

Issues With Use of Airfield LED Light Fixtures

DETAILS

35 pages | 8.5 x 11 | PAPERBACK

ISBN 978-0-309-22369-0 | DOI 10.17226/22746

AUTHORS

Bullough, John D.

BUY THIS BOOK

FIND RELATED TITLES

Visit the National Academies Press at NAP.edu and login or register to get:

- Access to free PDF downloads of thousands of scientific reports
- 10% off the price of print titles
- Email or social media notifications of new titles related to your interests
- Special offers and discounts



Distribution, posting, or copying of this PDF is strictly prohibited without written permission of the National Academies Press. (Request Permission) Unless otherwise indicated, all materials in this PDF are copyrighted by the National Academy of Sciences.

AIRPORT COOPERATIVE RESEARCH PROGRAM

ACRP SYNTHESIS 35

**Issues With Use of Airfield
LED Light Fixtures**

A Synthesis of Airport Practice

CONSULTANT

John D. Bullough
Lighting Research Center, Rensselaer Polytechnic Institute
Troy, New York

SUBSCRIBER CATEGORIES

Aviation • Design

Research Sponsored by the Federal Aviation Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2012
www.TRB.org

AIRPORT COOPERATIVE RESEARCH PROGRAM

Airports are vital national resources. They serve a key role in transportation of people and goods and in regional, national, and international commerce. They are where the nation's aviation system connects with other modes of transportation and where federal responsibility for managing and regulating air traffic operations intersects with the role of state and local governments that own and operate most airports. Research is necessary to solve common operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the airport industry. The Airport Cooperative Research Program (ACRP) serves as one of the principal means by which the airport industry can develop innovative near-term solutions to meet demands placed on it.

The need for ACRP was identified in *TRB Special Report 272: Airport Research Needs: Cooperative Solutions* in 2003, based on a study sponsored by the Federal Aviation Administration (FAA). The ACRP carries out applied research on problems that are shared by airport operating agencies and are not being adequately addressed by existing federal research programs. It is modeled after the successful National Cooperative Highway Research Program and Transit Cooperative Research Program. The ACRP undertakes research and other technical activities in a variety of airport subject areas, including design, construction, maintenance, operations, safety, security, policy, planning, human resources, and administration. The ACRP provides a forum where airport operators can cooperatively address common operational problems.

The ACRP was authorized in December 2003 as part of the Vision 100-Century of Aviation Reauthorization Act. The primary participants in the ACRP are (1) an independent governing board, the ACRP Oversight Committee (AOC), appointed by the Secretary of the U.S. Department of Transportation with representation from airport operating agencies, other stakeholders, and relevant industry organizations such as the Airports Council International-North America (ACI-NA), the American Association of Airport Executives (AAAE), the National Association of State Aviation Officials (NASAO), Airlines for America (A4A), and the Airport Consultants Council (ACC) as vital links to the airport community; (2) the TRB as program manager and secretariat for the governing board; and (3) the FAA as program sponsor. In October 2005, the FAA executed a contract with the National Academies formally initiating the program.

The ACRP benefits from the cooperation and participation of airport professionals, air carriers, shippers, state and local government officials, equipment and service suppliers, other airport users, and research organizations. Each of these participants has different interests and responsibilities, and each is an integral part of this cooperative research effort.

Research problem statements for the ACRP are solicited periodically but may be submitted to the TRB by anyone at any time. It is the responsibility of the AOC to formulate the research program by identifying the highest priority projects and defining funding levels and expected products.

Once selected, each ACRP project is assigned to an expert panel, appointed by the TRB. Panels include experienced practitioners and research specialists; heavy emphasis is placed on including airport professionals, the intended users of the research products. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, ACRP project panels serve voluntarily without compensation.

Primary emphasis is placed on disseminating ACRP results to the intended end-users of the research: airport operating agencies, service providers, and suppliers. The ACRP produces a series of research reports for use by airport operators, local agencies, the FAA, and other interested parties, and industry associations may arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by airport-industry practitioners.

ACRP SYNTHESIS 35

Project A11-03, Topic 09-04
ISSN 1935-9187
ISBN 978-0-309-22369-0
Library of Congress Control Number 2012934405

© 2012 National Academy of Sciences. All rights reserved.

COPYRIGHT INFORMATION

Authors herein are responsible for the authenticity of their materials and for obtaining written permissions from publishers or persons who own the copyright to any previously published or copyrighted material used herein.

Cooperative Research Programs (CRP) grants permission to reproduce material in this publication for classroom and not-for-profit purposes. Permission is given with the understanding that none of the material will be used to imply TRB or FAA endorsement of a particular product, method, or practice. It is expected that those reproducing the material in this document for educational and not-for-profit uses will give appropriate acknowledgment of the source of any reprinted or reproduced material. For other uses of the material, request permission from CRP.

NOTICE

The project that is the subject of this report was a part of the Airport Cooperative Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board, the National Research Council, or the program sponsors.

The Transportation Research Board of the National Academies, the National Research Council, and the sponsors of the Airport Cooperative Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the report.

Published reports of the

AIRPORT COOPERATIVE RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at
<http://www.national-academies.org/trb/bookstore>

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

ACRP COMMITTEE FOR PROJECT 11-03

CHAIR

JULIE KENFIELD
Jacobs Engineering, Inc.

MEMBERS

RANDALL P. BURDETTE
Virginia Department of Aviation
KEVIN C. DOLLIOLE
Unison Consulting, Inc.
LINDA HOWARD
Bastrop, Texas
ARLYN PURCELL
Port Authority of New York & New Jersey
BURR STEWART
Seattle, Washington

FAA LIAISON

PAUL DEVOTI

ACI-NORTH AMERICA LIAISON

A.J. MULDOON

AIRCRAFT OWNERS AND PILOTS ASSOCIATION

JOHN L. COLLINS

TRB LIAISON

CHRISTINE GERENCHER

COOPERATIVE RESEARCH PROGRAMS STAFF

CHRISTOPHER W. JENKS, *Director, Cooperative Research Programs*
CRAWFORD F. JENCKS, *Deputy Director, Cooperative Research Programs*
MICHAEL R. SALAMONE, *Senior Program Officer*
JOSEPH J. BROWN-SNELL, *Program Associate*
EILEEN P. DELANEY, *Director of Publications*

SYNTHESIS STUDIES STAFF

STEPHEN R. GODWIN, *Director for Studies and Special Programs*
JON M. WILLIAMS, *Program Director, IDEA and Synthesis Studies*
JO ALLEN GAUSE, *Senior Program Officer*
GAIL R. STABA, *Senior Program Officer*
DONNA L. VLASAK, *Senior Program Officer*
TANYA M. ZWAHLEN, *Consultant*
DON TIPPMAN, *Senior Editor*
CHERYL KEITH, *Senior Program Assistant*
DEMISHA WILLIAMS, *Senior Program Assistant*
DEBBIE IRVIN, *Program Associate*

TOPIC PANEL

FRANK BARCZAK, *Orlando International Airport*
RICHARD A. CUNARD, *Transportation Research Board*
SOMNATH MUKHERJEE, *Port Authority of New York and New Jersey*
STEVE PITTMAN, *Rifenburg Construction, Inc., Durham, NC*
ED RUNYON, *ADB Airfield Solutions, Columbus, OH*
VERNE R. SKAGERBERG, *Alaska DOT and Public Facilities, Juneau*
THOMAS ZEIDLIK, *University of North Dakota, Grand Forks*
ALVIN LOGAN, *Federal Aviation Administration*
THOMAS MAI, *Federal Aviation Administration (Liaison)*
ALEX BAKER, *US Environmental Protection Agency (Liaison)*

Cover figure: In-pavement taxiway centerline light fixtures (foreground) and elevated taxiway edge light fixtures (background) are among the types of airfield lighting systems increasingly using light-emitting diode sources.

ACKNOWLEDGMENTS

Helpful technical input was provided by N. Narendran of the Lighting Research Center (LRC), Rensselaer Polytechnic Institute. Terence Klein and Nicholas Skinner of the LRC provided important assistance in conducting the airport survey.

FOREWORD

Airport administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to the airport industry. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire airport community, the Airport Cooperative Research Program authorized the Transportation Research Board to undertake a continuing project. This project, ACRP Project 11-03, "Synthesis of Information Related to Airport Practices," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an ACRP report series, *Synthesis of Airport Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

*By Gail R. Staba
Transportation
Research Board*

Light-emitting diode (LED) airfield lighting is growing in use at airports in the United States and abroad. The objective of the present synthesis study is to provide documentation about the performance of LED airfield lighting systems, and it is primarily intended for airfield operations managers and airport electrical maintenance staff. Information about LED lighting systems in terms of performance, cost, and other operations issues is not readily found in a single location. This report is an effort to gather information about airport experiences and feedback with LED airfield lighting.

A literature review and a survey of individuals representing airports having experience with LED airfield lighting were conducted. Individuals from 22 airports and aviation agencies agreed to participate in the survey and all 22 completed it (a 100% response rate).

John D. Bullough, Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

1	SUMMARY
3	CHAPTER ONE INTRODUCTION Background, 3 Methodology, 3 Report Content, 4
5	CHAPTER TWO CURRENT PRACTICES AND CHALLENGES IN AIRFIELD LIGHTING Current Practices, 5 LED Airfield Lighting Challenges, 5 Organization of Topical Chapters, 9
10	CHAPTER THREE INSTALLATION ISSUES Summary, 10 LED Installation Expectations, 10 Ease of Installation, 11 Compatibility Considerations, 11 Installation Personnel, 12
13	CHAPTER FOUR OPERATION AND MAINTENANCE ISSUES Summary, 13 Operating Differences Between LED and Incandescent Lighting, 13 Failure Modes and Frequency, 14 Compatibility with Legacy Systems, 15 Weather and Environmental Issues, 16 Physical Durability, 17 Response of Flight Crews to LED Airfield Lighting, 17 Interference from LED Airfield Lighting, 17 Maintenance and Monitoring Issues, 17
19	CHAPTER FIVE ECONOMIC ISSUES Summary, 19 Expectations, 19 Funding Sources, 19 Installation Costs, 19 Life-Cycle Cost and Return on Investment, 19 Operating Cost, 22
23	CHAPTER SIX FUTURE OUTLOOK Plans for Future LED Airfield Lighting Installations, 23 Reasons for Future LED Installations, 23
24	CHAPTER SEVEN CONCLUSIONS
25	TERMS, ABBREVIATIONS, AND ACRONYMS

26	REFERENCES
29	APPENDIX A TECHNICAL INFORMATION REGARDING LED LIGHTING SYSTEMS
30	APPENDIX B SURVEY QUESTIONNAIRE AND RESULTS
33	APPENDIX C LIST OF SURVEY PARTICIPANT ORGANIZATIONS AND AIRPORTS WITH LED INSTALLATIONS
34	APPENDIX D RESOURCES

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

ISSUES WITH USE OF AIRFIELD LED LIGHT FIXTURES

SUMMARY Light-emitting diode (LED) airfield lighting is increasingly used at airports in the United States and abroad. The objective of this synthesis study is to provide documentation about the performance of LED airfield lighting systems, and it is primarily intended for airfield operations managers and airport electrical maintenance staff. Information about LED lighting systems in terms of performance, cost, and other operations issues is not readily found in a single location. This report is an effort to gather information about airport experiences and feedback with LED airfield lighting.

A literature review and a survey of individuals representing airports that have experience with LED airfield lighting were conducted. Individuals from 22 airports and aviation agencies agreed to participate in the survey and all 22 completed it (for a 100% response rate).

In general, the study findings confirm that LED airfield light fixtures reduce energy use and maintenance requirements, compared with conventional airfield lighting technologies. LED airfield lighting systems have been in use for a number of years, and most feedback on their visibility and performance is positive. Early compatibility issues appear to have been largely overcome through technological progress and through efforts of the FAA to address LED technologies in its guidance to airports.

Although most electrical power systems for airfield lighting systems were designed for the incumbent incandescent lighting technology, LED airfield lighting systems are not incompatible with this infrastructure. Replacing parts of the electrical infrastructure can yield greater energy efficiency and reliability in lieu of simply replacing the incandescent light fixtures with LEDs.

Despite the presently higher initial cost of LED light fixtures relative to conventional incandescent fixtures, reductions in energy use and savings in maintenance costs are likely to result in a return on this initial investment over a period of several years. Future research could more precisely quantify the economic impacts of the lower maintenance requirements of LED airfield lighting systems in comparison to incandescent systems.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Light-emitting diodes (LEDs) are being used increasingly for many different safety-related applications including exit signs (Boyce 1994), road traffic signals (Conway and Bullough 1999), vehicle brake and turn lights (Olson 1987), street lighting (Radetsky 2010), and airfield lighting. LEDs have several characteristics that make them especially attractive for visual signaling applications (also see Appendix A for a description of LEDs and comparisons between LED and incandescent sources):

- Durability and longevity as solid state devices
- Wide range of available colors (including all aviation signal light colors)
- Narrowband wavelength output resulting in saturated color appearance
- Relatively low energy requirements
- Immediate “switch-on” and “switch-off” time.

The primary incumbent lighting technology on most airfields, incandescent filament-based lamps, tend to have shorter useful operating lives than LEDs. Typical operating lives for incandescent lamps are on the order of a few hundred to a few thousand hours (Bullough 2000). In comparison, well-designed LED lighting systems can last tens of thousands of hours.

Incandescent lamps also tend to have lower luminous efficacy (lumens per watt, lm/W) than LED light sources, resulting in relatively higher energy requirements. Energy legislation such as the Energy Independence and Security Act (EISA) of 2007 is accelerating the development of alternatives to conventional incandescent lighting systems for many lighting applications, largely because of the relatively low luminous efficacy of incandescent lamps. Although the EISA does not impact airfield lighting directly, the rapid development of alternatives to incandescent lamps for general lighting has contributed to substantial interest in and use of LED signal lighting on airfields in the United States.

Some differences between LEDs and incandescent technologies might be perceived as possible impediments to the more widespread use of LED airfield lighting. The narrowband spectral output of LEDs means they do not produce infrared energy (heat) that might be useful in melting snow and ice build-up during very cold weather. LED airfield

fixtures must work with the existing specialized electrical infrastructures of airfield lighting. In addition, because LED fixtures are, at present, relatively expensive in terms of initial cost compared with incandescent systems, there can be concerns about whether the technological advantages of increased operating life and reduced energy use will enable airports to recover initial investments when using LED light fixtures.

The present synthesis study was conducted through ACRP of TRB to gather information from the literature and from airports and other organizations with experience using LED airfield lighting, and to help airport operations and maintenance personnel consolidate and sift through the issues related to this emerging technology. The lessons learned by airports that have used this technology in airfield lighting will be useful to other organizations facing the question of whether, or when, to install LED airfield lighting, what questions to ask, and what benefits or problems might be anticipated.

METHODOLOGY

To gather the information synthesized in the present report, two primary methods were used, a literature search and a survey of organizations having experience with LED airfield lighting.

Literature Search

A literature review was conducted to identify examples of airports and other organizations that had used or were planning to use LED airfield lighting. Sources that were reviewed for this information included suggestions from ACRP Synthesis Topic Panel members for this study, the Transport Research International Documentation (TRID) database maintained by TRB (<http://trid.trb.org>), and databases of trade publications, newswires, and press releases (e.g., ProQuest ABI/INFORM, Gale Business and Company Resource Center, Reed Elsevier Lexis-Nexis).

Information was reviewed and organized by different topics such as installation issues, operation and maintenance, and economics, and is presented in subsequent chapters of this synthesis report.

Survey Questionnaire

With assistance from the members of the Topic Panel, U.S. airports with experience using LED airfield lighting were identified for possible participation in a survey (Appendix B contains the survey questionnaire and results). Individuals from these organizations were contacted to confirm their willingness to participate; 22 agreed to participate and all 22 completed the survey, for a 100% participation rate (Appendix C lists participating organizations, as well as other airports that are known to have installed LEDs). Figure 1 summarizes the types of airports represented among survey participants.

