June 29, 2017

DOE Award Number: DE-EE0007081

Luminaires for Advanced Lighting in Education

Recipient: RTI International
PO Box 12194
Research Triangle Park, NC 27709-2194

Teaming Partner: Finelite, Inc.
30500 Whipple Road
Union City, CA 94587-1530

Principal Investigator: Dr. J. Lynn Davis

RTI Project Number 02014911

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RTI Project Number
0214911

Luminaires for Advanced Lighting in Education

June 29, 2017

Prepared for U.S. Department of Energy

Prepared by RTI International

RTI International
3040 E. Cornwallis Road
Research Triangle Park, NC 27709

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List of Acronyms

AC	Alternating current
AF	Acceleration factor
AFF	Above finished floor
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
AST	Accelerated stress testing
AV	Audiovisual
Ave:min	Average-to-minimum
CALiPER	Commercially Available LED Product Evaluation and Reporting
CCT	Correlated color temperature
CIE	*Commission International de L'eclairage* (International Commission on Illumination)
COF	Classroom of the future
COV	Coefficient of variation
CRI	Color rendering index
CSM	Chromaticity shift mode
DC	Direct current
DMX	Digital multiplex
DOE	United States Department of Energy
DUT	Device under test
EWD	Education and workforce development
fc	Foot-candle
FOA	Funding opportunity announcement
FTC	Federal Trade Commission
GaN	Gallium nitride
HP-LED	High-power LED
HTOL	High-temperature operational life
IC	Integrated circuit
IEEE	Institute for Electrical and Electronics Engineers
IES	Illuminating Engineering Society of North America
InP	Indium phosphide
K–12	Kindergarten through 12th grade
LED	Light-emitting diode
LPD	Lighting power density
lpw	Lumens per watt
LSRC	LED Systems Reliability Consortium
MOSFET	Metal-oxide-semiconductor field-effect transistor
MP-LED	Mid-power LED
NICLS	Next-Generation Integrated Classroom Lighting System
NGLIA	Next-Generation Lighting Industry Alliance
PCB	Printed circuit board
PFC	Power factor correction
PWM	Pulse-width modulation
R_a	Color rendering index
R_f	Color fidelity
R_g	Color gamut
RH	Relative humidity
RTI	RTI International
SMPS	Switched-mode power supply
SPD	Spectral power distribution
SSL	Solid-state lighting

THD	Total harmonic distortion
T_j	Junction temperature
TWL	Tunable white lighting
TU-Delft	Delft University of Technology
UI	User interface
WHTOL	Wet high-temperature operational life

1. ACKNOWLEDGEMENTS

Many RTI International team members contributed to this work and made the project so successful. Among these individuals are:

- J. Lynn Davis, PhD
- Karmann Mills
- Elisabeth Hensley
- Michael Levine
- Michael Lamvik, PhD
- Curtis Perkins
- Jean Kim
- Katherine Leu
- Kelley Rountree
- Cortina Johnson
- Robert Yaga

RTI would also like to gratefully acknowledge the many outstanding contributions of our partner, Finelite Incorporated of Union City, CA. The success of this project would not have been possible without their contributions, especially those of Terry Clark, Aaron Smith, Jane White, Jennifer Langsam, Stephen Radovich, and Jerry Mix.

In addition, we would like to acknowledge the many technical discussions held with our project manager from the United States Department of Energy, Brian Dotson, and the lighting staff at Pacific Northwest National Laboratory, especially Robert Davis, Naomi Miller, and Andrea Wilkinson.

Finally, we would like to acknowledge the contributions of the teachers, administrators, facility staff, and other school lighting professionals who formed the focus groups used in this work to provide the voice of the customer in evaluating different options for the Next-Generation Integrated Classroom Lighting System.

2. EXECUTIVE SUMMARY

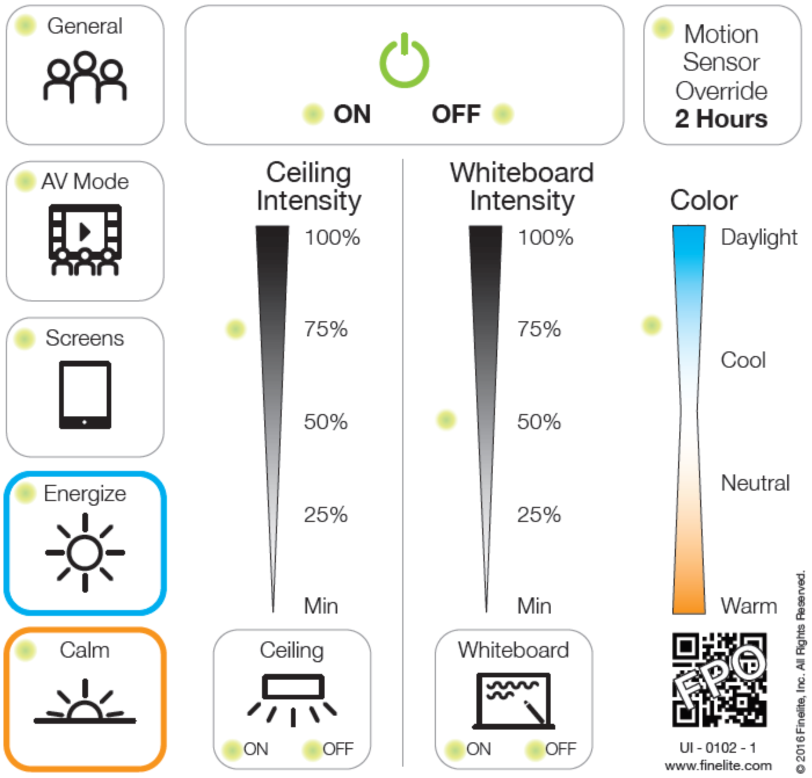
The modern classroom requires multipurpose lighting to accommodate a myriad of educational activities, such as direct instruction; group work; individualized instruction, including computer work; and audiovisual (AV) presentations. For too long, classroom lighting systems have been basic devices with no controls other than an on/off switch, not even dimming. Since the average age of public schools in the United States is 44 years, and the average functional age of these buildings in nearly 20 years [1; 2], the lighting systems of most public schools are minimalistic and outdated. These facts have likely contributed to the high level of dissatisfaction with lighting in public school buildings. A recent survey found that school lighting was rated the most unsatisfactory part of the average facility [2]. Clearly, the lighting technology used in many schools today has robbed teachers of a potentially valuable tool to supplement their teaching skills and benefit their students: the ability to adjust lighting color and illuminance levels to match the educational task at hand.

To overcome this impediment, RTI International and Finelite, Inc., have used funding from the United States Department of Energy (DOE) (through Award DE-EE0007081) to build the Next-Generation Integrated Classroom Lighting System (NICLS). NICLS provides high-efficacy (> 125 lumens per watt [lpw]) lighting, full illuminance control (1% to 100%), and white light tunability (2,700 K to 6,500 K) in a Made-in-the-United States lighting system designed to improve the educational environments of facilities that focus on learners of all ages. This effort culminated in the incorporation of NICLS technology in the DOE Classroom of the Future (COF) demonstration site at Finelite's facility in Union City, CA. This system was designed with the help of teachers for use by educational professionals. A picture of this facility tuned to different colors of white light is shown in **Figure 1.1**.

Figure 1.1 Composite Picture of the Tunable White Lighting (TWL) Capability of NICLS for Educational Facilities

In building this system, more than 80 teachers and school administrators participated in focus groups held at the NICLS technology demonstration site to provide guidance on the use of the advanced lighting technologies in the classroom and the design of the user interface (UI) for the lighting system. These focus group members provided an overwhelmingly positive assessment of the impact of such lighting technology on the learning environment for their students. Teachers of special needs individuals, especially those who are autistic or vision impaired, also pointed out the benefits of the NICLS technology for students with sensory stimulation needs. Together, these focus groups helped to design a UI that is intuitive and simple to use for teachers, students, and substitutes. This UI is designed to accommodate the ability to shift modes quickly because teachers cannot get distracted in the classroom. As shown in **Figure 1.2**, this UI utilizes colors and icons to provide an intuitive, easy-to-use, and inviting appearance. The NICLS UI represents a new paradigm in lighting system controls and is a significant advancement over previous lighting control systems designed for building managers. The focus group members also expressed a strong desire for more information and research on how best to use fully dimmable, tunable light-emitting diode (LED) technology to benefit their students.

Figure 1.2 Intuitive UI Design Developed Exclusively for the NICLS Technology



The extensive research and development program used by RTI and Finelite to develop the NICLS technology started with the identification and acquisition of state-of-the-art mid-power LED technology to provide high luminous efficacy performance to the NICLS platform. The next step was the identification of luminaires that would meet the aggressive goals established for this project by the DOE. In performing this evaluation, more than 100 luminaire designs and options were considered, and those that could not meet the stringent luminous efficacy goals of the project or produced excessive amounts of glare were discarded. In the end, five designs, including direct/indirect pendant luminaires and troffers, were identified that would meet or exceed DOE's performance goals at the end of the project. In independent, third-party testing, the level of performance of the NICLS technology was demonstrated to provide high luminous efficacy (> 125 lpw at all correlated color temperature [CCT] settings) performance in a TWL product that is cost competitive and made in the United States.

Once the NICLS technology demonstration site was completed, a full characterization of the performance of the technology was conducted at the room level. The demonstration site covered over 1,000 ft^2 and contained 12 troffers (2 foot by 2 foot) and five wall wash luminaires for whiteboards. All luminaires in the site have full dimming (100% to 1%) and

TWL capabilities, and the settings of the ceiling luminaires can be varied independent of the whiteboard luminaires, creating a range of scenes for the classroom. The CCT range of the TWL system is continuous from 2,700 K to 6,500 K using a linear tuning algorithm; this range far exceeds that specified by DOE. The system delivers lighting at better than 125 lpw at all CCT values with exceptional color metrics (color rendering index [CRI] > 82, color fidelity metric [R_f] ≥ 81, and color gamut [R_g] ≥ 97 at all CCT values).

At the systems level, the NICLS technology was found to perform exceptionally. With all the luminaires in the NICLS technology demonstration site turned on and set to 100%, the lighting power density (LPD) was only 0.67 watts per square foot (W/ft^2), which is well below the requirements of American Society of Heating, Refrigerating, and Air-Conditioning Engineers 90.1 and California Title 24. Built-in daylight harvesting and occupancy sensors reduce the LPD value even further. At the 100% level for all luminaires, the NICLS technology provides better than 60 foot-candles (fc) at desk height and completely fills the space with even, glare-free lighting. The lighting levels can be cut back to 75% and still provide better than 50 fc at desk height while consuming less than 0.5 W/ft^2. Further dimming levels can be readily achieved with the NICLS technology, and LPD values as low as 0.007 W/ft^2 can be reached (i.e., ceiling and whiteboard luminaires at 10% dimming).

The NICLS system is also designed to be exceptionally robust and will last for 10 years or more during normal use with minimal maintenance. Accelerated stress testing (AST) of the LED modules demonstrated minimal lumen depreciation under these conditions, and the technology can exceed DOE's requirement of better than 85% of the initial luminous flux remaining after 50,000 hours of use. In fact, depending upon the use profile with the NICLS system, the technology can be used for much longer times and still produce more than 85% of the initial luminous flux. The chromaticity shift in the LED boards was also found to be minimal in laboratory testing. While no projections of the operational time necessary to produce a significant color shift (e.g., seven-step chromaticity shift) are possible at this time, the minimal color shifts that were found in accelerated tests reinforce the finding that the NICLS technology will last for 50,000 hours or more with exceptional performance. The robustness of the LED drivers in the NICLS technology was also verified using ASTs developed by RTI, including an operational life test conducted at 75°C and 75% relative humidity. Over 2,500 hours of testing in this environment, minimal changes were found in the drivers chosen for the NICLS technology demonstration site. These findings confirm that the LED drivers in the NICLS platform will exceed DOE's goals of better than 50,000 hours with less than 50% mortality.

This project met or exceeded every goal established by DOE for an advanced lighting system for educational environments, including the following:

- Demonstrating a luminous efficacy value for NICLS luminaires in excess of 125 lpw at all CCT values;

- Demonstrating a TWL range of 2,700 K to 6,500 K while maintaining a CRI of 83 or higher at all values;
- Providing the capability for full-range dimming (100% to 1%) at all CCT values with flicker levels below industry guidelines, such as Institute for Electrical and Electronics Engineer recommended practice P1789, and compatibility with American National Standards Institute C82.77 requirements for luminaires;
- Incorporating daylight and occupancy sensing to provide automatic control of lighting zones to further reduce energy consumption;
- Achieving a rated lifetime on the system exceeding 50,000 hours with a lumen maintenance of at least 85% at 50,000 hours; and
- Creating a teacher-focused UI located at the front of the classroom to operate the lighting system. A smartphone-based UI is also available to accommodate teacher movement in the classroom.

In conclusion, the NICLS technology is an advanced lighting system for educational settings that meets or exceeds all DOE photometric, electrical, and reliability goals for the COF. The NICLS technology has been demonstrated at the classroom level, and the feedback from the dozens of teachers and educational professionals who visited the demonstration site has been overwhelmingly positive. NICLS provides a state-of-the-art lighting environment that adjusts the lighting conditions—both color and illuminance levels—to the needs of students and teachers for the task at hand. Early research has suggested that such lighting conditions will improve not only teacher effectiveness but also a student’s ability to concentrate on tasks or calm down and decompress, as needed. The ability of the NICLS technology to tune lighting conditions to the needs of students and teachers applies to both grade school and adult learners.

Ultimately, an investment in advanced lighting systems such as NICLS for the classroom is an investment in the community and its citizens. The energy savings that could be realized by installing the NICLS technology in a classroom are significant, but they represent the tip of the iceberg. The larger long-term gains from advanced solid-state lighting (SSL) systems in the classroom are likely to come from the benefits to the community of having higher-performing schools and better-educated citizens. Given the generally poor perception of lighting quality in public schools, the investment in advanced SSL systems for educational facilities is one that should be seriously considered.

3. COMPARISON OF ACTUAL ACCOMPLISHMENTS WITH THE GOALS AND OBJECTIVES

This project closely followed the original plans as described in the proposal submitted to the United States Department of Energy (DOE). Accordingly, as shown in **Table 3.1**, in most cases, the project accomplished the planned milestones by the planned completion date. The exceptions were that the demonstration site (Milestone 9) was completed ahead of schedule, while the milestones for the design of the LED module (Milestone 1) and demonstration of 120-lumens per watt (lpw) performance at all correlated color temperature (CCT) values (Milestone 7) each slipped by one month. As described in this report, early results from design simulations indicated that the Next-Generation Integrated Classroom Lighting System (NICLS) technology would meet or exceed all goals established by DOE for this project. Consequently, the decision was made to proceed with construction of the demonstration site ahead of schedule, and construction was completed 5 months early. The early completion of the NICLS technology demonstration site provided significant benefit to the program in that a deeper study of the performance of facility was possible, and the focus group could use the facility sooner than planned.

Table 3.1 Comparison of Actual and Planned Completion Dates for Project Milestones

Milestones		Planned Completion Date	Actual Completion Date
M1:	Design of LED module complete	September 2015	October 2015
M2:	Initial luminaire designs completed and ability to meet project goals confirmed by simulations	December 2015	December 2015
M3:	LM-79 testing on LED modules demonstrate at least 140 lpw at all CCT values	March 2016	January 2016
M4:	Participation in DOE Peer Review	March 2016	May 2016
M5:	Room-level AGi32 simulations demonstrate that the system can meet goals for illuminance and luminous efficacy	March 2016	January 2016
G	Go/no go decision. Project check in.	March 2016	March 2016
M6:	Accelerated testing of light engines demonstrates L85 of > 75,000 hours	June 2016	June 2016
M7:	LM-79 testing demonstrates that luminaire efficacy is at least 120 lpw at all CCT values	November 2016	December 2016
M8:	Lumen maintenance analysis of luminaires demonstrates L85 > 75,000 hours	June 2016	June 2016
M9:	Technology demonstration site installation completed	September 2016	April 2016
M10:	Commissioning of demonstration site completed	November 2016	November 2016
M11:	User feedback on lighting system and UI collected	December 2016	January 2017
M12:	DOE workshops or other conferences	December 2016	February 2016

CCT = correlated color temperature; DOE = United States Department of Energy; LED = light-emitting diode; lpw = lumens per watt; UI = user interface

Part of the more detailed study of the NICLS technology demonstration facility included a thorough investigation of flicker performance and power consumption at all levels of dimming. As detailed in this report, the flicker performance of the NICLS technology exceeds the goals set for this technology by DOE, and the power consumption sets a new benchmark in performance for the industry. The accomplishments of this project were significant and the goals set by DOE for the Classroom of the Future (COF) were exceeded in all cases, and in many cases, these goals were substantially exceeded. The list of significant accomplishments of this project includes the following:

- Demonstrating a luminous efficacy for NICLS luminaires in excess of 125 lpw at all CCT values. The original goal set by DOE was 120 lpw.
- Demonstrating a continuous tunable white lighting (TWL) range of 2,700 K to 6,500 K while maintaining a color rendering index (CRI) of 83 or higher at all CCT values. The original goal set by DOE was a minimum of four different CCT values between 2,700 K and 5,000 K with a CRI of 80.
- Providing the capability for full-range dimming (100% to 1%) at all CCT values with flicker levels below industry guidelines, such as Institute for Electrical and Electronics Engineers (IEEE) recommended practice P1789, and compatibility with American National Standards Institute (ANSI) C82.77 requirements for luminaires. This matches the DOE goals regarding dimming range and power quality and exceeds the DOE requirements for flicker.
- Incorporating daylight and occupancy sensing to provide automatic control of lighting zones to further reduce energy consumption. This aligns with the DOE requirements.
- Achieving a rated lifetime exceeding 50,000 hours with a lumen maintenance of at least 85% at 50,000 hours. Testing indicates that the NICLS technology will significant exceed the DOE requirements.
- Building a demonstration site for the technology at Finelite's facility in Union City, CA.
- Creating a teacher-focused UI located at the front of the classroom to operate the lighting system. A smartphone-based UI is also available to accommodate teacher movement in the classroom.
- Satisfying a "Qualified Made in USA" claim according to Federal Trade Commission (FTC) guidelines.

4. SUMMARY OF ACTIVITIES FOR ENTIRE FUNDING PERIOD

4.A Background

4.A.1 Lighting for Educational Facilities

Educational facilities in the United States present a challenging lighting environment that is underserved by traditional technologies, such as linear fluorescent lighting. The emergence of solid-state lighting (SSL) technologies as a competitive general lighting approach offers the opportunity to rethink the school lighting environment and improve its impact on the core mission of educational facilities. This focus on the lighting environment can help to promote positive outcomes in students of all ages (i.e., children and adults) and provide new and potentially powerful tools for students, teachers, and administrators to be more effective. The likely benefits of an improved SSL classroom lighting system go beyond lower energy and maintenance costs and include long-term gains for the community that will be produced by an enhanced learning environment in its schools. In short, classrooms and other educational spaces are perhaps some of the most important facilities across the United States, not only for their impact on young minds but also for their long-term economic impact on the region and the country through the creation of an educated work force, knowledgeable citizens, and life-long learners.

Many educational facilities in the United States were built more than 40 years ago at a time when teaching methods were predominantly lecture-based instruction with little to no technology use. A survey in 1998 determined that the age of the average public school building in the United States was 42 years old [1]. More recent statistics from the United States Department of Education show that as of 2013, the average age of public schools remained virtually unchanged more than a decade later at 44 years of age [2]. At the time these buildings were constructed, teacher lectures were the dominant instructional format in both grade schools and colleges; computers were rarely found in the classroom; and tablets, video monitors, and smartboards were nonexistent. However, in the intervening time, educational methods have undergone a revolution and now incorporate new approaches and technologies to increase student learning and aid teachers in doing their job. The explosive growth of on-line educational tools, project-based learning, and individualized instructional plans has radically altered the classroom environment, yet the lighting environment has remained largely stagnant. Among the changes in instructional methods fostered by this revolution in the teaching environment are the following:

- Learning has become more student centric with increased use of individual instruction through tablets, videos, and other new technologies.
- Learning continues to occur in a group instructional setting but with less use of a lecture format, greater student participation, and more teacher movement throughout the classroom.

- The increased use of small group instruction means that learning can occur anywhere in the classroom, not just at a desk.

In addition to these revolutionary teaching methods, the educational tools used in the modern classroom have changed drastically in the last 20 years with greater use of technology, as shown in **Figure 4.1**. While these technological enhancements have improved the learning environment, they have also created a number of new challenges that any lighting system must address, including the following:

- Controlling veiling reflections on video monitors, tablets, and computer screens;
- Producing even vertical illumination on whiteboard and smart board surfaces to enhance visibility from anywhere in the classroom;
- Controlling lighting levels to enable viewing and note-taking during audiovisual (AV) presentations; and
- Balancing energy savings with daylight harvesting and uniformity in illuminance across the classroom.

Figure 4.1 The Use of Technology in the Classroom has Revolutionized the Learning Opportunities Available to Students of All Ages

Recognizing the challenges presented by modern learning environments to the design of classroom lighting systems, research has been performed by Finelite, Inc. to investigate new lighting technologies for the classroom [3; 4]. While this work was performed before SSL technologies had established a significant marketplace presence, the major findings provide guidance on designing classroom lighting systems to accommodate new teaching methods. Among the key finding of these studies sponsored by the California Energy Commission and the New York State Energy Research and Development Authority are the following:

- Most teachers can teach in nearly any environment, but the better the setting, the easier it is to teach and for students to learn.
- Uniform lighting, including both vertical and horizontal illuminance, such as that provided by direct/indirect luminaires, should be used to provide low-glare lighting and to evenly illuminate ceilings and teaching walls. This type of lighting was preferred by teachers nearly 9:1 in these studies.
- At a minimum, two-scene control providing for general use and AV use is recommended. This approach reduces veiling reflections on video monitors and allows the teachers to maintain eye contact.
- Consideration should be given to the use of wall wash luminaires for special surfaces, such as whiteboards
- Controls for the lighting system should be at the front of the classroom for easy access by the teacher. The master on/off switch should be by the door.

Recognizing the potential to develop lighting systems with improved energy efficiency that meet these rising challenges in educational settings, DOE released funding opportunity announcement (FOA) number DE-FOA-0001171 with a goal of delivering an innovative classroom lighting system that can provide “the proper quantity and quality of light where it is needed, when it is needed, while also minimizing lighting effects that may create glaring or distracting conditions” [5]. Additional capabilities sought by DOE included a flexible classroom lighting system that can accommodate the needs of both children and adults and a dynamic lighting system that allows for variation in illuminance levels and color quality to promote greater student attentiveness, comfort, and group interactions.

This report summarizes the major findings to date of the research and development activities conducted jointly by RTI International and Finelite, Inc., to develop the NICLS and to build a demonstration site for this breakthrough technology. NICLS is a high-efficiency, LED-based lighting system with the capability to tune the color of white light between 2,700 K and 6,500 K. Among the major achievements of the NICLS technology are the following:

- Demonstrating a luminous efficacy for NICLS luminaires in excess of 125 lpw at all CCT values. This level of performance is better than 96% of the fixed-CCT troffers in the Lighting Facts database for devices with CCT values of 2,800 K or lower [6].
- Demonstrating a TWL range of 2,700 K to 6,500 K while maintaining a CRI of 83 or higher at all CCT values.
- Providing the capability for full-range dimming (100% to 1%) at all CCT values with flicker levels below industry guidelines, such as IEEE recommended practice P1789, and compatibility with ANSI C82.77 requirements for luminaires.
- Incorporating daylight and occupancy sensing to provide automatic control of lighting zones to further reduce energy consumption.

- Achieving a rated lifetime exceeding 50,000 hours with lumen maintenance of at least 85% at 50,000 hours.
- Building a demonstration site for the technology at Finelite's facility in Union City, CA.
- Creating a teacher-focused UI located at the front of the classroom to operate the lighting system. A smartphone-based UI is also available to accommodate teacher movement in the classroom.
- Satisfying a "Qualified Made in USA" claim according to FTC guidelines

4.A.2 The Impact of Lighting on the Classroom

Educational facilities cover a broad segment of the building inventory in the United States and encompass elementary school classrooms, high school science laboratories, adult educational and vocational training facilities, and college lecture rooms, to name a few. While an aggregation of the total square footage and energy consumption of all educational facilities in the United States is difficult to find, information is available on kindergarten through 12th grade schools (K–12 schools), which likely represent a substantial portion of the educational lighting market. According to government statistics, K–12 schools spend more than $8 billion per year on energy, the second highest operating expense behind salaries [7; 8; 9]. To put this number into perspective, energy costs for K–12 schools total more than what is spent by schools on computers and textbooks combined [7; 8]. Of this energy expense, roughly 19% ($1.5 billion) is directly consumed by the school's lighting system, so improving lighting system efficiency can have a direct return to the stakeholders in the school district [10].

Despite this large nationwide expenditure for energy to operate the lighting systems in schools, there is generally greater dissatisfaction with classroom lighting than with any other aspect of the educational environment. This high level of dissatisfaction is present in all school types, and the trend appears to be increasing. This finding was underscored in a recent study performed for the United States Department of Education [2], and a comparison of the percentages of public schools with unsatisfactory physical plant (e.g., lighting, heating, and air) factors is given in **Table 4.1**.

Statistics from the United States Department of Education also indicate that the average public school is 44 years old and that, taking into account renovations, the average functional age of public schools is approximately 19 years [2]. This fact has several implications for SSL technologies. The first implication is that products used in the schools' infrastructure are expected to remain in operation for many years before being replaced. Therefore, any lighting product used in schools should be expected to operate for 20 years or more. The second implication is that these facts indicate that the penetration of SSL technologies into schools is still in a nascent stage, which may explain the poor overall impression of the lighting environment. Clearly, the lighting environment is less than optimal in many schools around the United States, which will have a huge impact on the quality of education, teacher effectiveness, and students' ability to learn.

Table 4.1 Percentages of Public Schools for which the Conditions of Environmental Factors were Rated Unsatisfactory.

School Level	Lighting (%)	Heating (%)	Ventilation (%)	Indoor Air Quality (%)	Acoustics (%)
ALL	**23.1**	**15.1**	**18.3**	**11.7**	**16.1**
Elementary	23.5	13.9	17.9	11.9	16.2
Secondary	22.2	18.5	18.6	11.1	14.6
Combined	20.7	19.2	26.9	12.6	25.5

NOTE: Data cover the 2012–2013 school year.

Source: Reference [2].

While the potential energy savings of installing SSL technologies in the classroom are significant, to fully understand the lifetime return on an advanced lighting system, the long-term impact on the teachers and students must also be considered. In commercial building spaces, there is a popular rule of thumb called the 3-30-300 rule. This rule estimates that commercial spaces spend $3 per square foot per year on utilities, $30 per square foot on rent, and $300 per square foot on employees. Clearly, the most substantial opportunity for savings in commercial building is associated with creating an environment that makes employees more productive because a 10% improvement in productivity equals a $30 return on investment. Extending this rule to educational spaces, the long-term impact of an advanced lighting system, such as the NICLS TWL technology described in this report, can be substantially greater than energy and maintenance cost avoidances. The impact of producing a better-educated work force, higher-performing schools, and more-effective teachers must also be considered. Consequently, when schools make a long-term decision about lighting, the benefits created in the classroom and the energy savings must be included in the analysis. Choosing an LED-based TWL system, such as the NICLS technology described in this report, is easy for schools because it improves learning and teaching, creates realized productivity opportunities, and directly saves energy. These benefits allow schools to more than pay for this system over the life of the installation.

In addition to providing the illumination for classroom activities, a well-designed lighting system can also tune the color of the white light illumination to be more compatible with classroom activities. Early research on the correlation between the color of illumination, as measured by CCT, and student performance has been promising. Indeed, this research has shown that students' concentration increases when lighting with higher CCT values is used and that students' levels of relaxation and calmness are increased by lighting set to lower CCT values [11; 12].

It is a generally accepted fact that light activation of the retina in the eye greatly influences humans' physiological responses and behavior. Although the understanding of this phenomenon is still emerging, many lighting organizations, including DOE [13], the Illuminating Engineering Society of North America (IES) [14], and the *Commission Internationale de L'eclairage* (International Commission on Illumination [CIE]) [15], have published documents describing the fundamentals of this effect. As described by Lucas et al., illumination can provide a variety of non-visual responses, including activating the pupil light reflex, increasing alertness, reducing lapses in attention, and raising the heart rate and core body temperature [16]. In addition, non-visual responses to light striking the retina can also impact melatonin and cortisol production and, thereby, affect circadian rhythms.

Recent advances in SSL technologies provide the opportunity to deliver high-efficacy white light that is tailored to the needs of both the user and the task being performed. There is perhaps no application in which these capabilities of SSL technology can have a more substantial impact than lighting for educational facilities. Currently, lighting in public schools is widely viewed as being outdated, and by capitalizing on recent technology developments, an investment in advanced educational lighting will provide dividends to students, teachers, the school, and the community.

4.A.3 TWL Technologies

Single-color LED-based luminaires are achieving significant market penetration in many demanding lighting applications, and LED lighting systems are establishing a level of performance that all future lighting systems must meet or exceed. However, the next wave of LED lighting technology is likely to be TWL technologies that can adjust the spectrum of the emitted light along a range of values. This capability allows the lighting system to produce white light of an appropriate spectrum for the task at hand, which early research indicates is potentially useful in a classroom environment [11; 12]. For example, a warmer light (i.e., with a lower CCT) could be used for more relaxed tasks, such as group work or discussions, while a cooler light (i.e., with a higher CCT) could be used for tasks requiring greater concentration and higher visual acuity, such as tests or lectures.

There are at least two primary approaches that can be used to create TWL LED lighting systems, and each has advantages and disadvantages [17; 18]. The primary differences between these approaches are the number and colors of the LEDs that are used in the TWL system.

In two-LED TWL systems, LED modules composed of two independent LED assemblies are used to provide light. Each LED assembly contains white LEDs of a set CCT value, and typically, separate assemblies of warm white and cool white LEDs are placed in proximity on the printed circuit board (PCB) used for the LED modules. An example of the LED module used in NICLS luminaires is shown in **Figure 4.2** as a demonstration of this approach. Each LED assembly constitutes a primary white LED and serves to establish the endpoints of the tuning range, as shown in **Figure 4.3**. The orange-colored warm white LEDs in Figure 4.2 provide the illumination indicated by the 2,729 K point in Figure 4.3. The yellow-colored cool white LEDs provide the illumination indicated by the 6,471 K point in Figure 4.3.

Figure 4.2 LED Module Containing Assemblies of Warm White (Orange-colored) and Cool White (Yellow-colored) LEDs.

