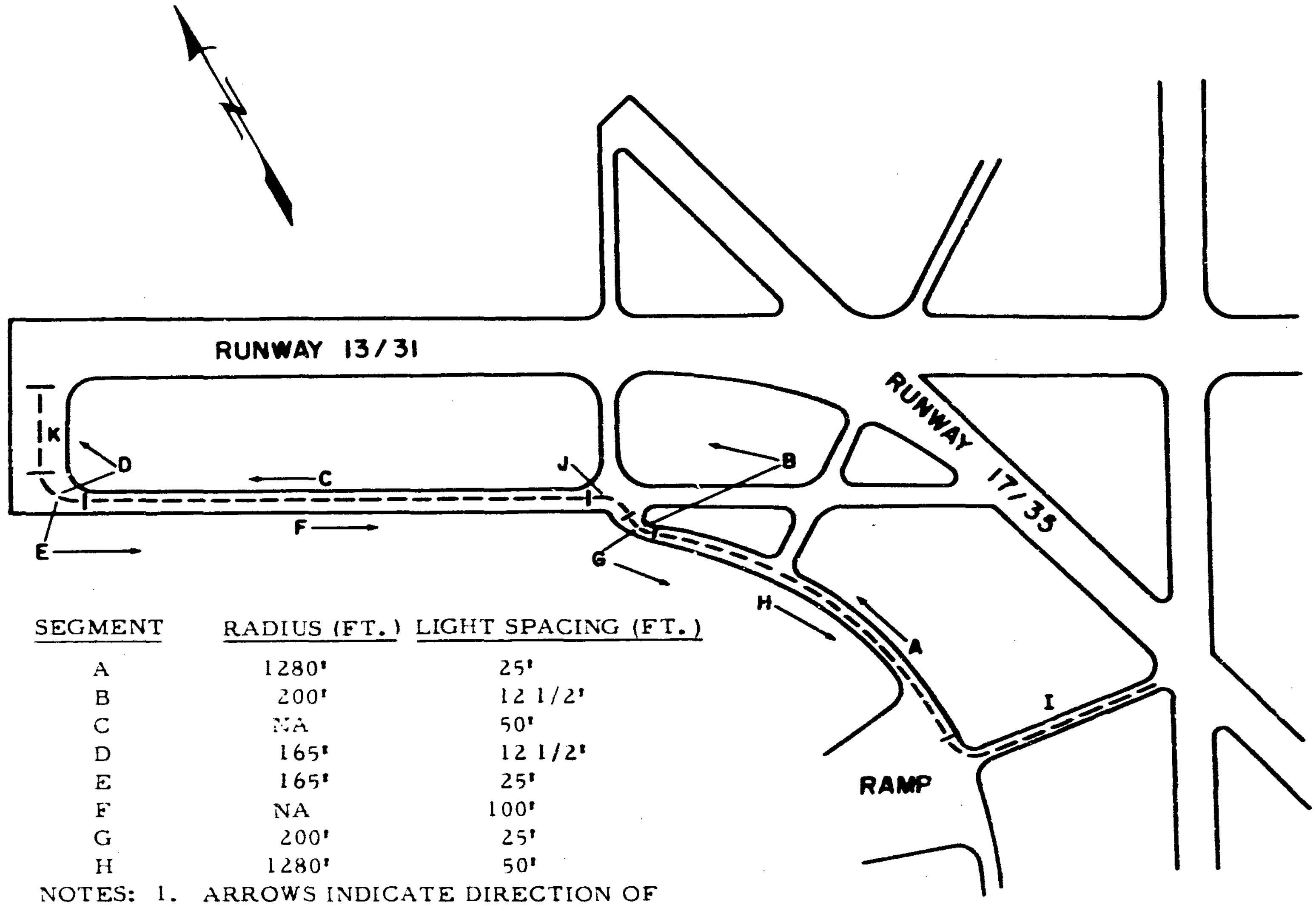
Taxiway Centerline Lighting Fixtures: Four types of bidirectional pancake open lighting fixtures were installed in the taxiway centerline system. All fixtures contained a General Electric, 45-watt, "quartzline," lamp with a coiled filament rated at 6.6 amperes.

Two hundred and seventy-one Structural Electric Products Corporation fixtures were installed in Taxiway B, G, and E. Forty-seven 5-7/8-inch Strong Electric Corporation fixtures were installed in Runway 17-35. One hundred and thirteen 7-13/16-inch Strong Electric Corporation fixtures were installed in Runway 17-35 and Taxiway H. One hundred and sixty-nine Stillman Rubber Company fixtures were installed in Runway 8-26 (FIG. 3).

The 5-7/8-inch fixture was the earlier of the two Strong Electric Corporation fixtures. The 7-13/16-inch fixture was developed later to provide a lower profile.

Structural Electric Products Corporation Fixtures - The Structural Electric Products Corporation fixtures (FIGS. 4 and 5) are connected in series circuits. A film cutout connected in parallel across the lamp provides a continuous circuit if the lamp should fail. The fixture is 7-13/16 inches in diameter and 1-1/4 inch high at the center. The fixture extends 1/4 inch above the runway surface when installed. Two "U" shape tension clips are riveted to the base of the fixture inside the lamp recess for holding colored filters in place. The lamp terminals are mounted in rubber.

Strong Electric Corporation Fixtures - The Strong Electric Corporation fixtures are connected in series but do not require a film cutout because each unit contains a small isolating transformer. The primary of the small transformer is molded into the base of the fixture while the secondary winding, with the lamp connected, is in a removable lamping assembly. These fixtures were provided in two sizes. The larger fixture is 7-13/16 inches in diameter (FIGS. 6 and 7) and 1-1/2



SEGMENT	RADIUS (FT.)	LIGHT SPACING (FT.)
A	1280'	25'
B	200'	12 1/2'
C	NA	50'
D	165'	12 1/2'
E	165'	25'
F	NA	100'
G	200'	25'
H	1280'	50'

NOTES: 1. ARROWS INDICATE DIRECTION OF AIRCRAFT TRAVEL

2. SEGMENTS I, J, AND K WERE NOT USED IN THE TAXIING TESTS, THEREFORE NO DIRECTION OF TRAVEL NEED BE ASSOCIATED WITH THEM

FIG. 2 LOCATION AND RADII OF TAXIWAY CURVES

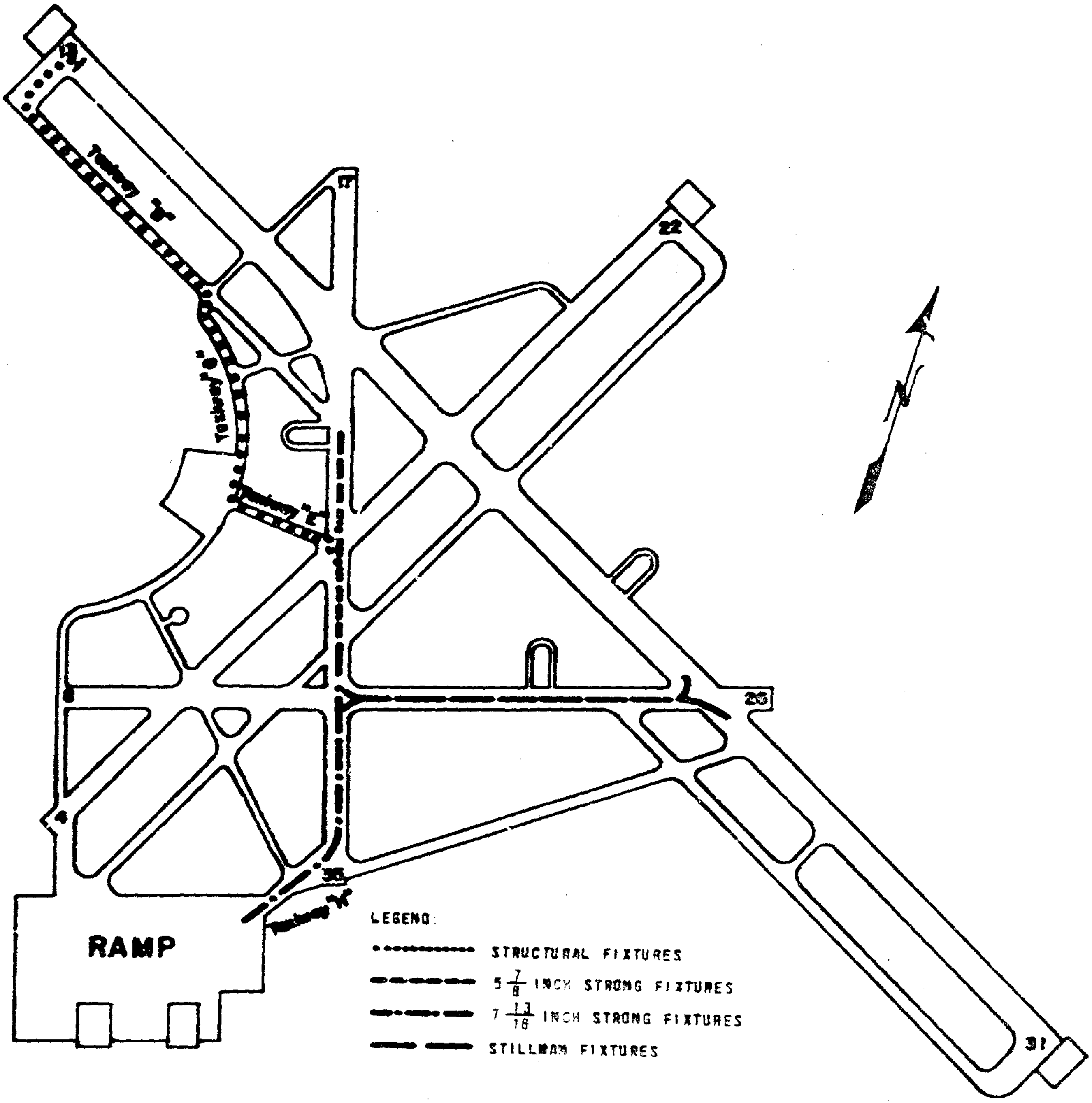


FIG. 3 LOCATION OF TAXIWAY CENTERLINE LIGHTING FIXTURES

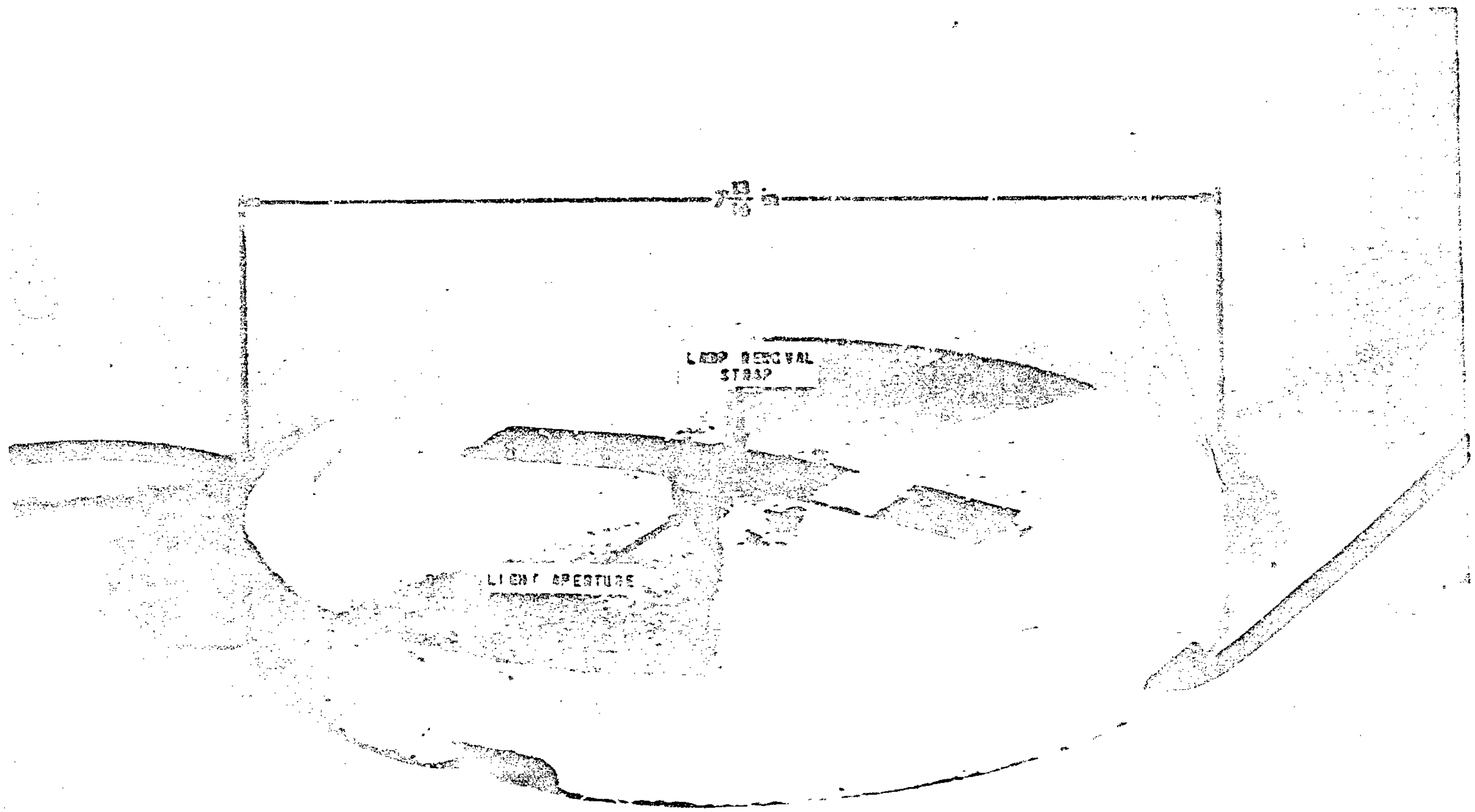


FIG. 4 STRUCTURAL ELECTRIC PRODUCTS CORPORATION FIXTURE

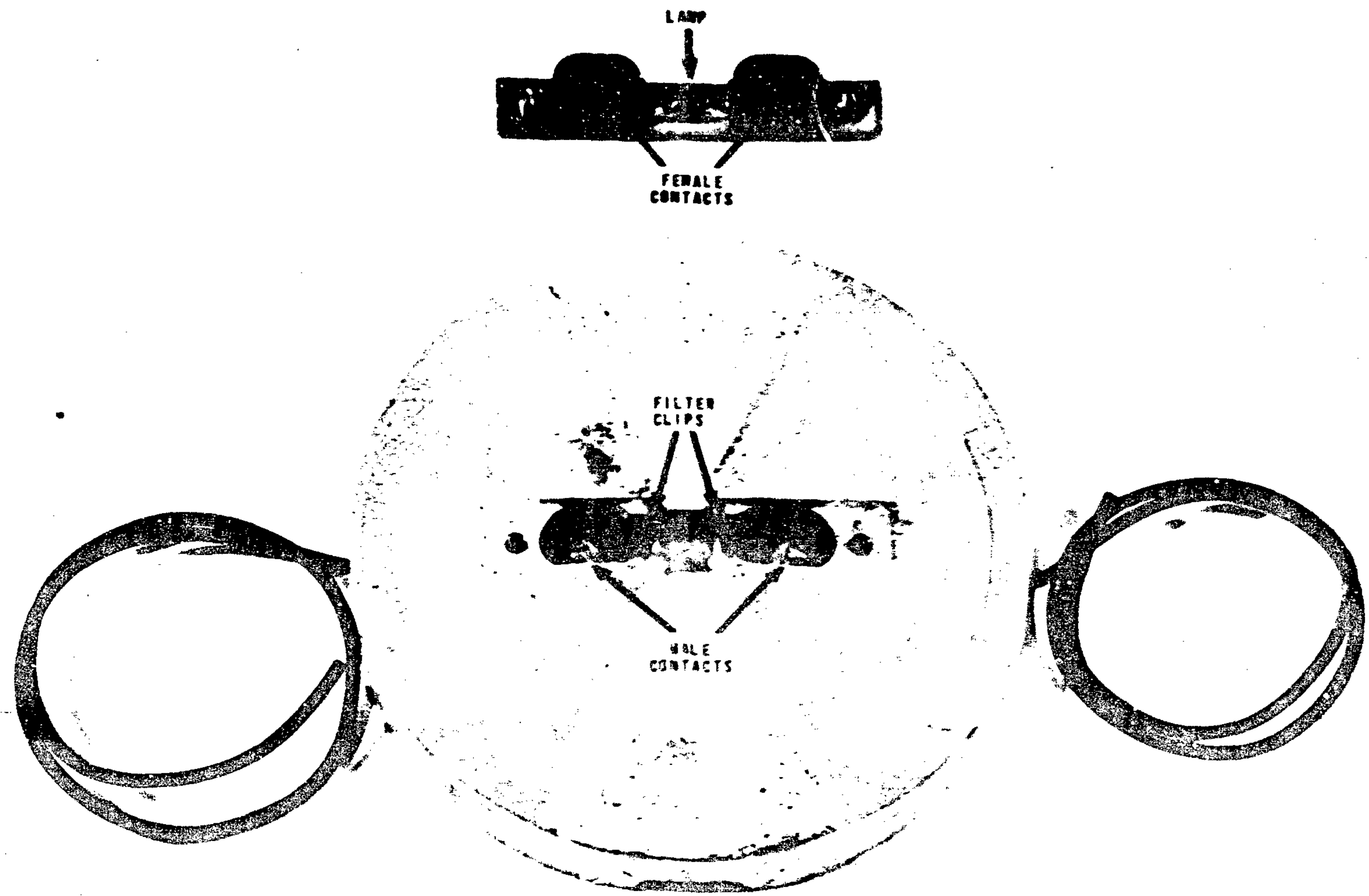


FIG. 5 STRUCTURAL ELECTRIC PRODUCTS CORPORATION FIXTURE
(LAMP STRAP REMOVED)