The survey was distributed individually as a text document (Microsoft Word); participants could enter their responses directly into the document and return by means of e-mail, or print the document and complete the survey by hand (and fax or scan and e-mail the completed form). Participants were also given the opportunity to complete the survey by telephone. The survey was administered during the summer and autumn of 2011. In addition to the 22 survey

participants from the United States, two additional surveys were completed by European airports. Their responses are not included in the survey results in Appendix B, but were consistent with those of the U.S. respondents.

REPORT CONTENT

Following a short chapter summarizing current practices and challenges with LED airfield lighting, this report is structured according to the primary issues identified in the literature search and survey questionnaire:

- Installation issues,
- Operation and maintenance issues, and
- Economics.

These topical chapters are followed by a chapter containing the primary findings, conclusions, and outlook for LED airfield lighting, including practical guidance airports can use in decision making.

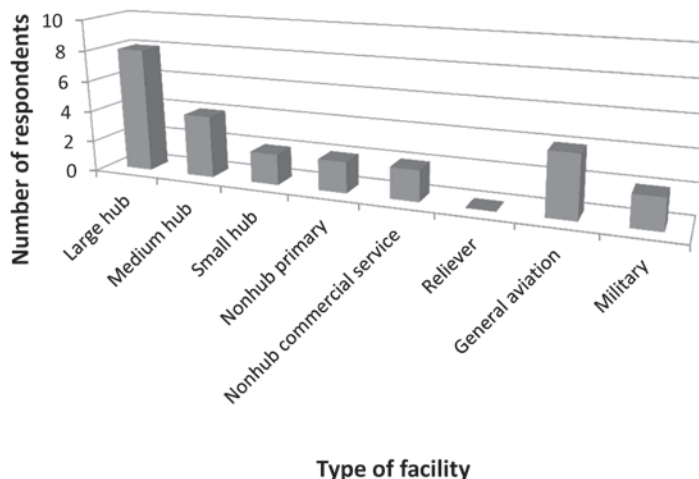


FIGURE 1 Distribution of airport types among survey participants.

CHAPTER TWO

CURRENT PRACTICES AND CHALLENGES IN AIRFIELD LIGHTING

CURRENT PRACTICES

Airfield lighting systems encompass a large variety of types varying in luminous intensity, color, and geometric configuration. These systems demarcate runways and taxiways, provide traffic control for movement of aircraft and other vehicles on the airfield, indicate the location of hazards and obstructions, and provide information about ambient conditions on the airfield. Figure 2 shows a simple schematic of a typical LED airfield lighting fixture. A series of FAA Advisory Circular (AC) and Engineering Brief (EB) documents describe the design, performance, and maintenance requirements of airfield lighting systems. The FAA also has a process for the certification of airfield lighting fixtures that meet the performance requirements, and publishes a list of certified fixtures. Key FAA documents pertaining to airfield lighting and uniform resource locators (URLs) for obtaining these documents online are listed in Appendix D.

As described in the previous chapter, LED output contains little to no infrared energy, which means that LEDs do not radiate heat directly. Because of this, it has been stated that airfield fixtures using LEDs might not generate sufficient heat to melt snow and ice that could build up on fixtures, making them less visible (Marsh et al. 2008; Rosenkrans 2008), although LED taxiway lights installed at Pullman–Moscow Regional Airport in Washington State did produce enough heat to keep snow and ice melted (Moll 2006) and no problems regarding snow and ice buildup were reported from Canadian airports (Seymour 2007). At any rate it does not appear that this is an inherent issue with LED systems, because substantial heat can be generated in the LED junction, which must be conducted away from the chip for efficient operation of the light source (Bullough 2003). Redesigned LED taxiway lights that conduct heat from the chip through a heat sink that makes contact with the fixture lens (Gu et al. 2007; Taylor 2010) were found to be able to prevent snow and ice buildup at very low temperatures. At present, not all LED light fixtures produce the temperature increase on the fixture lens specified by the FAA in its EB for keeping the lens clear of snow and ice. The use of heaters with LED light fixtures has been reported by several airports, as described in chapter four, Operation and Maintenance Issues.

Types of LED Airfield Fixtures in Use

As described in the previous chapter and in Appendix A, LEDs have a number of characteristics that appear to be well-

suited for aviation signaling applications. Figure 3 illustrates the types of lighting systems in use among the participants in the survey on LED use.

The most common types of LED lighting systems among survey participants are elevated taxiway edge lights, in-pavement taxiway edge lights, illuminated wind cones, and obstruction lights. In general, Figure 3 shows that LED taxiway lighting systems tend to be used more often than LED runway lighting systems. Indeed, LED taxiway lighting systems have been available longer than LED runway lighting systems. One reason for this is that per FAA's AC 150/5345-46, "Specification for Runway and Taxiway Light Fixtures," taxiway lighting systems tend to have lower luminous intensity (candlepower) requirements than runway systems, which must be seen from greater distances than many taxiways. LED lighting and signage systems for traffic control (elevated and in-pavement runway guard lights and L-858 signs) also have relatively high incidence of use compared with other types such as runway lights and touchdown zone lights (Figures 4 through 10 show examples of LED airfield lighting fixtures).

Many of the survey respondents reported that their airports have had LED airfield lighting systems installed for more than 12 months (Figure 11).

Most of the time airports acquired LED systems from a single manufacturer (reported by 15 survey respondents), and less frequently by more than one manufacturer (reported by 5 respondents).

LED AIRFIELD LIGHTING CHALLENGES

Compatibility of LED airfield lighting systems appears to be among the primary concerns and challenges regarding this relatively new technology. Many of the installations that have been described in the literature and in the survey of organizations regarding LED airfield lighting (Appendix B) were replacements of fixtures on the existing electrical infrastructure (Figure 12). It has been pointed out that just as with roadway traffic signals (Urbanik 2008), the electrical infrastructure for most airfield lighting (see Figure 13) was designed for use with incandescent lighting systems, requiring substantially higher power. Redesigned systems with LED electrical characteristics in mind (Taylor 2010), such as lower voltage parallel circuits (Vaughan

Simplified Diagram for LED Fixture

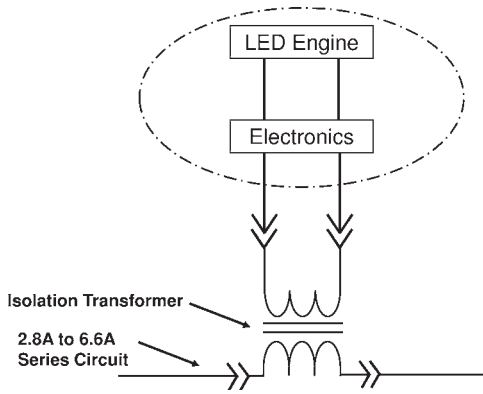


FIGURE 2 Simple schematic diagram of an LED airfield lighting fixture.



FIGURE 5 LED in-pavement taxiway edge light.

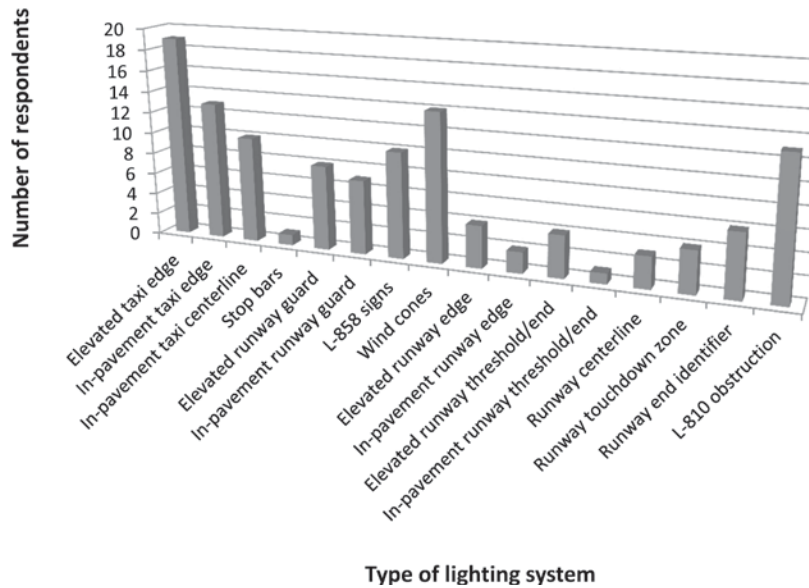


FIGURE 3 Percentage of survey respondents whose airports have LED versions of various lighting system types in use.



FIGURE 4 LED elevated taxiway edge light.



FIGURE 6 LED illuminated wind cone.



FIGURE 7 LED obstruction light.

2011), could result in more efficient LED operation (Nadel 2009) and even greater electrical energy savings than has been reported in some LED conversion projects.

The FAA (Seymour 2007) and some airports such as Orlando International Airport (Barczak et al. 2010) and Rafael Núñez International Airport (Colombia) (Marsh et al. 2008) have investigated new electrical infrastructures to overcome reduced efficiencies of LEDs operated on legacy electrical circuits. Maximizing the re-use of existing facilities and the electrical staff’s experience with these systems is important so that staff can apply their expertise to new infrastructures, minimizing the need for re-training.

Indeed, LEDs may offer potential for eliminating some of the electrical infrastructure traditionally associated with airfield lighting (Rosenkrans 2008), and in some cases they are already doing so. An FAA EB on this topic (No. 76) entitled “Using Solar Power for Airport Obstruction Lighting,” has been published (see Appendix D). Randolph County Airport Indiana has installed several solar-powered LED obstruction lights (Cook 2011).

Because LED technologies are evolving at a rapid pace, the characteristics of electrical systems optimized for their



FIGURE 8 LED elevated runway guard light.



FIGURE 9 LED in-pavement runway guard light.



FIGURE 10 LED runway end identifier light.

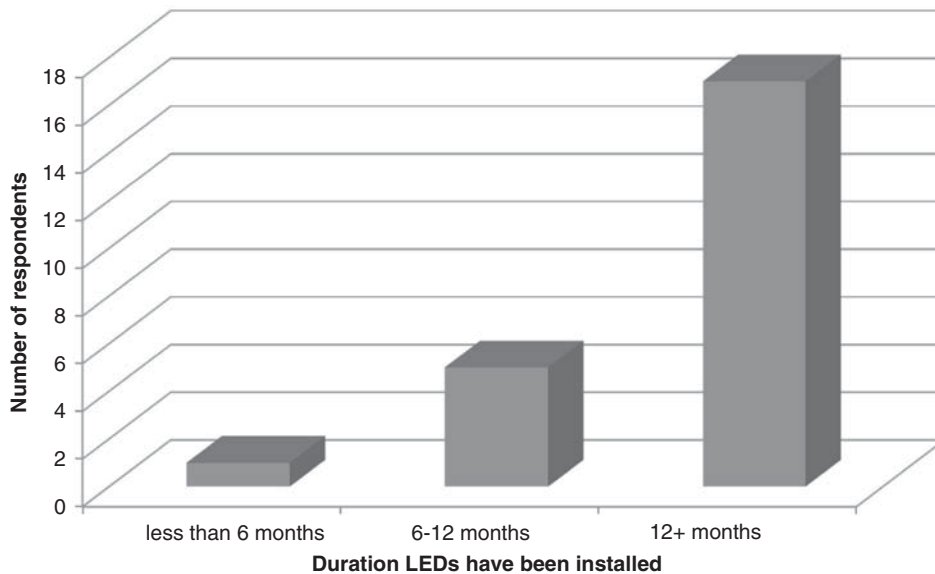


FIGURE 11 Length of time survey respondents have had LED airfield lighting systems installed.

performance are also likely to evolve. Tensions within airports to take advantage of near-term savings in energy and maintenance cost with simpler replacement project scopes, versus longer-term and larger savings with more complex electrical and lighting system alterations having larger initial costs, will likely exist for some time to come.

Electrical infrastructure issues are certainly not the only challenges related to LED airfield lighting systems.

As described earlier, the lack of heat emitted directly by LEDs has been a concern. LED airfield lighting fixtures also generally have higher initial costs than their incandescent counterparts (Marsh et al. 2008; Muriuki 2008; Hough and Gilbreath 2010), and this was confirmed in the survey conducted for the present ACRP study (Appendix B). Moreover, some airports are structured so that any reduced operating or maintenance costs are not realized by the same department that procures these more initially expensive

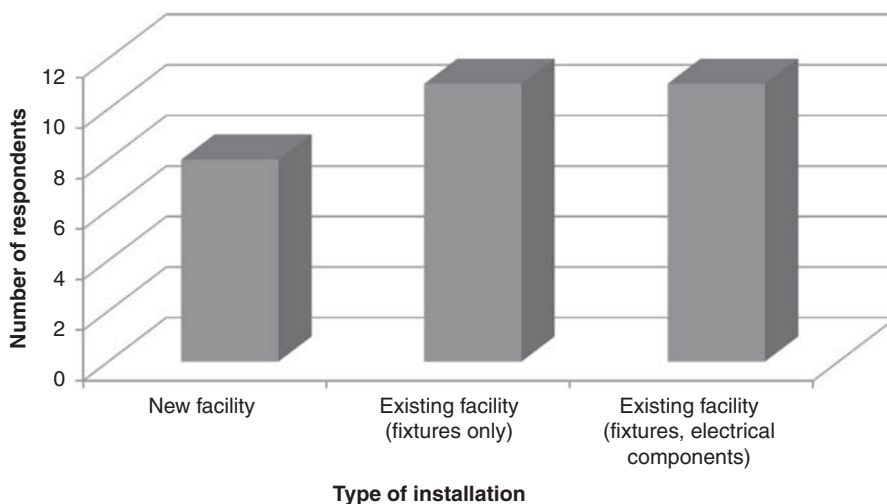


FIGURE 12 Distribution of LED installation types on new facilities, as LED-fixture-only replacements on existing facilities, or as fixture replacements alongside replacement of part or all of the electrical system (e.g., controls or regulators) on existing facilities (percentages exceed 100% because some respondents provided answers for more than one LED airfield lighting system at their organizations).

Typical LED Series Circuit Diagram

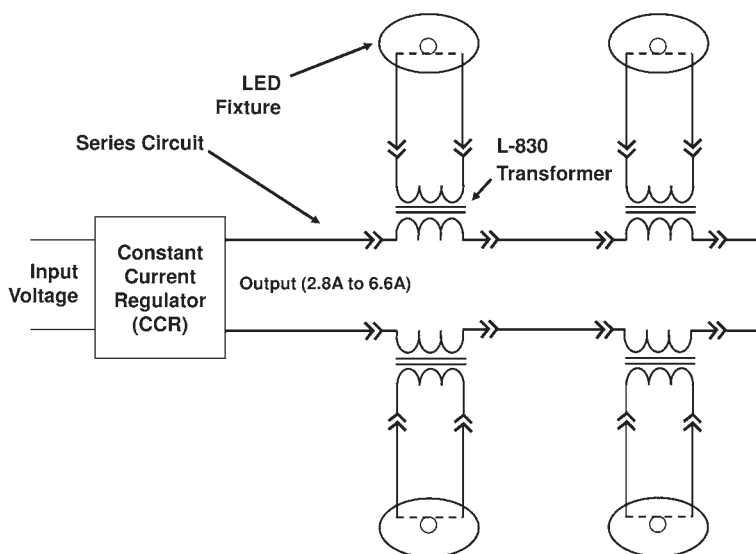


FIGURE 13 Simplified schematic diagram of an electrical circuit for an LED airfield lighting system.

fixtures, presenting a possible barrier to their specification (Vaughan 2011).