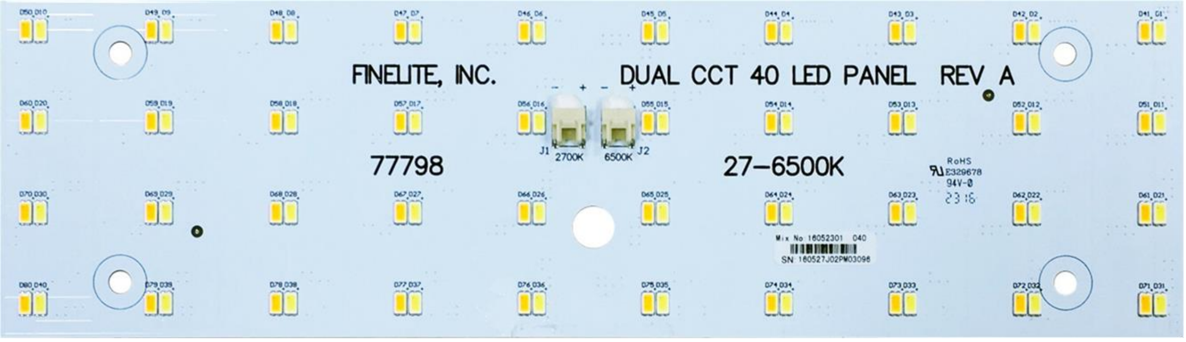
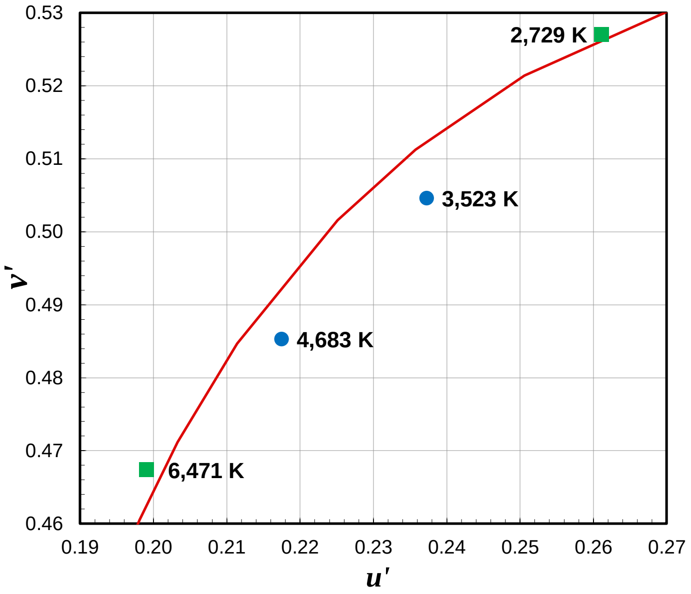


Figure 4.3 Chromaticity Diagram Showing the Tuning Range of the NICLS Two-LED TWL System.



NOTE: The primary LED colors—warm white and cool white—are indicated by the green squares.

Supplying current to only one LED assembly produces illumination at the CCT of that LED (e.g., 2,729 K or 6,471 K in Figure 4.3). Supplying current in varying proportions to both LED assemblies allows CCT values lying on a straight line connecting the endpoints to be achieved. Consequently, this type of TWL technology is sometimes termed "linear white tuning." For simplicity, two of these points are illustrated by blue circles in Figure 4.3, although a continuum of CCT values between the endpoints can be produced. Each LED assembly is driven by a separate channel on the same driver or separate drivers, which allows the current supplied to each to be altered independently. Although lighting produced by two-channel TWL devices does not follow the black body locus (i.e., the Planckian locus), research on lighting preference has found that light sources such as these that lie just below the black body locus are favored by most observers [19].

The LEDs used in two-channel TWL solutions utilize the same gallium nitride (GaN) semiconductor technology to form the LED, although there is some difference in the phosphors used to convert the emissions from the GaN LED into warm white and cool white lighting. Consequently, the performance of the warm white and cool white LEDs can be expected to be similar over time. As will be shown later in this report, the use of the same LED base chemistry produces similar, but not identical, aging characteristics in the two LED TWL solutions. This nearly uniform behavior helps to greatly simplify the system design.

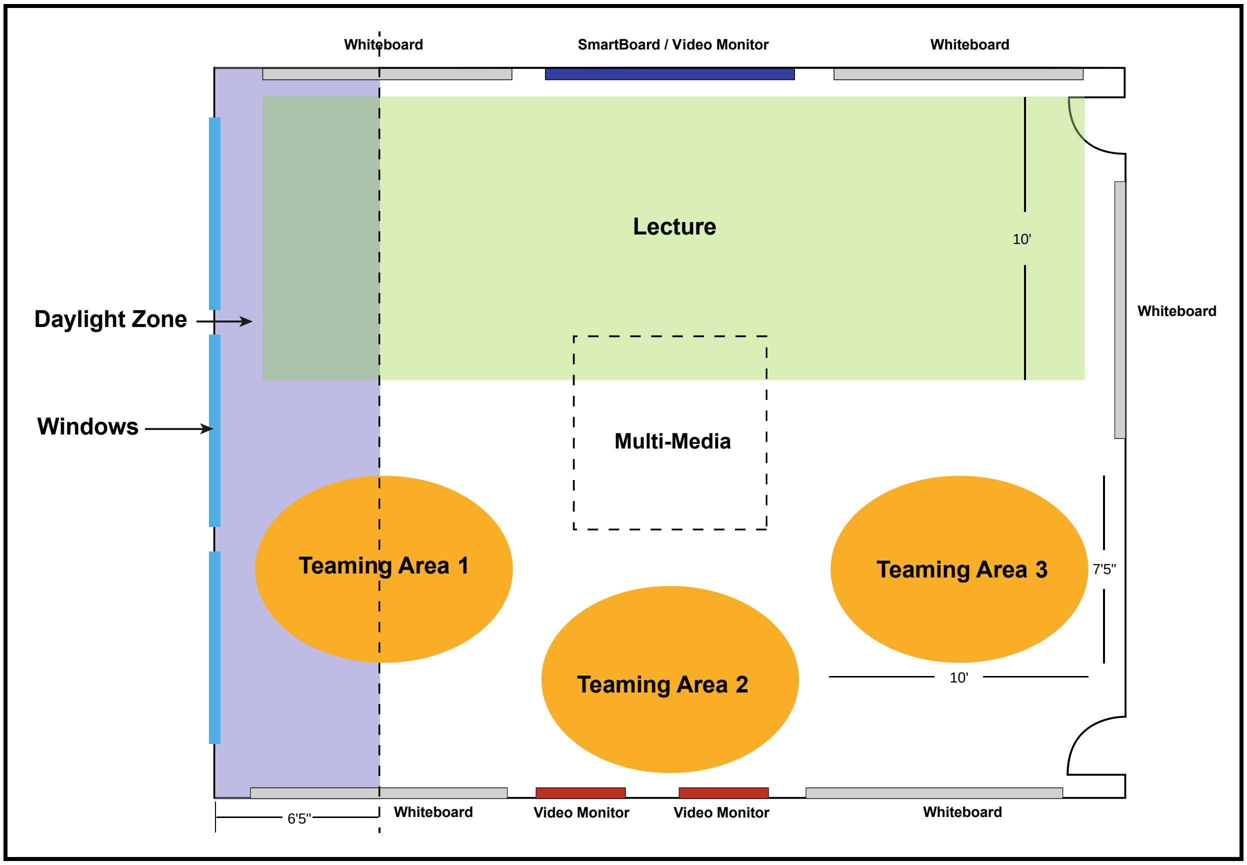
In a multi-LED TWL system, three or more different LED assemblies are used to provide TWL. These three-LED assemblies could include saturated colors (e.g., red, green, and blue LEDs utilizing different semiconductor chemistries, such as indium phosphide [InP] or GaN) or a mix of warm white, cool white, and direct red-emitting LEDs. A primary advantage of these multi-LED TWL systems is that the illumination can be adjusted to follow the black body locus. For this reason, these types of TWL luminaires are termed non-linear white-tuning devices. However, because multi-LED TWL systems are composed of LEDs with different semiconductor chemistries, the aging characteristics of the LEDs can vary greatly, which complicates the long-term system control. Additional details on multi-LED TWL systems are given in Commercially Available LED Product Evaluation and Reporting (CALiPER) Report 23 [17].

Although the two-LED TWL solution does not follow the black body locus, this approach to TWL has a number of advantages. First, the luminous efficacy of these devices is inherently higher than the non-linear tunable white systems [17]. Other advantages of the two-LED TWL solution cited in CALiPER Report 23 are the better color uniformity and easier color mixing possible with the two-chip solution and that this approach is less prone to chromaticity changes during dimming [17]. Another major difference is that the two-chip solution requires only two channels in an LED driver, whereas solutions involving three or more chips require more channels and more components in the LED driver, which could impact the reliability of the driver [20]. The higher luminous efficacy and simpler design of the two-chip solution can also produce greater lifetime savings from both reduced energy consumption and lower maintenance costs [21]. For this reason, RTI and Finelite made the judgement that the two-chip solution is the only approach that can achieve the aggressive goals that DOE established for the COF.

4.A.4 System Requirements for the DOE COF

DOE established very aggressive performance targets for the COF, and a representative layout was also included as part of DE-EE0001171 [5]. As shown in **Figure 4.4**, the representative layout separated the classroom into different areas to represent the diversity of activities that occur in the modern classroom. These areas are a lecture zone, teaming areas, and a multi-media area. In addition, there are five whiteboards (two on the north wall, one on the east wall, and two on the south wall) and three video monitors (one on the north wall and two smaller ones on the south wall) in the room. A multimedia center consisting of four ceiling-mounted video monitors is located in the center of the classroom. Specific requirements were developed by DOE for each area and for the classroom as a whole. These requirements are listed in **Table 4.2**. As will be shown throughout the remainder of this report, ***the NICLS system developed by RTI and Finelite exceeded these performance requirements,* and in many cases, the requirements were exceeded substantially**.

Figure 4.4 Floor Plan of the Representative Layout Developed by DOE as Part of the COF.



Source: Reference [5].

Table 4.2 DOE’s Classroom Lighting System Performance Requirements.

Performance Metric	COF Requirement
Luminous efficacy	120 lpw
CRI	≥ 80 at all available CCT values
Light output control	100% to 1% of light output at all available CCTs
Lumen maintenance	≥ 85% of initial value at 50,000 hours
Rated lifetime	Better than 50% survival at 50,000 hours
Lecture area	Maintained horizontal illuminance at 30” above finished floor (AFF) of 400 lux during lecture and 50 lux during AV mode with an average-to-minimum (ave:min) ratio no greater than 2:1
	Maintained vertical illuminance at 48” AFF of 150 lux during lectures and 30 lux during AV mode
	Ability to achieve at least four CCT values between 2,700 K and 5,000 K
Teaming area	Maintained horizontal illuminance at 30” AFF of 300 lux for note-taking during discussions and of 30 lux during AV mode with an ave:min ratio no greater than 3:1
	Maintained vertical illuminance at 48” AFF of 75 lux during
	Ability to achieve at least four CCT values between 2,700 K and 5,000 K
Project areas and video monitors	Ability to limit the vertical illuminance at each point on the defined areas to ≤ 50 lux during AV mode.
Whiteboard surfaces	Maintained vertical illuminance of the whiteboard surface of 300 lux with an ave:min ratio no greater than 3:1
Daylight zone	Ability to vary the output of the lighting system to achieve artificial light levels between 0% (i.e., off) and 100% (i.e., full-on) based on available daylight.

Source: Reference [5].

4.A.5 Project Plan for NICLS Technology Development

The primary objectives of this project were to develop and test novel, high-efficiency, tunable white SSL luminaire designs for use in an educational setting. These designs comprise the NICLS technology portfolio, and the core building block of each luminaire is a light engine composed of two high-efficiency LEDs of different CCT values. Ultimately, the NICLS technology can be implemented in a variety of luminaire types, including troffers, wall wash, downlights, and direct/indirect pendants, although this project concentrated on troffers and wall wash luminaires. A design goal of this effort was to make the NICLS technology flexible enough to work with most system control architectures, including digital multiplex (DMX), digital addressable lighting interface, or 0–10 V. The technology demonstration classroom discussed below used DMX controls. This project was led by RTI and leveraged both the engineering and education and workforce development (EWD) business groups within RTI. Finelite served as the technical lead on the development tasks associated with the LED modules, NICLS luminaires, and the entire lighting system and will commercialize the NICLS technology after this project.

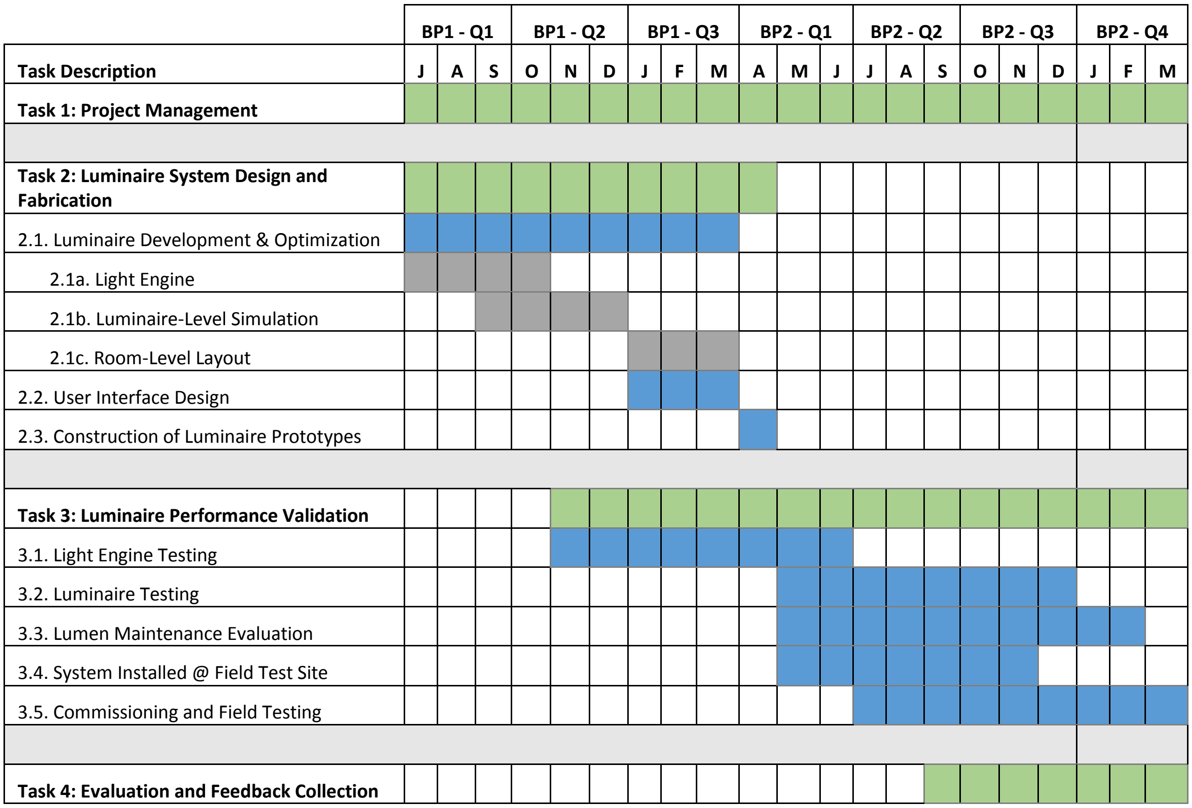
A unique element of this project was that teachers, administrators, school designers, and school facility personnel were recruited to provide input on the lighting system and its use in the classroom and to give guidance on the layout of the UI. The intent of this activity was to leverage input from potential users of the lighting system to gain information on how TWL technologies could be incorporated into the classroom curriculum. Special considerations were given to the design of the UI to make the system more compatible with the techniques that teachers use in the classroom.

The culmination of this project was the construction of a demonstration site to showcase the NICLS technology. The layout provided by DOE (Figure 4.4) was used for the demonstration site with accommodations made for its location in Finelite's facility. The intent of the demonstration site was to build a facility to showcase the capabilities of dynamic lighting systems in modern classroom settings. Once installed, the demonstration site was fully characterized to ensure that the NICLS technology exceeded the design goals specified by DOE at the beginning of this project:

- Continuously variable CCT values between 2,700 K and 5,000 K;
- Luminous efficacy exceeding 120 lpw at all CCT values;
- CRI values exceeding 80 at all CCT values;
- Full dimming capability between 0% and 100% of the maximum luminous flux controlled by a daylight intensity sensor;
- Rated lifetime (B50 value) exceeding 50,000 hours with lumen maintenance exceeding 85% at 50,000 hours; and
- Domestic US manufacturing, satisfying the "Qualified Made in USA" claim according to guidelines from the FTC.

To accomplish these objectives, this project was divided into one project management task and three research and development tasks. The Gantt chart summarizing the project plan and timeline is provided in **Figure 4.5**. The project stayed close to this timeline throughout with minimal slippage. Additional details on the actual project schedule are given in Section 3 of this report. The remainder of this report will provide a summary of the major findings from the three research and development tasks. List of outputs from this project, including publications, presentations, networks formed, and experimental methods, are found in the Appendices to this report.

Figure 4.5 Gantt Chart for the NICLS Technology Development and Demonstration.



	BP1 - Q1			BP1 - Q2			BP1 - Q3			BP2 - Q1			BP2 - Q2			BP2 - Q3			BP2 - Q4		
Task Description	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**
Task 1: Project Management	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Task 2: Luminaire System Design and Fabrication	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩											
2.1. Luminaire Development & Optimization	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦												
2.1a. Light Engine	▨	▨	▨	▨																	
2.1b. Luminaire-Level Simulation			▨	▨	▨	▨															
2.1c. Room-Level Layout							▨	▨	▨												
2.2. User Interface Design							🟦	🟦	🟦												
2.3. Construction of Luminaire Prototypes										🟦											
Task 3: Luminaire Performance Validation					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
3.1. Light Engine Testing					🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦									
3.2. Luminaire Testing											🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
3.3. Lumen Maintenance Evaluation											🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	
3.4. System Installed @ Field Test Site											🟦	🟦	🟦	🟦	🟦	🟦	🟦				
3.5. Commissioning and Field Testing													🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Task 4: Evaluation and Feedback Collection															🟩	🟩	🟩	🟩	🟩	🟩	🟩

Section 4.B of this report describes the foundational work that was performed on the design and fabrication of the LED modules and luminaire designs for the NICLS technology. These activities form Task 2 of this project; Finelite was the leader of this task. When possible, Photopia simulations of the LED modules and luminaires were performed to ensure that the NICLS-enabled luminaires would meet the program goals. Upon completion of the Photopia simulations, AGi32 simulations were used to lay out the NICLS technology demonstration site and provide an indication of the level of performance that could be expected.

Section 4.C of this report details the extensive characterization work conducted to validate the performance of the NICLS technology. A variety of characterizations were performed at the LED module, luminaire, and technology demonstration site levels. This analysis included full electrical and photometric testing by independent third parties, extensive flicker measurements, and accelerated stress testing (AST) of major system components. These activities formed Task 3 of this project and were led by the engineering branch of RTI with technical support provided by Finelite.

Section 4.D of this report summarizes the major findings from the focus groups formed to provide input on the applicability of the NICLS technology to a classroom environment. These activities comprised Task 4 of this project and were led by the EWD business unit of

RTI, with technical support from RTI's engineering function and Finelite. Focus groups were held at the NICLS technology demonstration site located at Finelite's manufacturing facility in Union City, CA. During this task, feedback was collected from teachers, school administrators, and other potential users and stakeholders regarding all aspects of the NICLS system, including the quality of light and design of the UI.

4.B Task 2: Luminaire System Design and Fabrication

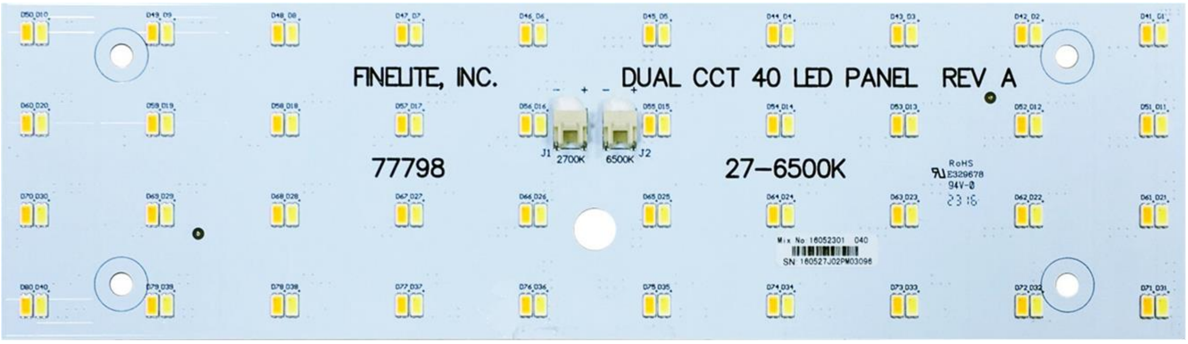
4.B.1 Luminaire Development and Optimization

NICLS LED Module Design

The initial step in the design of the NICLS LED module was to look at different mid-power LED (MP-LED) packages and identify the package with the highest level of performance. The decision to use an MP-LED product instead of other LED package types was based on the need for a distributed light source combined with Finelite's experience with this type of LED package. Once the decision was made to use an MP-LED package, several different products were examined, including a 2323 package and a 5630 package. After an extensive review of the manufacturers' data on the performance of different MP-LED packages, it was determined that only the 5630 MP-LED package had sufficient performance to meet the goals of this project.

Leveraging exclusive supply agreements that Finelite has established with leading LED suppliers, we obtained high-efficiency MP-LEDs in the 5630 package at nominal CCT values of both 2,700 K and 6,500 K. These LEDs were used as the basis for the design of the TWL LED modules. The performances of several different LED module designs were initially simulated using the light ray-tracing software Photopia. Based on the results of these simulations, a design that met the project requirements was chosen. Test boards were fabricated to measure performance in actual hardware. At the end of this analysis, the decision was made to use the 80-LED module shown in **Figure 4.6** as the core light source in NICLS luminaires.

Figure 4.6 80-LED Module Containing 40 Warm White and 40 Cool White MP-LEDs that Forms the Core Light Source in the NICLS Luminaires.



Samples of this LED module (Finelite Part Number 77798) were sent to an external laboratory for photometric testing as an independent validation of performance. Because the LEDs were not mounted on a heat sink, this initial photometric testing was performed with each LED color turned on for only 30 seconds before a reading was taken. This approach minimized any heating effects during operation of the module, which would reduce the luminous flux. The photometric performances measured in third-party testing for both the warm white and cool white assemblies are given in **Table 4.3**. These photometric measurements demonstrate that the performance of the 77798 TWL LED module is excellent with high luminous efficacies (168 lpw for the cool white LED assembly operated at 700 mA and 153 lpw for the warm white LED assembly using the same setting).

Table 4.3 Third-party Photometric Test Results for the 77798 TWL LED Module Used in the NICLS Technology.

	Cool White		Warm White	
Current	**350 mA**	**700 mA**	**350 mA**	**700 mA**
Power	3.88 W	8.13 W	3.88 W	8.13 W
Luminous Flux	707 lm	1,363 lm	646 lm	1,243 lm
Luminous Efficacy	182 lpw	168 lpw	166 lpw	153 lpw
u'	0.1988	0.1988	0.2619	0.2614
v'	0.4698	0.4688	0.5267	0.5263
CCT Value	6,351 K	6,407 K	2,713 K	2,726 K
R_a (CRI)	82.1	82.1	83.0	82.9
R_9 (Red)	10.7	11.4	12.5	11.8
R_{10} (Yellow)	64.0	63.8	79.0	78.7
R_{11} (Green)	84.1	84.4	81.4	81.2
R_{12} (Blue)	61.3	61.9	75.9	75.8

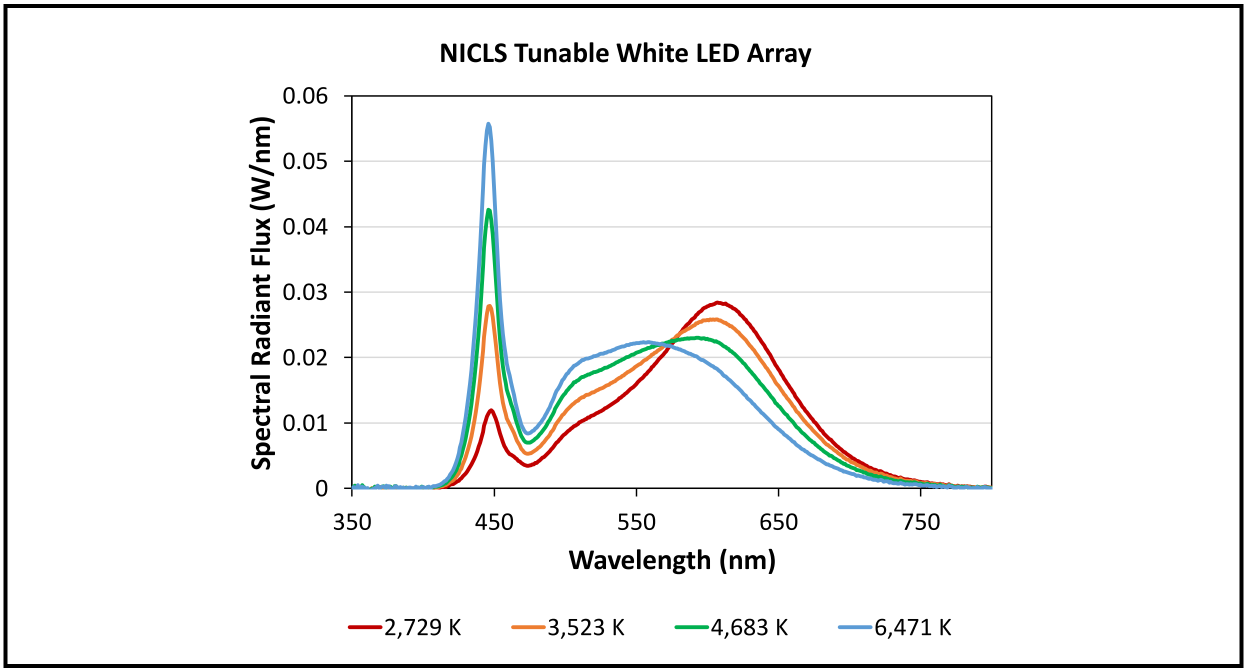
In parallel with these efforts, RTI also measured the photometric performances of different samples of the 77798 TWL LED module but with a different experimental protocol. In RTI's protocol, the LED modules were operated at 700 mA for 1 hour prior to photometric measurement, and no heat sinking was applied to the boards because of their relatively low temperature rise. This approach resulted in the board temperature rising to approximately 10°C above the ambient temperature. At the end of 1 hour, each LED module was placed in a calibrated 65" integrating sphere, and the full photometric properties were measured while the device was operated at 700 mA per LED module or 70 mA per LED. During the measurement, each LED module was powered with a Keithley sourcemeter (Model 2401, Keithley Instruments, Solon, OH) operated at 700 mA. The photometric properties measured by RTI for the 77798 TWL LED module are given in **Table 4.4**. Good agreement was found with the results from the independent test lab (see Table 4.3), although the luminous efficiency of the modules measured using RTI's protocol was lower by 5–9%, possibly because of the differences in the operating temperature of the LED module between the two methods. The standard deviations are also included in Table 4.4, and the narrow spread in values indicates that the LEDs used in the NICLS technology are tightly binned. The spectral power distributions (SPDs) at the two prime LED settings and two intermediate settings are given in **Figure 4.7**. The corresponding white tuning range of the NICLS technology built with these LEDs is given in Figure 4.3.

Table 4.4 Photometric Properties Measured by RTI for the 77798 TWL LED Module Used in the TWL NICLS Technology.

	Cool White	Warm White
Current	700 mA	700 mA
Power	8.41 W	8.26 W
Luminous Flux	1,341 (± 16) lm	1,233 (±18) lm
Luminous Efficacy	165 (± 2) lpw	147 (±2) lpw
u'	0.1988 (± 0.0001)	0.2611 (± 0.0003)
v'	0.4663 (± 0.0003)	0.5271 (± 0.0001)
CCT Value	6,558 (± 21) K	2,733 (± 6) K
R_a (CRI)	82.0	82.8
R_9 (Red)	12.2	10.7
R_{10} (Yellow)	63.1	79.3
R_{11} (Green)	84.8	80.5
R_{12} (Blue)	62.8	75.6

NOTE: The values in the table represent the averages of five different LED modules, and the standard deviation of each measurement is given in parentheses.

Figure 4.7 SPD at Different CCT Settings for the TWL LED Modules Used in NICLS Luminaires.



NOTE: The SPDs of the two primary LED assemblies (2,729 K and 6,471 K) are shown along with those of two intermediate values (3,523 K and 4,683 K). The tuning range of the module is given in Figure 4.3.

To understand the changes in chromaticity, color rendering, and CCT as the NICLS TWL LED module is tuned between different settings, a TM-30 analysis was conducted using the IES TM-30-15 advanced calculation tool [22; 23; 24; 25]. The TM-30 analysis provides two metrics: a color fidelity metric (R_f) and a color gamut (R_g) metric. In addition, TM-30-15 also calculates a graphical representation of color that provides a visual indication of the changes in hue and saturation relative to a reference illuminant, which is a black body at the same CCT.

The color fidelity metric, R_f, provides a measure of the ability of a light source to render colors accurately and is analogous to the traditional CRI metric (R_a). The color fidelity metric provides greater accuracy than CRI, and a key difference between the two is that CRI is calculated from a limited range of standard colors, whereas R_f is calculated from a larger number of standard colors. CRI is calculated as the average of eight mostly pastel colors, and saturated colors, such as red, yellow, green, and blue, are each assigned different metrics separate from the classical CRI value. In contrast, R_f is calculated from the theoretical rendering of 99 different color samples (including saturated and non-saturated colors) by a test light source relative to the reference light source.

The color gamut metric (R_g) provides an indication of the average level of color saturation relative to the reference illuminant, and the information provided by R_g is not captured in either CRI or R_f. A value of R_g above 100 indicates greater color saturation for the test light source relative to the black body reference illuminant, whereas a value of R_g below 100 indicates less color saturation. The TM-30-15 color vector graphic provides an indication of the R_g values for all visible wavelengths.

As shown in **Figure 4.8**, the NICLS TWL LED modules exhibited a CRI (R_a) value of 82 or higher at all CCT values. The CRI value increased in the middle of the tuning range and was approximately 86 over the 3,500 K–5,000 K range. An examination of the TM-30-15 metrics revealed that the light source exhibited an excellent color gamut of 96 or higher at all CCT values. The TM-30-15 color vector graphics for four different CCT values of the NICLS TWL system are given in **Figure 4.9**, and a comparison of the SPDs of the NICLS TWL and reference illuminant at each CCT value is given in **Figure 4.10**. There are some wavelengths (e.g., blue and yellow) where the LED light source produced slightly higher levels of saturation than the reference black body illuminant. Likewise, there were wavelengths (e.g., cyan and red-orange) where the LED light source produced slightly less saturated colors than the reference black body illuminant. In addition, there were very slight differences in the color vector graphic depending on the CCT setting, but the consistency across the tuning range was excellent. The color fidelity generally tracked R_a at all CCT values but was consistently one to two points less than R_a at all values. Based on these findings, the LED module used in NICLS luminaires produces excellent, largely undistorted color rendering across the visible spectrum.

Figure 4.8 CRI (R_a), Color Fidelity (R_f), and Color Gamut (R_g) Metrics of the NICLS TWL LED Module under Different Tuning Conditions.