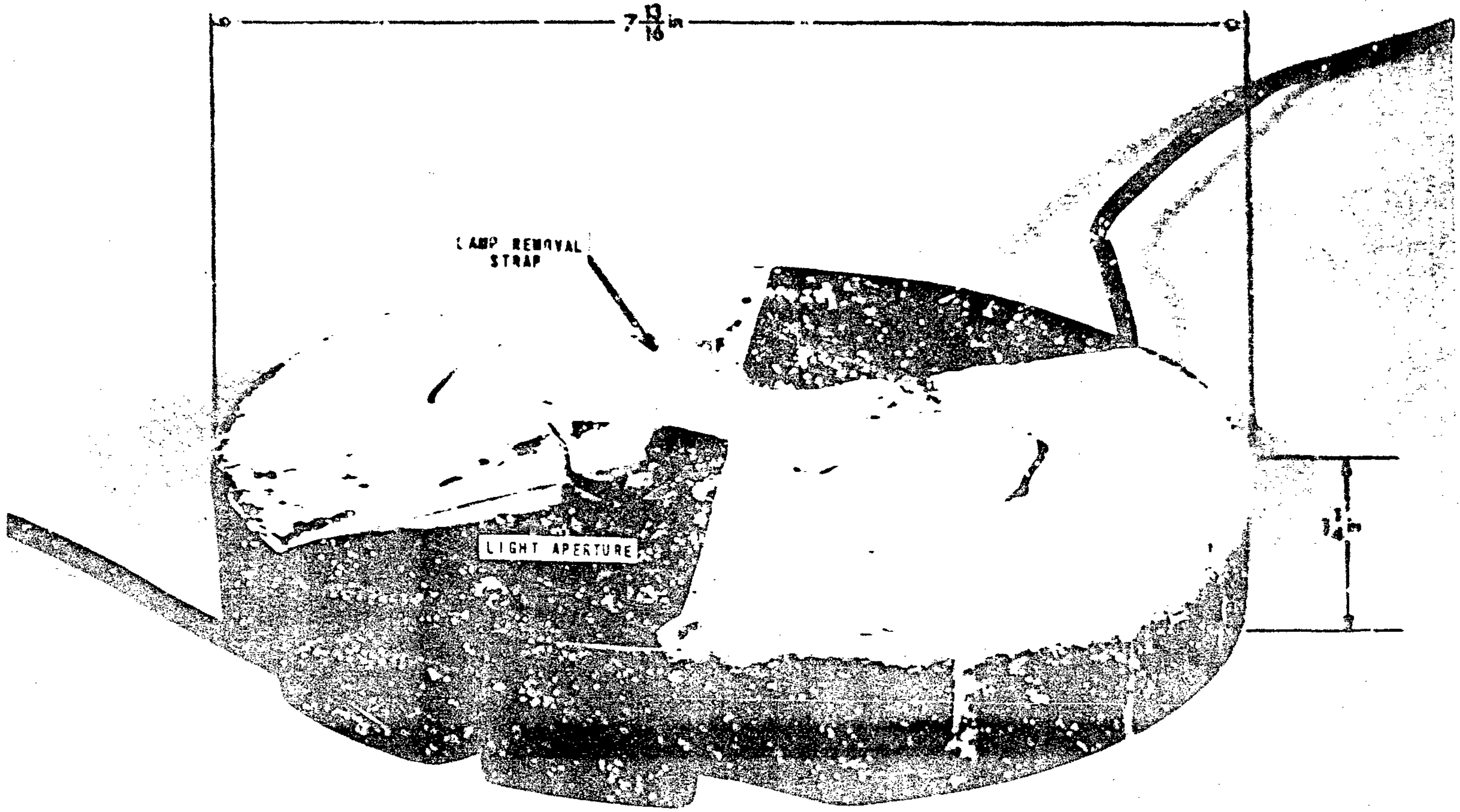


FIG. 6 STRONG ELECTRIC CORPORATION 7 13/16-INCH FIXTURE

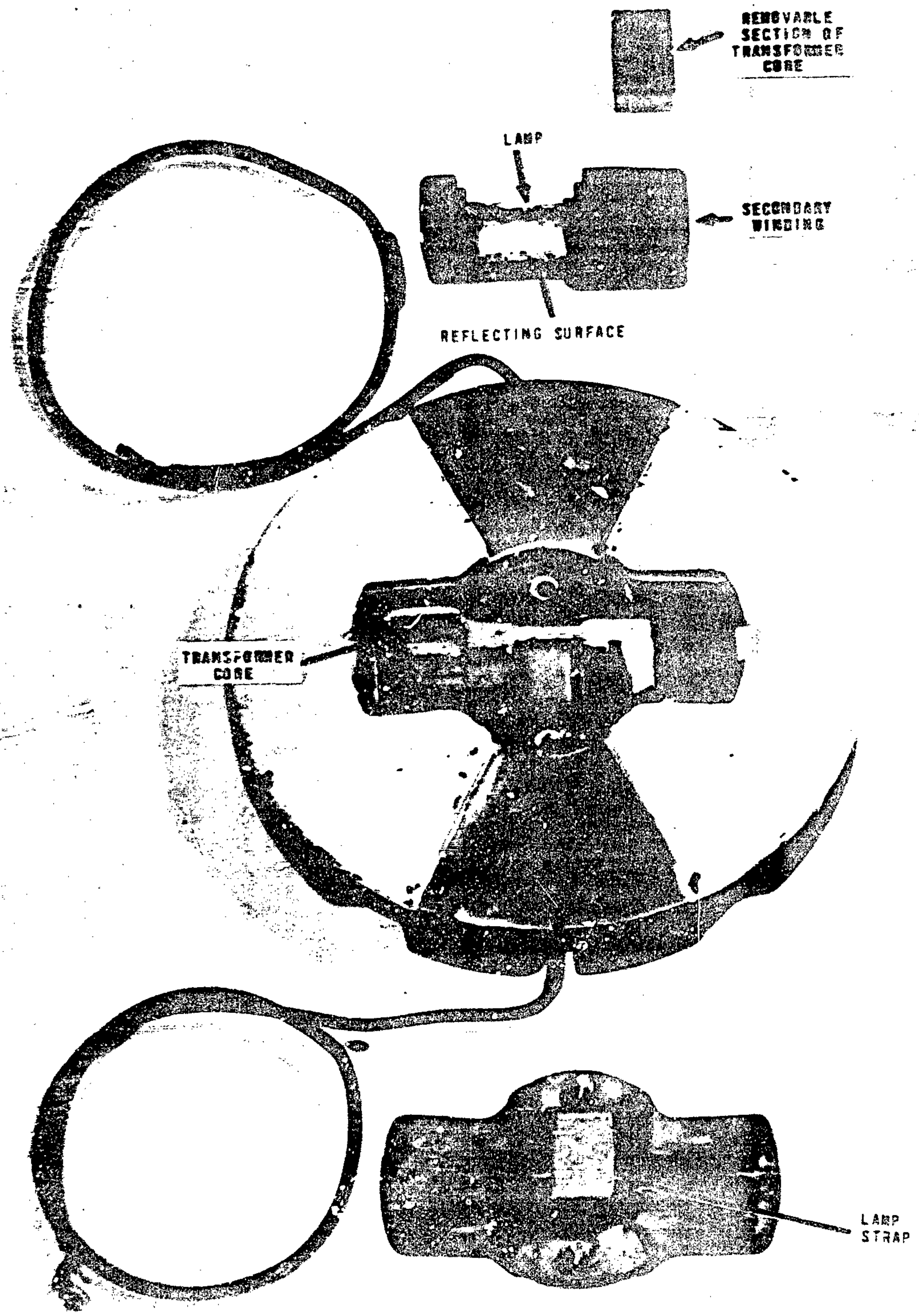


FIG. 7 STRONG ELECTRIC CORPORATION 7 13/16-INCH FIXTURE (LAMP STRAP REMOVED)

inches high at the center. It extends 1/4 inch above the runway surface when installed. The smaller fixture is 5-7/8 inches in diameter (FIGS. 8 and 9) and 2-1/8 inches high at the center. It extends 3/8 inch above the runway surface when installed. The Strong Electric Corporation fixtures have no provisions for installing colored filters. The lamp terminals in this fixture are mounted in a rigid plastic material.

Stillman Rubber Company Fixtures - The Stillman Rubber Company fixtures (FIGS. 10 and 11) are connected in series circuits with a film cutout connected in parallel with each lamp. It is 7-15/16 inches in diameter, 1-13/16 inch high at the center, and extends 9/16 inch above the runway surface when installed. The center part of the top assembly containing the lamp is mounted within the rubber diaphragm. The top assembly is attached to the base assembly by eight 9/16 inch machine screws holding a mounting ring to which the diaphragm is attached. An aircraft rolling over the top assembly depresses the lamp assembly flush with the rim of the base assembly (or runway surface). Air, compressed by the downward force, cushions the impact and returns the top assembly to its normal position once the aircraft has passed. The rubber diaphragm is 1-3/16 inch wide and 1/8 inch thick between the mounting ring and the center part of the top assembly. A wedge shaped portion of the rubber extends 1/16 inch below the top assembly to cushion the impact of the top assembly when bottoming occurs against the base assembly. A portion of the molded rubber serves as a gasket to seal the unit at the outer rim of the base assembly adjacent to the machine screws. Current is delivered to the lamp in the top assembly through leads that are 7-1/4 inches in length, coiled in a loop beneath the center part of the top assembly, and attached to connectors in the base assembly. The lamp terminals are mounted in rubber. A recess is provided beneath the lamp strap for mounting filters in the fixture.

Reflective Markers: The reflective edge marker (FIG. 12), trade named "Silver Airport Wicket," consists of a 1/8 inch diameter wire strand, shaped like a wicket, with a reflective canvas sleeve pulled over it. The sleeve is 12 inches long and 9 inches wide and coated with a reflective material on its outer surface. The marker is installed by pressing its wire ends into the ground. The reflective edge markers are manufactured by the Minnesota Mining and Manufacturing Company under Specification Number MIL-R-726A. The markers were installed adjacent to each taxiway edge light along Taxiways B, G, and E.

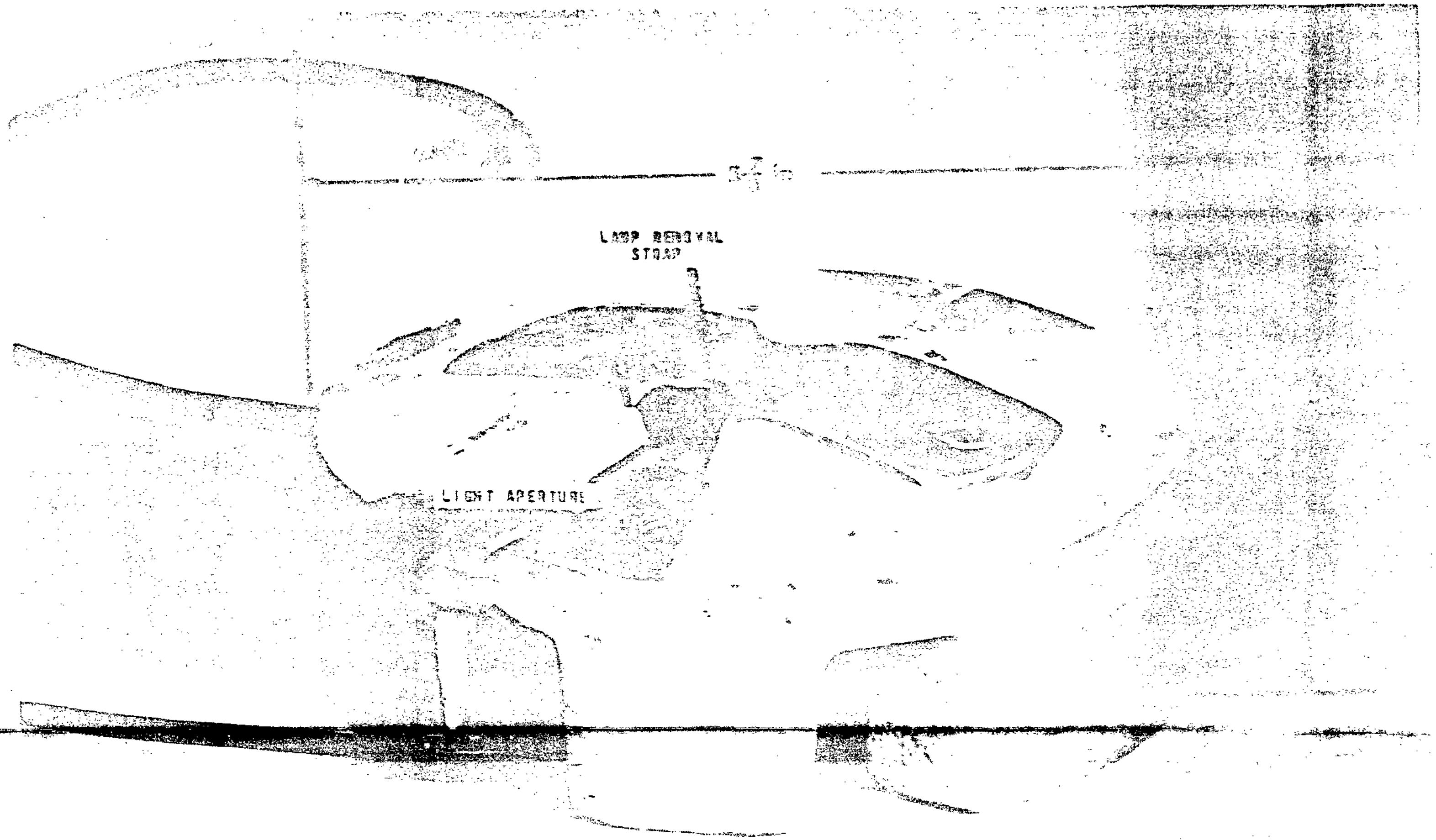


FIG. 8 STRONG ELECTRIC CORPORATION 5 7/8-INCH FIXTURE

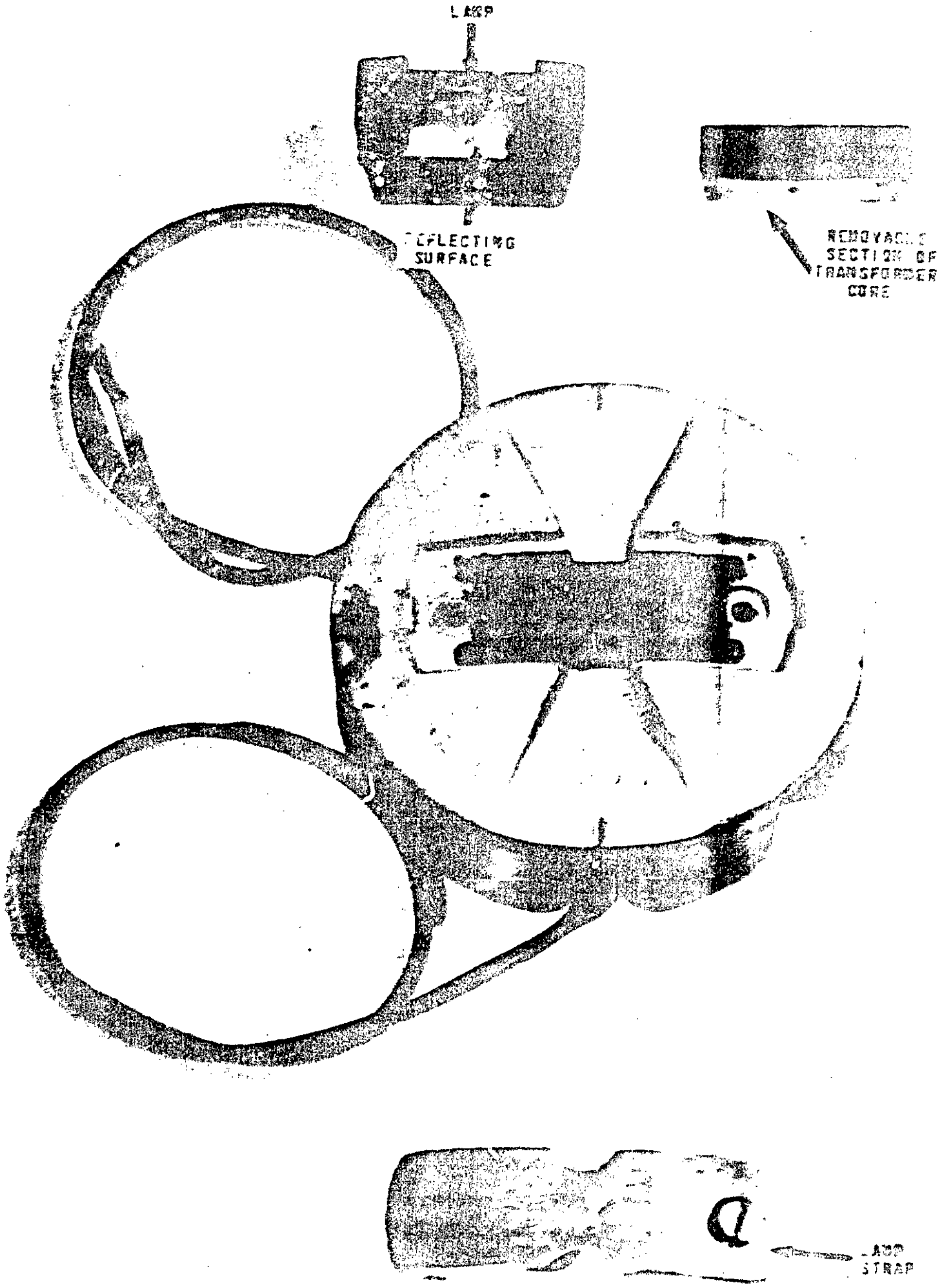


FIG. 9 STRONG ELECTRIC CORPORATION 5 7/8-INCH FIXTURE
(LAMP STRAP REMOVED)

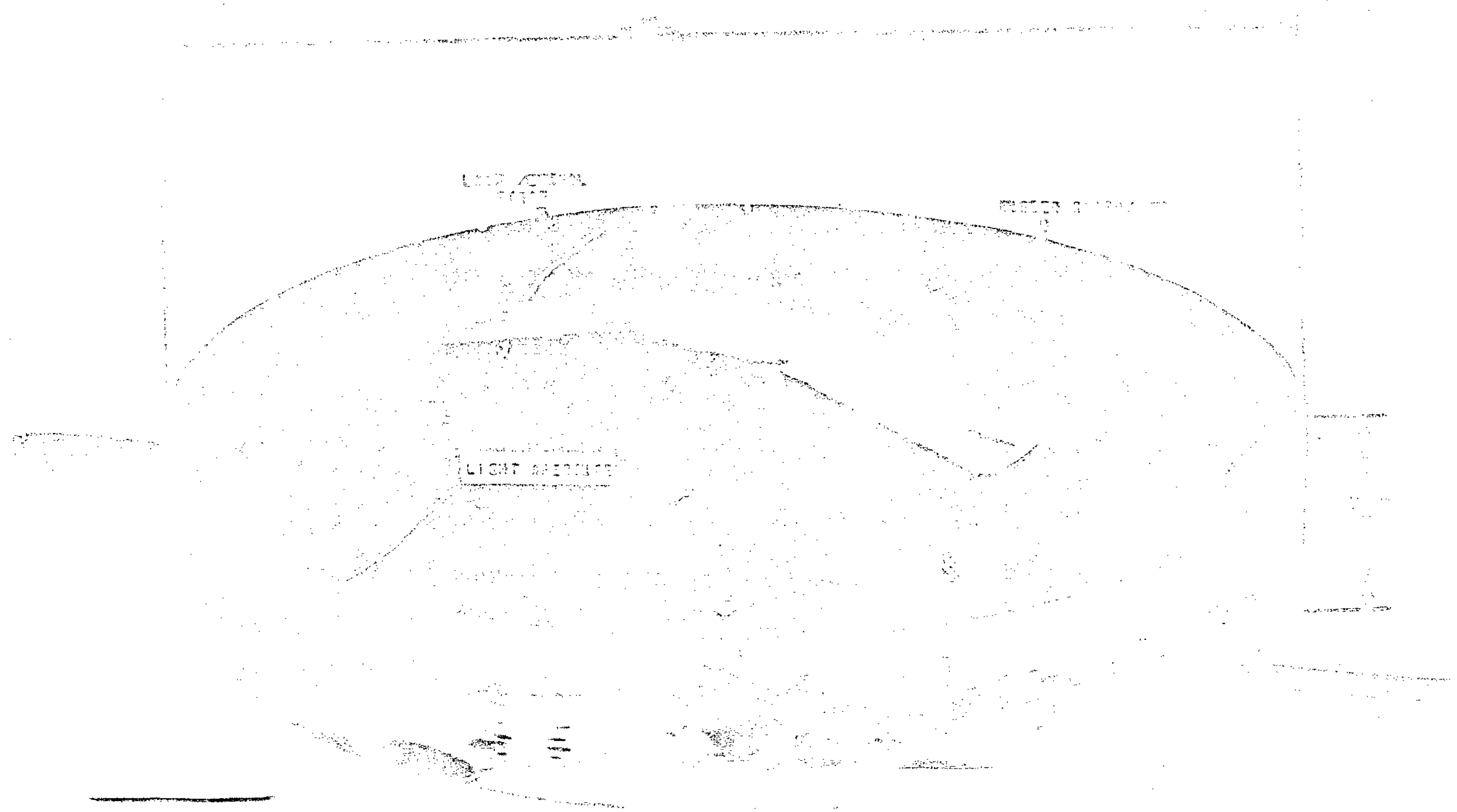


FIG. 10 STILLMAN RUBBER COMPANY FIXTURE

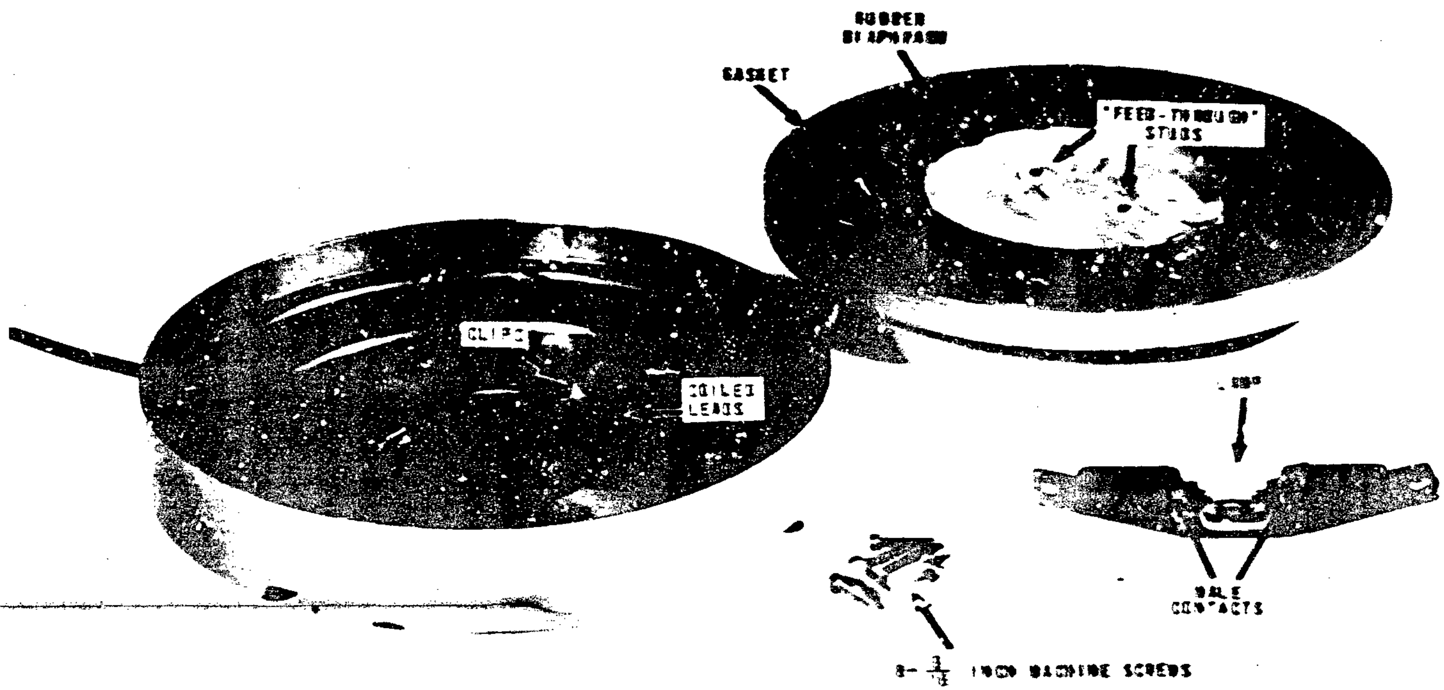


FIG. 11 STILLMAN RUBBER COMPANY FIXTURE
(TOP ASSEMBLY AND LAMP STRAP REMOVED)

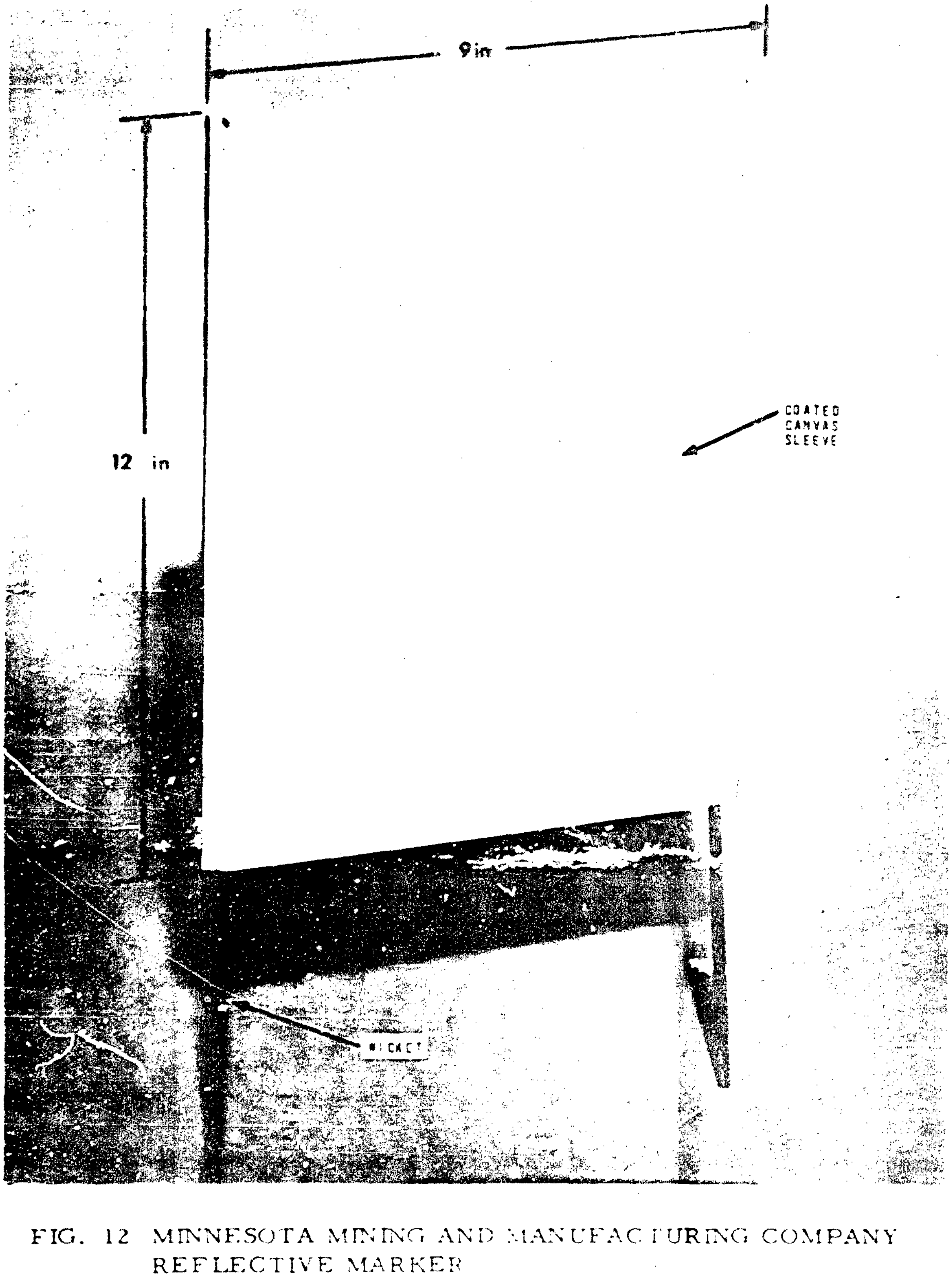


FIG. 12 MINNESOTA MINING AND MANUFACTURING COMPANY REFLECTIVE MARKER

Power and Control: Power for the taxiway centerline lighting systems was regulated by three 20 KW, 180-cycle, 4160/2300 volt, constant current regulators manufactured by the Hevi-Duty Electric Company (FIG. 13) and controlled by a panel (FIG. 14) located in the NAFEC experimental lighting control and power distribution center. The 180-cycle power was required to permit use of small transformers molded into the base of the Strong Electric Corporation Fixtures.

The Structural Electric Products Corporation and Stillman Rubber Company pancake fixtures were wired in series, ten lights per circuit, and used a 500-watt, 20 ampere to 6.6 ampere direct burial type transformer for each circuit. These transformers were located in L-837 transformer cans located near the edge of the taxiways. The Strong Electric Corporation Fixtures were operated in a single series circuit.

Selector switches were installed to permit the operator to select either right or left turns from straight taxiway sections as well as to select lighting for straight sections only.

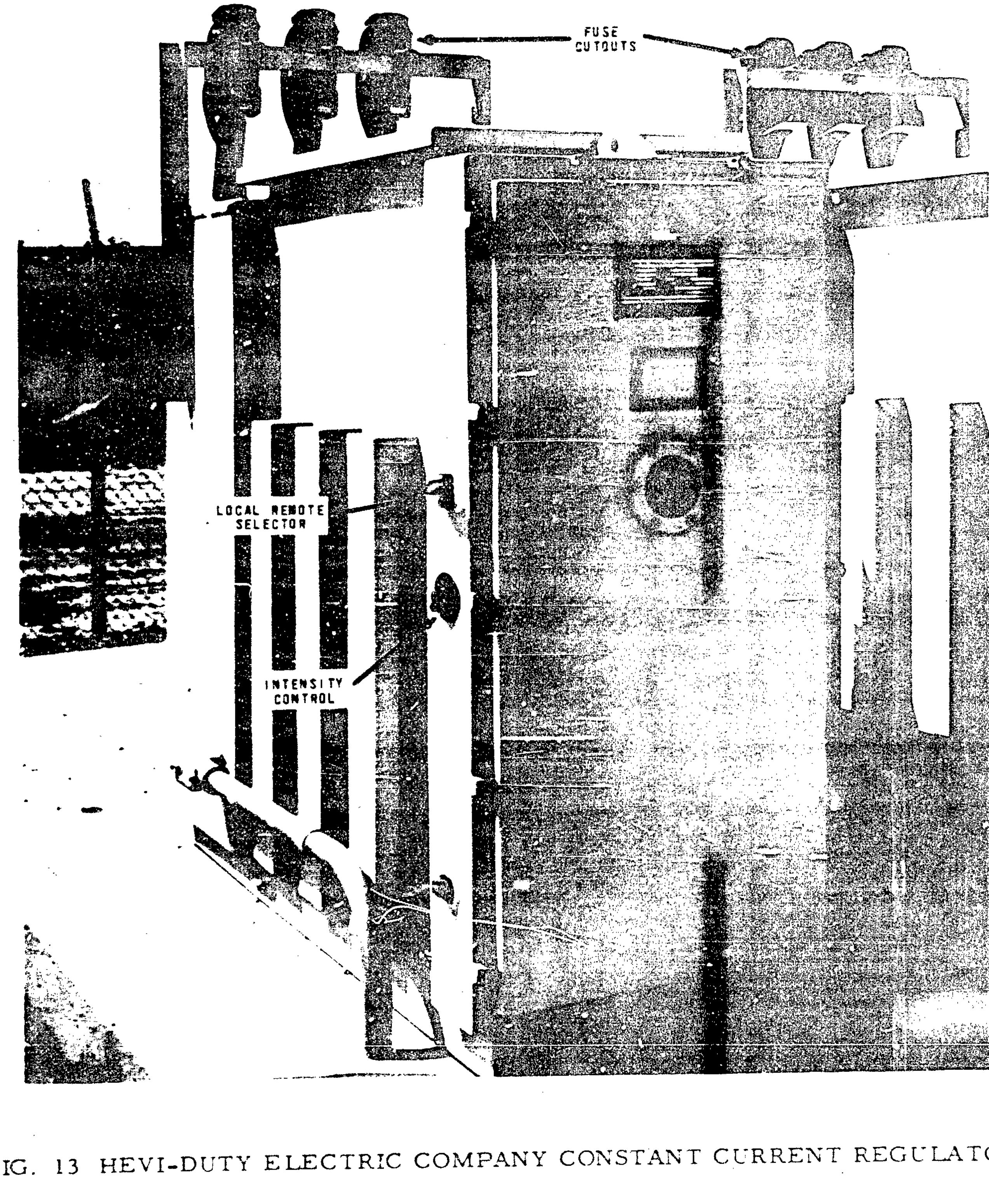


FIG. 13 HEVI-DUTY ELECTRIC COMPANY CONSTANT CURRENT REGULATOR

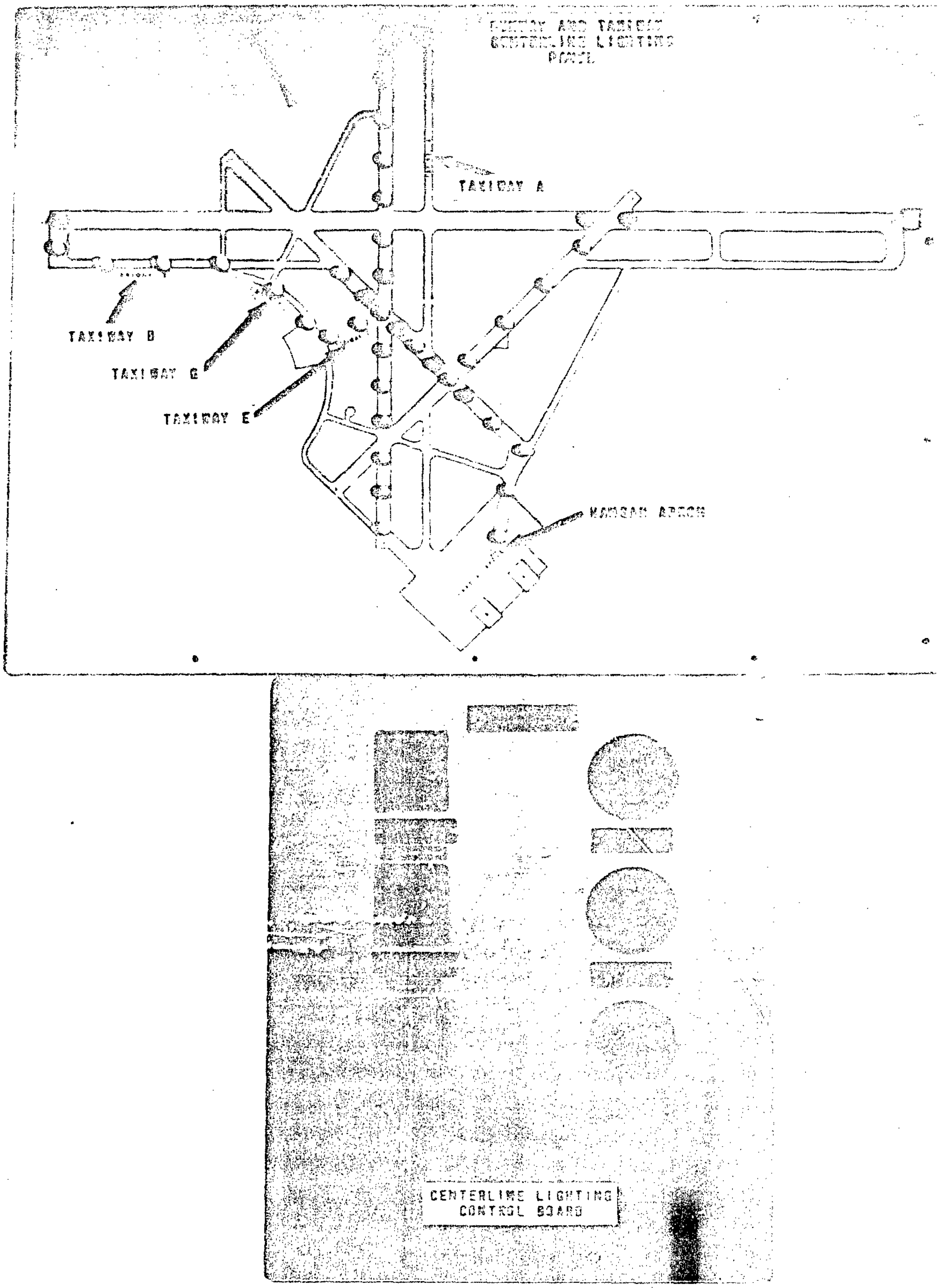


FIG. 14 TAXIWAY CENTERLINE LIGHTING CONTROL PANEL

DISCUSSION

Test Procedure

The test program was divided into three sections; (1) Aircraft Taxi Tests, (2) System Environmental Tests, and (3) Photometric Tests.

Aircraft Taxi Tests: The aircraft taxi tests were conducted in two phases. Phase I concerned taxiway lighting configurations and colors of taxiway centerline lighting. Phase II concerned the effectiveness of various fixture spacings in the taxiway centerline lighting system.

Fog conditions in both phases were simulated by placing Mylar film, which had been sprayed with lacquer, in the pilot's field of vision. The film attenuated and scattered light in a manner similar to fog. A sheet of Mylar film having a taxiway centerline light visibility (TCLV) of 1500 feet and mounted in fixed panels was used in Phase I. The density of the "fog" for Phase II could be adjusted from a 200 foot TCLV to a 600 foot TCLV by turning knobs that moved variable density Mylar film on rolls mounted in a frame. The Mylar film was mounted in a position that allowed the pilot complete freedom of head movement in both Phase I and Phase II tests. All taxi test runs were performed at night to reduce the possibility of extraneous visual references that could inadvertently provide taxiing guidance.

Pilots used as subjects in the taxi tests were instructed to taxi as they normally would and at a speed they considered to be comfortable for the visual guidance received from the lights.

Project observers were present in the cockpit for each test run. They sequenced the lighting patterns, adjusted the Mylar film, and interrogated subject pilots concerning the adequacy of patterns, color, and fixture spacing.

Phase I - Configuration and Color - The taxi tests in Phase I were timed by the cockpit observer from the start of the run at the intersection of Taxiways E and Runway 17-35 to the end of the run at the threshold of Runway 13. The taxiing times obtained gave an indication of relative pattern effectiveness.

Twelve subject pilots participated in Phase I. To obtain experience with a variety of cockpit cut-off angles and heights, the following five types of aircraft were used in Phase I tests: Douglas C-54, Gulfstream G-159, Convair 340 (C-131-B), Aero-Commander 680E, and Beechcraft C-45. Each pilot taxied once over each pattern and then acted as copilot for the next subject pilot. All runs were made with a TCLV of 1500 feet.

The configurations evaluated in Phase I were as follows:

1. Taxiway edge lighting (blue)
2. Taxiway centerline lighting (blue, green, and white)
3. Taxiway edge lighting combined with taxiway centerline lighting
4. Taxiway edge reflectors combined with taxiway centerline lighting (aircraft taxi lights used)

<u>Phase II - Spacing</u> - Nine subject pilots participated in Phase II. Each pilot taxied a Convair 340 aircraft twice over the test course (Sections A-H, FIG. 2). The first run was made with a TCLV of 600 feet. The second run was made with a TCLV of 200 feet. The taxiway segments were arranged so that some pilots first taxied with widely spaced centerline lights and later were exposed to closer spacing while other pilots initially taxied over the closely spaced lights and ended with the wider spacings. The average speed and errors in steering the aircraft were judged by observers who followed in an automobile.

To select spacings for Phase II, preliminary trials were conducted with the fog simulator mounted in an automobile. Following a small sample of the automobile runs, pairs of spacings were selected to represent what seemed to be reasonably good visual guidance at the narrow spacing extreme, and poor or marginal guidance at the wider extreme. These pretrials indicated that the sharpest turn (165 foot radius) was noticeably different from the next sharpest turn (200 foot radius) and presented a more difficult guidance situation.

The test taxiway consisted of four segments. Two fixture spacings (one in each direction) were obtained from each segment by masking one or both sides of certain of the bidirectional fixtures. By starting at one end of the course, traversing it, and returning to the starting position, the pilot used eight different configurations.

The color of the taxiway centerline lights was white for all segments. Breakage of the green filters, caused by the pressure of the aircraft wheels rolling over the fixtures, precluded the use of green light in this phase of the tests.

The following data were obtained while the pilot taxied over each segment:

1. The pilot was asked if the guidance he was obtaining was adequate or inadequate.
2. The pilot was asked how many lights he was aware of using while taxiing the aircraft.
3. The average deviation made by the nose-wheel of the aircraft away from the taxiway centerline.
4. The average ground speed of the aircraft.

Environmental Tests: These tests consisted of a series of inspections of all fixtures (including the reflective markers) to determine what effects weather and traffic imposed on them. This also included disassembly of the fixtures at periodic intervals to permit a visual inspection of the internal surfaces and components.

Photometric Tests:

Fixtures - Candlepower distribution curves on new lamps were obtained for each of the fixture types. Additional photometric data were obtained for the fixtures by using lamps that had been operated and subjected to the airport environment for the test period.

Reflective Markers - Four reflective markers were installed on an outside test pad. Two panels were used as controls and remained in their original container except when brightness measurements were being taken. Measurements were made with a Freund photometer. The markers were illuminated with 65 footcandles for the brightness measurements. Measurements were taken periodically to determine the decrease in marker brightness due to actual usage on the taxiway.

The reflectance factor for the markers was obtained by dividing the brightness of the panels expressed in footlamberts by illumination on the panel expressed in footcandles.

Test Results

Aircraft Taxi Tests:

Phase I - Configuration and Color -

1. Configuration - Two tests were applied to each configuration: (1) Pilot's preference for configuration as indicated by his responses on a questionnaire, and (2) Pilot's performance preference as indicated by the amount of time he required to taxi over a specified test course.

a. Pilot's Preference. The subject pilots were requested to rate the four taxiway lighting configurations in order of preference. In the analysis of the questionnaires, ranks were assigned to the orders of preference in the following manner: Rank 1 was assigned to the configuration having the highest order of preference, Rank 2 was assigned to the configuration preferred next, and so on until the fourth order of preference had been assigned. The ranks for each configuration were then totaled (Table I).

TABLE I

ORDER OF PILOT PREFERENCE FOR FOUR TAXIWAY LIGHTING CONFIGURATIONS TESTED

Configuration	Summation of Ranks	Order of Preference
Centerline plus edge lights	20	1
Centerline plus edge reflectors	23	2
Centerline lights only	31	3
Edge lights only	46	4

Inspection of the summation of ranks in Table I reveals little difference in pilot preference between edge lights and edge reflectors when combined with centerline lighting. The summation of ranks also reveals that centerline lights without edge lights or reflectors was preferred less than either of the two combination configurations. The edge lighting configuration was the least preferred of the four configurations tested.

The Friedman Two-Way Analysis of Variance Test[1] was applied (Appendix I) to the pilot responses on configuration to determine whether the differences of the sums of the ranks were due to random effects. It was determined that differences were due to other than random effects.

The t-test[2] (Appendix II) for the difference between two sample means was applied to the different pairs to determine if the differences could have been caused by chance. The differences between the first two preferences could have been due to random effects. However, the differences existing with both the third and fourth preferences were not from random effects.

b. Timed Runs. The timed run data was analyzed in the same manner as the data from the pilot preference questionnaires. Rank 1 was assigned to each pilot's fastest time, Rank 2 was assigned to the next fastest, and so on to the fourth order.

Table II lists the taxiway lighting configurations in the order of their timed performance and shows the summation of ranks.

TABLE II

ORDER OF CONFIGURATION PERFORMANCE OF TIMED TAXI RUNS

Configuration	Summation of Ranks	Order of Performance
Centerline plus edge reflectors	15	1
Centerline only	20	2
Centerline plus edge lights	24	3
Edge lights only	31	4

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[1] Siegel, Sidney, Nonparametric Statistics for the Behaviorial Sciences. McGraw-Hill, New York, 1956, pp. 166-172

[2] Davies, O. L. The Design and Analysis of Industrial Experiments. Hafner, New York, 1960, pp. 25-26

Inspection of the summation of ranks indicates that little difference existed between the centerline configurations. The edge lighting configuration required the most taxiing time and the differences between it and the centerline configurations proved to be statistically significant.

The timed runs rated the centerline plus edge reflectors configuration ahead of the other centerline configurations. This apparent shift was caused by the fact that pilots were able to obtain guidance and speed indications from the surface of the taxiway when the aircraft taxi lights were used to obtain light for the reflectors.

2. Color - Three colors (white, green, and blue) were initially included in this evaluation. When approximately 50% of the test runs had been completed, the data were evaluated to determine if a trend had developed that would allow a reduction in project cost. It was found that the subject pilots who had completed the test were unanimous in their opinion that green and white were preferred to blue because the blue lacked intensity (FIG. 18). The tests on the blue color were discontinued at this point in the evaluation.

Table III shows the questions asked each subject pilot, as well as a summary of the responses.

TABLE III

PILOT RESPONSES TO COLOR OF TAXIWAY CENTERLINE LIGHTING

Question	Summary of Responses	
Should white, blue or green	White	8
lights be used in an all-weather	Blue	0
centerline lighting aid?	Green	7
(The following question replaced the question above when blue was dropped from the test)		
Did you consider either	Yes	2
white or green unacceptable	No	10
for taxiway lighting use?		

A preference for white or green could not be determined from this analysis. Pilot comments (Appendix III) revealed that about one-half of the pilots who preferred green did so because it differentiated between taxiway lighting and runway lighting, and because it is a restful color. Those preferring white did so because of the greater intensity.

<u>Phase II - Spacing</u> - The following three tests were used to determine the spacing of taxiway centerline lights that would provide adequate guidance to the pilot when taxiing in 600 feet and 200 feet of TCLV: speed over the taxiway segment, displacement of the nosewheel from the centerline, and pilots' opinion of the adequacy of guidance given. An analysis has been made on the spacing of fixtures for a taxiway lighting system based on the results obtained in this program. The analysis is presented at the end of this section of the report. The results of the three tests listed above were as follows:

1. <u>Straight Taxiway</u> - Table IV lists the results of the tests applied to the straight taxiway (Segments C and F).

With the centerline lights spaced 100 feet and 50 feet apart in a TCLV of 600 feet, there was no real difference indicated by the test data on mean speed and mean displacement. Opinion of the pilots indicated that either spacing was adequate.

In a TCLV of 200 feet, with the lights spaced 100 feet and 50 feet apart, there was no real difference indicated by the test data on mean speed. However, a real difference, favoring a 50-foot spacing, was indicated by the test data on mean nosewheel displacement. Opinion of the pilots supports the difference indicated by nosewheel displacement.

Neither the mean nosewheel deviation nor the maximum nosewheel deviation (about 3 feet) recorded in the test data for the straight taxiway section placed the aircraft in danger of running off the taxiway.

2. <u>Curved Taxiway (1280 foot radius)</u> - Table V lists the results of the tests applied to the curved taxiway with a 1280-foot radius (Segments A and H).

TABLE IV

STRAIGHT TAXIWAY (SEGMENTS C AND F) TEST RESULTS

TCLV = 600 feet

Light Spacing (ft.)	Mean Speed Over Segment (mph)	Mean Nosewheel Displacement (ft.)	Summary of Pilots' Opinion of Adequacy
100	15.0	1.5	Adequate
50	15.6	1.7	Adequate

TCLV = 200 feet

Light Spacing (ft.)	Mean Speed Over Segment (mph)	Mean Nosewheel Displacement (ft.)	Summary of Pilots' Opinion of Adequacy
100	13.8	1.5	Inadequate
50	14.4	0.9	Adequate

TABLE V

CURVED TAXIWAY (SEGMENTS A AND H 1280 FOOT RADIUS)
TEST RESULTS

TCLV = 600 feet

Light Spacing (ft.)	Mean Speed Over Segment (mph)	Mean Nosewheel Displacement (ft.)	Summary of Pilots' Opinion of Adequacy
50	14.0	1.5	Adequate
25	13.3	1.7	Adequate

TCLV = 200 feet

Light Spacing (ft.)	Mean Speed Over Segment (mph)	Mean Nosewheel Displacement (ft.)	Summary of Pilots' Opinion of Adequacy
50	11.9	1.1	Inadequate
25	10.9	0.9	Adequate

With the centerline lights spaced 50 feet and 25 feet apart on a curve with a 1280 foot radius, and with a TCLV of 600 feet, there was no real difference indicated by the test data on mean speed and mean displacement. Opinion of the pilots indicated that either spacing was adequate.

In a TCLV of 200 feet, with the lights spaced 50 feet and 25 feet apart, the test data on mean speed and mean nosewheel displacement indicated a small apparent difference in favor of the 25 foot spacing. Opinion of the pilots supports the difference indicated by both speed and displacement.

Here again, neither the mean nor the maximum (8 feet) nosewheel deviation recorded in the test data placed the aircraft in danger of running off the taxiway. This information may be useful when considering future taxiway design where centerline lighting is to be used.

3. Curved Taxiway (200 foot radius) - Table VI lists the results of the tests applied to the curved taxiway with a 200-foot radius (Segments B and G).

When the TCLV was 600 feet, and the lights were spaced 25 feet and 12.5 feet apart, the mean speed and mean nosewheel displacement indicated a small difference in favor of the 25-foot spacing. However, the opinion of the pilots indicated that either spacing was adequate.

For the 200 foot TCLV, the mean speed and mean displacement indicated a moderate difference in favor of the 25-foot spacing. However, opinion of the pilots indicated that the 25-foot spacing was inadequate. This paradox could probably be resolved in favor of the pilots' opinion by noting the data on nosewheel displacement when the TCLV was 200 feet (Tables IV, V, VI, and VII). On the straight and large radius curved taxiways the nosewheel deviation varied directly with light spacing and thus was greater at the same time opinion of the pilots rated the longer spacings as inadequate. Because these taxiways did not involve a high rate of turn in the low visibility, pilots felt secure in letting the nosewheel wander off course a small amount. However, as the curves became sharper the pilots felt more secure when they kept the nosewheel as close to the centerline as possible and, therefore, made a greater effort to control the rate of turn when the guidance received was considered inadequate.

Here again the mean nosewheel deviation in both TCLV's was less than two feet.

TABLE VI

CURVED TAXIWAY (SEGMENTS B AND C - 200 FOOT RADIUS) TEST RESULTS

TCLV = 600 feet

Light Spacing (ft.)	Mean Speed Over Segment (mph)	Mean Nosewheel Displacement (ft.)	Summary of Pilots' Opinion of Adequacy
25	9.8	1.4	Adequate
12.5	8.6	1.8	Adequate

TCLV = 200 feet

Light Spacing (ft.)	Mean Speed Over Segment (mph)	Mean Nosewheel Displacement (ft.)	Summary of Pilots' Opinion of Adequacy
25	8.7	1.0	Inadequate
12.5	7.0	1.6	Adequate

4. Curved Taxiway (165 foot radius) - Table VII lists the results of the tests applied to the curved taxiway with a 165-foot radius (Segment D and E).

When the TCLV was 600 feet on this curve, and the lights were spaced 25 feet and 12.5 feet apart, the mean speed test data indicated no real differences. However, the mean nosewheel displacement test data indicated that a real difference did exist in favor of the 25-foot spacing. Pilots' opinion rated the 25 foot spacing as inadequate and the 12.5 foot spacing as adequate. Here again, pilot opinion was reasonable even though not substantiated by performance data.

For the 200 foot TCLV on this curve (165-foot radius), the mean speed and mean nosewheel deviation test data indicated that no real differences existed between the two light spacings. Pilots' opinion indicated that both spacings gave inadequate guidance and thus supported the no real difference indications of the speed and deviation test data.

The mean nosewheel deviation on this final curve was similar to the three previous taxiway segments. It remained less than two feet and strengthened the possibility that this information might be useful in future design of taxiways with centerline lighting.

Environmental Tests

Structural Electric Products Corporation Fixture: The tests made on these fixtures resulted in very few lamp burn-outs. Both the lamps and filters, however, accumulated thick films of dirt and numerous filters were cracked or broken. When the damaged filters were replaced, the filter clips, which had rusted, would break. Three of these fixtures had to be replaced because the male contact in the fixture base became electrically grounded. The grounding apparently was caused by poor electrical contact with the lamp strap, which in turn caused charring and pitting. Charring and pitting were also found in fixtures that had not failed. Finally, deposits of sand and dust were found in the lamp strap recess of the base in all fixtures. It was evident that enclosing the lamp compartment of these fixtures with lenses or prisms would correct a number of the faults.

Strong Electric Corporation Fixture: Ice expansion in the recesses of both the 5-[illegible] inch and 7-13/16 inch fixtures caused the lamps to crack or shatter. Freezing of these fixtures made it very difficult to remove the lamp assembly for repairs. Efforts to pry the lamp assembly free of the fixture resulted in breaking the strap of the fixture away from the lamp assembly.

TABLE VII

CURVED TAXIWAY (SEGMENTS D AND E - 165 FOOT RADIUS)
TEST RESULTS

TCLV = 600 feet

Light Spacing (ft.)	Mean Speed Over Segment (mph)	Mean Nosewheel Displacement (ft.)	Summary of Pilots' Opinion of Adequacy
25	9.0	1.1	Inadequate
12.5	9.2	1.6	Adequate

TCLV = 200 feet

Light Spacing (ft.)	Mean Speed Over Segment (mph)	Mean Nosewheel Displacement (ft.)	Summary of Pilots' Opinion of Adequacy
25	7.1	1.0	Inadequate
12.5	7.8	1.0	Inadequate

In addition to the ice damage, numerous transformer cores were rusted and core laminations were separated (FIG. 15).

A laboratory test was conducted on the fixtures by filling four of the fixtures with water and subjecting them to a temperature of 0° F until freezing occurred. The frozen fixtures were allowed to remain at 0° F three hours after freezing and then were thawed at room temperature. The test results are shown in Table VIII.

TABLE VIII

RESULTS OF FREEZING TEST

Fixture Type	Damage Sustained
Strong 7-13/16 inch	Lamp envelope severely cracked
Strong 7-13/16 inch	Lamp envelope broken into several pieces
Strong 5-7/8 inch	Lamp envelope completely shattered
Strong 5-7/8 inch	Lamp envelope broken into several pieces

Construction work on Runway 17-35 interfered with all tests of the Strong Electric Corporation fixtures except environmental tests. It had been planned that the Strong Electric Corporation fixtures would be operated when the runway repairs were completed. Problems encountered with the freezing conditions indicated above made further tests unnecessary.

Stillman Rubber Company Fixtures: The rubber diaphragms of the Stillman Rubber fixtures were unable to withstand repeated aircraft tire strikes. Hairline cracks in the rubber appeared shortly after installation and these cracks gradually become larger (FIGS. 16 and 17). A summary of rubber diaphragm failures from May 1962 through March 1963 is shown in Table IX.

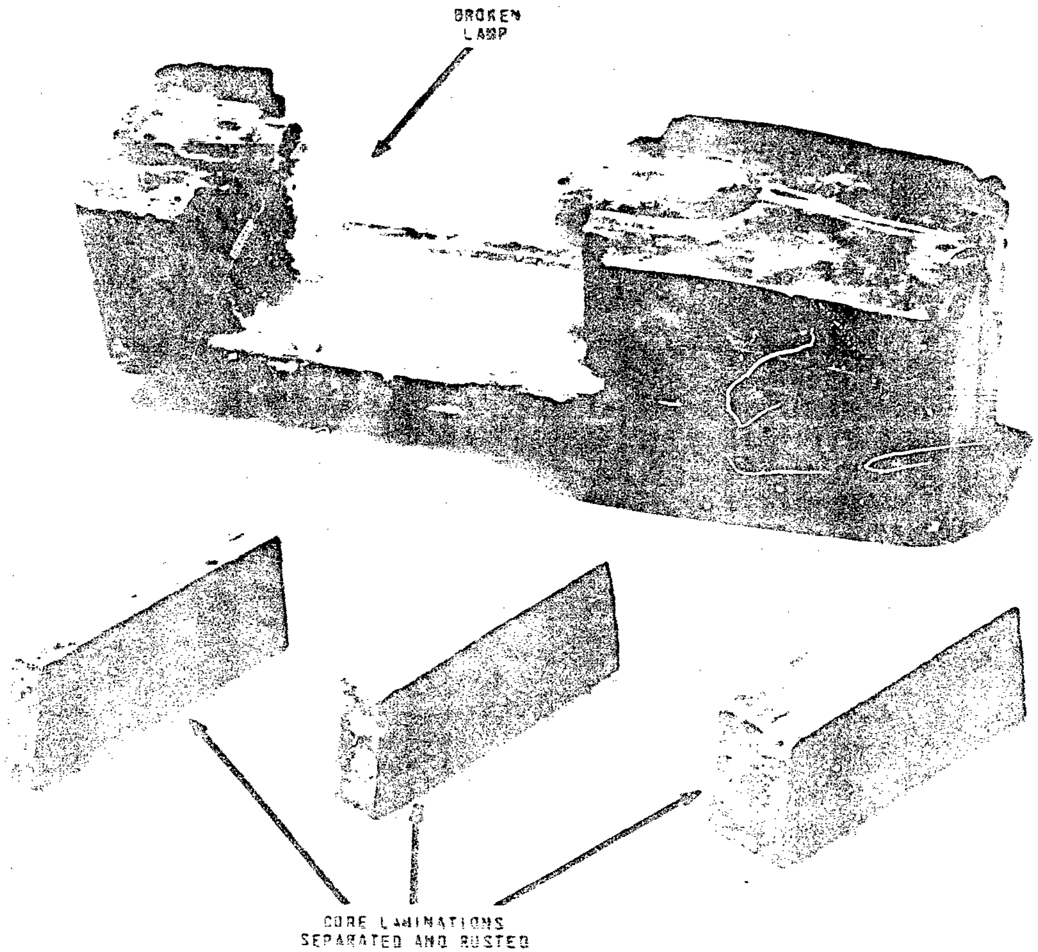


FIG. 15 DAMAGE TO COMPONENTS OF THE 7 13/16-INCH STRONG ELECTRIC CORPORATION FIXTURE

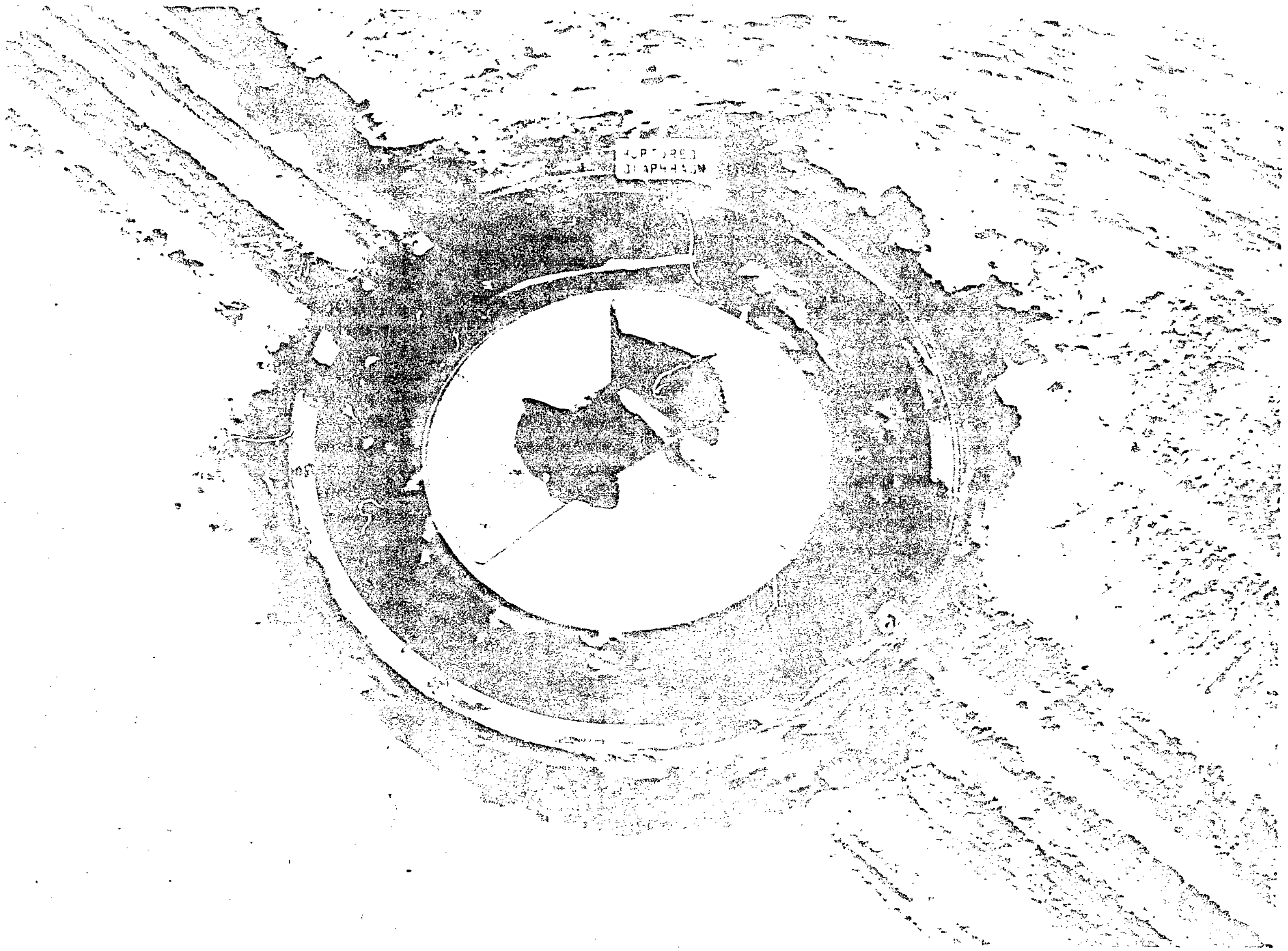


FIG 15 TYPICAL DAMAGE SUSTAINED BY
STILLMAN RUBBER COMPANY FIXTURES

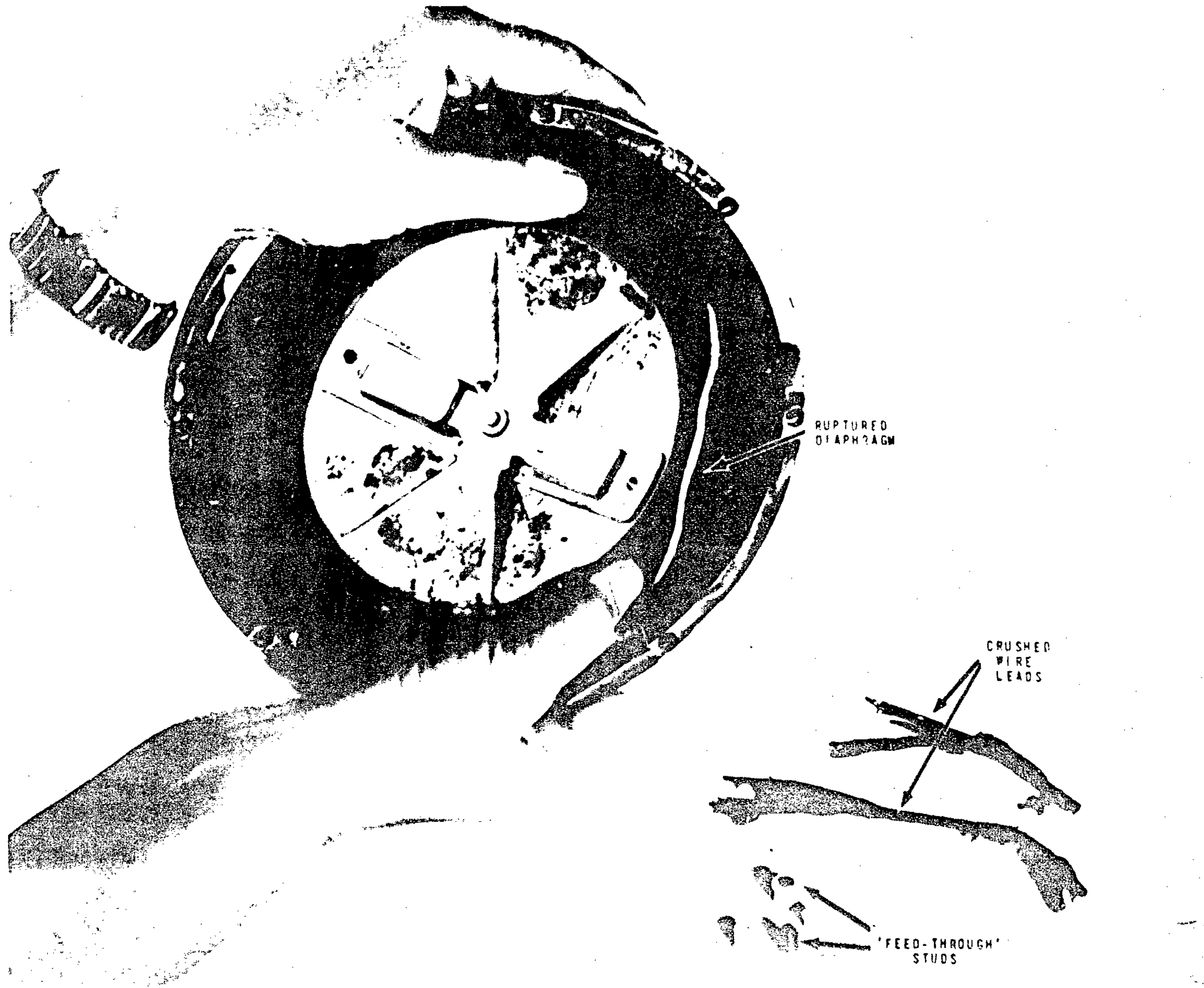


FIG. 17 EXAMPLE OF SEVERE RUBBER DIAPHRAGM DAMAGE SUSTAINED BY STILLMAN RUBBER COMPANY FIXTURE

TABLE IX

RUBBER DIAPHRAGM FAILURES ON THE STILLMAN FIXTURE BETWEEN MAY 1962 AND MARCH 1963 (RUNWAY 8-26)

Damage Sustained	Number of Fixtures	Percent of Installation
None apparent	15	10
Surface ruptures	24	16
Severe ruptures and slight separation	76	51
Severely ruptured requiring removal of the top assembly	33	22
Top missing	2	1

Table X contains additional data concerning the 33 fixtures which were severely ruptured and which required removal of the top assembly.

TABLE X

ADDITIONAL DATA CONCERNING 33 SEVERELY DAMAGED STILLMAN FIXTURES

Failure	Number of Fixtures
Broken lamps	7
Male contacts broken from top assembly	14
"Feed through" studs detached from top assembly	18
Clips broken off wire leads	16
Clips disconnected from male portion of "feed through" stud	9

Inspection of the individual fixtures proved to be difficult because the top assembly could not be easily removed. The top assembly became wedged in the base assembly because of the initial tight fit of the top assembly and the added pressure applied to the rim of the base after installation. The Stillman Rubber Company modified a lamp strap into a tool for removing the top assemblies, but it bent because of inadequate strength. A heavier tool was then fabricated at NAFEC which permitted removal of the top assemblies. Inspection revealed that crushed or broken wires between the studs in the top assembly and the power leads was the primary damage. Attempts to repair the electrical damages proved to be costly and time consuming and thus were discontinued. Periodic visual inspection of the fixtures was continued, however.

Power: No problems were encountered with the 180-cycle regulator or the switching components in the power circuit. This system operated in a satisfactory manner throughout the test program.

Reflective Markers: The reflective markers often were dislodged or bent from their original position by jet and propeller blasts. The sandy soil at NAFEC would not hold the wire strand securely enough to withstand the force of jet or prop wash from aircraft operating along the taxiway. A more permanent reflector installation, such as the small button reflector commonly seen along highways, would probably require very little maintenance and would be less subject to dirt accumulation.

Photometric Tests

The results of the photometric tests are shown in Figures 18 and 19. Figure 18 compares the photometric characteristics of the fixtures evaluated and also shows the photometric characteristics of a Structural Electric Corporation fixture equipped with green or blue filter.

The wide horizontal beam spread of the fixtures used in this test was adequate for all sections of taxiways except the 115-foot radius (Segment J) and the 95-foot radius at the intersection of taxiways E and G. An analysis has been made of the horizontal beam-spread requirements for a taxiway lighting system, based on the results obtained in this program. The analysis is presented at the end of this section of the report and in Appendix IV.

Figure 19 compares the reflectance factors of new (control) and installed reflective markers over a period of sixty-six weeks.

Filters: When blue or green filters were installed in the fixtures, the intensity of light output decreased approximately 80 percent for green and

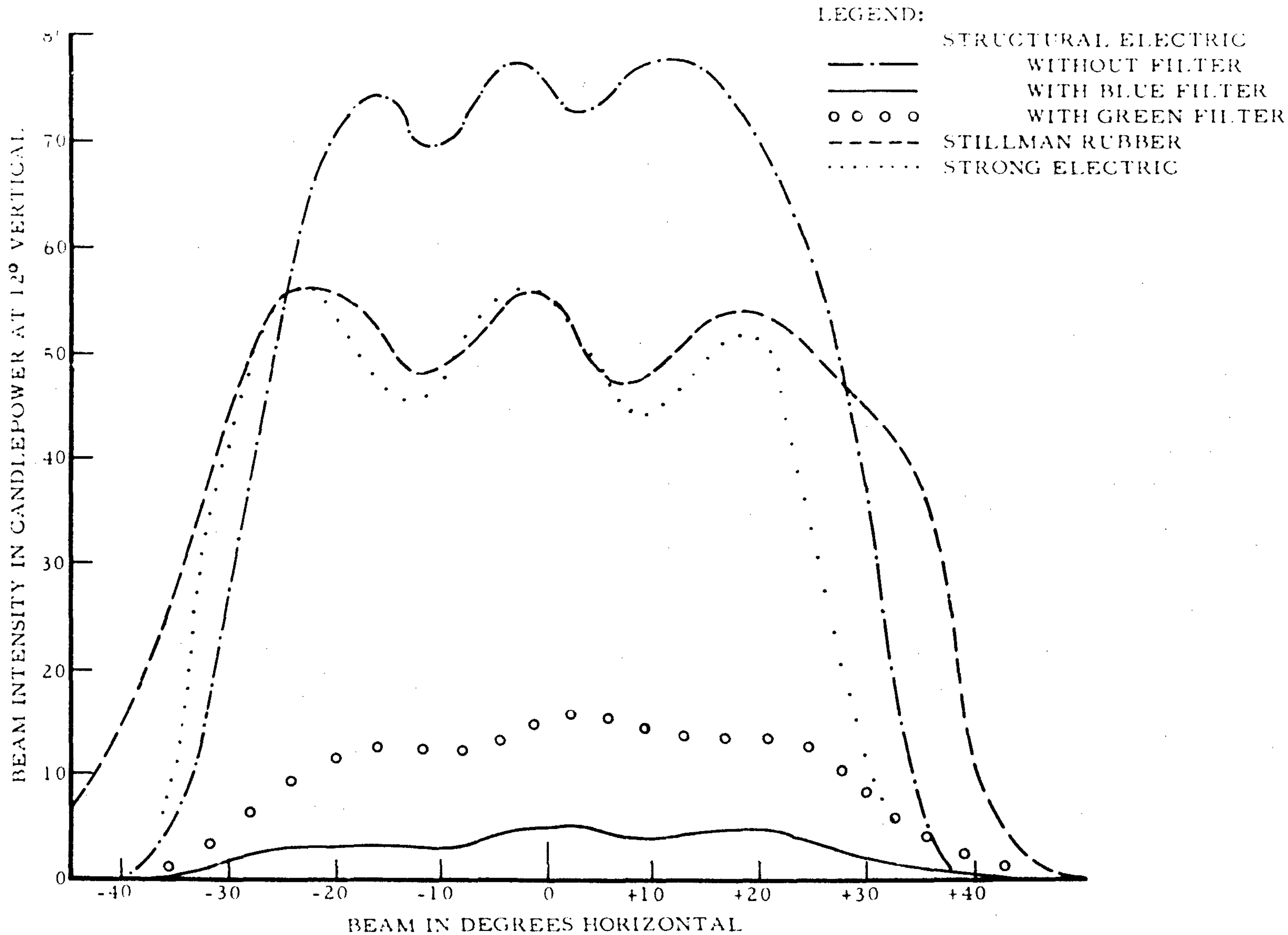
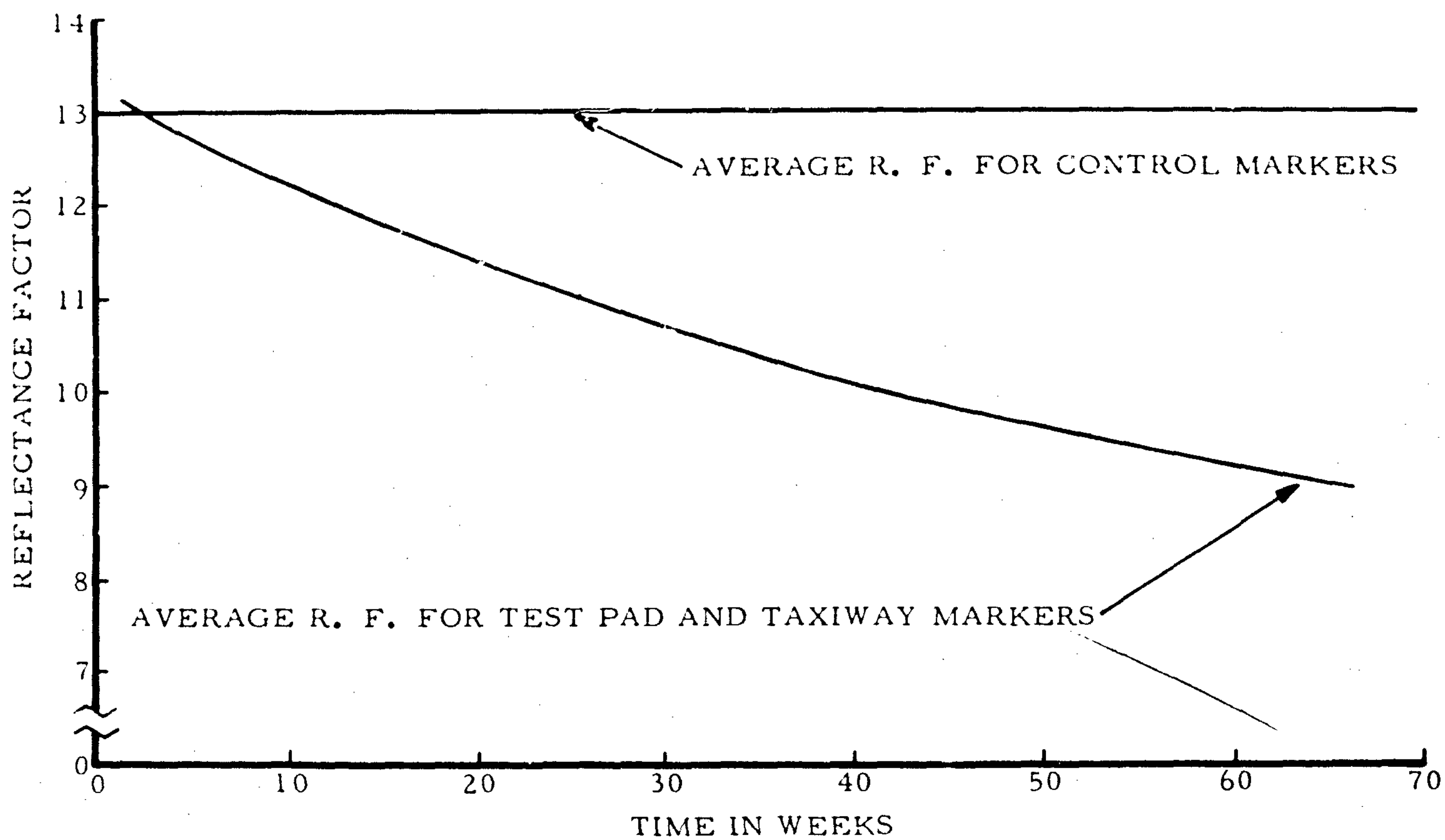


FIG. 18 PHOTOMETRIC DATA ON STRUCTURAL ELECTRIC PRODUCTS CORPORATION, STRONG ELECTRIC CORPORATION, AND STILLMAN RUBBER COMPANY FIXTURES



NOTE:

$$\text{REFLECTANCE FACTOR} = \frac{\text{BRIGHTNESS (FOOT LAMBERTS)}}{\text{ILLUMINATION (FOOT CANDLES)}}$$

FIG. 19 PHOTOMETRIC DATA ON MINNESOTA MINING AND MANUFACTURING COMPANY REFLECTIVE MARKERS

96 percent for blue (FIG. 18). Observations of the filtered light during daylight hours revealed that the intensity of both blue and green lights was inadequate for daylight use.

Reflective Markers:

Reflectance Factor - The average reflectance factors for the reflective markers exposed on the test pad and those installed along the taxiway edge varied. The reflective markers on the test pad were located some distance from the taxiway and thus were subjected to different environmental conditions.

Any variation in reflectance factor with time was caused by variations in environmental conditions, i.e., dust on the reflector in dry periods and partial cleaning of the reflector by rain or wind. Data were taken to obtain a comparison of reflectance factors between dry and damp reflectors. This comparison indicated very little difference in reflectance factor.

The reflective markers along the taxiway were washed at the end of the test period and a comparison of reflectance factors between washed and unwashed markers was made. The washed markers produced a 17 percent increase in reflectance factor over the unwashed.

Useful Life - The evaluation period was not long enough to determine the useful life of the reflective markers except in those cases where their usefulness was ended by the jet or propeller blast of passing aircraft. Figure 19 compares the average reflectance factors of control reflective markers used as reference and reflective markers that had been installed on the airfield for a period of 66 weeks.

Analysis of Test Results

Adequacy of Spacing: A method of making perspective diagrams, used extensively by E. S. Calvert of the United Kingdom, [1] was employed in the following analysis to facilitate the interpretation of results obtained in the evaluation program.

Briefly, this procedure (APPENDIX V) produces a diagram which depicts the view a pilot sees from the cockpit of an aircraft (FIG. 20 through 31). In this evaluation perspective diagrams were made for each

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[1] E. S. Calvert, B.Sc., A.R.C. Sc. I., The Use of Perspective Diagrams in Problems Relating to Airfield Lighting, Royal Aircraft Establishment, Farnborough, Hants, England, Report Number EL 1413, January 1947

taxiway segment, TCLV, and centerline light spacing. The diagrams were analyzed and compared with the pilots' opinion of the adequacy of guidance he received from the centerline lights. It was determined from this comparison that each time the prevailing pilots' opinion rated the spacing of the lights on a curve adequate for taxiing guidance, four or more lights were enclosed in a 10-degree cone which had its apex at the pilot's eye. Three or more lights provided adequate guidance on straight sections. The 10-degree cone is the 10-degree horizontal angle which contains the most lights.

The TCLV in Figures 20 through 31 is 200 feet, the cockpit cutoff (the lower limit of pilots' vision caused by aircraft configuration) is 15 degrees at the center of the perspective, and the pilot's head is assumed to be in a normal position. The cockpit cutoff chosen is one typical of large jet transport aircraft.

Figures 20 and 21 are perspective drawings which illustrate the pilots' view of a straight segment of taxiway centerline lighting.

Figure 20 illustrates what is seen when the lights are spaced 100 feet apart. The pilots rated this as inadequate guidance. Figure 21 illustrates what is seen when the lights are spaced 50 feet apart. The pilots rated this as adequate guidance.

Figures 22 and 23 illustrate the pilots' view of a curved taxiway which has a centerline radius of 1280 feet. In Figure 22, the lights are spaced 50 feet apart. The pilots rated the guidance received as inadequate. Figure 23 is the same as Figure 22 except that the lights are spaced 25 feet apart. The pilots rated the 25-foot spacing as adequate.

Figures 24 and 25 illustrate the pilots' view of a curved taxiway which has a centerline radius of 200 feet. In Figure 24, the lights are spaced 25 feet apart, and the pilots rated the guidance received as inadequate. Figure 25 illustrates the same curve as Figure 24 except that the lights are spaced 12.5 feet apart. The pilots rated the 12.5 foot spacing as adequate. Again, the 10-degree cone contained less than four lights when the guidance was rated inadequate, and four or more lights when the guidance was rated adequate.

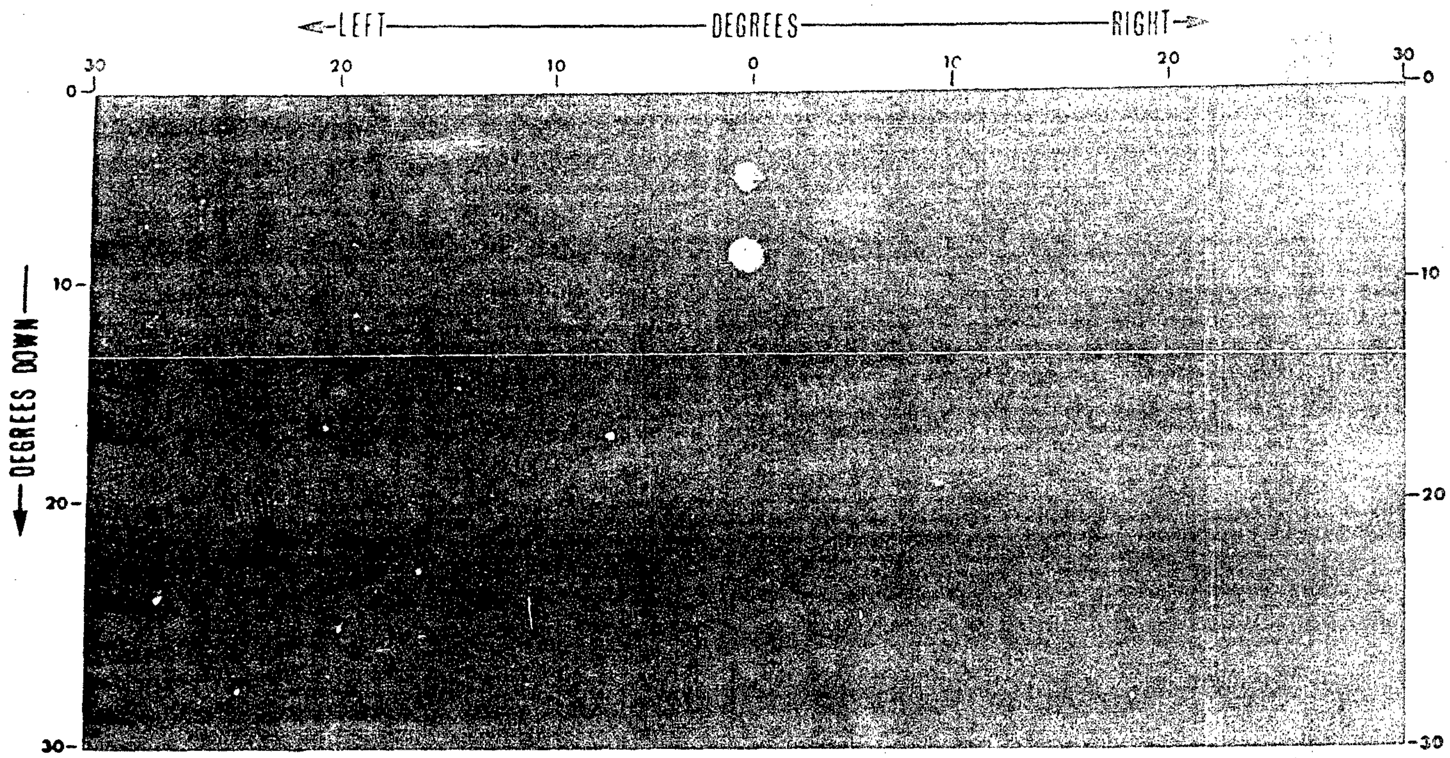

FIG. 20 PERSPECTIVE DIAGRAM. STRAIGHT TAXIWAY, TCLV 200 FEET AND CENTERLINE LIGHTS SPACED 100 FEET APART. GUIDANCE INADEQUATE.

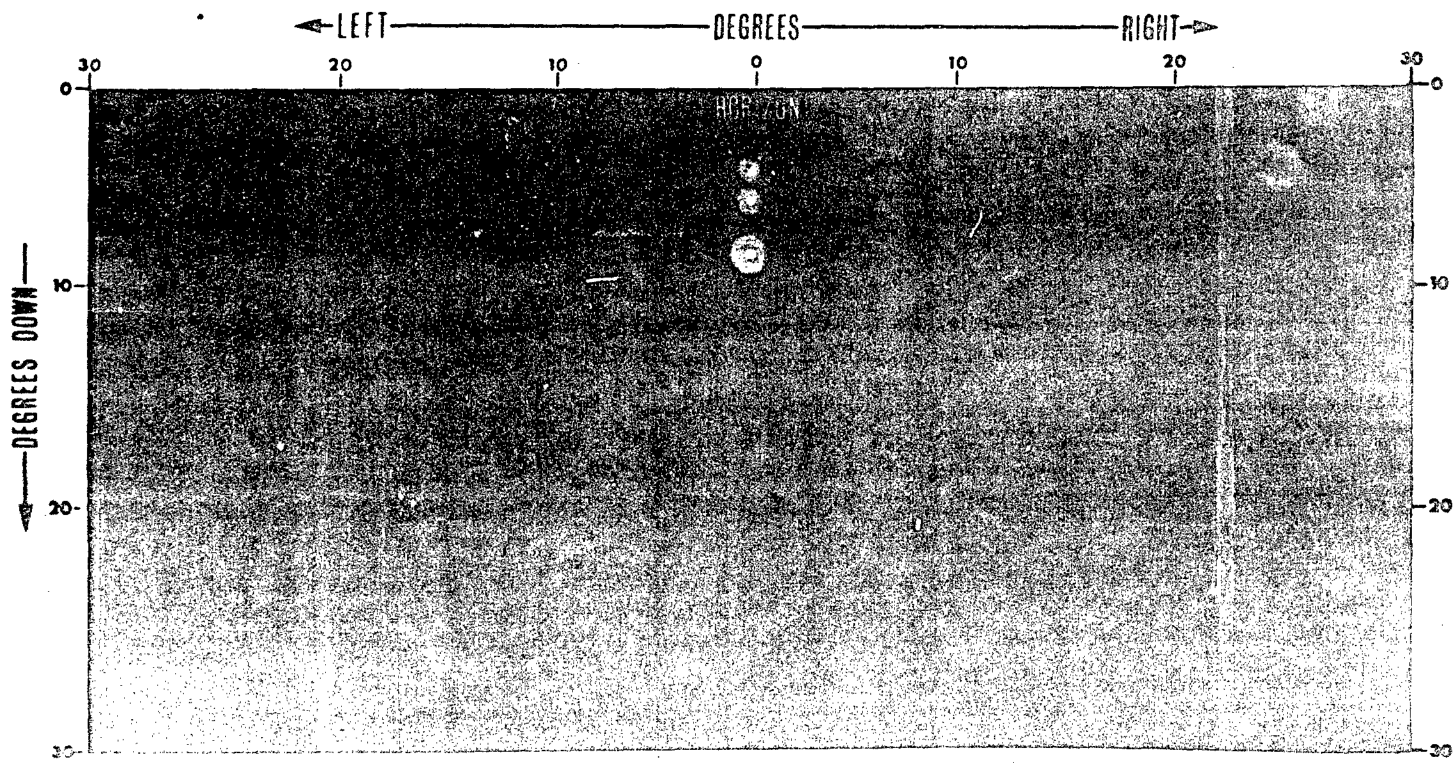

FIG. 21 PERSPECTIVE DIAGRAM. STRAIGHT TAXIWAY, TCLV 200 FEET, AND CENTERLINE LIGHTS SPACED 50 FEET APART. GUIDANCE ADEQUATE.

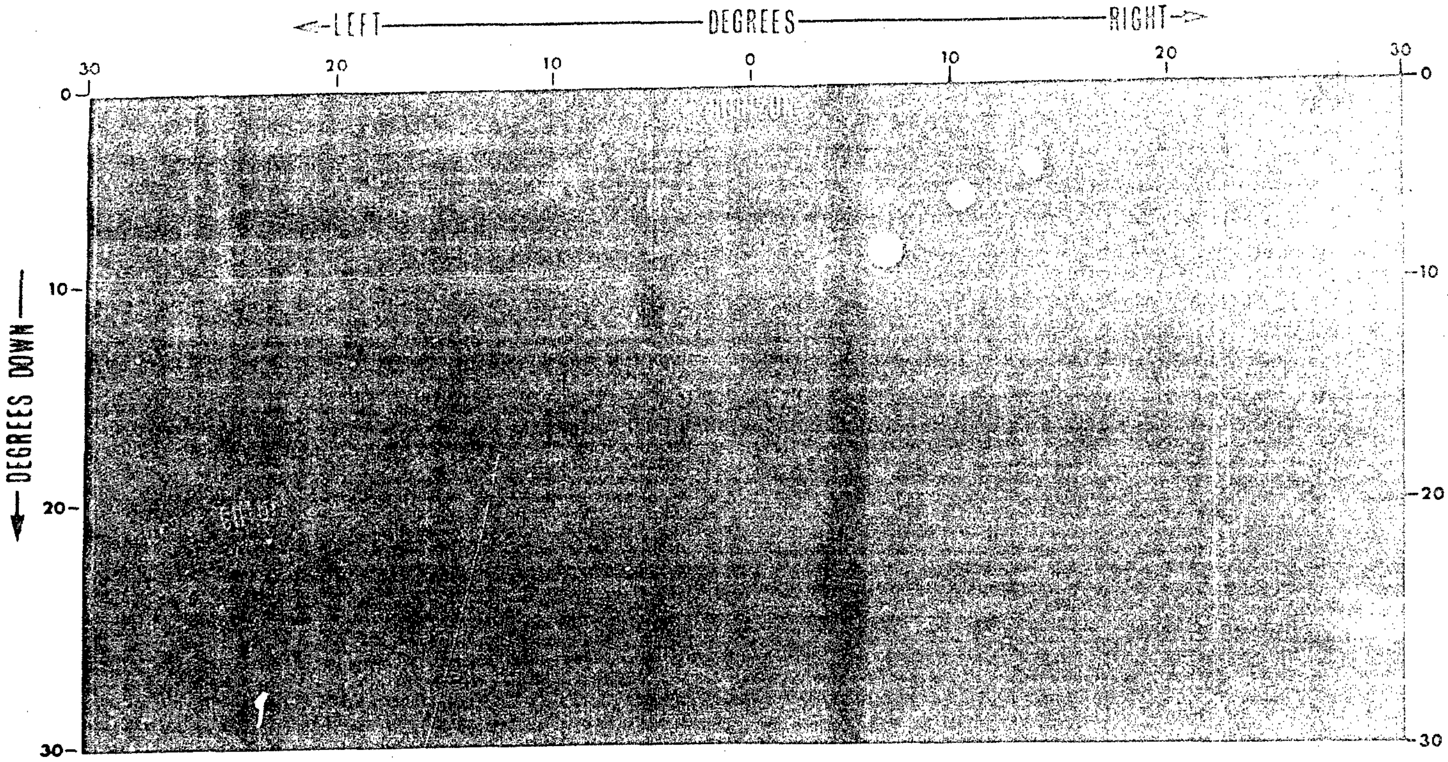

FIG. 22 PERSPECTIVE DIAGRAM. 1280 FOOT RADIUS CURVE, TCLV 200 FEET, AND CENTERLINE LIGHTS SPACED 50 FEET APART. GUIDANCE INADEQUATE.

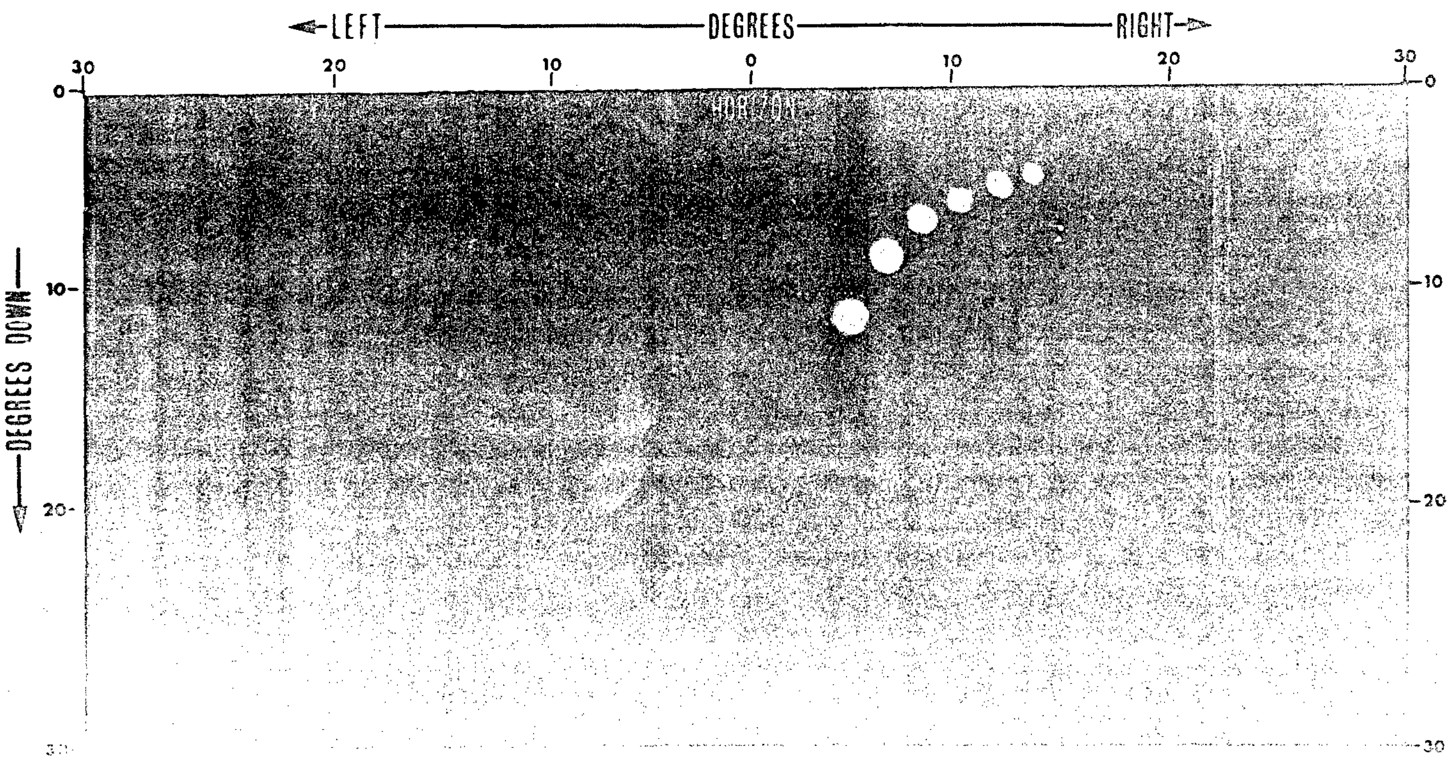

FIG. [illegible] PERSPECTIVE DIAGRAM. 1280 FOOT RADIUS CURVE, TCLV 200 FEET, AND CENTERLINE LIGHTS SPACED 25 FEET APART. GUIDANCE ADEQUATE.

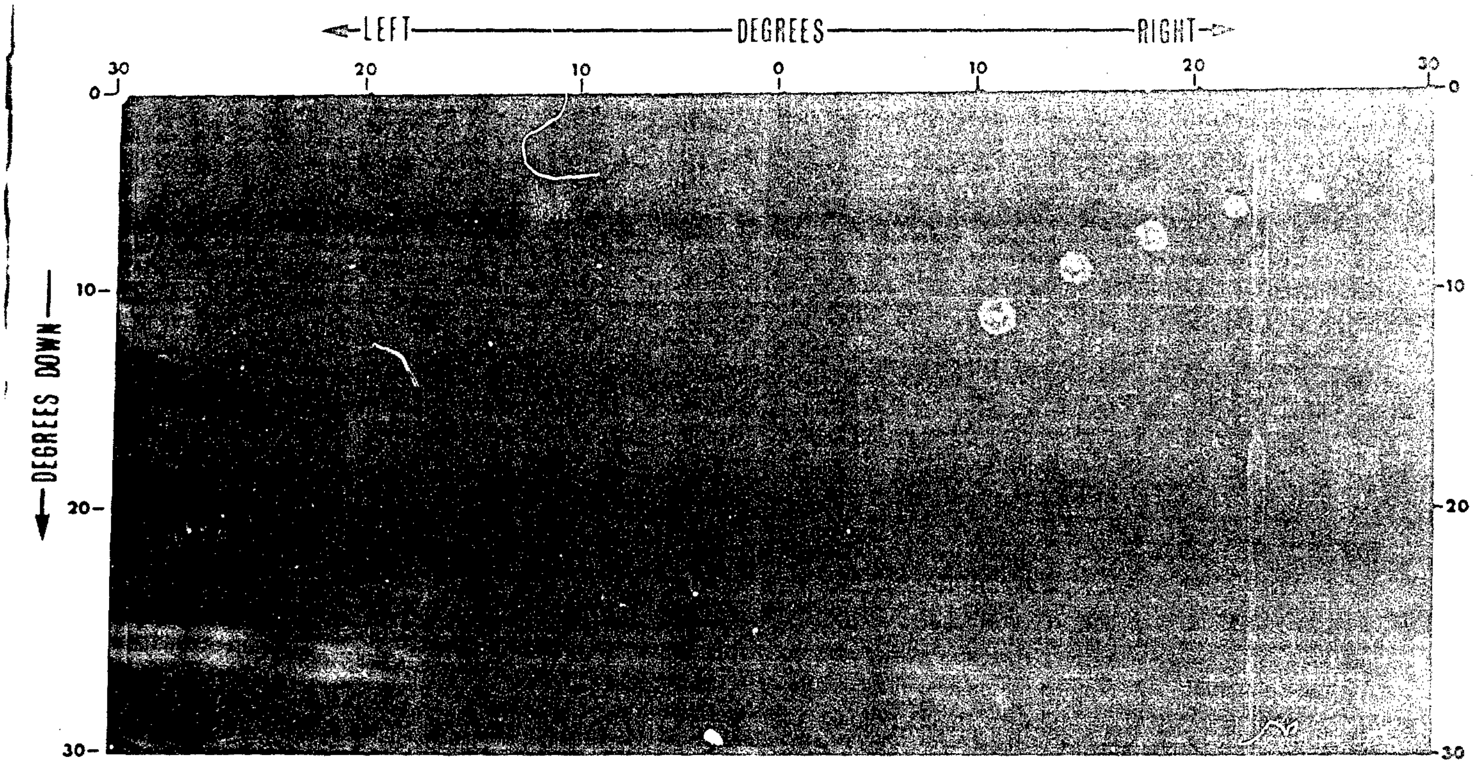

FIG. 24 PERSPECTIVE DIAGRAM. 200 FOOT RADIUS CURVE, TCLV 200 FEET, AND CENTERLINE LIGHTS SPACED 25 FEET APART. GUIDANCE INADEQUATE.

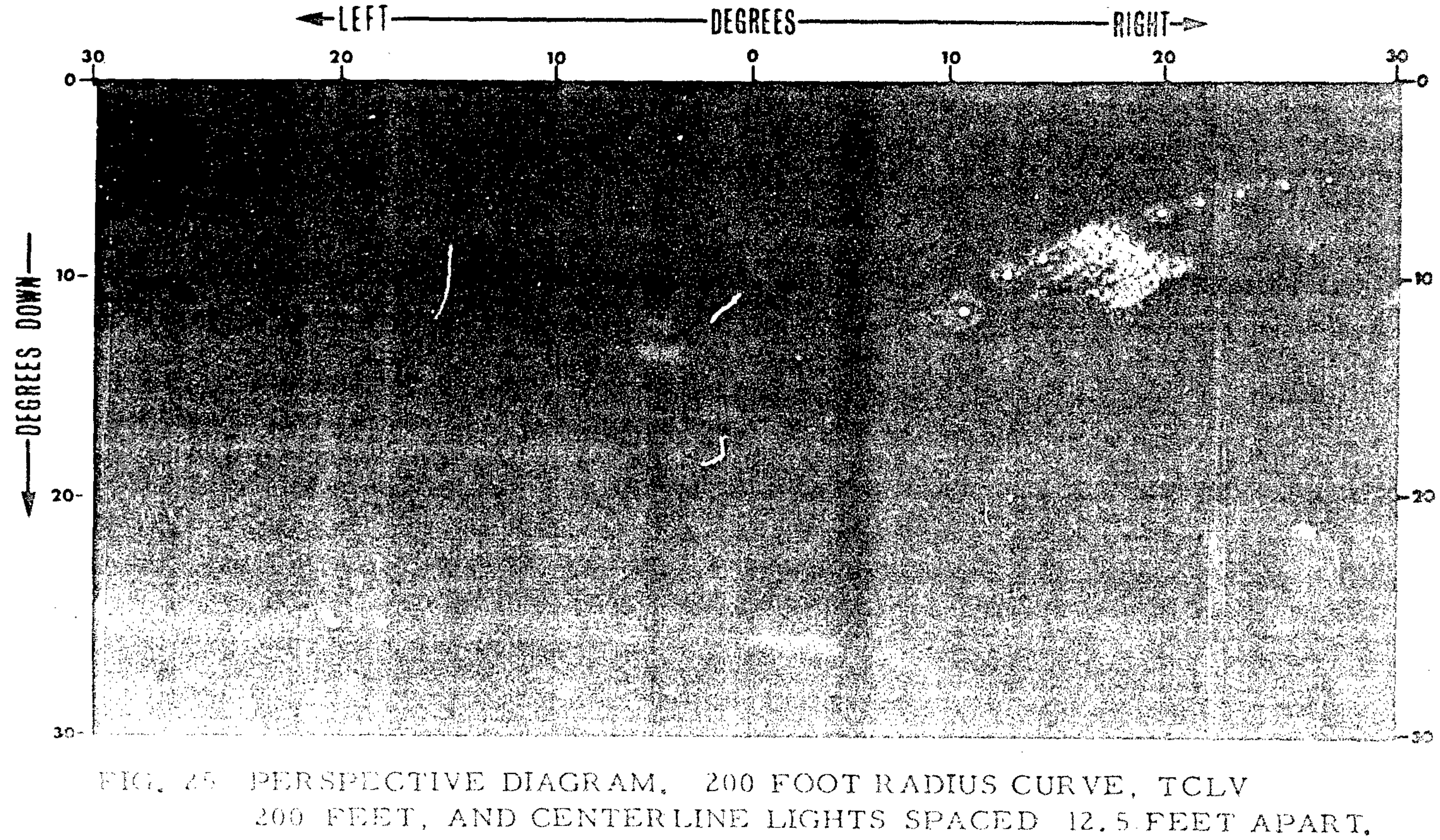

FIG. 25 PERSPECTIVE DIAGRAM. 200 FOOT RADIUS CURVE, TCLV 200 FEET, AND CENTERLINE LIGHTS SPACED 12.5 FEET APART. GUIDANCE ADEQUATE.

Figures 26 and 27 illustrate the pilots' view of a curved taxiway that has a centerline radius of 165 feet. When the lights were spaced 25 feet apart (FIG. 26) the pilots rated the guidance as inadequate, and when the lights were spaced 12.5 feet apart (FIG. 27) the pilots still rated the guidance as inadequate.

The apparent inconsistency between the results from the pilots' ratings (Table VII) and the results from the perspective diagrams (FIG. 27) is reasonable since the pilots made their judgments while taxiing a C-131-B aircraft. The C-131-B has a cockpit cutoff approximately five degrees higher than the typical jet transport cutoff selected for the perspective diagrams. This higher cutoff caused the pilot to lean forward and move his head to the left in an attempt to improve his view. Head and body movement improved the angle of view by approximately three degrees.

The view to the right would also be improved if the pilot cut inside the curve; however, such an operation should not be encouraged.

The curves illustrated in Figures 28 and 29 were not available for field testing. However, perspective diagrams were made and the "10-degree cone" theory was applied to the curves. Figure 28 illustrates the pilots' view of a curve with a centerline radius of 115 feet and a light spacing of 12.5 feet, which was rated by the 10-degree cone theory as inadequate. Figure 29 illustrates the pilot's view of a curve with a centerline radius of 125 feet and a light spacing of 12.5 feet. Application of the 10-degree cone theory produced a guidance rating of adequate. It appeared that the 125-foot radius was the minimum usable with aircraft having cockpit cutoff similar to that shown in the perspective diagrams.

Taxiway curves with centerline radii between 200 feet and 1280 feet were not available for field testing the adequacy of 25 foot spacings. Consequently, perspective diagrams were made of several intermediate radii and 400 feet was found to be the minimum radius for using 25 foot fixture spacings (FIG. 30 and FIG. 31). Figure 30 illustrates the pilots' view when the lights were spaced 50 feet apart, and Figure 31 illustrates the pilot's view with the lights spaced 25 feet apart. A spacing of 25 feet was found to be adequate by applying the 10-degree cone of vision theory.

When taxiing along the straight segment or the 1280-foot radius curve in a TCLV of 200 feet, pilots often brought the aircraft to a sudden stop when encountering turns. Their comments then indicated that the curve had appeared suddenly and they had stopped to assess the situation before proceeding. Several pilots suggested that a visual warning "a couple hundred feet" ahead of a curve would be helpful.

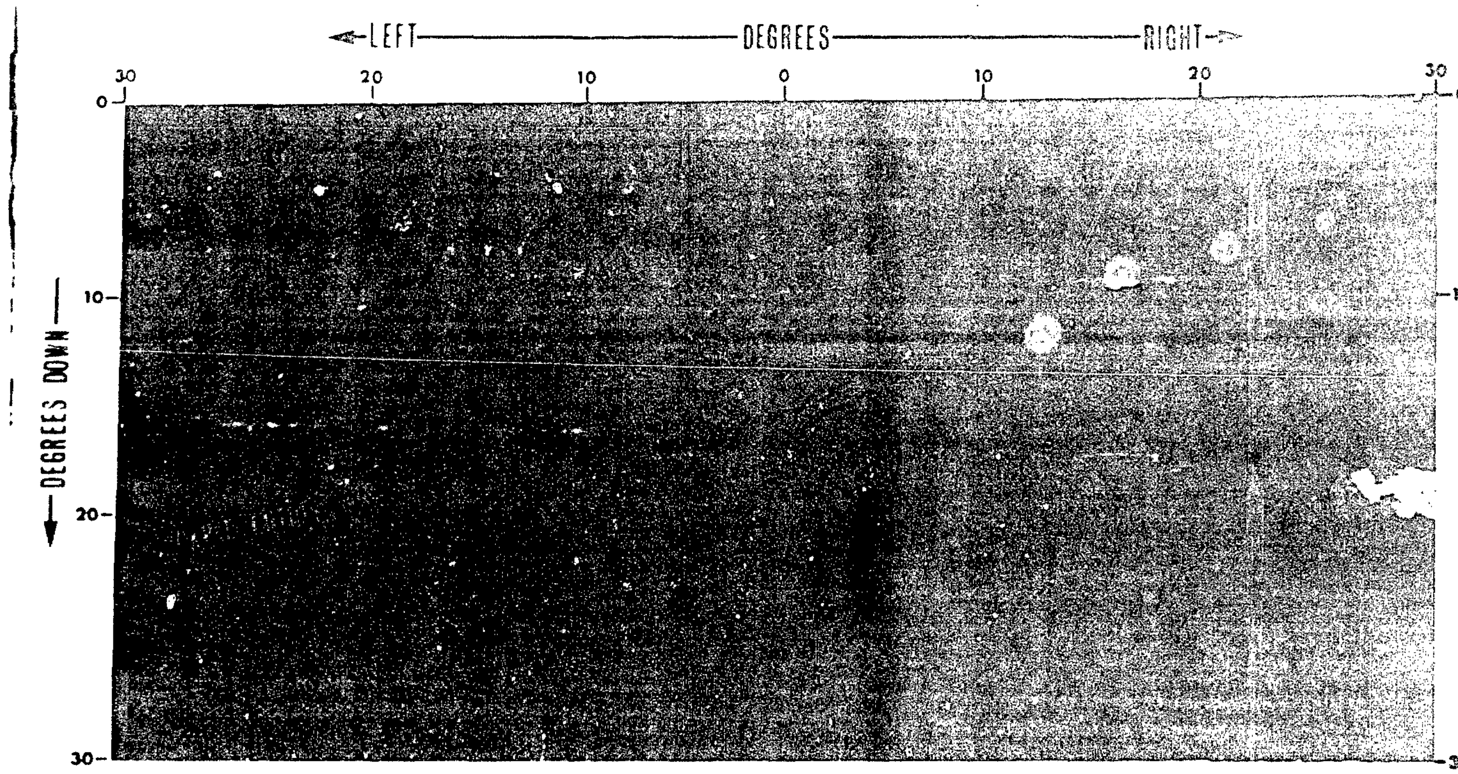

FIG. 26 PERSPECTIVE DIAGRAM. 165 FOOT RADIUS CURVE, TCLV 200 FEET, AND CENTERLINE LIGHTS SPACED 25 FEET APART. GUIDANCE INADEQUATE.

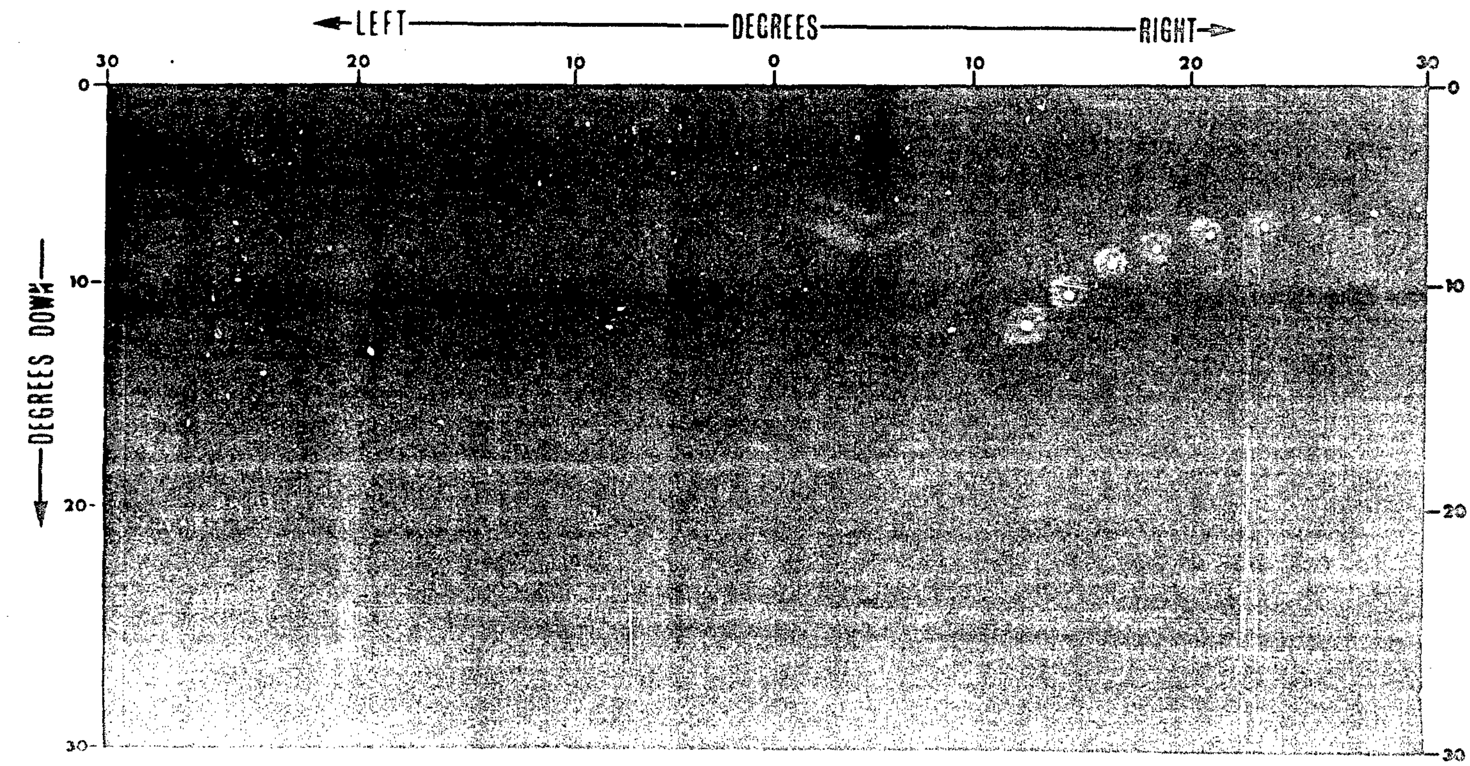

FIG. 27 PERSPECTIVE DIAGRAM. 165 FOOT RADIUS CURVE, TCLV 200 FEET, AND CENTERLINE LIGHTS SPACED 12.5 FEET APART. GUIDANCE ADEQUATE.

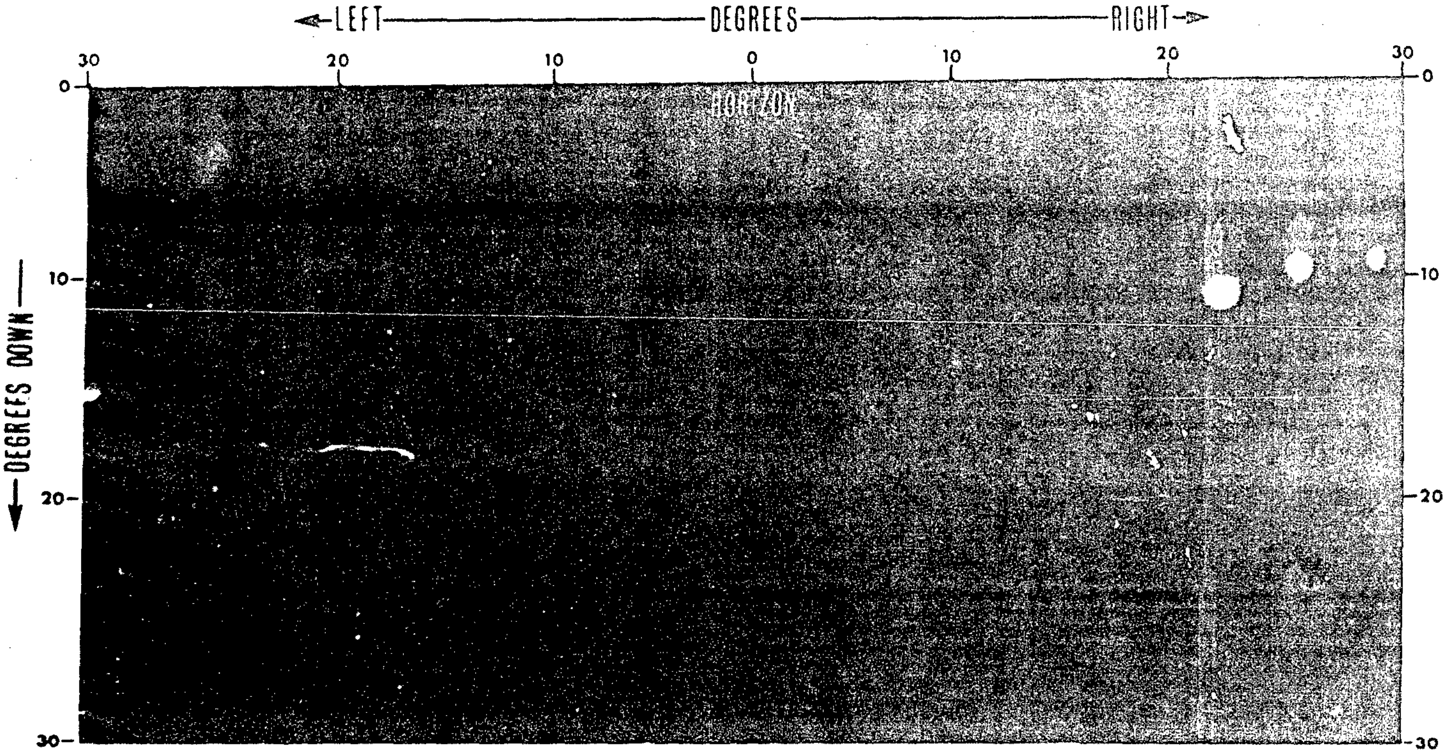

FIG. 28 PERSPECTIVE DIAGRAM. 115 FOOT RADIUS CURVE, TCLV 200 FEET, AND CENTERLINE LIGHTS SPACED 12.5 FEET APART. THEORETICAL GUIDANCE INADEQUATE.

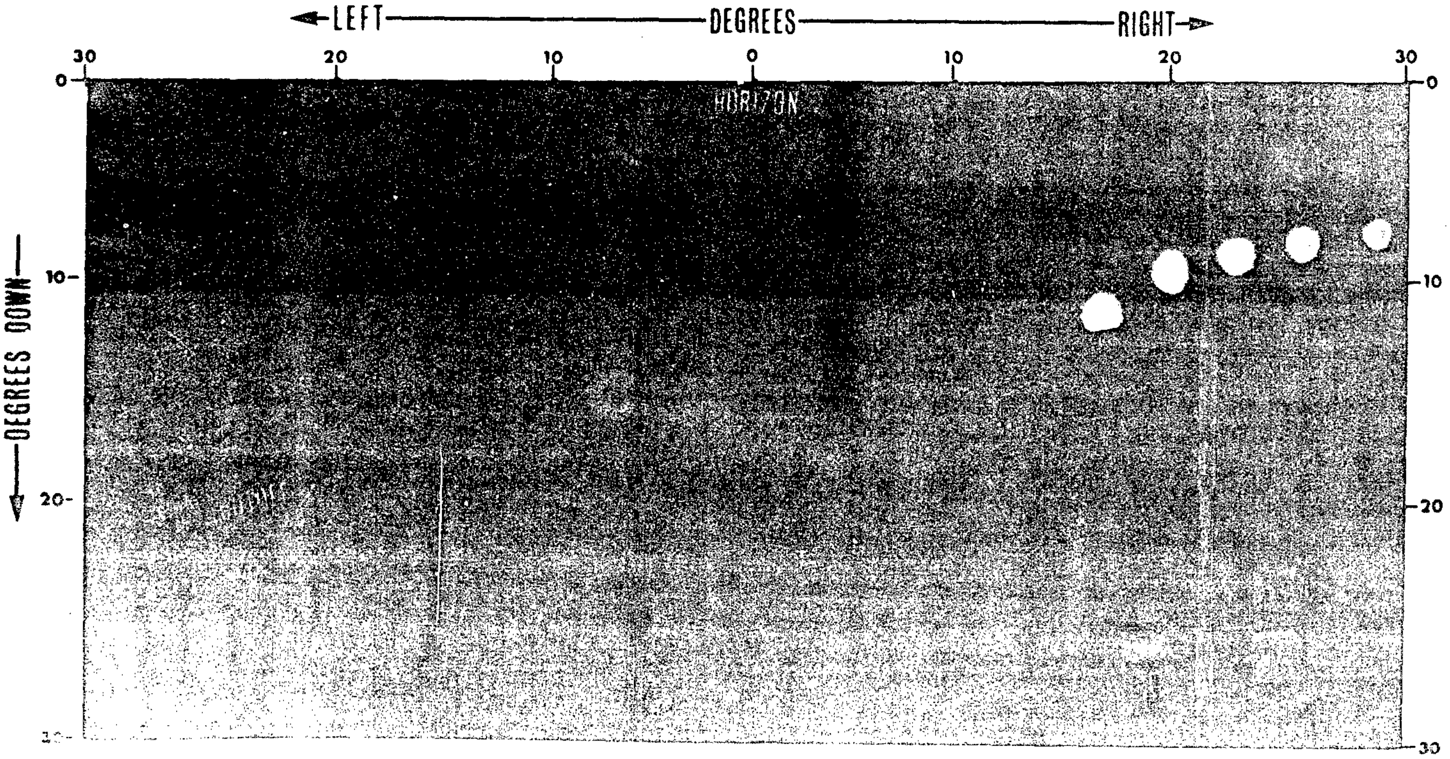

FIG. 29 PERSPECTIVE DIAGRAM. 125 FOOT RADIUS CURVE, TCLV 200 FEET, AND CENTERLINE LIGHTS SPACED 12.5 FEET APART. THEORETICAL GUIDANCE ADEQUATE.

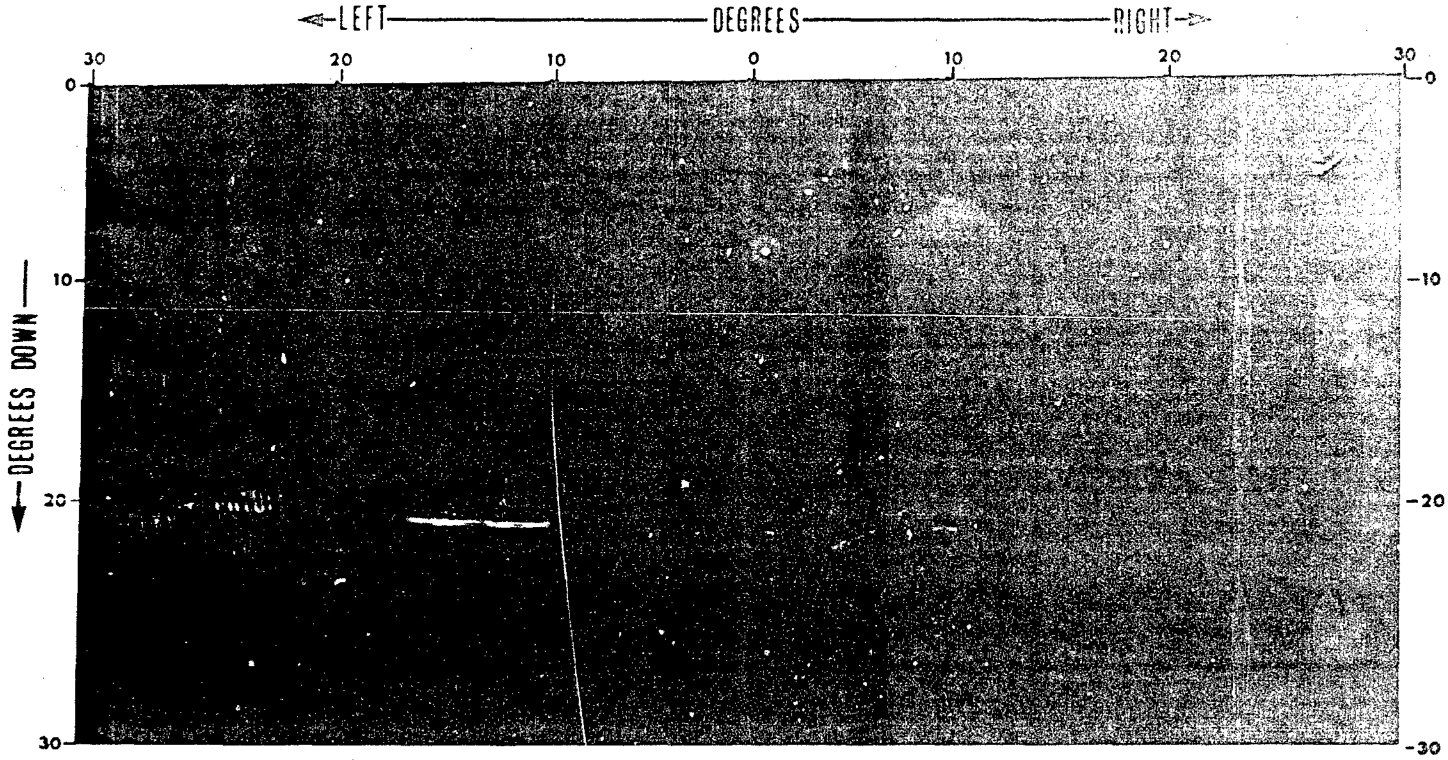

FIG. 30 PERSPECTIVE DIAGRAM. 400 FOOT RADIUS CURVE, TCLV 200 FEET, AND CENTERLINE LIGHTS SPACED 50 FEET APART. THEORETICAL GUIDANCE INADEQUATE.

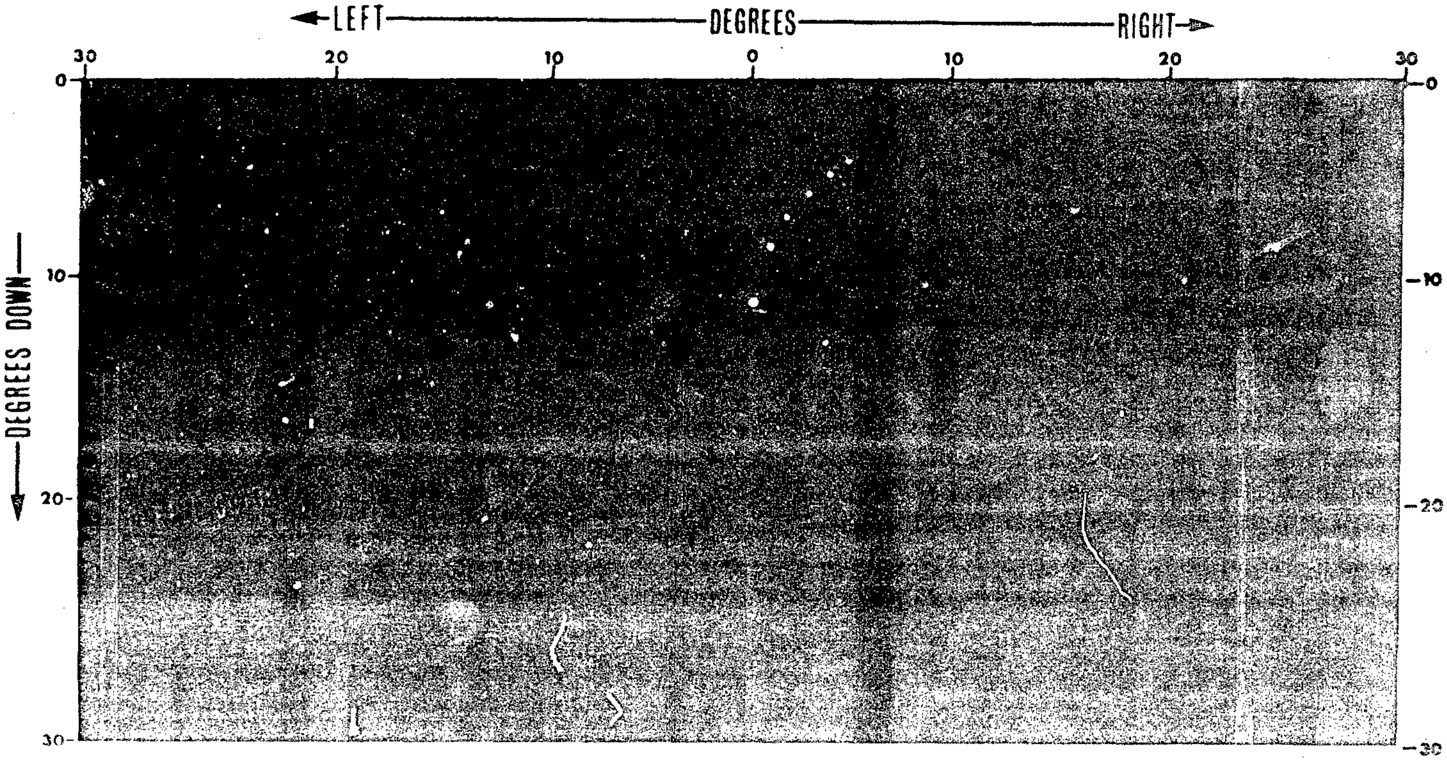

FIG. 31 PERSPECTIVE DIAGRAM. 400 FOOT RADIUS CURVE, TCLV 200 FEET, AND CENTERLINE LIGHTS SPACED 25 FEET APART. THEORETICAL GUIDANCE ADEQUATE.

Adequacy of Light Distribution:

Straight Sections - In calculating the horizontal beam width for the straight taxiway section, a five-foot lateral displacement from the centerline was assumed, and it was assumed that the closest light would disappear under the nose of the aircraft at approximately 50 feet. The calculations (APPENDIX IV) showed that a horizontal beam width of approximately 12 degrees would provide the necessary guidance on a straight section.

Curved Sections - The horizontal beam width requirements for fixtures to be used on curves depend upon the radius of the curve. In the interest of economy, it may be desirable to develop only three fixtures. Each of the three fixtures would be suitable for a specific band of radii. Three possible beam widths were calculated (sample calculation in APPENDIX IV) and the results presented in Table XI.

In calculating the horizontal beam width for a curved taxiway section, the aircraft was assumed to remain within 10 feet of the arc of the curve, the fixtures were installed with the central rays of each light source aligned tangent to the curve, and the fourth fixture above cockpit cutoff was used. By using the fourth fixture above cutoff, a minimum of four lights (the number rated as adequate for guidance by pilots) was assured.

TABLE XI

PROPOSED HORIZONTAL BEAM WIDTHS FOR CENTERLINE LIGHTS ON CURVES

Curve Radius (ft)	Horizontal Beam Width (Degrees)
125 - 400	63
400 - 1000	41
1000 and above	19

Straight Sections Adjacent to Curves - When considering the straight sections of taxiways adjacent to curves, several factors must be considered. First, the maintenance of an adequate guidance rating, i.e., three lights visible on a straight taxiway and four lights visible on a curved taxiway. Second, the desirability of keeping the system cost to a minimum.

The first factor, adequate guidance, pointed to the need for a minimum of three lights visibile to the pilot on a straight section (See Page 42) and to the need for the lights to have greater horizontal beam width than the 12 degrees calculated (APPENDIX IV) for straight taxiways.

The second factor, system cost, pointed to the need for using the same fixture throughout the curve and adjacent straight section rather than designing a special fixture for the adjacent straight section only. For example, the straight sections approaching a curve having a radius of 200 feet would required a fixture with a horizontal beam width of 63 degrees (TABLE XI). The fixtures would be spaced 12.5 feet apart (TABLE VI) in a 200 foot TCLV, and there should be a minimum of three of these lights in the straight section before the spacing is increased and the beam width reduced.

Vertical Beam Spread - Pilots view taxiway lights at close range as the lights disappear below the lower edge of the windshield. The cockpit cutoff angle for most aircraft is approximately 15^{o} at the center of perspective. Thus, any vertical beam width in excess of 15^{o} would normally not be used by a pilot and would only add to the overall background brightness of an airport. This 15^{o} maximum would be applicable to both straight and curved portions of taxiways.

SUMMARY OF TEST RESULTS

1. There was no significant difference in taxiing guidance between edge lighting combined with centerline lighting and reflective edge markers combined with centerline lighting.

2. Pilot preference was slightly greater for both the edge lighting combined with centerline lighting and the reflective edge marker combined with centerline lighting than for the centerline lighting only.

3. The edge-lighting-only configuration was clearly the least preferred of the four configurations evaluated.

4. Pilots were unanimous in their opinion that white or green colored taxiway centerline lights were preferred over blue centerline lights.

5. No significant operational difference was found to exist in the use of green or white taxiway centerline lights as rated by pilot opinion.

6. The results of the evaluation of various fixture spacings on straight and curved taxiway segments were as follows:

Type Taxiway	Fixture Spacing (ft.)	TCLV 600 ft.	TCLV 200 ft.
Straight	100	A	I
	50	A	A
Curve (1280 ft. Radius)	50	A	I
	25	A	A
Curve (200 ft. Radius)	25	A	I
	12.5	A	A
Curve (165 ft. Radius)	25	I	I
	12.5	A	I

Note: A = Adequate
I = Inadequate
TCLV = Taxiway Centerline light visibility

7. The environmental tests resulted in major problems with each of the four types of taxiway centerline fixtures evaluated. The lamps in the Structural Electric Products Corporation fixtures accumulated a film of dirt which lowered their photometric effectiveness. Both types of the Strong Electric Corporation fixtures failed when water which had collected in the fixture recess froze and damaged the lamps. The Stillman Rubber Company fixtures failed because aircraft tires caused the rubber diaphragms to rupture.

8. The reflective markers did not withstand jet and propeller blast of taxiing aircraft. A 66 week test period resulted in a reflectance factor decrease of approximately 20 percent.

9. The intensity of the light output decreased approximately 80 percent when a green filter was installed and approximately 96 percent when a blue filter was installed.

10. The 180-cycle electric power regulator system operated in a satisfactory manner throughout the test program.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible] taxiway centerline lighting of [illegible]

[illegible] reflective markers [illegible] used with taxiway centerline [illegible] with reflective markers is used [illegible] to replace [illegible]

[illegible] is to taxi aircraft [illegible] feet of the lighted taxiway centerline, thus [illegible] to less than 75 feet [illegible] full strength taxiway [illegible] and large radii curves.

[illegible] that pilots will, in low visibility, [illegible] their viewing position is within a few feet of the lighted taxiway centerline, fillets may be required for short radii curves to prevent [illegible] of large (long wheel base) aircraft from running off the full strength taxiway pavement.

[illegible] taxiway centerline lighting with a light spacing of 12.5 feet [illegible] guidance on curves having radii of 115 feet or greater. [illegible] centerline lighting with a light spacing of 25 feet [illegible] on curves having radii of 450 feet or greater. A light [illegible] feet provides adequate guidance on a straight taxiway.

[illegible] enclosed fixture, with improved structural characteristics [illegible] higher intensity than the fixtures evaluated in this program [illegible] lighting [illegible]

[illegible]

[illegible]

ACKNOWLEDGMENTS

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APPENDIX I

SAMPLE CALCULATION - FRIEDMAN TWO WAY ANALYSIS OF VARIANCE TEST

In order to determine whether a significant difference existed between the lighting configurations, the Friedman Two-Way Analysis of Variance Test[1] was applied to the responses obtained from 12 subject pilots who were requested to rate the four configurations in order of preference. The ranks for each configuration were then totaled. If no significant differences existed between configurations, the ranks were expected to be randomly distributed and the totals for each configuration would have been nearly equal. However, if the rank totals were not equivalent, the statistic X_r^2 was computed and used to determine if the probability that the differences between totals resulted from random effects.

Assumptions.

1. The level of significance (α) was 0.05.

2. The null hypothesis (H_O) was, "Any differences existing between configurations were due to random effects."

Sample Calculation from Pilot Preference Data

$$X_r^2 = \frac{12}{Nk(k+1)} \sum_{j=1}^{k} (R\ )^2 - 3N(k+1)$$

N = number of rows = number of subjects = 12
k = number of columns = number of configurations = 4
R = total of subject's ranks for each system

$$X_r^2 = \frac{12}{12(4)(5)} \left[(20)^2 + (23)^2 + (31)^2 + (46)^2 \right] - 3(12)(5)$$

$$= \frac{1}{20} \left[400 + 529 + 961 + 2116 \right] - 180$$

$$= \frac{1}{20} \left[4006 \right] - 180 = 200.3 - 180$$

1. Siegel, Sidney, Nonparametric Statistics for the Behaviorial Sciences, McGraw-Hill, New York, 1956, pp. 166

Then

$$X_r^2 = 20.3$$

The computed X_r^2 is greater than 7.82, the tabulated X_r^2 value at 0.05 significance level for three degrees of freedom from Table C of Siegel's "Nonparametric Statistics for the Behaviorial Sciences".

Therefore:

H_o is rejected.

APPENDIX II

SAMPLE CALCULATION - t-TEST FOR FINDING THE DIFFERENCE BETWEEN TWO SAMPLE MEANS

Reference: Davies, O. L., The Design and Analysis of Industrial Experiments, Hafner, New York, 1960, pp. 25-26

Formula:

$$t = \frac{\overline{X_1} - \overline{X_2}}{S\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}}$$

Where:

$\overline{X_1}$ = Sample mean for i th population

$$S^2 = \frac{\sum_{j=1}^{N_1} (X_{1j} - \overline{X_1})^2 + \sum_{j=1}^{N_2} (X_{2j} - \overline{X_2})^2}{N_1 + N_2 - 2}$$

N = Sample size for i th population

The alternative hypothesis (H_1), $\mu 1 = \mu 2$ is accepted unless there is positive evidence that it is not true by giving the test at a 0.01 significance level.

μ = mean of i th population

$\overline{X_1} = 2.970$

$X_2 = 2.587$

$N_1 = 9$

$N_2 = 9$

$S^2 = 0.264, \quad S = 0.514$

$$t = \frac{X_1 - X_2}{S\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}} = \frac{2.970 - 2.587}{0.514\sqrt{\frac{1}{9} + \frac{1}{9}}}$$

$$= \frac{0.383}{0.514(0.471)} = \frac{0.383}{0.242} = 1.583$$

The computed t-value is less than 2.921, the tabulated value at 0.01 significance level.

Therefore:

H_1 is accepted.

APPENDIX III

PILOT'S COMMENTS

Pilots were asked to answer the following questions about the color of the taxiway centerline lights.

1. What color should taxiway centerline lighting be for an all-weather aid? Blue____White____Green____

2. Why did you select the color you did?

The individual answers to these questions were as follows:

Pilot 1: (1) Green. (2) Good intensity without excessive glow as occurs with white lights. Sharp taxiway identification.

Pilot 2: (1) White. (2) White lights create a continuous line, other lights tend to phase into fog.

Pilot 3: (1) White. (2) Greater visual range. Sharper source light.

Pilot 4: (1) White. (2) No comment.

Pilot 5: (1) White. (2) This should be determined under actual low visibility conditions.

Pilot 6: (1) White. (2) Because of intensity.

Pilot 7: (1) White. (2) Green not visible with taxi light on.

Pilot 8: (1) Green. (2) Different than runway centerline.

Pilot 9: (1) Green. (2) More penetrating, less halo.

Pilot 10: (1) Green. (2) Easiest on the eyes, most definitive, least distortion.

Pilot 11: (1) White. (2) Would show up better during fog conditions.

Pilot 12: (1) Green. (2) Cool, less distracting, less scatter.

Pilot 13: (1) White. (2) Point source of light can be distinguished more readily through the screen.

Pilot 14: (1) Green. (2) Differentiate from runway centerline lighting.

Pilot 15: (1) Green. (2) Soft, easy to see.

APPENDIX IV

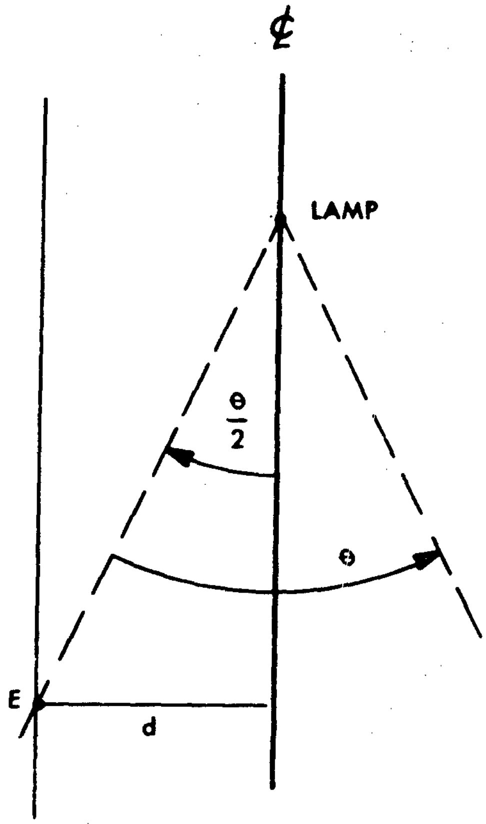
SAMPLE CALCULATIONS - HORIZONTAL BEAMWIDTH REQUIREMENTS FOR TAXIWAY CENTERLINE LIGHTS

Straight Taxiway Segment

Assumptions:

1. The point on the taxiway directly below the pilot's eye (E) remains within five feet of the centerline.

2. Cockpit cutoff characteristics obscure the first 50 feet of the centerline.



CL = centerline
E = point on taxiway directly below pilot's eye
d = maximum deviation of E (in this case 5 feet) perpendicular to the centerline
θ = beam width of centerline light
y = distance to first point seen on centerline by pilot

FIG. 4-1 Horizontal beam width - straight taxiway

Therefore, in this case: $\frac{\theta}{2} = \sin^{-1} \frac{d}{y}$,

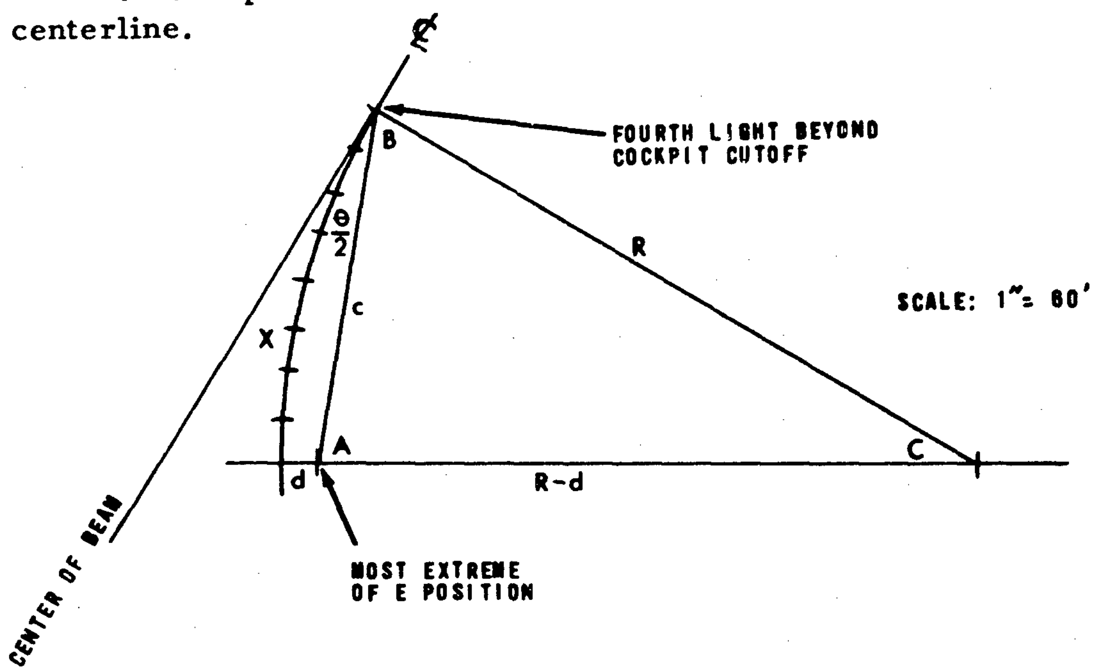
$\frac{d}{y} = \frac{5}{50} = 0.1$, $\frac{\theta}{2} = 5.7^\circ$, and $\theta = 11.4^\circ$

Curved Taxiway Segment

Assumptions:

1. The point on the taxiway directly below the pilot's eye (E) remains within 10 feet of the centerline.

2. Cockpit cutoff characteristics obscure the first 50 feet of the centerline.



R = radius of curve
CL = centerline
E = point on taxiway directly below pilot eye
d = maximum deviation of E (in this case 10 feet)
θ = beam width of centerline light
x = distance between lights
c = distance to light in question (in this case the fourth light visible beyond cockpit cutoff)

FIG. 4-2 Horizontal beam width - curved taxiway

Since: $= 2(90-B)$

and: $\text{Cos } B = \frac{R^2 + c^2 - (R-d)^2}{2Rc}$

If:

$R = 200'$
$d = 10'$
$x = 12.5'$
$c = 105'$ (measured from scale drawing)

$$\text{Cos } B = \frac{4 \times 10^4 + 1.1 \times 10^4 - 3.6 \times 10^4}{2 \times 200 \times 105}$$

$$1.5 = 0.357$$

$B = 69^{\circ}$

Then:

$$= 2 \times 21^{\circ} = 42^{\circ}$$

APPENDIX V

SAMPLE CALCULATION - LOCATING A POINT ON A PERSPECTIVE DIAGRAM

E. S. Calvert, B. Sc., A. R. C. Sc. L., of the United Kingdom, in his report, "The Use of Perspective Diagrams in Problems Related to Airfield Lighting," used a grid (FIG. 5-1) upon which the angle of depression from the horizon and angle from the center of perspective of a given object was to be plotted. The grid he used also included a line of "cut-off datum." This line represented the lower limit of the view from inside the cockpit. Plotting the position of airport lighting configurations on this diagram assists the engineer in the task of determining the feasibility of the configuration and analyzing its faults.

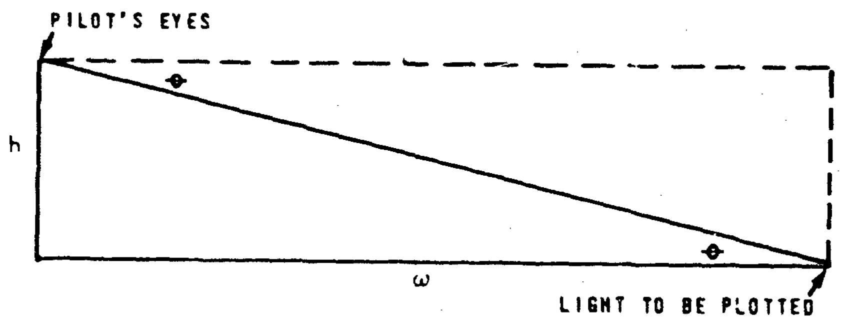
The angle of depression from the horizon was found in the following manner:

1. Determine the height (h) of the pilot's eyes above ground (15 feet in the example below).

2. Determine the horizontal distance (w) to the light in question (100 feet in the example below).

3. Let θ equal the angle of depression.

4. Apply the trigonometric formula $\theta = \tan^{-1} \frac{h}{w}$



$h = 15$ feet

$w = 100$ feet

$\theta = \tan^{-1} \frac{15}{100} = \tan^{-1} 0.15 = 8.5^{\circ}$

FIG. 5-1. Finding the depression angle (θ).

The angle to the right or left of the center of perspective was found in the following manner.

1. A convenient scale was selected and an arc was drawn to represent the centerline of the curved taxiway under analysis.

2. The position of the specific light under analysis was plotted.

3. A line was drawn from the pilot's eyes to the light and the angle between this line and the center of perspective line was measured. This was the angle to the right (in this case) of the center of perspective.

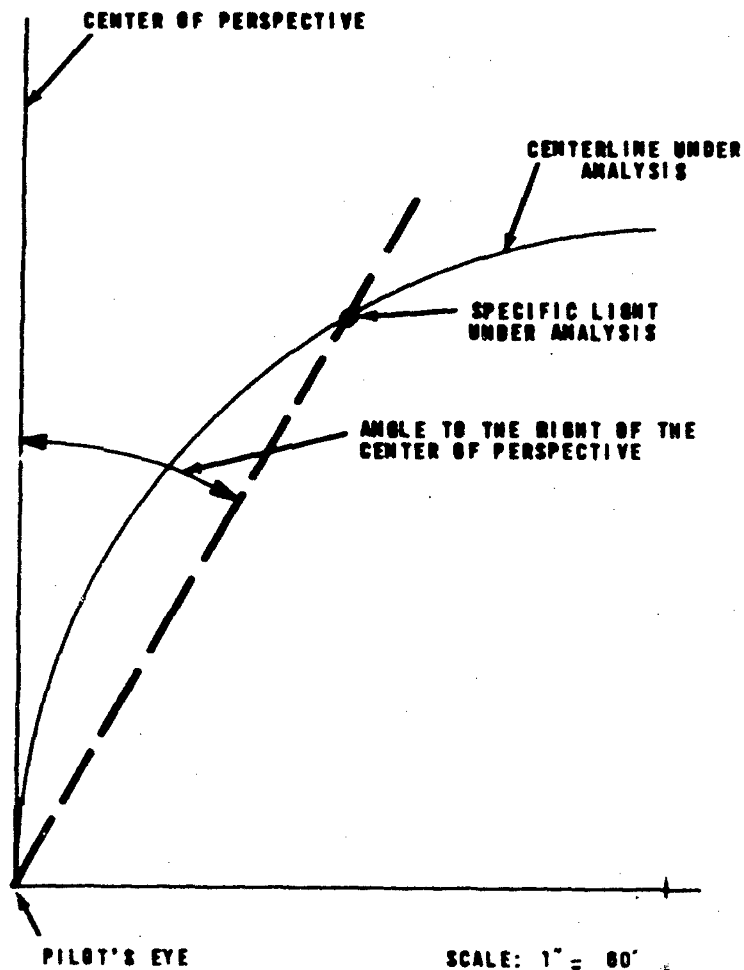


FIG. 5-2. Finding the angle right of center.

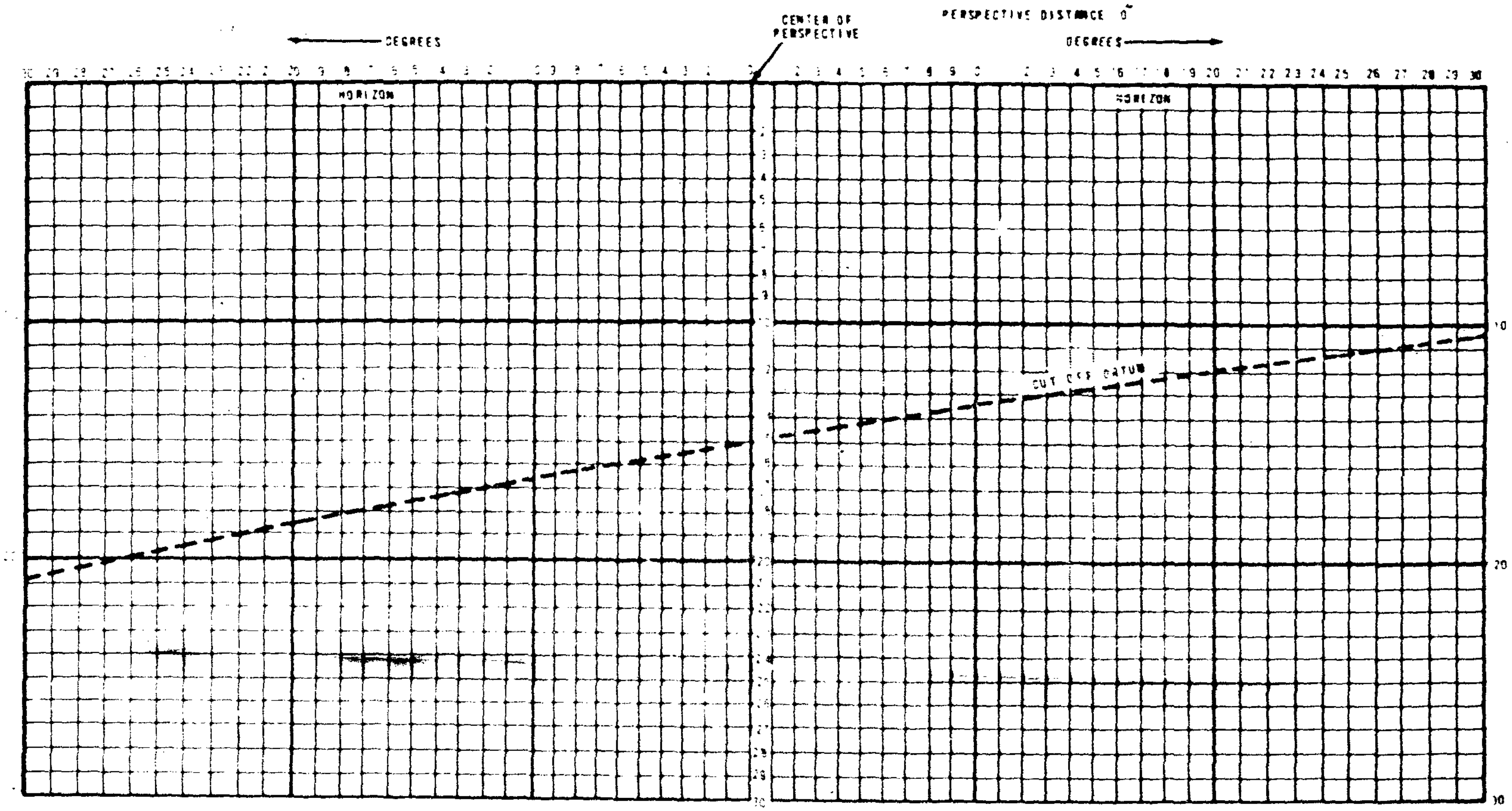


FIG. 5-3 THE PERSPECTIVE DIAGRAM GRID (REDUCED FROM 11 1/2" x 5 3/4")