Another challenge regarding LED airfield lighting is where information about LED systems can be obtained, and indeed one of the objectives of the present ACRP synthesis study is to gather this information in a single document. Figure 14 shows the primary sources of information about LEDs used by the survey respondents. The most frequent source of information (cited by 20 survey respondents) is vendors or manufacturers of LED systems; each of the other sources—colleagues, technical reports, and trade publications—was cited by fewer participants in the survey.

ORGANIZATION OF TOPICAL CHAPTERS

The subsequent chapters of this report summarize the issues with LED airfield lighting with respect to installation, operation and maintenance, and the economics of these systems. They are intended to provide a snapshot as of late 2011 of the status of LED airfield lighting, the potential advantages of using these systems, and the challenges that face decisions to use LED technologies. Chapters are organized largely around the structure of the survey questionnaire presented in Appendix B, with a summary of relevant literature to supplement the responses from the participating survey respondents.

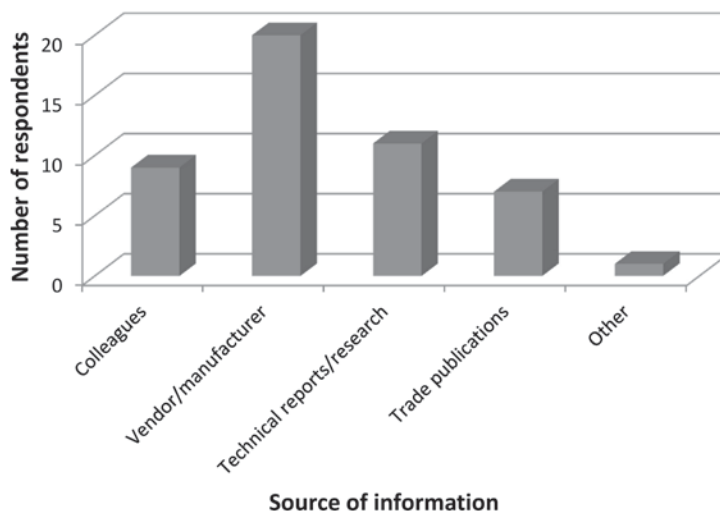


FIGURE 14 Sources of information about LEDs according to survey respondents.

CHAPTER THREE

INSTALLATION ISSUES**SUMMARY**

In general, both the responses to the survey questionnaire (Appendix B) and the published literature suggest that there are some important issues that might be considered when an airport is preparing to install LED airfield lighting:

- Installation of LED airfield lighting fixtures appears to be no more difficult than installation of incandescent fixtures. Training programs and technical symposia with information about LEDs are available, and several of these are listed in Appendix D.
- Compatibility between LED airfield light fixtures and existing electrical infrastructure designed to operate incandescent lighting systems can arise. Checking with the manufacturer of the LED systems before installing to ensure compatibility with existing regulator and control equipment is important.
- It is often important to develop a strong working relationship with the manufacturers of LED lighting fixtures to assist with troubleshooting and potential unforeseen issues during the installation process. Pittman (2010) reports that at Raleigh–Durham International Airport (North Carolina) the manufacturer became a key member of the LED installation team and was frequently consulted throughout the process.

LED INSTALLATION EXPECTATIONS

According to the individuals who participated in the synthesis survey, the primary reasons for installing LED airfield lighting were to reduce maintenance costs (20 respondents), to reduce energy use (18 respondents), and to improve visibility of airfield lighting (13 respondents). Interestingly, none of the survey respondents indicated that the reasons included any legislative mandate. Although national energy legislation, such as the EISA of 2007, increasing the luminous efficacy requirements for general service lamps will make many existing incandescent lamps noncompliant over the next decade, this legislation appears to have little impact on the decision making of airports with respect to lighting. This is likely in part because the legislation contains exclusions for specialty light source types such as rough service and for some critical applications, such as airfield lighting (NRDC 2011).

Reduced Maintenance

Anticipation of reduced maintenance was also referred to frequently in the literature. At Copenhagen Airport, it was stated that recently installed LED obstruction lights were expected to last 100,000 hours, substantially longer than the 2,000-hour life reported for their incandescent counterparts (Stegmann 2010); and an operating guarantee from the manufacturer of five years was reported. The Airports Council International (2007) reported that LED taxiway lights were expected to reduce maintenance costs over incandescent versions at Vancouver Airport. LED stop bars at Newcastle International Airport (United Kingdom) were expected to increase maintenance cycles for these systems from a few months to six years (Marsh et al. 2008). Similar expectations were in place for LED taxiway and runway lighting at Burlington (Vermont) International Airport (Edelstein 2009), Stewart International Airport (Little Rock, Arkansas) (*States News Service* 2009a), Trenton–Mercer Airport (New Jersey) (*TendersInfo* 2010a), San Bernardino (California) International Airport (*TendersInfo* 2010b), Raleigh–Durham International Airport (*News and Observer* 2010), and Tulsa (Oklahoma) International Airport (Stewart 2011a).

Reduced Energy Use

Reducing energy use was another primary reason for installing LED lights instead of incandescent airfield lighting systems. Similar expectations are found in the literature about LED airfield lighting (Airports Council International 2007; Rainey 2007; Nowak 2011). The U.S. General Accounting Office (U.S. GAO 2010) lists LED airfield lighting as one of four common energy conservation devices at airports. Reduced energy use is stated as a justification for installation of LED taxiway lights at Stewart International Airport (*States News Service* 2009a; *Targeted News Service* 2010) where LEDs were expected to use only 25% to 33% of the energy of incandescent lights. Burlington International Airport (Edelstein 2009; *States News Service* 2009b), Little Rock National Airport (*States News Service* 2009c), and Trenton–Mercer Airport (*TendersInfo* 2010a) also expected to realize energy reductions with LED taxiway lighting. San Bernardino International Airport was replacing taxiway and runway lighting with LEDs in part because LEDs are purported to use only a fraction of the energy used by incandescent lighting (*TendersInfo* 2010b). Montreal–Pierre Elliott Trudeau International Airport expected its LED taxiway and runway lighting to use one-third

of the energy used by incandescent lights (*Canadian Corporate Newswire* 2008a). LED runway centerline lighting at Prince George Airport (British Columbia) is expected to use less energy than older lighting (Nielsen 2008).

Improved Visibility

As stated earlier, a majority of survey respondents noted that improved visibility of airfield lighting was one of the reasons for their decision to install LED airfield lighting. In general this is borne out by observations of the rapid onset and offset times of flashing LED signal lights (Rainey 2007), which is expected to improve conspicuity for runway guard lights (RGLs). Bullough et al. (2007) reported that blue, green, and white LEDs appear brighter than incandescent sources having the same luminous intensity, largely because of increased color saturation, but that this effect is reduced when viewing lights in foggy atmospheres because the fog scatters light from the ambient environment that reduces the apparent saturation of light.

The saturated color of green LED sources can also assist pilots in identification of the colors of signal lights (Skinner and Bullough 2011). Both color-normal and color-deficient pilots could sometimes identify a green incandescent signal light incorrectly as white, because of the relatively desaturated appearance of the green incandescent signal. Such misidentification did not occur when a green LED signal light was used.

Many white LED sources have a “bluer” appearance than unfiltered incandescent lamps. Because incandescent lamps appear “yellowier” when they are dimmed, such as on lower intensity steps for airfield lighting, they can sometimes be misidentified as yellow lights. LEDs undergo very little color shift when dimmed, and this can improve correct identification of the light as white by pilots (Bierman et al. 2009).

Although not mentioned by the survey respondents, the relatively rapid onset and offset times of LED sources compared with incandescent lamps can be advantageous in terms of conspicuity. The rapid flashing of LEDs, unlike the more gradual increase and decrease in light output of an incandescent source, can result in shorter response times to a flashing light (Sivak et al. 1994; Bullough et al. 2002). Radetsky et al. (2009) and Skinner and Greenfield (2011) reported that RGLs using LED sources could have lower luminous intensities than incandescent RGLs while still having the same conspicuity and visibility, largely because the faster onset and offset times resulted in a more effective warning signal.

EASE OF INSTALLATION

Compared with conventional (mainly incandescent) airfield lighting, the majority of respondents (16 of 22) to the sur-

vey questionnaire (Appendix B) indicated that installation of LED lighting systems was easy, and five respondents indicated that effort was moderate. None of the survey respondents indicated that LED airfield lighting installation was difficult. When asked about unanticipated costs (Question C4 in Appendix B), survey respondents mentioned a few items that suggested that certain issues sometimes arose. These focused on components within the electrical regulation and control systems, such as requiring circuit board modifications for LED fixtures to ensure compatibility with thyristor-type constant-current regulators (CCRs), or the decision to replace isolation transformers to account for the lower electrical load of LED fixtures.

In a separate survey question (Question C8 in Appendix B), participants were asked whether the installation of LED airfield fixtures required any special tools, equipment, staffing, or training. Most respondents (16 of 22) indicated that no special equipment or training was needed. One respondent noted that airport electrical staff participated in a training course provided by the LED system supplier and another stated that airfield technicians needed to be trained on the operation of the new system. One respondent stated that connections to the communications and control equipment were performed by the manufacturer observed by airport personnel.

The results of the survey questionnaire regarding the ease of installation of LED airfield lighting fixtures were largely consistent with the published literature on this topic (*News and Observer* 2010; Stewart 2011a), which reported no evidence that LED airfield lighting systems were any more difficult to install than conventional incandescent systems.

COMPATIBILITY CONSIDERATIONS

Issues related to the compatibility of LED airfield lighting systems with existing electrical regulator and control equipment were also explicitly addressed in the survey questionnaire (Questions C5 and C6). Overall, survey respondents reported few widespread problems with compatibility. Most respondents (19 of 22) reported that their LED systems were compatible with the existing infrastructure, and 17 stated specifically that LED fixtures were compatible with the regulator, control, and monitoring equipment. Only a few reported issues related to how well the LED fixtures worked with silicon controlled rectifier (SCR) regulators. One respondent stated that ferroresonant regulators were eventually installed to improve compatibility with their LED fixtures, and one respondent stated that the airport had to adjust some regulators to correct issues with flicker.

Some compatibility issues are mentioned in the literature on LED airfield lighting. It is stated by Hough and Gilbreath (2010) that RGLs using LEDs can be used with thyristor or

ferroresonant CCRs. Gallagher (2008) pointed out that early LED taxiway edge lights did not appear to dim appreciably when operated on lower intensity steps. In response to these early dimming issues, the FAA in its version “C” revision to EB No. 67, “Light Sources Other than Incandescent and Xenon for Airport and Obstruction Lighting Fixtures,” defined a dimming curve to ensure that LED intensity would behave similarly to incandescent systems when operated at different currents (see Appendix D).

To maximize compatibility, a number of airports replaced some electrical regulation or control components in the installation of their LED lighting systems. Springdale Municipal Airport replaced their taxiway lights with LEDs, and simultaneously installed lower power isolation transformers (Hough and Gilbreath 2010). When replacing more than 800 airfield lights with LEDs, Will Rogers World Airport (Oklahoma City, Oklahoma) replaced 45 W isolation transformers with 10 and 15 W transformers (Hough and Gilbreath 2010).

Runyon and Chapman (2009) point out that LED airfield lighting systems can be designed to be compatible

with SCR regulators as well as ferroresonant high crest factor regulators, but not all systems may be optimized for such compatibility. Confirming compatibility with the electrical system components that an airport plans to use is important before LED lighting systems are purchased.

INSTALLATION PERSONNEL

Survey participants were asked (Question C7) who performed the installation of LED light fixtures at their airports. The majority of respondents (18 of 22) indicated that a contractor installed the LEDs. Nearly half (ten of 22) reported that electrical staff at the airport participated in the installation, either alone or in conjunction with a contractor. As noted in a previous section of this chapter (“Ease of Installation”), no respondents indicated that the manufacturer or vendor performed the installation; however, one respondent pointed out that the manufacturer led the connection of control and communications equipment to the LED airfield lighting system.

CHAPTER FOUR

OPERATION AND MAINTENANCE ISSUES**SUMMARY**

The survey of individuals representing different airports with experience using LED airfield lighting systems, integrated with literature on the operation and maintenance of these systems, resulted in several key findings:

- Many maintenance issues with LED airfield lighting fixtures, including mechanical damage from snow plowing and sweeping equipment and water ingress, are similar to those for incandescent lighting systems. Operations such as plowing and sweeping must be performed carefully in all cases.
- LED airfield lighting systems largely meet widespread expectations of using substantially less energy and requiring much less maintenance than incandescent systems, and failure rates are low. As a result, maintenance intervals with LEDs are longer than with incandescent lighting systems. Although LED airfield lighting systems have been in use for a number of years, long-term performance data for these systems are scarce because such data have not been systematically collected and reported.
- A few instances of incomplete compatibility with legacy systems and infrastructures have been found, and some airports were forced to replace regulators to address or avoid such problems. Newer generations of LED airfield lighting fixtures have been redesigned to avoid issues occurring with earlier products, and FAA guidance has been updated to address and prevent incompatibility issues.
- LED airfield lighting systems appear to experience few issues related to snow and ice buildup on fixtures; however, widespread systematic data are scarce. Many airports in cold climates have reported success with LED fixtures that do not contain heating units; however, most airports have not performed analyses to determine whether heaters are actually needed in their climates.

OPERATING DIFFERENCES BETWEEN LED AND INCANDESCENT LIGHTING

Survey participants were asked whether they noticed any substantial differences between their LED lighting installations and existing incandescent installations (Question D1 in Appendix B). Most (17 of 22) stated that there were noticeable differences and half reported that the LED fixtures were

brighter. Nearly one-third (seven respondents) noted that the LED fixtures were more visible than incandescent lights, whereas five reported that they used less energy and four that the color was different. One respondent stated that the LED fixtures appeared to have a more uniform brightness than previous incandescent lighting.

These responses are largely consistent with findings from the published literature on LED airfield lighting. Promise for LED airfield lighting has long been very high (*Air Safety Week* 2002). It has been reported that LED airfield lighting has been judged favorably by a number of airports, including Prescott (Arizona) Municipal Airport (Marsh et al. 2008), based on factors such as lower electricity use, but also that the increased brightness of early LED lighting systems might have been excessive especially at higher intensity steps (*Public News Service* 2008). Officials at Prescott Municipal Airport stated that the short on-off times of LEDs made them appear more conspicuous when used in flashing systems than incandescent fixtures (Seymour 2007). LED taxiway edge lights at Davis Field Airport (Muskogee, Oklahoma) were reported as appearing brighter than incandescent taxiway lights (Spaulding 2011). Although one survey respondent reported that LED airfield lighting tended to produce more uniform brightness appearance, test installations of LED RGLs at Grand Forks (North Dakota) International Airport and at Phoenix (Arizona) Sky Harbor International Airport revealed substantial intensity variations between lights, although these were never reported as being problematic by pilots (Les 2009).

It has been reported that the saturated color appearance of LED airfield lights at Chicago O'Hare International Airport distinguishes them easily from incandescent lights (Pease 2007). It has also been reported that at some airfields, LED lights, possibly operated using pulse-width modulation, produced flicker at a high enough frequency that flicker could not be perceived directly (>100 Hz), but might be detected indirectly (Pease 2007), resulting in the appearance of an array of "dots" when one's gaze moves between locations on the airfield. Although this effect is noted as a difference between LED and incandescent fixtures, it was not reported as a perception issue.

The literature survey identified other operating differences between LED and incandescent airfield lighting systems. There were a number of similar expectations regarding

the impact of increased life and longer maintenance cycles of LED lighting on system operation. LED airfield lights at Hartsfield–Jackson Atlanta International Airport were reported to have longer lives and longer maintenance cycles (Masters et al. 2006); and maintenance workers had to make fewer trips to fix problems after LEDs were installed (Schwartz 2009). LED taxiway edge lights at Davis Field Airport were expected to last 120,000 hours, decreasing maintenance requirements (Spaulding 2011). Lower power requirements of LED taxiway lighting at Prescott Municipal Airport in a test installation were expected to increase reliability of operation and improve worker safety compared with higher-voltage systems (*U.S. Fed News Service* 2006). Similar expectations regarding increased reliability of electrical lines and generators were expressed for Will Rogers World Airport following the installation of LED taxiway lighting (Brus 2011). In conjunction with a simplified electrical infrastructure, LED airfield lighting at Rafael Núñez International Airport in Cartagena, Colombia, was reported to result in improved power factor and harmonic content (Marsh et al. 2008).