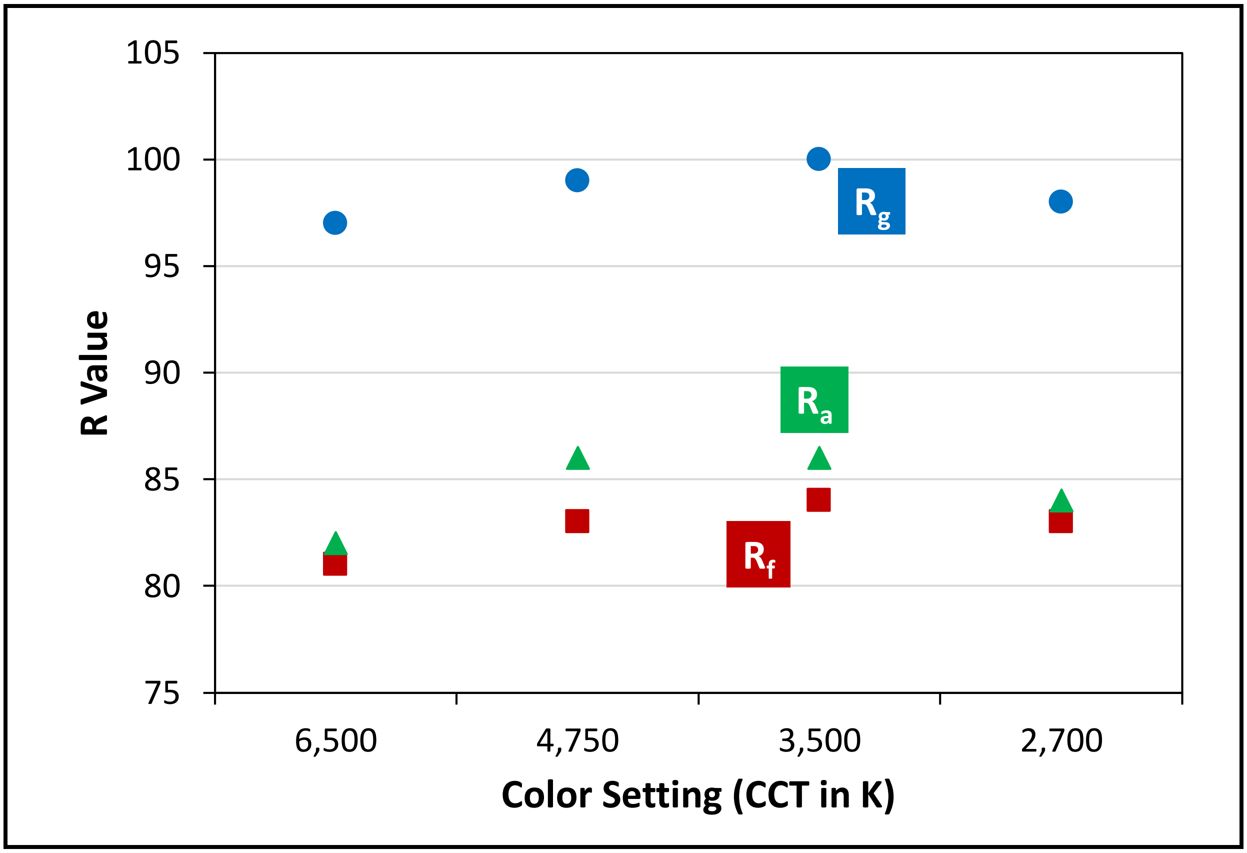
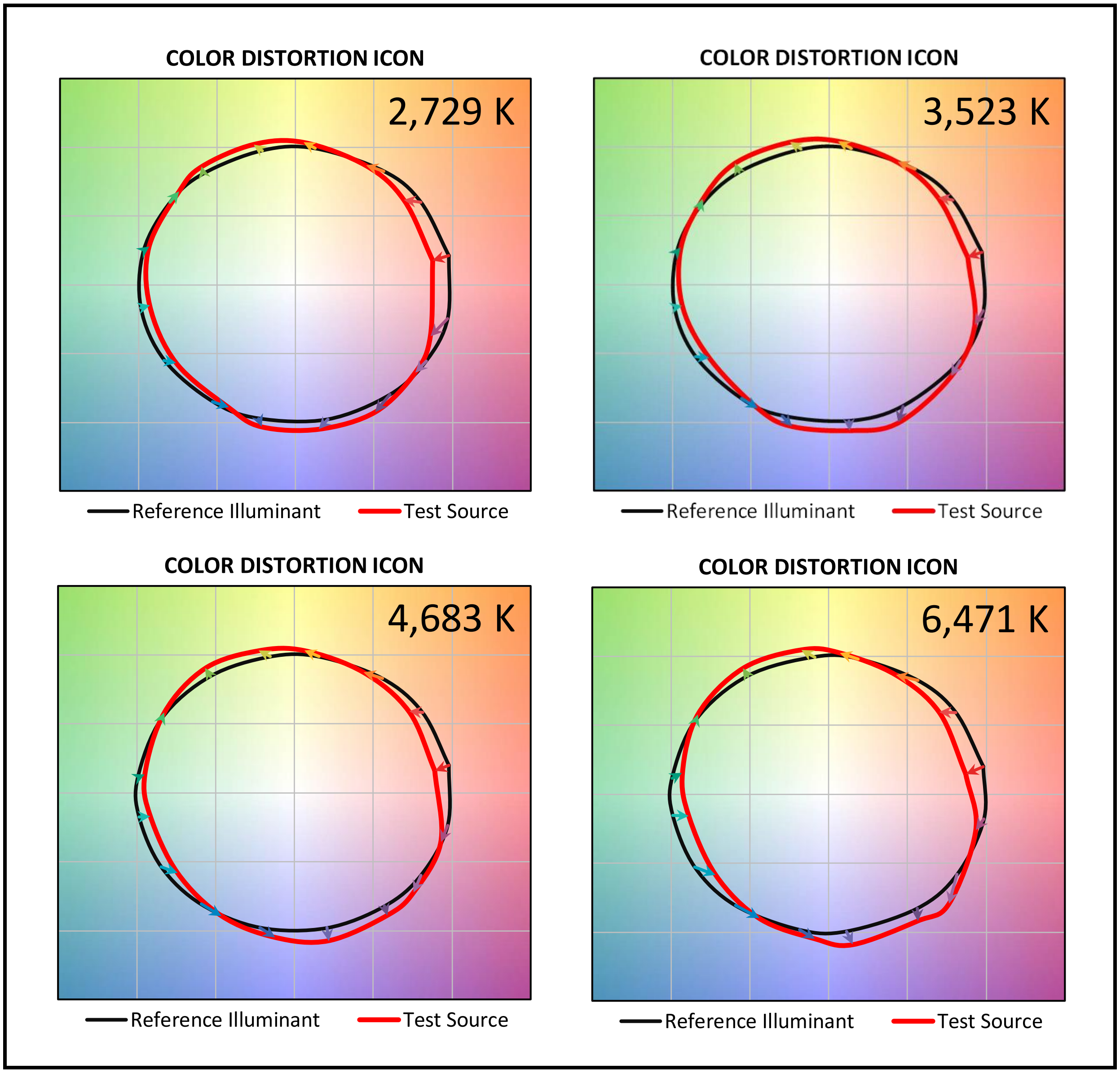
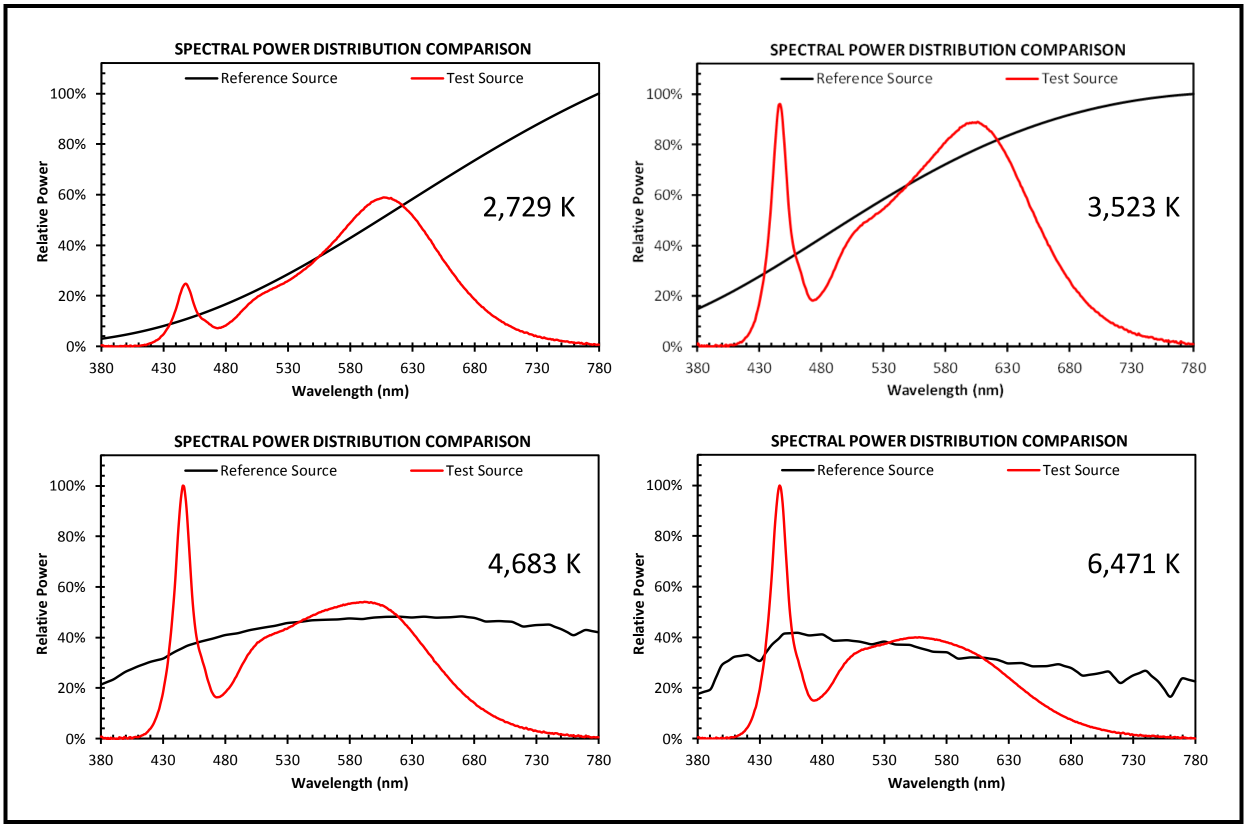


Figure 4.9 TM-30-15 Color Vector Graphics for the 77798 LED Module Used in NICLS TWL Luminaires Tuned to Four Different CCT Values.



NOTE: The red line in each graphic corresponds to the characteristics of the NICLS LED module tuned to the indicated CCT value. The black line corresponds to the characteristics of the reference black body illuminant at the same CCT value.

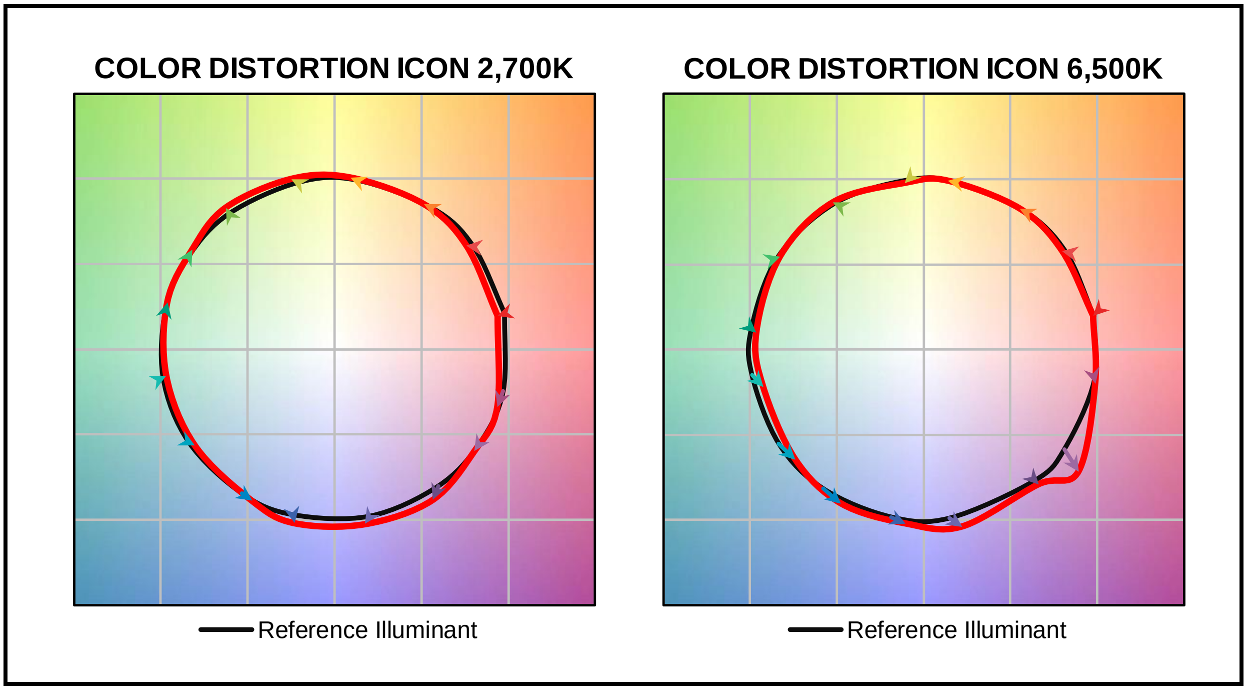
Figure 4.10 Comparison of the SPDs of the 77798 TWL LED Module Used in NICLS Luminaires with those of the Reference Black Body Illuminants



NOTE: The red line in each graphic corresponds to the SPD of the NICLS LED module tuned to the indicated CCT value. The black line corresponds to the SPD of the reference black body illuminant at that CCT value.

In addition to the standard NICLS TWL LED module, a high-CRI version is available with higher color rendering but lower luminous efficacy than described here. The higher-CRI version provides color fidelity and color gamut metrics that are even closer to the reference black body illuminant. As a demonstration of the capabilities of this NICLS option, the color vector graphics for the warm white and cool white primary LEDs in the NICLS TWL module are shown in **Figure 4.11**. This option is especially useful in situations such as biology laboratories or art classes where very high color rendering is important. For most classroom applications, the exceptional performance that was measured with the standard NICLS LED module will likely be sufficient. For this reason, the standard NICLS LED module was installed in the luminaires in the demonstration classroom and will be the subject of the remainder of this report.

Figure 4.11 Color Vector Graphics for the High-CRI Version of the NICLS TWL LED Module.



NOTE: For the 2,700 K primary, R_f = 91, and R_g = 101. For the 6,500 K primary, R_f = 89, and R_g = 101.

NICLS Luminaire Design

The next step was to evaluate the NICLS LED module in various luminaire designs and identify the designs for use in the demonstration site. During this process, several direct/indirect luminaires were evaluated in addition to different troffer designs. Both classes of luminaires are commonly used in many educational luminaire lighting designs, meriting their inclusion in this analysis.

During this analysis, combinations of luminaire designs, lenses, finishes, and other components were evaluated. In total, 111 different luminaire options were evaluated for luminous efficacy, glare, and compatibility with the program goals set by DOE. From this evaluation, five different luminaires designs were identified that would be able to meet the program goals at the end of this project. Then, ray-tracing simulations were performed on the designs using Photopia [26], and the expected performances based on the Photopia simulations of these five designs are given in **Table 4.5**. An expected improvement in LED performance during this project was also considered. In Table 4.5, Gen 1 designs assume LED performance at the beginning of the project, while Gen 2 and Gen 3 designs assume the LED performance levels that were expected by the end of the project based on commitments made by LED suppliers.

Table 4.5 Evaluation Metrics for the Different Luminaires Meeting the Project Goals.

Test Conditions	Luminaire	Lumens per Lamp - LED Module (lm)	Luminous Efficacy - LED Module (lpw)	Luminous Flux - Luminaire (lm)	Luminous Efficacy - Luminaire (lpw)
Actual Hardware Reference Case	Design 1	34.2	162.9	4,722	124
Single-channel Driver and Fixed-CCT LEDs	Design 1	34.2	162.9	4,784	126
TWL Driver and LEDs, Gen 1	Design 1	34.2	162.9	4,784	119
TWL Driver and LEDs, Gen 2	Design 1	38.0	181.0	5,316	132
TWL Driver and LEDs, Gen 3	Design 1	40.0	190.5	5,595	139
Actual Hardware Reference Case	Design 2	34.2	162.9	4,401	116
Single-channel Driver and Fixed-CCT LEDs	Design 2	34.2	162.9	4,385	116
TWL Driver and LEDs, Gen 1	Design 2	34.2	162.9	4,385	109
TWL Driver and LEDs, Gen 2	Design 2	38.0	181.0	4,872	121
TWL Driver and LEDs, Gen 3	Design 2	40.0	190.5	5,129	128
Single-channel Driver and Fixed-CCT LEDs	Design 3	34.2	162.9	4,566	120
TWL Driver and LEDs, Gen 1	Design 3	34.2	162.9	4,566	114
TWL Driver and LEDs, Gen 2	Design 3	38.0	181.0	5,073	126
TWL Driver and LEDs, Gen 3	Design 3	40.0	190.5	5,340	133
Actual Hardware Reference Case	Design 4	25.9	164.4	6,979	127
Single-channel Driver and Fixed-CCT LEDs	Design 4	25.9	164.4	6,906	125
TWL Driver and LEDs, Gen 1	Design 4	25.9	164.4	6,906	118
TWL Driver and LEDs, Gen 2	Design 4	28.8	182.7	7,673	131
TWL Driver and LEDs, Gen 3	Design 4	30.3	192.3	8,077	138
Single-channel Driver and Fixed-CCT LEDs	Design 5	25.9	164.4	7,130	129
TWL Driver and LEDs, Gen 1	Design 5	25.9	164.4	7,130	122
TWL Driver and LEDs, Gen 2	Design 5	28.8	182.7	7,922	135
TWL Driver and LEDs, Gen 3	Design 5	30.3	192.3	8,339	143

NOTE: Design 1 is a direct/indirect pendant luminaire, and Designs 2–5 are different configurations and sizes of troffers. All measurements and Photopia calculations were performed assuming a CCT value of 3,500 K. The results for the Actual Hardware Reference Cases were determined in third-party testing by an independent test laboratory using a fixed-CCT luminaire set to 3,500 K.

Several of the luminaires (e.g., Design 1, Design 2, and Design 4) are similar to commercial products currently sold by Finelite. Consequently, the measured photometric properties of these luminaires are included in Table 4.5 for a fixed 3,500 K configuration, along with the Photopia calculations for these luminaires. A comparison of the measured values and

Photopia simulations demonstrates excellent agreement between the two and provides increased confidence in Photopia calculations for a TWL luminaire in an untested design.

The Photopia calculations indicate that all the five luminaires listed in Table 4.5 will meet the project requirements at the end of the project and that one design (Design 5) is expected to meet the project goals at the outset. In choosing a luminaire design to install in the NICLS demonstration site, a decision was made to intentionally select a design that would challenge the goals of this project, as listed in Table 4.2. Consequently, the decision was made to install Design 2 luminaires in the demonstration site. The Design 2 luminaire, which is a 2×2 troffer, has the lowest luminous efficacy of the five designs and would present the greatest challenge to reaching the 120-lpw threshold. Therefore, if this luminaire can achieve that level of performance, the other luminaires will as well.

Demonstration Room Layout

Leveraging the photometric profiles of the 2×2 troffer (i.e., Design 2), AGi32 simulations were performance on the proposed technology demonstration site using the layout provided by DOE (Figure 4.4) [27]. In performing these calculations, several assumptions about the properties of finishes and fixtures in the room were made, as listed in **Table 4.6**.

Table 4.6 Assumed Properties of the Finishes and Fixtures in the NICLS Technology Demonstration Site Used in AGi32 Layout Simulations.

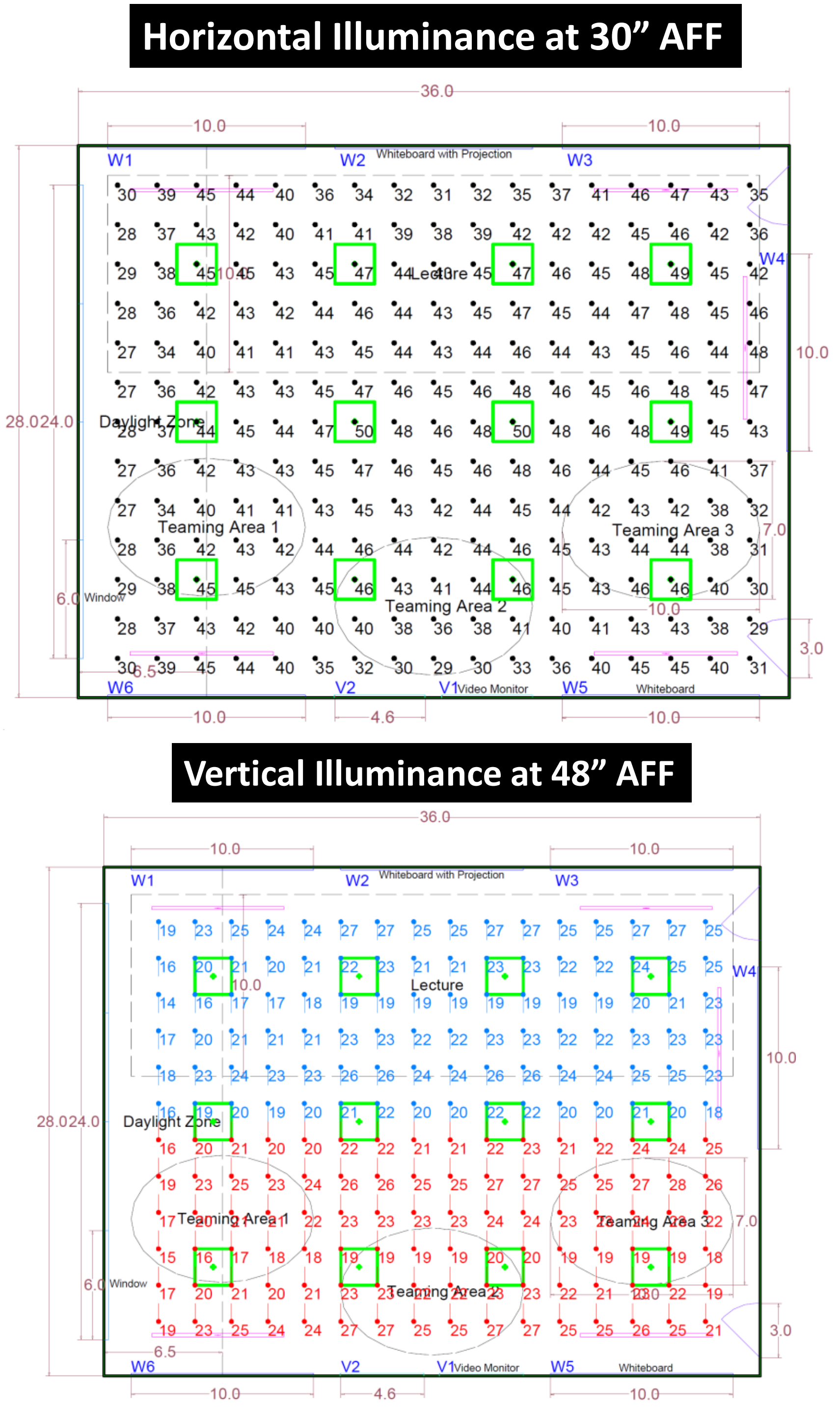
Room Property	Assumed Value
Ceiling height	9.5 feet
Ceiling reflectance	0.83
Wall reflectance	0.50
Floor reflectance	0.20
Whiteboard height	4 feet
Bottom of whiteboard	2.5 feet AFF
Whiteboard reflectance	0.80
Video monitor height	Not specified by DOE
Bottom of video monitor	Not specified by DOE
Video monitor reflectance	Not specified by DOE

The space in the demonstration classroom was configured assuming dedicated whiteboard wall wash luminaires for each of the five whiteboards in the layout. For the remainder of the space, the configuration of the 2×2 luminaires was varied to provide a lighting system that would exceed all DOE goals at this end of this project when Gen 2 performance will be available. The outputs from the AGi32 simulations for the general lighting and AV lighting modes are given in **Figure 4.12** and **Figure 4.13**, respectively. No contributions from natural sunlight were assumed in the AGi32 simulations, and the illumination levels along the west side of the room are lower than those in the rest of the room to compensate for sunlight. Even with this consideration, the illuminance levels across the classroom were relatively uniform with a range of 27 foot-candles (fc) to 50 fc in general lighting mode and between 3 fc and 8 fc in AV lighting mode. The average illumination across the room were determined to be 41.4 fc in general lighting mode and 5.94 fc in AV lighting mode. This resulted in ave:min ratios of 1.53 for general lighting mode and 1.98 for AV lighting mode. These values exceed all of the DOE requirements for this space.

The illumination values on the whiteboards and video monitors in general lighting mode are given in Figure 4.13. The values on the three video monitors are exceptionally consistent, with a range of 20 fc to 23 fc, and the ave:min ratio was calculated to be 1.09. Such consistent illuminance is essential to minimize veiling reflections and to ensure that the video screen is visible throughout the classroom. A greater variation in illuminance was calculated for points on the whiteboard, and the values ranged between 20 fc to 43 fc. The lowest illuminances were generally toward the bottom of the whiteboard. Even with this larger variation in illuminance levels across the whiteboard surface, the ave:min ratios for the five whiteboards were 1.37, 1.29, 1.23, 1.35, and 1.50, indicating highly uniform lighting across the entire surface of the whiteboard. Again, all of these values surpass the requirements set by DOE for this project

A comparison of the AGi32 calculations for the demonstration site assuming the use of 2×2 troffers containing the NICLS TWL LED module and the project goals set by DOE is given in **Table 4.7**. Based on this analysis, the chosen 2×2 troffer format can be expected to meet or exceed all project goals established by DOE at the end of the project, including horizontal and vertical illuminance levels throughout the classroom and lighting uniformity as measured by ave:min ratios. Having demonstrated that the NICLS technology meets all project goals at the LED, LED module, luminaire, and classroom layout levels, construction of the demonstration site was completed with 2×2 troffers, and full characterization of the installation was performed as described in Section 4.B.2 and Section 4.C.2.

Figure 4.12 Ouputs from AGi32 Simulations in General Lighting Mode for 2×2 NICLS Troffers and Wall Wash Luminaires in the NICLS Technology Demonstration Site



Horizontal Illuminance at 30” AFF

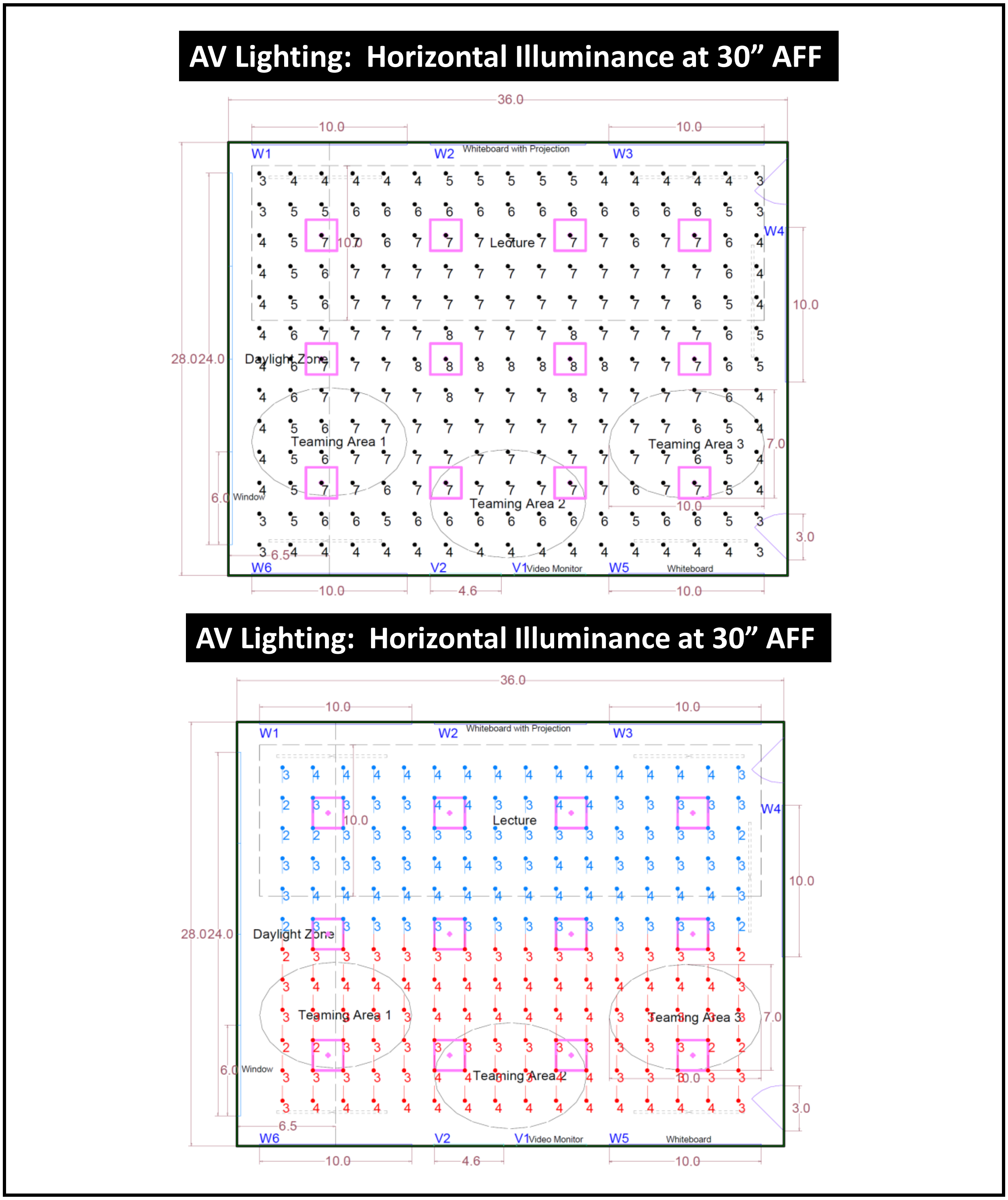
30	39	45	44	40	36	34	32	31	32	35	37	41	46	47	43	35
28	37	43	42	40	41	41	39	38	39	42	42	42	45	46	42	36
29	38	45	45	43	45	47	44	40	45	47	46	45	48	49	45	42
28	36	42	43	42	44	46	44	43	45	47	45	44	47	48	45	46
27	34	40	41	41	43	45	44	43	44	46	44	43	45	46	44	48
27	36	42	43	43	45	47	46	45	46	48	46	45	46	48	45	47
28	37	44	45	44	47	50	48	46	48	50	48	46	48	49	45	43
27	36	42	43	43	45	47	46	45	46	48	46	44	45	46	41	37
27	34	40	41	41	43	45	43	42	44	45	44	42	43	42	38	32
28	36	42	43	42	44	46	44	42	44	46	45	43	44	44	38	31
29	38	45	45	43	45	46	43	41	44	46	45	43	46	46	40	30
28	37	43	42	40	40	40	38	36	38	41	40	41	43	43	38	29
30	39	45	44	40	35	32	30	29	30	33	36	40	45	45	40	31

Vertical Illuminance at 48” AFF

19	23	25	24	24	27	27	25	25	27	27	25	25	27	27	25
16	20	21	20	21	22	23	21	21	23	23	22	22	24	25	25
14	16	17	17	18	19	19	19	19	19	19	19	19	20	21	23
17	20	21	21	21	23	23	22	22	23	23	22	22	23	23	23
18	23	24	23	23	26	26	24	24	26	26	24	24	25	25	23
16	19	20	19	20	21	22	20	20	22	22	20	20	21	20	18
16	20	21	20	20	22	22	21	21	22	23	21	22	24	24	25
19	23	25	23	24	26	26	25	25	27	27	25	25	27	28	26
17	20	21	21	22	23	23	23	23	24	24	23	23	24	23	22
15	16	17	18	18	19	19	19	19	20	20	19	19	19	19	18
17	20	21	20	21	23	23	22	22	23	23	22	21	20	22	19
19	23	25	24	24	27	27	25	25	27	27	25	25	26	25	21

NOTE: The green squares indicate the locations of the 2×2 troffers, and the magneta rectangles indicate the locations of the wall wash luminaires for the whiteboards. AGi32 simulation results are given in fc, and there are 12.57 lux per fc.

Figure 4.13 Ouputs from AGi32 Simulations in AV Lighting Mode for 2×2 NICLS Troffers in the NICLS Technology Demonstration Site



NOTE: The magenta squares indicate the locations of the 2×2 troffers. AGi32 simulation results are given in fc, and there are 12.57 lux per fc.

Figure 4.14 Illuminance Values for the Whiteboards and Video Monitors in the General Lighting Mode for the NICLS Technology Demonstration Site Calculated with AGi32

Table 4.7 Comparison of the DOE Project Requirements and Expected Performance of the NICLS Technology in the Demonstration Site Based on AGi32 Simulations

Classroom Area	Lighting Mode	Metric	DOE Requirements	AGi32 Layout
Lecture	Lecture[1]	Horizontal illuminance	400 lux (37.2 fc) at 30” AFF	41.4 fc
		Ave:min ratio	< 2:1	1.53
		Vertical Illuminance	150 lux (13.9 fc) at 48” AFF	21.9 fc
	AV	Horizontal illuminance	50 lux(4.54 fc) at 30” AFF	5.94 fc
		Ave:min ratio	< 2:1	1.98
		Vertical illuminance	30 lux(2.79 fc) at 48” AFF	3.31 fc
Projection areas and video monitors	AV	Vertical illuminance	< 50 lux (4.65 fc) at all points on screen	3.0 fc
		Ave:min ratio	< 2:1	1.0
Whiteboard	Lecture[1]	Vertical illuminance	300 lux (27.9 fc) average	31.3 fc
		Ave:min Ratio	<3:1	1.3
Teaming	Lecture[1]	Horizontal illuminance	300 lux (37.2 fc) at 30” AFF	41.4 fc
		Ave:min ratio	< 3:1	1.53
		Vertical Illuminance	75 lux (6.97 fc) at 48” AFF	22.2 fc
	AV	Horizontal illuminance	30 lux (4.54 fc) at 30” AFF	5.94
		Ave:min ratio	< 3:1	1.94
		Vertical illuminance		

NOTE: Ave:min ratio = the ratio of the average illuminance to the minimum illuminance.

fc = foot-candles = lumen per square foot

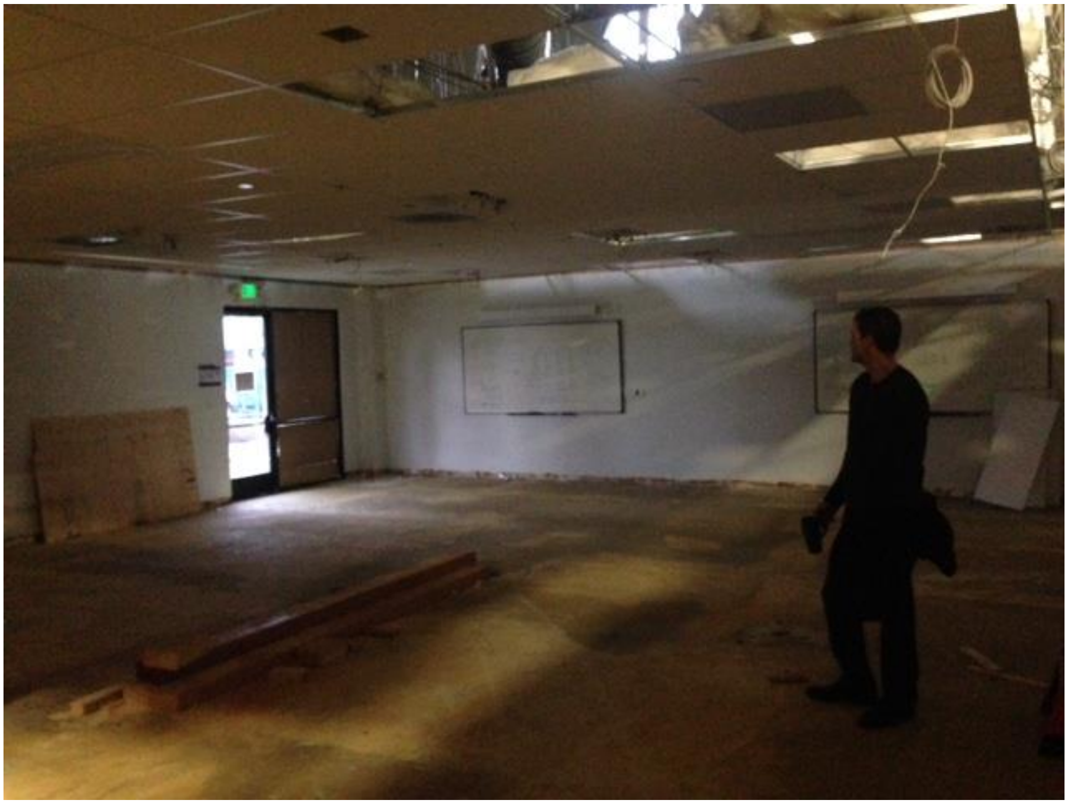
lux = lumen per square meter

[1] Lecture is the terminology that DOE applied in setting the original specifications and is equivalent to the “General” setting in the NICLS technology. As discussed later, our focus groups of teachers and educational professionals felt that the term “Lecture” reinforced bad teaching habits, so the term general lighting is used in the NICLS platform.

4.B.2 Construction of the NICLS Technology Demonstration Site

Based upon the promising results of the Photopia and AGi32 simulations of the 2×2 luminaires equipped with the NICLS LED modules, the decision was made to build the NICLS technology demonstration site at Finelite's manufacturing facility in Union City, CA. To build this facility, an area of at least 36 feet by 28 feet (1,008 ft^2) was needed. A picture of the site chosen for this technology demonstration before construction is shown in **Figure 4.15**.

Figure 4.15 Picture of the NICLS Technology Demonstration Site for the DOE COF after Partial Demolition of the Area.



To locate the demonstration site in this facility, several changes were required. First, because of the orientation of the space and the requirements of the office park where Finelite is located, actual windows could not be installed. Instead, approval was obtained from DOE to use blue light boxes to simulate windows. A second accommodation was that the ceiling of the space was raised by 6 inches so that the total ceiling height would be 9.5 feet throughout. A third accommodation was required to address a load-bearing 4-inch by 4-inch structural beam in the facility. Because it would cost roughly $25,000 to move the beam, the decision was made to keep the beam in the space and work around it. A picture of the space near the end of construction is shown in **Figure 4.16**.

Figure 4.16 Picture of the NICLS Technology Demonstration Site for the DOE COF during Construction.

A closer examination of Figure 4.16 reveals several nuances of the demonstration site that deserve mention. First, the installed 2×2 troffers and wall wash luminaires are turned on and are visible in the ceiling. Second, white partitions line the perimeter of the space and provide uniform reflectance for the walls. In the finished demonstration site, additional white partitions covered the open spaces in the wall and provided a uniform perimeter. Third, the 4-inch by 4-inch structural beam that remains in the space is visible in the foreground. Finally, the blue light boxes that are used as simulated windows can be seen in the background. Further changes were made to the space that are not visible, including the addition of numerous power drops throughout the room and information technology cabling.

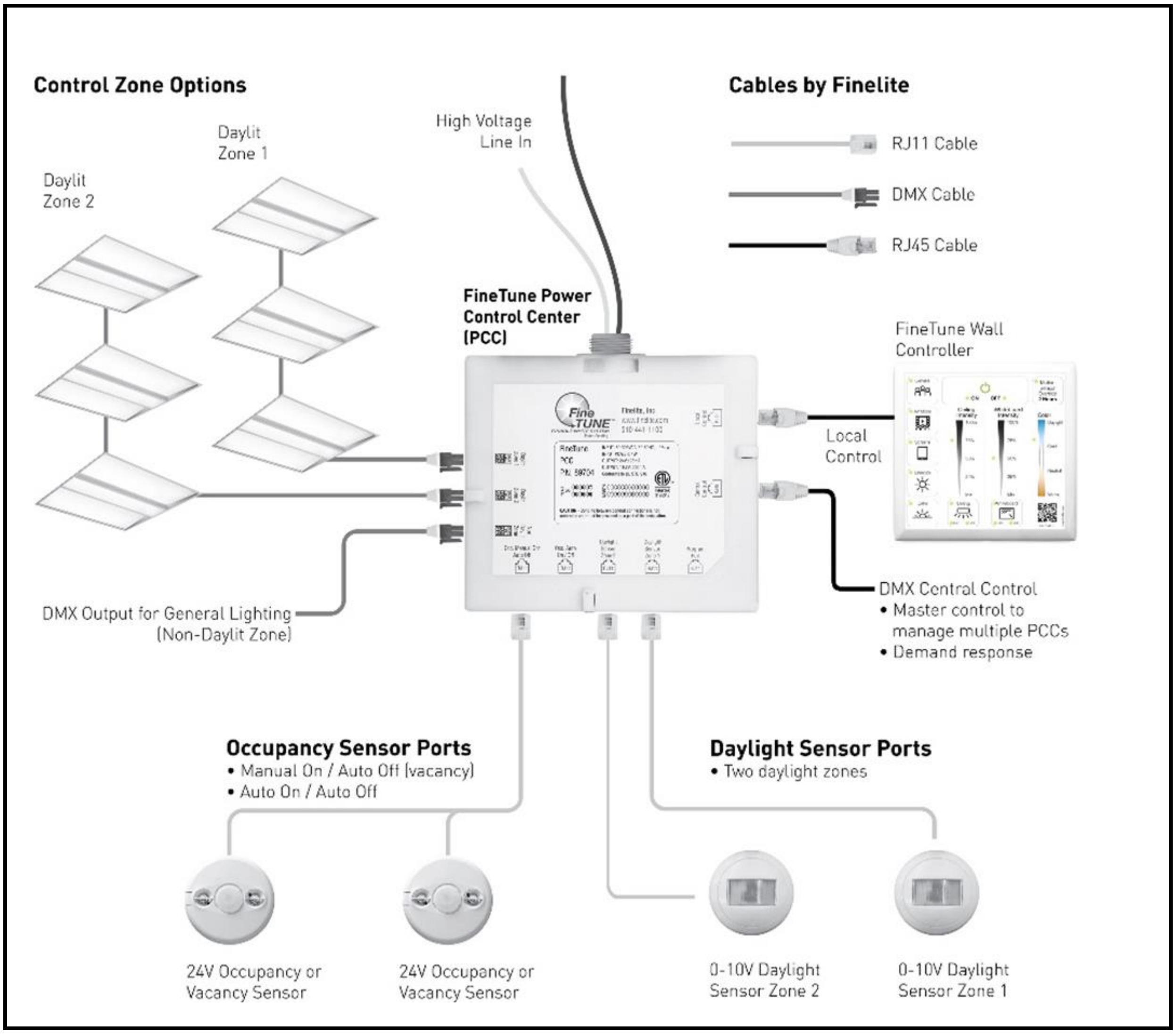
Fixtures and finishes were added to the space so that the final product resembles a normal classroom as much as possible. An epoxy flooring was poured over the concrete slab to provide a surface comparable to the linoleum found in most schools. The room was also outfitted with whiteboards, desks, tables, and chairs to mimic the appearance of a standard classroom. A whiteboard was used as a substitute for the front video monitor, and the areas corresponding to the two video monitors at the back of the room are simulated by blue tape. Pictures of a group of lighting professionals visiting the demonstration site are given in **Figure 4.17** with the lighting system set to warm white and cool white settings. A composite picture of the demonstration room tuned to 6,500 K, 3,500 K, and 2,700 K is given in **Figure 4.18**.

Figure 4.17 Picture of a Tour of Lighting Professional at the Finished NICLS Technology Demonstration Site.

Figure 4.18 Composite Picture of the Completed NICLS Technology Demonstration Site Tuned to Three Different CCT values.

A DMX control system was installed at the demonstrate site to operate the NICLS fixtures. The control system operates all the NICLS troffers and wall wash luminaires and can be accessed through a UI mounted on the wall at the front of the classroom or through a wireless application on a smart phone. The UI is configured so that the troffers can be controlled independently of the wall wash luminaires. In addition, the luminaires in different parts of the room can be turned off when needed. For example, the front luminaires can be turned off during a video presentation to eliminate glare on the video monitor. It addition to this level of control, sensors for daylight dimming and occupancy are incorporated into the control system. The daylight harvesting sensors automatically dim two zones of luminaires nearest the window if natural sunlight is streaming into the room. The occupancy sensor will turn off the luminaires in the NICLS demonstration site after a pre-determined period of time. The system is connected using standard cables providing a plug-and-play feature that greatly simplifies installation and can reduce installation costs. A schematic of the control system architecture is given in **Figure 4.19**.

Figure 4.19 Schematic Diagram of the Control System Used in the NICLS Technology Demonstration Site.



4.C Task 3: NICLS Technology Performance Validation

4.C.1 Third-party Testing of NICLS Luminaires

To verify the performance of the NICLS luminaires, third-party LM-79-08 testing [28] was performed by ITL in Boulder, CO. The tested luminaire was a 2×4 device with 320 warm white LEDs and 320 cool white LEDs. The luminaire was tested in a vertical base-up configuration with the FineTune power control system shown in Figure 4.19 connected to a UI. The use of the full control system allowed the luminous efficacy of the entire system to be measured and the dimming level and CCT values to be set so that measurements could be collected at different settings. The dimming level was set to the "Max" value throughout testing, and the CCT level was set to one of the four preset values (2700, 3500, 4500, and 6500). The universal driver was operated at either 120 V or 277 V during testing. Operating the universal power supply at 277 V reduces the luminous efficacy by approximately 4 lpw at all CCT values. Data were collected at a distance of 35 feet using a goniophotometer.

The measured values obtained by the third-party test laboratory are given in **Table 4.8** for the four measured preset CCT values. During the initial test of the luminaire, the luminous efficacy for the 2,700 setting was below the 120-lpw threshold, whereas the measurements at higher CCT values were above this requirement. After the initial test, the luminaire was reconfigured with the latest generation of warm white LEDs toward the end of the project and retested at the 2,700 K setting only. In this instance, the luminous efficacy at the 2700 setting rose to 128.6 lpw. Because the measured luminous efficacies of both primary LEDs were now above 125 lpw, the luminous efficacy for the NICLS system was assumed to be above 125 lpw at all settings. In Table 4.8, to save testing costs, the luminous efficacy at intermediate settings was not remeasured with the newer LEDs because it had already been demonstrated to exceed the project goal.

Table 4.8 Photometric Properties of the NICLS TWL System as Measured by an Indpendent Third-party Test Laboratory

CCT Setting (K)	Power (W)	Luminous Flux (lm)	Luminous Efficacy (lpw)	Power Factor	Current THD (%) at 120 V
2,700 – retest	50.3	6,471	128.6	0.997	6.0
2,700 – first test	51.8	5,856	113.1	0.997	6.0
3,500	48.0	5,799	120.8	0.995	5.9
4,500	46.6	5,852	125.6	0.993	5.9
6,500	52.6	6,579	125.1	0.993	6.0

THD = total harmonic distortion

The radiation pattern of the luminaire was also measured at each preset CCT value, and the findings are given in **Table 4.9**. The radiation pattern from the luminaire is exceptionally consistent, and there was virtually no change as the CCT value was changed. As might be expected, the luminaire beam angle, measured at the 50% point for luminous flux, changed by only 0.8° as the CCT setting of the luminaire was changed, with the lowest beam angle (101.6°) measured for the 2,700 K setting and the highest beam angle (102.4°) measured for the 6,500 K setting.

Table 4.9 Luminous Flux Percentage Distribution for NICLS 2×4 Troffer as Measured by an Independent Third-party Test Laboratory

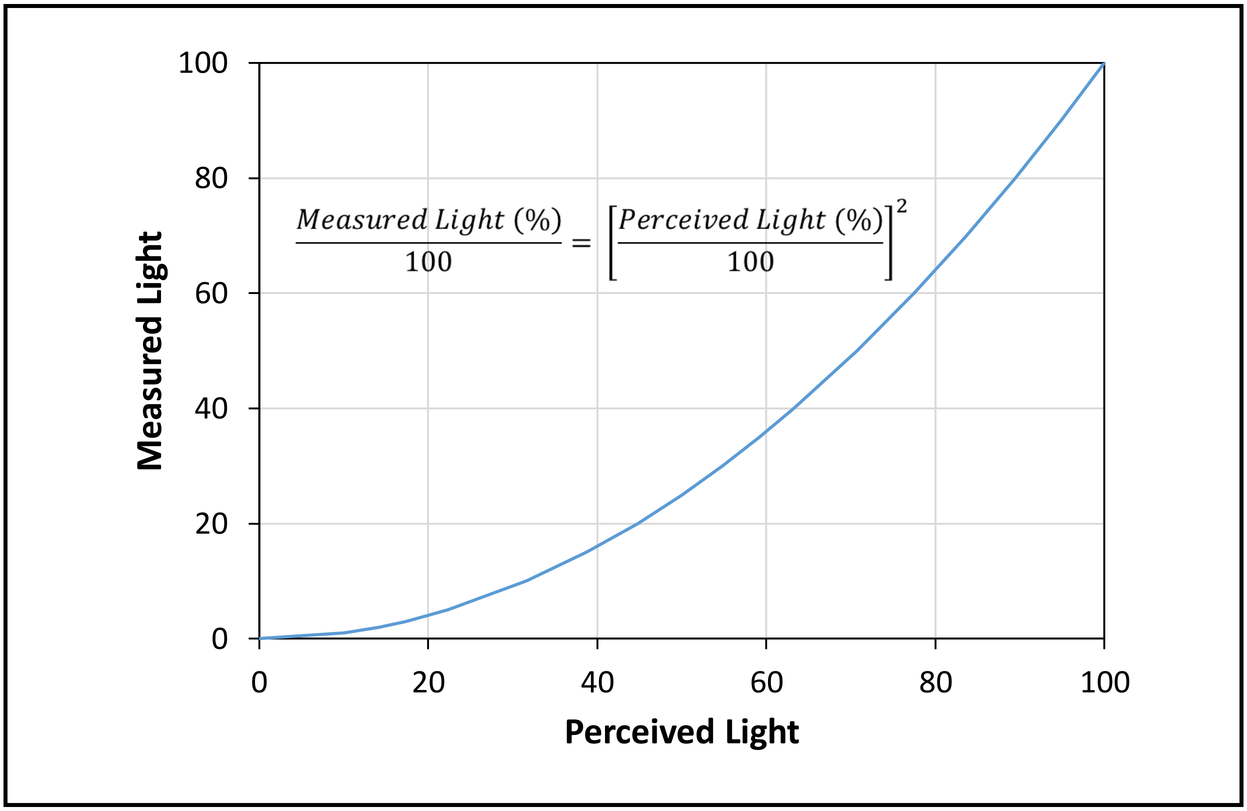
CCT Setting (K)	0°–30° Zone	0°–40° Zone	0°–60° Zone	0°–90° Zone
2,700 – retest	30.2%	48.5%	81.6%	100.0%
2,700 – first test	30.2%	48.5%	81.6%	100.0%
3,500	30.2%	48.4%	81.6%	100.0%
4,500	30.1%	48.4%	81.6%	100.0%
6,500	30.0%	48.2%	81.5%	100.0%

These independent test results confirm that the NICLS luminaires can exceed the 125-lpw threshold at both primary LED settings and should also exceed this value at all intermediate CCT values. The luminous efficacy values in this test of the NICLS technology were measured at the system level (i.e., luminaire + power control center + UI) and provide a total system perspective, not just the luminaire perspective. In addition to this excellent energy efficiency, the drivers used in the NICLS technology exhibit very high power factors (> 0.99) and minimal THD (< 7%). A scan of the luminous efficacy of the troffers listed on the Energy Star database shows that only 9.7% of the fixed CCT luminaires exhibit a luminous efficacy of 125 lpw or higher at any CCT value, and these results were recorded at the luminaire level only [6]. These test results demonstrate that the NICLS technology can exceed this threshold at the system level (i.e., luminaire + power control center + UI) and provide TWL at any CCT value with this level of efficacy or higher.

4.C.2 Commissioning of the Technology Demonstration Site

When commissioning a lighting installation with dimming capability, it is important to consider the perceived brightness of a light source compared to the measured illuminance. The human eye responds to a reduction in light levels by enlarging the pupil, allowing more lighting to enter the eye. Consequently, there is a significant difference in the perceived and measured brightness of an installation. Because a wider pupil increases the light impinging on the retina, a dimmer source will be perceived to be brighter than its measured illuminance value [29]. In general, there is a square root dependence of perceived lighting upon the actual illuminance level measured with an illuminance meter, as shown in **Figure 4.20**. The drivers used in the NICLS technology demonstration site are programmed to deliver the desired level of perceived light, which results in added energy savings because less power is required. For example, at the 75% dimming level, the perceived light level is 75% of the initial level, but the power consumption is only 56% of the initial level. As another example, the 50% dimming level can be realized with only 25% of the initial power consumption.

Figure 4.20 Comparison of Perceived and Measured Lighting Levels

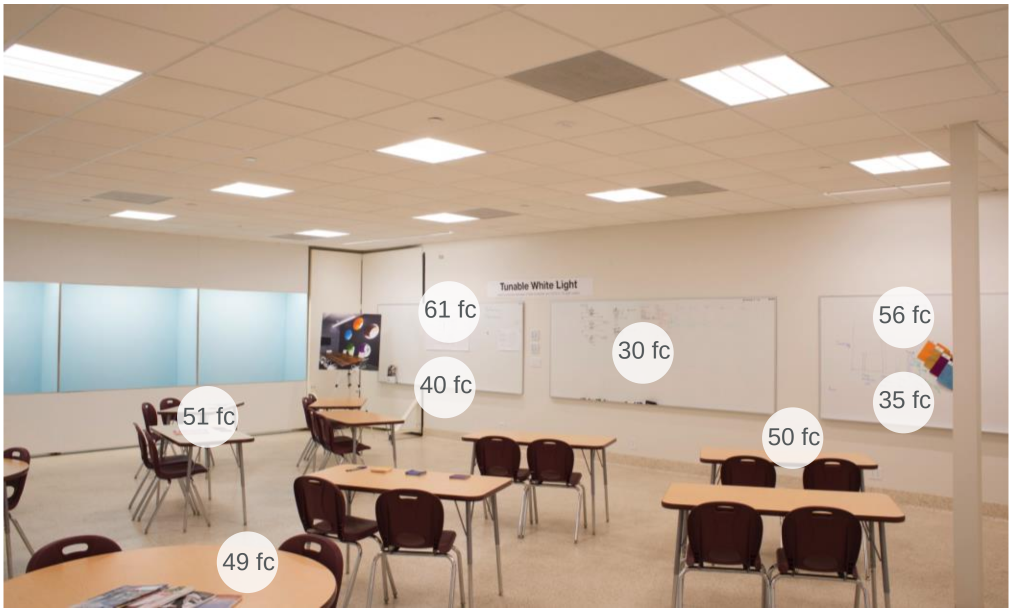


$$\frac{Measured\ Light\ (\%)}{100} = \left[\frac{Perceived\ Light\ (\%)}{100}\right]^2$$

Source: Reference [29].

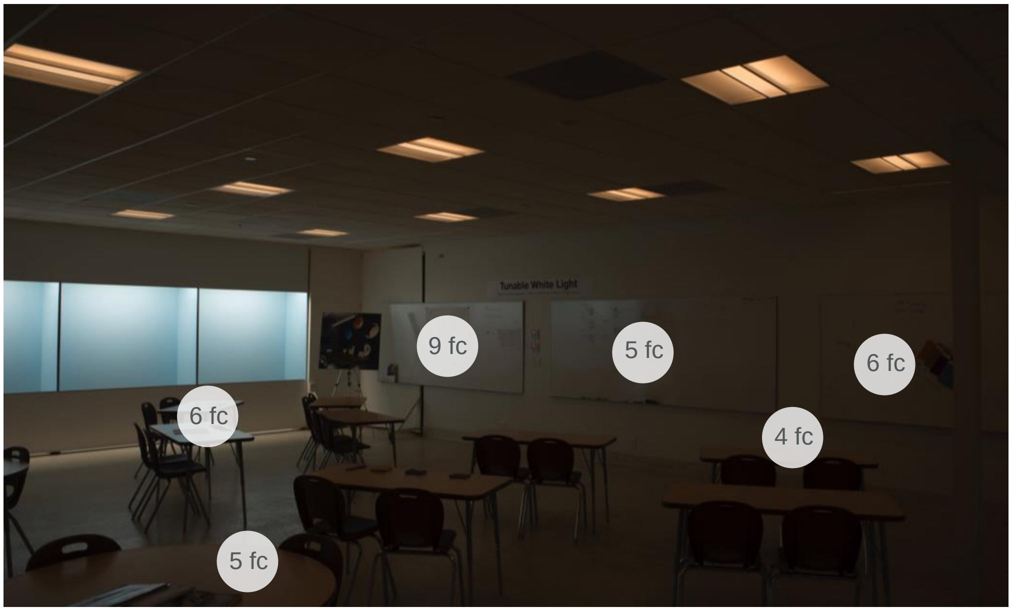
Initial photometric measurements at the field demonstration site were taken using a spectrometric illuminance meter at a variety of NICLS system settings. **Figure 4.21** demonstrates that measurements taken at 4,250 K and 75% dimming for the ceiling luminaires show a consistent illuminance of approximately 50 fc across the room. This level of performance exceeds the DOE goals for general lighting (Table 4.2) and was achieved with a system-level energy consumption of only 0.46 watts/ft^2. In addition to exceeding the DOE goals for this project, this level of performance is well below the maximum guidelines set by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 90.1 and California Title 24 by 50% or more [30; 31]. The measured illuminance levels at the locations indicated in Figure 4.21 are also higher than the values calculated for the technology demonstration site using AGi32, which were typically in the 42 to 48 lux range. The higher measured illuminance is likely attributable to the greater floor reflectance in the field demonstration site than assumed in the calculations. Analogous measurements taken at a 10% dimming level for the ceiling luminaires and a CCT value of 2,700 K are shown in **Figure 4.22**. Even at this low dimming level, the measured illuminance values are better than the DOE goals for this project (Table 4.2), and this level of performance was achieved using only 0.007 W/ft^2 of energy.

Figure 4.21 Illuminance Measurements and Energy Consumption at the 75% Dimming Level for Ceiling Luminaires and 100% Dimming Level for Whiteboard Luminaires



CCT 4250K / Ceiling .27 W/sq ft at 75% / Whiteboard .19 W/sq ft at 100% / Total: .46 W/sq ft

Figure 4.22 Illuminance Measurements and Energy Consumption at the 10% Dimming Level (Ceiling Luminaires Only) in the Demonstration Site for the NICLS Technology



CCT 2700K / Ceiling .005 W/sq ft at 10% / Whiteboard .002 at 10% / Total: .007 W/sq ft

The lighting power density (LPD) of the NICLS system was examined for various dimming settings for the 2×2 troffers in the ceiling and the wall wash luminaires for the whiteboards. To perform these measurements, the CCT settings for the ceiling and wall wash luminaires were set to the same value to reduce the number of experimental variables. In practice, they can be adjusted independently. As shown in **Table 4.10**, the LPD value across the NICLS technology demonstration site was exceptional and varied from 0.67 W/ft^2 at the maximum setting to less than 0.01 W/ft^2 at the lowest setting.

Table 4.10 System-level LPD Values for Different Settings of the NICLS Technology in the Demonstration Site

CCT Setting (K)	Ceiling Dimming Level	Whiteboard Dimming Level	Total LPD (W/ft^2)
6,500	100%	100%	0.67
5,450	80%	100%	0.50
4,250	80%	100%	0.50
3,750	60%	50%	0.22
3,750	30%	Off	0.04
2,700	10%	10%	0.007

Because photometric flicker can also be an important issue in a lighting installation, the flicker levels in the NICLS technology demonstration site were measured using a handheld flicker meter. The device used for this analysis was a GigaHertz-Optik BiTec Sensor Luxmeter (Model BTS256-EF, Giga-Hertz Optik USA, Amesbury, MA). This instrument contains a cosine diffuser on the light input and two different photodetectors behind the light diffuser. A silicon photodiode is used to measure total illuminance levels, and a complementary metal-oxide semiconductor diode array spectrometer is used to measure the spectral content. Because both sensors perform their measurements in the same field of view of the same light source, they can be used for mutual correction, which increases the accuracy of the measurement [32]. As noted in a previous report by DOE, this device is one of the few handheld flicker meters available but has some limitations in performance at low illuminance levels [33]. We have found that illuminance levels below 200 lux can lead to some distortions in the SPD, which impacts the calculated photometric properties. For desktop measurements (i.e., at approximately 30” AFF), this corresponds to a dimming level of 50%.

During the initial analysis of the room, the photometric flicker meter was placed at various locations, and measurements were recorded using a laptop computer connected to the meter. Most of the measurements were taken in the center of the room, but some measurements, especially of the wall wash luminaires, were taken around the perimeter. The findings taken at the center of the room on two different days are given in **Table 4.11**. The measured CCT values are generally lower than the setting, and we attribute this finding to light absorption from the fixtures in the room. In addition, there were also slight variations in illuminance measurements and CCT values between different days, which we attribute to experimental variations.

Table 4.11 Illuminance and Photometric Flicker Measurements Taken at Desk Height in the Center of the NICLS Demonstration Site

Date	Room Setting		Whiteboard		Measured Values				
	CCT (K)	Intensity	CCT (K)	Intensity	Illuminance (lux)	CCT (K)	Flicker Freq. (Hz)	Flicker (%)	Flicker Index
Sep-16	2,700	100	2,700	100	940	2,672	299	1.5	0.0041
Jul-16	2,700	100	off	off	905	2,652	301	1.9	0.0037
Sep-16	2,700	75	off	off	428	2,641	304	3.7	0.0075
Jul-16	2,700	75	off	off	466	2,630	300	3.0	0.0065
Sep-16	4,000	100	4,000	100	899	3,634	300	3.4	0.0080
Jul-16	4,000	100	off	off	855	3,651	235	1.9	0.0032
Jul-16	4,000	75	off	off	521	3,676	1552	7.8	0.0132
Sep-16	6,500	100	6,500	100	1014	5,864	301	1.7	0.0039
Sep-16	6,500	100	off	off	927	5,954	294	2.1	0.0039
Jul-16	6,500	100	off	off	964	5,990	301	2.3	0.0055
Jul-16	6,500	75	off	off	503	5,906	301	2.7	0.0046

To measure the wall wash luminaires, the flicker meter was placed on top of a 6-foot ladder, and spectra were recorded. For this measurement, a CCT value of 4,000 K was chosen as the setting, and three dimming levels were recorded. The driver used in the demonstration site adjusted the modulation frequency dynamically to achieve optimal energy efficiency and eliminate visible flicker. This driver technology has a lower modulation frequency at the 100% dimming setting (typically around 300 Hz), and the frequency shifts to a higher value as the luminaire is dimmed. According to IEEE 1789 guidelines, % flicker values as high as 20% are acceptable for photometric flicker frequencies of 300 Hz, and % flicker value of up to 100% are acceptable if the photometric flicker frequency is above 1,440 Hz because such high-frequency photometric variations are not detected by humans. This change-over to higher-frequency modulation in the driver occurs at approximately the 75% dimming level for intermediate CCT values (i.e., CCT values requiring both warm white and cool white LEDs). However, this transition to higher modulation frequencies does not occur for the primary LEDs until a slightly lower dimming level is reached. This fact can be seen in Table 4-11 and

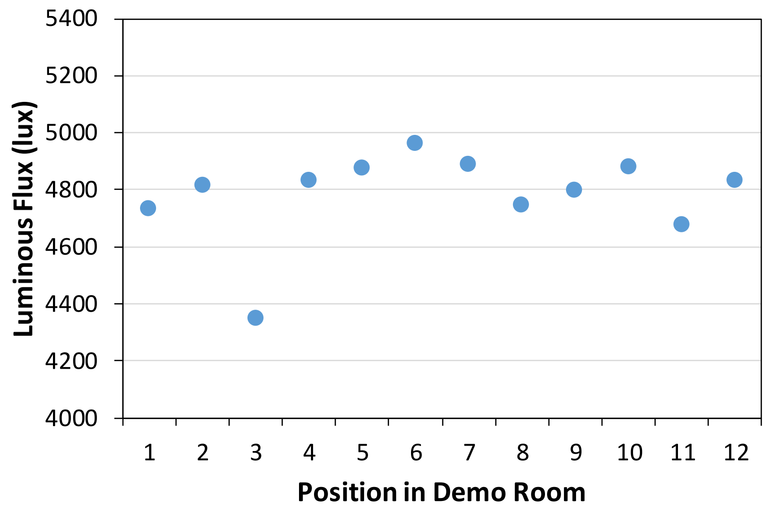
Table 4-12, where the flicker frequencies at 2,700 K and 6,500 K remain near 300 Hz at the 75% dimming level but jump to higher frequencies for the 4,000 K setting.

