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Evaluation of Light Emitting Diode Linear Source Devices

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16. Abstract

With rapid advances in the light emitting diode (LED) design and production arena realized in the latter half of the 1990s, increases in intensity and reduction in cost made the use of LED source devices practical for airport use. In particular, airport engineers and designers realized that the LED, when configured in a linear array, might well serve to enhance and embolden the conventional paint markings on the airport movement area. This report describes the evaluation that was conducted to determine the effectiveness and applicability of the LED configured in a linear array to enhance paint markings on the airport surface, and to develop specifications and certification procedures for these sources. The evaluation was conducted over a 5-year period at the Federal Aviation Administration William J. Hughes Technical Center, and elsewhere, by subjective visual inspections and pilot opinion of various configurations, sizes, and colors. During this time, two different products were evaluated—a flexible strip of encapsulated LEDs and a rigid strip of encapsulated LEDs. The results of the investigation showed that both the flexible and rigid linear LED strips enhanced the visibility of the paint markings as indicated by the increased acquisition distances. However, the installation and robustness of these sources needs more attention from the vendors to enable the use of this product on airports. The specifications and certification criteria for LED linear strips were developed and are included in appendix A.

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LIST OF ACRONYMS

LED	light emitting diode
FAA	Federal Aviation Administration
IGS	Illuminated Guidance Systems
LSI	Lighting Sciences Inc.

EXECUTIVE SUMMARY

The work described in this report was performed in response to a request from the Office of Airport Safety and Standards, Airport Engineering Division, AAS-100. The purpose was to determine the effectiveness and applicability the light emitting diode (LED) configured in a linear array to enhance painted markings on the airport surface and to develop specifications and certifications procedures for these sources. Testing of this particular type of light source has been continuous, at the Federal Aviation Administration William J. Hughes Technical Center and other locations, for approximately 5 years. This report consolidates the results of these multiple projects. During this time, two different products were evaluated: a nonrigid strip of encapsulated LEDs (LED-line) and a rigid encapsulated LED fixture.

The results indicated that the concept of using the LED linear source to enhance paint markings on the airport surface is promising. Achievable LED intensity levels have increased significantly while costs have concurrently diminished, and such sources now have considerable potential, from a visual standpoint, for airport use. Having multiple single sources in close proximity, as in a linear array of many sources, would be advantageous in that a single outage would not significantly diminish the overall effectiveness of the visual presentation.

Virtually all the difficulties encountered during testing and evaluation of the LED-line devices resulted from installation problems. It may be said that, in general, the off-the-shelf variations of this type of linear light source are not readily adaptable to airport surface installation and that some considerable redesign and adaptation will have to be applied before they would be suitable. Shortly after the installation was completed, the rigid encapsulated fixtures were damaged when snow removal equipment sheared off one of the power connection box covers. In addition, it appeared that moisture entered several of the fixtures and shorted out a considerable number of LED strings, and the Lexan cover showed signs of cracking. The installation and robustness of linear sources needs more attention from the vendors to enable the use of this technology on airports.

During the evaluation period, issues that were nonexistent with standard incandescent lighting have been identified with LEDs and should be considered when implementing this technology. The following issues have been identified.

- How will this technology interact if interspersed with standard incandescent lights on airport circuits?
- What are the impacts of intensity changes with LEDs? Experience has revealed that dimming or purposely reducing the intensity of LED devices to reduce glare poses some problems, and these problems would be exacerbated should the system include both conventional filament and LED devices.
- What causes the human eye to perceive the LEDs as brighter than incandescent when photometrics show that the candela values are less for LEDs?
- Does the narrow spectral band of LED impact pilots with certain types of color-deficient vision?

- Can LEDs be seen on an enhanced vision display that uses the infrared emissions present with incandescent?

While this technology has potential for use on airports, developing criteria for handling the above-mentioned issues, which were not a concern with the older technology, needs to be addressed to ensure that adequate guidance can be provided for their implementation.

1. INTRODUCTION.

1.1 PURPOSE.

The purpose of this report is to describe an evaluation effort accomplished to determine effectiveness and applicability the light emitting diode (LED) configured in a linear array to enhance paint markings on the airport surface and to develop specifications and certification procedures for these sources. Testing of this particular type of light source has been continuous, at the Federal Aviation Administration (FAA) William J. Hughes Technical Center and other locations, for approximately 5 years. This report consolidates the results of these multiple projects. During this time, two products were evaluated: a nonrigid strip of encapsulated LEDs (LED-line) and a rigid encapsulated LED fixture.

1.2 BACKGROUND.

LED devices have been available for many years, but the limited intensity capability has, until recently, restricted their use typically to that of indicator lights and low-level novelty applications in toys and electronic installations.

With rapid advances in the LED design and production realized in the latter half of the 1990s, increases in intensity and reduction in cost made the use of LED source devices practical for airport use. In particular, airport engineers and designers realized that the LED, when configured in a linear array, might well serve to enhance the conventional paint markings on the airport movement area.

Although the early LED linear products obtained for testing were relatively unsophisticated and rather unsuited for the hostile airport environment, they did serve as a tool in investigating the use of linear light sources on airports. Furthermore, and as will be described herein, improvements in LED linear products have resulted in devices that, with certain limitations, may well find numerous uses on both large and small airports.

1.3 RELATED ACTIVITIES AND DOCUMENTS.

One important use for LEDs that is familiar to almost everyone has been their application, when arranged in circular clusters, as replacements for conventional traffic lights, vehicular taillights, etc. While such LED applications have been tested for use in the airport arena and have shown considerable promise, a discussion of this research and development effort, also conducted at the William J. Hughes Technical Center, must be considered as outside the scope of this research.

Another significant use of LEDs, also outside the scope of this research, has been in the enhancement of painted and retro-reflective signs, both on airports and in the commercial advertisement area. This research is also being investigated by the William J. Hughes Technical Center.

Prior to the start of work at the William J. Hughes Technical Center, in 1999, a prototype LED light strip system called LED-line distributed by Hil-Tec International Limited, in the form of a yellow holding position line at a taxiway run-up position, was installed by the Port Authority of

New York and New Jersey at the John F. Kennedy International Airport. The installation, serving to demonstrate installation techniques, was inspected by various airport engineering and operations groups over a period of 2 years. Figure 1 shows the installation.

FIGURE 1. JOHN F. KENNEDY INTERNATIONAL AIRPORT TEST SITE

In addition, at about the same time, a somewhat more complex configuration, in the form of a numbered gate indicator with centerline track depiction, was installed for demonstration on the apron at the Vancouver International Airport, Vancouver, B.C. Figure 2 shows the configuration under standing water conditions.

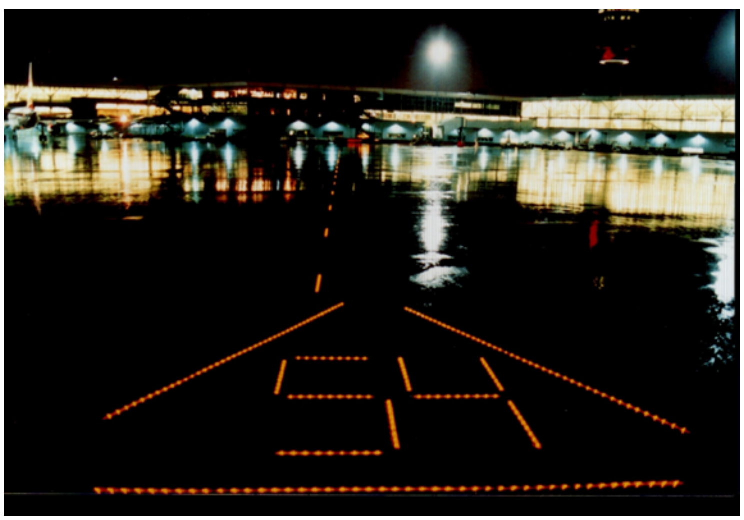

FIGURE 2. VANCOUVER INTERNATIONAL AIRPORT TEST SITE

No documentation concerning either of the above installations was made available for inclusion in this report.

A number of memorandums, reports, and other documents have been published during the past 5 years and are covered in this report. However, the following list is provided to facilitate research into details of the efforts described:

- "In-Pavement Light Emitting Diode (LED) Light Strip Evaluation," Interim Report, DOT/FAA/AR-01/39, August 2001.

- "Airport Pavement Marking Evaluation for Reducing Runway Incursions," Final Report, DOT/FAA/AR-TN01/2, February 2001.

2. EVALUATION EFFORTS.

2.1 APRON PARKING POSITION INDICATOR.

To provide an initial experience with the installation and use of a LED-line configuration, in mid-1999, a decision was made to procure first-generation/prototype LED devices for installation and evaluation on the FAA apron (ramp) at the William J. Hughes Technical Center.