In a study of taxiway edge lighting using incandescent and LED fixtures with different electrical infrastructures (Rainey 2007), installation of LED fixtures on the existing circuit used 30% to 50% of the energy of the baseline system consisting of incandescent fixtures on the original circuit. Using LEDs with a smaller transformer resulted in lower energy use, between 20% and 40% of the baseline system's energy use. If the entire circuit was replaced from a conventional 6.6 A circuit to one that only required up to 2.8 A, the resulting LED system required only 2% to 13% of the baseline system's energy use. The findings demonstrate the potential for increased energy savings that can be achieved when both the light sources and the electrical infrastructure are changed.

Although expectations for the impacts of LED airfield lights on reliability of operation are high, and there is anecdotal evidence in the literature supporting improved reliability, it can be acknowledged that systematic data comparing LED and incandescent lighting system reliability are scarce.

The FAA is presently investigating possible new electrical infrastructures to improve reliability, efficiency, and performance with LED airfield lighting technologies. It has assembled an Electrical Infrastructure Research Team to conduct tests and present recommendations regarding electrical system characteristics optimized for LED system performance (Bassey 2011).

FAILURE MODES AND FREQUENCY

Survey respondents were asked whether any LED failures of different types had been experienced at their airports (Question D2 in Appendix B, see Figure 15). The majority of respondents (17 of 22) stated that LED fixtures had been “burned out,” eight stated that they had experienced flickering of one or more LED fixtures, five experienced reduced light output from LED fixtures, and two reported that some LED fixtures were incompatible with the control or regulator system. Five respondents reported miscellaneous failure modes, including problems with moisture penetration that led to malfunction and damage from snow plowing and paint grinding equipment, all issues that could be experienced with incandescent lighting systems as well. One respondent mentioned that only very few minor issues of any kind had been experienced with LED light fixtures.

One respondent reported an early case in which all of the LED fixtures failed over a short period of time and had to be replaced; however, this occurred at a time when LED sys-

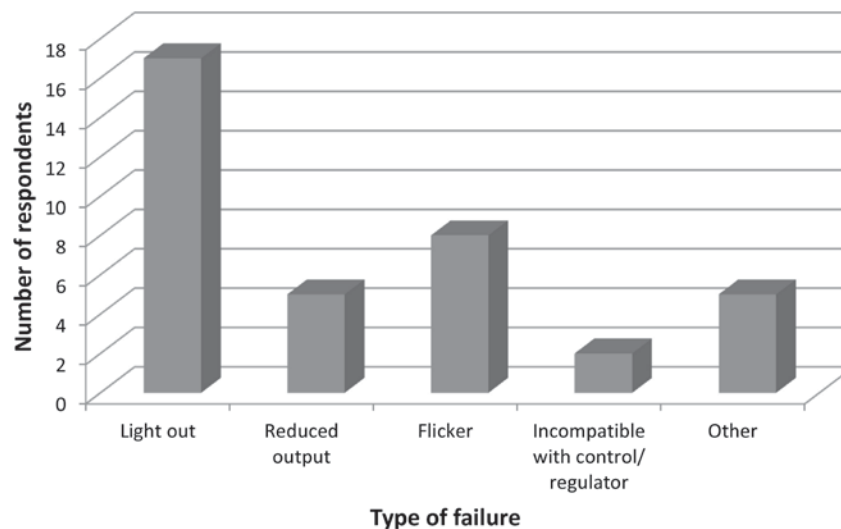


FIGURE 15 Failure modes reported by survey respondents.

tems were newer and there was less guidance from agencies such as the FAA regarding the operation of LED lighting fixtures. As described in Appendix D, various revisions of EB No. 67, “Light Sources Other than Incandescent and Xenon for Airport and Obstruction Lighting Fixtures,” have addressed many of the operations issues that were identified with some early systems. In addition, this EB requires minimum warranty periods for LED airfield lighting equipment.

Survey respondents were also asked when the LED light fixture failures they experienced occurred, and how many occurred during each period (Question D3 in Appendix B). Five of the survey respondents experienced failures during the commissioning and warranty period of the fixtures (when replacement was the responsibility of the vendor or manufacturer), with reported LED fixture failure rates ranging from less than 1% to 1%. Only two of the survey respondents experienced failures within three months of the end of warranty, ranging from less than 1% to 1%. For the period between three and six months after the end of warranty, four of the survey respondents experienced failures ranging from less than 1% to less than 2% of LED fixtures. For the period between six and 12 months after the warranty period, six respondents experienced failures during this time, ranging from less than 1% of LED fixtures to 3%. Nine stated that failures were seen 12 months or longer after the end of the warranty period for the LED fixtures. Regarding the number of failures that occurred during this time, responses ranged from less than 1% of LED fixtures to less than 2%. In general, the failure percentages reported by survey respondents for LED airfield fixtures were lower than those reported in a recent survey of municipalities for LED traffic signals (Urbanik 2008) and are substantially lower than expected incandescent lamp failures for airfield lighting.

Estimated failure rates, based on the percentage of respondents reporting failures during different periods of time and on the median percentages of failures, are illustrated in Figure 16. Although the sample size for the survey was small, limiting precision, the data in this figure are broadly consistent with the so-called “bathtub” curve (Wilkins 2002; Bullough et al. 2009) whereby an initially high failure rate (“infant mortality”) occurs followed by a low failure rate that eventually increases beyond the warranty period.

Officials at Raleigh–Durham International Airport reported that over a two-year period following acceptance of fixtures, none of the LED airfield lights that were installed experienced any failures, and none had to be handled by airport maintenance staff (Pittman 2010). In comparison, incandescent airfield lighting systems require relatively short maintenance cycles. It is reported in the literature that incandescent airfield lighting fixtures require lamp replacement approximately twice per year (Nordstrom 2010).

When asked how their airports remedied failures that they experienced (Question D4 in Appendix B), 16 respondents replied that they replaced the fixtures with another LED fix-

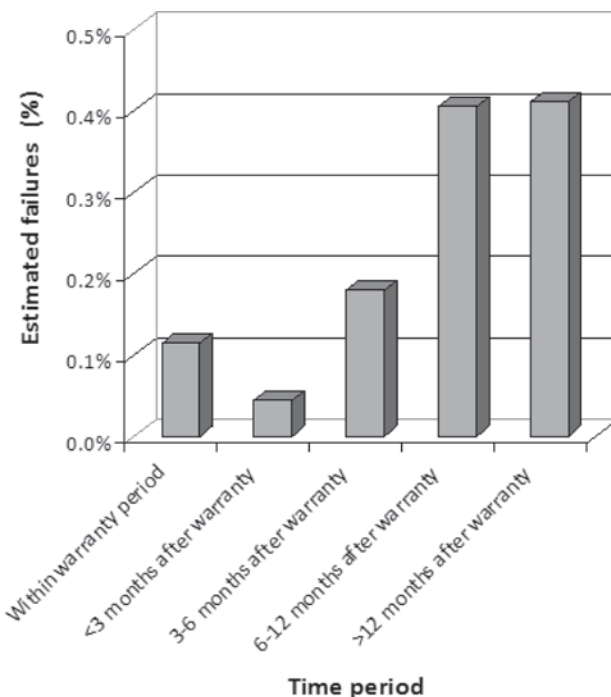


FIGURE 16 Estimated LED airfield lighting fixture failure percentages based on responses to the survey questionnaire.

ture (three while under warranty), and seven repaired the LED fixtures. Other respondents stated that they sent the defective fixtures to the manufacturer for analysis or that they replaced only the LED module inside the fixtures, and one respondent stated that their airport replaced failed LED fixtures with incandescent fixtures of the same type.

The responses to the survey were insufficient to ascertain whether there were any trends between the date of installation of LED lighting systems and their reliability in terms of failure rates. In a study of long-term LED traffic signal performance conducted for NCHRP (Bullough et al. 2009), it was found that many system reliability issues with early LED fixtures were resolved in subsequent generations of the same products, minimizing failures that had been experienced in earlier years. It is expected that the same cycle of improvements, in tandem with additional guidance from FAA regarding LED system performance as published in EB No. 67 and other documents (see Appendix D), will continue to result in fewer operational reliability concerns over time.

COMPATIBILITY WITH LEGACY SYSTEMS

Most survey respondents (19 of 22) reported that the operation of their airport’s LED airfield lighting systems was compatible with other incandescent systems or with control and regulator equipment. Respondents who reported issues with legacy systems pointed to regulators. One respondent stated that adjustment of the regulator was performed to improve compatibility. Another reported that regulators for LED taxiway lighting

were used with multiple light fixtures to deal with the reduced electrical load, and another reported that the LED systems were basically compatible with existing regulators but did not “mesh well” and eventually the regulators were replaced.

WEATHER AND ENVIRONMENTAL ISSUES

As described earlier in chapter two, LEDs do not directly generate heat in their emission; because of this there are questions about keeping LED airfield fixtures clear of snow and ice in very cold weather. In addition, because LED light output and to a much lesser extent, color, is dependent on the junction temperature of the LED chip in the light source, external temperature can also have some influence on LED airfield lighting system performance.

Snow and Ice

When asked if they experienced any issues related to snow and ice with their LED airfield fixtures (Question D6), 11 of the survey respondents indicated that their airports were located in a warm climate where the issue of snow and ice was not relevant to their lighting systems (see Figure 17). Six respondents reported no problems with snow and ice, and five stated that they used heaters within their LED light fixtures that apparently prevented any problems. Two respondents stated that periodic cleaning of any snow and ice from the light-emitting lens of the LED fixtures was sufficient to keep them working properly, and one respondent stated that LED fixtures were operated at a higher intensity than would be normally used to generate additional heat through conduction or convection to melt any snow and ice.

The decision to use heaters was sometimes (by five of the survey respondents) based on the recommendation of the

vendor or consultant that supplied the LED airfield lights. One respondent indicated that the airport staff performed their own analysis to determine whether heaters were needed, and another reported that they initially thought heaters would be needed but determined subsequently that they would not.

Issues identified in the literature regarding snow and ice were summarized previously in chapter two.

Lightning (and Power Surges)

Survey respondents were asked if their airports experienced any problems with their LED airfield lighting systems related to lightning strikes or power surges (Question D8). Most (19 of 22) did not; in one case there were problems, but they were resolved by replacing the fixtures.

Temperature Extremes

When asked if they experienced any problems with their LED systems related to temperature extremes (i.e., very cold or very hot weather), most survey respondents (20 of 22) stated that they did not.

Humidity, Moisture, and Water or Chemical Fluid Ingress

Most of the survey respondents (19 of 22) reported no issues or problems related to the performance of their LED system under different humidity conditions (Question D10). A single respondent stated that the airport was experiencing condensation within some LED fixtures during very humid conditions.

Survey respondents were asked if their airports experienced any issues with water intrusion in the LED fixtures

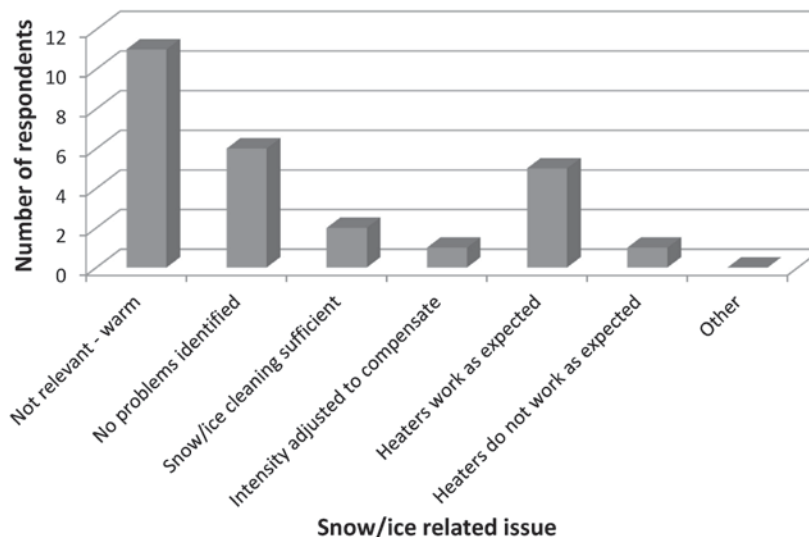


FIGURE 17 Summary of responses to question about experience with snow and ice.

or with flooding, including after flooding (Question D11). A majority (15 of 22) reported no issues; however, five respondents did report some problems. These included reports that plowing or sweeping equipment could damage fixtures in such a way that they continued to work well until water intruded into the fixtures (two respondents). Water intrusion in the fixture caused damage to the circuit board of LED fixtures of two respondents, causing shorts or other faults; however, it is worth noting that those issues would be equally applicable to incandescent airfield lighting fixtures if damage by plows or other equipment resulted in water ingress.

When asked if there were any problems with LED light fixtures regarding the use of de-icing fluids or other chemicals on the airfield (Question D12), most survey respondents (17 of 22) said no.

PHYSICAL DURABILITY

Survey participants were questioned about the durability of their LED airfield lighting systems, particularly with respect to airplane landings, snow plowing, and similar issues (Question D13). Most (16 of 22) reported no problems. One respondent noted that vibrations from airplanes or other airfield traffic could cause an outage of loose fixtures. Three respondents reported ongoing problems at their airports; all were related to physical damage of the fixtures, from snow plowing or sweeping equipment, etc., issues that would not be different with incandescent fixtures.

RESPONSE OF FLIGHT CREWS TO LED AIRFIELD LIGHTING

Responses to a question about whether airports received any comments from pilots about LED airfield lighting after installation (Question D14) were roughly evenly split among those who reported no comments from pilots (seven respondents), those who reported that pilots approved of the LED airfield lighting (eight respondents), and those who reported that pilots complained about the LED lighting (six respondents). Three respondents reported that pilots had indicated that they noticed the LED lighting but expressed no opinion about it. When comments were made by pilots, they were mostly made within three months of the LED lighting installation (12 survey respondents); however, three of the respondents indicated that their airports continued to receive comments from pilots after this time. Survey respondents reported that whether pilots approved or complained about the LED lighting, their comments were always related to the brightness of the fixtures (e.g., they found them either too bright or they liked the increase in brightness). At one airport, pilot complaints changed to approval after LED fixtures were adjusted downward in intensity one or two steps.

In the literature, it has been reported that pilots responded to LED taxiway centerline and edge lighting enthusiastically

at Raleigh–Durham International Airport (Pittman 2010). Pilots at Manchester Airport and at London Oxford Airport also reported that LED taxiway edge lights were an improvement over incandescent lighting systems (Marsh et al. 2008). In addition, it was reported that LED approach lights with a novel linear configuration, rather than a point configuration, were judged clearer during a test installation at Ted Stevens Anchorage (Alaska) International Airport (Parmalee 2009).

INTERFERENCE FROM LED AIRFIELD LIGHTING

None of the airports surveyed reported problems with electrical or radio interference from LED airfield lighting systems (Question D16). Twenty of the 22 reported that interference had never been an issue, and one respondent stated that interference with the tower radio from LED fixtures had occurred but was immediately fixed by providing better grounding for the light fixtures. Several very early LED airfield lighting fixtures were measured by Cyrus (2005) and it was found (at the time) that a majority produced sufficient emissions that they might, under certain conditions, cause potential electrical interference. Revised specifications have ensured that electrical interference is not an issue.

