THE DEVELOPMENT OF AIRPORT TAXI GUIDANCE SIGNS

By

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SUMMARY

This report describes the development of an elevated sign or route marker for use along runways and taxiways in airport taxiway guidance systems The sign, unlighted during the daytime and lighted at night, is conspicuous and legible from a distance of 500 feet under variations in visibility ranging from one-fourth mile up to an unlimited condition. Lighted translucent flush block letters make the sign visible and legible at night, these letters are outlined in black on a chrome yellow background to give the desired daytime effect.

INTRODUCTION

Because of the great increase in airplane operations and traffic in recent years, the problem of ground traffic control at most airports has taken on added complexity and importance It has been found desirable, therefore, to supplement the directions of the airport traffic controllers by providing additional guidance to taxiing airplanes at controlled airports Such guidance is also needed at airports that are without control towers

Since airport ground traffic is comparable to highway or street traffic in many ways, it was logical that an attempt would be made to solve the airport problem by using a sign system, as is done in the case of streets and highways Engineers of the Port of New York Authority and managers of the Baltimore and Boston airports have installed partial sign systems to furnish taxiway guidance. Managers of other airports have also been interested in installing such systems. Consequently, it was considered desirable to develop an airport taxiway guidance sign system that will serve as a standard, so that the type of guidance offered at all airports will be uniform and more easily recognized and interpreted by pilots

During the course of the development a study was made of the signs installed at Baltimore, New York, and Boston Engineers of the Office of Airports and others in the Civil Aeronautics Administration co-operated in proposing designs based on their own observations and experience Thus, the final solution evolved gradually from a series of tests conducted at the Technical Development and Evaluation Center and from an accumulation of ideas and experience from other sources

It was necessary to undertake the development of the signs as well as the system of guidance, and both phases of this work were correlated and carried on concurrently. A number of painted signs were constructed with letters and symbols having what were believed to be the proper dimensions, and these signs were installed in accordance with a proposed configuration or system. After daytime observation modifications were made in lettering, dimensions, and configuration to permit further study

Meanwhile, work continued on the design of lighted signs in order that, when the development approached completion, a number of these could be procured for installation in a system to be observed at night. A partial system embodying desirable principles established as a result of the daytime studies was installed at Weir Cook Airport, Indianapolis, Indiana. The present report covers only the design of the signs The evolution and design of the taxiway guidance system as a whole is discussed in another report.[1]

DESIGN CRITERIA

An important consideration in setting up criteria for the design of a sign is the manner in which it will be used The purpose of a taxiway sign is to indicate direction to a destination or to identify an intersection. In order to accomplish this effectively the sign must be conspicuous and easily readable up to a certain critical distance based on taxi speeds and stopping distances of aircraft

The Illuminating Engineering Society (IES) Taxiway Lighting Subcommittee had decided that at night this distance should be 500 feet when the visibility is 1/16 mile (330 feet) and that during the day it should be equal only to the actual atmospheric visibility. See Appendix I, Items 4 and 5. While CAA engineers endorsed the desirability of reading the signs at 500 feet they believed that legibility at 500 feet with a 1/16-mile visibility condition was too stringent a requirement, especially in view of the fact

[1]Bernard A Hemelt and Marcus S Gilbert, "The Development of an Airport Taxi Guidance System," Technical Development Report No 171, June 1952

that the current landing minimum visibility at representative airports is 1/2 mile with take-off permitted at 1/4-mile visibility.

The CAA Taxiway Sign Evaluation Committee, composed of representatives from the TDEC and from the Offices of Aviation Safety, Federal Airways, and Airports, stated the legibility requirement as follows "The sign should be of sufficient size to accommodate letters and figures that can be seen and read at a distance of 500 feet under present-day minimum weather requirements"

The CAA Committee also agreed that the sign should have qualities which would make it conspicuous when viewed against the normal airport background at distances greater than the legibility distance This requirement is considered at least as important as legibility, because the pilot should be warned of the approach to a possible point of turnoff even before it is necessary to identify it

Another important and conflicting requirement is that each sign must be small enough and designed and located in such a manner that it would not become a hazard to taxiing aircraft This requirement has become more important with the advent of low-winged jet aircraft with wing-tip fuel tanks. Previously the chief hazard was due to the low-sweeping propellers of larger multiengined aircraft

DESIGN CHARACTERISTICS

General.

The development of a sign for both day and night airport use requires consideration of the following characteristics

1. Method of lighting.
2. Letter design for legibility
   a. For day use
   b. For night use.
3. Size of sign
4. Color, contrast, and brightness
   a. For day use
   b. For night use.
5. Lamp requirements.
   a. Series use.
   b. Multiple use
6 Mounting

1. Method of Lighting

Floodlighted painted signs were tested The manufacturing difficulties necessitated by separate light sources and the difficulty of providing adequate illumination without allowing spill light and glare made this type impractical Silhouetted signs, where opaque letters are viewed against a lighted background, were abandoned when it was found that the background illumination tended to obscure the letters when seen from a distance

The use of retroreflective letters was also considered Experiments showed that this type of marker, however, is effective only when the direction of the incident light and the direction of the light reflected to the observer are not divergent by more than one or two degrees This would be the case when such signs are viewed by the pilot of an aircraft equipped with a nose light, or taxiing light If the aircraft is equipped solely with standard landing lights, the retroreflective markers can be really effective when the weather is clear, since the angle between the line of incidence and the line of reflection becomes small enough for effectiveness only at the greater distances

A sign consisting of luminous letters against an unlighted background seemed to offer the most effective solution. Although the letters for a sign of this type could be composed of luminous tubing or could be outlined with lamps, such construction offers material difficulties in the control of brightness and in protection of the lamps An alternate construction, therefore, was adopted This consists of an internally lighted box with a mask having letter outlines cut out to show the desired letter shape through the mask Diffuse color filters are used behind the mask to give distinctiveness to the sign and uniform brightness to the letters. The mask and filters are combined into removable panels so that various letter designs and combinations can be mounted on the box. By using appropriate color combinations and with letters and background of the proper size and proportions, such a sign can be made suitable for both day and night use

Limited experiments in which retroreflective backgrounds were applied to the lighted signs showed that such material made no substantial contribution to their effectiveness.

2. Letter Design for Legibility

In the design and selection of letters for best legibility, consideration must be given to the characteristic form of the letter, the height, the stroke, and the width While a number of distinctive types of lettering are in general use, experience has shown that the inherent simplicity and legibility of block letters make them most adaptable for sign construction. Consequently, this general type was selected for experiment and adaptation Figs 1 and 2 illustrate two systems of block

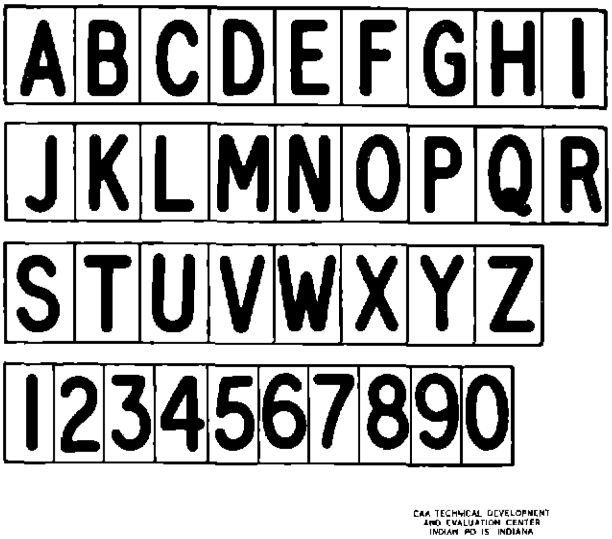

Fig 1 Conventional Lettering

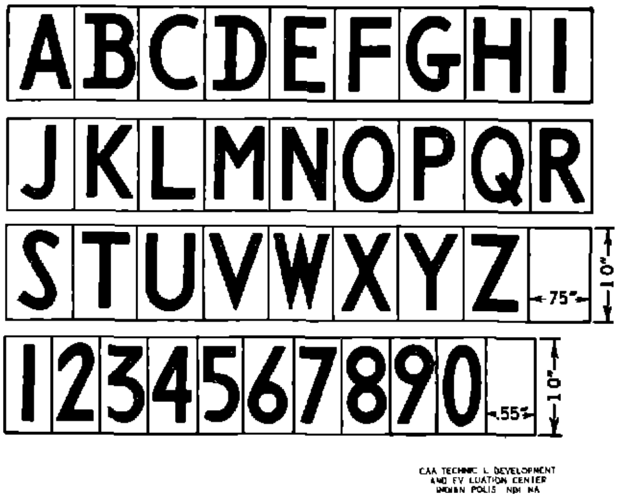

Fig. 2 Mackworth Lettering

letters The letter forms developed by Mackworth and shown in Fig 2 give better legibility than the conventional forms [2]

The Mackworth lettering was used as a basis for experimental work, but the letter shapes and proportions were modified when observations indicated possibilities of error and confusion in reading For example, confusion was found to occur in the case of the letter B and numeral 8, the letter S and numeral 5, the numerals 2 and 5, and the numerals 9 and 4 In the case of lighted letters, when a number of strokes intersect at a given point there is a tendency toward halation This was quite noticeable in the case of a lighted arrow in which the head lost its distinctiveness until separated from the arrow shaft, while the unlighted arrow was more effective with the head and shaft joined In the case of both lighted and unlighted letters, optimum legibility will result when intersecting strokes meet at angles of approximately 90 degrees

The final design of letters and numerals developed for a recommended standard is illustrated in Fig 3. It will be noted that with the exception of the numeral 4, which was found to resemble a 9 unless left open at the top, these letters do not deviate greatly from the general shape of Mackworth's lettering

The study to determine optimum letter height was begun with the premise that letters approximately 12 inches high would be satisfactory This was based on previous observations of experimental signs employing 15-inch letters which appeared to be higher than necessary Some confirmation of the choice of 12-inch letters was found in recommended practice for silhouette sign design in which letter heights vary from 1/440 to 1/660 of the desired reading distances [3] For the initial experiments, ratios of eight to one for vertical height to stroke width and five to three for vertical height to average letter width were used Numerous field observations indicated that 12-inch letters of the proper design were legible under normal visibility conditions from distances up to 700 feet. Tests also revealed that the requirements might be met through use of slightly smaller letters but that a 10-inch height would be the minimum

Experimental signs were fabricated with black letters of the selected design and dimensions painted on a yellow background. Daytime observations indicated that 12-inch letters with 1 1/2- to 2-inch stroke were satisfactory. With lighted translucent letters, however, it was found necessary to reduce the stroke width to 3/4 of an inch. This was parallel to the findings of Berger who conducted similar experiments [4] After many

[2] A Chapanis, W R. Gardner, and C T Morgan, "Applied Experimental Psychology — Human Factors in Engineering Design," John Wiley and Sons, Inc., 1949, pp 174-180

[3] IES Lighting Handbook, second edition, pp. 11-8 to 11-13

[4] Chapanis, Gardner, and Morgan, loc cit.