The test LED strip configuration installed was in the form of a parking location T figure, purposely collocated with an existing paint marking of the same pattern (figure 3). It was comprised of five 3-meter (10-foot) sections, or strips, forming the crossbar of the T, and an additional nine sections forming the tail of the T. Each individual LED section contained 96 encapsulated LED devices (lights) in groups of four with 32-mm (1.25-inch) spacing between each LED (figure 4). All strips were installed in a saw-cut trench and temporarily supported during pouring of the surrounding sealant so that the top surface of each strip was approximately 2.5 mm (1/10 inch) below the surrounding concrete. Three 120 Vac and 12 Vdc constant voltage power supplies were connected to the individual LED strips at both ends within the two, five-strip and one, four-strip groupings. Connections were made at both ends of all strips to provide redundancy in the event of an end connector failure.

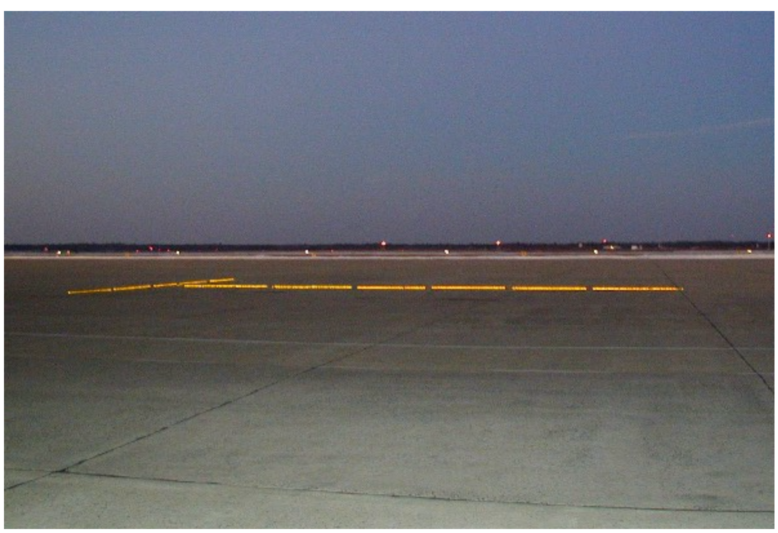

FIGURE 3. FEDERAL AVIATION ADMINISTRATION WILLIAM J. HUGHES TECHNICAL CENTER PARKING POSITION TEST SITE

FIGURE 4. ENCAPSULATED LED DEVICE

The end connectors, provided by the manufacturer and preinstalled at the factory, used spring-loaded contacts butted against the metallic ribbon conductor encapsulated with the LED lamps. This provided only a minimum contact area between the feeder wires and the ribbon conductor, which was a continuing problem until replaced with a more positive connector retrofitted by the FAA Airport Technology R&D Branch personnel.

Some difficulty was experienced with maintaining a constant level with the surrounding pavement within each strip due to what seemed to be excessive flexibility of the U channel provided to support the encapsulated LED lights. Even with using closely spaced mounting templates, per the manufacturer's instructions, it was necessary to add 1/2″ by 1/2″ angle iron strips underneath the channel for rigidity during installation in the saw-cut trench.

Once the installation had been completed, subject pilots and visual guidance engineers were afforded the opportunity of evaluating the LED strip parking locator presentation from a taxiing Convair 580 aircraft. Each subject was briefed on the purpose of the evaluation, the taxi route to be followed, and the manner in which to indicate the point at which the LED display was first identified. Subjects also completed postsession questionnaires, giving their opinions as to the effectiveness of the LED strip installation. The questionnaire, with response summary, is provided in figure 5a.

Subjects were also afforded an opportunity to observe a temporary above-ground installation of additional LED strips in the configuration of a taxiway/taxiway holding position indicator (a single dashed line). Inclusion of this movement area marking enhancement was to obtain some preliminary evaluation of a configuration that was to be more completely evaluated later. The questionnaire, with response summary, is provided in figure 5b.

SUMMARY OF RESPONSES

LED STRIP PILOT QUESTIONNAIRE

Name:____________________ Date:__3/3/99________ Weather:______CAVU____

FIRST CONFIGURATION (PARKING LOCATION)

1. Did you see and identify the LED strip lighting in time to easily execute your approach to the parking spot?

   Yes:__**8**__ No:__**0**___ (If "No", please explain deficiencies)

   Comments:____

2. Was the LED lighting presentation sufficiently clear that it identified the location for what it was – a parking position?

   Yes:__**9**___ No:__**0**___ (If "No", please explain deficiencies)

   Comments:____

3. How would you rate this proposed addition/modification to painted surface markings?

   Well worthwhile:__**8**___ Marginal help:__**1**___ Waste of money:__**0**___

   Comments:____

FIGURE 5a. QUESTIONNAIRE RESPONSE SUMMARY (First Configuration)

SUMMARY OF RESPONSES

SECOND CONFIGURATION (HOLDING POSITION)

1. Did you see and identify the LED strip holding position locator in time to comfortably stop short of the position?

   Yes: **9** No: **0** (If "No", please explain deficiencies)

   Comments:____

2. Was the LED lighting presentation sufficiently clear that it identified the location for what it was – a holding position?

   Yes: **9** No: **0** (If "No", please explain deficiencies)

   Comments:____

3. How would you rate this proposed addition/modification to painted surface markings?

   Well worthwhile: **8** Marginal help: **1** Waste of money: **0**

   Comments:____

Please include here any general comments you may have about the potential for using LED strip devices on airports:

____

FIGURE 5b. QUESTIONNAIRE RESPONSE SUMMARY (Second Configuration)

The evaluation taxi route and display locations are shown in figure 6.

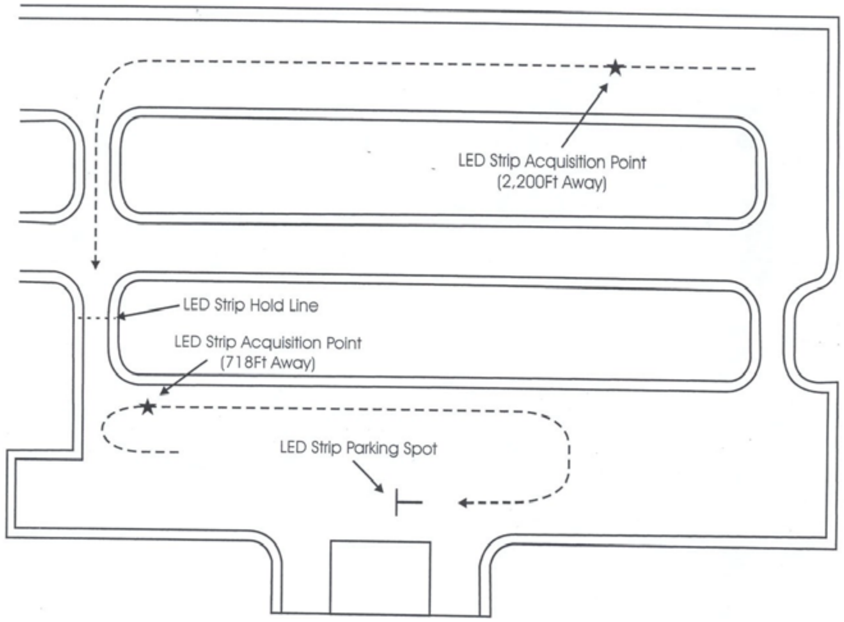

FIGURE 6. TAXI ROUTE AND DISPLAY LOCATION

As was deduced from the questionnaire responses, the subject pilot opinion of the LED-lines to define a parking position location was very positive, as was their opinion regarding the simple single dashed line holding position indicator.

In addition to the LED strip evaluation, a continuous line of LED lights was added to the dashed line configuration during the final portion of the test. Even though separated by a distance of approximately 1 foot, the solid line of LED lights tended to overwhelm the dashed line portion of the display, materially reducing the effectiveness. As an enhancement to a painted pattern, the LED configuration does not need to perfectly mimic the basic pattern, but can be left simple and present only the unique (dashed) characteristic.

The vendor stated that the LED strips would be visible under snow or ice up to 2″. But in fact, they were rendered ineffective by no more than 1 inch of snow. It was not anticipated that snowplowing would be a problem, since the LED strips are installed approximately 1/8″ below the surrounding surface, but this would also result in the LED strips being covered after plowing. LED lights do not generate any appreciable heat, therefore, there will be virtually no chance of any self-cleaning or melting of the snow or ice covering.