MAINTENANCE AND MONITORING ISSUES

Equipment and Expertise Required for Maintenance and Monitoring

One survey question (D17) asked if airports needed any specialized tools, equipment, staffing, or training in the operation, maintenance, and monitoring of their LED airfield lighting systems. Most (15 of 22) reported that they did not; however, a few answered in the affirmative. Three stated that their airfield staff needed training or certification related to LED lighting system operation and maintenance.

Methods for Monitoring Performance

Survey respondents were asked (Question D18) how they monitored the performance of the LED airfield lighting systems at their airports (see Figure 18). Visual inspections (18 of 22 respondents) and checking maintenance and repair logs (12 respondents) were the most common methods for monitoring performance. Six answered that they examined energy use data to monitor airfield lighting operations, and reports from pilots about malfunctioning lighting systems were used by five respondents. A few respondents reported that their airports conducted field measurements that included light levels. One respondent reported that its airport conducted weekly electrical resistance measurements to ensure proper functioning, and another gathered reports on failures from among airport operations staff. FAA AC guidance requires airfield lighting fixtures to maintain 70%

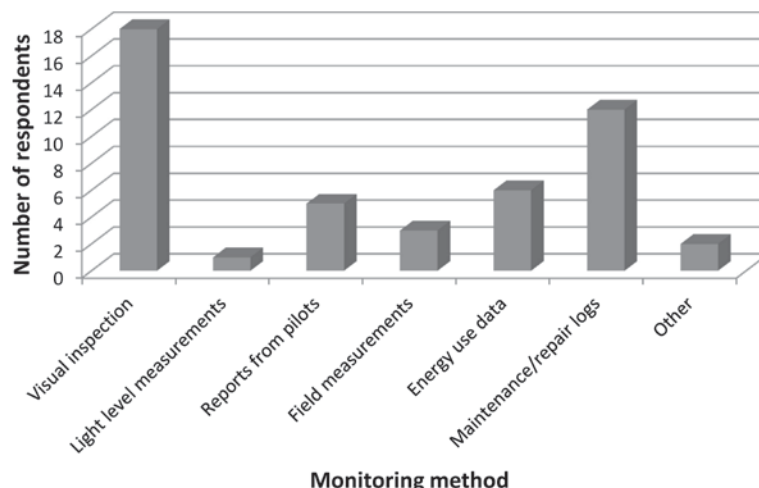


FIGURE 18 Methods used by survey respondents to monitor LED airfield lighting system performance.

of their initial light output (see Appendix D). Future guidance from FAA regarding photometric measurement of in-service airfield lighting fixtures and real-time electrical monitoring of airfield lighting systems (e.g., to identify when a certain percentage of fixtures is not operating) is expected. Until photometric measurements are more common, visual inspection will continue to be a primary monitoring approach.

The majority of survey respondents (13 of 22) did not consider costs of monitoring LED lighting system performance as part of the overall planned project cost of installing and operating such systems, whereas four stated that they did incorporate these costs into their planning process. Two respondents were unsure whether their airports considered costs of monitoring the lighting system as part of their planning.

The potential for new electrical infrastructures optimized for LED lighting system characteristics also has promise for intelligent monitoring of airfield lighting systems through mechanisms that could allow lighting system components (e.g., fixtures or control equipment) to provide status information to a centralized location. Although individual fixture information may be impractical at present, control equipment could monitor when a certain percentage of the light fixtures are not drawing power, reducing the lighting system's effectiveness. Airport certification requirements for fixing nonfunctioning lights rapidly may accelerate the use of monitoring technologies, and FAA's Electrical Infrastructure Research Team program is evaluating possibilities for the implementation of such systems (Gallagher 2011).

Criteria for LED Fixture Replacement

The primary criterion for replacing an LED airfield lighting fixture is when a fixture no longer emits any light (by 19 of 22 survey respondents to Question D21). Two further criteria mentioned by a majority of survey respondents included flickering of the light fixture (13 respondents) and a reduction in the intensity of the fixture (12 respondents). Two survey respondents stated that a missing or physically damaged LED fixture might warrant replacement.

Through a forthcoming revision of EB No. 67, "Light Sources Other than Incandescent and Xenon for Airport and Obstruction Lighting Fixtures," the FAA plans additional guidance for airports to help identify when a fixture can be considered no longer operational; that is, if more than 25% of the LEDs within a fixture are not functioning (see Appendix D).

LED Airfield Fixture Replacement Strategies

A majority of survey respondents (14 of 22 respondents to Question D20) indicated that their airports used a spot replacement strategy for replacing individual failed LED airfield fixtures. Three respondents indicated that their airports used a group replacement strategy for replacing LED fixtures, whereas five reported having no specific replacement strategy.

Published values for the life of LED airfield lighting systems are not commonly found in the literature, making strategies such as group replacement used by some transportation agencies for LED traffic signals (Urbanik 2008; Bullough et al. 2009) impractical.

CHAPTER FIVE

ECONOMIC ISSUES**SUMMARY**

Taken together, the results from the survey and the literature review concerning funding sources and installation, operating, and maintenance costs, confirmed the following:

- Funding for LED airfield lighting projects at commercial airports has come from several sources, often in combination:
 - Airport Improvement Program (AIP) funds
 - Passenger Facility Charges (PFCs)
 - Federal stimulus funds (e.g., American Reinvestment and Recovery Act)
 - State or municipal aviation funds
 - Other airport funds such as capital improvement, land rental, fuel fees, or excise taxes.
- The lower expected operating costs of LED airfield lighting have been confirmed through reduced maintenance costs and through reductions in energy use of LED fixtures. It is likely that the majority of economic savings is from reduced maintenance costs; however, the precise economic value of impacts on maintenance costs is not well understood and should be more systematically documented in the future.

EXPECTATIONS

Because LED airfield lights use less energy than incandescent lighting systems (Airports Council International 2007; Nowak 2011), and generally is expected to have longer operating lives as well as longer maintenance cycles, LED systems are expected to reduce operating costs and likely offset the typically higher initial costs of LED airfield lighting fixtures (Hampton 2006; Marsh et al. 2008; Muriuki 2008; Hough and Gilbreath 2010).

FUNDING SOURCES

Survey respondents were asked (Question B7 in Appendix B) how airports that had installed LED airfield lighting paid for these systems. Nearly two-thirds (14 of 22) stated that the FAA's AIP was a significant source of funding. Airport funds were identified by 11 survey respondents, and PFCs and state funds were each identified as sources by four survey respondents. Another four survey respondents, all from military air bases, specified military or gov-

ernment funds as the main source for funding LED airfield lighting installation.

A number of descriptions of funding for LED airfield lighting systems were found in the literature, although details are not always given (such as whether a project was for taxiway lighting only, or for both taxiway and runway lighting). Table 1 summarizes these reports, which supplements the survey responses by listing available details on the sources of funding and the cost of LED lighting installation projects that were sometimes a part of a larger runway refurbishment project or other larger project.

INSTALLATION COSTS

When asked about the initial cost of materials and equipment associated with LED airfield lighting fixtures (Question C1 in Appendix B), nearly all survey respondents (20 of 22) indicated that initial costs were higher than for the installation of incandescent fixtures, and one respondent noted that the costs were about the same. In comparison, the labor costs associated with installation (Question C2) were rated about the same as for incandescent airfield lighting systems by the majority (14 of 22) of survey respondents. Five survey respondents reported that there were some unanticipated costs associated with the installation of LED airfield lighting (Question C4). These included some failed units during installation, the decision to install smaller isolation transformers, and higher costs of repair parts that became evident during installation.

LIFE-CYCLE COST AND RETURN ON INVESTMENT

Survey participants were asked whether their airports conducted an economic analysis before installing LEDs, such as a life-cycle cost analysis or a return-on-investment (ROI) calculation (Question E1 in Appendix B). Half of the respondents (11 of 22) reported that an economic analysis was performed, four responded that one was not, and three were unsure (four did not provide a response to this question).

A number of life-cycle cost calculation tools are available online that may assist airports in estimating cost savings from reduced energy and maintenance associated with LED airfield lighting; several are listed in Appendix D. Many of the available tools are generic in the sense that they are not specific to airfield lighting but rather lighting systems in general.

TABLE 1
SUMMARY OF PUBLISHED INFORMATION DESCRIBING FUNDING DETAILS
AND SOURCES FOR LED AIRFIELD LIGHTING INSTALLATIONS

Airport and (Author Date)	Airfield Lighting System(s)	Project Cost	Funding Source(s)
Bartlesville Municipal Airport (<i>TendersInfo</i> 2010c)	Taxiway lights	\$525,000	Municipal excise tax credit funds
Brunswick Golden Isles Airport (Hawkins 2008)	Airfield signs	\$762,000	FAA (possibly AIP)
Burlington International Airport (Edelstein 2009; <i>States News Service</i> 2009b)	Taxiway lights	\$549,000	Federal funds
Columbia Metropolitan Airport (<i>TendersInfo</i> 2010d)	Runway lights	\$13 million	U.S. DOT (\$9.5 million)
Davis Field Airport (Spaulding 2011)	Taxiway edge lights	\$194,000	FAA (possibly AIP): 95% of cost
Jones Riverside Airport (Stewart 2011b)	Airfield signs	\$1.8 million	Capital improvement program
Little Rock National Airport (<i>States News Service</i> 2009c)	Taxiway lights	\$3 million	Recovery Act funds
Louisville International Airport (<i>States News Service</i> 2009d)	Taxiway edge lights	\$6.8 million	U.S. DOT
Midland International Airport (Campbell 2010)	Runway and taxiway lights	\$1.3 million	N/A
Modesto Airport (Ramsay 2010)	Wind cones	\$17,000 (as part of \$1.1 million runway project)	Federal grant
Montreal-Pierre Elliott Trudeau International Airport (<i>Canadian Corporate Newswire</i> 2008)	Runway and taxiway lights	\$12 million (Canadian)	N/A
Pangborn Memorial Airport (Irwin 2011)	Airfield signs	\$1.6 million \$35,000	FAA (possibly AIP) Washington DOT
Plattsburgh International Airport (<i>TendersInfo News</i> 2011)	Taxiway lights	\$1.4 million	AIP
Prescott Municipal Airport (<i>U.S. Fed News Service</i> 2006)	Taxiway lights	\$1 million	FAA (test installation)
Pullman-Moscow Regional Airport (Moll 2006)	Taxiway lights	N/A	Passenger facility charges
Raleigh-Durham International Airport (<i>Airport Business</i> 2009; <i>News and Observer</i> 2010; Pittman 2010)	Runway centerline lights, touchdown zone lights, guidance signs and taxiway lights (2000+)	\$2.5 million \$5.9 million \$8.1 million \$3.5 million	North Carolina DOT Recovery Act funds AIP Airport funds
San Bernardino International Airport (<i>TendersInfo</i> 2010b)	Runway and taxiway lights	\$4 million	FAA (possibly AIP): 95% of cost

TABLE 1
(continued)

Airport and (Author Date)	Airfield Lighting System(s)	Project Cost	Funding Source(s)
Stewart International Airport (<i>Targeted News Service</i> 2010)	Taxiway edge lights	\$10.6 million (lighting: \$2.9 million)	FAA (possibly AIP): \$4.7 million
Trenton-Mercer Airport (<i>TendersInfo</i> 2010a)	Taxiway lights	\$3.1 million	FAA (possibly AIP)
Tulsa International Airport (Stewart 2011a)	Taxiway edge lights	\$775,000	Recovery Act funds
Vero Beach Municipal Airport (<i>TendersInfo</i> 2010e)	Taxiway lights	\$500,000	Land rental, fuel fees; Federal grants; State grants
Will Rogers World Airport (Hough and Gilbreath 2010)	Airfield lights (800+)	\$700,000	N/A

N/A = not available.

When asked if the initial investment associated with installation of LED airfield lighting has been recovered (Question E2), nine replied that they were unsure. Three survey participants responded in the negative, and the same number in the positive, with ROI occurring within three years. Five survey respondents indicated that they had not yet recovered the initial investment at the time of completing the survey, but that they expected to do so. When asked how long the recovery or payback period was expected to be, responses from survey participants ranged from two years to ten years, with a median response of four to five years. In comparison, Hough and Gilbreath (2010) estimated that the ROI for LED runway end identifier lights was between five and eight years.

Published evidence is consistent with the notion that LED airfield lighting can, or will, reduce operating costs. Prescott Municipal Airport expects to have saved \$7,000 per year in

energy costs from LED taxiway lighting along one taxiway, and it is estimated that similarly sized airports could reduce energy costs \$35,000 per year by changing all taxiways to LEDs (Klein and Napit 2007). Other airports are expected to save energy and record energy savings through LED airfield lighting installation as well including Copenhagen Airport (Stegmann 2010), Naval Air Station North Island (Marsh et al. 2008), Rafael Núñez International Airport (Marsh et al. 2008), Springdale Municipal Airport (Hough and Gilbreath 2010), Los Angeles International Airport (*GlobeNewsWire* 2010), Royal Air Force Station Marham (*States News Service* 2010), Little Rock National Airport (*States News Service* 2009c), and Hartsfield–Jackson Atlanta International Airport (Masters et al. 2006).

Table 2 summarizes published reports of expected or realized economic savings (in dollar amounts) through

TABLE 2
SUMMARY OF REPORTS OF EXPECTED OR REALIZED ECONOMIC COST SAVINGS
ASSOCIATED WITH LED AIRFIELD LIGHTING

Airport and (Author Date)	Airfield Lighting System(s)	Savings (Expected or Realized)
Prescott Municipal Airport (<i>U.S. Fed News Service</i> 2006; Klein and Napit 2007)	Taxiway lights (one taxiway)	\$9,800/year: energy and maintenance (expected)
Raleigh–Durham International Airport (Pittman 2010)	Airfield lights	\$400,000/year: energy and maintenance (realized)
Tulsa International Airport (Stewart 2011a)	Taxiway edge lights	\$25,000/year: energy (expected)
Vero Beach Municipal Airport (<i>TendersInfo</i> 2010e)	Taxiway lights (one taxiway)	\$7,700/year: operating costs (expected)
Will Rogers World Airport (Hough and Gilbreath 2010; Brus 2011)	Airfield lights (800+)	\$60,000/year: energy and maintenance (expected)

LED airfield lighting installations. In general, reduced maintenance requirements with LED lighting fixtures might be expected to result in even greater economic savings than decreased energy use (Linebaugh 2011); however, it is generally easier and more straightforward to quantify savings from lower energy use (Nordstrom 2010; Pittman 2010). Future research could be undertaken to document the economic savings associated with LED airfield lighting system use.

OPERATING COST

Survey respondents were asked how the operating costs of their LED airfield lighting systems compared to planned costs. Responses were evenly split, with nine respondents stating that operating costs were as planned and nine that they were unsure. Two respondents indicated that operating costs were lower than planned. None of the respondents indicated that costs were higher than expected.

CHAPTER SIX

FUTURE OUTLOOK

PLANS FOR FUTURE LED AIRFIELD LIGHTING INSTALLATIONS

When asked about future plans for installing LED airfield lighting installations (Question F1 in Appendix B), a majority (18 of 22) replied affirmatively. Figure 19 shows a breakdown of the types of lights that are planned for installation.

Despite some potential advantages of new electrical infrastructures that would take advantage of the reduced energy use of LED airfield lighting fixtures, most survey respondents (19 of 22) indicated that their airports were not planning any major electrical infrastructure work, such as the installation of photovoltaic cells, that could be used to power airfield lighting. Three respondents had plans for power system improve-

ments. Two respondents mentioned plans to reduce the number of regulators used with LED lighting systems, and one stated that the long-term installation of photovoltaics was planned within the next 20 years.

REASONS FOR FUTURE LED INSTALLATIONS

When asked what the major reasons for their decisions on whether, or when, to install LED airfield lighting (Question F3 in Appendix B), respondents listed energy use (20 of 22 survey participants), maintenance load (19), cost savings (17), reliability (16), and visibility (15). One respondent stated that the airport anticipated lower electrical power requirements for future LED systems, and that this could be expected to reduce costs even further from present levels.