Table 4.12 Illuminance and Photometric Flicker Measurements Taken at 6-Feet AFF in the Center of the NICLS Demonstration Site

Whiteboard Setting		Measured Values				
CCT (K)	**Intensity**	**Illuminance**	**CCT (K)**	**Flicker Freq. (Hz)**	**Flicker %**	**Flicker Index**
4,000	100%	768	3,867	256	4.4	0.0033
4,000	75%	481	3,835	2,207	29.4	0.0701
4,000	50%	247	3,776	1,136	48.7	0.0661

To investigate the performance of the luminaires in the demonstration site, illuminance and photometric flicker measurements were also taken on the individual luminaires. To accommodate these measurements, individual luminaires were measured with a sampling cone of approximately 36 inches in length that was made of coil-coated metal. This sampling method allowed each luminaire to be measured individually with minimal interference from neighboring fixtures. In addition, because the distance between the luminaire and the meter was smaller in the setup, the entire dimming range can be studied in this arrangement. The illuminance levels of all 12 troffers in the NICLS technology demonstrate site were measured at the 50% dimming level, and the measured luminous flux levels are shown in **Figure 4.23**. The average illuminance was 4,783 lux at 50% dimming with a standard deviation of ±157 lux and a coefficient of variation (COV) of 3.3%. One luminaire, #3, was found to exhibit a lower illuminance than the others; otherwise, the standard deviation and COV values would have been even smaller.

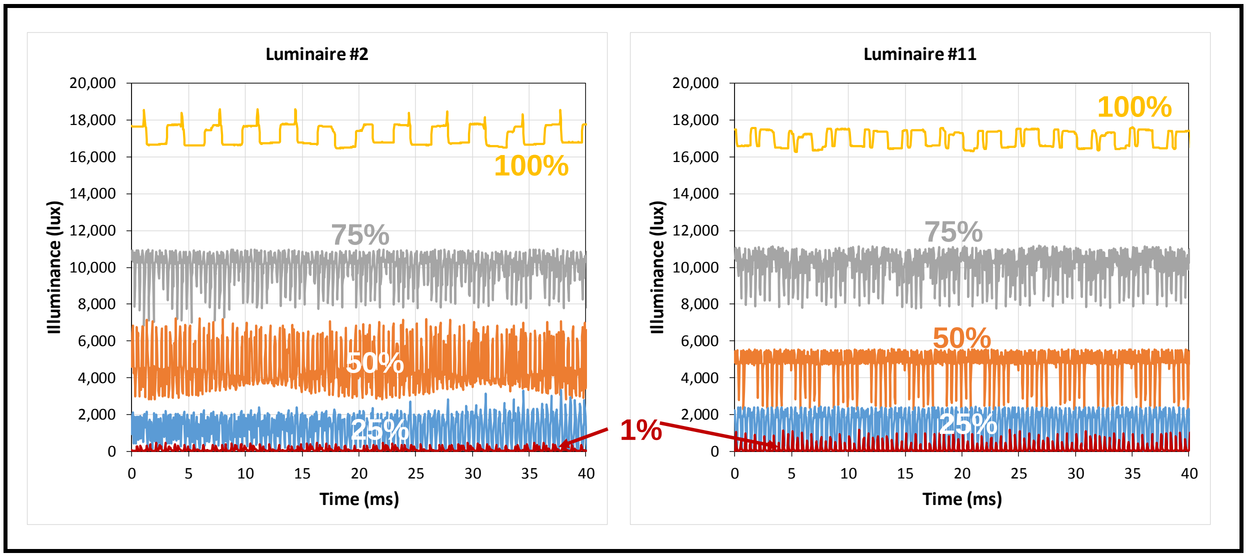
Figure 4.23 Variation in Luminous Flux at the 50% Dimming Level for NICLS Troffers in the Demonstration Site



NOTE: Troffer #1 is in the upper left-hand corner of the room (near the simulated windows), and the troffers are numbered sequentially from left to right across the room. Troffers #1, #5, and #9 are near the simulated windows.

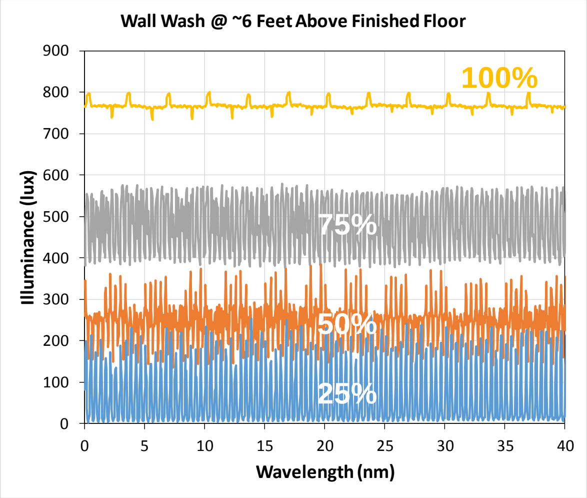
The photometric flicker waveforms for luminaires in the demonstration site were also analyzed. Because of the variety of settings, this analysis concentrated on two troffers (#2 and #11) and one wall wash luminaire (located near troffer #4). The photometric flicker waveforms for the two troffers are given in **Figure 4.24** and in **Figure 4.25** for the wall wash luminaire. As mentioned above, the driver used at the demonstration site employs a dynamic algorithm for the power supplied to the LEDs. This algorithm changes constantly, even at the same dimming level, based on a variety of factors, including current, power consumption, dimming level, and temperature. Low-frequency (~ 300 Hz) modulation is applied to the LEDs at full power (i.e., 100% dimming/illuminance level) and is clearly visible in Figure 4.24 and Figure 4.25. Although the waveforms are different, the frequency is approximately the same. The % flicker was found to be below 2% in instances where only one of the LED assemblies was run at full power and is slightly higher when both LEDs are used in conjunction with a 100% setting at any CCT value. At approximately 75% dimming/illuminance levels, the power supply transitions to a high-frequency (~ 2,400 Hz) modulation of variable amplitude. In this case, the % flicker varied between 20% and 98% depending on the dimming/illuminance level, with higher percentages measured for lower dimming levels. Because the flicker frequency is above 1,000 Hz under these conditions, the human eye does not respond to the illuminance variations, and such devices are deemed acceptable under IEEE 1789 guidelines.

Figure 4.24 Photometric Flicker Waveforms for Luminaires #2 and #11 in the NICLS Technology Demonstration Site



NOTE: Measurements were taken with the aid of a collection cone. The luminaire was set to a CCT value of 4,000 K for all measurements.

Figure 4.25 Photometric Flicker Waveform for a Wall Wash Luminaire in the NICLS Technology Demonstration Site



NOTE: Measurements were taken at the top of a 6-foot ladder with the overhead luminaires turned off. The luminaire was set to a CCT value of 4,000 K for all measurements. The wall wash luminaire chosen for this analysis was near troffer #4.

In summary, the commissioning of the luminaires in the NICLS technology demonstration site confirmed the high luminous efficacy of this technology and the outstanding energy savings that will be achieved as a result. The illuminance produced by each luminaire was very consistent with a COV of 3.3% across the dozen luminaires installed in the room. The photometric flicker performance was well within IEEE 1789 requirements for the flicker frequency, % flicker, and flicker index at all levels of dimming. Based on this analysis, the NICLS technology installed in the technology demonstration site can be judged to meet and, in most cases, exceed the photometric and electrical performance requirements established by DOE for this project.

4.C.3 Accelerated Testing of NICLS TWL LED Modules

Motivation for AST

The average age of public schools in the United States is 44 years, and major renovations of the average public school occur approximately every 20 years and may or may not include an upgrade of the lighting system [2]. The widely held dissatisfaction with lighting in schools [2] combined with the rise of high-reliability SSL technologies is likely to accelerate new investment in school lighting during the next decade. However, because SSL technologies are a relatively new approach to general lighting, greater performance is expected of these systems, and they must overcome the shortcomings of traditional lighting technologies to gain market share. For example, given the higher reliability of SSL technologies, many schools expect a new SSL system to last for more than 20 years with minimal maintenance.

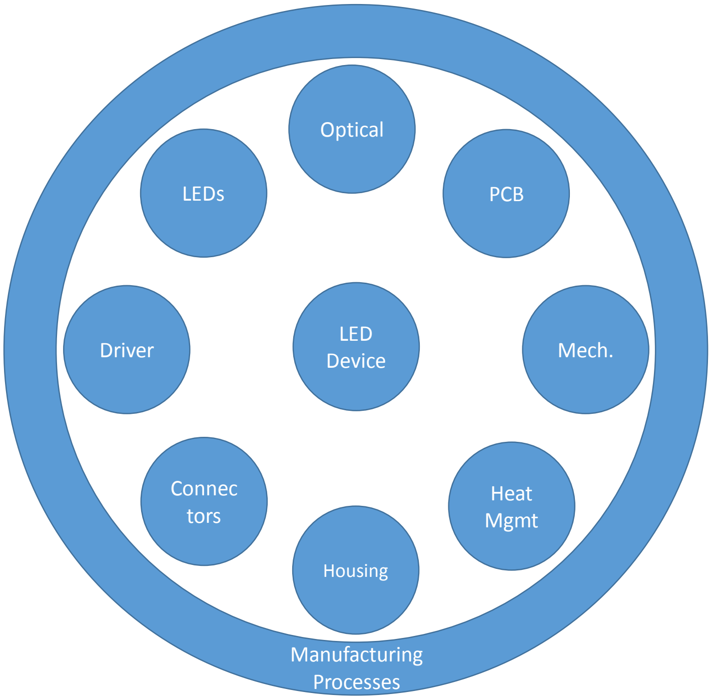
Determining upfront whether a product will last for 20 years or more requires simulating the long-term use of the light system through accelerated aging in a laboratory. To provide a basis for this type of testing, a panel of experts was convened by DOE and the Next Generation Lighting Industry Alliance (NGLIA) to form the LED Systems Reliability Consortium (LSRC). The goal of the LSRC is to provide guidance to the lighting industry on key issues concerning the reliability of SSL technologies. Many of these potential reliability issues (e.g., lumen maintenance, chromaticity shifts of light sources, and failure of electronics) are well known in conventional lighting technologies and are tolerated because of regular maintenance, including periodic lamp and ballast replacement (e.g., relamping) and the minimalistic view of current lighting technologies. However, as evidence continues to grow that lighting systems can provide a variety of benefits in the classroom, increased attention will be paid to the long-term performance of any SSL technologies that are used. In particular, SSL systems will be expected to perform with higher reliability than conventional lighting technologies, and failure modes, such as lumen maintenance, color shift, and electronics reliability, will increase in importance when lighting systems are operated for 20–30 years with minimal maintenance [21].

The LSRC published a list of differences between conventional lighting technologies and SSL technology to provide the lighting industry, including manufacturers, designers, specifiers, and users, with additional information for evaluating LED lighting systems [34]. Several key points of difference highlighted by the LSRC are as follows:

- For LED luminaires, the end of life may involve a gradual reduction in luminous flux, and thus, lumen maintenance is important.
- Because the lifetime of LEDs operated under proper conditions is generally long, the LED luminaire may fail before the light source. Therefore, many SSL technologies have the light source integrated into the housing, making "relamping" more difficult than with traditional lighting technologies.
- Overstress testing of SSL devices is useful for identifying design flaws and manufacturing defects.

Recently, the LSRC published another document to provide guidance to the lighting industry on color shift in SSL devices [35]. The LSRC continues to advise that a holistic systems approach is needed to evaluate the reliability of SSL devices for any possible failure mode. Such a systems approach includes not only the LEDs but also the luminaire optics, driver electronics, PCBs, and other system components, as shown in **Figure 4.26**.

Figure 4.26 The Long-term Reliability of the NICLS Luminaire is Dependent on the Reliability of Each System Component

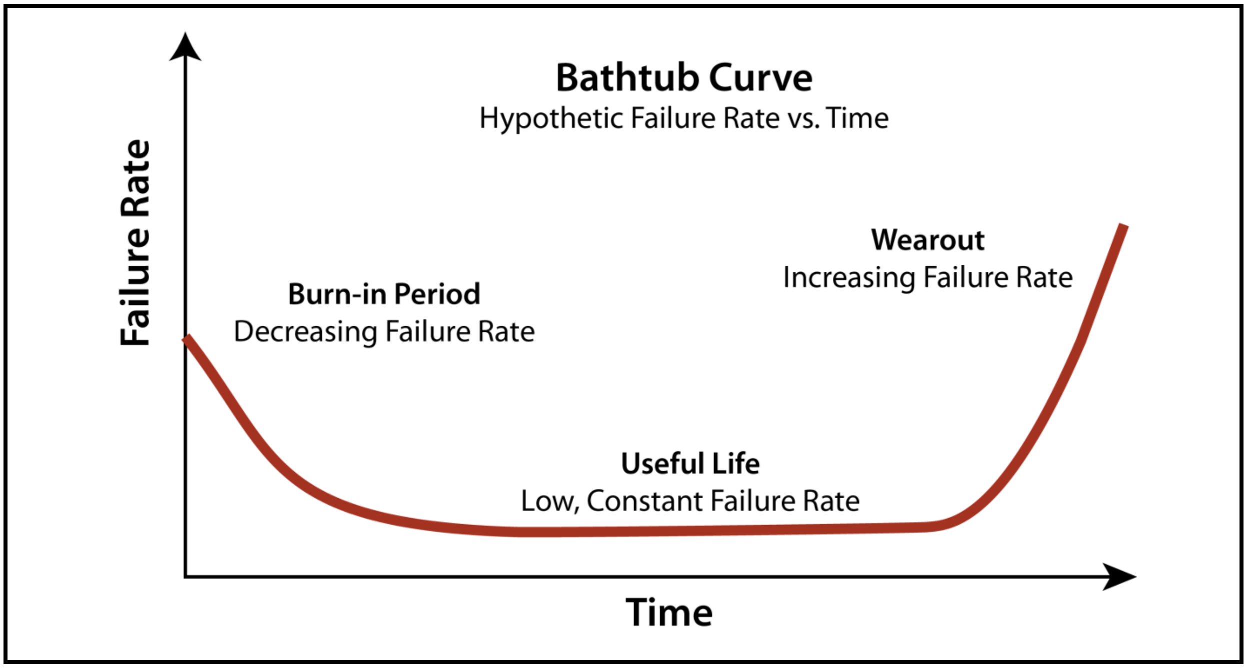


Note: PCB = printed circuit board, Mech. = mechanical, Heat Mgmt = heat management

Source: Reference [34].

AST is widely used in the electronics industry to accelerate failure in electronics devices. All products will fail over time, but some fraction of a sample population will fail quickly, while others will take longer to fail. The failure rate of a population of a product can be described with a hazard function, such as the bathtub curve shown in **Figure 4.27**. Failure in this context can be an abrupt failure, where the device no longer produces light, or a parametric failure, where an operational parameter of the lighting device (e.g., lumen maintenance or color stability) falls outside of an accepted range. In this approach to product reliability, a portion of the population contains latent defects and will fail quickly during the short burn-in stage when a device is first turned on. Fortunately, these early failures are sorted out quickly, and the remaining population enters a region of normal operation that is typically characterized by a long duration with a nearly constant failure rate. As the usage time for the population grows, parts begin to wear out, and the failure rate increases. The primary goal of AST protocols is to select experimental conditions that will shorten the useful life stage of a device and produce device wear-out in a time convenient for laboratory testing. Depending on the type of information sought, this laboratory period can vary from several weeks to several months.

Figure 4.27 Product Hazard Function as Represented by a Bathtub Curve



With a goal of understanding the mechanisms responsible for both abrupt and parametric failures of SSL devices, DOE tasked RTI with examining the failure modes of SSL devices, creating models to describe device failure, and developing test methods for accelerating failure. In this work, RTI extensively studied the failure modes occurring in SSL devices and, by leveraging this knowledge, developed experimental protocols to accelerate device wear-out. For properly designed experiments, these accelerated tests can be correlated with normal operational conditions through the acceleration factor (AF) of the experiment. In essence, the AF provides a measure of how much faster a device fails in the accelerated conditions compared to normal operating conditions. The findings from this work performed by RTI are given in the project report [36].

Guidance provided by the LSRC and confirmed experimentally by RTI shows that the accelerated aging of SSL devices or components can be achieved by subjecting the device under test (DUT) to a higher level of environmental stress than is commonly encountered in normal operation. Typical environmental stresses that are used to accelerate aging include temperature (both high and low), humidity, dust, vibration, and electrical transients. For indoor luminaires, elevated ambient temperatures are an accepted approach to accelerate aging because the chemical kinetics associated with aging processes, such as lumen depreciation and color shift, have a temperature-dependent component [36]. This is consistent with the general rule of thumb, often taught in freshman chemistry classes, that for every 10°C increase in temperature, the reaction rate doubles. This rule of thumb is derived from the Arrhenius equation, which can be used to calculate the AF value of a temperature-dependent process [37]. Clearly, the goal of any accelerated test is to speed up the degradation reaction without causing new reactions or failure mechanisms to occur.

Consequently, excessive environmental conditions should be avoided in any AST protocol, and that guidance was followed in testing the NICLS devices.

To understand the long-term performance of the NICLS technology, RTI and Finelite divided the testing of the NICLS technology into major components, as suggested by the LSRC (Figure 4.26). Previous testing of the polymethyl methacrylate lens material and the high-performance paint used as reflector and housing finishes has demonstrated that these materials will change little during use [36]. Consequently, this study focused on the LEDs and driver. Another advantage of addressing this issue at the major component level is that LED components are smaller than the LED system, occupy less space in test chambers, and are less expensive to test in larger numbers. Consequently, the discussion that follows concentrates on the lumen and chromaticity maintenance behavior of the NICLS TWL LED modules and the electronic performance of the two-stage multi-channel drivers used in the NICLS system. Luminaire-level tests were conducted at an independent test laboratory (as described in Sections 4.C.1 and 4.C.2) and in the technology demonstration site. These tests provide an initial benchmark of performance for comparison with the accelerated tests.

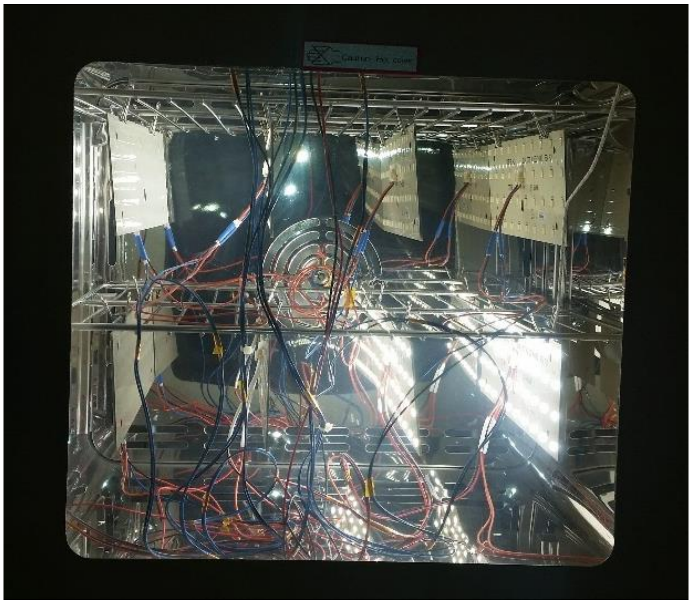
Lumen Maintenance Testing

MP-LEDs are widely used in LED lamps, modules, and luminaires that are mainly intended for indoor use. As part of our work on the reliability of LED devices, RTI has analyzed more than 250 LM-80 reports from major LED manufacturers. Included in this analysis are 95 different datasets for MP-LEDs [36]. Our analysis has concluded that the lumen maintenance decay rate constants (α) are generally higher for MP-LEDs than for high-power LEDs (HP-LED) and chip-on-board LED packages. In addition, the combined influence of temperature and current plays a major role in lumen and chromaticity maintenance for MP-LEDs and other LED packages [36; 38; 39; 40]. Independent studies performed at Padua University and Delft University of Technology (TU-Delft) have also reached the same conclusions. The Padua University study demonstrated that the aging characteristics of four different commercial MP-LEDs increase in a nearly linear fashion with ambient temperature over a large temperature range (45°C to at least 105°C) [41]. The studies performed at TU-Delft also confirmed thermally activated degradation mechanisms for MP-LEDs and indicated that high-temperature operational life (HTOL) testing and wet HOTL (WHOTL) testing are appropriate acceleration test procedures for MP-LEDs [42].

The degradation of the polymeric molding compound and encapsulants used in the MP-LED package is believed to be a leading cause of luminous flux loss and chromaticity shifts in this package [38; 39; 40; 43; 44]. As these polymer materials age, they begin to absorb portions of the visible light produced by the LED, resulting in a drop in the luminous flux and a shift in the chromaticity. These reactions appear to occur only in the presence of both high temperature and high-energy photons (i.e., blue or ultraviolet photons), which likely accounts for the observed dependences on temperature and forward current. These dependences are especially strong if the molding resin is a nylon-based material, such as polyphthalamide, which is used in many MP-LED packages. Newer molding resins, such as epoxy molding compound and silicone molding compound, are more resistant to these degradation pathways because of their slower oxidation chemical kinetics, but this benefit results in increased LED costs [36; 38; 39; 40]. Based on research by three different independent laboratories, the conclusion can be drawn that the best approach to obtaining high lumen and chromaticity maintenance in MP-LEDs is to minimize the temperature and current of the LEDs by using many devices dispersed over large areas. This is exactly the approach used with the NICLS technology.

The previous findings of AST experiments involving MP-LEDs provide a scientific foundation for accelerated aging experiments of the NICLS TWL LED modules because of the linearity observed over wide temperature and current ranges. To understand the long-term performance of the NICLS technology, RTI conducted elevated ambient testing on a series of NICLS TWL LED modules (77798 design). During the elevated ambient testing, a group of LED modules was placed in an oven with the temperature set to either 75°C or 95°C. No humidity was intentionally introduced during these HTOL tests. The LED modules were hung vertically from metal racks using metal clips, and no additional heat sinks were applied to the boards. Four boards were hung from each metal rack, and each board irradiated the backside of its neighboring board, which was covered with white solder mask. The spacing between adjacent boards was approximately 4 inches to allow sufficient air flow to maintain thermal equilibrium during the test. A picture of the LED modules in the elevated ambient test oven is given in **Figure 4.28**, and additional details on the LED modules and their testing can be found in a paper by Davis et al. [20].

Figure 4.28 Picture of NICLS TWL LED Modules Undergoing Elevated Ambient Temperature Testing.



The LED samples were divided into four groups, and both LED assemblies on each module were operated simultaneously at one of four preselected currents: 350 mA, 700 mA, 1,000 mA, and 1,500 mA. Because the LED modules were configured with 10 parallel strings of LEDs, the actual current delivered to each LED was 1/10th of the total drive current. Both LED assemblies on a selected LED module were operated at the preset current level when in the elevated temperature environment, and separate electronics were used to provide power to each LED assembly. The modules were switched on a 1-hour-on/1-hour-off cycle, with the 700 mA and 1,000 mA samples switching together, and the 350 mA and 1,500 mA samples switching together. The LED assemblies set to 350 mA, 700 mA, and 1,000 mA were operated by dedicated single-channel LED drivers programmed to the specific, constant current level. The LED assemblies operated at 1,500 mA were controlled by two-channel laboratory power supplies.

This configuration used in RTI's experiments on NICLS TWL LED modules exposes the LEDs to both elevated ambient temperatures and elevated irradiation levels from both warm white and cool white LEDs. This approach was used to accelerate aging by maximizing the amount of environmental stress on the LED modules. In general, we found that the board temperature increased by 12–14°C relative to the elevated ambient temperature of the boards when both LED assemblies operated with a forward current of 1,500 mA (i.e., 150 mA per LED). These experimental conditions are well within the range of linear behavior demonstrated in the literature [41; 42], which ensures that the results found under accelerating conditions can be correlated to behavior in a normal operational environment.

Photometric measurements were taken at regular intervals on these boards, and 9,000 hours of data have been recorded to date. After exposure to the elevated temperature environment, each LED assembly was measured separately in a calibrated integrating sphere. Photometric testing was performed after every 500 hours of HTOL exposure up to 7,000 hours. Subsequently, photometric data were collected every 1,000 hours. During photometric testing, a forward current of 700 mA was applied to each LED assembly, corresponding to 70 mA per LED, regardless of the forward current used in the HTOL tests.

In analyzing the data, RTI developed a new approach for modeling lumen maintenance. The first step uses a procedure for determining lumen maintenance decay rate constants, which is derived from the traditional TM-21-11 method [45], and the second step uses the data acquired for a particular CCT value to calculate the relationship between α, temperature, and forward current using linear bivariate regression. In calculating the α values, the RTI method discards the first 1,000 hours of data because many LEDs, including those used in the NICLS technology, increase in efficiency for approximately the first 1,000 hours of operation and then begin to exhibit the exponential decrease that is typical of lumen depreciation [46]. The RTI method used here still calculates the lumen maintenance decay rate constant α, but this α value is somewhat different from that calculated using the TM-21-11 method, as will be explained below. The α values calculated using the RTI method for both warm white and cool white LED assemblies at the various currents and temperatures are given in **Table 4.13**.

Table 4.13 α Values of the NICLS TWL MP-LED Modules under Different Ambient Temperatures and Forward Currents

	75°C Elevated Ambient		95°C Elevated Ambient	
Current	**Warm White**	**Cool White**	**Warm White**	**Cool White**
350 mA	2.82×10^{-6}	2.61×10^{-6}	3.98×10^{-6}	3.63×10^{-6}
700 mA	1.57×10^{-6}	3.29×10^{-6}	5.01×10^{-6}	2.34×10^{-6}
1,000 mA	6.69×10^{-6}	4.38×10^{-6}	5.49×10^{-6}	3.45×10^{-6}
1,500 mA	8.16×10^{-6}	6.44×10^{-6}	9.94×10^{-6}	8.29×10^{-6}

NOTE: These α values were calculated using the RTI lumen maintenance modeling approach, which used the data from 1,000 hours to 9,000 hours.

As noted above, the RTI approach used here to calculate the lumen maintenance decay rate constant (α) differs from the TM-21-11 method [45] in two ways. First, in the RTI method, data taken between 1,000 and 9,000 hours were used to build the model for lumen maintenance for the NICLS TWL LED modules. In contrast, the TM-21-11 method would only use the data taken between 4,000 and 9,000 hours, which places greater emphasis on the most recent part of the lumen maintenance curve. As a result, the α values calculated using TM-21-11 will be smaller than those calculated with the RTI method; thus, the lumen maintenance will be longer with the traditional TM-21-11 approach. The second difference is that the RTI method uses all data acquired between 1,000 and 9,000 hours, whereas the TM-21-11 method requires data taken at regular intervals so only the data taken at 1,000-hour increments are used. Taken together, these differences indicate that the RTI method is more conservative than the TM-21-11 method and will produce higher α values.

The second step in the RTI method is to calculate the dependence of α on ambient temperature and forward current. Separate linear regression models were calculated for the warm white and cool white LEDs, and the results are shown in **Table 4.14** and **Table 4.15**, respectively. Based on this analysis, the lumen maintenance of the cool white and warm white LEDs in the NICLS TWL LED module is clearly dependent on both temperature and current. This finding has significant implications for TWL systems. First, the way to achieve high lumen maintenance in such a system is to minimize the current and ambient temperature for the LED. A second implication is that the lumen maintenance of a TWL system will depend upon the use profile. Therefore, system settings, such as the dimming level and chosen CCT value, will impact the time for the luminous flux produced by the system to degrade to a pre-determined threshold, such as 85% of its initial value (i.e., L_{85}).

Table 4.14 Model of the Dependence of α on Temperature and Current for the NICLS Warm White LED Modules.

	Coefficient	Standard Error	Student's t Stat	p-Value
Intercept	-1.02×10^{-5}	2.21×10^{-6}	-4.64	0.006
Current	5.35×10^{-9}	5.94×10^{-10}	9.01	< 0.001
Temperature	1.57×10^{-7}	2.50×10^{-8}	6.27	0.002
R^2		0.960		
F Test		60.23		
Equation	$\alpha = (5.35 \times 10^{-9})(\text{Current}) + (1.57 \times 10^{-7})(\text{Temp.}) - 1.02 \times 10^{-5}$			

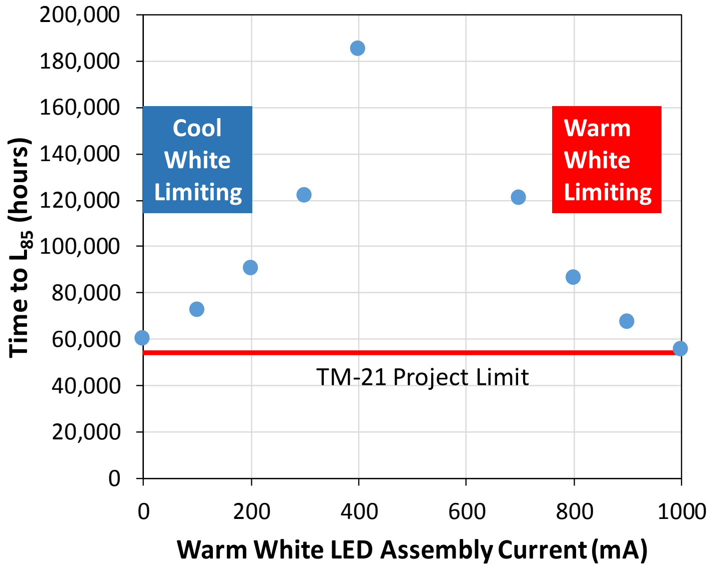
Table 4.15 Model of the Dependence of α on Temperature and Current for the NICLS Cool White LED Modules.

	Coefficient	Standard Error	Student's t Stat	p-Value
Intercept	-8.01×10^{-6}	3.71×10^{-6}	-2.16	0.083
Current	4.58×10^{-9}	9.97×10^{-10}	4.59	0.006
Temperature	1.23×10^{-7}	4.21×10^{-8}	2.92	0.033
R^2		0.856		
F Test		14.82		
Equation	$\alpha = (4.58 \times 10^{-9})(\text{Current}) + (1.23 \times 10^{-7})(\text{Temp.}) - 8.01 \times 10^{-6}$			

Using these models for lumen maintenance of the warm white and cool white components of the NICLS LED modules, the expected time for the NICLS TWL system to reach L_{85} can be projected if the ambient temperature and forward current are known. The projected times for the NICLS LED modules to decay to the L_{85} level are shown in **Figure 4.29** for the case in which the ambient temperature is 50°C, and the total current supplied to the LED module is 1,000 mA. This current is split between the warm white and cool white assemblies in the LED module. Thus, if the current setting of the warm white LED assembly is 200 mA (i.e., 20 mA per individual LED), then the current supplied to the cool white LED assembly would be 800 mA (i.e., 80 mA per individual LED). The model also quantifies that the current split between the LED assemblies will affect the time required to reach L_{85}. As the current is more evenly divided between the warm white and cool white assemblies, the time to reach L_{85} increases. However, as more current is supplied to one LED assembly over the other (e.g., 900 mA to the warm white assembly and 100 mA to the cool white assembly [i.e., a 90/10 split]), the LED assembly with the higher current will determine the time to L_{85}. This calculation assumed no dimming, and if a dimming profile is included, the time to L_{85} will increase further. A key takeaway from this analysis is that the lifetime of the LED module can be significantly extended through the judicious choice of the use conditions of the TWL system.

TM-21-11 limits the projection time for future lumen maintenance values to six-times that of the experimental time, which in this case would be 54,000 hours. This time period is denoted by the solid red line in Figure 4.29. Assuming that an educational lighting system is used for 12 hours per day and 200 days per year, the 54,000-hour limit still equates to 22.5 years of use. This conservative value for lumen maintenance exceeds the goals established by DOE at the beginning of the project. Further, as discussed above and shown in Figure 4.29, the normal adjustment of the CCT values and dimming levels that occur in a TWL system will further increase the time necessary to reach L_{85}. Consequently, lumen maintenance is not likely to be an issue with the NICLS system in a properly engineered installation, and other failure modes, such as color shifts or electronics failures, need to be examined.

Figure 4.29 Estimated Time for the NICLS LED Module to Decay to L85



NOTES: The solid red line denotes the maximum projected lumen maintenance value permitted by the TM-21-11 method, and the blue circles denote the projected results obtained using the RTI method. These calculated results assumed that the ambient temperature around the LED module was 50°C and that the total current supplied to the LED module was 1,000 mA. This current is split between the warm white and cool white LED assemblies.

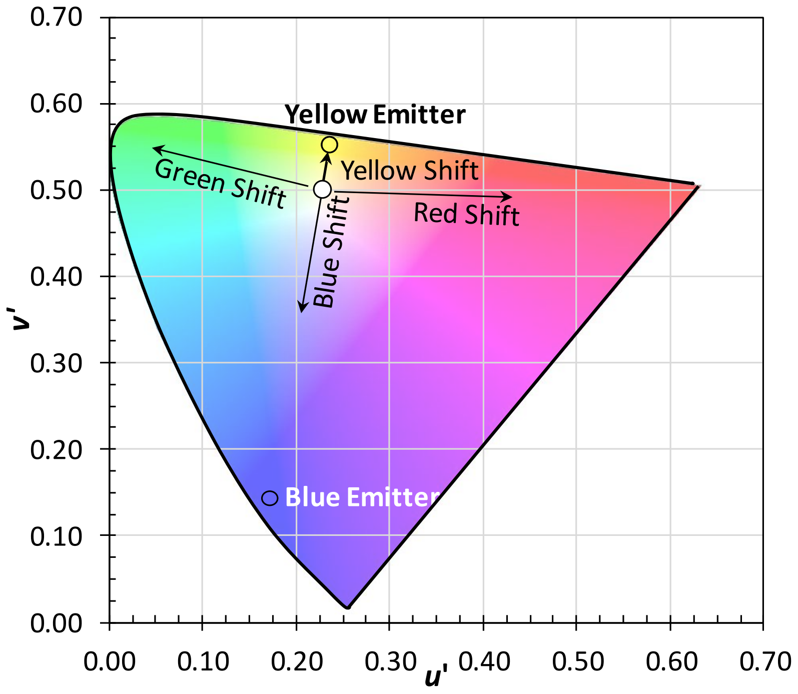
Chromaticity Stability Testing

Within the last 3 years, significant gains have been made in understanding the causes of color shifts in SSL devices. It has been demonstrated that the chromaticity changes of white light luminaires proceed in an orderly fashion and are often dominated by the behavior of the LEDs [35; 36; 39; 40; 44; 47; 48]. Technically, the chromaticity of the SSL device is changing in addition to the color, and thus, the term chromaticity shift will be used in this report instead of color shift because the illumination is white light. In addition, although a TWL system can adjust for chromaticity changes in the primary LEDs if a potentially complex feedback system is added to the controls, it is informative to focus on the chromaticity stability of the primary light sources without any compensation to gauge whether further adjustments will be needed as the system ages. Consequently, the discussion below will examine the chromaticity stabilities of the warm white and cool white MP-LEDs used in the NICLS LED modules separately. The ideal TWL system would be able to hold its chromaticity within a narrow range for an extended period and, thereby, avoid the need for complex correction algorithms and sensors.

Although the total chromaticity shift is often expressed as the distance, measured by $\Delta u'v'$, between the current chromaticity point and the original chromaticity point, $\Delta u'v'$ only provides information on the magnitude of the shift, not the direction. A significant amount of information about the causes of chromaticity shift can be gleaned by looking at the direction of the shift, which can be gauged from changes in the individual chromaticity coordinates (i.e., $\Delta u'$ and $\Delta v'$) and an examination of the SPD.

As shown in **Figure 4.30**, white light from LEDs can be produced by combining a blue-emitting LED (e.g., 450 nm) with a phosphor that emits at a nominally yellow wavelength (e.g., cerium-doped yttrium aluminum garnet phosphors). The relative amounts of blue emissions and yellow phosphor emissions produced by the white LED determines the initial chromaticity point, and any chromaticity point on the blue-yellow line can be achieved by changing the relative amounts of blue and yellow emissions. An increase in blue emissions (or a decrease in yellow emissions) produces a shift from the original chromaticity in the blue direction, and an increase in yellow emissions (or a decrease in blue emissions) produces a shift in the yellow direction. Hence, a natural linkage exists between blue and yellow chromaticity shifts.

Figure 4.30 1976 CIE Color Space Showing Different Directions of Chromaticity Shifts that Can Occur in LEDs.



Chromaticity shifts can also occur in the green and red directions; however, these shifts are not caused by changes in the relative intensity of blue and yellow emissions but also require a change in emission wavelength of the light sources. For multi-component phosphors, such a spectral change may be difficult to observe in the SPD profile because emissions occur over a broad wavelength range. Consequently, a deeper analysis of the SPD is required to understand the spectral changes responsible for chromaticity shifts [47]. Using this approach, chromaticity shifts in the green direction can usually be attributed to oxidation of the phosphor and a reduction of the emission wavelength. Chromaticity shifts in the red direction can be attributed to a quenching of green phosphor emissions, which shifts the overall emission profile [48]. In this way, red and green shifts have some similarity in that they often involve spectral changes in the phosphor.

To date, five chromaticity shift modes (CSMs) have been identified in SSL devices, such as LEDs, lamps, and luminaires [43; 47]. These CSMs can be characterized by the direction of the shift during the steady state, as shown in **Table 4.16**. For MP-LEDs, such as those used in the NICLS TWL LED modules, the chromaticity can shift in any of the major directions (i.e., blue, green, yellow, or red), although the final chromaticity shifts tend to be in the blue direction [43; 47]. CSM-4 behavior is especially prevalent with plastic leaded chip carriers, such as MP-LEDs, and has been attributed to photo-oxidation of the molding resin over time [44]. This general behavior of the chromaticity shift applies to both the warm white and cool white LEDs used in the NICLS LED module, but there are likely to be some differences in the chromaticity shift behavior between LEDs at the two CCT values because of the different phosphor mixes.

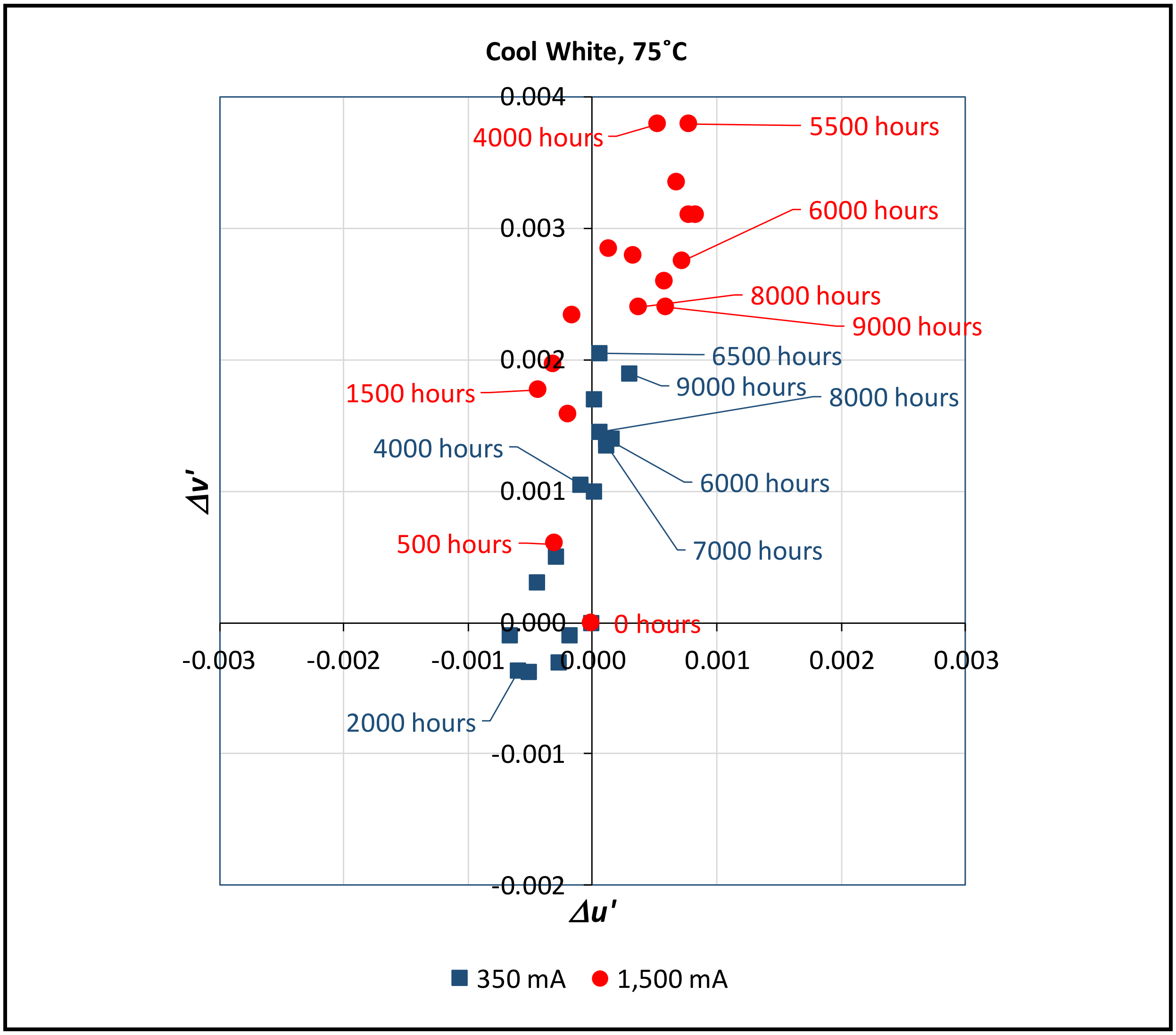
Table 4.16 Common CSMs of LED Devices and Directions of Chromaticity Shift during the Steady State.

CSM Mode	Shift Direction	Change in *u′*	Change in *v′*
1	Blue	Decrease	Decrease
2	Green	Decrease	Minimal to positive change
3	Yellow	Small increase	Larger increase
4	Yellow then blue	Decrease	Decrease
5	Red	Increase	Minimal to positive change

The measured changes in the chromaticity coordinates for the cool white LED assemblies from NICLS LED modules are given in **Figure 4.31** for devices operated at an elevated temperature of 75°C. Forward currents of 350 mA, 700 mA, 1,000 mA, and 1,500 mA were tested at these conductions, but only average data from the 350 mA and 1,000 mA measurements are shown in Figure 4.31. At a forward current of 350 mA, the chromaticity initially shifts in the blue direction (i.e., both $\Delta u'$ and $\Delta v'$ are negative). After approximately 2,000 hours, the chromaticity shift changes direction and begins moving in the yellow direction (i.e., $\Delta u'$ changes little, whereas $\Delta v'$ increases sharply). Despite these changes, the total chromaticity shift after 6,500 hours of operation exposure, as measured by $\Delta u'v'$, is only 0.002 (i.e., a 2-step MacAdam ellipse), which is well within Energy Star requirements for LED devices [49]. At this point, the chromaticity again reverses direction and shifts back toward the initial chromaticity. Relative to the chromaticity at 6,500 hours, this latest shift is in the blue direction. Based on this analysis, the chromaticity of the cool white LEDs used in the NICLS TWL LED modules initially shifts in the blue direction, exhibits a period of shifting in the yellow direction, and then begins to shift in the blue direction again. This behavior is typical of a CSM-4 shift, which is prevalent in many LEDs in molded plastic packages [43; 44; 47].

For the samples operated at a forward current of 1,500 mA, the first shift that was recorded is in the yellow direction relative to the initial chromaticity, and this shift continues until 5,500 hours of testing. At that point, the total chromaticity shift, as measured by $\Delta u'v'$, is only 0.004 (i.e., a 4-step MacAdam ellipse) with the shift occurring almost completely in the yellow direction (i.e., predominantly along the $\Delta v'$ axis). This amount of chromaticity shift is within the guidelines given by EnergyStar [49] and is acceptable for most applications. After 5,500 hours of testing at 75°C and 1,500 mA forward current, the chromaticity begins to shift in the blue direction and moves toward the initial chromaticity value. As a result, the total chromaticity shift after 9,000 hours of testing is only 0.0025, which is less than the maximum observed during this testing. Apart from the initial blue shift observed during testing at 350 mA, the chromaticity shift directions of the samples operated at 350 mA and 1,500 mA are similar. However, the magnitude of the chromaticity shift was greater and the timing of the reversal of the yellow shift shorter for samples operated at 1,500 mA. The likely reason for an initial blue shift not being measured at 1,500 mA is that this process happens much quicker at this current setting than at 350 mA and was completed before the first measurement at 500 hours.

Figure 4.31 Chromaticity Changes Measured for the Cool White LED in the NICLS Module in Tests at 75°C



NOTE: The temperature of the LED module ($T_{substrate}$) was approximately 88°C in this test. The blue squares denote data taken from the sample population operated at a drive current of 350 mA during the elevated ambient temperature test. The red circles denote data taken from a different sample population operated at a drive current of 1,500 mA during the same test.

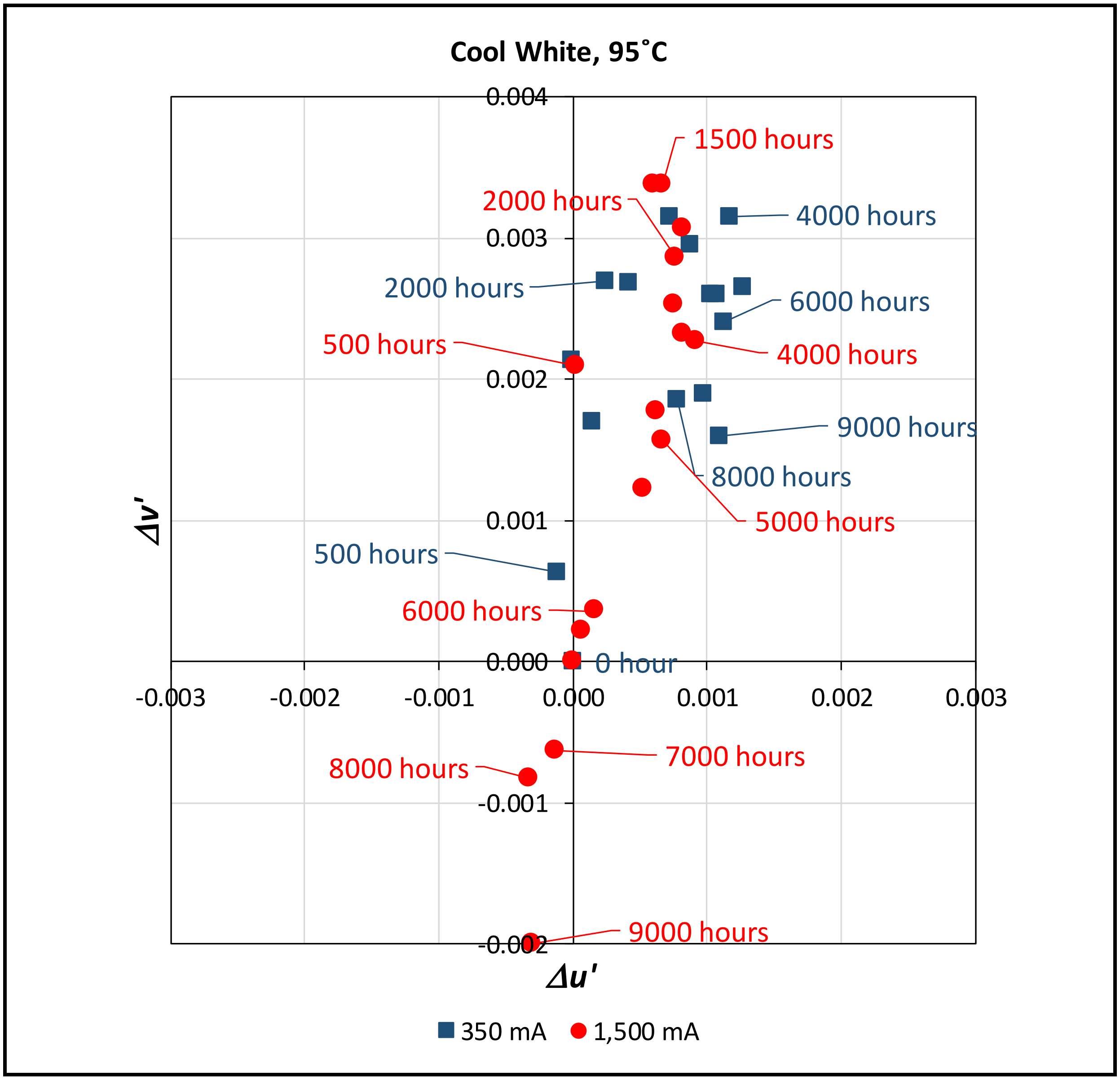
For the cool white LEDs in the 95°C elevated ambient environment, the general trends observed for the 350 mA and 1,500 mA samples were similar to those observed at 75°C, but the timing and extent of the chromaticity shifts were different (**Figure 4.32**). For the samples operated at 350 mA, the first measured chromaticity shift was in the yellow direction (i.e., primarily along the positive v' axis), and this shift was recorded for the first 4,000 hours of operation. The total chromaticity shift after that time was 0.0034. At that point, the chromaticity began to reverse and started to shift in the blue direction (relative to the chromaticity at 4,000 hours). Consequently, the chromaticity began moving back toward the initial value, and the total chromaticity shift after 9,000 hours of testing at 95°C and 350 mA was 0.0019.

For the 1,500 mA samples in the 95°C test, the chromaticity shift also initially proceeded in the yellow direction for the first 1,500 hours of testing. Then, the chromaticity reversed and shifted in the blue direction toward the initial point. Between 6,000 and 7,000 hours of testing, the chromaticity returned to a value near the initial point. Beyond that time, the chromaticity continued to shift in the blue direction and proceeded away from the initial chromaticity. At the end of 9,000 hours of HTOL testing at an elevated ambient temperature of 95°C ($T_{substrate}$ ~ 107°C) and a forward current of 1,500 mA, the total chromaticity shift for the tested LED modules, as measured by $\Delta u'v'$, was 0.002.

Taken together, the combined behaviors of the samples in these four tests provide strong evidence that cool white LEDs in the NICLS TWL LED module will exhibit CSM-4 behavior during actual use. There will likely be an initial shift in the blue direction that will be short (less than 500 hours) under extreme conditions but could last for 2,000 hours or more under milder conditions. Then, the chromaticity will shift in the yellow direction, followed by a second shift in the blue direction. These tests also produced two additional findings. First, the extent of the initial yellow shift is bounded, and the upper limit is determined by the temperature and current. In this test, the maximum value of this yellow shift was $\Delta u'v' \leq 0.004$, which was observed under the most severe test conditions. For the mildest test condition (i.e., 350 mA and 75°C), the maximum yellow shift was only $\Delta u'v' = 0.002$. Second, parametric failure resulting from excessive chromaticity shift (i.e., $\Delta u'v' \geq 0.007$) was not observed in this test, despite the harsh conditions used. This is a significant finding because the extreme conditions did not lead to a parametric failure. It can be hypothesized that the second blue shift could continue until $\Delta u'v' = 0.007$, and this hypothesis is supported by extrapolating the data taken at 1,500 mA and 95°C. However, there is not yet experimental evidence for this process proceeding until $\Delta u'v' = 0.007$. The bounded nature of chromaticity shifts will slow down the rate of change of the chromaticity and, in some cases, lead to its reversal, as observed for the cool white LEDs. Consequently, it is possible that the blue shift observed for the cool white LEDs after long exposure times to high temperature slows down before the parametric threshold is reached.

Most notably, the lower operating current slowed the chromaticity shift process, and as a result, the maximum yellow shift occurred after 4,000 hours. In addition, the chromaticity point after 9,000 hours of testing was in a yellow direction relative to the starting point (i.e., both *Δu′* and *Δv′* were positive relative to the starting point), although the chromaticity shifted back to the initial value (i.e., in the blue direction).

Figure 4.32 Chromaticity Changes Measured for the Cool White LED in the NICLS Module in Tests at 95°C



The chromaticity shifts of LEDs usually consist of a fast-acting component that occurs when an LED is first turned on and one or more slow-acting components that take time to emerge. Often, these slow-acting components take 2,000 hours or more to progress sufficiently to impact chromaticity, and in some cases (e.g., low operating temperatures and currents), it may take 10,000 hours or more before the slow-acting components affect the chromaticity. RTI has developed a process for modeling the chromaticity change of LEDs in which the fast-acting component is modeled using a bounded exponential function (see **equation 4.1**), and a generalized logistic function (see **equation 4.2**) is used to model the slow-acting components [36]. Another feature of RTI's models of chromaticity shift is that multiple processes are often involved, and the impact of each process on the chromaticity shift does not proceed indefinitely. That is, there is an upper bound to any process that causes a chromaticity shift. Sometimes, this upper bound is beyond the parametric limit, but this is not so in every instance. In LEDs studied to date, the model of chromaticity shift at a chosen temperature and current contains no more than one bounded exponential function but may contain several logistic functions when different chromaticity shift mechanisms become prevalent as the LED ages.

$$\text{Bounded Exponent} \qquad A(1 - e^{-kt}) \tag{4.1}$$

$$\text{Generalized Logistic} \qquad \frac{A}{1+Ce^{-kt}} \tag{4.2}$$

where:

A = maximum or asymptotic value

C = a fitting parameter

k = rate of change in the curve

Using this approach, models were created for the chromaticity shift in both the u' and v' directions for the NICLS cool white LEDs subjected to the 75°C ambient environment. For simplicity, only the models for the change in v' are given here because the change in the cool white LEDs occurs mainly in the v' direction. As shown in **Figure 4.33**, the v' chromaticity coordinate of the cool white LEDs rises to a plateau value after a certain period of time. The chromaticity stays at that value for the remainder of the test period for the 350 mA and 700 mA settings but may decrease slowly after 5,000 hours of testing at the higher setting. Consequently, the duration of the plateau, or incubation period, is longest for the lowest current and becomes progressively shorter as the current is increased. In addition, the extent of the chromaticity shift increases with the current, with $\Delta v'$ reaching maximum values of roughly 0.0016 for 350 mA, 0.0025 for 700 mA, 0.0029 for 1,000 mA, and 0.0030 for 1,500 mA. The asymptotic value indicates that the extent of the chemical mechanism responsible for this chromaticity shift reaches is a maximum value after approximately 2,000 to 5,000 hours of use at 75°C, depending on the forward current. The processes responsible for this chromaticity shift cannot produce a total chromaticity shift that exceeds the parametric limit (i.e., $\Delta u'v' \geq 0.007$) because there is an upper bound on the extent of this shift. Beyond that point, the chromaticity shift remains at the upper limit during the test period at lower current settings (i.e., 350 mA and 700 mA), whereas $\Delta v'$ may decrease slowly at higher current settings.

A similar trend was found for the initial chromaticity shift for the cool white LEDs in the 95°C elevated ambient environment. As shown in **Figure 4.34**, the chromaticity shift was much faster in this case, possibly because of the higher temperature, and was modeled with a bounded exponential function. As before, there is clearly an upper bound to this chromaticity shift mechanism that is dependent on the current. For LEDs operated at 350 mA in the 95°C environment, this upper bound was 0.0035. This value slowly increased with current in the 95°C environment. A second chromaticity shift mechanism that results in a decrease in *Δv′* is clearly evident beginning at approximately 3,000 hours. This shift is in the blue direction, as discussed above, and can also be modeled with a generalized logistic function. It is possible that this blue shift mechanism will eventually occur at lower temperatures, but this phenomenon was not observed in the timeframe of the experiments performed to date at 75°C and forward currents of 350 mA and 700 mA.

Figure 4.33 Shifts in the *v′* Chromaticity Coordinate for NICLS Cool White LEDs Subjected to Testing at 75°C.

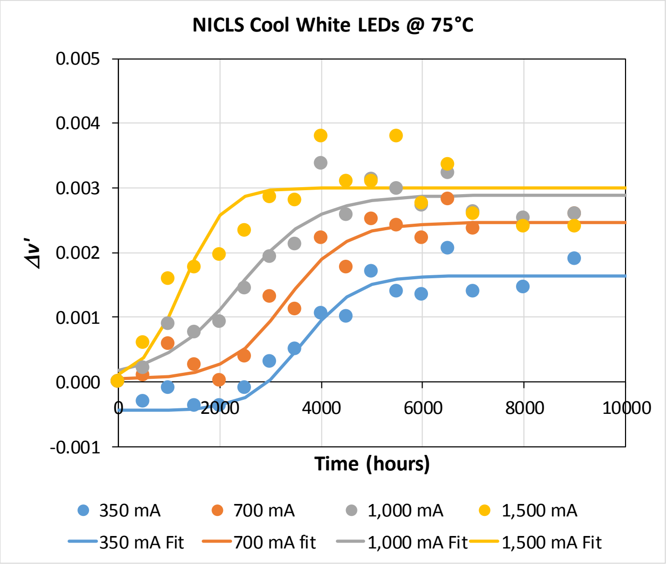
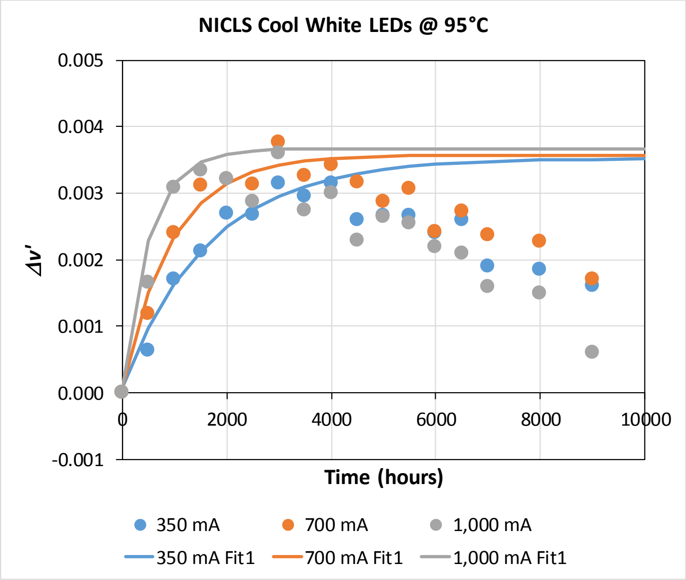


Figure 4.34 Shifts in the v' Chromaticity Coordinate for NICLS Cool White LEDs Subjected to Testing at 95°C.



Despite the harsh conditions used in this accelerated test, the chromaticity shift of the cool white LEDs was minimal through 9,000 hours of testing. Consequently, the processes that could ultimately produce a parametric failure (i.e., $\Delta u'v' \geq 0.007$) have not been fully demonstrated in testing to date. In this instance, a parametric failure would correspond to the wear-out phase in the hazard function, as given in Figure 4.27. Therefore, projections of the time necessary for parametric failure because of excessive chromaticity shift are not yet possible; however, given the minimal changes found for these LEDs via this elevated ambient temperature testing, it is anticipated that the total chromaticity shift under normal operating conditions will be minimal over 60,000 hours or more of normal use. It is possible that the second blue shift observed under some conditions will ultimately cause parametric failure; however, this cannot be assumed for two reasons. First, the length of the incubation time for this shift at milder conditions (i.e., low temperature and current) was not determined in 9,000 hours of testing. This incubation time is short for more severe conditions, and as a result, the subsequent blue shift became apparent during the experimental timescale. However, no indication of the emergence of the blue shift was found in the 350 mA and 700 mA data acquired at 75°C. The second reason that a projection cannot be made is that even the most severe conditions—95°C and 1,500 mA—did not produce a parametric failure. Consequently, it cannot be assumed that the processes responsible for the blue shift will proceed at the same rate until $\Delta u'v'$ exceeds 0.007. Indeed, the shift could reach an asymptote short of the parametric failure threshold, as observed for other chromaticity shifts with this LED.

For the warm white LEDs in elevated ambient temperature testing, a significantly different chromaticity behavior was observed. As shown in **Figure 4.35** and **Figure 4.36**, the chromaticity shift measured for the warm white LEDs occurs more in the *u′* direction than in the *v′* direction observed for cool white LEDs. A shift to higher *u′* values is a red shift, whereas a shift to lower *u′* values is a green shift. These shifts can also be modeled using a combination of the bounded exponential and generalized logistic functions given in equation 4.1 and equation 4.2. The models of samples exposed to the 75°C and 95°C ambient environments are given in **Figure 4.37** and **Figure 4.38**, respectively. Only the changes in u′ are shown in these figures because the changes in the chromaticity of the warm white LEDs used in the NICLS TWL system occur mainly along this axis. Examining Figure 4.37 and Figure 4.38 reveals several major trends. Based on the 75°C data, at least three different sequentially occurring processes appear to be responsible for the measured chromaticity shifts in the warm white LEDs based on 9,000 hours of data. There is evidence for at least two such process in the 95°C data. The emergence and extent of these processes are clearly dependent upon both the time and temperature. For simplicity, only the last change in the chromaticity coordinates measured during the 9,000 hour test is modeled in **Figure 4.39** and **Figure 4.40**. This chromaticity shift process reaches an asymptotic limit in all tested cases, and this limit is between 0.0006 and -0.0035, depending on the temperature and current. Consequently, an additional chromaticity process must occur for the color to shift outside the parametric limit. In other words, the devices have not yet reached the wear-out stage in testing. Some evidence suggests that this next shift will be in the blue direction (see the data for 1,500 mA in Figure 4.36), but this has not been experimentally confirmed. If such a blue shift were to occur, it would represent a fourth additional process impacting the chromaticity of these LEDs. However, such a shift would be consistent with the CSM-4 behavior that can be expected for this LED package.

Models were also built for the *v′* chromaticity of the warm white LEDs used in the NICLS TWL LED modules. At a test temperature of 75°C, the *v′* chromaticity slowly increased to an asymptotic value of approximately 0.001 (one-step MacAdam ellipse) for forward currents of 350 mA, 700 mA, and 1,000 mA. The *v′* chromaticity stayed at that limit for the remainder of the test period. For samples tested with a forward current of 1,500 mA at 75°C, a slow decrease in the *v′* chromaticity value was observed after 7,000 hours of testing, suggesting a possible shift in the blue direction. For all samples tested at 95°C, there was also a decrease in the *v′* chromaticity value, and this change was apparent after 4,000 hours of testing at a forward current of 350 mA and continued for the remainder of the test period. At higher currents, the decrease in the *v′* chromaticity value occurred after shorter times and was evident at 2,000 hours of testing for forward currents of 1,000 mA and 1,500 mA. However, even under the most extreme test conditions (1500 mA and 95°C), the change in the *v′* chromaticity value relative to the initial value was less than 0.001.

Figure 4.35 Chromaticity Changes Measured for the Warm White LEDs in the NICLS Module in Tests Conducted at 75°C

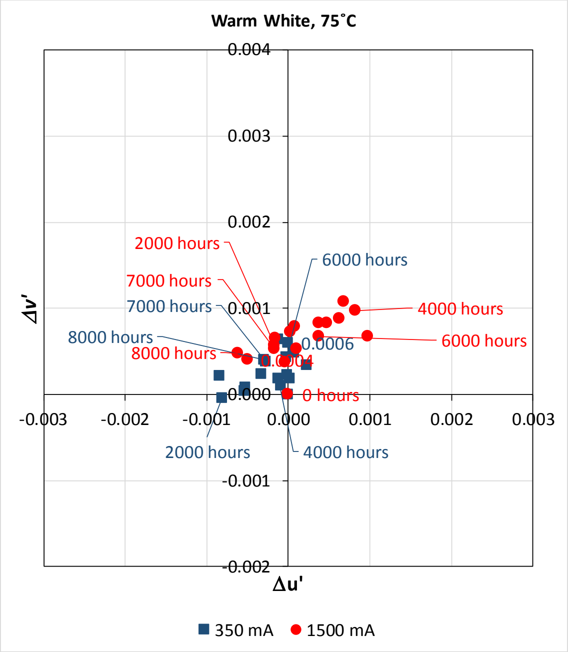


Figure 4.36 Chromaticity Changes Measured for the Warm White LEDs in the NICLS Module in Tests at 95°C

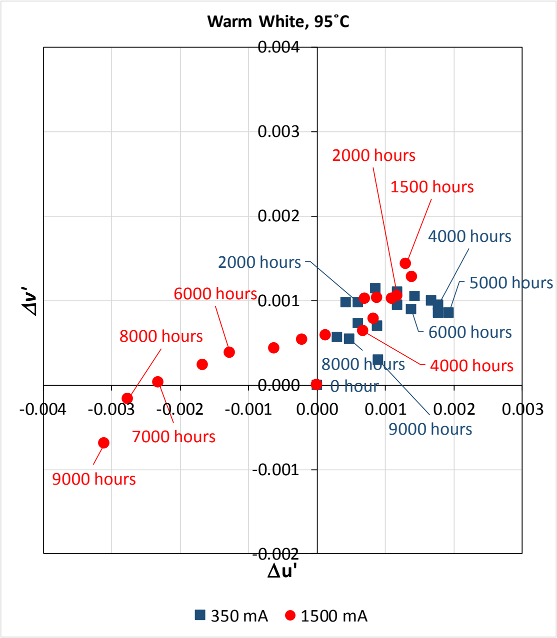


Figure 4.37 Shifts in the *u'* Chromaticity Coordinate for NICLS Warm White LEDs Subjected to Testing at 75°C.

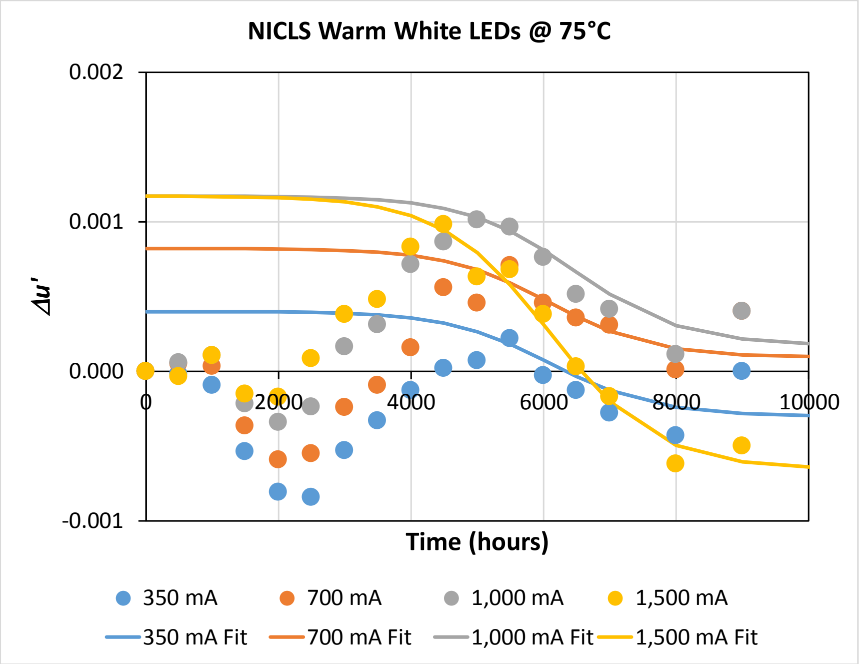
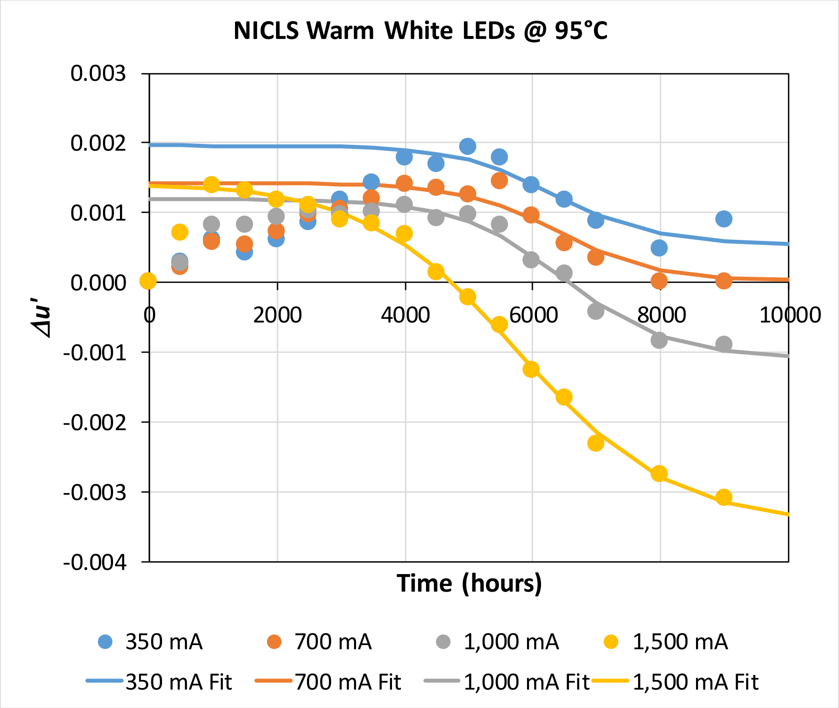


Figure 4.38 Shifts in the *u'* Chromaticity Coordinate for NICLS Warm White LEDs Subjected to Testing at 95°C



Based on this analysis, the likelihood of the NICLS TWL LED modules exhibiting excessive chromaticity shift under normal operating conditions is viewed as highly doubtful. Despite the extreme test conditions, including operation at 1,500 mA in a 95°C ambient environment, the total chromaticity of none of the modules shifted by more than 0.0032, and some of this shift may be attributed to the discoloration of the solder mask rather than changes in the LED. Overall, projections of the time required for $\Delta u'v'$ to exceed the 0.007 threshold cannot be made for the NICLS TWL LEDs because the terminal chromaticity shift mechanism has not been fully identified for either cool white or warm white LEDs through 9,000 hours of testing in extreme conditions. Consequently, we believe that it is safe to assume that the chromaticity stability of the NICLS TWL LED modules will be excellent over 60,000 hours at a minimum.

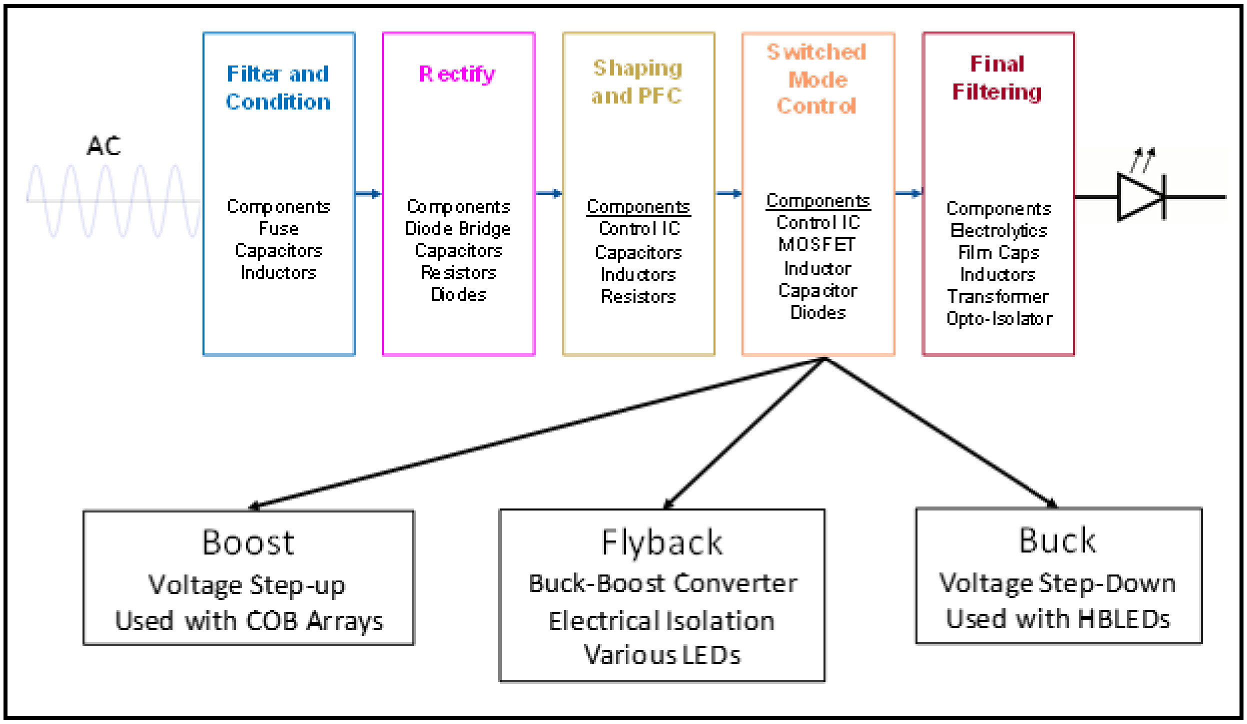
4.C.4 Accelerated Testing of NICLS Luminaire Drivers

Driver technology is a key enabler for TWL luminaires because the different LED assemblies that must be controlled separately to achieve a functional white tuning range. This level of control can be accomplished by using separate drivers for each LED assembly; however, such an approach results in multiple drivers being placed in a luminaire, which increases the weight and complexity of the fixture. A more elegant approach is to leverage semiconductor integration technologies to produce a single driver that can operate multiple LED assemblies simultaneously. Switched-mode power supplies (SMPSs), such as those used as drivers in SSL devices, typically convert power from the alternating current (AC) electrical supply to the direct current (DC) required for LED device operation. To achieve this power conversion, an SSL driver actually consists of five or more electronic circuits, as shown in **Figure 4.39**. The primary electrical circuits in an AC-to-DC driver include circuits for the following:

- Filtering and conditioning the input AC power;
- Rectifying the input AC power to DC power;
- Shaping the DC power to reduce ripple and provide power factor correction (PFC);
- Operating the switching transistor in the SMPS and regulating the DC output power; and
- Filtering the DC output power supplied to the LEDs.

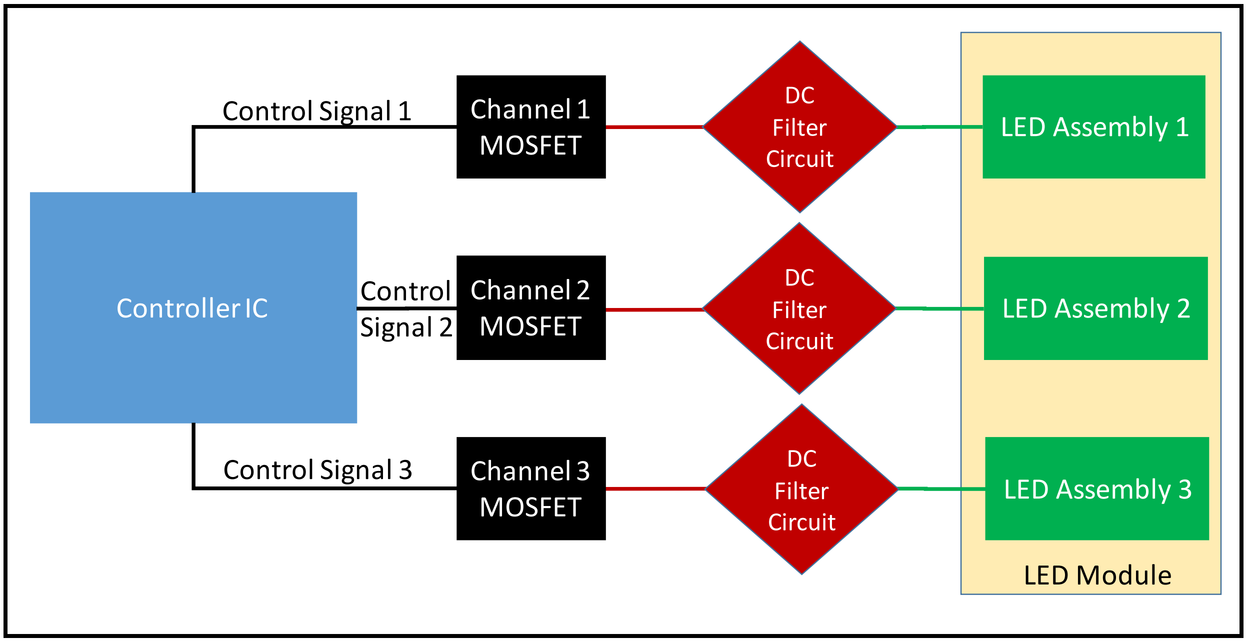
For a driver used in a tunable white device, the different LED assemblies can share the first three circuits (i.e., Filter and Condition, Rectify, and Shaping and PFC). Parts of the fourth circuit, Switched Mode Control, such the integrated circuit (IC) controller, can also be shared. However, each LED assembly needs to have its own switching components because they are used independently for current regulation. In addition, each LED assembly needs to have separate Final Filtering stages, which are directly connected to the LED assemblies. In general, the IC provides control signals to operate the different LED assemblies. In SMPS devices, this control signal is supplied to the gates of metal-oxide semiconductor field-effect transistors (MOSFETs), which act as switches to rapidly turn the LED assemblies on and off and provide current regulation [50]. The SMPS design increases the overall driver efficiency, especially compared with that typically obtained using a linear power supply, but can also introduce flicker into the light output [33].

Figure 4.39 Generalized Schematic of the Electrical Circuits Commonly Used in SMPS Drivers for SSL Devices



Because control of the current supplied to each LED assembly is essential for TWL operation, separate MOSFETs and control signals are necessary for each LED assembly comprising the LED module. Schematically, this can be represented by different signals originating from a single controller IC (assuming an integrated multi-channel driver architecture) that are routed to different MOSFETs, which, in turn, feed the different LED assemblies, as shown in **Figure 4.40**. A filtering and DC cleanup stage is inserted between the MOSFETs to provide constant power to the LEDs when the MOSFETs are switched off and to minimize any variation in the DC voltage supplied to the LEDs. This filtering stage is often modeled after a buck driver and includes a buck inductor in series with the LEDs and a capacitor in parallel.

Figure 4.40 Schematic Illustration of the Driver Structure for Multi-channel TWL Drivers

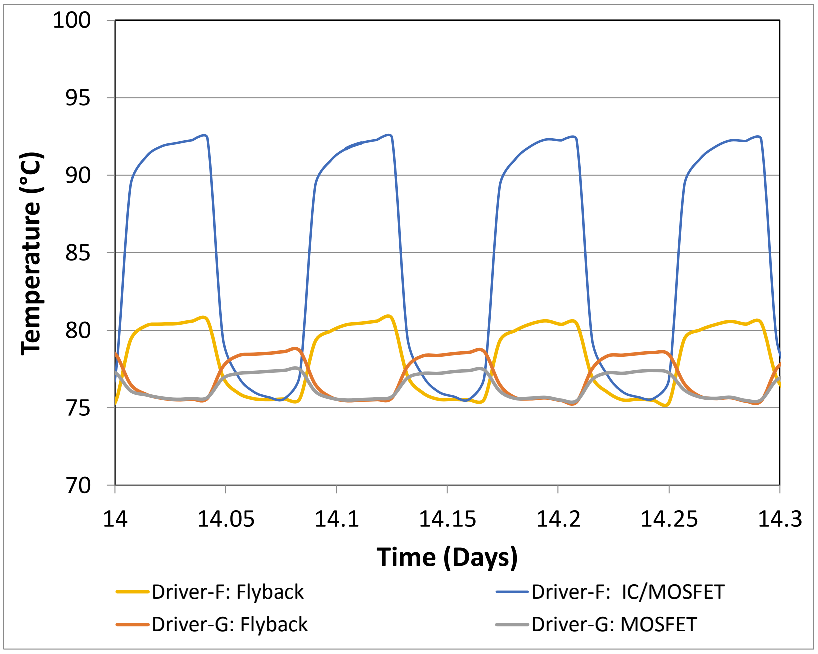


Previous studies conducted by RTI have used WHTOL tests to investigate the robustness of SSL drivers [36; 43]. WHTOL tests are conducted in a constant high-relative humidity (RH) environmental and are widely used in the electronics packaging industry for measuring the reliability of ICs. One WHTOL test that RTI typically uses in our assessments is performed at 75°C and 75% RH; this test is termed 7575 for the remainder of this document. In our previous studies, roughly 30% of the test population failed in under 2,500 hours of 7575 testing. Much better performance was observed for the NICLS drivers in our testing, as explained below.

For the NICLS luminaire system, two different commercial drivers were examined as candidates for use in the demonstration site. One driver uses a dynamic modulation scheme for DC power output, as discussed above, and the second driver uses a more traditional pulse-width modulation (PWM) scheme. The SMPS driver with the dynamic modulation output scheme is labeled Driver-G in the discussion below, and the traditional PWM driver is labeled Driver-F. In addition, the MOSFETs used for current regulation were integrated into the same package as the controller IC for Driver-F. The package is a 56-pin quad flat no leads package, which has a higher thermal resistance than a normal MOSFET. While this approach conserves board space and can reduce the size of the driver, it also results in a higher temperature for the combined IC/MOSFET package because MOSFET switching is a leading source of power loss (and heat) in drivers. In contrast, Driver-G uses discrete MOSFET components that are separate from the controller IC, resulting in better thermal management characteristics.

To understand the potential impact of accelerated tests on various DUTs, it is important to know the actual temperature profiles of the DUTs; these data are shown in **Figure 4.41** for one sample of Driver-F and one sample of Driver-G in 7575. For Driver-F, two temperature measurements were taken: one on the external housing near the flyback transformer and the second directly on the IC/MOSFET chip. For Driver-G, two temperature measurements were also taken: on the external housing near the flyback transformer and on the external housing near the bank of MOSFETs on the PCB. The temperatures of these devices increased rapidly when the driver was turned on, and the DUT achieved roughly 90% of the total temperature rise in the first 10 minutes of operation. Cool down was rapid when the device was turned off, but the last 10–15% of the cooling cycle was much slower. The temperature heating and cooling cycles displayed larger temperature changes for the IC/MOSFET package used for Driver-F, which can be expected because the values were measured on the IC and not on the case. At room temperature, the total temperature range was 25% to 50% larger than that measured in 7575, possibly because of heat removal by the control system of the environmental chamber under 7575 conditions. Consequently, larger temperature changes will likely occur during normal use, but the maximum temperature will be lower than that observed under 7575 conditions. So, while the elevated temperature of 7575 does provide some level of test acceleration, the main impact of the test is the aging effect of moisture on semiconductors and electronic components.

Figure 4.41 Temperature Profile of Driver-F and Driver-G DUTs in 7575.



NOTE: The drivers were switched on and off on an hourly basis with Driver-F and Driver-G on opposite cycles. For Driver-F, the temperature was measured on the external case near the flyback transformer and directly on the IC/MOSFET chip. For Driver-G, the temperature was measured on the external case near the flyback transformer and near the MOSFET switches.

Candidate drivers for the NICLS technology demonstration site were evaluated via 7575 testing in conjunction with other luminaire drivers of similar power levels, and the complete findings from this study are available elsewhere [20]. For the two drivers under consideration for the NICLS system, no failures occurred during 2,500 hours of testing, which indicates that both products have excellent reliability. In contrast, 30% of the downlight products that RTI has tested failed in less than 2,500 hours of 7575 [36; 43]. Although there were no failures among the three different commercial single-channel driver products examined in this broader study, the two-channel driver included in this study failed at 1,750 hours of testing [20]. This failure was traced to the failure of a film capacitor in the PFC circuit.

Because there were no signs of failure in the samples of the two commercial driver products under consideration for the NICLS technology demonstration site, alternative methods of evaluation were needed to look for any degradation in performance due to accelerated aging in 7575 tests. An examination of the power consumptions of Driver-F and Driver-G showed a slight increase in power consumption for Driver-F but essentially no change for Driver-G [20]. A second level of analysis was involved looking for degradation in the photometric flicker waveforms, especially at lower dimming levels. The flicker waveforms have been shown to be sensitive to component degradation in some devices, especially in key components, such as the MOSFETs or filter capacitors [36].

In this study of the photometric flicker performance of Driver-F and Driver-G, photometric flicker waveforms were measured with the drivers still in the environmental chamber but at room temperature following extended exposure to 7575 test conditions. LEDs were placed outside the environmental chamber and used as electrical loads during testing. This approach ensured that only the driver would experience the effects of the 7575 AST environment. Additional details on this method can be found elsewhere [20]. The flicker waveforms for Driver-F at 100% and 1% dimming levels are shown in **Figure 4.42**, and the flicker waveform for Driver-G at the 1% dimming level are shown in **Figure 4.43**. Of particular note in these graphs is the finding that there is no change in flicker frequency or the shape of the waveform at low dimming levels. The rise time and pulse decay at low dimming levels would be especially sensitive to any significant degradation in driver components because of the accelerated testing. The absence of any significant change in either driver demonstrates their robustness.

Figure 4.42 Flicker Profiles for Driver-F obtained from a Control (i.e., Unexposed) Sample and a Sample Exposed to 2,500 hours of 7575

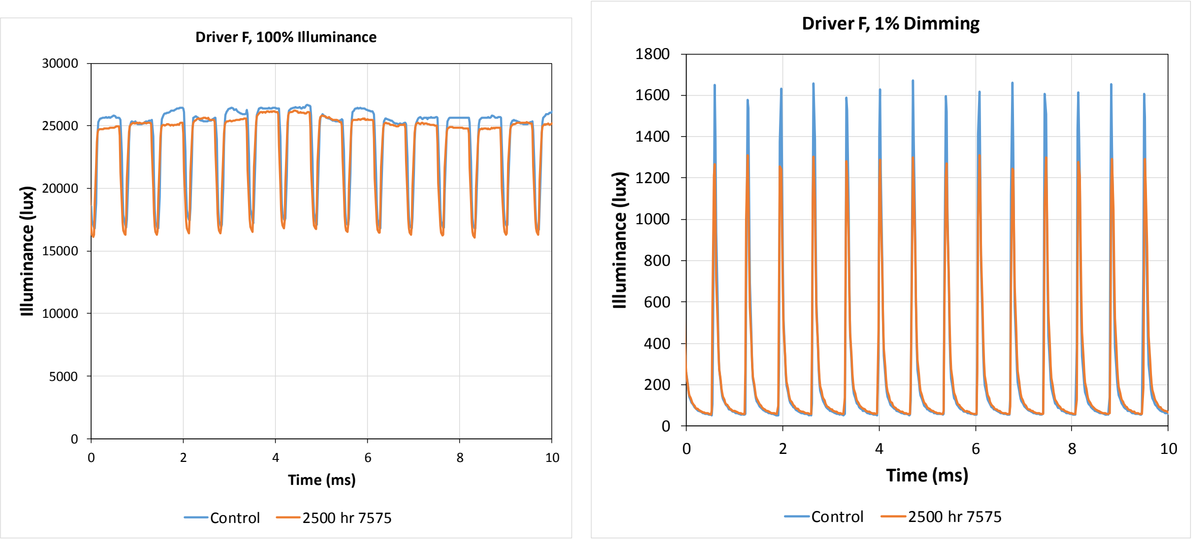
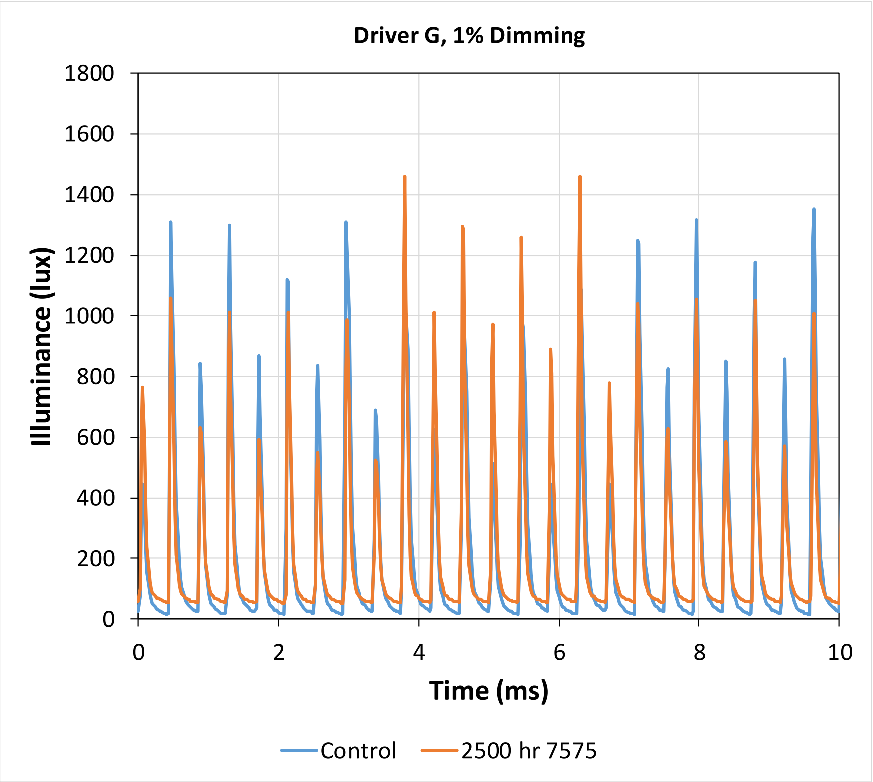


Figure 4.43 Flicker Profiles for Driver-G obtained from a Control (i.e., Unexposed) Sample and a Sample Exposed to 2,500 hours of 7575



The accelerated aging testing of drivers under consideration for use in the NICLS technology demonstration site proved that both commercial products are reliably built and perform better than most drivers that RTI has tested. We found minimal signs of degradation in the two drivers and no changes in their photometric properties, despite subjecting the samples to the stress of the 7575 environment for 2,500 hours. The DOE goals for driver reliability are a rated lifetime of at least 50,000 hours, as measured by the time required for 50% of the devices to fail. As demonstrated by these accelerated tests, either driver product should be able to meet this threshold. In addition, these drivers will also be warranted by Finelite in any commercial product, and thus, the NICLS technology will exceed the DOE requirements with either driver. Ultimately, the decision was made to install Driver-G in the demonstration site because of the slightly higher efficiency of the variable modulation scheme used in this device.

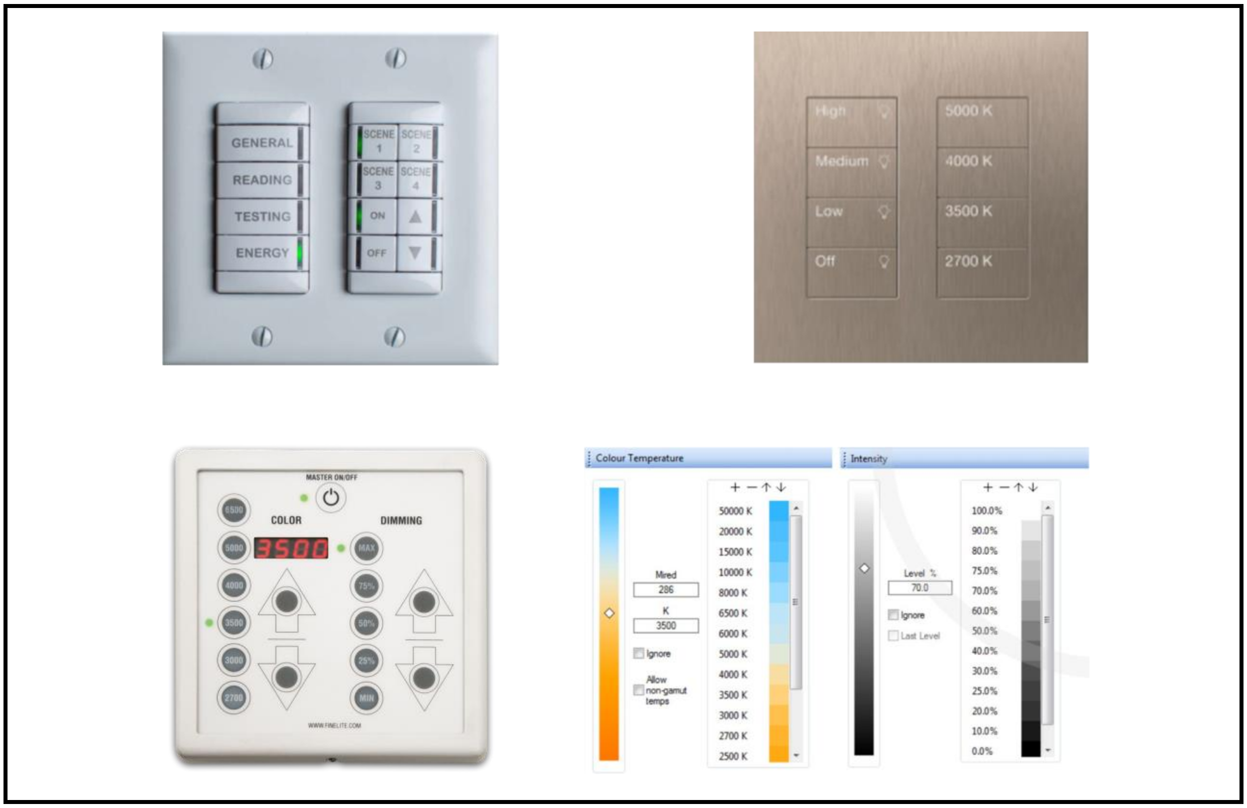
4.D Task 4: Feedback Collection on the NICLS Lighting System

A key portion of this project focused on understanding the UI preferences of potential users in the classroom setting. Teachers require a lighting system that is easy to use and allows shifting between modes or scenes quickly with minimal effort. Although a TWL system can improve the effectiveness of teaching in the classroom, the RTI and Finelite investigators acknowledge that the level of effectiveness relies upon the user’s ability to incorporate this lighting breakthrough into their curriculum. Because the UI is the link between the user and the lighting system, this part of the NICLS technology must be done correctly to create interest in the broader benefits of SSL technologies in the classroom. Recognizing the need for guidance from classroom teachers and educational professionals at all levels, administrative and academic staff were brought in for focus groups to glean their interest in and understanding of the NICLS system and determine the intuitiveness of the UI iterations and features.

Light System Controls

In general, lighting system controls are designed for use by the building manager and are often locked to prevent manipulation by the user. Some of the first controls built for TWL systems followed this approach and were designed more for professional engineers and building managers than for everyday users. While terms like CCT setting, dimming level, and occupancy sensor override are well known to lighting professionals, they can be confusing to an untrained individual, especially in a classroom setting with dozens of students. Therefore, lighting systems controls must be intuitive, easy to use, and convey the capabilities of a modern lighting system. In addition, teachers often do not have time to program a lighting system with scenes and settings, and facilities personnel in school districts have too much on their plates to set up lighting systems. Thus, any viable classroom lighting system must be easy to install, intuitive to use, and pre-configured for most users but must also provide options for customization. The industry has tried several approaches to UIs for tunable lighting systems, including sliders to adjust CCT and illuminance levels, preset values, and limited pre-programmed scenes. Examples of UIs developed for use with tunable lighting products are given in **Figure 4.44**. The use of numbers and arrows on these UIs may be helpful for the building manager but will likely be less intuitive for everyday users.

Figure 4.44 Examples of UIs Used with Classroom TWL Systems

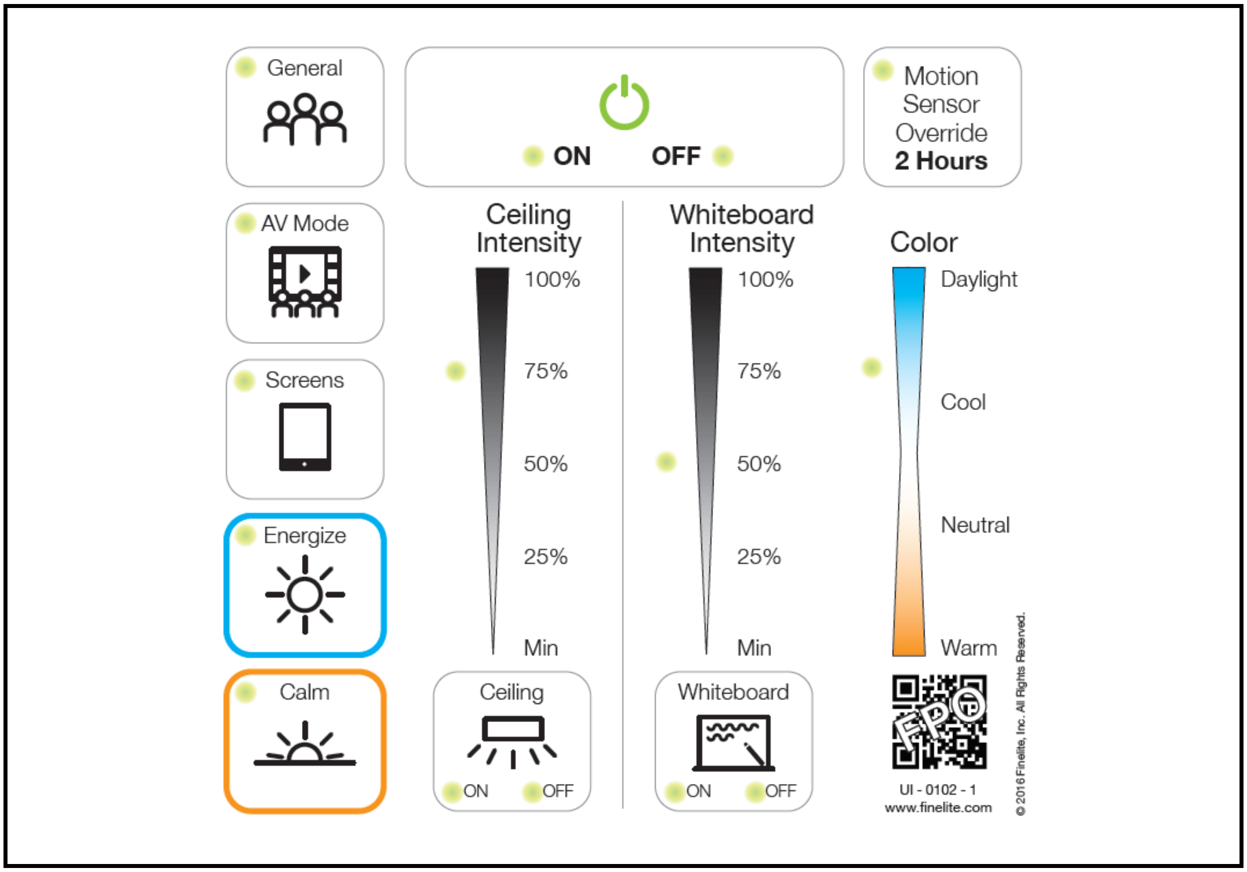


Sources: Reference [18], LEDucation.org, Finelite, Inc., and Helvar, Inc.

One of the original goals of this project was to develop a UI for use with the NICLS technology that was designed with the needs of teachers, student, and substitutes in mind. The initial designs incorporated separate controls for the ceiling and whiteboard luminaires, sliders for CCT and illuminance level control, and variable occupancy sensor times. Inputs from the focus groups indicated that some of these UI elements were useful, but the entire UI needed to be rethought from the perspective of ease-of-use and the real estate occupied by different functions.

As a result, subsequent designs of the UI leveraged greater use of icons and colors to quickly convey the meaning of each button. The icons and terminology on the UI were topics of significant discussion in the focus groups, with the teachers preferring fewer settings but more functional terminology. Consequently, terms such as “General” and “Screens” are used instead of “Lecture” and “Classwork”. Coloring was added around the borders of the “Energize” and “Calm” settings on the UI to tie these settings to the CCT color scale on the sliding switch. Separate on/off switches were added for the ceiling and whiteboard luminaires at the bottom of the dimming slider for each. A master on/off switch for the system is located at the top of the UI, and an occupancy sensor override, preset for 2-hour increments, is located beside the master on/off switch. Finally, a quick response code is added to the lower right-hand corner of the UI to provide a link to additional information on the NICLS technology platform and research on the use of TWL technologies in the classroom. The completed UI for the NICLS platform is shown in **Figure 4.45**. In addition to the wall-mounted UI at the front of the classroom, there is also a wireless app that can be installed on tablets and smartphones. This additional feature allows teachers to move throughout the classroom and adjust the lighting system as required.

Figure 4.45 Final UI Design for Use with the NICLS Technology



Focus Group Data Collection Methods

The original plan for data collection from the focus groups was for RTI to survey feedback from approximately 40 stakeholders after the completion of the NICLS technology demonstration site. In the original plan, local stakeholders from both school sites and district offices who have knowledge of the range of instructional approaches used to serve heterogeneous classroom populations and the variety of purposes the modern classroom must serve were to be recruited. To get input from both school-based users and managers of lighting systems, RTI proposed to seek feedback from approximately 30 classroom instructors and 10 site and/or district administrators, including facilities managers. Then, this information would be used to produce a summary report of findings from the focus groups.

The project team closely adhered to the original plan for data collection and reporting, only varying when certain stakeholders were engaged, and the number of stakeholders consulted was higher than originally planned. Ultimately, feedback was collected at three key points of the project and from three levels of stakeholders: 1) administrators and experts knowledgeable in classroom instruction, instructional technology, and classroom facilities; 2) school site administrators knowledgeable about the range of instructional needs within a school site; and 3) teachers and other school site staff working directly with students. Initial focus groups were held in conference rooms at Finelite that could be used to demonstrate the benefits of color-tunable lighting and advanced SSL technologies in the classroom. Focus groups held after April 2016 were conducted in the NICLS technology demonstration site at Finelite's facility in Union City, CA, which provided a broader range of advanced lighting functions.

Details on the three phases of data collection

At project inception, it was determined that the design and placement of the UI and the locus of overall system control were critical elements for the design of the NICLS technology demonstration site. Construction of the demonstration site was ahead of schedule, and thus, the team determined it would be important to gather stakeholder input as early as late 2015, before the NICLS technology demonstration site was finalized. Because the questions being considered included those relating to the locus of control of the system, it was determined that input from district-level administrators responsible for instructional technology and facilities management in their school systems would prove most valuable for making the necessary decisions regarding the design of the classroom at that point in the project. Furthermore, experts at these levels could provide insight on what aspects of the NICLS technology demonstration site were most likely to resonate with school and district staff. Therefore, in February and March 2016, RTI convened two stakeholder groups composed of, respectively, five and six instructional experts and district administrators to present them with the initial plans for the demonstration classroom and the UI. The goal of these meetings was to gather their initial input on the NICLS technology and the UI. Participants were compensated for their participation in the focus groups because up to four hours of their time was needed. Leveraging RTI's networks in the educational community in the San Francisco, CA, area, the participants were recruited from local school districts and instructional support organizations.

Feedback from the initial stakeholder groups informed the installation of the NICLS technology demonstration site and the preliminary plans for the UI, but the project required actual input on the design and features of the UI faceplate by June 2016. The team planned to convene several representatives from the initial stakeholder group to show them a mock-up of the UI design and get their input. To ensure that data collection would be efficient and generate optimal results, the team used the June convening of stakeholders to test a focus group question protocol. In June, two groups of five teachers and a third group of administrators and instructional experts returning from the February/March groups were convened. Feedback from these groups was meant to provide time-critical information to Finelite for the design of the UI and to RTI for the development of the focus group structure and content. The sessions with the returning experts provided more in-depth feedback on the UI based on demonstration site details that could be incorporated over the summer before the formal teacher and site administrator focus groups were convened.

In August 2016, RTI began recruiting teachers for the system evaluation focus groups. With permissions from school districts within 15 miles of the Finelite facility, principals from several elementary, middle, and high schools were contacted via phone and/or email and informed that a series of 60- to 75-minute focus groups about school lighting would be held in Union City, CA, in September and October. If they agreed, they were sent a link via email to a sign-up protocol presenting them with a series of dates for participation that they were encouraged to forward to their staff or any teachers in the area who might be interested in participating. The sessions were scheduled for weekday afternoons, after typical school dismissal times. Each session was designed to accommodate 6–10 participants based on best practices established by RTI for the optimal size, to ensure effective participation of all focus group members. In keeping with the original plan for data collection, sessions were scheduled to ensure feedback from approximately 40 respondents. The requirement was established that, for a session to be confirmed, a minimum of six sign-ups would be required one week prior to the session. To ensure at least 40 respondents, 12 session options were originally offered, with 3 being cancelled for not meeting the minimum number of attendees. Ultimately, nine fall focus-group sessions were held, and a total of 60 participants attended. Of these, eight were principals or other site-based instructional supervisors (e.g., math instructional coach), five had non-instructional or support roles (e.g., school psychologist), and the rest were classroom teachers, including seven special education teachers. Approximately one third of the participants worked at an elementary site, one third worked at a middle school, and one third worked at a high school. Key findings from the focus groups are summarized below.

Summary of Findings from First Phase (Winter 2016) of Evaluator Feedback

<u>How do high-level administrators, including facilities and instructional technology experts, react to the concept of color-tunable and fully dimmable lighting for classrooms?</u> Overall, the response to the potential of the NICLS technology was highly positive and enthusiastic, though some did raise concerns about cost, especially because the potential positive impact on education outcomes was untested. The potential to use the system in alignment with children’s alertness cycles, an area of growing interest in education circles, garnered substantial interest from the group. They also saw the system as having strong potential to support effective integration of the growing variety of new learning technologies being deployed in contemporary classrooms into instruction.

<u>What should the priorities be for the location and boundaries for system control, i.e., the UI?</u> The concept of relying solely on a device-mounted, soft UI versus a wall-mounted panel had appeal but was deemed overall to be too problematic to allow for the system to be reliably managed in all instructional situations. The consensus seemed to be that basic functions must be available on a hard, wall-mounted panel, while more granular, advanced settings could be managed from a software application. There were some concerns that allowing teachers full control over the system could result in the settings being aligned more with teacher preference than to optimize student learning, but the group felt that giving teachers high degrees of control would likely promote more effective instruction and that, as long as there would be bounds on the overall energy usage, especially if those bounds could be centrally specified and managed, high degrees of classroom-centered control would be optimal. Respondents underscored that having several presets for common instructional scenarios, such as when students are working with laptops or tablets, would likely encourage teachers to "do more" with the system than just turning it on/off. They also suggested that the UI panel should use symbols and key terms to communicate the types of instructional modes it could support.

<u>How are teachers likely to use the features of a color-tunable and fully dimmable classroom system and how might that system affect instructional practice?</u> Key ideas for how teachers might use the system were raised by the group and included the following: manipulating the color spectrum to promote particular levels of alertness at various points in the day, cuing behaviors or changes in the instructional mode through dramatically shifting the color and intensity of the lighting, and "spotlighting" particular areas of the classroom to focus student attention. It was also suggested that the UI could be used to suggest more effective modes of instruction; for instance, rather than having a "lecture" preset that might encourage teachers to stand in front of the classroom and lecture—an instructional mode that has been demonstrated to be minimally effective for learning when relied on too heavily—the presets could use terms such as "group mode" to encourage more collaborative work or "AV mode" to promote the use of alternative information delivery.

Summary of Findings from Second Phase (June 2016) of Evaluator Feedback

Members of the originally convened group of experts and administrators were invited back to the Finelite facility to see the installed NICLS demonstration site and to review the first iteration the UI wall-mount design. They expressed significant enthusiasm for the layout and functionality of the system. Because student presentations are an important means of allowing students to demonstrate learning, one member recommended adding another lighting mode called "presentation mode" that would allow for lighting the front of the classroom and dimming the other ceiling mounts. This idea was endorsed by several other participants. The group also provided feedback on the initial layout of the UI wall-mounted panel. They generally endorsed the modes of instruction that were included as presets but made recommendations for renaming some of the functions and for providing more, or less, "real estate" for things that they considered more, or less, instructionally important.

Two groups of teachers attended pilot teacher focus group sessions to allow RTI to test and refine the focus group protocol. One group was provided with an overview of the system prior to being asked any questions, and the other was asked several "warm-up" questions about lighting and their experiences using lighting in their instruction to focus their thoughts and ensure their engagement and participation before being given a demonstration of the system. While participants were more engaged and thoughtful when given the "warm-up" questions, this mode required more time and seemed to result in flagging attention at the end of the session. The "no-warm-up" mode was more efficient but resulted in lower levels of verbal participation by members. The resulting plan for the fall focus groups was to have members respond to warm-up questions as part of the focus group enrollment protocol. This would allow them to consider questions about lighting in their instruction and be ready to provide feedback on the NICLS demonstration while keeping the session run-time limited to 75 minutes.

Summary of Findings from Third and Final Phase (Fall 2016) of Evaluator Feedback

Below are the summary findings from the nine focus groups conducted with site administrators and teachers in September and October 2016:

<u>How important is lighting to classroom teachers and how are they currently using it?</u> Two thirds of the participants endorsed the idea that lighting conditions were very important in their work environment, though most indicated they were dissatisfied with the lighting in their classrooms and that they had minimal control over classroom lighting.

Even with the minimal control currently available to them, many of the respondents indicated they tended to use lighting to cue changes in activities or to change or support particular levels of student energy.

Teachers were also most likely to change the lighting in their classrooms to support AV technology, such as projectors (e.g., by turning off lights to increase the visibility of projections onto whiteboards).

<u>Feedback on UI design</u>. Teacher users' key priorities for the UI was ease of use and the ability to shift lighting modes quickly. The point was made numerous times that, while teaching, instructors cannot engage with technology that detracts from having their attention on their students. Therefore, the interface needs to be easy to understand and should support quick transitions across the lighting scenes available in the NICLS technology.

The idea of presets with clear, easy-to-understand labels was highly endorsed, and participants responded enthusiastically to anything that helped align the ideas of color with levels of energy (i.e., blue = alert and yellow = calm).

Teachers generally valued the ability to customize and adjust the lights more granularly on the wall mount or via a phone- or web-based software app but considered this secondary to having easy access to clearly labeled mode buttons on a wall mount.

What kind of impact could the NICLS technology have on their instruction and how could it best support their practice? The teachers recognized that classroom instruction now involves a wider variety of modes of learning and that students often switch between reading from reflective surfaces, such as Chromebooks, to looking at projected images on a whiteboard, to interacting with other students while doing partner work. Ideally, the lighting system should support and complement each of these activities, and they generally indicated that if the lighting system supported these various modes, they would be more likely to use lighting to support their instruction.

The potential for the use of white light tuning to cue behavior and support engagement and student well-being was highly endorsed by almost all the attendees. There was audible endorsement for changing the lighting color in all the classrooms. Typically, participants expressed surprise at the feature when it was activated and then began emphasizing the idea that it could be used to encourage students to “wake up” or “settle down.” Several teachers talked about incorporating the warm light color and dimming to support mindfulness practices they have been using to promote student well-being and reduce misbehavior. Others expressed enthusiasm for being able to use the cool lights to wake their students up in the mornings.

Special education teachers were especially enthusiastic about the potential of the system to support the needs of their vision-impaired and autism-spectrum students who have sensory stimulation needs.

Overall, participants demonstrated enthusiasm about the system, and some expressed that their experience in the NICLS demonstration site had them thinking differently about how to use lighting in their classrooms. They highly prioritized giving teachers substantial control over the system, and most were interested in being able to customize presets to meet the needs of their students and classrooms.

Outstanding questions or concerns of teachers and site administrators. Teachers and administrators often asked what types of data were already available that demonstrated the NICLS technology could impact teaching or learning. They often encouraged the project team to collect this type of evidence.

Focus group participants frequently expressed doubts that their school districts would invest in the system without demonstrated evidence that the system could positively impact learning and student behavior.

References

1. Rowland, Cassandra. "How Old are America's Public Schools*.*" Washington, D.C.: National Center for Education Statistics, 1999. https://nces.ed.gov/surveys/frss/publications/1999048/.

2. Bahr, Steven, and Dinah Sparks. *Changes in America's Public School Facilities: From School Year 1998-99 to School Year 2012-13*. Washington, D.C.: National Center for Education Statistics, 2016. https://nces.ed.gov/pubs2016/2016074.pdf.

3. Clark, T., M. McMillan, and D. Bourne. "PIER 4.5 Classroom and Office Lighting Research." *Finelite*. Last modified 2005, http://www.finelite.com/sustainability/research.html.

4. McMillan, Marc, Terry Clark, Jennifer Brons, Peter Morante, Brian Blackhart, Vickie Lauck, and Aloke Gaur. *Classroom Lighting System Demonstration Research Study: Final Report*. Albany, NY: New York State Energy Research and Development Authority, 2008. http://www.finelite.com/download_files/ICLS/NYSERDAFinalReport.pdf.

5. DOE. *DE-FOA-0001171: Solid-State Lighting Advanced Technology R&D - 2015*. Washington, D.C.: DOE, 2014.

6. "Lighting Facts Database". Accessed June 7, 2017. http://www.lightingfacts.com/.

7. Energy Star. *Building Manual: Chapter 10. Facility Type: K-12 Schools*. Washington, D.C.: U.S. Environmental Protection Agency, 2006. https://www.energystar.gov/sites/default/files/buildings/tools/EPA_BUM_CH10_Schools.pdf.

8. Energy Star. *Schools: An Overview of Energy Use and Energy Efficiency Opportunities*. Washington, D.C.: U.S. Environmental Protection Agency, 2011. https://www.energystar.gov/sites/default/files/buildings/tools/SPP%20Sales%20Flyer%20for%20Schools.pdf.

9. National Renewable Energy Laboratory. *Advanced Energy Retrofit Guide: Practical Ways to Improve Energy Performance - K-12 Schools*. Washington, D.C.: DOE, 2013. http://www.nrel.gov/docs/fy14osti/60913.pdf.

10. Xcel Energy. *Managing Energy Costs in Schools: A Guide to Energy Conservation and Savings for K-12 Schools*. Published November 2007. https://www.xcelenergy.com/staticfiles/xe/Marketing/Managing-Energy-Costs-Schools.pdf.

11. Sleegers, P. J. C., N. M. Moolenaar, M. Galetzka, A. Pruyn, B. E. Sarroukh, and B. van der Zande. "Lighting Affects Students' Concentration Positively: Findings from Three Dutch Studies." *Lighting Research and Technology* 45 (2013): 159–175.

12. Choi, K., and Suk, H. J. "Dynamic Lighting System for the Learning Environment: Performance of Elementary Students. *Optics Express* 24, no. 10 (2016).

13. DOE. *2016 Human Physiological Responses to Lighting Meeting Report*. Washington, D.C.: SSLS Inc. and Navigant, 2016. https://energy.gov/sites/prod/files/2016/09/f33/ssl_humanresponse_sept2016.pdf.

14. IES. TM-18-08. *Light and Human Health: An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Response*. 2008.

15. CIE. *Technical Report 158:2009. Ocular Lighting Effects on Human Physiology and Behavior.* 2009.

16. Lucas, R. J., S. N. Peirson, D. M. Berson, T. M. Brown, H. M. Cooper, C. A. Czeisler, M. G. Figueiro, P. D. Gamlin, S. W. Lockley, J. B. O'Hagan, L. L. A. Price, I. Provencio, D. J. Skene, and G. C. Brainard. "Measuring and Using Lighting in the Melanopsin Age." *Trends in Neurosciences* 37, no. 1 (2014): 1–9.

17. Pacific Northwest National Laboratory. *CALiPER 23: Photometric Testing of White-Tunable LED Luminaires*. *Report Number PNNL-24595.* 2015.

18. Wilkerson, A. "DOE SSL Explorations into Color Tuning." Presentation at LIGHTFAIR International, Philadelphia, PA, May 2017.

19. Dikel, E. E., G. J. Burns, J. A. Veitch, S. Mancini, and G. R. Nesham. "Preferred Chromaticity of Color-tunable LED Lighting." *Leukos* 10, no. 2 (2014): 101–115.

20. Davis, J. L., A. Smith, T. Clark, K. Mills, and C. Perkins. "Lifetime Predictions for Dimmable Two-channel Tunable White Luminaires." Presentation at the 2017 Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITHERM 2017), Orlando, FL, 2017.

21. Clark, T. "Future-proof Tunable White Lighting is a Smart Choice for Classrooms." *LEDs Magazine,* 2016, 31.

22. IES. *TM-30-15: IES Method for Evaluating Color Source Rendition*. New York, NY: IES, 2015.

23. IES. *TM-30-15 Advanced Calculation Tool.* 2015

24. Royer, M., and K. Houser. *Understanding and Applying TM-30-15.* Joint DOE and IES webinar, 2015. https://energy.gov/sites/prod/files/2015/09/f26/tm30-intro-webinar_9-15-15.pdf.

25. DOE. *TM-30 Frequently Asked Questions*. 2016. https://energy.gov/eere/ssl/tm-30-frequently-asked-questions#TM-30 Measures and Meaning

26. More information is available at http://www.ltioptics.com/en/photopia-general-2017.html.

27. More information is available at http://www.agi32.com/.

28. IES. *IES LM-79-08, Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products*. New York, NY: IES, 2008.

29. DiLaura, D. L., K. W. Houser, R. G. Mistrick, and G. R. Steffy. *Illuminating Engineering Society: The Lighting Handbook, Tenth Edition: Reference and Application*. New York, NY: IES, 2011.

30. ANSI/ASHRAE/IES. *Standard 90.1-2016 - Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta, GA: ANSI, ASHRAE, and IES, 2016.

31. California Energy Commission. *2016 Building Energy Efficiency Standards for Residential and Nonresidential Buildings*. Sacramento, CA: California Energy Commission, June 2015. http://www.energy.ca.gov/2015publications/CEC-400-2015-037/CEC-400-2015-037-CMF.pdf.

32. Gigahertz-Optik. *BTS256-EF product literature*. https://www.gigahertz-optik.de/en-us/product/BTS256-EF/getpdf.

33. Perrin, T. W., C. C. Brown, M. E. Poplawski, and N. J. Miller. *Characterizing Photometric Flicker, Report Number PNNL-25135.* Washington, D.C.: DOE, 2016.

34. NGLIA and LSRC. *LED Luminaire Lifetime: Recommendations for Testing and Report, Third Edition.* Washington, D.C.: DOE, 2014. https://energy.gov/sites/prod/files/2015/01/f19/led_luminaire_lifetime_guide_sept2014.pdf.

35. NGLIA and LSRC. *LED Luminaire Reliability: Impact of Color Shift*. Washington, D.C.: DOE, 2017. https://energy.gov/sites/prod/files/2017/04/f34/lsrc_colorshift_apr2017.pdf.

36. RTI. *System Reliability Model for Solid-State Lighting (SSL) Luminaires. Project DE-EE0005124.* Washington, D.C.: DOE, 2017.

37. Nelson, Wayne B. *Accelerated Testing: Statistical Models, Test Plans, and Data Analysis*. Hoboken, NJ: John Wiley & Sons, 2004.

38. Hansen, M., and J. L. Davis. "The True Value of LED Packages." Presentation at the 2015 Strategies in Light Conference, Las Vegas, NV, 2015.

39. Hansen, M., and J. L. Davis. "Package Impact on Color Shift in LEDs." Presentation at the 2016 Strategies in Light Conference, Santa Clara, CA, 2016.

40. Brodrick, J., ed. *Solid-State Lighting R&D Plan. Document DOE/EE-1418*. Washington, D.C.: DOE SSL program, 2016.

41. Buffolo, M., C. De Santi, M. Meneghini, D. Rigon, G. Meneghesso, and E. Zanoni. "Long-term Degradation Mechanisms of Mid-power LEDs for Lighting Applications." *Microelectronics Reliability* 55 (2015): 1754–1758.

42. Huang, J., D. S. Golubovic, S. Koh, D. Yang, X. Li, X. Fan, and G. Q. Zhang. "Degradation Mechanisms of Mid-power White-light LEDs under High-temperature-humidity Conditions." *IEEE Transactions on Device and Materials Reliability* 15, no. 2 (2015): 220.

43. Davis, J. L., K. Mills, R. Yaga, C. Johnson, M. Hansen, and M. Royer. "Chromaticity Maintenance in LED Devices." In *Solid State Lighting Reliability: Components to Systems*, edited by W. D. van Driel, X. Fan, and G. Q. Zhang. New York, NY: Springer, 2017.

44. Tuttle, R., and M. McClear. 2014, February. "Understanding the True Cost of LED Choices in SSL Systems." *LEDs Magazine*, February 2014, 43.

45. IES. *TM-21-11: Projecting Long Term Lumen Maintenance of LED Light Sources*. New York, NY: IES, 2011.

46. Bobashev, G., N. Baldasaro, K. Mills, and J. L. Davis. "An Efficiency Decay Model for Lumen Maintenance." *IEEE Transactions on Device and Materials Reliability* 16, no. 3 (2016):277–281. doi: 10.1109/TDMR.2016.2584926

47. Davis, J. L., J. Young, and M. Royer. *CALiPER Report 20.5: Chromaticity Shift Modes of LED PAR38 Lamps Operated in Steady-State Conditions*. *Report Number PNNL-25201*. Washington, D.C.: DOE, 2016.

48. Davis, J. L., K. Mills, M. Lamvik, C. Perkins, G. Bobashev, J. Young, R. Yaga, and C. Johnson. "Understanding and Controlling Chromaticity Shift in LED Devices." In *Proceedings of the 18th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE 2017)*, Dresden, Germany, 2017.

49. Energy Star. *Energy Star Program Requirements for Luminaires*. 2015. https://www.energystar.gov/sites/default/files/Luminaires%20V2%200%20Final_0.pdf.

50. Winder, S. *Power Supplies for LED Driving*. Amsterdam, the Netherlands: Elsevier/Newnes, 2008.

Appendix A:
Products—Technologies and Techniques

This project demonstrated that tunable white lighting (TWL) technologies can achieve high luminous efficacies across a wide correlated color temperature (CCT) range. The Next-Generation Integrated Classroom Lighting System (NICLS) technology developed during this project has additional benefits including:

- Developing the NICLS TWL lighting-emitting diode (LED) modules achieving luminous efficacies in excess of 150 lumens per watt (lpw) at the LED module level;
- Demonstrating a luminous efficacy value for NICLS technology in excess of 125 lpw at the system level for all CCT values;
- Demonstrating a TWL range of 2,700 K to 6,500 K while maintaining a color rendering index (CRI) of 83 or higher at all values;
- Providing the capability for full-range dimming (100% to 1%) at all CCT values with flicker levels below industry guidelines, such as Institute for Electrical and Electronics Engineer recommended practice P1789, and compatibility with American National Standards Institute C82.77 requirements for luminaires;
- Incorporating daylight and occupancy sensing to provide automatic control of lighting zones to further reduce energy consumption;
- Achieving a rated lifetime on the system exceeding 50,000 hours with lumen maintenance of at least 85% at 50,000 hours;
- Achieving state-of-the-art lpw values for TWL technologies: in the fully on state, the lpw is only 0.67 W/ft^2, which is well below the industry standards set by ANSI 90.1, whereas the LPW will be below 0.091 W/ft^2 at a 10% dimming level; and
- Creating a teacher-focused user interface (UI) located at the front of the classroom to operate the lighting system: this UI is designed with greater use of icons and color than earlier UIs to provide teachers with an intuitive, easy-to-use interface, and a smartphone-based UI is also available to accommodate teacher movement in the classroom.

In achieving these outstanding results, a number of techniques were developed and are described further in this report. Among these techniques are the following:

- Advanced survey and data collection techniques for obtaining inputs on advanced lighting technologies from broad focus groups of educational professionals;
- Procedures for evaluating the flicker waveforms of TWL systems at both the room and individual luminaire levels;
- Techniques for evaluating the impact of driver aging (using accelerated stress testing protocols) on flicker waveforms in tunable lighting systems;
- Modeling procedures for calculating the chromaticity shift in both warm white and cool white LEDs used in a TWL system and to evaluate the change in the tuning range as the system ages;

- Methods to correlate lumen maintenance with the temperature and forward current used for different LED assemblies in linear TWL LED modules; and
- Procedures for calculating the lumen maintenance of linear TWL systems and demonstrating the change in lumen maintenance with the dimming level.

Appendix B: Products—List of Papers and Presentations

Table B.1 Products - List of Papers.

Document Title	Authors	Publication	Year	Vol.	Start Page	End Page
Future-proof tunable white lighting is a smart choice for classrooms	T. Clark	LEDs Magazine	2016	13	31	33
Leveraging accelerated testing to assess the reliability of two-stage and multi-channel drivers	J.L. Davis, C. Perkins, A. Smith, T. Clark, and K. Mills	2017 18th International Conference on Thermal, Mechanical, and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)	2017		1	14
Lifetime predictions for dimmable two-channel tunable white luminaires	J.L. Davis, A. Smith, T. Clark, K. Mills, and C. Perkins	The Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronics Systems (ITHERM)	2017			

Table B.2 Products - List of Presentations

Presentation Title	Authors	Presentation Site	Month	Year
Luminaires for Advanced Lighting in Education	J.L. Davis, K. Mills, T. Clark, A. Smith, E. Hensley	DOE SSL R&D Workshop, Raleigh, NC	February	2016
Tunable Lighting for Educational Settings	A. Smith, T. Clark, K.C. Mills, E. Hensley, J.L. Davis	Illumination Engineering Society Research Symposium III – Light and Color, Washington, DC	April	2016
Lighting the Classroom of the Future	T. Clark	LightFair International, Las Vegas, NV		2016
Key Issues in SSL Technologies	J.L. Davis	DOE SSL LED Product Development and Manufacturing Roundtable, Washington, D.C.	April	2016
Lighting the Classroom of the Future	T. Clark	Illumination Engineering Society Annual Conference, Orlando, FL	October	2016
White Tunable Lighting Case Studies	A. Smith	DOE SSL Marketing Introduction Workshop, Denver, CO	November	2016
Luminaires for Advanced Lighting in Education	J.L. Davis, K. Mills, E. Hensley, T. Clark, A. Smith	DOE SSL R&D Workshop, Long Beach, CA	Feb.	2017
Lifetime Predictions for Dimmable Two-Channel Tunable White Luminaires	J.L. Davis, T. Clark, A. Smith, K. Mills, C. Perkins	IEEE Intersociety Conference of Thermal and Thermomechanical Phenomena in Electronic Systems (ITHERM), Orlando, FL.	June	2017

Appendix C:
Products—Networks and Collaborations Fostered

It is RTI International’s belief that the results of this project will be most useful to our client and the industry with a rich contribution from the industry itself. Through partnerships and expert input, RTI fostered industry buy-in to the concepts developed during this project.

Project Partner:

Organization Name: Finelite, Inc.
Location of Organization: Union City, CA
Partner Contribution to the Project

- Development of light-emitting diode (LED) modules, light engines, and luminaires;
- Fabrication of LED modules, light engines, and luminaires;
- Leveraging of existing supply agreements to obtain high access to critical components, such as high-efficiency LEDs and drivers, which were critical to the success of the project;
- Construction of the demonstration site for the United States Department of Energy Classroom of the Future;
- Presentation of results at technical conferences; and
- Financial support.

Additional Project Collaborators:

Organization Name: Pacific Northwest National Laboratory
Location of Organization: Portland, OR
Partner Contribution to the Project

- Technical consultations on aspects of tunable white lighting technologies in the classroom, including system design, user interfaces, and flicker performance.

Appendix D:
Products—Inventions/Patent Applications

No patents were filed nor any inventions disclosed during the period of performance of this project.