With regard to the method of connecting LED-line sections together, the butted against method, proved most difficult to maintain since aircraft passing over the joint depressed the connectors and ultimately broke the connection. The use of such connections necessitated the addition of U-shaped metal covers (figure 4) to shield the connectors and bridge the open joint between LED-line segments. With the advent of winter, snowplow blades hooked the cover edges and tore up several portions of the installation.

It was also noted that since the LED strip was embedded in a somewhat flexible rubber U channel, the LED-line segments were able, to a degree, to follow slight undulations in the apron surface adjacent to the installation and remain visible at lower viewing angles which might not be the case for designs using a more rigid encapsulation.

In summary, the results of this initial LED-line evaluation showed considerable promise for the concept of this linear display, but the mechanical and structural design had not been developed sufficiently to resist the relatively hostile airport environment.

2.2 TAXIWAY/RUNWAY HOLDING POSITION INDICATOR.

During April 2002, a nighttime evaluation of the same first-generation LED-line light sources was undertaken, with configurations intended to enhance surface paint taxiway/runway holding position markings. Four different arrays (figure 7) were evaluated, and are described as follows in order of decreasing complexity.

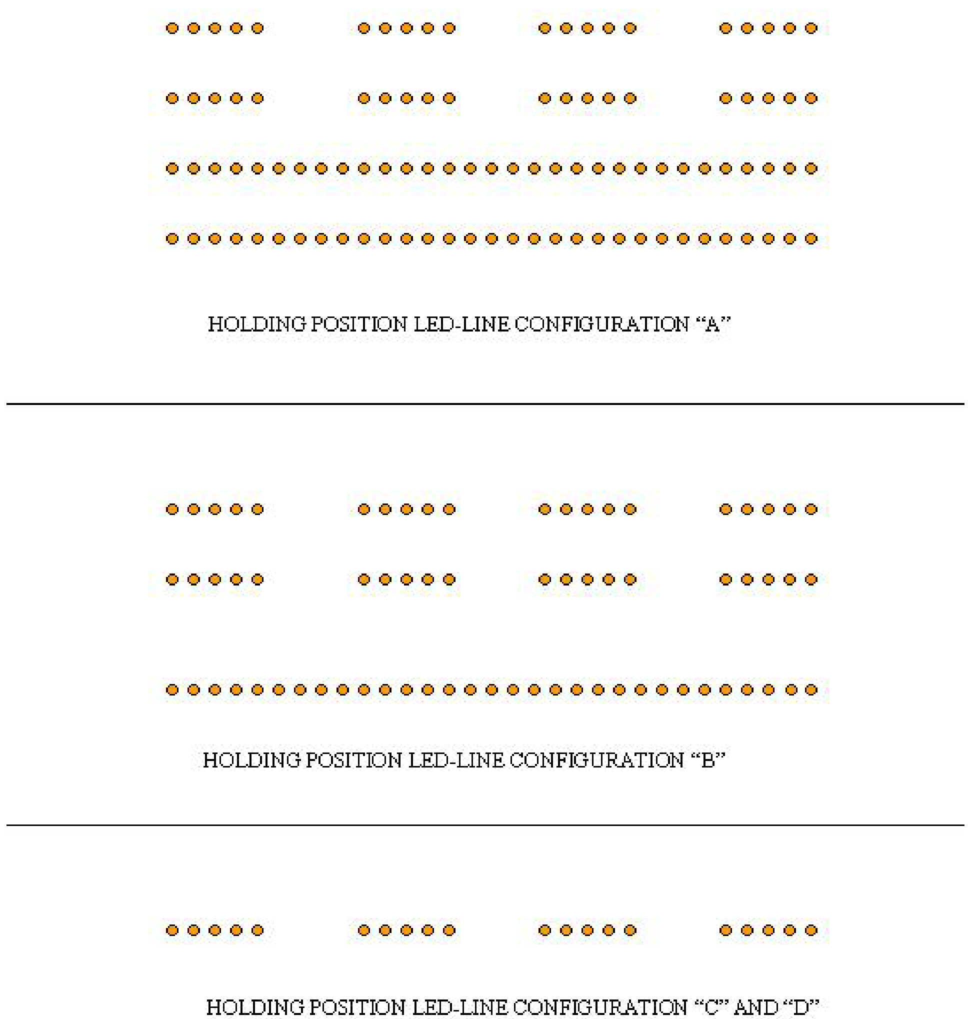

FIGURE 7. HOLDING POSITION INDICATOR CONFIGURATIONS

- Configuration A—a proposal for enhancement of the paint runway/taxiway holding position marking, consisted of four 25-foot lengths of LED-line and virtually duplicated the standard paint marking. The difference from the standard was the spacing between the dashed and solid lines. The standard is 1-foot spacing, and configuration A was 2 feet.

- Configuration B—a slightly reduced version of configuration A, consisted of three 25-foot lengths of LED-line. The reduction of the number of solid line segments, from 2 to 1, was proposed as an attempt to eliminate any overpowering of the dashed lines by the solid segments.

- Configuration C—an attempt to provide a LED-line enhancement of the standard taxiway/taxiway (intermediate) holding position marking, consisted of a single 25-foot length of dashed 3-foot sections.

- Configuration D—intended as an alternative to the standard inset runway guard light system, consisted of the configuration C pattern flashed at 1-second intervals.

Configurations A and B were presented for evaluation in both a steady-burning and flashing mode. The flashing mode consisted of alternating 1 second on and 1 second off periods. Configuration C was presented only in the steady-burning mode.

Each of the configurations described were 25 feet in width and located transversely across the taxiway width.

A group of experienced visual guidance and airport engineers, along with several FAA test pilots, gathered at the William J. Hughes Technical Center on the evening of April 30, 2002, to evaluate the selected LED-line configurations.

Configurations A through D were displayed in alphabetical sequence, at the runway 31/taxiway Bravo intersection, for observation and evaluation by the participants. The FAA Boeing 727 aircraft, based at the William J. Hughes Technical Center, was taxied up to a point immediately in front of each displayed configuration and then halted, as though awaiting clearance onto the runway, to provide additional time for evaluation. The aircraft was then taxied onto the runway and turned to approach the LED-line array from the reverse side to allow the evaluators the view that a pilot would have when exiting the runway after landing.

The evaluators were thoroughly briefed prior to boarding the aircraft about the purpose and desired characteristics of the lighting configurations that they were about to evaluate. They were also given the questionnaire that they would be required to complete during the course of the evaluation.

Once configurations A and B, the proposed runway holding position enhancements, had been presented to the evaluators during taxiing runs with the B-727 aircraft, they were asked to fill out the first section of the questionnaire.

Immediately thereafter, taxi runs on the next two configurations, C and D replicating the taxiway/taxiway holding position marking and runway guard lights respectfully, were conducted. The evaluators were again afforded an opportunity to complete the appropriate sections of the questionnaire after each taxi run.

The questionnaires were collected immediately after the taxi evaluation session was completed and a general debriefing discussion ensued. A summary of the questionnaire responses is provided in figures 8a and 8b. Some remarks noted during this session are reflected in the short results discussion that follows.

SUMMARY OF RESPONSES

POST-TAXI QUESTIONNAIRE

Subject Name:_____**Summary**______________ Date:____**4/30/02**________
Weather:____________________

Please answer these questions after you have had an opportunity to view the first two LED Line configurations and operating modes (flashing/steady). The objective is to identify the least complex configuration/mode that will effectively identify the runway holding position location in the event that the painted markings are obscured by rain water, sand, etc.

1. Which of the two configurations did you think was most effective?

   2 Dashed/2 Solid __**6**__ 2 Dashed/1 Solid __**5**__

   Comments:____

2. Do you think that it would be desirable (or necessary) to flash the signal?

   Yes __**3**__ No __**8**__

   Comments:____

3. Did you feel that these LED Line holding position lights might confuse or concern a pilot approaching the configurations from the runway side?

   Yes __**1**__ No __**10**__

   Comments:____

FIGURE 8a. QUESTIONNAIRE RESPONSE SUMMARY (Configurations A and B)

Please answer these questions <u>after</u> you have had an opportunity to view the fourth LED Line configuration (Dashed Line/Steady Burning). The objective is to provide an enhancement to the standard taxiway/taxiway (intermediate) holding position marking that will effectively identify that location in the event that the painted markings are obscured by rain water, sand, etc.

1. Do you think that this configuration is sufficiently distinctive that it would readily identify the taxiway/taxiway holding position?

   Yes **10** No **1**

   Comments:____

2. Do you have any concern that this lighting configuration might be mistaken for the <u>runway</u> holding position indicator which mandates a stop for ATC clearance?