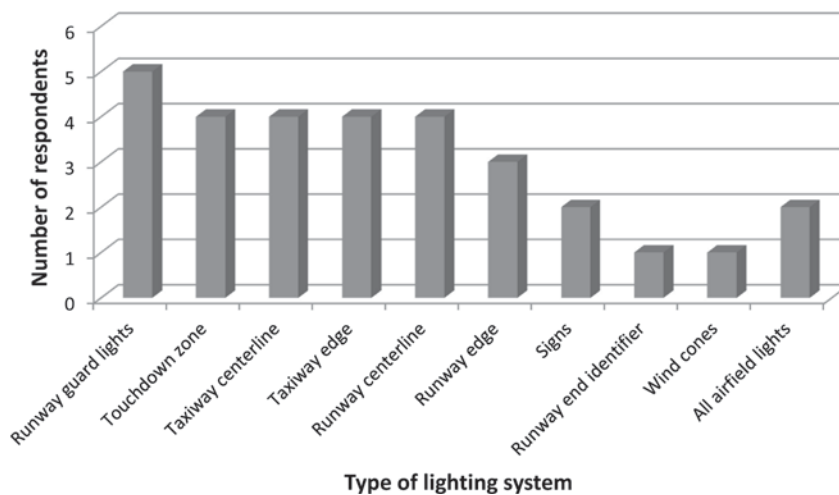


FIGURE 19 Types of LED airfield lighting systems planned for future installation.

CHAPTER SEVEN

CONCLUSIONS

Overall, the data gleaned from the survey of organizations having experience with LED airfield lighting, and the findings from the published literature, are largely consistent, in that they reinforce the following conclusions:

- LED airfield lighting systems for taxiway and runway applications are presently available and functional. The FAA, through its Airport Lighting Equipment Certification Program in AC 150/5345-53, lists LED airfield lighting products that have been certified for use in meeting the appropriate FAA performance requirements for specific lighting system types outlined in FAA's Advisory Circular documents, and eligible for federal aviation grant assistance.
- The lower operating costs of LED airfield lighting have been confirmed through reduced maintenance costs and reductions in energy use. Together, these can offset the present higher costs of installing LED airfield lighting fixtures within a few years. It is likely that the majority of economic savings comes from reduced maintenance costs.
- LED airfield lighting systems do not appear to require extensive equipment or training to install or to maintain. Early issues with system reliability and compatibility with existing electrical infrastructure have been largely overcome through continued evolution in LED product design and through FAA guidance to airports regarding the performance requirements of LED systems. Reliability and compatibility appear to improve with each generation of LED airfield lighting products, much as they have with LED roadway traffic signals.
- Current electrical power systems for incandescent airfield lighting systems are not optimized for LED lighting technology. Installing LEDs on existing electrical infrastructure may limit the amount of energy savings that can be achieved. Increased initial costs of electrical

system modifications to achieve higher efficiency can be offset by reduced energy use of the lighting system.

The literature review and survey questionnaire results also point to information gaps that, if addressed, would help provide clearer guidance to airports considering the installation of LED airfield lighting fixtures:

- Data on the long-term performance and lifespan of LED airfield lighting systems are largely unavailable. Future research could investigate the operating life of LED airfield systems as experienced by airports that have installed them in different environments and locations, as well as the different mechanisms for LED lighting system failures.
- Reductions in maintenance activities are probably the largest contributor to overall reduced costs of operating LED airfield lighting systems; however, these are often difficult to quantify by many airports. Systematic documentation of the economic impacts of LED airfield lighting system maintenance would allow airports to factor this into their life-cycle cost analyses.
- Additional research into methods for determining when an LED light fixture requires a heater to prevent snow and ice damage, based on factors such as the fixture type and shape, local snow and wind characteristics, and airport maintenance practices, would be helpful to airports considering LEDs.
- As described previously, electrical characteristics of airfield lighting are designed and optimized for the performance of incandescent lighting systems, not for LEDs. Since it appears likely that LED technologies will continue to see increased use on airfields, research on the characteristics of a common electrical infrastructure optimized for LED performance would help promote more widespread implementation.

TERMS, ABBREVIATIONS, AND ACRONYMS

AAAE	American Association of Airport Executives
AC	Advisory Circular
ACIP	Airports Capital Improvement Program
AIP	Airport Improvement Program
CCR	Constant current regulator
DOE	Department of Energy
DOT	Department of Transportation
EB	Engineering Brief
EISA	Energy Independence and Security Act of 2007
GAO	Government Accounting Office
LED	Light-emitting diode
LRC	Lighting Research Center
NRDC	Natural Resources Defense Council
PFC	Passenger Facility Charge
RGL	Runway guard light
ROI	Return-on-investment
SCR	Silicon controlled rectifier
TRID	Transport Research International Documentation
YAG	Yttrium Aluminum Garnet

REFERENCES

- Airport Business*, “Briefings,” *Airport Business*, Vol. 23, No. 8, 2009, pp. 4–7.
- Air Safety Week*, “Better Awareness on ‘Both Ends of the Radio’ Needed to Improve Runway Safety,” *Air Safety Week*, Oct. 14, 2002, p. 1.
- Airports Council International, *Case Study 1: Airport Becomes Power ‘Smarter’ with Solar Panels*, Airports Council International, Montreal, QC, Canada, 2007.
- Barczak, F., J. Pace, and C. Johnson, “DC Powered LED Taxiway Centerline Lighting System: A Case Study,” *Illuminating Engineering Society Aviation Lighting Committee Technical Conference*, Illuminating Engineering Society, Galloway, N.J., Oct. 17–21, 2010.
- Bassey, R., “Research and Development Update,” *Illuminating Engineering Society Aviation Lighting Committee Technical Conference*, Illuminating Engineering Society, Wilmington, N.C., Oct. 16–20, 2011.
- Bierman, A., N. Skinner, and N. Narendran, “Re-Evaluating the Chromaticity Boundaries for Aviation White Light,” *Illuminating Engineering Society Aviation Lighting Committee Technical Conference*, Illuminating Engineering Society, Las Vegas, Nev., Oct. 25–29, 2009.
- Boyce, P. R., *Specifier Reports: Exit Signs*, National Lighting Product Information Program, Rensselaer Polytechnic Institute, Troy, N.Y., 1994.
- Brus, B., “It’s a Living: Airfield Maintenance Electrician at Will Rogers World Airport in OKC,” *Oklahoma City Journal Record*, July 27, 2011.
- Bullough, J. D., “La Vita è Bella,” *Lighting Futures*, Vol. 4, No. 3, 2000, pp. 1, 4–5.
- Bullough, J. D., *Lighting Answers: LED Lighting Systems*, National Lighting Product Information Program, Rensselaer Polytechnic Institute, Troy, N.Y., 2003.
- Bullough, J. D., H. Yan, and J. Van Derlofske, “Effects of Sweeping, Color and Luminance Distribution on Response to Automotive Stop Lamps,” In *Advanced Lighting Technology for Vehicles*, Society of Automotive Engineers, Warrendale, Pa., 2002, pp. 179–183.
- Bullough, J. D., Y. Gu, N. Narendran, and J. Taylor, *ASSIST Recommends: LED Life for General Lighting—Definition of Life*, Lighting Research Center, Rensselaer Polytechnic Institute, Troy, N.Y., 2005.
- Bullough, J. D., Z. Yuan, and M. S. Rea, “Perceived Brightness of Incandescent and LED Aviation Signal Lights,” *Aviation, Space and Environmental Medicine*, Vol. 78, No. 9, 2007, pp. 893–900.
- Bullough, J. D., J. D. Snyder, A. M. Smith, and T. R. Klein, *Web-Only Document 146: Replacement Processes for Light Emitting Diode Traffic Signals*, Transportation Research Board of the National Academies, Washington, D.C., 2009.
- Campbell, B., “Airport Fuel Leak Threatens Underground Water,” *Midland Reporter-Telegram*, Jan. 20, 2010.
- Canadian Corporate Newswire*, “Montreal–Trudeau: Restoration and Standardization of Taxiway A, May 20 to September 30, 2008,” *Canadian Corporate Newswire*, May 14, 2008.
- Conway, K., and J. D. Bullough, “Will LEDs Transform Traffic Signals as They Have Exit Signs?” *Proceedings of the Illuminating Engineering Society of North America Annual Conference*, Illuminating Engineering Society, New Orleans, La., Aug. 9–11, 1999, pp. 1–9.
- Cook, B., “Sustainability Projects Mounting: Airports Are Going Green,” *Airport Magazine*, Feb./Mar. 2011, pp. 24–26, 32–34.
- Cyrus, H. M., *Light Emitting Diode Taxiway Edge Lights Emissions Evaluation*, DOT/FAA/AR-TN05/10, Federal Aviation Administration, Washington, D.C., 2005.
- Edelstein, A., “Smaller and Fewer Air Carriers Flying into Burlington,” *Vermont Business Magazine*, Oct. 2009, p. 28.
- Fox, D. and C. Michael, “Glass Fundamentals as Applied to LED Technology,” *Illuminating Engineering Society Aviation Lighting Committee Technical Conference*, Illuminating Engineering Society, Austin, Tex., Oct. 19–23, 2003.
- Gallagher, D. W., “Light Emitting Diodes for Airport Applications: Not Just ‘Plug and Play’,” *International Airport Review*, No. 5-2008, Sep. 30, 2008.
- Gallagher, D. W., “Visual Guidance: Research and Development,” *34th Annual Eastern Region Airport Conference*, Hershey, Pa., Federal Aviation Administration, Mar. 1–3, 2011.
- GlobeNewsWire*, “New Category 6 Crossfield Taxiway at LAX Completed on Time, on Budget: One Million-Plus Pound QANTAS Airbus A-380 Becomes First Aircraft to Use Taxiway,” *GlobeNewsWire*, May 24, 2010.
- Gu, Y., A. Baker, and N. Narendran, “Investigation of Thermal Management Technique in Blue LED Airport Taxiway Fixtures,” *7th International Conference on Solid State Lighting, Proceedings of SPIE*, No. 6669, 2007, p. 66690U.
- Hampton, T., “Airport Owners Raise Red Flag on ‘Green’ Movement Lapse,” *Southeast Construction*, Vol. 6, No. 13, Nov. 2006, p. 21.
- Hawkins, C., “Brunswick Airport to Get New Lights: A \$761,606 Federal Grant Will Help Replace Outdated Systems,” *Florida Times-Union*, Apr. 24, 2008, p. B-3.
- Hough, J. and B. Gilbreath, “Performance Guarantee Contracting Can Help Implement New Airfield Technology,” *Southwest Region Airports Division Fall Conference*, Federal Aviation Administration, Fort Worth, Tex., Nov. 15–17, 2010.
- Irwin, M., “Grants to Fund Pangborn Runway Improvements,” *Wenatchee World*, Sep. 3, 2011.
- Klein, R. and S. Napit, “A Bright Future,” *Airport Magazine*, Vol. 19, No. 2, Apr./May 2007, pp. 22–25.

- Les, C.B., "LED Lighting Ready for Takeoff," *Photonics Spectra*, June, 2009.
- Linebaugh, K., "The Math Changes on Bulbs," *Wall Street Journal*, Nov. 30, 2011, p. B1.
- Marsh, L., R. Cole, M. Lanning, and N. Sellers, *Light Emitting Diodes: An Efficient Choice for Airfield Lighting*, Kent State University, Kent, Ohio, 2008.
- Masters, K., R. H. Mahfood, D. R. Stubbs, and S. L. Kahle, "Defeating Delays," *Civil Engineering*, Aug., 2006, pp. 62–80.
- Moll, K., "Airport Upgrades to Meet Updated FAA Standards: The Pullman–Moscow Regional Airport Has Made Improvements and Is Looking to New Projects," *University Wire*, Feb. 14, 2006.
- Muriuki, A., "Sunshine for Airstrip Safety," *African Business*, Vol. 346, Oct. 2008, p. 72.
- Nadel, J., "Evaluation of Alternative Airfield Lighting Infrastructures," *Illuminating Engineering Society Aviation Lighting Committee Technical Conference*, Illuminating Engineering Society, Las Vegas, Nev., Oct. 25–29, 2009.
- Natural Resources Defense Council, *Shedding New Light on the U.S. Energy Efficiency Standards for Everyday Light Bulbs*, Natural Resources Defense Council, New York, N.Y., 2011.
- Navigant Consulting, *Energy Savings Potential of Solid-State Lighting in General Illumination Applications: 2010 to 2030*, U.S. Department of Energy, Washington, D.C., 2010.
- News and Observer*, "RDU Closes Runway Beside Terminal 1 for Four Weeks," *Raleigh News and Observer*, May 19, 2010.
- Nielsen, M., "Alaska Cargo Airports Consider Price Hikes," *Prince George Citizen*, Oct. 24, 2008, p. 1.
- Nordstrom, R., "Raleigh–Durham Int'l Lights the Way with Airfield LEDs," *Airport Improvement*, Sep., 2010, pp. 18–20.
- Nowak, G., "Airfield Pavement Design and Construction—Using a Sustainability Matrix: Case Studies," *Canadian Airfield Pavement Technical Group Workshop*, Canadian Airfield Pavement Technical Group, Montreal, QC, Canada, Sep. 15, 2011.
- Olson, P., "Evaluation of a New LED High-Mounted Stop Lamp," *Society of Automotive Engineers Technical Paper 870065*, Society of Automotive Engineers, Warrendale, P., 1987.
- Parmalee, P. J., "Linear Thinking in the LED Realm," *Aviation Week and Space Technology*, Vol. 170, No. 16, 2009, p. 64.
- Pease, B., "Bob's Mailbox," *Electronic Design*, Oct. 25, 2007, p. 16.
- Pittman, S., "Is LED Airfield Lighting Right for Your Airport?" *International Airport Review*, No. 3-2010; Jun. 9, 2010.
- Public Service Review*, "LEDing the Way," *Public Service Review*, Vol. 14, Jan. 17, 2008.
- Radetsky, L. C., *Specifier Reports: Streetlights for Collector Roads*. National Lighting Product Information Program, Rensselaer Polytechnic Institute, Troy, N.Y., 2010.
- Radetsky, L., C. O'Rourke, N. Narendran, and D. Gallagher, "Minimum Intensity Requirements for Temporally Modulated Runway Guard Lights," *Illuminating Engineering Society Aviation Lighting Committee Technical Conference*, Illuminating Engineering Society, Las Vegas, Nev., Oct. 25–29, 2009.
- Rainey, D., "Power Distribution for the All-LED Circuit," *Airport Magazine*, Vol. 19, No. 2, Apr./May, 2007, pp. 26–29.
- Ramsay, B., "Modesto Airport Repairs Take Off," *Modesto Bee*, Mar. 10, 2010.
- Rea, M. S., Ed., *IESNA Lighting Handbook: Reference and Application*, 9th ed., Illuminating Engineering Society, New York, N.Y., 2000.
- Rosenkrans, W., "Rising Stars," *AeroSafetyWorld*, Dec., 2008, pp. 30–32.
- Runyon, E. and J. Chapman, "ADB Airfield Solutions Answers Questions About the Latest Generation of Applications for High Intensity Airfield Lighting," *Airport Business, Airport and Airfield Operations*, Supplement, May 2009, pp. 5–8.
- Schwartz, A. C., "Green Grow the Airports," *Air Transport World*, Vol. 46, No. 2, Feb. 2009, pp. 62–64.
- Seymour, M., "LED Technology: Lighting the Way," *Journal of Air Traffic Control*, Fall 2007, pp. 45–51.
- Sivak, M., et al., "Reaction Times to Neon, LED, and Fast Incandescent Brake Lamps," *Ergonomics*, Vol. 37, No. 6, 1994, pp. 989–994.
- Skinner, N.P. and J.D. Bullough, "Color Identification of LED and Incandescent Aviation Signal Lights," *Illuminating Engineering Society Aviation Lighting Committee Technical Conference*, Illuminating Engineering Society, Wilmington, N.C., Oct. 16–20, 2011.
- Skinner, N.P. and H. Greenfield, "Optimizing the Performance of Elevated Runway Guard Lights with LEDs," *Illuminating Engineering Society Aviation Lighting Committee Technical Conference*, Illuminating Engineering Society, Wilmington, N.C., Oct. 16–20, 2011.
- Spaulding, C., "Davis Field Gets Needed Facelift," *Muskogee Phoenix*, Jan. 5, 2011.
- States News Service*, "Port Authority to Replace Taxiway Edge Lights at Stewart International Airport with Energy-Efficient Lighting," *States News Service*, July 23, 2009a.
- States News Service*, "Leahy Announces \$12M in Federal Funds to Spur Job Growth and New Development Projects at Burlington International Airport," *States News Service*, Sep. 11, 2009b.
- States News Service*, "Little Rock, Airport Leaders Announce Plans for \$3.033 Million Runway Upgrade at Airport," *States News Service*, May 28, 2009c.
- States News Service*, "Funding Will Be Used to Install New Airfield Signage," *States News Service*, Feb. 13, 2009d.
- States News Service*, "Marham Runway Project Adopts a Green Approach," *States News Service*, May 24, 2010.

