PNNL-13535

Pacific Northwest
National Laboratory
Operated by Battelle for the
U.S. Department of Energy

New Technology Demonstration Program

Results of an Attempted Field Test of Multi-Layer Light Polarizing Panels in an Office Space

E. E. Richman

June 2001

Prepared for the U.S. Department of Energy
Federal Energy Management Program
under Contract DE-AC06-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

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Preface

The mission of the U.S. Department of Energy's Federal Energy Management Program (FEMP) is to reduce the cost of government by advancing energy efficiency, water conservation, and the use of solar and other renewable technologies. This is accomplished by creating partnerships, leveraging resources, transferring technology, and providing training and technical guidance and assistance to agencies. Each of these activities is directly related to achieving requirements set forth in the Energy Policy Act of 1992 and the goals that have been established in Executive Order 13123 (June 1999), but also those that are inherent in sound management of Federal financial and personnel resources.

The Pacific Northwest National Laboratory (PNNL)[(a)] supports the FEMP mission in all activity areas. This responsibility includes working with various Federal energy managers to identify, monitor, and evaluate the performance of new energy efficiency technologies suitable for installation at Federal sites.

This report provides the results of a field evaluation that PNNL conducted for FEMP under the New Technology Demonstration Program. The report examines the performance of multi-layer light polarizing technology installed in a small office test area in the General Services Administration (GSA) headquarters building in Washington, D.C. Participating in this effort were Polarized Lighting Inc., GSA, and PNNL. The light polarizing panels were provided by Polarized Lighting and installed by GSA Facility Services at the site. PNNL monitored the technology's installation process and the operating performance of the polarized lighting system.

(a) Pacific Northwest National Laboratory is operated by Battelle for the U.S. Department of Energy under contract DE-AC06-76RL01830.

Summary

Laboratory tests, anecdotal data, and the understanding of the physics of light have been instrumental in defining, proving, and promoting the potential benefits of vertically polarized light. This bank of knowledge, data, and understanding have led to the hypothesis that the polarization of lighting in the work environment can lead to more efficient visual acuity at lower overall light levels, which in turn leads to reduced lighting energy use. A "real-world" test demonstration of this hypothesis was undertaken under the Department of Energy's (DOE's) Federal Energy Management Program (FEMP) New Technology Demonstration Program (NTDP). The test demonstration involved cooperation from the technology proponent (Myron Kahn of Polarized Lighting Inc.), a Federal test site (General Services Administration Headquarters building in Washington, D.C.), and an analysis laboratory (Pacific Northwest National Laboratory).

A Cooperative Research and Development Agreement (CRADA) was used as the format for this cooperative multi-organization project. The CRADA document identified responsibilities and activities in the project as well as a test methodology and project plan agreed to by all parties. The test protocol developed for this project was a comparison of the perceived ability of the occupants to perform their visual tasks under two different lighting systems and at different light levels on the horizontal work surface plane. The general lighting levels in foot-candles (fc) that the occupants were comfortable with and that they believed provided adequate lighting for their tasks would form the basis for determining potential energy savings. Any difference in the chosen levels for both systems could be considered potential energy savings (fewer lumens of light required for equivalent visual performance = fewer watts of power needed, and thus lower energy costs).

The first part of the testing was a baseline phase where the comfort and effectiveness of the current typical federal office lighting was evaluated through real world occupant responses to varying light levels (three different levels). Some initial concerns from the occupants with the lowest light level were noted and corrections to the test protocol were made. At the midpoint of the test project, the new polarized lighting lenses were installed and the second half of the test initiated. This testing was performed using the same modified (based on initial light level concerns) test protocol used in the first half. However, the test space occupants choose not to continue with the testing activities after the first week of polarized lighting. The primary reason offered was dissatisfaction with the lowering of light levels under the new polarized lighting as part of the test activity. Similar concerns were raised during the first half of the test when adjustments were made.

Because of the halt in the test project, it was not possible to collect the critical data regarding occupant reactions to the technology and their capabilities while working under it. Therefore, no analysis could be completed and no results could be determined from the testing. The inability to complete the test does not provide any concrete information about the applicability or visual effectiveness of the polarized lighting itself. Anecdotal comments from the occupants indicate that there was a noticeable difference between the two lighting systems. The occupants perceive the polarized lighting system as generally dimmer even though the horizontal light levels were the same. This effect of the visual perception of polarized lighting in a field view is a known attribute of the technology. It is the opinion of the author that this phenomenon and the fact that the occupants were aware that this was a test of "new" lighting were the primary drivers in the discontinuation of the test demonstration.