   Yes **3** No **8**

   Comments:____

Please answer these questions <u>after</u> you have had an opportunity to view the third LED Line configuration (Dashed Line/Flashing). The objective is to provide a LED Line alternative to the standard Runway Guard Inset Lights that will effectively enhance the <u>runway</u> holding position location in the event that the painted markings are obscured by rain water, sand, etc.

1. Was this single dashed line of flashing LED lights sufficiently unique that it would readily identify the runway holding position location?

   Yes **4** No **6**

   Comments:____

2. Did you feel that this alternate form of Runway Guard Lights might confuse or concern a pilot approaching it from the runway side?

   Yes **8** No **2**

   Comments:____

If you have any further comments or opinions about the issues addressed here, please note them on the reverse of this questionnaire sheet.

FIGURE 8b. QUESTIONNAIRE RESPONSE SUMMARY (Configuration D)

After having observed all four configurations from both aspects several times, it was the viewer group's consensus that the first, and unfortunately the most complex, configuration (configuration A in figure 7) was the most effective. It faithfully represented the painted marking and would be least likely to be mistaken for a taxiway/taxiway or movement area limit designator. The 2-foot separation between the dashed and solid LED-lines, rather than the standard 1-foot spacing, helped considerably in making the configuration more discernable at lower viewing (greater distance) angles.

A brief evaluation of the effectiveness of the configuration A pattern, two dashed and two solid LED-lines, when flashed at 1-second intervals was undertaken. While the flashing signal was certainly more attention getting, the steady-burning signal was sufficiently attractive without change. It was the participants' consensus that introducing yet another flashing visual aid into the airport environment should be avoided at all cost, and it is definitely not required in this case.

2.3 NEW PROTOTYPE LED LINEAR SOURCE EVALUATION.

An evaluation of rigid encapsulated LED linear strip assemblies (figure 9), manufactured by Illuminated Guidance Systems, Inc. (IGS), was accomplished at the William J. Hughes Technical Center during the afternoon and evening of November 20, 2002. The purpose of this quick look evaluation of the IGS devices was to determine whether this particular application of LED technology would better serve airport visual guidance and, in particular, whether this unique technique for packaging the LED devices would better resist the harsh airfield environment.

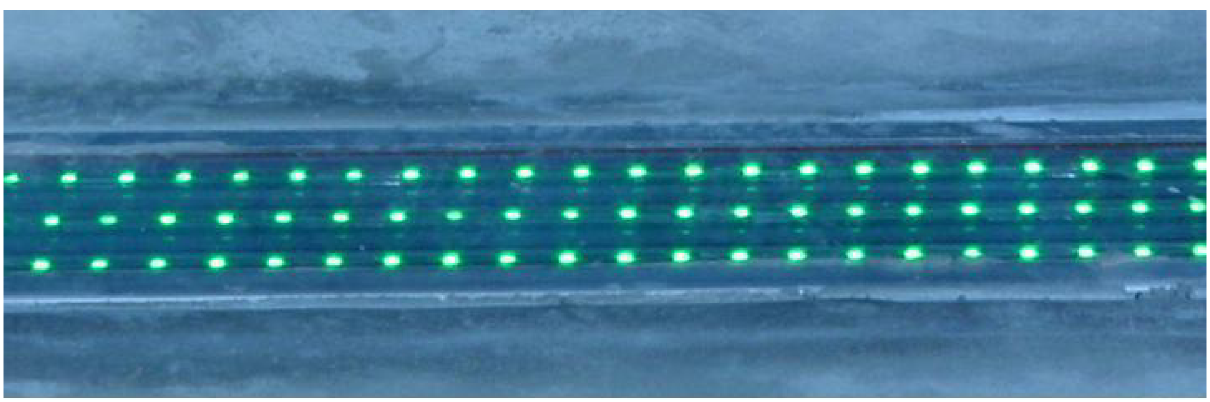

FIGURE 9. RIGID LED FIXTURE

The basic IGS assembly consists of three rows of encapsulated LEDs, parallel to each other and of 3- to 8-foot lengths depending upon the purpose, installed within a rigid aluminum box-like container that also provided a mounting for the associated direct current power supply. For the evaluation effort, the manufacturer provided eight short (approximately 3-feet long) blue LED assemblies, intended to serve as flush-mounted taxiway edge lights, and a considerably greater number of longer (approximately 8-feet long) yellow LED assemblies, intended to provide an enhanced (lighted) replica of the standard paint runway holding position marking. The assemblies were intended to be mounted permanently with the top surface flush with the surrounding pavement but, for this evaluation, the units were simply placed directly on the pavement. Power, at 120 Vac, was provided with portable generators, and where necessary, the

6.6-ampere feed was obtained with VARIAC devices. Each assembly also contained a background layer of retro-reflective material, of the appropriate color, to provide a measure of daytime conspicuity.

A simulated 75-foot-wide taxiway segment was established on the FAA apron at the William J. Hughes Technical Center, with four blue LED taxiway edge light units placed linearly 50 feet apart and 10 feet from each edge of the taxiway. Additionally, yellow LED assemblies were placed transversely across the taxiway segment to exactly duplicate the two solid line and two dashed line holding position marking pattern. The total appearance of the installation was that of a 150-foot taxiway segment having blue edge lights and an illuminated enhanced holding position indicator.

Ground vehicles (trucks and vans) were driven through the installation so the evaluators and observers could judge the system appearance from a moving vehicle. Additionally, an air-stair platform, with a maximum height of approximately 22 feet, was provided to simulate the view from the cockpit of a typical air carrier aircraft (DC-9, B-727, L-1011, etc.).

Observation conditions were excellent, with partial sunlight during the afternoon session and typical airport ambient lighting levels existing after dark. Local ramp floodlights were turned off during the nighttime evaluation, but some stray light was perceptible from remote floodlights on the adjacent civil apron. In general, nighttime lighting conditions were typical of what would be encountered at a relatively busy commercial airport.

Sixteen individuals, all familiar with airport visual aid development and problems, attended the evaluation session and were given ample time to observe the two (edge light and holding position indicator) applications proposed for LED utilization.

A consensus of those attending the evaluation session, as derived from spontaneous comments and notes taken at a subsequent debriefing, revealed the following:

- The LED components used had sufficient intensity for nighttime use but were virtually invisible during daylight, under which conditions only the retro-reflective material provided any guidance. A single yellow assembly, using enhanced LEDs and having significantly greater intensity, was displayed and appeared to be a better option for airport usage.

- The method of connecting adjacent yellow LED units required the insertion of blank, or unlighted, segments. This, to some extent, reduced the impression of continuous lines within the holding position configuration.

- Since the LEDs strips are narrow when viewed perpendicularly, they tend to blend together at low viewing angles. Thus, the critical holding position configuration is not evident as such, except when viewed from the higher elevation of the air-stair platform. The configuration would probably be easily viewed and interpreted from an air carrier aircraft cockpit, but might not prove so effective for pilots of lower cockpit general aviation and business aircraft.

- The manufacturer has stated that available internal heaters will provide sufficient heat to keep the LED unit surfaces clear of snow and ice up to 3-inch/hour accumulation levels. This would seem to be sufficient, but the possibility exists that snow buildup on the adjacent taxiway surfaces might prevent the flush fixtures from providing adequate information/guidance. Standing water from rain showers would also reduce the effectiveness of the flush assembly to a degree.

- Initial procurement and installation costs would be considerable, which could be more than offset over a period of time, by significantly lowering maintenance and power costs. Each 8-foot, yellow LED assembly requires only 8 watts of power, compared to the 105-watt requirement for a typical conventional inset lighting fixture.

In summary, the participants felt that LED fixtures of this type seemed to show promise for airport use, but cannot be considered as airport ready at this stage of development. Use in applications where the LED strips would normally be viewed lengthwise, rather than transversely would produce better results.

At the time that this report was written, a number of the IGS LED fixtures had been installed on the FAA apron at the William J. Hughes Technical Center for evaluation. They are configured in the form of a parking position indicator shaped as the letter T, in the same location as described in section 2.1. The purpose was to subject the rigid fixtures to a typical airport environment for a prolonged period of time. Shortly after the installation was completed, however, snow removal equipment, sheared off one of the power connection box covers. In addition, it appears that moisture has entered several of the fixtures and shorted out a considerable number of LED strings. Repairs are being made, and the installation will be monitored for further performance. Again, the installation and robustness of linear sources needs more attention from the vendors to enable the use of this technology on airports.

2.4 SURFACE TECHNOLOGY PRODUCT TEAM.

2.4.1 Omaha Epply Field Evaluation.

In September of 2002, in response to a request from FAA/Washington Surface Technology Product Team, AND-520, a team of lighting experts from the Airport Technology R&D Branch accomplished an inspection of the in-pavement LED-line installation at Epply Field, Omaha, Nebraska. The LED strips were installed on taxiway C between runways 32R and 32L in a hold position line marking configuration and in a letter C surface paint marking configuration (figure 10).

The following are excerpts from the inspection team's trip report, which will provide insight into the problems resulting from this in-service evaluation installation. The LED-line devices were virtually identical to the first-generation units tested earlier at the William J. Hughes Technical Center, with the exception of the technique used to power-link the segments.

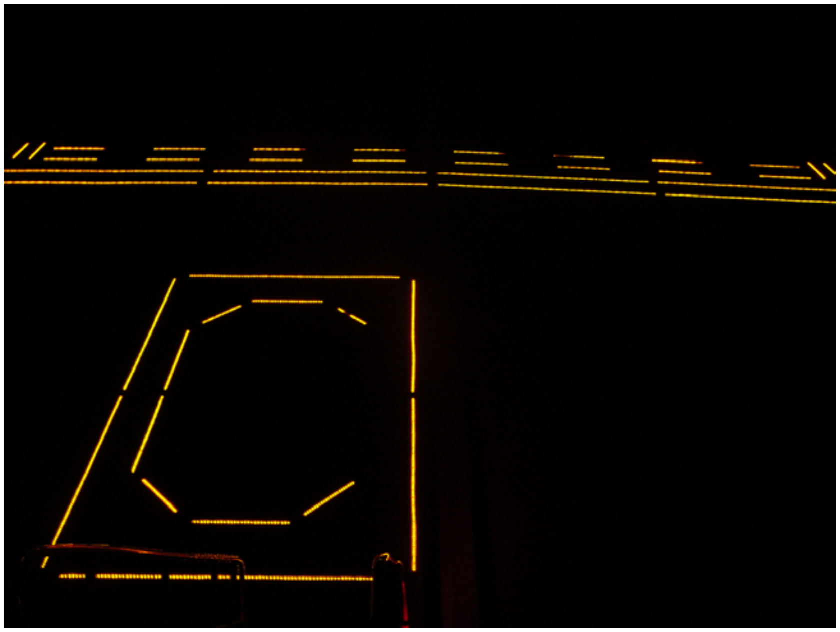

FIGURE 10. LED-LINE HOLDING POSITION AND LETTER C CONFIGURATION

- Trip Summary

September 17, 2002, Airport Technology R&D Branch—The light strips were installed in two configurations at taxiway C as a hold position line and a surface mounted taxiway C designator sign. The LED-line light strips were located at the hold position marking at the intersection of runways 18/36 and 14R/32L on taxiway C to just short of the holding position at runway 14L/32R. All participants viewed the LED light strips during daylight and nighttime hours.

On initial inspection, it was observed that parts of the light emitting from the hold position line and letter C designator sign disappeared quicker than other parts of the installation, making it difficult to decipher any of the configurations when viewed from a distance. All participants agreed that the quality of the installation was poorly implemented, as discussed below, but it was still possible to complete the assignment as requested.

The procedure to validate vendor acquisition distances was then conducted. Air stairs, borrowed from the airport fire department, were used to simulate different cockpit heights and to observe at what point the configurations became clear and unclear. The air stairs were positioned on the centerline of the taxiway, and then driven along the centerline until the participants agreed that the effectiveness of the LEDs was beginning to deteriorate. This process was repeated for each of the six predetermined heights. The actual distance and height was recorded at each location by the project engineers. The team used the data that was previously collected by the LED light strip vendor as a guideline to ensure that the proper data points were being collected.

- Installation Inspection Details

Electrical Connections—Prior experience with the LED strips has found that the most vulnerable area of this technology was the electrical connections between the light strips. This area was the most susceptible to problems due to its exposure to environmental and operational conditions. This installation used shorter LED strips with connections intentionally made at every pavement expansion joint, significantly increasing the number of susceptible areas in the system. The letter C, due to its very design, also required a significant amount of connectors to be installed. The vendor developed a new connector design that fits within the trench, but it still presents a problem with loading from passing aircraft.

Trench Depths—It was observed that the LED light strips were not imbedded into the pavement at a uniform depth. The depth of the strips ranged from 1/8 of an inch, as recommended by the vendor, to as much as 4/10 of an inch below the pavement surface (figure 11). This variation caused a problem with acquisition distances, as it tended to hide the lower LEDs from the viewer, causing a series of dark spots within the configuration. Comparing figure 9 with figure 12 illustrates how the varying depths can seriously affect the performance of the LEDs.

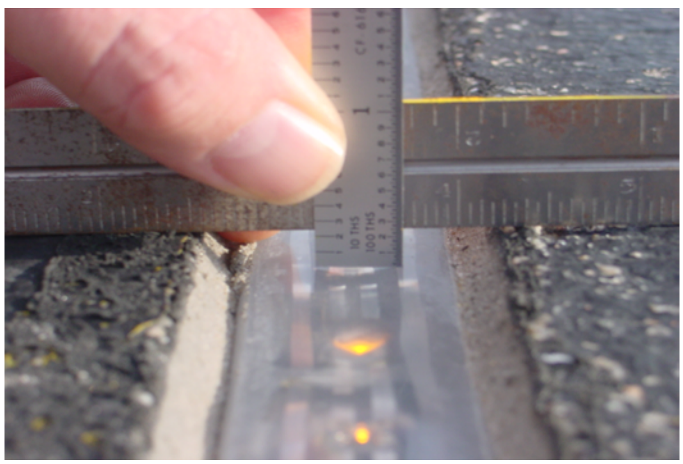

FIGURE 11. EXAMPLE OF LED-LINE DEPTH VARIATION

Product Quality—The quality of the LED product itself was also questioned, as it appeared as though numerous things were possibly overlooked. Within each LED extrusion, it was noted that there was a serious misalignment with the LED lamps themselves within the plastic extrusion. This caused the emitted light from the LED to be directed in various directions, versus being aligned with the rest of the LEDs. This caused hot spots, where that particular LED is viewed as brighter, due to it being aimed at the viewer, or conversely, caused a dark spot when the LED was aimed away from the viewer. It was also noted that two different color groupings were used within the yellow LED Strips. The color changes occurred at definite places within the lines.

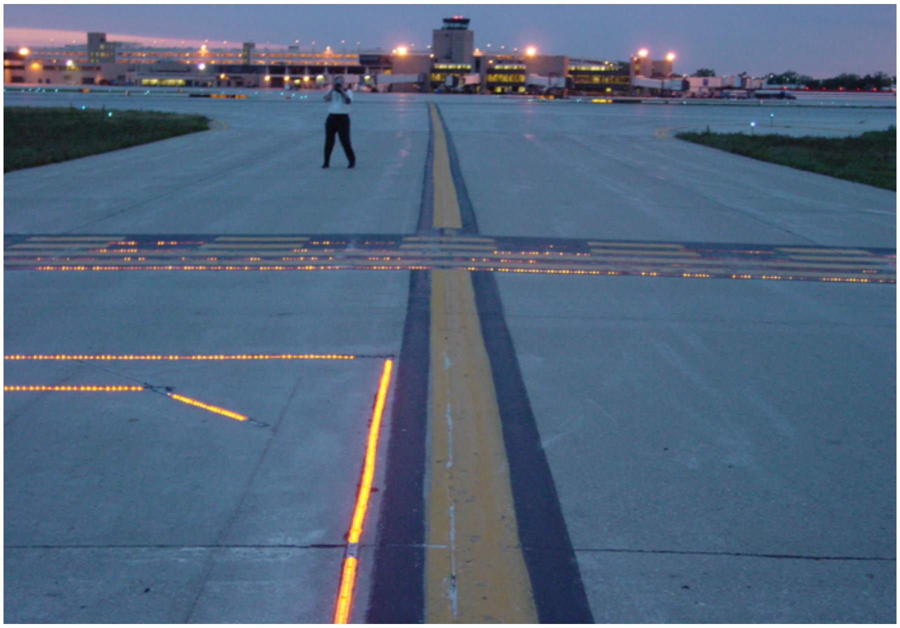

FIGURE 12. VISUAL RESULTS OF TRENCH DEPTH VARIATIONS

It was also noted that a section of LEDs had failed within one of the LED strips, as is illustrated in figure 13. The LEDs, as designed, fail in groups of four, which in some cases caused a larger dark area that was created by a single LED failure.

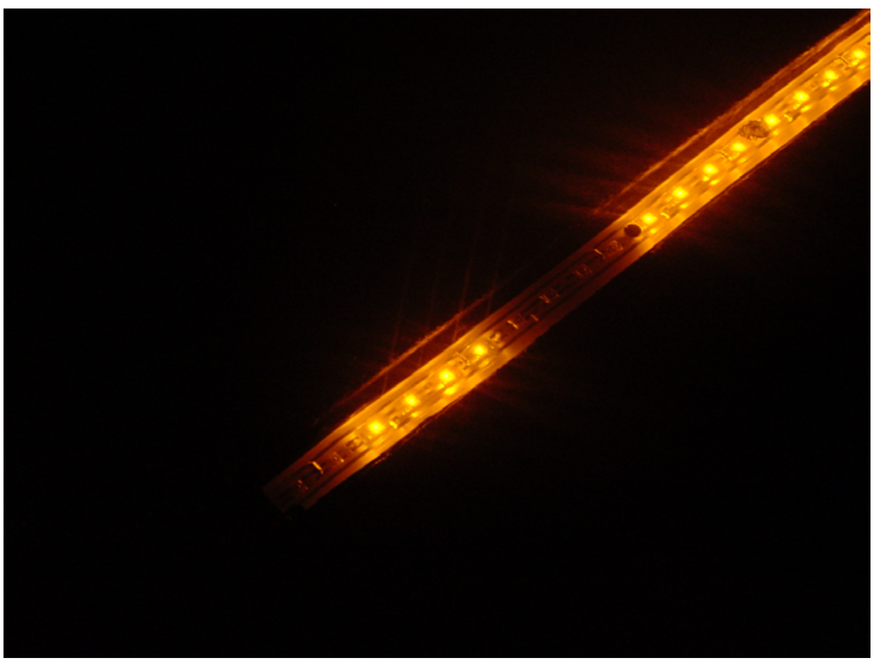

FIGURE 13. FAILED FOUR-LED GROUP

Installation Technique—It was noted that the typical U channel, which provides support for the light strips, was not used in this installation. This omission of the U channel, in the opinion of the observers, attributed to the uneven condition. The channel typically acts as a backbone for the very flexible plastic material and prevents it from varying in height. The width of the trench dug into the pavement was considered satisfactory, as it minimized the amount of space between the LED and the concrete.

- LED Acquisition Observations

Acquisition Distances—Upon completion of the evaluation, a complete set of data were established for both the LED hold line and the inpavement C. In addition, data were collected at the point where the LEDs were no longer clear, i.e., that the entire LED configuration was identifiable, and where the LEDs were first visible, meaning that the observers detected the presence of lighting but were unable to determine what it was. These acquisition distances were based solely on subjective data in the form of observations from the participants, though the distances were agreed upon as a group versus as individuals. Figures 10 and 12 illustrate the two critical points at which the clear and visible events occurred.

Acquisition Distance Relativity—In an effort to better comprehend the angles of view of the LEDs from actual aircraft, a series of measurements were collected from various types of aircraft, ranging from smaller general aviation aircraft, up to taller standing commercial jets, and then compared against the data. Figures 14 and 15 illustrate the distances at which each type of aircraft would be able to see the LED hold line and LED C clearly. These calculations are based on the measurements taken during the September 17, 2002, observations. A listing of representative aircraft for each pilot eye height distance is also provided on these two figures for reference.

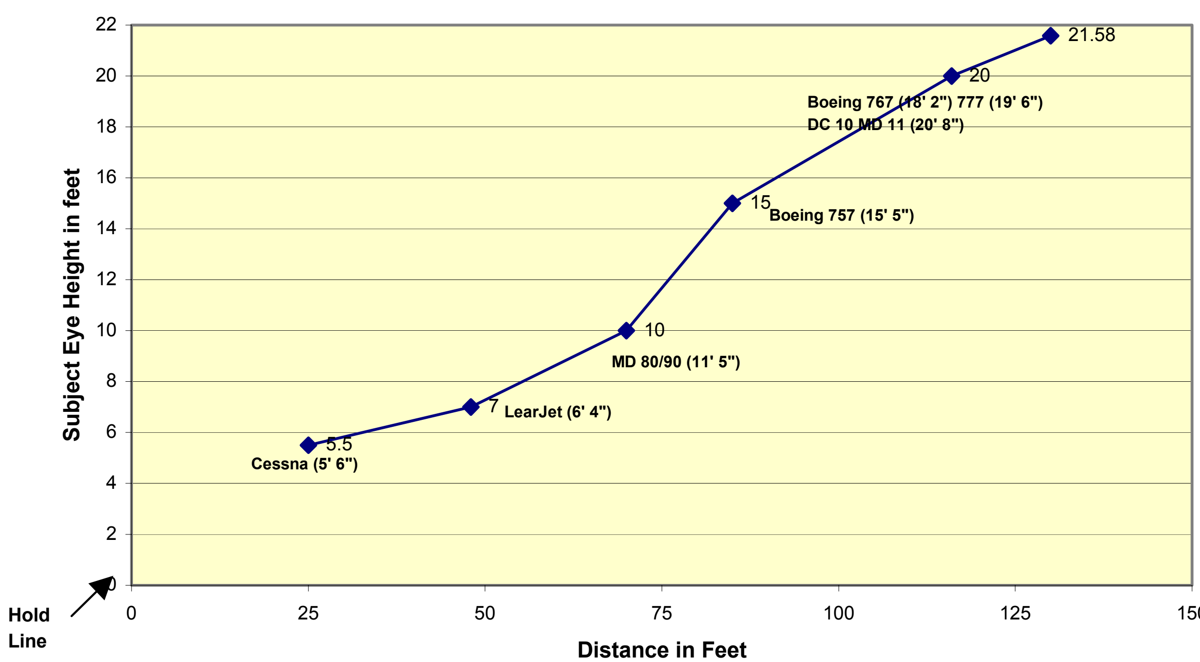

FIGURE 14. MAXIMUM RANGE TO ACQUIRE HOLDING POSITION LED-LINES

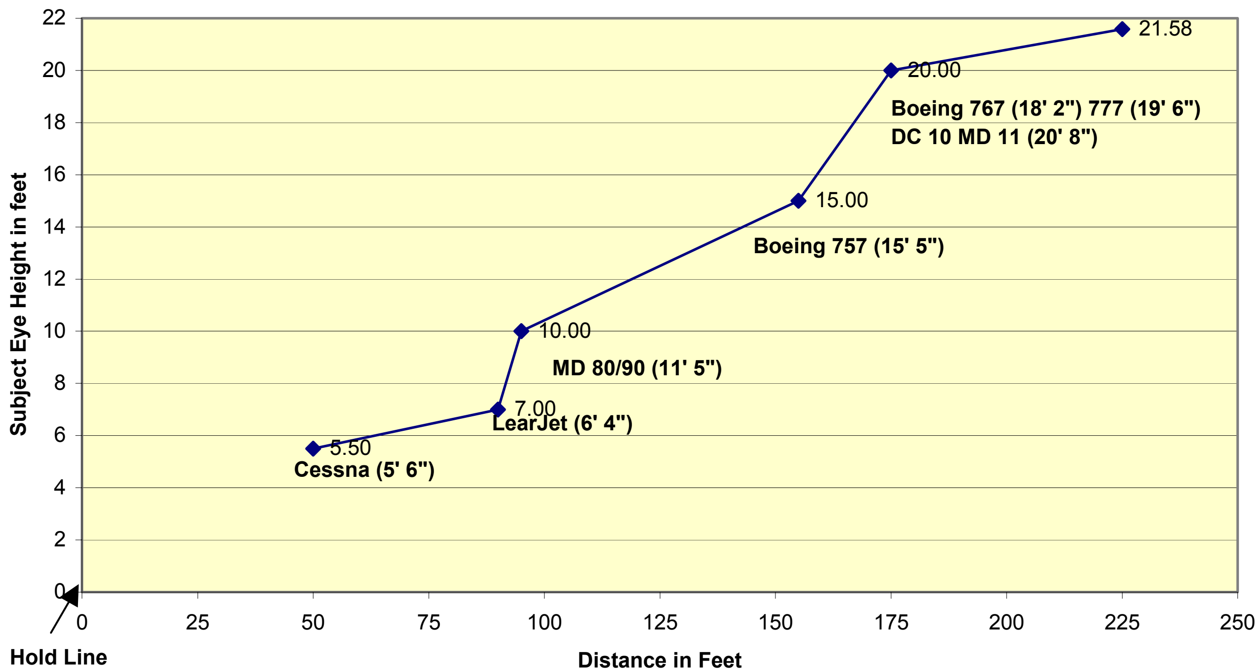

FIGURE 15. MAXIMUM RANGE TO ACQUIRE THE LETTER C

In figure 14, which contains data for the hold line clear acquisition, the distances range from 25 ft at 5 ft 6 in. to 130 ft at 21 ft 7 in. The distances for the LEDs being visible, though not depicted on the charts, ranged from 70 to 265 ft.

Acquisition Comparison—A research evaluation conducted at the William J. Hughes Technical Center in 2001, whose results are included in a report titled "Airport Pavement Marking Evaluation for Reducing Runway Incursions," DOT/FAA/AR-TN01/2, proved that freshly painted hold position markings (with beads) were visible from 250 ft during daylight hours, and from 150 ft away during nighttime conditions. These measurements were made from an eye height of 20 ft. By referencing figure 15, one can see that the LEDs, during nighttime conditions, could only be viewed as clear up to a distance of 120 ft at an equal eye height of 20 ft.

2.4.2 Findings From Omaha Field Evaluation.

Having completed the site visit, data collection, and data analysis, the following conclusions have been made:

- The LED product that was provided by the vendor for the installation suffered from a number of problems, many of which were simple quality control issues. The product itself contained variations in color, LED alignment, and physical deformities within the plastic extrusion.

- The LED installation, as provided by the vendor, also suffered from a series of problems that dramatically reduced the effectiveness of the product. The most noticeable problem was that of the inconsistent depth that the product was installed in the pavement. In addition, the lack of a U channel or any type of rigid material to support the LED strips contributed to the problem.

- The increased number of connections that were added to the LED strips to span across joints in the concrete created two main areas of concern. The first area of concern was the breaks in the LEDs changed the image of the hold line. The two long, straight lines within the hold line should be unbroken. The image depicted by this installation showed four, uneven, nonsymmetrical dashed lines of varying length. The second area of concern was the addition of these connections also seriously increased the likelihood of system or strip failure. The installation at the William J. Hughes Technical Center was continuously plagued with problems, all originating from faulty electrical connections. One connection was identified at Omaha Eppley Field that could be broken by applying pressure to the connector plate.

- The acquisition distances for the LED hold line and letter C for larger aircraft heights was considered sufficient, giving the pilot approximately 120 ft of distance to slow the airplane to a stop. Smaller aircraft, only appreciated approximately 25 ft of taxiway from the point the LEDs were clear to the hold point.

- The substantial amount of time and distance between when the pilot first notices the LEDs and when the LEDs are considered clear, actually cause a distraction as the pilot would spend time attempting to figure out what he is seeing on the taxiway ahead. Seeing an unknown lighting cue prior to being able to clearly (and immediately) identify the cue would cause confusion and trigger the pilot to make additional calls to air traffic control for clarification.

- The acquisition distances associated with freshly beaded and painted stripes were greater than those of the LEDs, mostly in part to the poor installation of the strips. The LEDs fixtures provided a significant amount of early warning, though not identifiable, to the pilot that was not available with a paint marking. A direct comparison of the paint versus the LEDs at Omaha Epply Field was not possible, due to the very poor condition of the paint marking at the location.

<u>2.4.3 Recommendations From the Omaha Epply Field Evaluation</u>.

The following recommendations were made in reference to further investigations of in-pavement LED lighting technology.

- Efforts to continue to monitor the LED installation at Omaha Eppley Field should be continued, as it does represent the first in-service installation of its kind. Periodic visits to the test site would enable project engineers to monitor the systems performance, and identify any problems that may be encountered after a lengthy operational period. In addition, it would provide information on how the system withstands the impacts of snow removal operations.

- It may be feasible to attempt to correct the problems at Omaha Eppley Field. Correcting the problems and making the site more usable would be appropriate, since a lot of time and money went into the initial effort.

3. ADDITIONAL APPLICATION CONSIDERED.

During the evaluation period, one other application showed promise for a linear configuration. Over the years pilots have complained of the problem of identifying the active runway at airports with multiple runways. A series of the LED-line product was placed on the runway number designator on runway 4 at the William J. Hughes Technical Center for a few approaches to that runway. As shown in figure 16, the appearance was dramatic and deemed a very useful cue.

FIGURE 16. RUNWAY NUMBER LED LINEAR SOURCE APPLICATION

4. OBSERVATIONS.

- LEDs are, of course, monochromatic and are available in all the colors normally used for airport visual aids. It may be that some or all of the pure colors will not fall exactly within the limits established by airport color specifications, but it may also be that a change or modification to these specifications, to allow use of LED sources, would be warranted.

- In general, having multiple single sources in close proximity, as in a linear array of many sources, would be advantageous in that a single outage would not significantly diminish the overall effectiveness of the visual presentation.

- LEDs are noted for having longer life than standard sources used on airports.

During the evaluation period, issues that were nonexistent with standard incandescent lighting were identified with LEDs and should be considered when implementing this technology. The following issues have been identified:

- How will this technology interact if interspersed with standard incandescent lights on airport circuits?

- What are the impacts of intensity changes with LEDs? Experience has revealed that dimming or purposely reducing the intensity of LED devices to reduce glare poses some problems, and these problems would be exacerbated should the system included both conventional filament and LED devices.

- What causes the human eye to perceive the LEDs as brighter than incandescent when photometrics show that the candela values are less for LEDs?

- Does the narrow spectral band of LED impact pilots with certain types of color-deficient vision?

- Can LEDs be seen on an enhanced vision display that uses the infrared emissions present with incandescent?

- The nonrigid encapsulated LED-line devices were so flexible that it was almost impossible to maintain a uniform depth of installation such that the top of the encapsulation material followed the contour of the surface immediately adjacent to the trench itself. Even placing the temporary support strips, intended to maintain a uniform depth, very close together was not adequate. It was necessary to attach angle iron braces to the bottom of the encapsulation material to provide support. Figure 17 illustrates this problem in the extreme, as found during the inspection of the Omaha Epply Field installation that did not incorporate any supplemental bracing of the LED-line devices.

FIGURE 17. NONRIGID STRIP DISTORTION

5. CONCLUSIONS.

While each of the evaluation and investigative effort descriptions contain some discussion relating to the effectiveness of the visual presentation and to the ease or difficulty of installation, the following is a compilation of the conclusions reached after several year's experience.

- The concept of using the light emitting diode (LED) linear source to enhance paint markings on the airport surface is promising. Achievable LED intensity levels have increased significantly, while costs have concurrently decreased, thus the sources evaluated have considerable potential, from the visual standpoint, for airport use.

- The linear LED strips are especially effective when viewed along the line of sight rather than across it, i.e., along a taxiway centerline rather than at right angles to the centerline.

- In general, the off-the-shelf linear light sources were not readily adaptable to airport surface installation, and a redesign and adaptation needs to be done before they would be suitable. Major difficulties were experienced, including:

- The nonrigid encapsulated LED-line devices were so flexible that it was almost impossible to maintain a uniform depth of installation such that the top of the encapsulation material followed the contour of the surface immediately adjacent to the trench itself.

- The rigid LED devices were easier to install while maintaining a uniform depth or surface relationship with the surrounding area.

- Providing space between individual lengths of LED linear sources for making wire-to-wire splices introduced several problems. The considerable amount linear space, wherein no LED lights are contained, required for the connections breaks up or interrupts the linear light presentation, lessening its effectiveness. Additionally, covers or shielding must be provided to protect the connection area, and experience has revealed that this discontinuity along the system surface invites snowplow and vehicular damage. Both types of power connection installations have sustained significant damage from snow removal equipment strikes.

- LED linear devices suitable for airport use will have to be designed specifically for that purpose, and not be an adaptation of devices originally developed to serve other purposes.

- Lighting Sciences Inc. developed photometric testing procedures and a hand-held field photometric device to verify operational performance. Appendix A contains recommended procedures addressing the LED photometric measurement issue.

APPENDIX A—PROCEDURES FOR PHOTOMETRIC TESTING OF LIGHT EMITTING DIODE STRIPS

May 2004

X.X.1 Procedures. Before testing, photometric equipment shall be calibrated in accordance with section 5.2 of IESNA LM-35-02 and X.X.2 below. The photometric axes are established in relation to the strip; the horizontal axis passes through the center of the LED strip and is parallel to the long axis of the strip, and the vertical axis runs through the center of the strip and is perpendicular to the ground plane (figure A-1). Strips shall be operated until a stable light output is achieved before taking measurements, see X.X.8 below.

X.X.2 Calibration Adjustments. A calibrated and photopically corrected detector shall be used. Even well corrected detectors generally have errors in their spectral corrections that make measurements of near monochromatic light sources such as LEDs inaccurate. This is especially true at the ends of the visible spectrum. Therefore, it is necessary to make adjustments to the calibrated measurements of an LED, through determining a correcting factor by which all readings are multiplied. One of three methods shall be used to determine the necessary correction factor for a given LED. The three methods are described in X.X.2.1-X.X.2.3 below.

X.X.2.1 Calibration Adjustments Using a Calibrated Filter. This method of adjusting the detector calibration for an LED measurement involves measuring the transmittance of a reference filter with the photometric test equipment detector and a standard lamp. The steps in this process are as follows:

1. A calibrated filter shall be used, which has a known transmittance for light from an incandescent source having a color temperature of 2856 K. The filter shall be chosen such that the color coordinates of a standard lamp operated at a 2856 K color temperature filtered with the reference filter lie inside the region of color space defined by MIL C-25050A for the color of LED strip to be tested.

2. Set up the standard lamp and operate at the current required to produce a color temperature of 2856 K.

3. Measure the intensity of the standard lamp, I_{STD}, at any chosen test distance.

4. Place the filter selected in step 1 between the detector and the standard lamp. Check to be sure that the full aperture of the detector is unobstructed but covered by the filter.

5. Measure the intensity of the filtered standard lamp, I_{FL}.

6. Compute the measured transmittance, T_M , where $T_M = I_{FL} / I_{STD}$.

7. Look up the calibrated transmittance of the filter, T_{CAL}.

8. Compute the correction factor (CF), where $CF = T_{CAL} / T_M$.

The CF for a particular color shall be applied to all the intensity measurements of the LED strip of that color to give corrected intensity measurements, I'. I' is computed from I' = I CF, where I is the measured but uncorrected intensity measurement.

X.X.2.2 Calibration Adjustments Using a Spectrally Calibrated Detector. Another method for determining the CF for a particular LED color can be used if the spectral response of the detector is known.

Let $SR(\lambda)$ = Spectral response of the detector over wavelength range λ.
Let $V(\lambda)$ = CIE Spectral luminous response of the eye.
Let $S_{STD}(\lambda)$= Spectral output of the standard lamp used for instrument calibration.
Let λ_P = peak wavelength of the LED being measured, i.e., where its spectral output is maximum.

The CF is determined from:

$$CF = V(\lambda\mathrm{p}) / SR(\lambda\mathrm{p}) \cdot \{\int S_{STD}(\lambda) \cdot SR(\lambda) \cdot \mathrm{d}\lambda / \int S_{STD}(\lambda) \cdot V(\lambda) \cdot d\lambda\}$$

The CF for a particular color shall be applied to all the intensity measurements of the LED strip of that color to give corrected intensity measurements, I'. I' is computed from I' = I · CF, where I is the measured but uncorrected intensity measurement.

X.X.2.3 Calibration Adjustments Using a Reference Standard LED. See the International Commission on Illumination document CIE 127-1997 section 4.2.

X.X.3 Number of LEDs per Meter. The number of LEDs per meter of strip shall be determined.

X.X.4 Number of LEDs Tested per Strip. The number of LEDs tested on a strip shall be the number of LEDs, n, in a strip length of 0.33 meters. Thus, n shall be the smallest integer for which n / (number of LED's per meter) ≥ 1/3. A black opaque material shall be used to cover the ends of the LED strip such that n LEDs of the LED strip under test are exposed. The edges of the black strip material shall lie at points mid-way between two individual LEDs (figure A-2).

X.X.5 Test Distance. An LED strip shall be tested with a minimum optical path length between the LED strip and the detector of 30 times the exposed strip length.

X.X.6 LED Strip Test Fixture. Each LED strip shall be tested in a test fixture that simulates the installed LED strip. The test fixture shall be a U1 channel no more than 10 mm wider than the LED strip under test. The vertical sides of the test fixture shall be 3 mm higher than the top surface of the LED strip when mounted in the test fixture. The test fixture shall be painted flat black (figure A-3).

X.X.7 Thermal Requirements. The ambient air temperature in the area of the LED strip under test shall be held between 25° and 26°C (77° and 79°F).

X.X.8 LED Stabilization. The light output of the LED strip under test shall be stabilized before measurements occur. The LED light output shall be assumed to be stable when three successive readings of the strip light output taken 1 minute apart differ by less than 1%.

X.X.9 Test Angles. The intensity of the LED strip shall be measured over a range of vertical angles from 1° to 25° at each horizontal measurement angle. Successive measurements in the vertical plane shall be no more than 2° apart. The full 360° horizontal range shall be measured with no more than 30° between successive measurement planes.

X.X.10 Converting Measurement Units. The final measurements of the LED strip shall be in units of intensity per unit length, (candelas per meter). The conversion from color corrected measured intensity is made by multiplying the corrected measurements of the strip by the number of LEDs per meter divided by the number of LEDs tested, n, as determined in XX.4.

X.X.11 Chromaticity. Each LED strip shall be tested to ensure that it meets chromaticity requirements. The strip shall meet the requirements of MIL C-25050A when tested at full brightness.

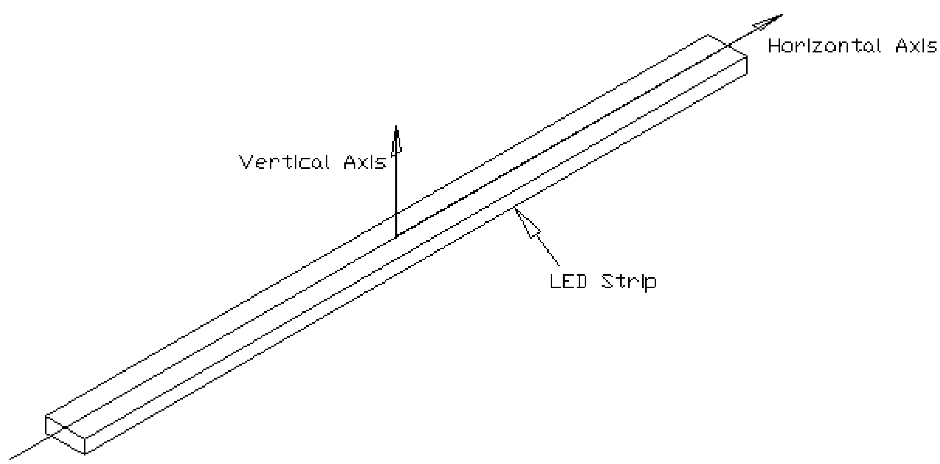

Figure A-1. Photometric Coordinate System Axes

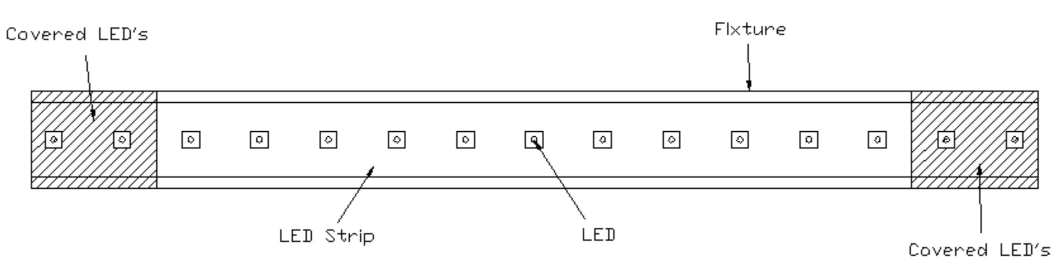

Figure A-2. LED Strip Covering

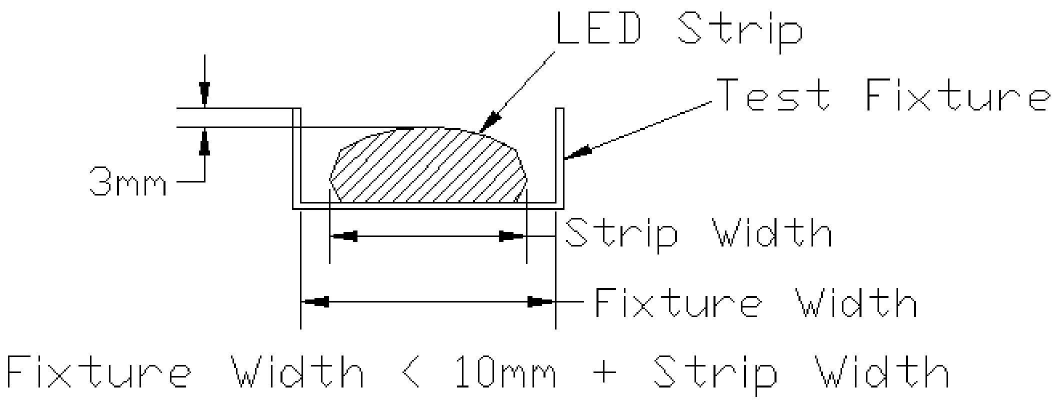

Figure A-3. LED Test Fixture