- Stegmann, J., "LEDs Replace Lighting at Copenhagen's Airport," *HazardEx*, Mar. 9, 2010.
- Stewart, D. R., "LED Lighting on Runways to Save Tulsa Airport Money," *McClatchy-Tribune Business News*, Apr. 26, 2011a.
- Stewart, D. R., "Airport Reports Financial Blow from February Storms," *McClatchy-Tribune Business News*, Mar. 11, 2011b.
- Targeted News Service*, "Hall Announces \$2.8 Million Grant for Stewart Airport Taxiway Lighting," *Targeted News Service*, Sep. 22, 2010.
- Taylor, J., "Transforming Airfield Lighting: The Research into LED Technology," *International Airport Review*, No. 5-2010, Oct. 1, 2010.
- TendersInfo*, "Trenton-Mercer Airport Should Create Jobs After Getting \$3.15M Federal," *TendersInfo*, Aug. 19, 2010a.
- TendersInfo*, "Highland Inks MOU with SBD," *TendersInfo*, Feb. 19, 2010b.
- TendersInfo*, "Bartlesville Airport Upgrades Continue," *TendersInfo*, Apr. 7, 2010c.
- TendersInfo*, "Major Runway Project Begins at Columbia Airport," *TendersInfo*, Apr. 23, 2010d.
- TendersInfo*, "\$3M Runway Rehabilitation Underway at Vero Beach Municipal Airport," *TendersInfo*, Aug. 21, 2010e.
- TendersInfo News*, "\$1.4 Million in Funds for Plattsburgh International Airport," *TendersInfo News*, July 7, 2011.
- U.S. Fed News Service*, "Prescott Airport Gets New Taxiway Light," *U.S. Fed News Service*, May 3, 2006.
- U.S. Government Accountability Office (GAO), *Systematically Addressing Environmental Impacts and Community Concerns Can Help Airports Reduce Project Delays*, GAO-10-50, GAO, Washington, D.C., 2010.
- Urbanik, T., *NCHRP Synthesis 387: LED Traffic Signal Monitoring, Maintenance, and Replacement Issues*, Transportation Research Board of the National Academies, Washington, D.C., 2008.
- Vaughan, S., "In the Spotlight," *Airport World*, Aug./Sep., 2011, pp. 82-84.
- Wilkins, D.J., "The Bathtub Curve and Product Failure Behavior, Part One: The Bathtub Curve, Infant Mortality and Burn-In," *Reliability HotWire*, Nov., 2002.

APPENDIX A

Technical Information Regarding LED Lighting Systems

LIGHT-EMITTING DIODES

Light-emitting diodes (LEDs) are solid-state devices that generate light when a current is passed through the semiconductor chip (Bullough 2003). As electrons move across the junction formed at the chip, photons are emitted. The color of the emitted light, which is determined by the wavelength of the photons, depends primarily on the materials in the junction, and to a lesser extent on the temperature. In high-brightness LEDs presently used for signal light applications, red, orange, and yellow light is produced mainly by aluminum gallium indium phosphide (AlGaInP) materials, and green and blue light by indium gallium nitride (InGaN) materials. White light can also be produced by a mixture of red, green, and blue LEDs, or more commonly, by using a blue LED in conjunction with a phosphor material, commonly cerium-doped yttrium aluminum garnet (YAG). The phosphor converts some of the blue light into longer-wavelength yellow light, and the resulting combination appears white.

The spectral output of colored LEDs is narrow in bandwidth, which results in highly saturated color appearance compared with signal lights using incandescent lamps with colored glass filters. This tends to make LED system efficacy (in lumens per watt) higher than that of incandescent lighting systems, particularly those producing colored light, because the filter reduces the light produced by the incandescent lamp in order to produce the appropriate color.

LIGHTING TERMINOLOGY

Two important attributes that describe the performance of a lighting system are *efficacy* and *life*.

Efficacy

The luminous efficacy of a light source is a measure of the light output it produces (in lm) as a function of the input power (in W) required to operate the source. It is often used as a measure of the energy efficiency of a light source; the higher the efficacy in lm/W, the more efficient the source is at converting electrical input power to light.

The efficacy of incandescent lamps can range from 10 lm/W to 25 lm/W (Rea 2000). These values can be reduced by between 30% and 95% when a colored filter is used to produce the various aviation signal light colors. Typical values of unfiltered and filtered (of different colors) incandescent sources are as follows (Fox and Michael 2003):

- White: 15 lm/W
- Green: 5 lm/W
- Yellow: 8 lm/W
- Red: 5 lm/W
- Blue: <1 lm/W.

Present values for the luminous efficacy of typical commercially available white LEDs were found through online searches of LED manufacturers during late 2011 to be as follows:

- White: 90 lm/W
- Green: 90 lm/W
- Yellow: 55 lm/W
- Red: 55 lm/W
- Blue: 35 lm/W.

LED efficacy continues to increase at a relatively rapid pace. The U.S. Department of Energy (Navigant 2010) estimates that the luminous efficacy of white LEDs is on track to increase in the following manner through 2030:

- 2015: 127 lm/W
- 2020: 168 lm/W
- 2025: 194 lm/W
- 2030: 204 lm/W.

Life

For incandescent and most conventional light sources, life is defined as the median amount of time (usually in hours) that a large sample of lamps is expected to operate before burning out. For incandescent lamps, typical life is on the order of 750 to 2,000 hours and the primary failure mechanism is evaporative losses of the tungsten filament within the bulb when the filament is heated to generate light. Operating lamps on dimming circuits can substantially increase the life of an incandescent lamp because the tungsten filament is not heated as much. (This also produces a “yellowed” color appearance compared with non-dimmed incandescent lamps.) Extended-life lamps are designed for higher voltages, so that the lamp is always operated in a dimmed state. Some incandescent lamps for traffic and other signaling applications can have operating lives of 8,000 hours.

Because they are solid-state semiconductor devices, LEDs have very long lives as defined for conventional light sources, such as incandescent lamps. Over time, however, the output of an LED light source will gradually reduce. Eventually, the LED may produce insufficient light for a given application even though it would function normally by all other criteria. To address this characteristic of LED sources, the lighting industry has developed a criterion called *useful life*, defined by the length of time an LED source can be expected to maintain its initial light output. Useful life of LED sources is strongly dependent on such factors as temperature and the current and voltage used to operate the lamp. It also depends on the acceptable minimum output for a given application. A value of 70% light output is often used as a criterion for the end of useful life for lighting applications when visual performance is important (Bullough et al. 2005); however, a value as low as 50% might be acceptable for decorative lighting applications.

When an LED system is designed properly with appropriate thermal management, the useful life of the LED source used can be 50,000 to 100,000 hours or even longer. Longer life can be obtained when the LED is dimmed, resulting in lower temperatures within the LED chip.

APPENDIX B

Survey Questionnaire and Results

This appendix gives the survey questionnaire and summarizes the responses to each question. The survey was divided into several sections, corresponding to demographic information about participating organizations, their experience with LED lighting systems, installation issues, operation and maintenance issues, economic issues, and future outlook. Twenty-two organizations participated in the survey. Most questions were yes/no or multiple-choice types, with participants asked to select one or more appropriate responses. Some questions requested clarifying information following a response. The number of respondents who selected each response is shown in parentheses after each question/response. For some questions, response totals exceed the number of respondents (22) if multiple answers were given; for other questions, totals might add to fewer than 22 if some respondents left blanks.

SURVEY INTRODUCTION

The Lighting Research Center (LRC) at Rensselaer Polytechnic Institute is conducting a study for ACRP to summarize issues related to the decision to install light-emitting diode (LED) airfield fixtures, such as costs, energy and maintenance savings, technical issues, and operation under different weather conditions. The intended audience consists of airport operators and managers considering use of LED airfield lighting. The report will be used by airports to help guide decisions and set some expectations about the benefits and potential problems associated with installation and operation of LED lighting systems, so that they can anticipate these issues and incorporate them into their planning processes. As part of the study, the LRC is interviewing selected airports to learn about their experience with lighting. Please be assured that your responses will be kept confidential and only reported in aggregate with other responses.

SECTION A. DEMOGRAPHIC INFORMATION

- A1. What type of facility is your airport?
- Large hub (8)
 - Medium hub (4)
 - Small hub (2)
 - Nonhub primary (2)
 - Nonhub commercial service (2)
 - Reliever (0)
 - General aviation (4)
 - Other (2: Military [2]).
- A2. Is your airport a Part 139 airport?
- Yes (13)
 - No (0).

SECTION B. EXPERIENCE WITH LED AIRFIELD LIGHTING

- B1. Has your facility used LED airfield lighting? If so, was it in accordance with relevant FAA guidance (i.e., AC 150/5345-53 and Engineering Brief 67)?

- Yes (21)
 - No (1).
- B2. If so, do you have experience with LEDs to share with other airports?
- Yes (20)
 - No (0).
- B3. What LED systems have been used? (Select all that apply.)
- Elevated taxiway edge lights (19)
 - In-pavement taxiway edge lights (13)
 - In-pavement taxiway centerline lights (9)
 - Stop bars (1)
 - Elevated runway guard lights (8)
 - In-pavement RGLs (7)
 - L-858 signs (10)
 - Wind cones (14)
 - Elevated runway edge lights (4)
 - In-pavement runway edge lights (2)
 - Elevated runway threshold/end lights (4)
 - In-pavement runway threshold/end lights (1)
 - Runway centerline lights (3)
 - Runway touchdown zone lights (4)
 - Runway end identifier lights (5)
 - L-810 obstruction lights (13)
 - Other (2: High speed turnouts, strobes).
- B4. For each LED system, how long has the system been in use?
- Less than six months (1)
 - Between six months and one year (5)
 - Longer than one year (17).
- B5. For each system, please specify:
- LEDs were installed for a new facility (8)
 - LED light fixtures only were replaced on an existing facility (11)
 - LED light fixtures and control/regulator systems were replaced on an existing facility (11).
- B6. If multiple LED systems are used, are they:
- All from the same vendor/manufacturer (15)
 - From different vendors/manufacturers (5).
- B7. How were systems paid for? (Select all that apply.)
- Airport funds (11)
 - Airport Improvement Program (14)
 - Passenger Facility Charges (4)
 - State funds (4)
 - Other (4: Military [3], taxes).
- B8. What were the primary reasons for installation of LEDs? (Select all that apply.)
- Energy (18)
 - Reduce maintenance (20)
 - Mandated by legislation (0)
 - Improved visibility (13)
 - Other (0).
- B9. What were the primary sources of information about LEDs? (Select all that apply.)
- Colleagues (9)
 - Vendor/manufacturer information (20)
 - Technical reports and research (11)
 - Trade publications (7)
 - Other (1: Existing users).

SECTION C. INSTALLATION ISSUES

- C1. What was the initial cost of materials associated with LEDs relative to conventional lighting?
- About the same (1)
 - Higher (20)
 - Lower (0).
- C2. What were the installation costs associated with LEDs relative to conventional lighting?
- About the same (14)
 - Higher (5)
 - Lower (2).
- C3. How would you judge the ease of installation compared with conventional lighting?
- Easy (16)
 - Moderate (5)
 - Difficult (0).
- C4. Were there any unanticipated costs?
- Yes (5: Compatibility of LED in-pavement runway guard lights to thyristor CCRs required circuit board modifications; failed units had to be removed/replaced; smaller isolation transformers needed; isolation transformers had to be replaced; repair parts cost more)
 - No (16).
- C5. Was the installation of the LED system compatible with existing infrastructure?
- Yes (19)
 - No (2: Old runway was a low voltage system with no regulator; all new infrastructure installed for LED taxiway lights).
- C6. Was the installation of the LED system compatible with control/regulator/monitoring equipment?
- Yes (17)
 - No (4: Whole new runway/taxiway was constructed so old infrastructure replaced [2]; LEDs did not mesh well with SCR regulators and ferroresonant regulators were eventually installed; regulator had to be adjusted to correct flicker; older regulators had to be rewired for 5-step operation).
- C7. Who installed the LED system?
- Airport electrical staff (10)
 - Vendor/manufacturer (0)
 - A contractor (18)
 - Other agency/authority staff; e.g., under a pavement rehab/replacement project (1).
- C8. Were any specialized tools, equipment, staffing, or training needed to install?
- Yes (3: Training course from vendor; airfield technicians had to be trained on theory of operation; hookup of communications and control systems performed by manufacturer with airport staff)
 - No (16).