Contents

Introduction

An assessment of the potential energy savings associated with the use of multi-layer light polarizing panels in an office space was initiated as part of the Department of Energy's (DOE's) Federal Energy Management Program (FEMP) New Technology Demonstration Program (NTDP) in 1997. This project was intended to provide information on the visual effectiveness and application of this technology that could help Federal energy managers and other interested individuals determine if this technology had benefits for their occupied spaces. The use of an actual working office area provided the capability of evaluating the technology's effectiveness in the "real world."

The report begins with some brief background on light polarizing technology and its reported benefits. This is followed by a description of the actual field test setup and planned administration of the test. This includes a basic assessment of the data that was collected and any pertinent results from it. The remainder of the report is devoted to a discussion of the general evaluation strategy that was developed specifically for this test. An appendix is included with copies of the documents and forms used in the collection of survey data and a summary of the actual response data.

Technology Background

Polarized Lighting (PL) is the result of a reorientation or selection of light waves in a vertical plane rather than all directions normally found in standard lighting systems. This vertical orientation of light has the property of eliminating part of the reflected glare on working surfaces that cause poor visual conditions.

By reducing glare on work surfaces, many believe that lower lighting levels of polarized lighting are sufficient to perform the same task that requires a higher level with standard unpolarized lighting. This can be particularly important to office-type environments where the reading of printed materials and computer screens forms a large part of the work. The reduction of glare through the polarization of light has been proven in laboratory testing. This effectiveness of polarization on reduced reflective glare has also been shown to depend greatly on the angle of view from the source of light. Laboratory tests have also shown that lighting levels can be reduced when the light is polarized without affecting the occupant's ability to see effectively. These laboratory test results provide the basis for an assertion that polarized lighting can be used to reduce lighting levels, and therefore energy use, in the workplace.[(a)]

However, some of the research questions the significance of the improved lighting quality in all situations, noting that while it does have definite benefits in specific viewing conditions this may not translate to a noticeable effect in real-world conditions.

(a) "Multilayer Polarized Light," Technical Memorandum (TM-4), Illuminating Engineering Society of North America, August 1997.

Field Test Setup

The assessment test was located in an office area in the General Services Administration (GSA) headquarters building in Washington, D.C. The area was chosen because the occupants spend the majority of their day under the lighting in the area and have no access to daylight. This serves to restrict their access to "other" lighting systems that could affect the results of the test. The occupants are engaged in typical office-type work and the surroundings are typical of Federal office environments. Dimmable ballasts and controls were installed in the fixtures in the space to facilitate the periodic adjustment of light level.

Test Procedure

The first 9 weeks of testing involve the existing T-8 electronic ballast standard GSA design lighting without polarizing lenses. Throughout these first 9 weeks, the level of the existing lighting was changed each week, either up or down according to a prescribed evaluation protocol by means of the dimming control. Each of three prescribed lighting levels was visited three times during the 9 weeks according to the following schedule:

	Week								
	1	2	3	4	5	6	7	8	9
Existing Lighting Levels	high	mid	low	mid	low	high	low	mid	high

This schedule ensures that each lighting level is visited three separate times and not always from the same direction (e.g., from a higher or a lower lighting level). The schedule incorporates a high to low set, a low to high set, a one level up and down set and a two level up and down set. This arrangement conforms to the statistically based Latin square design that is used to control effects due to the order of exposure to the various conditions (in this case lighting levels).

	Test #1	Test #2	Test #3
Week 1-3	Light level "high"	Light level "medium"	Light level "low"
Week 4-6	Light level "medium"	Light level "low"	Light level "high"
Week 5-9	Light level "low"	Light level "high"	Light level "medium"

The lighting is initially set at a "high" level consistent with current typical lighting practice (around 50 footcandles on the work surface). The "low" value was determined to be approximately 20 footcandles based on the light level typically designed for use by the Technology proponent (Kahn). The "mid" value was set midway between the high and low. The changes in

lighting level were made between Friday after hours and Monday start of workday. This provided the occupants with an entire weekend away from the workplace lighting between changes. This provides the best opportunity to allow for occupant evaluation of lighting on its own merits without direct, near-term comparison of previous lighting.

At the end of this 9-week evaluation period, multilayer polarizing lenses were installed in each of the fixtures. For the next 9 weeks the lighting levels was to be changed in a manner identical to that used in the first 9 weeks. The entire 18-week evaluation period should appear to the occupants to be one continuous consistent evaluation with as little as possible knowledge of lighting system changes.

The occupants in the evaluation area were surveyed once each week on or about Wednesday to allow them to become accustomed to that week's lighting. Weeks that incorporated a holiday or other major work schedule disruption were considered off-weeks. The lighting level for off-weeks was set the same as the previous week. However, the survey was administered in the same manner for that week.

The occupants were told that they are part of a study being conducted on occupant responses to lighting conditions in real-life settings. They were told that changes would be made periodically in the lighting system so that their response and assessment of it could be recorded. They were not told any details of the project such as when changes would be made and specifically what type of lighting is being installed. They were, however, given some minimal instruction at the start of the test as to what attributes of the lighting in their space we wanted them to be aware of.

Illumination measurements (for reference only) were taken at each workstation for each of the three proposed lighting levels. This allowed direct association of survey data with more precise lighting level conditions.

Survey Administration

The initial letter with data survey and the weekly response surveys were administered by GSA staff. One to 2 weeks prior to the start of the test, the initial survey and letter were distributed to each room occupant. The surveys were returned by the occupants directly to PNNL's Richland, Washington, office for processing. Names or other personal identifying information were not used on any of the survey responses. Each survey provided a blank for the last four digits of the occupants Social Security Number (SSN) to be used in comparing the results of each occupant individually. This method allows the tracking of individual data from week to week. It does not, however, allow the identification of the individual to the data because only the researcher has these four digits (surveys were sent directly to the researcher through U.S. mail,

not handled by the employer) and the researcher has no knowledge of the occupant's complete SSN. The inclusion of these four digits was, of course, voluntary and did not have to be provided if the occupant still had concerns about anonymity.

Survey Format

The survey instrument is the primary data collection portion of this evaluation. An initial characterization survey was administered prior to the test periods along with a letter describing the test project. This survey provided information on the kinds of work performed and visual concerns of the occupants. The weekly survey is designed to collect occupants' perceptions of how the lighting (that week) affects how they see with respect to their ability to comfortable and effectively do their work. The PNNL description letter, initial characterization survey, and weekly response survey are included in the Appendix.

General Evaluation Strategy

Major Issues

The assessment of lighting systems by human users is by nature very visually oriented. Humans naturally associate light level differences with visual ability (sundown—loss of exterior visibility). Therefore, a natural tendency of lighting users will be to initially assess lower light levels as less visually effective.

There is some level of light that must be maintained for an acceptable level of visual ability. The reported effects of polarized lighting indicated that much less light can be used effectively. However, the current lighting levels applied to buildings are subject to variation (factors of 2 and more) and therefore make the definition of a base lighting level (upon which comparison and energy savings are based) difficult. In addition, the level of light considered appropriate with polarized lighting must be chosen to achieve maximum energy savings without being considered a failure by the occupants providing their assessment.

Since this is a field evaluation and not a laboratory test, the conditions of environment, occupants, and activities cannot be strictly controlled.

The polarized lighting technology may be able to save money by decreasing the levels of light needed and therefore reducing the power required to light a facility. To assess and quantify these potential savings with respect to use in Federal facilities, the methodology must:

- Determine the applicability of the polarized lighting system (at a level that is cost-effective compared to standard lighting) to ensure it provides lighting that is functionally equivalent to existing lighting systems and is acceptable to typical occupants as workplace lighting.

- Determine typical potential savings associated with the application of an appropriate polarized lighting system and compare life-cycle costs with other lighting systems.

To accomplish this in a field setting, the evaluation must focus on occupant perception, comfort, and acceptance of the lighting system. Unlike laboratory assessments where occupants evaluate specific tasks under controlled conditions, this evaluation must be able to reasonably determine occupant satisfaction and effects on work environments.

Because of the natural tendency of humans to instantly perceive general light levels directly related to visual ability, a method must be used to mitigate this effect. Occupants must therefore be able to work in a normal fashion surrounded by one lighting system (existing or polarized lighting). This will help ensure that their opinions are based on their activity and reactions to the lighting system itself without constant comparison with a higher or lower level system nearby. Occupants must exist in this near 100% control or polarized lighting for a long enough period to allow them to become accustomed to and accept or reject the system on its own merits. This will be very difficult if occupants must travel through other differently lighted areas to and from or during work. Therefore, the space(s) chosen must be such that there is minimal contact with other lighting.

The primary evaluation tool must be occupant perceptions and reactions to various levels of polarized lighting and standard lighting systems. The evaluation can be strengthened by attempting to determine occupant perceptions of functionality of specific tasks (reading, writing, screen viewing, etc.). Other potential effects of changing lighting systems such as fatigue and eye strain must also be considered. Overall perceptions such as general visual enhancement should also be determined as part of a complete assessment of occupant reaction to the lighting system. This evaluation will be performed via an occupant survey or query. This query may be administered by mail or as an on-line query through existing computer systems if these are present in the evaluation areas.

Evaluation Parameters

- *level* - light levels for control area(s) and the polarized lighting area(s) must be set and documented as a measure of the relative light levels between technologies and as compared with current industry practice..

- *occupant acceptance* – this will need to be carefully measured over a long enough period of time to mitigate initial natural occupant perceptions and comparisons with other lighting systems. Fairly large numbers of subject occupants must also be used to ensure a reasonable sampling of occupant reactions.

- *Energy differences* – long-term metering is not required for this type of lighting evaluation. One-time measurements of operating fixtures as well as other manufacturers and independent test data and fixture counts will provide the needed energy consumption data.

- *Operational differences* – information on costs, maintenance, lifetime, etc. will be needed to calculate cost-effectiveness of the technology. Most of this will be available from manufacturers data and Federal site experience.

Experimental Design

Two independent variables have been determined to potentially affect user performance, behavior and job satisfaction. Each independent variable will be manipulated to determine its effect on user performance, behavior, and job satisfaction. The independent variables are lighting type (standard T8 lighting and polarized lighting) and lighting level (high, medium, and low). The dependent variables for this study generally fall under the categories of visual effectiveness and visual satisfaction. Measures for this study will be a seven-point, self evaluation questionnaire filled out by subjects during each of the testing periods.

The questions the subjects will be responding to cover brightness, reflections, glare, physical discomfort associated with the eye, suitability of the light for the tasks they perform, etc. A complete survey with the questions is attached.

To make an effective comparison between lighting levels and type of light, each subject will be exposed to each light level under both types of light. An absolute judgment of visual effecttiveness and visual satisfaction for the different lighting conditions is not required to determine which design is best for each subject. A relative measure is appropriate and will be obtained by applying a “within groups” format to the study. All levels of independent variables are combined with every level of every other independent variable. Many extraneous variables exist that could confound the study and should be addressed or measured to ensure valid results. These

variables include age, glasses/contacts, sickness, use of task lighting, background contrast and lighting distribution, type of task (e.g., computer, reading), number of breaks from workstation, length of shift.

Subjects

From a statistical view, the following formula (Snedecor and Cochran, Statistical Methods, 7th, 1980) provides a method of estimating the sample number of observations required to achieve significant results based on an estimated error variance and standard deviation.

$$n = \frac{(Z_{a/2})^2 (o)^2}{E^2}$$

where n = required sample size

$Z_{a/2}$ = the desired confidence level of the resulting sample size (1.65 for 90% confidence)

o = the estimated standard deviation variation in the entire sample based on the term 0.21*h for a skewed distribution where h is the maximum value of difference in the sample data. The survey questions had responses from 1(good) to 7(bad). Therefore the variation and resulting standard deviation value is 0.21*(7-1) or 1.26.

E = the error vale of the responses. This was chosen at 0.5 to represent a fairly tight distribution of responses around the expected value.

To achieve statistical power at 90% confidence level, at least n=18 subjects are needed.

Test Progression and Results

The project initially began with interest from the Pentagon Building in Washington, D.C., in providing real-life testing within office interiors. Several meetings were held at the site and specific rooms were identified. However, delays in obtaining the polarized lenses for installation and the ongoing major renovation efforts and associated schedule conflicts forced the Pentagon to decline participation. A search for another test site resulted in a CRADA agreement with the GSA headquarters building, also in Washington, D.C. An office area that was recently refurbished was chosen as a test space and the first nine weeks of the test with standard efficient office lighting (no polarizing lenses) began as planned. The GSA contact made the lighting level changes (low = 20 footcandle [fc], mid = 35 fc, High = 50 fc) and distributed the surveys each week. At week 3 of the test period the light level was set for the first time at the low level average of 20 fc. Early in this week the site contact received several complaints about how dim the space had become. The decision was made to return the lighting to the mid level of 35 fc for that week. From this point on the three light levels were reset at low = 35, high = 50, and mid set between 35 and 50. This set of levels was used for the remainder of the first half of the test. It

has long been understood that light level differences below approximately 15 fc are often not readily discerned by the human eye unless the change is seen taking place. However, there was no practical way to reconfigure this test at the time to account for this possibility.

At the halfway point of the test, the lenses in the fixtures in the entire space were replaced with multi-layer polarizing lenses. The second half of the testing began the week after the replacement of the lenses. The first level was at 50 fc and no concerns were noted. The second week started off with a reduction over the weekend to midway between 35 and 50 fc. This light level sparked several comments to the site contact regarding concerns of the lighting being too dim. Based on these comments and concerns, the site contact chose to discontinue the testing.

Because there is essentially no survey data from the second half of the test, it is not possible to present any comparisons between the two lighting systems. Because this was the ultimate goal of the test project, there are no actual reportable results. However, the data from the first half of the testing can provide some insight into occupant perceptions of the effect and effectiveness of different light levels with the same lighting system. The data at first look tends to confirm the expected results that at lower light levels perception abilities degrade and the problems with low light levels tend to increase. However, from a statistical standpoint the evidence is not very strong.

A 95% confidence level (F-test at 0.05) of statistical significance was applied to the responses to the questions for the three different light levels averaged over the three test weeks for each level. Of the 20 questions only 3 (#5, 11, 15) indicate that the occupants had a true and **perceivable** preference for higher light levels. The results of the remaining 17 questions were either borderline significant (#7) or not at all significant. A further look at the significance of differences between the sets of weekly tests is perhaps even more interesting. In this case the same statistical significance test for differences was applied between the three sets of weeks within which each light level was visited once. These results indicate a significant difference in the responses for 7 of the 20 questions. This shows that differences in responses over time may be more significant than the differences associated with light level changes. It is impossible with this specific test protocol to determine the exact causes of these specific results. However, these data do suggest that the small difference between light levels (7.5 fc) used in this test may have been imperceptible compared to other changes with time in environment.

Appendix

Initial Study Letter to Occupants
Initial Characterization Survey
Weekly Response Survey

March 4, 1998

Dear GSA Staff Member,

As you are undoubtedly aware, the room you work in has been selected as a trial space for lighting systems under consideration for use in GSA and other Federal facilities. The light level adjustments and weekly surveys you were asked to participate in last year were the first half of the test. The second half begins this week and will continue for an additional 9 weeks.

I appreciate the fact that filling out the one page survey seems redundant at times and it is very easy to decide not to provide this information. I would ask that you please bear with this effort so that sufficient data can be collected to determine if various lighting technologies are better than others.

As with the first half of the testing, the lighting in your workspace will be changed several times by GSA facilities staff and you will be asked to give your candid evaluation of how effective, comfortable, and useful the lighting is to you. The different lighting system changes will be made using the existing fixtures currently in place and you may not be aware of changes by simply looking at the fixtures. The changes will be made with minimal disturbance and as much as possible during off-work hours.

Again we ask that you use just the last four digits of your social security number (you cannot be identified by these four digits alone and this information will never be released to anyone) so that we can compare your specific preferences among the lighting systems. A prepaid and addressed envelope is provided with each survey (**starting with the one attached for this week**) so that your responses are not available to anyone but the research staff from Battelle PNNL.

If you were not in this workspace during the last set of testing (Sept. 9 through November 13), we would still like your input. For comparison records we would also like to get some background information from you and ask that you fill out the attached background information survey.

We appreciate your willingness to evaluate various lighting systems and provide us your candid input. You are, of course, free to choose at any time whether or not to provide us with responses to our surveys. Your participation has no effect on your work situation or relationship with your employer and as mentioned above your responses can never be associated with you specifically. If you have any questions about this activity please contact either your room contact, Ralph Walters or myself.

Thank you,

Eric Richman
(509) 375-3655
Principal Investigator
Battelle, Pacific Northwest National Laboratory

[PLEASE FILL THIS OUT IF YOU DID NOT FILL ONE OUT DURING THE FIRST HALF OF THE TEST IN SEPTEMBER OF 1997]

Lighting Test Background Information Last four digits of SSN ___ ___ ___ ___

Age group: ___ less than 40 ___ 40-55 ___ greater than 55

Sex: ___ M ___ F

At work do you normally wear:

___ Contacts?

___ Eyeglasses?

___ Reading Glasses?

To your knowledge are you colorblind/color deficient? ___ Y ___ N

Do you have cataracts or other vision impairments that currently effect your vision? ___ Y ___ N

How much of your typical workday (hours) involves:	Less Than 1 Hour	1 to 4 Hours	More Than 4 hours
computer word processing?			
computer data input and analysis?			
reading print on white paper?			
reading print on glossy paper (i.e., magazines, brochures)?			
looking at small print or objects with fine details?			

Do you have any problems or concerns about your current workplace lighting?

When completed please return in the attached prepaid preaddressed envelope. Thank you for your time!

Lighting Survey ID Number _____

Today's Date: _____ Time: _____

Please answer the following questions based on how you feel about the overhead lighting in your workspace this week. Please use the following 7-point scale to indicate your level of agreement with each of the statements below by circling **ONE** of the seven numbers next to each statement.

Disagree Very Strongly	Disagree Fairly Strongly	Disagree	Undecided	Agree	Agree Fairly Strongly	Agree Very Strongly
1	**2**	**3**	**4**	**5**	**6**	**7**

1 2 3 4 5 6 7 -- This lighting allows me to see comfortably.

1 2 3 4 5 6 7 -- Under this lighting I experience difficulty reading my computer screen.

1 2 3 4 5 6 7 -- There is a distracting noise coming from the overhead lighting fixtures.

1 2 3 4 5 6 7 -- The overhead lighting is too bright for me.

1 2 3 4 5 6 7 -- Under this lighting reading printed materials is difficult.

1 2 3 4 5 6 7 -- I am using my task lighting (undershelf lights) for longer periods of time.

1 2 3 4 5 6 7 -- I have experienced more headaches than usual while at work.

1 2 3 4 5 6 7 -- This overhead lighting is acceptable for the work I do.

1 2 3 4 5 6 7 -- My eyes tire more easily at work than usual.

1 2 3 4 5 6 7 -- I find printed materials are easy to read with this lighting.

1 2 3 4 5 6 7 -- At work I am having more trouble than usual focusing my eyes.

1 2 3 4 5 6 7 -- This overhead lighting is insufficient for the tasks that I perform.

1 2 3 4 5 6 7 -- Under this lighting, reading glossy materials (magazines, brochures) is difficult.

1 2 3 4 5 6 7 -- This lighting is pleasant to work under.

1 2 3 4 5 6 7 -- This lighting makes colors in the room appear natural.

Please use the following 7-point scale to indicate how easy or difficult it is to read each of the four sentences below by circling **ONE** of the seven numbers next to each statement.

Unable To Read Very Easy To Read

1 2 3 4 5 6 7

1 2 3 4 5 6 7 -- While other plants put the sun's energy to work, the fungus must look elsewhere.

1 2 3 4 5 6 7 -- The end result of this project will be a sky atlas that includes 1,870 photographs of celestial bodies and their statistics.

1 2 3 4 5 6 7 -- Whenever you see a pile of leaves turning to compost, you are watching a fungus eating. The fungus has become the earth's scavenger.

1 2 3 4 5 6 7 -- Sky Survey astronomers have made scores of important discoveries including the fact that our universe is probably twice as old as previously believed. The Sky Survey indicates that the universe is probably more than 4 billion years old.

- Overall, how do rate the current overhead lighting from 1-(unacceptable) to 7-(great). _____
- Comments?

When completed please place in GSA mail to _____. Thank You!

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Julia Kelley
Oak Ridge National Laboratory
P.O. Box 2008, Building 3147
1 Bethel Valley Road
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Stephanie Tanner
National Renewable Energy Laboratory
901 D. Street, S.W., Suite 930
Washington, D.C. 20024-2157

No. of Copies

Myron Kahn
Polarized Lighting, Inc.
Box A
Tarzana, CA 91357

Ralph Walters
General Services Administration
7th & D Streets, SW
Washington, D.C. 20407

Kenneth Gray
General Services Administration
7th & D Streets, SW
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