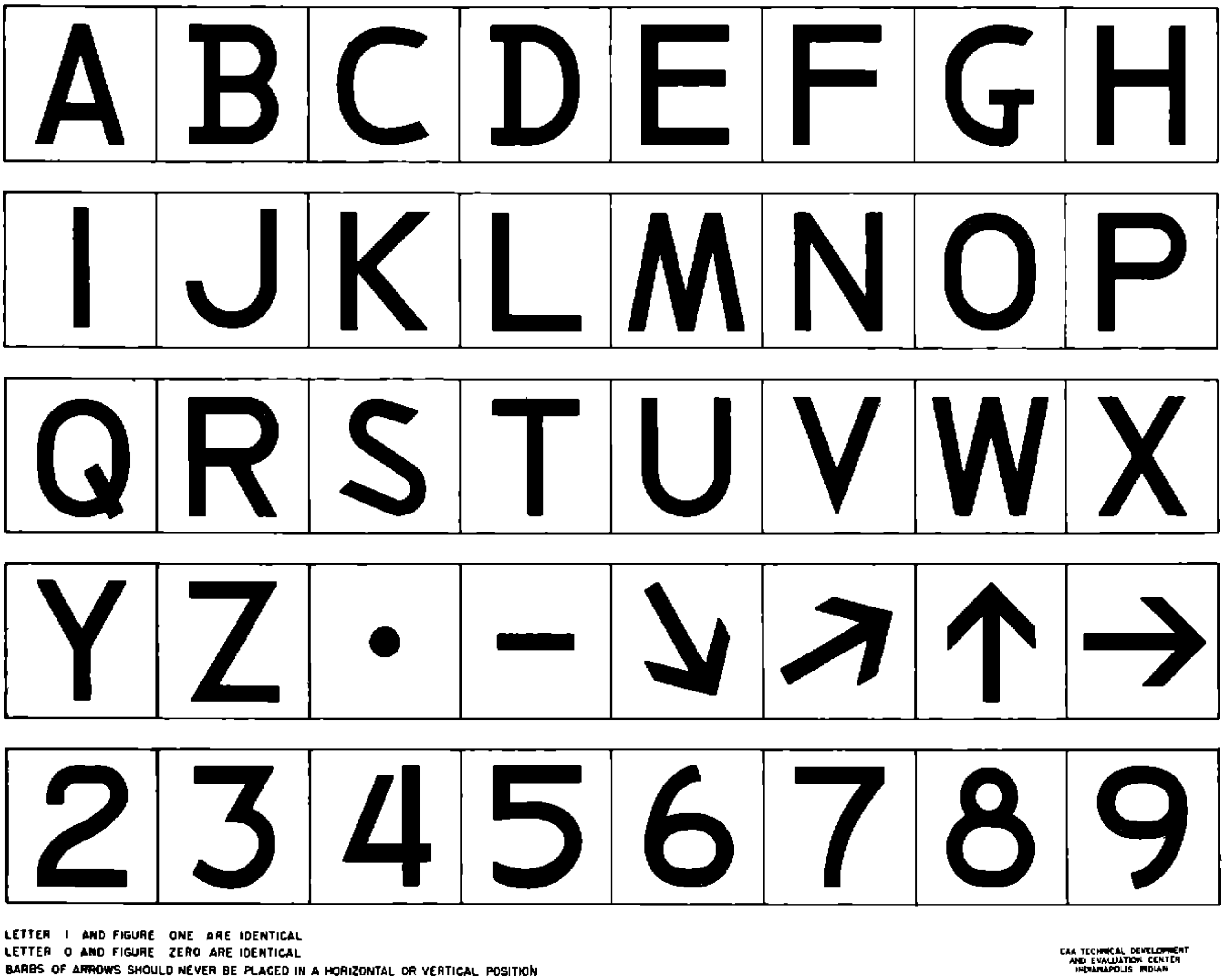

Fig. 3 Letters and Symbols Recommended for CAA Taxiway Guidance Signs

observations it was decided to use lighted letters with a 3/4-inch stroke and to paint a border 5/8 inch wide around each letter stroke for daytime use. Daytime and nighttime views of the experimental signs are shown in Figs 4A and 4B At airports where operations are limited to daylight conditions, painted signs with solid letters could be used

3. Size of Sign.

The dimensions of the complete sign depend upon the number, size, and arrangement of letters on the sign. It is the intention of the CAA Committee to limit each sign to not more than one 4-letter word or abbreviation plus an arrow or other symbol, although it might be necessary to make exceptions By using panels 14 inches square, which will easily accommodate 12-inch letters, the length of a five-panel sign can be limited to a maximum of approximately 70 inches The minimum height of the sign will be governed by the height of a single row of letters, the necessary background border around the letters, and the height of the breakable coupling By use of square 14-inch panels, the over-all height of the sign can be held to approximately 20 inches. It is possible to eliminate the breakable couplings and mount a sign directly on a concrete slab in such a manner that it can be torn loose easily if struck. The lower height would be achieved, however, at the expense of legibility, because uncut grass or drifting snow would interfere with the view of the sign, if so mounted.

For locations where there is the possibility of heavy snowfall, provision can be made to raise the signs above the snow by means of a telescoping type of mounting.

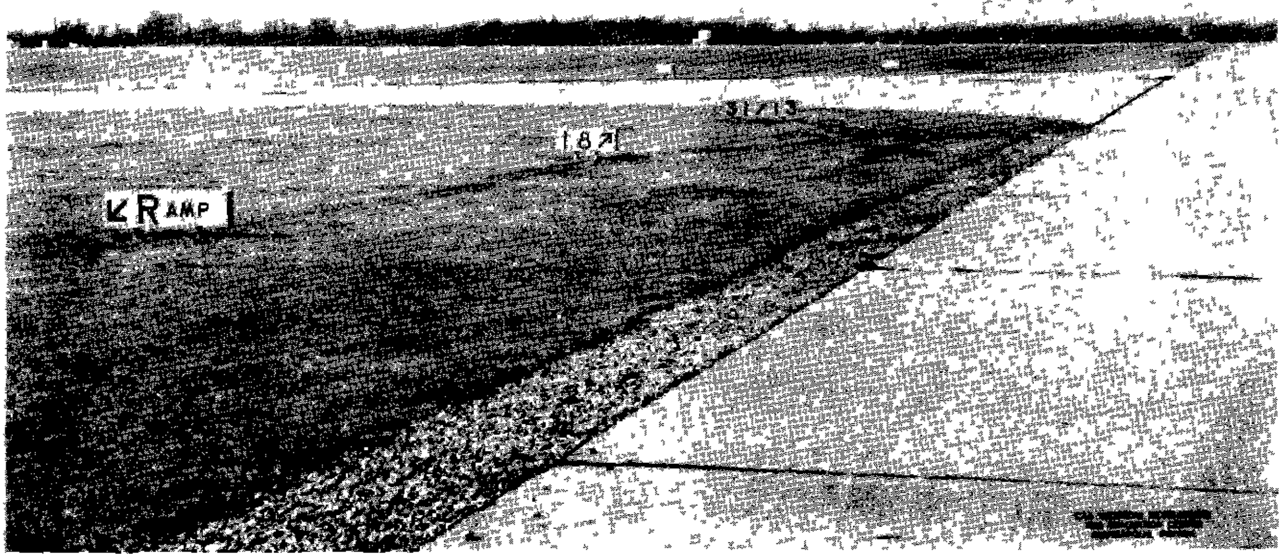

Fig. 4A Installation of Experimental Taxiway Guidance Signs (Daytime View) Three Signs in Foreground are Four-, Three-, and Five-Panel, Respectively, Starting With Sign Nearest Camera. Over-all Height – 20 Inches Spacing Between First Sign and Camera – Approximately 75 Feet, Between Adjacent Signs – Approximately 50 Feet, Between Pavement and Nearest Edge of Sign – 20 Feet.

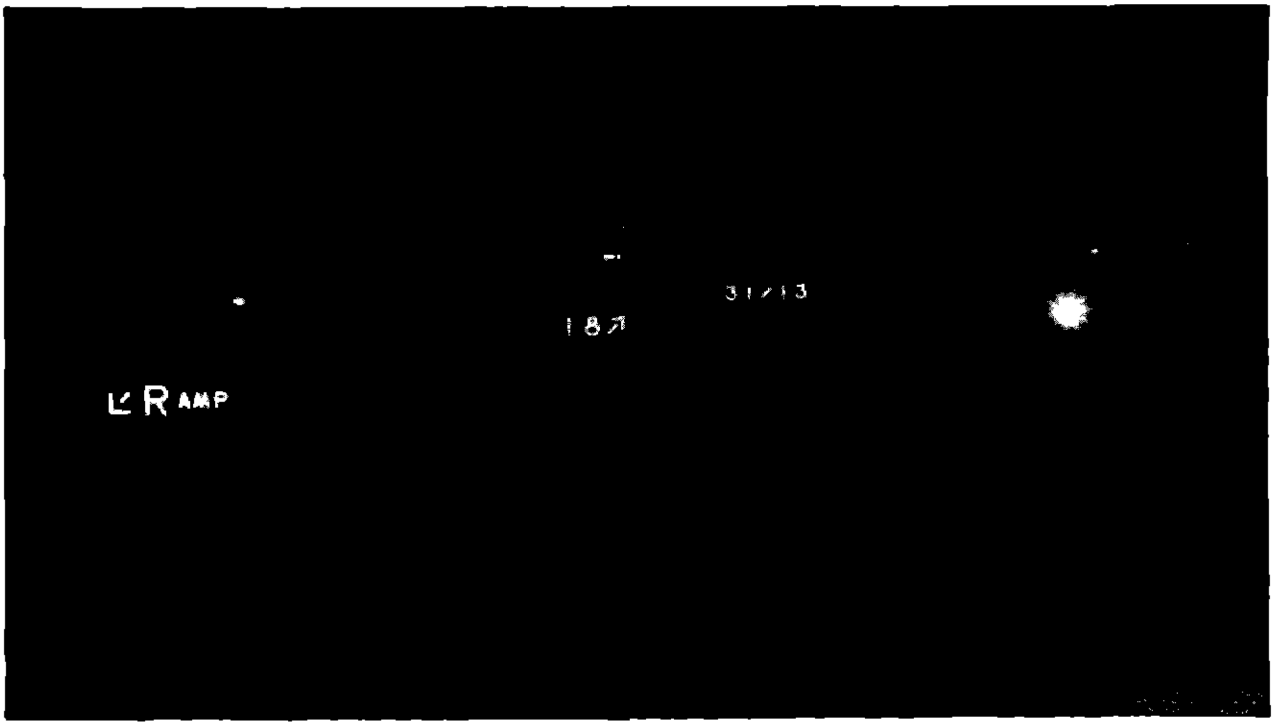

Fig. 4B Installation of Experimental Taxiway Guidance Signs (Nighttime View)

Any consideration of sign height should take into account the fact that there is little point in limiting the maximum height to 20 inches at airports where the elevated runway or taxiway lights are 30 inches high.

It is usual practice on signs or printed matter to vary the spacing between letters in keeping with the width, shape, and general appearance of the adjoining letters The purpose of this is to insure that the subject matter will present a well-balanced, coherent appearance The use of letters on interchangeable panels of equal width will not allow such variation in letter spacing On taxiway identification signs the letters normally are used as individual symbols, and spacing will not be a problem. Even though the letters may be used to form words or abbreviations for destination signs, it is unlikely that there will be such a combination of letters on a sign that spacing trouble will be serious. Although undesirable from the standpoint of simplicity and economy, signs with variable width panels can be built if required

In the design of single-face signs it was found that an over-all box depth, front to back, of approximately six inches was enough to accommodate lamps and sockets and to produce uniform brightness for the lighted letters When double-face signs are required, it will be necessary for them to be eight inches deep in order that the distance between lamp center and each panel will be four inches, the minimum for uniform brightness.

4. Color, Contrast, and Brightness

Choice of color combinations for daytime use is a very important factor, since the greater the contrast between letter and background and between the background and the surround the easier it is to see and to identify the letters. The question was raised whether dark letters on a light background, as used in the early experiments, are actually more effective than light letters on a dark background In further daytime experiments conducted with the 12-inch painted letters, it was found that the yellow letter on a black background always appeared smaller than the same letter in black on a yellow background and that the black on yellow was easier to read The black-on-yellow sign stood out better against the usual dark ground surface prevailing around an airport than did the sign with the black background

When comparing black on white with black on yellow, observers preferred the latter, which they claimed was less glaring and easier on the eyes when observed in bright sunlight With light snow on the ground the yellow signs were much more noticeable. By using a yellow background, the brightness of which is greater than the normal surround, it is not necessary to provide extra background area on the sign above and below the letter If a light letter on a black background were chosen, it would be necessary to provide materially greater area for the background In general, there is a tendency for dark signs to lose themselves in a neutral surround rather than to stand out from it as is the case with yellow or white signs

Results confirming those described have been recorded in earlier experiments by others In tests to determine relative reading speeds, it was found that black on white was read 16 per cent more rapidly than white on black. Green on white, blue on white, and black on yellow were almost as quickly read as black on white Combinations with poor brightness contrast such as orange on black, orange on white, red on green, and black on purple produce very low reading speeds.[5] With reference to legibility distance it has been found that blue on gray, black on gray, black on yellow, and red on gray could be read at the greatest distances[6] and that black on white was 15 per cent more legible than white on black.[7] The described tests and studies confirmed the decision that the signs should have chrome yellow enameled backgrounds with painted black borders surrounding the cutout letter openings

In order to select proper lamps and translucent filter material for the lighted letters it was necessary to establish optimum brightness and color requirements In early night tests an experimental sign with internally lighted white letters was set up in the field with provision for varying the voltage across the lamps Tests were then made at different voltage steps with varying brightness Observers, stationed out of

[5] Miles A Tinker and Donald G. Paterson, "Studies of Typographical Factors Influencing Speed of Reading," Journal of Applied Psychology, 1931, Vol 15, pp. 241-247 and pp. 471-479

[6] F. C. Sumner, "Influence of Color on Legibility of Copy," Journal of Applied Psychology, 1932, Vol 16, pp 201-204

[7] Grace Holmes, "The Relative Legibility of Black Print and White Print," Journal of Applied Psychology, 1931, Vol 15, pp. 248-251

range, moved forward until they could identify correctly 75 per cent of the letters on each sign tested It was found that brightness values ranging from 35 to 50 foot-lamberts gave excellent legibility at the 500-foot distance Later tests with a considerable range of filter colors confirmed these findings

Because of halation, higher brightness values (100 foot-lamberts or more) were found to reduce the legibility distance, especially for observers with eyes dark-adapted. Service experience, however, may indicate a need for greater brightness for very poor visibility conditions and for locations where signs are to be used on runways equipped with bright runway lights. Where higher values are desired for certain conditions, brightness control should be provided to insure optimum values at all times

Nighttime observations indicated that orange or yellow filters in either light or dark shades were relatively conspicuous and would be satisfactory for lighted signs The darker shades were more effective than the lighter shades for daytime use, because they blended better with the black outlines of the letters A 1/8-inch red-orange plastic was selected for initial tests It was the consensus of the CAA Taxiway Sign Evaluation Committee that the color of this filter was such that it might be mistaken for red, the color of obstruction lights. The Committee, therefore, recommended that yellow filters be used. In subsequent tests, a 1/8-inch orange-yellow plastic (similar to Rohm and Haas Plexiglas No 2068) was found satisfactory for both day and night use The specimen tested had a transmission of 22 per cent

5 Lamp Requirements

For simplicity of design it is desirable to use a unit construction, with the same lamp equipment in the same relationship to each panel unit This will tend to produce the same brightness regardless of the number of units in a sign With the filter selected either one 325-lumen series per panel or one 25-watt, 120-volt (260-lumen) multiple incandescent lamp per panel will produce proper uniform brightness if mounted four inches behind the face of the sign Although somewhat less flexible from a design standpoint, it is possible to obtain satisfactory results from a proper combination of gaseous tubular lamps and colored filters

6. Mounting.

It is necessary to use some type of breakable coupling for mounting, as is done in the case of elevated runway and taxiway lights. For the sake of standardization and simplicity, it was considered desirable to use the same coupling that is described in CAA Specification L-818 This specification calls for the coupling to be so fabricated that it will break cleanly when the column is struck horizontally by an impact of five foot-pounds applied on the column four inches above the weakened section.

In the case of a two-panel sign with a single pedestal mounting, there was no question that the coupling would serve as required In the case of the larger signs, where two pedestals per sign are used, there was some question as to the proper functioning of two frangible couplings operating in tandem, especially when struck by an impact in a direction parallel to a line joining them Consequently, laboratory tests were made to determine the adequacy of the standard breakable coupling for this application It was found that the amount of energy required to break the couplings and to displace and deform a five-panel sign would be approximately the same as that required in the case of a 62-pound Bartow runway light supported on a single coupling Static tests made to determine the broadside wind resistance indicated that the sign was sufficiently stable even for extreme wind conditions Details of the dynamic and static test methods and results are given in Appendix II

CONCLUSIONS

For airport taxiway guidance, excellent results can be obtained through use of a box-type sign on which the letters are outlined in black on a yellow background during the day and appear luminous on an opaque background at night The sign should be designed in conformance with the following specifications

1. Method of lighting — internal.
2. Letter design
   - a Form — block See Fig 3.
   - b Dimensions.
     - (1) Unlighted
       - (a) Height — 12 inches.
       - (b) Stroke width — 2 inches
       - (c) Letter width — approximately 60 per cent of height.
     - (2) Lighted
       - (a) Height — 10 3/4 inches.
       - (b) Stroke width — 3/4 inch
       - (c) Letter width — approximately 60 per cent of height.
3. Size of sign
   - a Height of letter panel — 14 inches.
   - b. Over-all height (including mounting) — 20 inches
   - c. Length — 14 inches per panel, with

2 to 5 panels per sign.

d. Depth
   (1) Single-face — 6 inches.
   (2) Double-face — 8 inches.

4. Color and brightness.
   a. Unlighted, for day use
      (1) Letters — hollow black superimposed over translucent orange-yellow filters giving desired appearance of solid black letters at a distance. (Solid black letters may be used at airports where lighted signs will not be required.)
      (2) Background — chrome yellow.
   b. Lighted, for night use.
      (1) Letters — luminous orange-yellow.
      (2) Background — opaque
      (3) Brightness — 50 foot-lamberts
      (4) Filter — orange-yellow plastic similar to Rohm and Haas Plexiglas No 2068.
      (5) Filter transmission — 22 per cent

5. Lamp requirements.
   a. Series One 325-lumen, 6.6 ampere, airport lamp per panel. Medium pre-focus base.
   b. Multiple. One 25-watt, 120-volt, standard lamp per panel. Medium screw base.

6. Mounting.
   a. Pedestal — single for 2-panel sign, double for larger signs
   b. Breakable coupling — described in CAA Specification L-818.

Signs constructed in accordance with the above' specifications are legible at 500 feet under one-fourth mile, day or night visibility conditions.

The lighted signs are legible at distances well over 500 feet under unrestricted night visibility conditions There is no noticeable glare at the 50 foot-lambert brightness even when the signs are viewed at close range

APPENDIX I

EXCERPTS FROM MINUTES OF IES TAXIWAY LIGHTING SUBCOMMITTEE NEW YORK INTERNATIONAL AIRPORT April 10, 1950

Taxiway Route Markers

The following characteristics for taxiway route marker lights were concluded to be desirable

1 The marker should be distinctive to attract attention to it prior to the time that it is legible

2 It should be designed to provide visibility for both day and night conditions

3 A functional standard should be adopted which can be utilized for all airports.

4 The intensity should be such that the markers will be visible at night up to 500 feet when the atmospheric visibility is 1/16 mile (330 feet) and in daytime for a distance equal only to the actual atmospheric visibility (This assumes the same visibility criteria commonly used in daytime)

5 The legibility of the markers should be such that they are easily legible from a distance of 500 feet This conclusion was based on reports submitted by the Port of New York Authority showing that average taxi speeds were 20 mph. These reports also show that the stopping distance of a plane going 40 mph is less than 400 feet

6 The color should provide a contrast with taxiway and runway markers. It was considered that aviation yellow with an orange cast appeared to have the most promise From developments to date, it appears that lighted letters with a dark matted finish as a background will provide the best solution

7. The letters should be no larger than necessary to keep marker size to a minimum. Field observations showed that a 15-inch letter was completely adequate. Further testing must be conducted to determine if a 12-inch letter will be satisfactory

APPENDIX II

TESTS OF BREAKABLE COUPLINGS FOR TAXIWAY SIGN USE

An impact tester was designed and built to determine the relative amounts of energy required to topple a double pedestal sign from its mounting when applied from different directions. The impact tester used was a pendulum modeled after the Charpy and Izod Testing Machines, but an aircraft wheel and tire were employed instead of a metal hammer head. This arrangement can simulate the type of impact to which a sign might be subjected when struck by an airplane. It also embodies features provided in testing methods outlined by the American Society for Testing Materials.

In preparation for impact tests the signs were mounted on a horizontal platform so that the impact would occur approximately 12 1/2 inches above the shearing point of the couplings. A fusible link was used for the pendulum release mechanism. This provided positive release when heated to the melting point. At the top of the pendulum a recording device was mounted. This provided a record of angular displacement of the pendulum, which record could be translated into impact energy.

Tests were made to determine the energy required to break the mounting of a five-panel fixture with the impact on the face, on the end, and on the corner at a 45° angle. See Column (a), Table I. It was realized that some of the energy indicated as being given up in impact was used in deforming the sheet metal sign. In order to determine the magnitude of this deforming energy a rigid fixture resembling the sign and having approximately the same weight and dimensions was fabricated and tested. The results of these tests are shown in Column (b), Table I.

It was also recognized that part of the indicated energy given up to the rigid sign was in reality lost due to the resilience of the pendulum itself. The amount of this energy was determined by permitting the pendulum to rebound from a solid wall and recording the residual energy after impact. See Column (c), Table I. This method of determination was accepted as having sufficient accuracy due to the fact that the follow-through angle, or angle of rise after impact, of the fabricated specimens was very small. On this basis it could be assumed that for practical purposes the specimens reacted the same as a solid wall during the time the pendulum was in contact with them.

Column (d) shows the amount of energy required to break the couplings and to displace and deform the specimen. This value is obtained by subtracting from the total energy (a) the energy lost due to the resilience of the pendulum (c). The energy lost due to sign deformation can be obtained by subtracting the values in column (b) from (a).

The impact energy required to break the mounting of a Bartow runway light on a single mounting was also determined for comparison purposes. It was found that in order to deform the tire, break the coupling, and displace the Bartow runway light the energy required was approximately 197.7 foot-pounds with the pendulum traveling at 13.02 feet per second. The comparatively large amount of energy needed in this case of a single coupling may be attributed to the larger inertia of the Bartow light, which weighed 62 pounds as compared to approximately 45 pounds each for the metal and wood specimens.

In order to determine the broadside wind resistance of the sign, a steadily increasing horizontal pressure was applied as uniformly as practicable over its face. The total force required to topple the sign was found to be approximately 700 pounds. In several tests one coupling broke, and the sign was subsequently pulled off the other coupling. The 700-pound value is equivalent to a wind velocity of about 200 mph blowing against the sign,[8] or to a B-45 twin jet engine blast directed at the sign from a distance of approximately 50 feet.[9]

[8] H. L. Dryden, "Wind Pressure on Structures," Section 9, Article 43, page 65, Handbook of Engineering Fundamentals, edited by Ovid W. Eshbach, published by John Wiley & Sons, Inc., 1936.

[9] Handbook of Erection and Maintenance Instruction, AN 01-60GFA-2, published under authority of Secretary of Air Force and Chief of Aeronautics, Oct. 15, 1949, revised Jan. 5, 1951, Section III, p. 41.

TABLE I

RESULTS OF IMPACT TESTS ON TAXI GUIDANCE SIGNS

	Sheet Metal Specimen Similar to Sign		Rigid Wood Specimen		Solid Wall – Energy Dissipated Due to Resilience of Tire		Residual Energy Required to Break Coupling and Displace Specimen
Direction Of Impact	(a) Energy* Foot-pounds	Pendulum Velocity Upon Impact Feet per second	(b) Energy* Foot-pounds	Pendulum Velocity Upon Impact Feet per second	(c) Energy Foot-pounds	Pendulum Velocity Upon Impact Feet per second	(d)* * Energy Foot-pounds
Broadside	201.7	13.18	181	13 18	127.4	13 18	74.3
Endwise	200.3	13.18	196	13 18	-	-	72.9
At 45° Angle	186.8	13.18	-	-	-	-	-

* Energy required to break couplings, deform tire, deform and displace specimen, this does not include windage and friction.

* * The residual energy (d) required to break the couplings, deform and displace the specimen was obtained by subtracting from the total energy (a) the energy absorbed by the resilience of the pendulum (c).

$d = a - c$