SECTION D. OPERATION/MAINTENANCE ISSUES

- D1. Were any changes noticed in LED appearance, light output, color, energy use, or other operation after initial installation?
- Yes (17 [including multiple responses]: Brighter [11]; more visible [7]; less energy [5]; color [4]; more uniform brightness)
 - No (4).
- D2. Have any LED failures been experienced? (Select all that apply.)
- Light out (17)
 - Reduced output (5)

- Flickering (8)
 - Incompatible with control/regulator (2)
 - Other (5: Multiple failure modes experienced with 100% of fixtures; moisture penetration; damage from snow equipment and paint grinders [2]; very few minor issues).
- D3. What was the percentage of LED failures within:
- During commissioning and warranty period (5: <1%; 1%)
 - 3 months after end of warranty (2: <1%, 1%)
 - 6 months after end of warranty (4: <2%, <1%, 1%)
 - 12 months after end of warranty (6: <2%, <1%, 3%, 1%)
 - Later than 12 months after end of warranty (9: <2%, <1%, 1%).
- D4. If failures were experienced, how were they remedied?
- (16 [including multiple responses]: Replaced fixture with LED [12]; repaired fixture [7]; manufacturer replaced under warranty [3]; shipped failures to factory for analysis; replaced fixture with incandescent; replaced LED module in fixture).
- D5. Was the operation of the LED system compatible with legacy systems (e.g., with other incandescent systems or control equipment)?
- Yes (19)
 - No (3: Had to adjust regulator; taxiway regulators were split to deal with reduced load; compatible but LEDs did not mesh well with regulators).
- D6. What is your experience with LEDs and snow/ice?
- Not relevant—warm climate (11)
 - No problems identified (6)
 - Snow/ice cleaning is sufficient (2)
 - Intensity is adjusted to compensate (1)
 - Heaters are used and work as expected (5)
 - Heaters are used and do not work as expected (1: Heaters created more moisture in extreme cold and are no longer used)
 - Other (0).
- D7. If heaters are used with LEDs, why?
- In-house analysis (1)
 - Vendor/consultant recommendation (5)
 - Other (1: Thought they were needed but were not).
- D8. What is your experience with LEDs and lightning or power surges? Is lightning protection in accordance with FAA guidance (i.e., AC 150/5340-30)?
- No issues/problems (19)
 - Initial problems and fixed (1: Fixtures replaced)
 - Still experiencing problems (1: Cannot get replacement lightning arrestors quickly enough).
- D9. What is your experience with LEDs and temperature extremes?
- No issues/problems (20)
 - Initial problems and fixed (1: Heaters discontinued because of moisture in very cold weather)
 - Still experiencing problems (0).
- D10. What is your experience with LEDs and humidity?
- No issues/problems (19)
 - Initial problems and fixed (0)
 - Still experiencing problems (1: Still experiencing condensation buildup).
- D11. What is your experience with LEDs and water intrusion, flooding and post-flooding?
- No issues/problems (15)
 - Initial problems and fixed (0)
 - Still experiencing problems (5: Plowing/sweeping equipment damages lights allowing water intrusion [2]; water intrusion damages circuit board [2];

- accumulation of condensation in winter; Fixtures short out when submerged under water too long).
- D12. What is your experience with LEDs and chemicals or de-icing fluids?
- No issues/problems (17)
 - Initial problems and fixed (0)
 - Still experiencing problems (1: De-icing fluid can cause corrosion).
- D13. Have you experienced any issues with LEDs and durability (e.g., during landings, plowing, etc.)?
- No issues/problems (16)
 - Initial problems and fixed (2: If fixture is loose then vibration can cause failure; problems with paint on fixture exterior)
 - Still experiencing problems (3: Damage occurs during plowing/sweeping [2]; in-pavement taxiway edge lenses get damaged).
- D14. Have you experienced comments from pilots about the LED lighting systems?
- None (7)
 - Complaints (6: Too bright [6])
 - Approval (8: Pilots like higher brightness [4]; pilot like them after reduction of 1–2 current steps)
 - Noticed difference but do not care (3).
- D15. When did most pilot comments occur (if at all)?
- Within 3 months of installation (12)
 - Continuously after installation (3)
 - Other (0).
- D16. Have you experienced any issues with LEDs and electrical or radio interference?
- No issues/problems (20)
 - Initial problems and fixed (1: Interference with tower radio fixed with better grounding)
 - Still experiencing problems (0).
- D17. Are any specialized tools, equipment, staffing, or training needed to operate and maintain LEDs?
- Yes (5: Airfield staff needed training or certification [3]; fixtures should be leak-checked)
 - No (15).
- D18. How do you monitor performance of LED systems? (Please also specify by whom and how often.)
- Visual inspections (18: Daily [1])
 - Light level measurements (1)
 - Reports from pilots (5)
 - Field measurements (3)
 - Energy use data (6)
 - Maintenance/repair logs (12)
 - Other (2: Operations staff note failures; weekly electrical resistance readings).
- D19. Were performance monitoring costs considered in the project cost during planning?
- Yes (4)
 - No (13)
 - Don't know (2).
- D20. What are LED replacement strategies at your airport?
- Spot replacement upon failure (14)
 - Group replacement planned (3: Planned if funding is available [1])
 - No specific replacement strategy (5).
- D21. What are the criteria for LED replacement?
- Total burnout (19)
 - Reduced intensity (12)
 - Flickering (13)
 - Other (2: Damaged or missing fixture [2]).
- D22. Have you experienced any unforeseen issues with LEDs?
- Yes (5: Widespread failures with one type; some in-pavement light failures; high part cost; lightning arrestors; unexpected driver board modifications affected spare parts inventory).

SECTION E. ECONOMIC ISSUES

- E1. Was a life-cycle cost analysis (LCCA) or return on investment (ROI) calculation performed before LED installation?
- Yes (11)
 - No (4)
 - Don't know (3).
- E2. Has the total initial investment associated with installing LEDs been recovered and how long did/will it take?
- Yes (3: In 2 years; in 2.5–3 years)
 - No (3)
 - Not yet (5: Expected in 2–3 years; expected in 3–4 years; expected in 5–6 years; expected in 10 years; installation of major electrical system pushed out return on investment)
 - Don't know (9).
- E3. Were LED operating costs as planned, expected, or promised?
- Yes (9)
 - Higher (0)
 - Lower (2)
 - Don't know (9: LED implementation was part of anti-corrosion effort).

SECTION F. FUTURE OUTLOOK

- F1. Are future LED installations planned at your airport?
- Yes (18: Runway guard lights [5]; touchdown zone [4]; taxiway edge lights [4]; taxiway centerline lights [4]; runway centerline lights [4]; runway edge lights [3]; signs [2]; all lights [2]; runway end identifier lights; wind cones)
 - No (1)
 - Not yet (2).
- F2. Is future work on the airfield power system or infrastructure related to LEDs planned (e.g., photovoltaic cells)?
- Yes (3: Combine circuits on one regulator; reduce number of regulators; photovoltaics planned in ~20 years)
 - No (19).
- F3. What are the primary reasons for your decisions regarding future LED installations?
- Energy (20)
 - Cost savings (17)
 - Maintenance load (19)
 - Reliability (16)
 - Visibility (15)
 - Other (1: Anticipate lower current needed for future LEDs, should reduce costs further).

SECTION G. ADDITIONAL COMMENTS

- G1. Do you have any additional comments regarding your organization's experience with LEDs (e.g., procurement, inventory management, etc.)?
- (8: Future maintenance costs as LEDs and drivers approach end of life unknown; loose fixture cans and water intrusion are biggest problems because LEDs cannot always be repaired after damage; outside of one type of lights with many failures, failures have been minimal; using a single manufacturer helps reduce parts inventory; have also used LEDs on roads, in traffic signals and in buildings; higher replacement cost when damaged by plows; pleased with improved visibility during bad weather; very satisfied with LEDs; procurement is an issue with FAA funding; specification of some fixtures requires excessive paperwork).

APPENDIX C

List of Survey Participant Organizations and Airports with LED Installations

Individuals from the following organizations participated in the survey:

- Alaska Department of Transportation and Public Facilities (AK; owns 252 rural airports)
- Bob Hope Airport (CA)
- Charlotte Douglas International Airport (NC)
- Dover Air Force Base (DE)
- George Bush Intercontinental Airport (TX)
- Grand Forks Airport (ND)
- Greater Orlando Aviation Authority (FL)
- John F. Kennedy International Airport (NY)
- John Wayne Airport (CA)
- Joint Base Elmendorf–Richardson (AK)
- Miami International Airport (FL)
- Naval Air Station Key West (FL)
- Newark Liberty International Airport (NJ)
- Norfolk International Airport (VA)
- North Carolina Department of Transportation (NC; oversees and assists 72 publicly owned airports)
- Phoenix Sky Harbor International Airport (AZ)
- Portland International Jetport (ME)
- Raleigh–Durham International Airport (NC)
- Randolph County Airport (IN)
- San Diego International Airport (CA)
- Seymour Johnson Air Force Base (NC)
- Teterboro Airport (NJ).

Based on the literature review in the present report and on input from Topic Panel members, other airports that have installed LED airfield lighting include:

- Alexandria International Airport (LA)
- Andrews Air Force Base (MD)
- Bartlesville Municipal Airport (OK)
- Brunswick Golden Isles Airport (GA)
- Burlington International Airport (VT)
- Chicago O’Hare International Airport (IL)
- Columbia Metropolitan Airport (SC)
- Copenhagen Airport (Denmark)
- Dallas/Fort Worth International Airport (TX)
- Davis Field Airport (OK)
- Denver International Airport (CO)
- Detroit Metropolitan Wayne County Airport (MI)
- Dobbins Air Reserve Base (GA)

- General Mitchell International Airport (WI)
- Hartsfield–Jackson Atlanta International Airport (GA)
- Jones Riverside Airport (OK)
- Lambert–St. Louis International Airport (MO)
- Little Rock National Airport (AR)
- Logan International Airport (MA)
- London Oxford Airport (United Kingdom)
- Los Angeles International Airport (CA)
- Louisville International Airport (KY)
- Lyon–Saint Exupéry Airport (France)
- Manchester Airport (United Kingdom)
- Marseille Provence Airport (France)
- McCarran International Airport (NV)
- Midland International Airport (TX)
- Mineta San José International Airport (CA)
- Modesto Airport (CA)
- Montreal–Pierre Elliott Trudeau International Airport (Canada)
- Nashville International Airport (TN)
- Naval Air Facility El Centro (CA)
- Naval Air Station Joint Reserve Base New Orleans (LA)
- Naval Air Station North Island (CA)
- Naval Air Station Pensacola (FL)
- Newcastle International Airport (United Kingdom)
- Paine Field Airport (WA)
- Pangborn Memorial Airport (WA)
- Pittsburgh International Airport (PA)
- Plattsburgh International Airport (NY)
- Prescott Municipal Airport (AZ)
- Prince George Airport (Canada)
- Pullman–Moscow Regional Airport (WA)
- Rafael Nuñez International Airport (Colombia)
- Roanoke Regional Airport (VA)
- Royal Air Force Station Marham (Canada)
- Salt Lake City International Airport (UT)
- San Bernardino International Airport (CA)
- Springdale Municipal Airport (AR)
- Stewart International Airport (NY)
- Tampa International Airport (FL)
- Ted Stevens Anchorage International Airport (AK)
- Trenton–Mercer Airport (NJ)
- Tulsa International Airport (OK)
- Vancouver Airport (Canada)
- Vero Beach Municipal Airport (FL)
- Wichita Mid-Continent Airport (KS)
- Will Rogers World Airport (OK)

APPENDIX D

Resources

All web links in this appendix are current as of December 2011.

FAA GUIDANCE

The FAA publishes a number of Advisory Circulars (ACs) and Engineering Briefs (EBs) pertaining to airfield lighting, signage, and control systems, including (but not limited to):

- AC 150/5340-18, “Standards for Airport Sign Systems”
- AC 150/5340-26, “Maintenance of Airport Visual Aid Facilities”
- AC 150/5340-30, “Design and Installation Details for Airport Visual Aids”
- AC 150/5345-3, “Specification for L-821, Panels for the Control of Airport Lighting”
- AC 150/5345-5, “Circuit Selector Switch”
- AC 150/5345-10, “Specification for Constant Current Regulators and Regulator Monitors”
- AC 150/5345-12, “Specification for Airport and Heliport Beacons”
- AC 150/5345-27, “Specification for Wind Cone Assemblies”
- AC 150/5345-42, “Specification for Airport Light Bases, Transformer Housings, Junction Boxes, and Accessories”
- AC 150/5345-43, “Specification for Obstruction Lighting Equipment”
- AC 150/5345-44, “Specification for Runway and Taxiway Signs”
- AC 150/5345-46, “Specification for Runway and Taxiway Light Fixtures”
- AC 150/5345-47, “Specification for Series to Series Isolation Transformers for Airport Lighting Systems”
- AC 150/5345-51, “Specification for Discharge-Type Flashing Light Equipment”
- AC 150/5345-53, “Airport Lighting Equipment Certification Program”
- AC 150/5345-56, “Specification for L-890 Airport Lighting Control and Monitoring System”

In particular, AC 150/5345-53, “Airport Lighting Equipment Certification Program” (ALECP) describes the process for obtaining FAA certification for airfield lighting fixtures. An addendum to this AC lists specific products that have been certified for use in airfield lighting systems using both conventional and LED technologies.

There is also guidance specific to LEDs and other light sources aside from incandescent and xenon lamps in FAA’s EB 67, “Light Sources Other than Incandescent and Xenon for Airport and Obstruction Lighting Fixtures.” This EB contains FAA’s primary guidance to airports regarding the use of LED airfield lighting systems, and has undergone a number of substantial revisions throughout its history:

- In the first revision, requirements for electronic monitoring of light fixtures were removed.
- In the second revision, obstruction lights were exempted from requiring an optional arctic kit to deal with potential ice buildup on the fixtures.

- In the third revision, a dimming curve for white lights was established to ensure that white LED fixtures operating on airfield lighting circuits would present appropriate intensities at each intensity step. New chromaticity requirements for LED white signals were provided, as well as dominant wavelength specifications for green LED signals. An alternative accelerated life test was also included, and an alternative method for determining power factor. This revision also included some new requirements for surge protection.
- In a current fourth revision (published March 2012), revised chromaticity requirements for all signal light colors using LEDs are provided. Requirements to prevent flicker perception issues are specified. A minimum warranty of four years is also specified to assist in life-cycle cost analyses and performance requirements for warranty are provided.

Another EB, No. 76, “Using Solar Power for Airport Obstruction Lighting,” contains application and technical guidance regarding the use of photovoltaic power for obstruction lighting, in recognition of the technical difficulties that sometimes arise in bringing electrical power to obstruction lights. It is noted in this document, however, that as of the date of publication (January 2008), no solar-powered obstruction lighting systems were certified and listed in the addendum to AC 150/5345-53, “Airport Lighting Equipment Certification Program.”

Current versions of all FAA ACs and EBs can be found online at the following URLs:

- http://www.faa.gov/airports/resources/advisory_circulars.
- http://www.faa.gov/airports/engineering/engineering_briefs.

The FAA’s Office of Airport Planning and Programming (APP) coordinates the Airports Financial Assistance Division, including the Airport Improvement Program (AIP), the Airports Capital Improvement Program (ACIP), and the Passenger Facility Charge (PFC) Program. Details about this office are online at: http://www.faa.gov/about/office_org/headquarters_offices/arp/offices/app.

To address issues related to future electrical system requirements suitable for LED airfield lighting fixtures, the FAA has established an Electrical Infrastructure Research Team (EIRT), whose charter is to conduct tests and develop recommendations regarding the characteristics of the electrical system that will maximize LED airfield lighting system efficiency and reliability, and permit new functionality such as monitoring that is not easily possible with the existing electrical infrastructure developed around incandescent lamps.

RELATED ORGANIZATIONS

In addition to the FAA, a number of other organizations provide technical information and training related to LED airfield lighting system installation and maintenance. The Aviation Lighting Committee of the Illuminating Engineering Society (IES, <http://www.iesalc.org>) conducts an annual technical conference with presentations from airport personnel, lighting manufacturers,

and academic researchers on the performance of airfield lighting, and LED systems are a common topic at these meetings. Presentation materials from recent conferences are posted online.

Training for electrical and maintenance staff is also available from a number of LED airfield lighting system manufacturers, as well as organizations such as the American Association of Airport Executives (AAAE, online at <http://www.aaae.org>).

ECONOMIC ANALYSIS TOOLS

Several online tools exist to assist individuals with comparing estimated life-cycle costs of different lighting systems. Most are generic in that they are not specific to airfield lighting systems. Several are provided by lighting system manufacturers, and their presence in this list does not imply any endorsement of these companies. They are provided here as preliminary reference points and have not been thoroughly checked for accuracy.

The U.S. Department of Energy (DOE) has gathered several energy and cost savings calculators from DOE and ENERGY STAR websites. Lighting calculators include exit signs and com-

put fluorescent lamps. The list is found online at: http://www1.eere.energy.gov/femp/technologies/eep_eccalculators.html.

The New York State Energy Research and Development Authority (NYSERDA) offers a life-cycle cost calculation spreadsheet for commercial lighting systems, which could be adapted to assess airfield lighting costs: <http://www.nyserdanyc.gov/Page-Sections/Business-Partners/Commercial-Lighting/Current-Partners.aspx>.

Lighting manufacturer General Electric provides a number of simple tools for estimating energy use and life-cycle costs on its website at: http://www.gelighting.com/na/business_lighting/education_resources/tools_software/toolkit.

Airfield lighting manufacturer ADB Airfield Solutions provides a spreadsheet tool for estimating the return on investment and life-cycle cost for a number of LED airfield lighting system types. It can be downloaded by going to the address below, clicking "LED Lighting," then clicking on any of the LED lighting products shown, and then clicking on the "Tools" tab provided: http://adb-airfieldsolutions.com/product_center/FAA.aspx.

Abbreviations used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI-NA	Airports Council International-North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation