FINAL REPORT

Daylight Redirecting Window Films

ESTCP Project EW-201014

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14. ABSTRACT

Daylight redirecting films were produced in a roll-to-roll format. The films were installed in six DoD buildings scattered across three broadly different climate zones. The key performance objective and results are summarized in this report. Significant findings from this study are also included.

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ACRONYMS

DoD	Department of Defense
HMG	Heschong Mahone Group
LEED	Leadership in energy and environmental design
DRF	Daylight redirecting film
HVAC	Heating Ventilation and Air Conditioning
PET	Polyethylene Terephthalate
kWh/sf	Kilo watt hour/squarefoot
PSA	Pressure Sensitive Adhesive
sDA	Spacial Daylight Autonomy
IES	Illumination Engineering Society
PO	Performance Objective

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EXECUTIVE SUMMARY

Improved daylighting in buildings has a substantial potential for energy savings. Lighting not only accounts for a large portion of the total building energy use, inefficient conversion of energy into light results in increased heat gain which in turn increases the cooling related expenses. The reduction in energy consumption results from the ability to dim or turn off electric lights as a result of daylight availability in the space. Daylight brings in other benefits such as reduced hospital stays for patients, increased retail sales and improved student achievements. However, penetration of sunlight into the building space can have negative consequences in terms of increased glare experienced by the occupants. This study was undertaken to evaluate the performance of a daylight redirecting film through field measurements as well as lighting and energy simulations.

Daylight redirecting films (DRF) were produced in a roll-to-roll format that consisted of acrylic micro-prismatic elements on a clear polyester (PET) substrate and coated with a pressure sensitive adhesive (PSA) on the backside. The microstructures are designed to maximize reflection of incident sunlight towards the ceiling and away from the perimeter walls to allow the ceiling surfaces to redistribute the light more uniformly in the space.

The films were installed in six different DoD buildings scattered across three different climate zones. The sites were selected based on user profile, building location, access, window design and structure as well as availability of similar, if not identical, space that could be designated as ‘control’ space in order to perform a side-by-side comparison.

The key performance objectives and results are summarized in the Tables below.

Performance Objective	Results
Increase daylight illuminance levels	**Success Criteria:** 10% increase in spatial daylight autonomy(sDA); increase in spatial-daylight uniformity; and increase in daylight autonomy **Fully met.** sDA in the treated spaces increased between 3%-24%, averaging 11%.
Economic Payback	**Success Criteria:** Savings to Investment Ratio (SIR): > 1.0; Net-present-value (NPV); Payback period: < 10 years **Frequently met.** Simple payback averages 10 years but dependent on electricity rates and climate (range of 3-35 years). NPV was positive and SIR ranged from 1.4 to 2.58
Potential to reduce lighting energy use	**Success Criteria:** Reduction in electric lighting by 25% at peak (200 hours/year) **Partially met.** 184-270 Full Load Equivalent hours (FLE) depending on blinds operation. Average peak demand reduction of 13%.
Reduce whole building energy use	**Success Criteria:** Reduction in whole building energy use (> 1.05 times the direct lighting energy savings) **Frequently Met.** Average annual whole building savings 1.30 times direct lighting savings. Range of 0.93-1.62 depending on climate.
Green-house Gas Emissions	**Success Criteria:** 10-year reduction of twice the manufacturing greenhouse gas. **Fully met.** CO2 emissions reductions due to the whole building energy savings are 0.59-3.26 lb/sf/yr. Embedded CO2 emission in the manufacture of the film is estimated to be 0.26 lb/sf.

Table 1. Quantitative performance objectives and demonstration results

Performance Objective	Results
Maintain or increase visual comfort	**Success Criterion:** Maintenance of or increase occupant visual comfort as determined from the survey response **Frequently met.** Occupant comfort was preserved or increased in all but one installation where the product was not installed high enough above eye level.
Improve preservation of views out from the building	**Success criterion:** Maintenance of or increase occupant visual comfort as determined from the survey response **Partially met.** Increase in occupant ranking of view quality. No discernible change in blinds operation
Reduce glare	**Success criterion:** Maintenance or reduction in subjective glare ratings **Frequently met.** Glare was unchanged or reduced in all but one space where DRF installed too close to eye level.
Maintainability of System	**Success criterion:** Film does not create significant film-maintenance needs **Fully met.** Staff did not report any maintenance concerns with DRF installation.

Table 2. Qualitative and other performance objectives and demonstration results

Following are the some of the significant findings from this study:

A. Energy savings that can be achieved as a result of the installation of DRF on clerestory windows are a function of building location, window orientation and type of photocontrols. The savings can range from 0.39 – 2.11 kWh/sf of the floor area based on the building location and window orientation.

B. Photocontrols are used in office space to reduce the electric lighting use that can result in substantial savings. However, the savings are restricted to a lighting zone within 8 feet from the window wall without the installation of DRF and may be significantly reduced if the occupants keep the blinds closed, as is frequently observed during this study and in other studies. This study has demonstrated that with the application of DRF, there is no risk of reduced energy savings from closed blinds. Furthermore, the savings with DRF can be higher than optimally adjusted blinds.

C. The daylit zone can be extended to at least 24 feet from the window wall compared to about 8 feet for a space with no DRF.

D. Spaces with DRF were perceived to be brighter and more cheerful.

E. It was necessary to position an optically diffusing surface in front of microstructured film adhered to the glazing surface to minimize the occasional glare. Due to the vagaries of the window design at each site, different methods were adopted to install the diffuser. The diffuser characteristics were carefully chosen to have no discernible impact on the optical characteristics of the system.[1]

F. The increase in illuminance due to DRF was not accompanied by a corresponding increase in glare. In some instances, glare was in fact reduced or eliminated as a result of application of DRF.

[1] Unless otherwise described, DRF in this report refers to the combination of microstructured and diffusing film and is taken as a system.

1. INTRODUCTION

1.1 BACKGROUND

Since the 1970's, the United States Congress has mandated improvement in building efficiencies and a reduction in energy consumption by all federal agencies. The Department of Defense (DoD) is the largest energy consumer in the United States and accounts for approximately 63% of the energy consumed by federal facilities and buildings [1]. Electric lighting accounts for 25% of a commercial building's total energy consumption and 40% of the electricity consumption in the United States [2]. In addition, the use of electric lighting results in substantial heat gain and cooling demands. Peak cooling loads are also increased because of the unnecessary use of electric lighting. Several studies have shown that better use of daylight can reduce energy demands by 20-40% while reducing emissions and carbon footprint [3].

There are also psychological benefits to better use of natural daylight. In addition to providing a connection to the outdoors, daylight can provide visual comfort, stimulate healthy circadian rhythm, reduce stress, and improve productivity and attentiveness [4,5,6].

The daylight availability is extremely dynamic due to the changing weather conditions from hour-to-hour, day-to-day and month-to-month. Building design and geographical location also play an important role in determining the daylight availability. Increasing the daylight availability by increasing the size of the window is not a good solution as it results in large variation in the light levels near the window to the back of the room. Increasing the window size can also increase solar heat gain and result in uncomfortable glare, especially for office occupants near the window.

Glare control and interior shading devices such as venetian blinds and movable screens are often provided with the window. Shades are lowered and blinds are closed to address the high glare producing weather conditions and are not changed back to make use of the available daylight when appropriate [17]. With the closed shades or blinds, electric lighting is the only way to provide adequate lighting within the room, thus increasing the energy demand. Buildings are often designed where the windows are split into view window and clerestory window. Clerestory windows are windows above eye level whose purpose is to bring daylight into the space. However, these windows frequently end up as a significant source of glare and are often covered up with various types of shading devices by the occupants, thus defeating their original purpose (for an example of such a situation encountered in one of the study spaces, please see Figure 7).

A variety of products such as light shelves, light redirecting blinds, prismatic panels, etc., are available in the marketplace to address the need for better daylighting [7]. These products are generally proposed during the design phase of a building and are often not implemented due to very high installation and maintenance cost. Most of these products are either not suitable or cost prohibitive for retrofitting to an existing window to make better the use of daylight.

As the need and desire for net zero energy buildings grow and the stock of existing buildings get upgraded for energy efficiency, it is understood that effective use of daylight is critical in meeting these goals. Organizations such as Green Building Council (GBC) through their LEED (Leadership in Energy and Environmental Design) program have been effective in promoting better use of daylight as one of the means for improving energy efficiency in buildings.

A significant amount of research and development has gone into developing devices that are efficient at redirecting sunlight or diffuse daylight deeper into the building interior. Devices such as angular selective glazing [8], and holographic optical elements [9] have high redirection efficiencies only for a narrow set of solar incident angles resulting in insignificant energy savings. Other static systems such as prismatic optical elements, mirrored louvers and lasercut panels [7] have improved performance over a range of solar altitudes but their effectiveness has not been proven. Even more complex solutions involve roof mounted, sun tracking heliostats coupled to mirrored ducts [10] or fiberoptics [11]. A thorough performance assessment is not available for many of these devices. Moreover, when available, the assessments have focused on lighting energy use savings without consideration of potential increased demand for cooling energy or the impact on glare. Since glare calculations and measurements are extremely difficult and fraught with errors, any glare assessment must be verified with human factor evaluations.

Thus there is a need to evaluate daylight redirecting films or systems under a variety of conditions and a thorough evaluation completed to better assess the potential for energy savings in DoD buildings.

1.2 OBJECTIVES OF THE DEMONSTRATION

In this project, we have attempted to address the above-mentioned issues in a comprehensive manner. Through this demonstration, our goals were to verify the performance of daylight redirecting film, scale-up the prototype daylight redirecting film to produce at least 48” wide film, quantify the potential for energy savings and qualitatively assess occupant satisfaction. Site measurements of ceiling and desktop luminance were conducted and compared with those predicted by simulation. The Daylight Redirecting Window film ESTCP Demonstration was initiated to gain real world feedback on a promising new daylighting retrofit technology that has the potential to reduce the energy use in existing Department of Defense (DoD) buildings.

We deployed a variety of techniques to determine the effectiveness of the film. Heshchong Mahone Group Inc. (HMG)[2], a professional consulting services company specializing in the field of building energy efficiency, was hired to assist in this study in the selected DoD buildings.

Luminance monitors were installed in selected spaces or portions of the building, utilized simulation techniques, and conducted surveys of the occupants. The surveys evaluated

[2] Heshchong Mahone Group was acquired by TRC on Jan. 14, 2013. http://www.trcsolutions.com/Pages/default.aspx

occupant comfort in terms of glare, light quality, and aesthetic quality. Surveys were conducted before and after installation of the window film to determine the effect of application of film.

Six buildings representing three major climate zones were chosen for the study. Not surprisingly, varying degrees of positive results were obtained. Clearly, our measured data shows a significant opportunity for lighting and whole building energy reduction in sunny climate (29 Palms, CA and Fort Bliss, TX). In locations where less direct sunlight is available, more moderate reductions is achievable. Overall, the occupant response pointed to either a significant reduction in glare (29 Palms) or no dissatisfaction as a result of application of daylight redirecting films. The simulation results indicate that 3M film enables persistent daylight harvesting savings eliminating the risk of these savings negated by occupants closing the blinds.

The daylight redirecting film studied in this project does not contribute to the energy savings by itself. It is designed to provide daylight deeper into the space thus reducing or eliminating the need for electric lighting. Therefore, it is necessary to have photocontrols that are designed to dim or turn off electric lights resulting in energy savings. Furthermore, since all of the study sites except one (29 Palms) had no photocontrols, energy savings were not tracked during the project. Instead, a simulation exercise based on the measured optical characteristics is to predict the potential energy savings in three different climate and geographical regions.

- **Validation:** Daylight distribution in the room was measured over at least six month period and compared with a similar control space to determine the increased illuminance provided by DRF. Potential to reduce energy usage in building was estimated by carrying out modeling studies.
- **Technology transfer:** The project team encountered unique situations within each of the sites not commonly seen in commercial real estate. While some of these, such as the turnover of site management, reluctance in carrying out window treatment modifications, etc., may not be relevant to a commercial project, they represent a barrier to widespread deployment of the technology for aftermarket applications. The project highlighted the difficulty in carrying out the present DRF design, i.e. the need for a separate diffusing pane. On the other hand, the project was very successful in demonstrating the DRF technology can result in significant energy savings and result in improved visual comfort if deployed correctly.
- **Acceptance:** The project was able to identify conditions where the DRF technology improved the occupant visual comfort. Studying, documenting and providing detailed explanation of these conditions will help DoD in meeting its energy reduction goals. The project helped identify the complexities of implementation of daylight redirecting technologies that gave researchers and product developers at 3M direction for further improvements of the product.
- **Additional benefits:** No benefits in addition to the ones already listed above were observed or demonstrated during this project.

- **Deliverables:** The project team collaborated with researchers in other organizations (LBNL) to validate characterization technique for complex glazing materials.

1.3 REGULATORY DRIVERS

Following legislations, executive orders and directives state a variety of plans, programs and approaches all aimed at reducing energy consumption.

- Energy Policy Act of 2005 (P.L. 109-58)
- Energy Independence and Security Act of 2007 (P.L. 110-140)
- National Defense Authorization Act for FY 2007 (P.L. 109-364)
- National Defense Authorization Act for FY 2008 (P.L. 110-181)
- National Defense Authorization Act for FY 2009 (P.L. 10-417)
- Executive Order 13423
- Executive Order 13514
- Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding

Various sections of these drivers address the overarching goals of increasing energy efficiency and conservation. In addition to improving energy efficiency and increasing energy conservation, there is a global trend to improve indoor air quality, decrease pollutant emissions, and increase the use of daylight in buildings. Daylight in buildings is a very active research subject with leading institutions from around the globe engaged in understanding, improving and implementing different strategies for better use of daylight.

2. TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

Sunlight incident on a vertical window is directed towards the ceiling by using window film specially designed microstructures on the surface. These structures run along the width of the window and are designed to redirect the incident light towards the ceiling. The microstructures are designed based on reflection principles and refraction effects are minimized to prevent coloration n the redirected light. The microstructures are chosen such that the incident light is directed as far into the room as possible. Photographs in Figure 1 show the effectiveness of one particular light redirecting film. It is readily evident that by applying the film on upper 1/3rd of the window, the light level in the room is substantially improved. Key features of this technology are graphically depicted in Figure 2.

Figure 1. Photographs taken with a fisheye lens demonstrates the effectiveness of the daylight redirecting film.

In Figure 1, the photograph on the left is taken with the daylight redirecting film on the window and one on the right without. The increase in brightness even in the corners of the room is remarkable. As evident from Figures 1 and 2, the light incident on the upper portion of the window is redirected towards the ceiling and the back of the room. It is also clear that the direction and intensity of the redirected light will be a strong function of the factors listed in Figure 2.

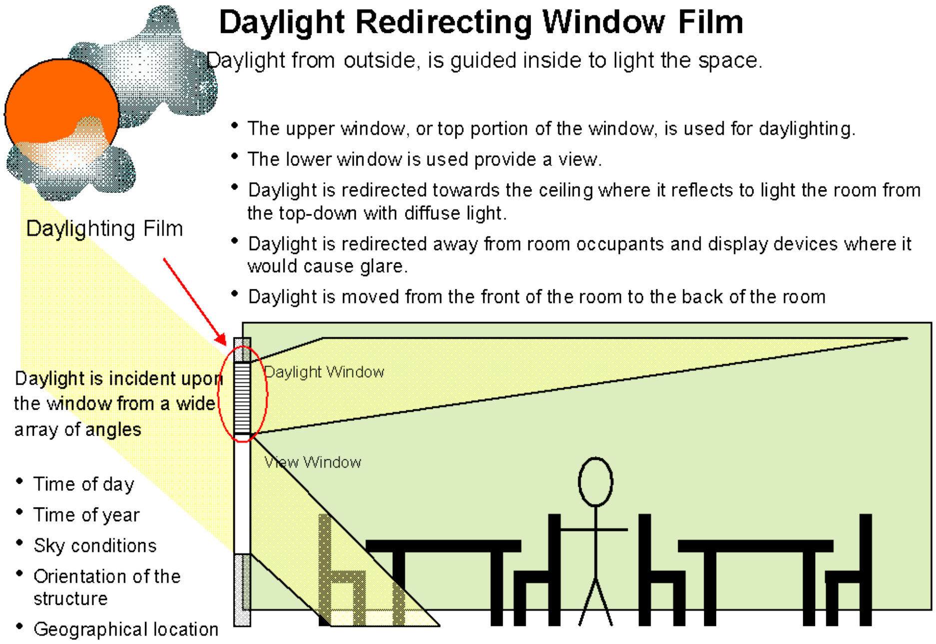


Figure 2. Graphical representation of daylight redirecting film technology

A cross section of the film installed on the window is shown schematically in Figure 3. The overall thickness of the light redirecting film is approximately 300 microns. In

addition to the film redirecting properties, a layer designed for infrared management was planned. However, due to a variety of technical reasons, this layer could not be incorporated in the prototypes used in this study. It was expected that by reducing the infrared light admission into the buildings, the DRF would reduce solar heat gain and contribute to a reduction in cooling costs. In principle, the solar heat gain of these films can be varied by choosing films and coatings that have different coatings. For example, for a facility in a cooling load dominated climate such as Houston, TX, a film having lower solar heat gain may be chosen. For a heating dominated climate such as Minneapolis, MN, a higher solar heat gain film may be selected. The solar heat gain properties were expected to be similar to the commercially available Prestige series of window films from 3M Company [11] and described in U.S. patent application number 20060154049 A1 [13] but were not implemented.

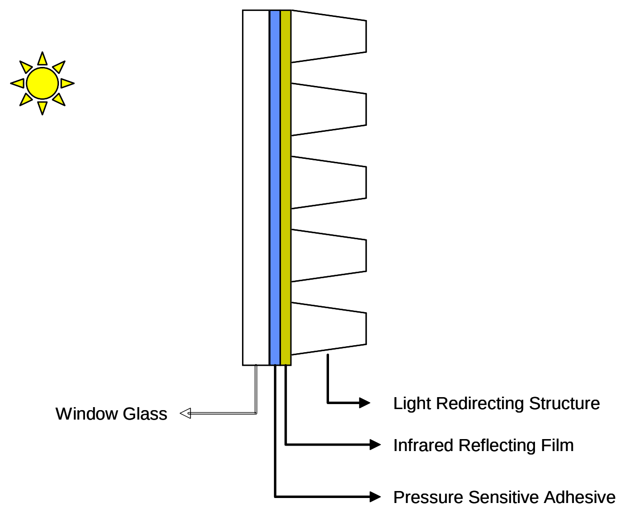


Figure 3: Schematic of the light redirecting film. (Not drawn to scale)

Even though the IR management feature of the DRF technology was not demonstrated in the field studies, it is nevertheless instructive to describe its features. A unique feature of the clear, polymeric IR reflecting film used in this construction is that the IR reflecting band shifts to lower wavelengths at higher incidence angles[14]. As a result, heat rejection is increased since the IR wavelengths closer to the visible band contain higher energy. The visible light transmission is not affected negatively. In addition, IR absorbing nanoparticle loaded coatings may also be used in the product construction as another tool for IR management. The IR rejection feature of 3M daylight redirecting window films is expected to contribute to the overall energy savings (in addition to lighting energy savings).

In principle the daylight redirecting film may be applied to any existing window in a building. However, it is best suited for buildings where the occupants experience glare and/or there is excessive heat gain in the building while attempting to utilize available daylight (e.g due to the use of high light transmission windows). In this regard, one of the study sites was perfectly suited for this technology (Naval Station, Norfolk, please see section 4.3.1). Since energy savings is realized by turning off the electric lights, auto dimming of electric lighting in the building is necessary for achieving the full potential of using daylight.

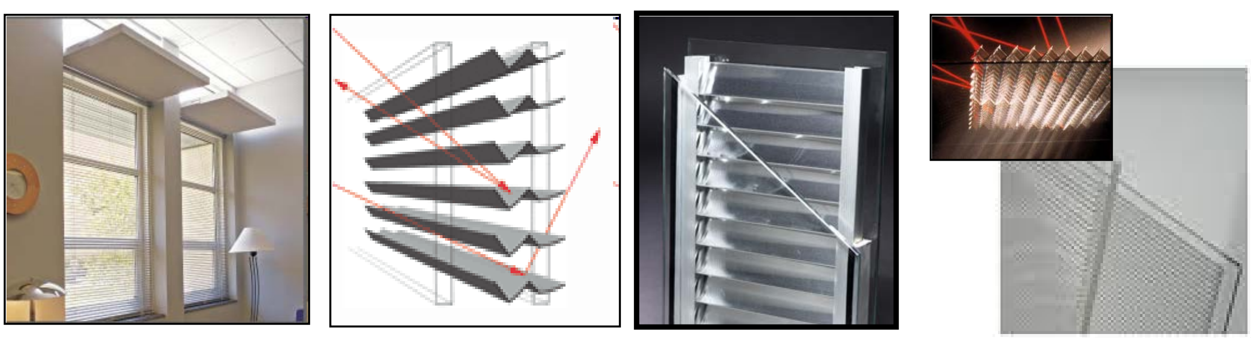
The daylight redirecting films are suitable for new constructions as well as retrofit applications. In new constructions, design features that maximizes the advantages of the films should be utilized. These design features include but are not limited to high visible light transmission windows, diffusely reflecting ceiling tiles and walls and flush mounted light fixtures. Judicious selection and placement of light sensors will ensure optimal operation of the electric lighting.

During the development of the prototypes for demonstration of this technology, it became evident that a small amount of light is directed downwards. The downward directed light, even though a small fraction of the total incident energy, is sufficient to cause glare if the occupant is in the direct path of the light. In order to overcome this glare, the research team modified the application method to include a diffuser in front of the microstructured film. Different methods were used to install the diffuser at different field sites due to various window designs encountered at these sites.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

A variety of products are used in the buildings to redirect or otherwise re-distribute the daylight incident on a window. Some of these are shown in Figure 4. These products are generally expensive, hard to maintain and/or difficult to retrofit. The daylight redirecting films in this demonstration project can be easily applied to the existing window and provide some level of infrared rejection without affecting the visible light transmission.

The performance of the daylight redirecting films is a strong function of the angle of incidence that in turn is dependent on the latitude and orientation of the building façade. In addition, sky conditions play a major role in the quantity of daylight available at any time of the day. The films are designed to maximize the ratio of light directed upwards to that transmitted towards the floor. The design rules are setup to achieve the best performance averaged over the entire year for a south facing window at given latitude. As such, there may be times when light is directed towards the occupant that results in discomfort glare.



Light shelf | Daylight redirecting blinds | IG Integrated daylight redirecting blinds | Prismatic and laser cut panel

Figure 4: Daylight redirecting products used in buildings.

The DRF technology relies on the re-distribution of daylight by bouncing light off the ceiling and walls, the design of the ceiling as well as choice of ceiling material is critical. A large variety of ceiling material is available, some with significantly lower reflectivity. Ceiling tiles having high reflectivity and low absorption is needed for maximizing the light redistribution.

Furthermore, the daylight redirecting films require direct sunlight illumination to function as a daylighting device. Transmission of the window glazing is important to the extent that the as much light is transmitted through the clerestory window as possible. Ideally, the view window needs to have a different specification than the clerestory window to maximize the daylight and minimize unnecessary heat gain.

The films also reject 99.9 % of UV incident on the window resulting in longer lasting furnishings within the building and contribute towards overall reduced cost of ownership and occupant health and comfort improvement.

3. PERFORMANCE OBJECTIVES

A summary of all performance objectives evaluated as part of the technology demonstration is shown in Figure 5. A number of performance criteria were used to evaluate DRF including lighting level changes, potential for energy and consequently greenhouse gas reduction, visual comfort, glare reduction, etc. Some of these were qualitative metrics and some were quantitative metrics as indicated in Figure 5. A detailed narrative for each of the performance metrics are presented in Section 6.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Key Quantitative Performance Objectives				
Increase daylight illuminance levels	spatial Daylight Autonomy (sDA) See discussion in Section 5.1.4	Grid of horizontal illuminance measurements, measured and/or simulated under controlled sky conditions	At least a 10% increase in daylight illuminance levels 20 feet from the windows; increase in spatial-daylight uniformity; and increase in daylight autonomy	**Fully met.** sDA in the treated spaces increased between 3%-24%, averaging 11% per simulation results.
Economic Payback	Life-Cycle Cost	Cost of energy impacts, cost of labor and materials for installation, cost of maintenance and replacement	Savings to Investment Ratio (SIR) greater than 1.0; Net-present-value; Payback period < 10 years.	**Frequently met.** Simple payback averages 10 years but dependent on electricity rates and climate (range of 3-35 years). NPV could turn negative and SIR fall below 0 depending on the assumptions.
Potential to reduce lighting energy use	Full-load equivalent hours (FLE) electric lights can be turned off (dimensionless) Peak lighting load intensity (kW/sf)	Lighting circuit current, task lighting power consumption; hourly operation schedules	At least 200 annual FLE and 25% reduction in daytime peak electric lighting need for the zone 15' to 25' from the windows;	**Partially met.** 184-270 FLE depending on blinds operation. Average peak demand reduction of 13%.
Other Desirable Quantitative Performance Objectives				
Reduce whole building energy use	Net kWh impacts on lighting and HVAC	Information on building envelope, HVAC equipment, and operation sufficient for simulation modeling	Net reduction in annual whole building energy use at least 1.05 times the direct lighting energy savings.	**Frequently Met.** Average annual whole building savings 1.30 times direct lighting savings. Range of 0.93-1.62 depending on climate.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Green-house Gas Emissions	Conversion of energy usage into green-house gas equivalents based on national averages	Green-house-gas-equivalent conversion factor for national level usage. Embedded costs of GHG in film production	Net reduction in greenhouse gas emissions over 10 years are at least twice the greenhouse gas cost of manufacturing.	CO2 emissions reductions due to the whole building energy savings are 0.59-3.26 lb/sf/yr.
Key Qualitative Performance Objectives				
Maintain or increase visual comfort	Likert scale and open response questions about glare and visual comfort	Survey of occupants before and after installation of the daylight redirecting window film	Maintenance of or increase in occupant visual comfort	**Frequently met.** Occupant comfort was preserved or increased in all but one installation where the product was not installed high enough above eye level.
Other Desirable Qualitative Performance Objectives				
Improve preservation of views out from the building	Likert scale and open response questions about quality of view Operation and openness of window blinds (percent open)	Survey of occupants before and after installation of the daylight redirecting window film Blinds operation observations	Increase perception of quality of available view Increase amount of time blinds can be left open to preserve views.	**Partially met.** Increase in occupant ranking of view quality. No discernible change in blinds operation
Reduce glare	Current quantitate glare indices are inadequate to task of rating new innovative products.	Glare assessment based on occupant surveys and informal interviews.	Maintenance or reduction in subjective glare ratings	**Frequently met.** Glare was unchanged or reduced in all but one space where DRF installed too close to eye level.
Maintainability of System	Change in maintenance practices	Interviews with site maintenance staff	Film does not create significant film-maintenance needs	**Fully met.** Staff did not report any maintenance concerns with DRF installation.

Figure 5. Performance objectives outcomes

3.1 QUANTITATIVE PERFORMANCE OBJECTIVES

3.1.1 INCREASE DAYLIGHT ILLUMINANCE LEVELS

Increased illuminance level is desirable in occupied office buildings particularly away from the windows. This performance objective is chosen to show the effectiveness of DRF technology in increasing light levels as a function of distance from the windows. Increased illuminance allows electric lights to be turned off without affecting the visual environment. Daylight availability away from the window is expected to provide other benefits such as visual comfort, improved attentiveness and a better sense of well being.

Illuminance measurements were taken in the study sites at several positions away from the window on a horizontal transect. Data loggers recorded the light levels every 15 minutes for about six months. In addition, annual simulations of prototypical space was performed for three different climate zones with a grid of sensor arrays to capture variation in light levels that may be missed by the measurements due to varying weather conditions or for various other reasons. Spatial daylight autonomy (sDA) metric developed by Illuminating Engineering Society (IES) was used to determine the spatial daylight uniformity.

Success criterion: > 10% increase in sDA. At least 10% increase in daylight illuminance levels 20 feet from the windows.[3]

3.1.2 ECONOMIC PAYBACK

This self-explanatory performance objective was used to determine the cost effectiveness of the DRF technology. Various costs related to the implementation were considered in the life cycle cost analysis to determine simple payback.

Success criteria: Savings to Investment Ratio greater than 1.0; Net-present-value; Payback period < 10 years.

3.1.3 POTENTIAL TO REDUCE LIGHTING ENERGY USE

Better use of daylight is expected to reduce lighting energy use. Illuminance sensors sense the light levels and dim or turn off the lights if a threshold is met is typically employed only near the window. With DRF applied to the clerestory windows, additional light can be made available away from the window. The purpose of this performance objective is to determine the effectiveness of DRF technology in converting the increased Illuminance into savings. Simulation data was used to determine the potential for reduction in lighting energy use.

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[3] Approved demonstration plan objectives lists success criteria is as follows: At least a 10% increase in daylight illuminance levels 20 feet from the windows; increase in spatial daylight uniformity; and increase in daylight autonomy. Since special daylight autonomy developed by IES is now an approved metric in addition to being more meaningful, sDA is reported as the primary success criterion.

Success criterion: At least 200 annual FLE hours and 25% reduction in daytime peak electric lighting need for the zone 15' to 25' from the windows

3.1.4 REDUCE WHOLE BUILDING ENERGY USE

Since lighting is an internal heat source, potential reduction in lighting energy can have an impact on the HVAC requirements. Thus, this performance objective was designed to determine an overall impact of DRF technology on the building energy consumption and is the most comprehensive quantitative metric. Data from simulations was used to determine the success of this performance objective.

Success criterion: Net reduction in annual whole building energy use at least 1.05 times the direct lighting energy savings.

3.1.5 GREENHOUSE GAS EMISSIONS

A reduction in GHG emissions is expected to result from the reduced energy consumption. This metric is a simple conversion of the energy savings to reduction in greenhouse gas emissions from US EPA estimates.

Success criterion: Net reduction in greenhouse gas emissions over the product's projected life at least twice the greenhouse gas cost of manufacturing.

3.2 QUALITATIVE PERFORMANCE OBJECTIVES

3.2.1 MAINTAIN OR INCREASE VISUAL COMFORT

Increased light level in the space has a potential to cause glare and decrease visual comfort. This is an important counterbalance for the performance objective described in 3.1.1. Since glare can be very subjective as well as temporal, we relied on a survey instrument to determine the effect of DRF on visual comfort. Surveys were conducted before and after installation of DRF in the space.

Success criterion: Maintenance of or increase occupant visual comfort as determined from the survey response

3.2.2 IMPROVE PRESERVATION OF VIEWS OUT FROM THE BUILDING

The purpose of this performance objective was to gauge the occupants' opinion of how the DRF films affected their view out from the building. The goal was to increase the perception of quality of view in the spaces where DRF was installed. This is a subjective assessment based on occupant feedback to the DRF installation.

Success criteria: Increase perception of quality of available view. Increase amount of time blinds can be left open to preserve views.

3.2.3 REDUCE GLARE

Extremely high contrast ratios can result in high glare situations in the workplace. Glare experienced by the occupants is evaluated using a survey instrument. Attempts were also made to quantify glare using high dynamic range photography.

Success criterion: Maintenance or reduction in subjective glare ratings

3.2.4 MAINTAINABILITY OF SYSTEM

Informal interviews with building manager and site staff were used to determine how the DRF affected maintenance of the system.

Success criterion: Film does not create significant film-maintenance needs

4. SITE/FACILITY DESCRIPTION

4.1 SITE/FACILITY LOCATION, OPERATIONS, AND CONDITIONS

Field studies were conducted at six locations:

- Naval Station Norfolk, Norfolk, VA
- Naval War College, Newport, RI
- Fort Bliss, El Paso, TX
- Marine Corps Air Ground Combat Center, Twentynine Palms, CA
- Naval Postgraduate School, Monterey, CA
- Naval Hospital Bremerton, Bremerton, WA

A quick summary of the sites is presented in Figure 6 below and shows that there were a range of building types and study conditions covered – from private offices with 1-2 windows to large open spaces with multiple rows of windows. Between the six sites, the study affected 123 workstations with DRF applied to 376 feet of windows and affecting around 262 building occupants.

State	Location	building name	number of types of spaces	number of treated spaces	total study spaces (treated + control)	number of treated window groups	linear feet of treated window	number of workstations in treated study spaces	total potential study population (treated and control)
VA	Norfolk	Z-133	1	1	1	6	72	48	120
CA	29 Palms	1416	5	7	14	13	108	31	62
RI	Newport	Hewitt Hall	2	5	9	19	88	24	40
TX	Fort Bliss	20400	2	7	15	7	60	12	24
WA	Bremerton	Naval Hospital	2	3	6	3	14	6	12
Ca	Monterey	Halligan Hall	1	4	8	4	48	8	16
		TOTALS	6	27	53	52	390	129	274

Figure 6: Summary of spaces and occupants affected by the demonstration study

4.1.1 NAVAL BASE NORFOLK, NORFOLK, VA

The Naval Base Norfolk is located in Norfolk, VA with a humid subtropical climate which receives 46” of precipitation in an average year, and experiences 60% of possible sunshine annually.

Building Z-133 is a five story facility used primarily as administrative office space for base personnel. The building is more than forty years old, and was recently retrofited with new windows. The final study spaces used were open offices; the six (6) west-most bays of south-facing facade were treated with the DRF product and the nine (9) east-most bays were used as the control spaces. This site was ideal for installing DRF as no exterior obstructions block direct sunlight from reaching any of the study area windows.

At the request of the building manager, an occupant acceptance pilot study was conducted in the fall of 2011 for a few months, with the DRF installed in two of the eastern most bays. At the end of the pilot study these were removed for the final demonstration. The study team requested that the blinds be re-mounted at the middle mullion, so that the blinds could be deployed on the lower windows. However the site manager did not want to relocate the blinds for the purpose of the study. Instead, the perforated horizontal mini-blinds were retracted to the top of the treated windows and the occupants in this area were instructed to leave the blinds in the retracted position for the duration of the study. Occupants in the control area, on the other hand, were allowed to adjust their blinds according to their preferences over the study period.

Upon the request of some of the occupants and the facility manager, we installed a tinted window film (NV 35[4]) across all of the lower view windows, in order to reduce the brightness of the view, especially for the treated windows, where deploying the blinds was no longer an option. Reflections of sunlight from car windows in a parking lot below and a white roof to the south of the study area were considered overly bright. For consistency, the tint was added to ALL windows in the open office space.

The open office area is 48' deep with a sloped ceiling designed to disperse light down into the cubicle workstations. The sloped ceiling starts at 12' above finished floor (AFF) near the windows slopes down to 8' AFF at the rear of the cubicle area. The study space windows consisted of groups of 3 double pane fixed windows per bay, for a total of 18 bays in the open office area. DRF was applied in the upper panes, from 6' AFF to 9' AFF. The retracted blinds blocked the top 6" of this area.

There were approximately 15 occupants in the treated space and a similar number in the control space. The occupants of the study and control area primarily did IT work, programming computers, or processing information on their computers. Cubicles either 4' (opaque) or 5' (clear top portion) tall are arranged in groups of eight, four deep by two wide, and held back from the windows by 5-feet, with a continuous work counter and walkway along the window wall. The occupants could generally see a small amount of the upper window from their cubical, but none of the lower view window. The occupants had a tendency to congregate along the work counter at the window for any work or social discussions. The occupants also reported that they enjoyed watching the airplanes practice landing and take offs on the landing strip to the south of the building. Standing by the windows, they enjoyed looking out to the waters of Norfolk Bay to the west of the building.

[4] http://solutions.3m.com/wps/portal/3M/en_US/Window_Film/Solutions/Markets-Products/Commercial/Sun_Control_Window_Films/Night_Vision_Series/

4.1.2 NAVAL WAR COLLEGE, NEWPORT, RI

The Naval War College is located adjacent to Newport, RI on the Atlantic coast with a humid, continental climate. The area experiences annual precipitation averages of 46” and is distributed evenly throughout the year. According to NOAA, nearby Providence, RI (22 miles north) experiences 58% of possible sunshine annually[5], it is assumed that Newport experiences a similar amount of sunshine annually. This site participated in both the pilot phase and the final phase of the study.

Hewitt Hall is a four story building that houses the colleges’ library and professors’ offices. This site was used for both the pilot and main study. The entrance to the building is oriented approximately due east, and the study spaces were located on the west and south facades of the building. The building is over fifty years old.

The windows have no exterior shading, but receive some minor shading from window recesses. In addition, a large building to the east created morning shade on some of the south-facing windows at various times of the year. A large roof deck below the study areas to the south, and the bay water to the west, often provided upwardly reflected sunlight into the study windows. The reflected sunlight from the roof deck was especially noticeable on sunny days or after a recent rain event.

There were two types of study spaces: a section of the second floor library oriented primarily to the South, with a corner that also included western exposure; and private offices located on either the second or third floors also oriented South, plus one pair of offices oriented to the West. Windows in the study spaces were 8’ high x 4’ wide, mounted 3’ above the floor, and flush with the 11’ high ceiling. The top 6’ consisted of inwardly opening casement windows, and the bottom 2’ x 4’ section non-operable, both with clear, double pane glass.

The portion of the library used for this study is approximately 30’ deep x 200’ long with a variety of dark wooden furniture including group desks, 4’ tall computer stations, sitting areas, and 4’-5’ tall book stacks. Furniture is located on the perimeter of the space near the windows and in the center of the study space with a walkway on each side. The south and west facing walls are white, and the back wall is cream in color. The electrical lighting system consisted of recessed 2x4 lensed troffers. The two rows of fixtures nearest the windows were operated on photocontrols. Other lights were left on whenever the space was open.

The fifteen treated windows of the library were originally provided with gold-colored curtains, which were occasionally closed to block direct sunlight. The casement windows were not actively used in the library. About two months after the DRF was installed, 1” horizontal blinds were installed below the DRF on the view portion of the windows. Thus the library windows had no operable shading for the two month period between initial installation of the DRF product and the subsequent installation of blinds on the view windows. Since a control space for the library was not possible, a six week period

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[5] http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgsun.html

prior to the installation of DRF was used to collect data for purposes of 'controls', this is the only space where this strategy was used.

Private offices are occupied by one or two professors each, who kept irregular office hours, or were frequently on assignment elsewhere. Each office is 14' x 25' with 11' dropped ceilings, and dark blue walls and carpeting. The furniture layout varies slightly in each office, but in general, occupant desks are located nearest the windows. Bookcases ranging from approximately 4' to 8' in height are a standard furnishing in each office and typically located away from the windows in each room. Other furniture consisted of couches and smaller working tables. The lighting system consisted of recessed 2x4 lensed troffers installed in the t-bar dropped ceiling. The lighting in each room is controlled by an occupancy sensor; no photocontrols exist in any of the private offices.

The offices have of two windows each. Window treatment consisted of curtains that were not removed for the duration of the study period. Unlike the library, the office occupants reportedly were active users of the casement windows, especially during the summer months. Installation of horizontal blinds would have prevented them from opening the windows, so the curtains were not removed during the study period.

Occupants did not make any unsolicited comments about the view from either the library or offices. However, all windows did have a distant view of other buildings on campus and the waters of the bay beyond.

4.1.3 FORT BLISS, TX

Fort Bliss is located near El Paso, Texas in a hot desert climate with annual average precipitation of approximately 9" per year and experiences 84% of possible sunshine annually[6], making this an ideal location for a daylighting study. Building 20400 is a three-story office building with the front entrance orientated south-east (approximately 170 degrees from due North). Study spaces are located on the second floor and consisted of private and open office plans on the south-east façade (facing 20 degrees east of south). The building is less than five years old. For the open office spaces, the six bays of windows in the eastern wing of the building were treated while the western wing was used as the control space. For the private office area, alternating perimeter offices in the east and west wings were treated with film in six of the twelve offices. Windows are dual-glazed low-E with approximately 40% visible light transmittance. Windows are non-operable and approximately 2' wide and 4' high. Ceilings in the open and private office spaces are approximately 8' high with white t-bar dropped ceilings.

In the treated spaces, the existing 1" horizontal mini blinds were lowered 18" below the ceiling to allow for the DRF to be installed in the top 2' of the window. In the control spaces, the existing 1" horizontal mini blinds were left at the top of the window.

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[6] http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgsun.html

While the climate conditions make this site an ideal location for a daylighting retrofit, the specifics of the building adds complications in evaluating the full potential of the DRF technology. The roof overhang creates shading of the study windows in the summer time, and the central tower created morning shading for the control area to the west, and afternoon shading to the study area to the east.

During the study, the treated space had less than five occupants, while the control spaces had between 7-10 occupants. Each space has both long-term and short term occupants having a mix of full-time and part-time hours.

Lighting consists of 2x4 parabolic troffers with occupancy sensors and no wall switches for all spaces. It was observed in some of the unoccupied spaces occupancy sensors were covered up, to keep lights from turning on.

In the treated space, Wing C, some occupants sat next to the windows with 5' high cubicle partitions. All partitions were opaque and gray in color. Occupants seated away from the windows have restricted views of the windows. In the control spaces, Wing A and B, no furniture was located near the windows. The 5' high cubicle partitions are located approximately 13' from the windows.

All offices are single-occupancy with two windows in each office. In each office, the occupant is seated near the window. Office furniture typically consisted of dark wood desks with book shelves and filing cabinets along the walls. Electric lighting consists of 2x4 parabolic troffers, controlled by occupancy sensors.

All walls and the dropped ceiling are white in color in both the treatment and control spaces.

The view from the study spaces is of a vast open space with small, young trees providing no shading for the study facades. Most occupants disliked the view outside their windows and expressed issues with glare on work surfaces; as a result blinds were lowered most of the time.

4.1.4 MARINE CORPS AIR GROUND COMBAT CENTER, TWENTYNINE PALMS, CA

The Marine Corps Air Ground Combat Center (MCAGCC) is located near Twentynine Palms, CA. The area experiences more than 300 days or 80% of possible sunshine annually and only about 4.5" of precipitation making it an ideal location for daylighting studies. Building 1416 is a two story facility containing administrative offices and medical offices in the form of a battalion aid station (BAS) which are part of this training facility used by the Marine Corps. This site participated in both the pilot phase and the final phase of the study.

The building entrance is oriented to the north-west (approximately 350 degrees from due North). The study spaces were located on the first and second floors on the south-east or south-west facades with the exception of a control space located on the north-east façade, and consisted of either open plan office layouts or smaller single or shared office spaces. There were seven pairs of study spaces selected, each pair with different geometries, as detailed in Appendix E.

The study spaces are occupied by two Marine Corp battalions undergoing training which are rotated at least annually. Therefore, there is little continuity in staff or occupancy. The windows in each space are sets of 4’ x 7’, non-operable double pane, high visible transmittance (VT), and aluminum framed windows. Each window has a 5’ high view window and a 2’ high daylighting section above, separated by a grated metal awning to shade the exterior of the lower window (see Appendix E for additional images). Some rooms had only one such window, others had groups in two or three, on one or more facades. The windows on the second floor also received some shading in the summer from the roof overhang depending on the time of the day.

Each window was fitted with a roller blind mounted below the mullion with the metal awning, but no operable shading devices were provided above the metal awning. Thus, direct sunlight entered the spaces from the upper windows. This was clearly a problem for many occupants, as many of them had already taken some action to block this direct sunlight, placing cardboard or aluminum foil in the upper windows (Figure 7).

Figure 7. Upper windows blocked with cardboard, paper, dark plastic sheet, foil, etc.

The view out of the windows was to other adjacent buildings, including a parking structure, and the sparsely vegetated desert. Many occupants commented that they did not like the view or the desert.

The electric lighting system was designed to comply with California’s Title 24 energy code. It consisted of 3-lamp T-8 parabolic 2x4 troffers placed 10’ x 10’ on center. Lighting controls include wall switches with bi-level switching, room occupancy sensors, and photo controls for fixtures within the ‘daylit zone’, i.e. within 10’ of a window. Even the emergency lighting was included on the photo control system.

Open office areas had 5’ high, grey colored partitions. Private offices and medical exam rooms had normal furniture for those space types. The record rooms had continuous shelving along the walls, with some work counters.

4.1.5 NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA

The Naval Postgraduate School is located in Monterey, CA, a pacific coastal region that receives about 66% of possible sunshine annually[7]. Sunshine is often only present for half of the day, with morning fog commonly burning off by noontime most of the year (January – August).

Halligan Hall is a two-story building built in the 1950s with the front entrance oriented to the northeast (approximately 80 degrees from due north). The study spaces are located on the southwest-facing façade. The building has two nearby structures providing some late afternoon shading. The building houses secretarial offices for administrative support staff; therefore, experiencing a consistent occupancy pattern.

Eight private offices were selected for the study; each containing two to three people and measuring 10' wide by 20' deep with southwest-facing windows. All offices have 10' high ceilings with an HVAC unit hanging from the ceiling near the door and electrical conduits running in the ceiling. Typical office furniture was found in each office with some offices having 4' gray partitions with a view window on the top half of the partition. All spaces have light colored furniture with white acoustic ceiling tiles and walls, with some rooms having a darker two-toned paint on the upper portion of the wall. Lighting fixtures were lensed 2x4 troffers, suspended at approximately 10' with a 2' void above. Some fixtures had only one lamp and no lighting controls present, only wall switches. Each desk was equipped with an individual task light.

Office windows were made up of five single-pane floor to ceiling windows. One of the window panes, the second from the top, is an inward operating hopper window. With no central air conditioning in the building, these hopper windows are frequently opened and closed, according to need of the occupants. The windows had old sun control film that was tattered indicating occupants' attempts at removing these. The old window film was only found on the upper windows and had to be scraped away to allow installation of DRF. Black shade screens are provided exterior of all windows to reduce afternoon heat gain and glare (see images and details in Appendix E).

Four rooms were treated with the DRF. Even though the site management agreed to remove the exterior screen for the duration of the study, the exterior screens were only removed from two of the four rooms. Once the exterior shades were removed, occupants felt strongly about the solar heat gain from the lower view windows. The exterior screens obstructed the outdoor view if standing closer than 12' back from the window. The view to the outside was of two nearby buildings; the occupants did not have an obvious affection for the view.

Each office had existing 2.5" Venetian blinds mounted at top of each window; occupants frequently operated these blinds. The top mounted blinds always interfered with the operation of hopper window. In the treated rooms, 1" horizontal blinds were installed

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[7] Based off NOAA's data for San Francisco, which has a similar climate. http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgsun.html

below the hopper window and the 2.5” blinds removed and stored for the duration of the study. This resulted in the DRF installed on the top two windows (including the hopper window).

4.1.6 NAVAL HOSPITAL BREMERTON, BREMERTON, WA

Bremerton Naval Hospital is located on Olympic Peninsula in Washington State. On average, Bremerton receives approximately 8” of snow and 52” of rain annually. Seattle located just across Puget Sound from Bremerton, experiences 43% of possible sunshine annually[8], Bremerton is assumed to experience similar amounts of sunshine annually.

The Naval hospital is a three story building with the front entrance orientated to the southeast (approximately 20 degrees from due East), with the study spaces located in the south-east wing on the second and third floors. The study spaces experience some shading from nearby vegetation, and afternoon shading from the western wing of the building. The building is less than ten years old.

The study spaces consist of six private medical offices with intermittent occupancy, by various, rotating medical staff. All rooms are approximately 10’ deep by 10’ wide, with 9’ high dropped ceiling. Offices contained non-operable, dual-glazed bronze anodized windows. Windows are 5’ by 7’6” on average with a sill height of 30”. Since the windows are continuous along the façade and the office layout does not always match the window sizes, the amount of window area per room varies.

All study rooms had existing cream colored, fairly thick roller shades. The occupants all noted that they highly valued the view out of the study space windows, of the trees and the sky, and liked the amount of daylight available in the spaces. However, patient privacy usually mandated that the window shades be completely pulled down while the space was occupied, reducing the clarity of the view and the presence of daylight. In the treated study rooms, 1” cream colored blinds were installed below the DRF. Occupants were instructed not to operate the blinds and leave down for patient privacy.

Furniture in all rooms is considered normal for medical exam rooms. The two side walls were cream in color, and the back wall a light blue. Lighting consisted of standard 2x4 recessed lensed troffers with bi-level controls with on/off wall switches

4.2 SITE/FACILITY SELECTION CRITERIA

The buildings for this project were required to meet criteria for both the diversity and for the suitability of the buildings for the study. A good, representative, sample was important to the applicability of the project objectives.

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[8] http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgsun.html

The selected sample of six sites represented geographic and climatic diversity, and architectural and cultural diversity of the building types, which is less tangible but also important. The suitability of the study sites was established using the criteria in sections 4.2.1 – 4.2.3.

4.2.1 Geographic and Climatic Diversity

The goal of the sample of study buildings was to cover as wide a range of daylight, latitude and temperature conditions within the U.S. as possible. The Department of Energy (DOE) climate zones (for temperature) were used in conjunction with NREL data on photovoltaic resource levels (for cloudiness and daylight availability) to ensure a balanced sample. Figure 8 shows the preferred climatic sample frame and Figure 9 the sample frame achieved for the study.

	Predominantly clear skies (>60% clear)	Mixed skies (<60% clear)
High latitude	2	2
Low latitude	2	2

Figure 8. Climatic sample frame goals

	Predominantly clear skies (>60% clear)	Mixed skies (<60% clear)
High latitude	0	2
Low latitude	2	2

Figure 9. Climatic sample achieved

The team was not able to identify two northern locations with predominantly clear skies. Approval from ESTCP office was obtained to reduce the number of study sites from eight to six. Studies were conducted for all other combinations of latitude and sky condition desired.

4.2.2 Architectural and Cultural Diversity

The project also set a goal of finding a range of architectural styles and cultural conditions that might be somewhat representative of the range of building conditions found within the DOD building stock. The team hoped to include building types from a spectrum of the services and administrative agencies within DOD, such as Army, Navy, Marines and Air Force, plus building types such as office buildings, recreation facilities, medical facilities, commissaries, etc., and a range of vintages and architectural styles.

The six final study sites do represent a range of build types and vintages, but are not claimed to be perfectly representative of the general population of all DOD buildings. As described below in the next section, recruitment for participation in the study was extremely difficult and time consuming.

4.2.3 FACILITY REPRESENTATIVENESS

The chosen sites encompass a variety of climate characteristics, from very cloudy (Bremerton, WA) to very sunny (Twentynine Palms, CA and El Paso, TX) meeting the study objectives with regards to geographical and climatic site diversity.

The study sites were representative of the standard civilian building types that are suitable for this product. The product could be installed on any building with unshaded windows that face east, southeast, south, southwest or west. The windows should have a clerestory (upper) window area at least 7' above finish floor, ideally have high visible light transmittance (VLT) (>45%) and with a high-occupancy building usage inside. Appropriate usages include, but are not limited to, open office space, private offices, outpatient treatment rooms, common areas, libraries, or any other existing or new building where view is not required through the upper windows. Of the 20 potential sites, 14 were rejected for one or more of the reasons described above.

4.3 RECRUITMENT AND SCREENING

Facility contacts were suggested to the study team by ESTCP liaison, and all were actively pursued. Each facility manager was first contacted by e-mail followed by a telephone conversation describing the overall goals of the project. A 'study prospectus' (see Appendix D) describing the purpose and conditions of the study was then sent to each facility manager requesting identification of any suitable buildings within their base or campus. If they responded positively, they were then sent a request to provide the following information for further screening:

- Site plans (showing orientation), floor plans, and reflected ceiling plans.
- Elevations of the windows to be treated.
- Exterior images of sites showing surroundings and any nearby solar obstructions.
- Photos of the interior workspaces, including furniture type, a view of the windows, any existing window treatments, and existing lighting fixtures.
- Hours of operation of building, or particular study sites.
- Full-time occupancy count for the space.
- Part-time / transient occupancy count of space (average and peak).
- Occupancy schedule.

In addition, if a site seemed promising, the team attempted to collect further information to support the analysis, such as:

- Electrical plans showing the location of lighting circuits and controls, types of lamps and ballasts, and controls.
- Furniture layouts and type of occupants (engineering, HR, financial, etc.).

- Data on the transmittance of windows and the reflectance of major room surfaces.
- Close-up photos of blinds, awnings, shades or other window treatments, showing color, size and operation type.
- Age of building, and date and information on recent retrofits.
- Section of building, showing ceiling type and height.
- Electric energy costs (kWh and demand charge schedules).
- Accessibility (security clearance required, distance from nearest airport or hotel, availability of staff and occupants for interviews and surveys, monitoring limitations, et cetera).

Ultimately, twenty DOD sites were contacted across the continental US and Puerto Rico, and 40 buildings were screened. More detailed information, including plans and photographs, were collected on 14 locations. Seven sites were visited for further confirmation. Only one was rejected as completely inappropriate for the study after making a site visit.

The rejected site was the Great Lakes Naval Station, classroom and office buildings 616 and 617, where it was found that existing high upper windows had been blocked via a retrofitted hung ceiling. There were no plans in place to return the ceiling to its original position, and thus the site was rejected. Unfortunately, this became clear only after visiting the site – an indication of the many difficulties of carrying out this demonstration project.

Recruitment of study sites was challenging, and took longer than expected for a number of reasons, in descending order:

- Communication with DOD facility managers was often time consuming. While a few were quite responsive, many never responded to initial inquires or failed to provide follow up information necessary for proper screening. Furthermore, staff turnover in this position was very high, such that for a given site, the project team often had a new facility manager contact every month or two.
- The number of DOD buildings meeting the most basic study criteria - high, unshaded windows - was much lower than expected. Based on the study team experience, it seems that a much larger proportion of the DOD building stock, compared to civilian buildings, includes exterior shading, or if they do have high windows, the buildings have been retrofitted with dropped ceilings, window tints, or other actions that make them poor candidates for a DRF retrofit.
- Many potential DOD sites were unavailable for the study, due to security concerns, extreme stress in meeting current troop rotation goals (e.g. Fort Bragg), or highly erratic occupancy patterns (e.g. Barstow).

To compensate for the limited number of available study sites, the study team pursued a diversity of conditions within each building when possible, such as including more than one orientations or space type within a selected building. Within the six study buildings, ultimately 27 different spaces were treated with the DRF, and 26 corresponding spaces were studied as controls.

4.4 SITE-RELATED PERMITS AND REGULATIONS

No permits or other regulatory barriers were encountered during the execution of this project. One of the site managers wondered whether participation in the study was tantamount to modification of the window thus triggering the need to upgrade the windows to meet blast resistance codes. The project team is confident that if DRF is anchored to the frame, it would meet at least some of the criteria for blast resistance. However, qualification of DRF for blast resistance was out of scope for this project and none was pursued.

The end of study disposition of the product was described in the site demonstration plan. This essentially consisted of an offer to remove the film if the site deemed it necessary. Only one of the sites (Norfolk) requested removal of the DRF and the request was complied with.

5. TEST DESIGN AND ISSUE RESOLUTION

5.1 CONCEPTUAL TEST DESIGN

5.1.1 STUDY VARIABLES

- Independent variable(s):
  The most common variable was the redirection of sunlight in the upper windows through application of the DRF. In treated spaces, the film was installed on the upper windows. In un-treated (control) spaces, the upper window panes did not receive the DRF product. Most sites had existing full length blinds or shades attached at the top of each window. In treatment spaces, at sites with existing horizontal blinds, where possible, the blinds were repositioned just below the DRF application. While other sites, with vertical shades, were replaced with horizontal blinds, just below the DRF application, for the duration of the study. Additionally, at some sites sun control window film was installed in the lower view windows to help mitigate solar heat gain, previously controlled by existing blinds or exterior sun screens.
- Dependent variable(s):
  Dependent variables were daylighting illuminance levels and use of electric lighting within the treated spaces. Illuminance loggers were placed in transects to capture variations in illuminance at different distances from the windows. Due to the limitation of the number of loggers as well as potential complexities of data analysis, most study sites used only one transect. Electric lighting usage was also monitored to understand potential light switching behavior of the occupants.
- Controlled variable(s):
  The intent of the study was to control as many confounding variables as possible to isolate the effects of the window films. Site selection criteria ensured that general parameters such as latitude, climate conditions and building types are the same between each set of treated vs. control spaces. In addition, the study was replicated at sites with different latitudes and climates to ensure the results are more generally applicable to the continental United States.

  The team selected treated and control spaces to be nearly identical in size and orientation, usage, and located adjacent to one another. The study team screened the sites for consistent building operations over the study period, such as avoiding major furniture or occupancy changes, but some changes occurred anyway.

  The project team gathered weather, outside illuminance, blinds operation, and electric lighting usage for each site. The weather conditions were downloaded from automated weather stations at nearby airports. Outside illuminance levels, blinds operation and electric lighting circuits were monitored on site.

5.1.2 Study Hypothesis

The team hypothesized that applying the window films to the treated spaces would increase daylight availability in the space, reducing the need for electric lighting. This would then enable a reduction in electric energy consumption if electric lights are automatically dimmed (triggered by photocontrols) when sufficient daylight was present. A secondary hypothesis was that the film would improve or at least not change occupant's visual comfort.

5.1.3 Study Phases

At the request of the ESCTP reviewers, the research study was split into two phases: a pilot phase with two monitoring sites, and a main study phase involving six monitoring sites. At each site, data was collected for calibration before the film was installed. Data was collected again post-intervention (film installation). Outlined below are the activities conducted for each phase:

- Pilot Site Phases: logger installation, calibration (pre-film) logging, film installation, post-intervention (post-film) logging, monitoring density reduction (loggers moved to other sites in January 2012), main study logging, and logger removal.

  Main Site Phases: logger installation, calibration (pre-film) logging, film installation, post-intervention (post-film) logging, and logger removal.

The pilot phase study was conducted over a six-month period (Summer 2011 through the end of the year) at Twenty-Nine Palms, CA and Providence, RI with extensive and detailed monitoring. This was to ensure the team took full advantage of the pilot phase to discover and resolve potential study complications. The knowledge gained during the pilot was then applied to the design and execution of the main study phase.

The main study phase started after the conclusion of the pilot phase. It was conducted over a six month period from winter (January 2012) through the summer (June 2012). The main study sites included the Twenty-Nine Palms and Naval War College sites with reduced granularity(less number of data loggers and transects) and four additional sites: the Naval Station at Norfolk, VA; Fort Bliss, TX; Naval Hospital, Bremerton, WA; and Naval Postgraduate School, Monterey, CA.

5.1.4 Test Design

Two types of data were collected: monitored quantitative data (lighting conditions in the space) and qualitative occupant visual comfort data. Collection of physical data involved monitoring illuminance levels at multiple locations throughout the study period. As illustrated in Figure 10, illuminance levels were measured at the following locations: inside and outside of the treated and control spaces, on the ceiling (facing lighting fixtures and facing down) and on the work surface. Occupant comfort data were collected via survey responses from occupants of these study spaces. Surveys were administered before and after window film installations to occupants in both the treated and control spaces.

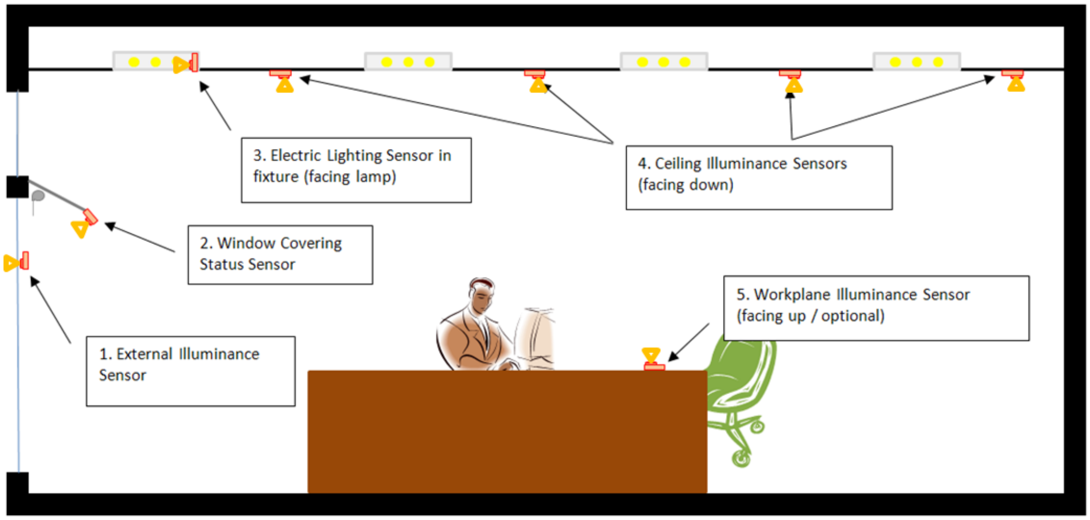

Figure 10. Cross section of study space showing locations of the monitoring equipment. The direction of view of each logger is represented by a triangle.

5.1.5 Pilot Phase - Lessons Learned

During the pilot phase conducted at Twenty-Nine Palms, CA and Providence, RI modifications were made to accommodate for lessons learned during the pilot phase of field monitoring, these are outlined below:

- **Blinds/Curtain Placement and Operation Monitoring:**

  Modifying existing window blinds or shades was necessary in order to conduct the study. Existing window blinds or shades often cover the entire window and are either top-down blinds or curtains that close down the middle. In either case, applying the DRF to portions of the windows without modifying the blinds would have resulted in less than ideal daylighting performance. The study team worked with the site contacts to develop protocols for replacing existing blinds/shades with those that covered just the view portion of the windows while leaving the clerestory windows without internal shades.

- **Occupant Comfort:**

  Glare: A survey of daylighting literature, reports and personal experience clearly shows that glare is a key issue that occupants try to overcome in daylit spaces. As one of the key counterbalances to increased daylight, the project team was keenly aware of this as a potential issue.

  During the course of the pilot phase, those surveyed in Newport reported no glare problems. At least one of the occupants in Twentynine Palms indicated glare at certain times of the day. It is certainly possible to experience glare if the occupant is in the direct path of the sun and looks directly at the treated window. However, such a condition exists in a very narrow cone and can be easily overcome by moving a few inches away on either side of the high glare location.

- **Occupant Surveys:**

  The study team modified the occupant survey document based on the initial implementation of the survey. The changes were mostly aimed at making the form easier to read and less complex while asking for additional information directly instead of analysis of responses to general questions.

5.1.6 SITE MONITORING OPTIONS

Site monitoring was done by one of two methods described below:

- **Side-by-side Comparison:**

  This comparison entailed monitoring spaces with similar physical features and occupancy patterns. One space(s) would act as the "treatment" receiving the DRF product application, while the other space(s) would act as the "control" not receiving the DRF product. The two spaces were located on the same façade on the same floor or one floor above or below each other. It may be noted that the floor layout between the treated and control spaces was not identical.

- **Before and After Comparison:**

  This comparison entailed monitoring a single space for a time period before the DRF product was installed and after installation. Ideally, monitoring would have occurred within 2 weeks of the summer or winter solstice events and each monitoring period, before and after, occur for six months to allow exposure to similar solar angles for both monitoring periods. However, this was not achieved due to delay in site identification and site access limitations.

5.2 DAYLIGHT PERFORMANCE METRICS

5.2.1 SPATIAL DAYLIGHT AUTONOMY (SDA)

sDA is a comprehensive performance metric, which describes the fraction of annual operating hours a specified amount of daylight is available in the space. The illumination level and time fraction are included as a subscript for the metric. For example, $sDA_{300,50\%}$ means that at least 300 lux of illumination is available for at least 50% of the annual operating hours. This metric has been adopted by Illuminating Engineering Society (IES)[9]. This method takes changes in daylight illuminance over both time and space into account in calculating sDA. It has been validated in some initial research projects, and is now being adopted by various building performance standards, such as LEED 2013.

[9] Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) http://www.ies.org/store/product/approved-method-ies-spatial-daylight-autonomy-sda-and-annual-sunlight-exposure-ase-1287.cfm

Thus, even though the sDA metric was not part of the original table of performance objectives, sDA has been selected as the most meaningful measure of daylight illumination resulting from the installation of this product. It replaced the metrics listed in the Performance Objectives table in the demonstration plan, such as increase in illumination at 20' from window and daylight uniformity since there is still no accepted measure for these metrics.

5.2.2 GLARE

There are over twelve metrics of glare currently in use, with at least three specifically designed to evaluate daylit conditions. However, there is no professional consensus on which to use under what conditions. Indeed, recent research at the University of Idaho[10] found very poor correlation between the most commonly used metrics and subject's reported experience of glare under common office space conditions, using simple window and blinds technology. Furthermore, all of these metrics are only for evaluating instantaneous conditions, not conditions aggregated over time. This raises the question about how to evaluate the overall glare performance of a product over the course of a full year's daylight cycle. Given the lack of acceptable glare metrics for daylight glare, the project team chose to rely upon observations, interviews and survey results to assess any change in the glare conditions in the treated and control study spaces.

The study found no increased complaints of glare in any of the treated study spaces, and indeed, there were many reports from interviews of greatly reduced glare, with one exception. The one exception was the installation at the Naval Air Base in Norfolk, Virginia, where the film was mounted lower, only 6' above the floor, instead of the 7-8' above the floor elsewhere. The study team believes that by mounting the film closer to eye level, the frequency of extremely bright views of the film increased, resulting in the complaints of occasional glare. It should also be noted, that the deeper the space from the treated window, and the wider it is, the higher the risk of glare from the film, and thus the higher above eye level it should be mounted. The Norfolk space was about 40' deep and over 200' wide, and thus also increased the risk of glare.

Overall, the study found that, if the product was appropriately mounted at 7-8' above the floor level, the installation reduced glare and created at least a neutral, and often a positive improvement, in visual comfort.

5.2.3 SIMULATION STUDY SETUP

A separate building energy simulation study was conducted to evaluate the effects of the DRF on illumination levels in the space and its resultant effect on lighting and whole building energy use. The simulation study was necessary in order to extrapolate the results and findings from the sites where we have data on a relatively limited amount of time (months) and to rationalize the energy savings numbers across sites. Daylighting is

[10] Van Den Wymelenberg, K. (2012). Patterns of occupant interaction with window blinds: A literature review. *Energy and Buildings, 51*, 165-176.

inherently dependent on the prevailing outdoor conditions (amount of sunshine, cloud cover etc.) and on the specifics of a given space (window details, shading, massing, space dimensions etc.). Thus using the raw data collected from each site is dependent on the specifics of each site. To project results from this raw data to a more rational comparison between sites and weathers, energy simulation studies were necessary.

HMG conducted two types of simulation studies:

- **Daylighting Analysis:** Illuminance values were simulated with ray tracing in the Radiance software package using the Dynamic Radiance approach (also known as the three-phase method). This is described in more detail in Appendix E.
- **Whole Building Analysis:** The whole building analysis was built on top of the daylighting analysis using a process developed by HMG in prior research projects. This approach combines the accuracy of the dynamic radiance approach to predict illuminance in the space with the ability of the eQuest building energy analysis tool to take the outputs of the dynamic radiance analysis as inputs to a whole building and lighting energy use analysis. This is described in more detail in Appendix E.

5.3 BASELINE CHARACTERIZATION

5.3.1 BASELINE AND OPERATIONAL DATA COLLECTION

To assess baseline visual comfort conditions, surveys were administered before the DRF was installed in both the treated and control spaces. After DRF installation, surveys were administered in two or three seasons to discern if DRF installation and blinds modification had adversely affected comfort. It was necessary to survey in multiple seasons to account for seasonal changes in the sun's position.

To assess the illuminance performance of the DRF, the research team collected baseline data at all sites for each activity type (e.g., private office vs. open office), and each window orientation. Onsite monitoring began before the DRF was installed to ensure the treatment and control rooms had reasonably similar operation. Onsite monitoring was conducted in treatment and control room pairs at each site whenever possible.

Monitoring was continued in both the treatment and control rooms for the operational testing phase of the study to control for changes in sun angles, weather, and occupant usage patterns.

For one study room a suitable control could not be found (the library at the Naval War College in Newport, RI). A before vs. after study was conducted instead. Monitoring was conducted before DRF installation to establish a baseline and monitoring continued for nearly a year as the operation testing phase of the study. It was not possible to fully account for changes in sun angles, weather, and occupant usage patterns at the Naval War College library though the study periods allow for comparing performance of the DRF at various sun angles representative of the location.

5.3.2 Baseline and Operational Data Collection Timeline

A baseline monitoring period for each site was conducted before the DRF was installed. The duration of this period varied by site as seen in Figure 11.

Site Name	Baseline Monitoring Period
Norfolk, VA	2 days
Newport, RI	33 days
El Paso, TX	11 days
Twentynine Palms, CA	32 days
Monterey, CA	3 days
Bremerton, WA	28 days

Figure 11. Baseline monitoring period

The research team conducted multiple field visits to each monitored site to install monitoring equipment, oversee DRF installation, record space characteristics and conduct occupant surveys. After the installation of logging equipment, the team went back on site to conduct a number of post-DRF installation surveys. These post-installation visits served the dual purpose of collecting occupant survey data as well as allowing the team to make timely fixes and adjustment necessary for continuous and quality data collection from monitoring equipment. Operational testing of the DRF began when the DRF was installed, lasting for a period of 6-12 months, and varied by site. The dates of these activities are presented in Figure 12.

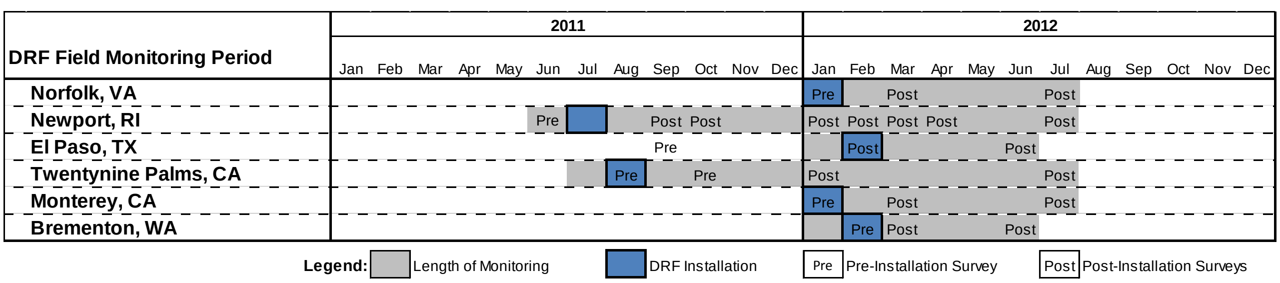

Figure 12. DRF Field monitoring and survey timeline

5.3.3 Baseline Energy Use Estimation

The study team collected data on installed lighting fixtures using data loggers that recorded the lighting on/off state.

Weather conditions were an important variable to account for. Weather at the airport nearest each study sites was downloaded and used as a proxy for weather at the study site. Weather data were categorized into clear-, mixed-, and cloudy-weather categories. Interior illuminance data was analyzed separately for clear, cloudy and mixed days to help understand the impact of weather on product performance.

Information about HVAC equipment type, efficiencies, and usage was NOT collected on site. Subsequent simulation estimates of changes in HVAC usage are based on default system assumptions and Typical Meteorological Year (TMY) weather data.

5.3.4 DATA COLLECTION EQUIPMENT

The research team utilized off-the-shelf monitoring equipment. Interior illuminance was monitored with HOBO U12-12 loggers; outside illuminance was monitored with HOBO UA-002-64 loggers. In addition, a hand-held illuminance meter (Minolta T-10) was used during site visits to obtain real-time illuminance readings. Time of illuminance readings were recorded so that they could be compared to data from the HOBO loggers to assess accuracy. Lighting circuits and blinds were monitored with DENT Lighting Loggers or Pacific Scientific Technology Lighting Loggers.

Other equipment used during the field observations included a digital camera equipped with a fisheye lens and software to enable high dynamic range imaging and visual field analysis.

5.3.5 DECOMMISSIONING OR TECHNOLOGY PROPERTY TRANSFER

As proposed in the demonstration plan, each site was asked whether they would like to retain the DRF or they prefer to have it removed at the end of study period. All except one site (Norfolk) decided to leave the DRF in the treated spaces. Since the evaluated technology is not a real asset, no 'transfer of property forms' were completed.

It is the intention of the project team to contact the sites in the near future to offer the next generation of DRF films in the control spaces to ensure a more uniform appearance. 3M will supply the film at no charge to the demonstration sites but will request the sites to cover the labor costs for the installation of the new film and removal of the old system.

5.4 SAMPLING PROTOCOL

5.4.1 DATA DESCRIPTION

Lighting circuit usage was monitored using DENT Lighting Loggers model TOU-L. One logger was installed on each electric lighting circuit in the space. Loggers attach magnetically and record on/off data through a photocell positioned directly adjacent to a lamp in the fixture. Care was taken to position loggers in a way that would not capture light redirected by the DRF.

Interior illuminance measurements were logged at 15-minute intervals via a HOBO U12-12 mounted at each logger point indicated on the research plan for each monitored space. The specific arrangement of the loggers was designed to capture the full-range of variation in lighting conditions in monitored rooms. Loggers were placed in similar configuration in each pair of monitored spaces to enable comparison between window film performance in the treated space and the baseline conditions in the control space.

Exterior illuminance measurements were logged at 15-minute intervals by a HOBO UA-002-64 positioned to look directly out the center of an un-shaded window.

Occupant surveys were administered before and after application of DRF. Surveys of both treated and control space were taken at the same time. Although the survey team tried to get to the same individual to respond to the survey at different time intervals, the one responding to the survey may not have been same in all buildings.

5.4.2 DATA COLLECTORS

HMG staff collected data from all sites with help from the site contacts as necessary. The surveys were either collected by the site contacts or were directly mailed to HMG. HMG personnel collected all of the illuminance, physical, photographic and electric lighting operation data.

5.4.3 DATA RECORDING

During the site visit, the study team retrieved monitored data from the loggers, administered occupant surveys and collected responses as necessary. Illuminance readings were taken with a handheld unit to aid in assessing visual lighting condition and illuminance levels reported from the monitoring equipment. Photographs were taken of the study space to document the visual conditions in the space. In additional High Dynamic Range (HDR) images were taken in the event glare analysis was needed. HDR imaging data was not used for glare analysis since there were no complaints of glare from the DRF and the illuminance readings as well as other photographic evidence did not necessitate glare analysis.

5.4.4 DATA STORAGE AND BACKUP

During site visits after data recording had begun, stored data was downloaded from loggers to a laptop for transfer to the research team's server. The research team's server employed mirrored hard drives for data security through redundancy, and data was backed up nightly for extra redundancy.

Some data was lost due to equipment failure and human error. Despite tests showing loggers were fully operational before deploying them in the field, some loggers still failed in the field. Some loggers simply disappeared from the sites during the study. Lastly, some equipment, including data loggers, was stolen from a car after it was removed from the sites, but before the data was downloaded.

5.4.5 DATA COLLECTION DIAGRAM

Figure 10 in section 5.1.4 illustrates the basic approach for the location of data loggers. The specific locations of the loggers for each pair of monitored spaces is best represented by the "study areas" figures included each of the site demonstration plans. These are included in appendix E of the report. The study plan for each site marked the monitored space pairs, as well as the intended locations for the loggers. Occasionally, site adjustments in logger location were made to accommodate actual furniture conditions or ceiling tile layouts.

5.4.6 Survey Questionnaires

The occupancy satisfaction survey used to solicit occupant's visual comfort in the study spaces is included in the Appendix E to the report. Figure 12 in section 5.3.2 shows the times and nature of the survey administered for each study site.

5.5 EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES

5.5.1 Equipment Calibration

To ensure data validity and accuracy, the HOBO loggers were calibrated against LI-COR sensors. The LI-COR sensors served as the standards in this case, and the sensors' calibration processes were performed following NIST standards by the manufacturer prior to their shipment. The research team then calibrated the HOBOs against the LI-COR sensor. The regression equations obtained from the calibration exercises were used to "correct" data obtained from the HOBO loggers back to the standard values.

5.5.2 Quality Assurance Sampling

The HOBO loggers were calibrated against the LI-COR sensors both before and after their field deployment. The purpose of these calibration processes was to detect whether the logger sensitivity had drifted during the study period. One team member was tasked with reviewing and examining data for anomalies. No loggers experienced significant drift and data was deemed usable without adjustment.

Interior illuminance was graphed with exterior illuminance for select days. Results were compared to both hand-held measurements and simulation results and good agreement was found for both. Hand-held measurements were taken with a Minolta T-10 (which exhibits superior accuracy to the HOBO sensors).

5.5.3 Post-Processing Analysis

Post-processing of monitored data was necessary to account for study design and irregularities in data.

By Design: To determine the impacts of daylighting in each space U-12 data loggers were placed in transects on the ceiling and workplanes. Two methods were used to estimate the electric lighting contribution based on data collected from U-12 Hobos and DENT loggers. DENT loggers were placed in lighting fixtures to determine on/off state of electric lighting. However, data from these loggers was not used due to data quality issues. Alternatively, night-time illuminance values from the U-12 loggers were used as a proxy for the electric lighting contribution. Night-time illuminance values were determined to be between the hours of 10:00 PM to 6:00 AM. When electric lighting was on during these hours, a constant illuminance value was seen in the data set, resulting in the electric lighting contribution value. This value was then subtracted from the overall illuminance values in the data set to determine the impact of daylighting only.

Data Issues: Several issues in the data set included: spikes in illuminance due to direct beams of sun, drifts in illuminance readings over time due to loggers falling down or placed the incorrectly, and sudden increases or decreases in illuminance levels not explained by site conditions. Each issue was addressed after performing diagnostics on the data set, potential contributing site conditions, and HMG staff field observations.

Some loggers experienced direct beams of sunlight during the late afternoon resulting in spikes in the data set. These spikes were addressed by averaging several hours before and after the spike to determine more accurate daylighting levels for these periods of time. The averages were then applied to the affected data, resulting in data more representative of the illuminance typically observed in the space. Other issues in the data were found due to loggers positioned incorrectly or found out of place for a period of time. Data from these time periods was eliminated from the analysis due to inconsistency in the readings over time. Lastly, sudden increases or decreases in illuminance levels not explained by a change in site conditions were processed for analysis. These could be a result of relocated loggers, changes in electric lighting operation, or other inexplicable reasons. In most instances the data could be reconciled by observing the before and after illuminance levels and adjusting the increased or decreased values to these patterns and did not materially affect the conclusions.

5.6 SAMPLING RESULTS

Detailed sampling results are provided in Section 5.6 of Appendix E.

6. PERFORMANCE RESULTS

6.1 INCREASE DAYLIGHT ILLUMINANCE LEVELS

Success in increasing daylight illuminance levels is achieved if there is an increase in the spatial Daylight Autonomy (sDA) due to the installation of DRF. The sDA metric is described in detail in Section 5.1.4.

The purpose of this performance objective is to show the new technology increases daylight in the space and distributes it more uniformly throughout the space. Increased daylight availability allows electric lights to be turned off, and more uniform distribution of light reduces glare potential, as occupants are exposed to less contrast in the visual environment. The DRF technology was shown to both increase daylight illuminance levels and uniformity.

Simulations of prototypical spaces were performed with a grid of sensors arrayed in the spaces to capture fine-scale variations in lighting levels that would be cost-prohibitive to collect in the field. Daylight levels were validated against field results and then illuminance levels and spatial daylight autonomy were calculated.

DRF installation increases sDA from 11% to 19% which exceeds the performance objective target.

6.2 ECONOMIC PAYBACK

Several different economic payback analyses was conducted since the savings are a strong function of building location, orientation and most importantly, the energy price. Simple payback analysis shown Figure 20 is a strong function of the electricity price. Payback ranges from 3 to 35 years depending on the location, orientation and electricity cost. Similar analysis was conducted to determine the net present value and savings-to-investment ratio (SIR) for the DRF technology. SIR ranges from 0.38 to 3.75, and NPV turns negative if low end of the electricity price along with non-ideal orientation is considered. A 3% discount rate was chosen for these calculations. Additional discussion on cost and cost drivers may be found in Section 7.2.

6.3 POTENTIAL TO REDUCE LIGHTING ENERGY USE

This performance objective was to reduce electric lighting usage 15’ to 25’ from the windows by at least 200 hours and reduce annual daytime usage by at least 25%. The purpose of meeting these goals would indicate the technology can provide significant electric lighting energy savings deep in the space from daylighting. Daylighting typically is not cost effective more than two window head heights from the windowed façade. The window head height is defined as the height of the window header (or top) above the finished floor.

Electric lighting usage was measured in Full-Load-Equivalent (FLE) On hours. For example, if half the lights are on for eight hours, then this is reported as 4 FLE On hours.

This metric is especially relevant to the dimming system that was simulated here. Partial hours of usage are summed up into an easily digestible number that directly reflects changes in usage measured at the electric meter.

This performance objective was met for most typical conditions observed in DoD facilities:

The first objective, reducing FLE On hours by at least 200 hours was fully met both when blinds are operated optimally (Figure 13) and when blinds are always closed (Figure 14).

		West		South		East	
		40% VLT	**70% VLT**	**40% VLT**	**70% VLT**	**40% VLT**	**70% VLT**
Northwest	Hours	735 hrs.	1158 hrs.	761 hrs.	1183 hrs.	656 hrs.	1076 hrs.
	% Change	26%	41%	27%	41%	23%	38%
Northeast	Hours	842 hrs.	1376 hrs.	883 hrs.	1342 hrs.	774 hrs.	1279 hrs.
	% Change	29%	48%	31%	47%	27%	45%
Southwest	Hours	1110 hrs.	1638 hrs.	1095 hrs.	1570 hrs.	924 hrs.	1452 hrs.
	% Change	39%	57%	38%	55%	32%	51%

Figure 13. Lighting energy savings 16 to 24' from the windowed façade with optimal blind control.

		West		South		East	
		40% VLT	**70% VLT**	**40% VLT**	**70% VLT**	**40% VLT**	**70% VLT**
Northwest	Hours	498 hrs.	750 hrs.	614 hrs.	972 hrs.	410 hrs.	643 hrs.
	% Change	17%	26%	21%	34%	14%	23%
Northeast	Hours	551 hrs.	868 hrs.	715 hrs.	1081 hrs.	492 hrs.	788 hrs.
	% Change	19%	30%	25%	38%	17%	28%
Southwest	Hours	804 hrs.	1088 hrs.	926 hrs.	1279 hrs.	626 hrs.	910 hrs.
	% Change	28%	38%	32%	45%	22%	32%

Figure 14. Lighting energy savings 16 to 24' from the windowed façade with always-closed blinds, DRF and photocontrols

The second objective, reducing annual lighting energy usage by 25% is achieved when the baseline does not have existing photocontrols in all climate zones and orientations modeled. When the baseline building has photocontrols in the first two zones, the 25% target is achieved on a consistent basis in the Southwest and Northeast climate conditions but not for the Northwest climate conditions as seen in Figure 15.

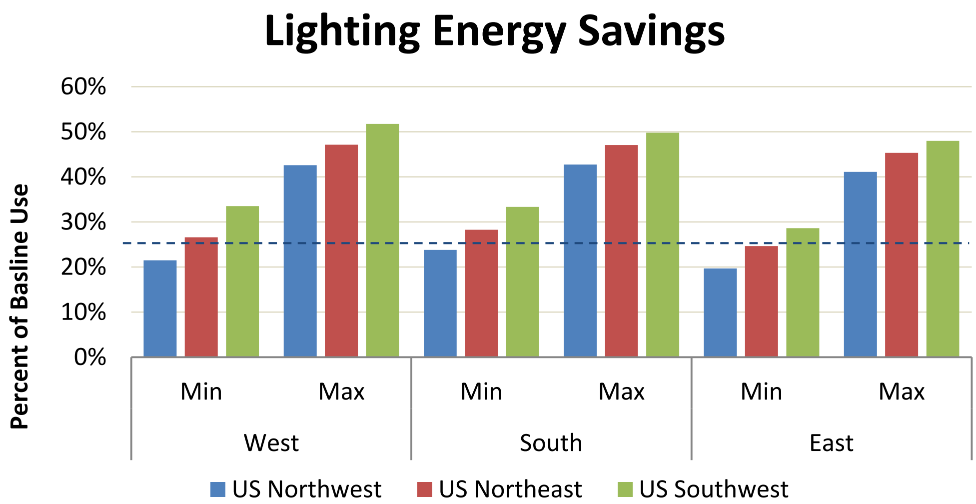

Figure 15. Percent lighting energy savings predicted from DRF and daylighting controls

6.4 REDUCE WHOLE BUILDING ENERGY USE

The success criteria for performance objective “reduce whole building energy use” was that whole-building energy use be at least 5% greater than the electric-lighting energy savings alone. The purpose was to show that adding the film and photocontrols can save energy on an annual basis to reduce energy demand and costs for DOD buildings. Success was judged solely on annual electricity use reported in kWh / sq. ft. / year.

Based on the lighting energy savings numbers presented in Figure 16. Predicted Lighting Energy Savings and whole building energy savings from Figure 17, one can calculate the additional whole building savings from HVAC impacts. This additional impact is on average 30% across all building models (orientations, climates etc.). Thus the performance objective is met on average. The only exception is the US Northwest where the cooling loads are not high and thus HVAC impacts are negligible.

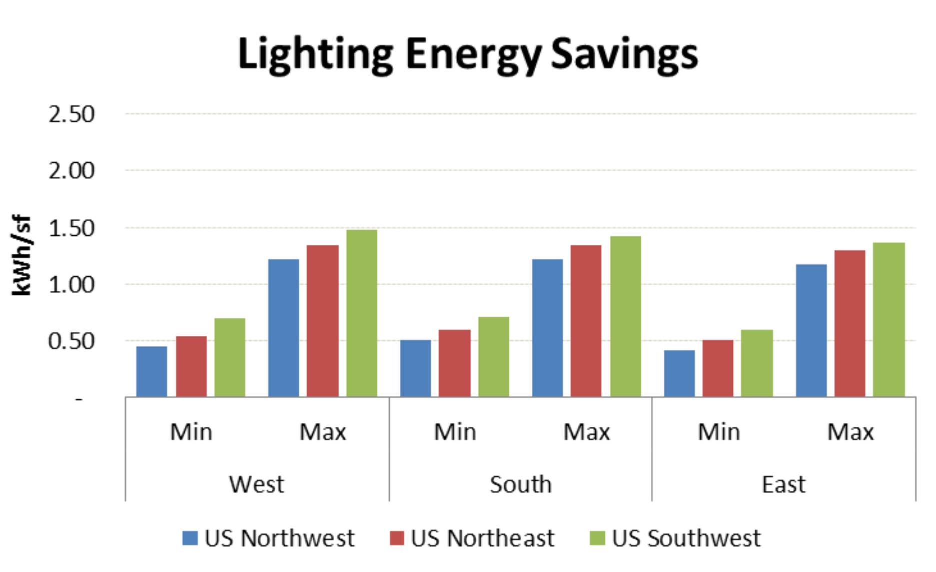

Figure 16. Predicted lighting energy savings

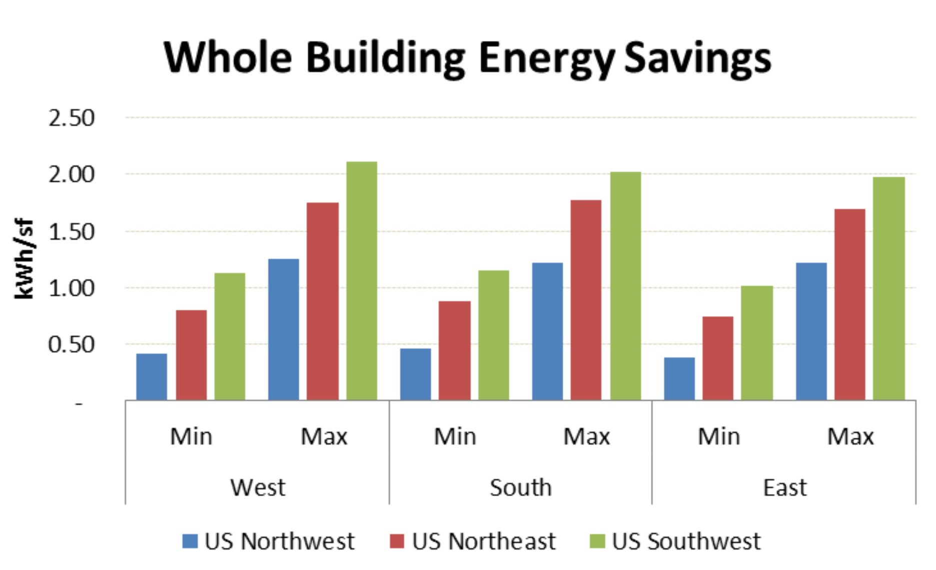

Figure 17. Predicted whole building energy savings

6.5 GREEN-HOUSE GAS EMISSIONS

Total electric and natural gas energy savings were converted to carbon equivalents and are presented in Figure 18. To develop the carbon equivalents, we used the US Environmental Protection Agency estimates[11].

CO2 Savings lb/sf/yr	West		South		East	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
US Northwest	0.65	1.83	0.76	1.86	0.60	1.76
US Northeast	0.89	2.20	1.02	2.33	0.74	2.13
US Southwest	0.66	2.21	0.84	2.26	0.51	2.13

Figure 18. CO_2 savings from DRF and photocontrols. (pounds of CO2 / sq. ft. / year)

The success criteria for this performance objective was to demonstrate that a net reduction in the greenhouse gas emission is expected when the embedded GHG gases in the manufacturing of the DRF is taken into account. Embedded GHG gases in the manufacture of DRF was estimated to be 0.265 lbs/sqft. The performance objective is fully met as the CO2 savings far exceed those emitted in the manufacturing process.

6.6 MAINTAIN OR INCREASE VISUAL COMFORT

This performance objective was to maintain if not increase the visual comfort of occupants in the spaces where DRF was installed. This is a subjective assessment based on occupant feedback to the DRF installation.

As detailed in the individual site findings in Appendix E, the DRF installation was largely seen as a success from the perspective of visual comfort. Occupant visual comfort was preserved or increased in all but one installation. In the installation where visual comfort decreased (Norfolk), the product was not installed high enough above eye level. In the installation at Twenty Nine Palms, the DRF actually improved the visual comfort of the occupants.

6.7 IMPROVE PRESERVATION OF VIEWS OUT FROM THE BUILDING

The goal of this performance objective was to increase perception of quality of available view due to improvement in overall visual comfort. This is a subjective metric based on

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[11] (EPA 2012). eGRID2012 Version 1.0, U.S. annual non-baseload CO2 output emission rate, year 2009 data, U.S. Environmental Protection Agency, Washington, DC.

occupant feedback to the DRF retrofit. Based on this subjective feedback, the performance objective is largely met across the sites. An increase in occupant ranking of view quality was observed when the DRF was installed. The impacts of blinds operation could not be analyzed based on the data available but anecdotal responses from the occupants indicate that the occupants preferred having control of the blinds and when they were told to not operate blinds or when site conditions prohibited them from doing so, they did not appreciate that.

6.8 REDUCE GLARE

This performance objective is also a subjective assessment of the impacts of DRF installation on reducing or affecting glare from windows on occupants. Based on occupant surveys, glare was unchanged or reduced in five out of six locations. In Norfolk, installation of film at 6’ AFF - too close to eye level - resulted in some glare complaints.

6.9 MAINTAINABILITY OF SYSTEM

This performance objective aims to document that the DRF installation does not create significant maintenance needs. While the study was a relatively short period (6-8 months per site), site staff did not report any maintenance concerns with final product installation. Thus we consider this performance objective to be met.

7. COST ASSESSMENT

The cost of the daylight redirecting film and the installation were tracked during this demonstration project. DRF technology is designed to reduce the electrical energy consumption as well as HVAC requirements. However, the demonstration project was not setup to track or determine the cost savings from the reduction in energy use in the demonstration sites. Instead, potential reduction in energy reduction was estimated using computer simulation.

7.1 COST DRIVERS

As with most projects, this demonstration project has three main drivers; regulatory drivers, technology drivers and economic drivers.

7.1.1 REGULATORY DRIVERS

As listed in section 1.3 of this report, a number of executive orders have been issued and laws passed to address the continually increasing energy demand. Since DoD is the largest real estate owner and energy consumer, each of these regulatory driver can play a significant role. Increasing facility energy efficiency is a top priority for all DoD facilities. Since lighting and heating & cooling constitute a large fraction of the total energy demand, any technology that can impact these costs must be considered as a potential solution to the energy consumption reduction problem.

7.1.2 TECHNOLOGY DRIVER

Better use of daylight in building can directly lead to not only a reduction in energy consumption but also in improved productivity and sense of well-being. Most new buildings have at least considered means to improve daylight use. However, existing buildings could benefit from a technology that is suitable for better use of daylight in the buildings. Through this project, we have attempted to demonstrate the energy saving potential of daylight redirecting film technology.

7.1.3 ECONOMIC DRIVER

Understanding return on investment at a holistic level is important in making sound decisions. In this demonstration project, we have attempted to quantify the energy saving potential of daylight redirecting films in different climate zones, façade designs and orientations and window configurations. Attempts were made to quantify the feedback from the occupants as much as possible since occupant behavior can have a significant impact in efficient operation of a building.

7.2 COST ANALYSIS AND COMPARISON

A simple cost model for the DRF technology is shown in Figure 19. These represent the actual costs incurred as a part of the demonstration project. The accompanying short notes are included as a footnote.

Cost Element	Data Tracked During the Demonstration	Estimated Costs
Daylight redirecting film cost	Cost of producing daylight redirecting film[12]	$11/ft^2$
Installation costs	Labor and material required to install[13]	$25/ft^2$
Consumables	No consumables required	NA
Facility operational costs	No operational costs incurred	NA
Maintenance	• Frequency of required maintenance • Labor and material per maintenance action	None
Estimated Salvage Value	Estimate of the value of equipment at the end of its life cycle	$ 0/ft^2$
Hardware lifetime	Estimate based on components degradation during demonstration[14]	15 years
Operator training	Estimate of training costs	None

Figure 19. Cost model for the DRF technology

[12] Only the microstructured film production related costs are reported here. Diffusing film used in this demonstration project is a commercially available 3M product. Cost for internal transfer of this film was charged to the project and was not traceable immediately. Additionally, some of the film used was considered “scrapped” and had zero assigned value.

[13] Some of the labor involved in the installation of film is not captured here. Specifically, complete installation and a significant fraction at the other sites was done by 3M personnel. This was accounted differently and not included in this cost.

[14] The film service life is shown to be 10 yrs since that is expected to be the warranted product life. In reality, window films have shown to be perfectly functioning much beyond the warranted lifetime.

The findings of this demonstration show that the energy savings achievable by the DRF technology depends on the successful use of lighting controls as well as building location and orientation among others. The cost of energy, which has a large range across the country, will have the most significant impact on the return on investment. As an exercise, the simple payback was calculated for three climate zones and three façade directions (Figure 20). Installed cost of $20/sq. ft. is assumed for the calculations. The min and max payback years range results from different blinds operations and whether the photocontrols are included in the base case or not.

Simple Payback (Years)						
Avg US Elec Rate	**West**		**South**		**East**	
cents 11.88/kWh	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
US Northwest	23	8	19	8	25	8
US Northeast	12	6	11	5	13	6
US Southwest	8	4	8	5	9	5
Max US Elec Rate	**West**		**South**		**East**	
cents 17.69/kWh	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
US Northwest	15	5	13	5	17	6
US Northeast	8	4	7	4	9	4
US Southwest	6	3	5	3	6	3
Min US Elec Rate	**West**		**South**		**East**	
cents 8.36/kWh	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
US Northwest	32	11	27	11	35	12
US Northeast	17	8	15	8	18	9
US Southwest	12	6	12	7	13	7

Figure 20. Simple payback based on calculated energy savings.

In a related study, Lawrence Berkeley National Laboratory (LBNL) has calculated much better ROI[15]. According to LBNL, "Site lighting energy use with a small clerestory aperture (WWR=0.18) over a 40-ft deep perimeter zone facing south, east, or west in northern and southern US climates. Occurrence of discomfort glare is less than 5% of annual occupied hours. Simple payback is 5 years, the IRR is 19%, and CCE is $0.08/kWh, assuming an installed cost of $20/ft^2, $0.20/kWh, 30 year life, and 6% discount rate."

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[15] http://eetd.lbl.gov/news/article/56882/daylighting-window-film-shows-p

8. IMPLEMENTATION ISSUES

At the start of the project, the DRF was intended to be a single film applied to the existing window using standard window film installation process. However, as the prototype film was developed and tested, it became apparent that a diffusing film must be positioned in front of the redirecting film to reduce or eliminate the glare. Several diffusing films and diffusing panels available were studied. Factors such as transmission, haze and clarity were used to select the optimal diffuser that reduced the glare while minimizing any loss in light transmission.

Different application techniques, shown in Appendix C, had to be used in order to achieve the same effect. Although requested by the research team, relocation of the blinds to lower position in the window was not permitted at Naval Station Norfolk. Similarly removal of the external shading device was delayed or not carried out by the building maintenance at Naval Postgraduate School, Monterey.

Several facility managers enquired about the blast resistance properties of the film. At this time, the blast resistance properties have not been tested. However, the research team believes that the film should be able to achieve a '3a' rating in GSA protection standard[16] based on the knowledge of other window film materials and constructions.

It is the author's belief that most of the barriers related to window and shading modifications encountered during the field testing of DRF technology were due to the temporary nature of the study. These should be easily overcome if the DRF were to be viewed not as an academic interest but a serious solution to the energy or glare reduction issue faced by the building or site manager.

It should also be noted that one of the diffusing panel came loose and fell off the frame much after the completion of monitoring period. The matter was discussed with the building manager and, all DRF films were removed as was originally described in the site study plan.

[16] http://www.gsa.gov/graphics/pbs/Standards_GSATestingStandard.pdf

APPENDIX A: MANAGEMENT AND STAFFING

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APPENDIX C: DRF CONFIGURATIONS USED AT FIELD SITES

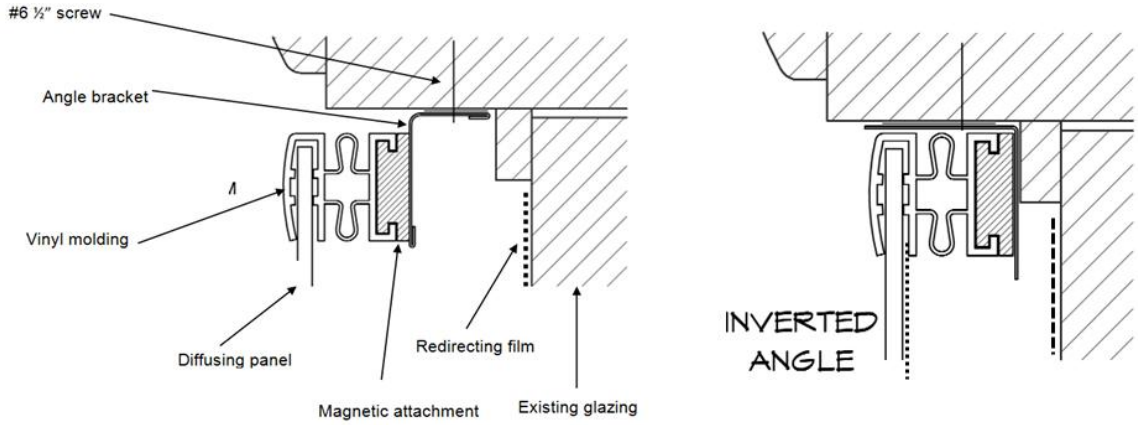

Figure C- 1. Vinyl molding based diffuser attachment method.

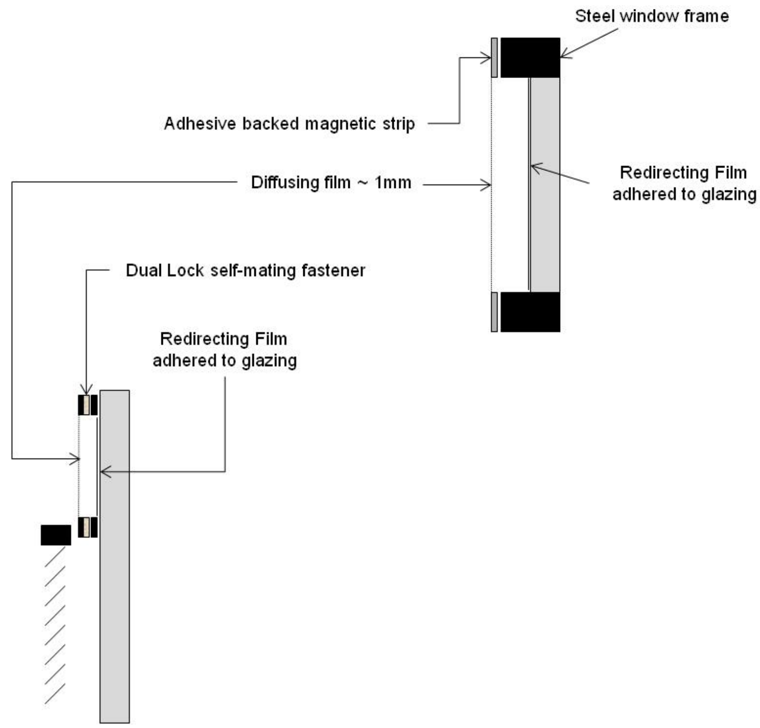

Figure C- 2. Adhesive backed magnetic strip and self-mating fastener to attach a 1 mm diffusing film to the frame.

state	Location	Orientation	Film applied to	Bottom of film AFF	Height of film	Diffuser type	Frame attachment type	Other treatment	Existing blinds type	Blinds for treated area	Other special conditons
VA	Norfolk	South	Glass	6'0"	3'0"	100%	Magnetic vinyl molding	35% VT window film on view windows	1" horizontal, perforated	retracted	none
CA	29 Palms	South east, South west	Glass	8'0"	2'0"	50%	Magnetic vinyl molding	none	roller screen	no change	none
RI	Newport	South	Glass	11	2'0"	50%	Magnetic vinyl molding	none	curtains, mounted at top of window	horizontal mini, mounted below film	casement windows
TX	Fort Bliss	South, South east	Glass	7'6"	1'6"	50%	3M dual-lock fastener	none	1/2" horizontal blinds	blinds lowered below the film	Reflective tinted windows
WA	Bremerton	South east	Glass	7	2'0"	50%	Magnetic vinyl molding	none	roller screen	1/2" horiztonal blinds, mounted below film	patient privacy requires blinds always down
CA	Monterey	West	Glass	7'6"	2'1"	50%	3M dual-lock fastener, flexible magnetic strip	40% VT window film installed on view windows	2/5" venetian	1/2" horiztonal blinds, mounted below hopper	hopper windows, exterior shade screen

Figure C- 3. Attachment types and window treatments at demonstration sites

APPENDIX D: STUDY PROSPECTUS

3M Company (3M) is seeking DoD building sites to investigate occupant acceptance and energy impacts of a new light-redirecting window-film product. The research is funded by the Department of Defense's (DoD) **Environmental Security Technology Certification Program** (ESTCP)[17]. The **Heschong Mahone Group** (HMG) is providing technical support for this study.

If you have an appropriate building with tall, south-, east-, or west-facing windows, 3M will install the window film and monitoring systems at no cost to your facility and provide advice on how to configure photo-controls and window coverings such as blinds, curtains, or roller shades in order to maximize energy savings and occupant comfort. This represents a chance to upgrade your building and advance energy efficiency options for the DoD.

A brief Description of 3M's New Light-redirecting Film

Sunlight entering through high, clerestory windows offers an opportunity for substantial daylighting benefits, but more frequently inundates building occupants with excessive glare or heat, necessitating actions to block the sunlight.

To ameliorate this, 3M developed a window film which redirects sunlight up onto the ceiling, where it bounces deeper into the space, effectively turning the ceiling surface into a daylight source. This film, when used in conjunction with automatic photo-control of the electric lights, can help reduce building energy use while also improving visual and thermal comfort for space occupants. The film is only applied to the upper portion of the window (seven feet or more above floor level). The lower area of the window is unaffected, preserving existing views, and with normal operation of blinds or curtains. Photographs at the end of this document show a laboratory installation of the film at 3M Headquarters in St. Paul, Minnesota.

Demonstration Site Volunteers Needed

- Project is funded to study six to eight DoD buildings within the continental United States
- South, West or East facing office-type spaces with un-shaded, clear windows at least nine feet high are needed
- Ideally, two, similar, adjacent spaces (or buildings) will be available to compare occupant comfort, lighting levels and resulting energy usage, with and with-out the film
- Spaces which have daylight-sensing photo-controls already installed are preferred

Participant Benefits

- Improve visual and thermal-comfort for occupants (goal)
- Quantified energy savings, and data on current lighting system operation (goal)
- Test-drive an innovative, low-impact product. Site may choose to keep the product after the study ends
- Assist with development of products and retrofit strategies which will help DoD meet its energy-efficiency goals

[17] http://www.serdp-estcp.org/About-SERDP-and-ESTCP

Publicity, Confidentiality and Security

If interested, participating DoD sites will have an opportunity for internal and/or external recognition as contributors to the study. On the other hand, some sites may prefer to remain fully anonymous, which is also an option. 3M and HMG will strictly respect all confidentiality and security requirements of participating sites.

Site Responsibilities

- The building manager makes the study spaces available for film installation and monitoring
- Film is left in place for the duration of the study period (six months to one year). No special maintenance is needed
- Test space and control space occupants are available to participate in brief comfort assessment surveys, at a few intervals during study. The surveys can be administered electronically or in person. Survey results will be made available for the site's review.
- Depending on existing conditions, reconfiguration of blinds or shades may be required to optimize daylight management

Project Schedule and Contacts

The study consists of two phases: a pilot study and a demonstration study. The pilot study is expected to begin in mid-March, 2011 and conclude in mid-May, 2011. The demonstration study is expected to begin in mid-June 2011 and continue for six to nine months. 3M and HMG staff will work around any workplace scheduling requirements to avoid impacting host schedules.

For further information, please contact:

Tim Perry at HMG, (916) 962-7001, tim.perry@h-m-g.com.

Or **Raghu Padiyath** at 3M, (651) 733-8952, raghupadiyath@mmm.com.

Figure D-1. Photographs of the same room before (left) and after (right) applying the light-redirecting film.

The bright patch on the ceiling is created by the films' redirection of sunlight from the upper half of the window. Sunlight reflecting off of the ceiling brings daylight deeper into the space, enabling occupants to reduce electric lighting usage.

APPENDIX E: HESCHONG MAHONE GROUP REPORT

Daylight Redirecting Window Film

ESTCP Project No: EW-201014

HMG Project No: 1004

August 2013

Submitted to:

3M Company

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1. EXECUTIVE SUMMARY

1.1 BACKGROUND AND STUDY SCOPE

Daylight redirecting window films (DRF) work by directing sunlight into deep interiors of buildings, where additional energy savings can be realized by reducing energy used by electric lighting. The films can be applied directly to a window surface, and maintenance is simple, since the film can be cleaned with water.

The Daylight Redirecting Window film ESTCP Demonstration was initiated to gain real world feedback on this promising new daylighting retrofit technology developed by 3M that has the potential to reduce the energy use in existing Department of Defense (DOD) buildings.

The Heschong Mahone Group, Inc. (HMG) was contracted to assist 3M, the Prime ESTCP contractor, in

- developing a field research study plan
- identifying and securing study sites
- observing installation issues
- monitoring changes in daylight availability due to the window film installation
- surveying occupants about their experience with the product
- estimating the whole building energy impacts of a film retrofit
- analyzing the findings
- and producing this final report

The goals of the project were twofold:

1.) Assess the potential energy savings and physical applicability of the product to DoD's existing building stock, including identifying:
    - Types of building use and geometric configurations most amenable to the product's installation
    - Most favorable climate locations for energy savings
    - Ancillary conditions that contribute to energy savings

2.) Provide useful feedback to the manufacturer on how to improve the product assembly, including
    - Occupant comfort and satisfaction with operation
    - Energy savings potential
    - Ancillary conditions that contribute to energy savings
    - Ease of installation and maintenance

As such, HMG was given independence to observe the success of the window film installations and report objectively on results. During the project, HMG did provide intermediate feedback to the manufacturer, 3M, in order to assist with mid-stream modifications of the product to improve the chances for success. During the project, modifications were made to the film assembly and the installation technique, both to improve visual comfort and to make the assembly easy to remove after the study period.

1.2 STUDY LOCATIONS

Field studies were conducted at six locations:

- Naval Station Norfolk, Norfolk, VA
- Naval War College, Newport, RI
- Fort Bliss, El Paso, TX
- Marine Corps Air Ground Combat Center, Twentynine Palms, CA
- Naval Postgraduate School, Monterey, CA
- Naval Hospital Bremerton, Bremerton, WA

1.3 OVERALL OBSERVATIONS

HMG observed and calculated the following performance advantages and factors limiting effectiveness of the DRF product in a retrofit setting as well as social acceptance of the DRF film based on the current demonstrations.

1.3.1 PERFORMANCE ADVANTAGES

The DRF product primarily increases the opportunity for electric lighting savings, while also improving overall visual comfort in treated spaces. Specific observations include:

- **Increased Energy Savings:** Estimates, based on annual simulation, suggest that a substantial amount of energy can be saved due to installation of this product, ranging of about 0.39-2.11 kwh/sf of floor area per year based on building location and window orientation, from dimming or turning off the electric lighting in treated spaces.
  The most important observation from the energy simulation analysis is that the electric lighting savings with DRF under worst case conditions (blinds always closed in view windows) are better than the electric lighting savings potential for the same windows with no DRF under the best case conditions (blinds operations automated). Thus, the DRF completely eliminate the downside risk of poor blinds operation, and greatly increase the upside opportunity for daylight savings. Details of the energy simulation analysis methodology are in Section 5.5 and results summarized in Section 6.3.
- **Increased daylight illumination:** The product takes advantage of the intense power of sunlight to raise overall daylight illumination levels in a space, both near windows and deeper into rooms. By redirecting sunlight up onto ceilings and the upper surfaces of walls, the treated spaces are perceived as brighter and more cheerful.
- **Increased daylight penetration:** On sunlit days, daylight illumination in the back of treated spaces was significantly higher than in untreated spaces. Thus, the area where photocontrols may be cost effectively employed increased by about 12%. A simple rule of thumb is that for upper window areas which regularly receive direct sun for part of the day, the depth of the daylight zone that is likely

to produce cost effective lighting energy savings increases by about 8’ for each 1’ height of treated film area. This value varies by climate, glass type, and window exposure to direct sunlight.

- **Increased safety:** A change of even 1 footcandle (fc) of available daylight at the back of a large room change occupant’s perception of the spaces, and potentially provide greater safety and resiliency for those spaces if the power goes off for any reason.

1.3.2 FACTORS LIMITING EFFECTIVENESS OF DRF

The product requires fairly specific geometric and climatic conditions to be successful and there are several conditions that limit the effectiveness of the product. These limiting conditions, in approximate order of importance, are:

- **Cloudy Sky**: The product depends on the availability of direct sunlight on windows which is a result of clear sky conditions. Under cloudy conditions, the product does not increase daylight availability. More cloudy days per year, the lower the resulting energy savings potential. It should be noted however, that the DRF films does not decrease daylight availability under cloudy conditions compared to the baseline conditions either – just that it does not offer any significant benefits.
- **Limited exposure to sunlight**: Because the product depends upon sunlight for operation, it does not provide any energy advantages along north facing facades (in the northern hemisphere), nor along the lower stories of buildings that are continuously shaded by trees, exterior shading adjacent buildings, or other obstructions.
- **Short/Shaded/Operable/Diffusing Windows**: The product should be applied to areas of glass that are more than 7’ above the finished floor in order to avoid creating excessive glare for the building occupants. The treated area of windows should receive significant sunlight (in excess of 3-4 hours/day) during occupied hours in order to provide adequate electric lighting savings. The treated windows should be stationary, in order to avoid changing the geometry of sunlight distribution. And the treated windows should be clear (not diffusing) with fairly high visible light transmission (>45%) in order to take maximum advantage of the sunlight.
- **Sporadically Occupied Spaces**: The energy savings from the product result primarily from reducing electric lighting energy use. In spaces that are only sporadically occupied, occupancy sensors may be more cost effective.
- **Window treatments**: Existing buildings inevitably have existing window treatments installed at the window head (as was the case in 5 of the 6 study sites). In order for the product to work, the upper window area treated with the product needs to be clear of the window treatments. Thus, the existing window coverings need to be lowered or replaced. See discussion below on social acceptance for more details.

- **Automatic Photocontrols**: In order to enable energy savings benefits of DRF, automatic photocontrols are recommend to ensure that electric lights are turned down or off when there is sufficient daylight. With wireless controls installations, this is easier and more cost effective to do than ever before. However, it is another step, capital budget, and intervention that needs to be coordinated in conjunction with the DRF installation.

1.3.3 Social Acceptance

We found that many occupants preferred the 'brighter' rooms which resulted from the application of the DRF. However, some building managers were reluctant to relocate the existing blinds or shades to accommodate the installation. In this regard, DRF may be better suited for a new building or a major interior renovation where occupants would not resort to an inevitable "before-and-after" comparison.

- **Window Coverings**: It may seem simplistic, but the greatest social barrier to acceptance of this technology may be the interior design tradition of mounting all blinds, curtains, and shades at the very top of a window opening. This is a deeply entrenched tradition that is applied by interior designers in almost all office building and workplaces around the USA. In our experience, few if any building managers have ever considered any other alternative.
  While split window covers, such as 'French blinds' and 'café curtains' are more common in Europe, they are rarely seen in the USA. While easy and inexpensive to do, learning to position window coverings below an upper 'daylight window' aperture may take a period of professional education to catch on.
- **Lack of View**: The Daylight Redirecting Window Film obscures views out of the upper window area where it is applied. This may be unacceptable in some buildings where occupants enjoy the view of the sky, trees or mountains through those upper portions of the window

1.4 DEMONSTRATION RESULTS

This section provides a summary of all performance objectives (POs) evaluated as part of the technology demonstration.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Key Quantitative Performance Objectives				
Increase daylight illuminance levels	spatial Daylight Autonomy (sDA) See discussion in Section **Error! Reference source not found.**	Grid of horizontal illuminance measurements, measured and/or simulated under controlled sky conditions	At least a 10% increase in spatial Daylight Autonomy	**Fully met.** sDA in the treated spaces increased between 3%-24%, averaging 11% per simulation results. Further details in Section 6.3.2
Economic Payback	Life-Cycle Cost	Cost of energy impacts, cost of labor and materials for installation, cost of maintenance and replacement (provided by others)	Savings to Investment Ratio greater than 1.0; Net-present-value; Payback period < 10 years.	**Frequently met.** Simple payback averages 10 years but dependent on electricity rates and climate (range of 3-35 years).
Potential to reduce lighting energy use	Full-load equivalent hours (FLE) electric lights can be turned off (dimensionless) Peak lighting load intensity (kW/sf)	Lighting circuit current, task lighting power consumption; hourly operation schedules	At least 200 annual FLE and 25% reduction in daytime peak electric lighting need for the zone 15' to 25' from the windows;	**Partially met.** 184-270 FLE depending on blinds operation. Average peak demand reduction of 13%.
Other Desirable Quantitative Performance Objectives				
Reduce whole building energy use	Net kWh impacts on lighting and HVAC	Information on building envelope, HVAC equipment, and operation sufficient for simulation modeling	Net reduction in annual whole building energy use at least 1.05 times the direct lighting energy savings.	**Frequently Met.** Average annual whole building savings 1.30 times direct lighting savings. Range of 0.93-1.62 depending on climate.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Green-house Gas Emissions	Conversion of energy usage into green-house gas equivalents based on national averages	Green-house-gas-equivalent conversion factor for national level usage. Embedded costs of GHG in film production	Net reduction in greenhouse gas emissions over 10 years are at least twice the greenhouse gas cost of manufacturing.	**This item will be provided by 3M.** CO2 emissions reductions due to the whole building energy savings are 0.59-3.26 lb/sf/yr.
Key Qualitative Performance Objectives				
Maintain or increase visual comfort	Likert scale and open response questions about glare and visual comfort	Survey of occupants before and after installation of the daylight redirecting window film	Maintenance of or increase in occupant visual comfort	**Frequently met.** Occupant comfort was preserved or increased in all but one installation where the product was not installed high enough above eye level.
Other Desirable Qualitative Performance Objectives				
Improve preservation of views out from the building	Likert scale and open response questions about quality of view Operation and openness of window blinds (percent open)	Survey of occupants before and after installation of the daylight redirecting window film Blinds operation observations	Increase perception of quality of available view Increase amount of time blinds can be left open to preserve views.	**Partially met.** Increase in occupant ranking of view quality. No discernible change in blinds operation
Reduce glare	Current quantitate glare indices are inadequate to task of rating new innovative products.	Glare assessment based on occupant surveys and informal interviews.	Maintenance or reduction in subjective glare ratings	**Frequently met.** Glare was unchanged or reduced in all but one space where DRF installed too close to eye level.
Maintainability of System	Change in maintenance practices	Interviews with site maintenance staff	Film does not create significant film-maintenance needs	**Fully met.** Staff did not report any maintenance concerns with DRF installation.

Figure 1. Performance Objectives Outcomes

1.5 IMPLEMENTATION ISSUES

1.5.1 PILOT PHASE LESSONS LEARNED

Some facility managers were concerned about mechanical attachments of a secondary diffuser to existing window frames. Over the course of the study 3M tested a number of different installation methods and developed a new version of the DRF film with an integral diffuser, which requires no mechanical attachments.

Most sites had existing window blinds, roller shades or curtains which covered the entire window, blocking the function of the DRF. The study team worked with the site contacts to devise various ways to modify existing blinds/shades so that they would only cover the lower, view portion of the windows while leaving the upper, clerestory windows unobstructed. This effort to relocate window coverings was not fully successful at all sites, and although technically easy, seems to constitute the most challenging social barrier for a DRF retrofit project.

1.5.2 MAIN STUDY SITE SELECTION

Appropriate study sites meeting the research design criteria were difficult to find. Ultimately, the study team selected six study sites, out of 20 candidate sites, with the goal of testing the product under a variety of field and climatic conditions.

These six study sites were representative of the standard civilian building types that this product was designed for, with large un-shaded windows. However, from the screening process it became clear that these types of buildings are more the exception and the rule among the population of DoD buildings, where a higher percentage of buildings seem to have climatically sensitive designs, and thus carefully shaded windows. Furthermore, low occupancy at some sites and high security concerns at others made them inappropriate as study locations.

The six sites represented three of the desired four climate conditions for the study. The team was not able to find any available study sites in high-latitude with clear skies, but met their objectives for study sites in other sky types and latitudes.

1.5.3 SITE DATA COLLECTION ISSUES

The site data collection had some problems with loss of data from dataloggers and logger theft on one site, but overall sufficient monitored data was available to compare to simulation findings, and provide insight to SRF operation under site conditions. Standard occupant survey forms were not particularly successful at the DoD study sites, due to sporadic and rotating populations. Sustained observations of occupant comfort were difficult under these conditions. Additional insight to occupant comfort was gained via personal interviews, where permitted.

1.5.4 PRODUCT INSTALLATION

Choosing daylight redirecting products involves aesthetic, safety, installation, maintenance, occupant comfort, and economic considerations. The team discussed these considerations with all potential sites during recruitment and has observed the outcome of product installation in 23 rooms spread over six sites.

1.5.5 AESTHETICS

The product changes the appearance and aesthetics of the space. The brighter appearance of the rooms was welcomed by most occupants. However, the film also eliminates the view of the outside through the upper, clerestory window. This study found occupants tolerated this well with one exception: at Norfolk the study one of the occupants reported lack of ability to watch the planes take off and land and was mildly irritated by the inability to see the planes through the film.

1.5.6 SAFETY, INSTALLATION AND MAINTENANCE

Compared to other products, such as light shelves or louvers, available to enhance daylighting in side-lit spaces, the 3M Window Film has fewer maintenance and safety issues. The film does not extend into the room making it easier to clean the windows, and in the event of a fire, the film would not obstruct the flow of water from fire suppression sprinklers, as might internal light shelves. Compared to louvers, the DRF does not collect dust and is easier to clean.

1.5.7 OCCUPANT COMFORT

The product should be installed on windows no less than 7’ above floor level to prevent excessive brightness at standing eye level at the back of a room.

In some study sites where the existing blinds were disabled or exterior sun screens were removed, occupants expressed thermal discomfort from additional solar heat gain. This was mitigated by installing an additional sun control film on lower panes.

1.5.8 ECONOMICS

The economics of a retrofit are complex and the benefit cost ratio will be sensitive to many variables including product cost, labor costs, climate and sun exposure, glazing type and area, blinds operation, room size, photo-controls and wiring costs, the cost of electricity, and the room’s occupancy schedule.

Consequently, this report provides benefit cost guidance for a generic condition. The electric lighting and HVAC savings attributable to retrofitting the DRF and photocontrols into a room use default ASHRAE schedules and equipment. 3M estimates the current (2013) cost of installation of the DRF and associated hardware to be $20/ft of window area covered by the DRF.

2. INTRODUCTION

The Daylight Redirecting Window film ESTCP Demonstration was initiated to gain real world feedback on a promising new daylighting retrofit technology that has the potential to reduce the energy use in existing Department of Defense (DOD) buildings.

HMG was contracted by 3M to assist in

- developing a field research study plan
- identifying and securing study sites
- observing installation issues
- monitoring changes in daylight availability due to the window film installation
- surveying occupants about their experience with the product
- estimating the whole building energy impacts of a film retrofit
- analyzing the findings
- and producing this final report

2.1 OBJECTIVES OF THE DEMONSTRATION

The goals of the project were twofold:

1. Assess the potential energy savings and physical applicability of the product to DoD's existing building stock, including identifying:
    a. Types of building use and geometric configurations most amenable to the product's installation
    b. Most favorable climate locations for energy savings
    c. Ancillary conditions that contribute to energy savings
2. Provide useful feedback to the manufacturer on how to improve the product assembly, including
    a. Occupant comfort and satisfaction with operation
    b. Energy savings potential
    c. Ancillary conditions that contribute to energy savings
    d. Ease of installation and maintenance

As such, HMG was given independence to observe the success of the window film installations and report objectively on results. During the project, HMG did provide intermediate feedback to the manufacturer, 3M, in order to assist with mid-stream modifications of the product to improve the chances for success. During the project, modifications were made to the film assembly and the installation technique, both to improve visual comfort and to make the assembly easy to remove after the study period. Many installation challenges were encountered, especially the relocation of existing window treatments such as blinds and curtains.

3. TECHNOLOGY DESCRIPTION

3.1 TECHNOLOGY OVERVIEW

Energy consumption, room lighting, aesthetics, and possibly even human productivity and satisfaction can be improved by increasing and dispersing natural daylight into a building as much as possible. 3M's light redirecting film (DRF) utilizes microstructure features on the film surface to direct sunlight incident on a vertical window towards the ceiling. This results in more uniform and comfortable distribution of light within the occupied building space. The microstructures are specifically designed so that incident light is directed as far into the room as possible for as many incident angles as possible. The exterior appearance of the building façade is unaltered by application of the daylight redirecting window film.

3.1.1 SOUND BITE

Daylight redirecting window films are projected to reduce solar heat gain (when combined with infrared reflecting films or coatings), improve energy efficiency, and lower overall operating costs. By admitting daylight into deep interiors of buildings, they claim to maximize energy savings. The films are easy to apply and projected to be cost effective. Building occupants are expected to benefit from reduced glare and will not be compelled to use shading devices such as blinds and screens. As a result of better access to daylight, an improvement in productivity may be expected.

3.1.2 COMPARISON TO EXISTING TECHNOLOGY

Traditional windows use blinds, shades and other devices to control daylight and sunlight penetration from windows – primarily to ensure glare protection and secondarily to provide daylight into the space. However, traditional windows are limited in their ability to provide daylight deeper into the space and the operation of internal blinds/shades further reduces the ability. The DRF product is an add-on film that can be applied to the top areas of existing glazing to change the daylight redirecting properties of the existing glazing. The DRF projects daylight deeper into the space and on to the ceiling of the space. Combined with relocation of blinds/shades this technological innovation increases the amount of usable daylight in the space.

3.1.3 ANECDOTAL OBSERVATIONS

Occupants in the study spaces where the DRF was installed have almost universally liked the product – even if they don't fully understand the benefits. The DRF has helped in reducing glare from existing glazing and has enabled greater daylight penetration in the study spaces.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

HMG observed and calculated the following performance advantages and factors limiting effectiveness of the DRF product in a retrofit setting as well as social acceptance of the DRF film based on the current demonstrations.

3.2.1 PERFORMANCE ADVANTAGES

The DRF product primarily increases the opportunity for electric lighting savings, while also improving overall visual comfort in treated spaces. Specific observations include:

- **Increased Energy Savings:** Estimates, based on annual simulation, suggest that a substantial amount of energy can be saved due to installation of this product, ranging of about 0.39-2.11 kwh/sf of floor area per year based on building location and window orientation, from dimming or turning off the electric lighting in treated spaces.
  The most important observation from the energy simulation analysis is that the electric lighting savings with DRF under worst case conditions (blinds always closed in view windoes) are better than the electric lighting savings potential for the same windows with no DRF under the best case conditions (blinds operations automated). Thus, the DRF completely eliminate the downside risk of poor blinds operation, and greatly increase the upside opportunity for daylight savings. Details of the energy simulation analysis methodology are in Section 5.5 and results summarized in Section 6.3.
- I**ncreased daylight illumination:** The product takes advantage of the intense power of sunlight to raise overall daylight illumination levels in a space, both near windows and deeper into rooms. By redirecting sunlight up onto ceilings and the upper surfaces of walls, the treated spaces are perceived as brighter and more cheerful.
- **Increased daylight penetration:** On sunlit days, daylight illumination in the back of treated spaces was significantly higher than in untreated spaces. Thus, the area where photocontrols may be cost effectively employed increased by about 12%. A simple rule of thumb is that for upper window areas which regularly receive direct sun for part of the day, the depth of the daylight zone that is likely to produce cost effective lighting energy savings increases by about 8’ for each 1’ height of treated film area. This value varies by climate, glass type, and window exposure to direct sunlight.
- **Increased safety:** A change of even 1 footcandle (fc) of available daylight at the back of a large room change occupant’s perception of the spaces, and potentially provide greater safety and resiliency for those spaces if the power goes off for any reason.

3.2.2 FACTORS LIMITING EFFECTIVENESS OF DRF

The product requires fairly specific geometric and climatic conditions to be successful and there are several conditions that limit the effectiveness of the product. These limiting conditions, in approximate order of importance, are:

- **Cloudy Sky**: The product depends on the availability of direct sunlight on windows which is a result of clear sky conditions. Under cloudy conditions, the product does not increase daylight availability. More cloudy days per year, the lower the resulting energy savings potential. It should be noted however, that the DRF films does not decrease daylight availability under cloudy conditions compared to the baseline conditions either – just that it does not offer any significant benefits.
- **Limited exposure to sunlight**: Because the product depends upon sunlight for operation, it does not provide any energy advantages along north facing facades (in the northern hemisphere), nor along the lower stories of buildings that are continuously shaded by trees, exterior shading adjacent buildings, or other obstructions.
- **Short/Shaded/Operable/Diffusing Windows**: The product should be applied to areas of glass that are more than 7' above the finished floor in order to avoid creating excessive glare for the building occupants. The treated area of windows should receive significant sunlight (in excess of 3-4 hours/day) during occupied hours in order to provide adequate electric lighting savings. The treated windows should be stationary, in order to avoid changing the geometry of sunlight distribution. And the treated windows should be clear (not diffusing) with fairly high visible light transmission (>45%) in order to take maximum advantage of the sunlight.
- **Sporadically Occupied Spaces**: The energy savings from the product result primarily from reducing electric lighting energy use. In spaces that are only sporadically occupied, occupancy sensors may be more cost effective.
- **Window treatments**: Existing buildings inevitably have existing window treatments installed at the window head (as was the case in 5 of the 6 study sites). In order for the product to work, the upper window area treated with the product needs to be clear of the window treatments. Thus, the existing window coverings need to be lowered or replaced. See discussion below on social acceptance for more details.
- **Automatic Photocontrols**: In order to enable energy savings benefits of DRF, automatic photocontrols are recommend to ensure that electric lights are turned down or off when there is sufficient daylight. With wireless controls installations, this is easier and more cost effective to do than ever before. However, it is another step, capital budget, and intervention that needs to be coordinated in conjunction with the DRF installation.

3.2.3 Social Acceptance

We found that many occupants preferred the ‘brighter’ rooms which resulted from the application of the DRF. However, some building managers were reluctant to relocate the existing blinds or shades to accommodate the installation. In this regard, DRF may be better suited for a new building or a major interior renovation where occupants would not resort to an inevitable “before-and-after” comparison.

- **Window Coverings**: It may seem simplistic, but the greatest social barrier to acceptance of this technology may be the interior design tradition of mounting all blinds, curtains, and shades at the very top of a window opening. This is a deeply entrenched tradition that is applied by interior designers in almost all office building and workplaces around the USA. In our experience, few if any building managers have ever considered any other alternative.
  While split window covers, such as ‘French blinds’ and ‘café curtains’ are more common in Europe, they are rarely seen in the USA. While easy and inexpensive to do, learning to position window coverings below an upper ‘daylight window’ aperture may take a period of professional education to catch on.
- **Lack of View**: The Daylight Redirecting Window Film obscures views out of the upper window area where it is applied. This may be unacceptable in some buildings where occupants enjoy the view of the sky, trees or mountains through those upper portions of the window.

4. SITE/FACILITY DESCRIPTION

This section provides a concise summary of the demonstration sites and facilities used in this study. Detailed plans of the study spaces are in Section 5.7 for interested readers.

4.1 SITE/FACILITY SELECTION CRITERIA

The sample of buildings for this project was required to meet criteria for both the diversity of the sample and for the suitability of the buildings. A good, representative, sample was important to the applicability of the project findings to a larger context.

The selected sample of six sites represented geographic and climatic diversity, and architectural and cultural diversity of the building types, which is less tangible but also important. The suitability of the study sites was established using the following criteria:

4.1.1 GEOGRAPHIC AND CLIMATIC DIVERSITY

The goal of the sample of study buildings was to cover as wide a range of daylight, latitude and temperature conditions within the U.S. as possible. A diverse sample allows us to assess the likely performance of the system in the wide range of locations in which DOD facilities are found.

The Department of Energy (DOE) climate zones (for temperature) were used in conjunction with NREL data on photovoltaic resource levels (for cloudiness and daylight availability) to ensure a balanced sample. Figure 2 shows the preferred climatic sample frame.

	Predominantly clear skies (>60% clear)	Mixed skies (<60% clear)
High latitude	2	2
Low latitude	2	2

Figure 2. Climatic sample frame goals

	Predominantly clear skies (>60% clear)	Mixed skies (<60% clear)
High latitude	0	2
Low latitude	2	2

Figure 3. Climatic sample achieved

Figure 4 shows the photovoltaic solar resource potential for the United States as measured by NREL[1]. The black arrows indicate the location of the selected study sites (described in Section 1.2 below). The team was not able to identify two northern locations with predominantly clear skies. Studies were conducted for all other combinations of latitude and sky condition desired.

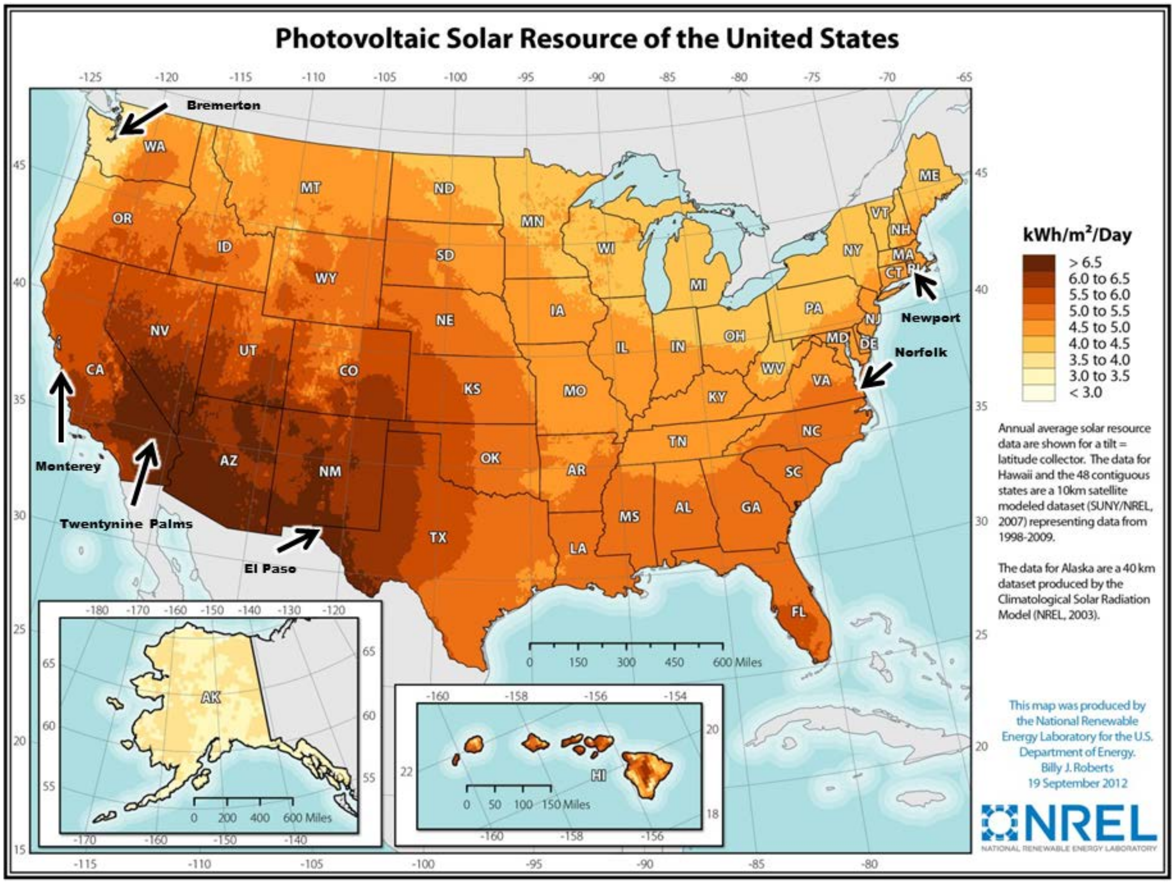

Figure 4. Photovoltaic Resource levels for the United States according to NREL

4.1.2 ARCHITECTURAL AND CULTURAL DIVERSITY

The project also set a goal of finding a range of architectural styles and cultural conditions that might be somewhat representative of the range of building conditions found within the DOD building stock. The team hoped to include building types from a spectrum of the services and administrative agencies within DOD, such as Army, Navy, Marines and Air Force, plus building types such as office buildings, recreation facilities, medical facilities, commissaries, etc., and a range of vintages and architectural styles.

In reality the six final study sites do represent a range of build types and vintages, but they cannot claimed to be statistically representative of the general population of DOD

[1] http://www.nrel.gov/gis/images/eere_pv/national_photovoltaic_2012-01.jpg

buildings. As described below in the next section, recruitment for participation in the study was extremely difficult and time consuming.

4.1.3 Facility Representativeness

The black arrows on the USA solar resource map in Figure 4 indicate the location of the six study sites that were chosen. They encompass a variety of climate characteristics, from very cloudy (Bremerton, WA) to very sunny (Twentynine Palms, CA and El Paso, TX) meeting the study objectives with regards to geographical and climatic site diversity.

The study sites were representative of the standard civilian building types that this product was designed for, with large unshaded windows, but we learned that these types of buildings seem to be rare within the population of DOD buildings, where a high percentage of buildings seem to have shaded windows. Appropriate study sites, meeting the research design criteria, were difficult to find. Ultimately, the study team rejected all proposed buildings at 14 out of 20 candidate sites.

Due to the DOD's ongoing commitment to reducing energy use and climatically appropriate design, most existing DOD buildings over the past 100 years have been constructed with overhangs or other architectural features shading south-facing windows. Consequently, the product is not applicable to many existing DOD buildings.

The product could be installed on any building with unshaded windows that face east, southeast, south, southwest or west. The windows should have a clerestory (upper) window area at least 7' above finish floor, ideally have high visible light transmittance (VLT) (>45%) and with a high-occupancy building usage inside. Appropriate usages include, but are not limited to, open office space, private offices, outpatient treatment rooms, common areas, libraries, or any other existing or new building where view is not required through the upper windows.

4.2 RECRUITMENT AND SCREENING

Key factors to finding optimal study sites included identifying buildings with un-obstructed windows that face south, east or west; un-shaded upper window glass for two or more feet starting 7' or more above-finished floor (AFF); and spaces actively occupied near the windows during the daytime so that photo control savings would likely exceed occupancy sensor savings.

Facility manager contacts were suggested to the study team by ESTCP, and all were actively pursued. Each facility manager was sent a 'study prospectus' describing the purpose and conditions of the study, and asked to suggest any suitable buildings within their base or campus. If they responded positively, they were then sent a request to provide the following information for further screening:

- Site plans (showing orientation), floor plans, and reflected ceiling plans.
- Elevations of the windows to be treated.
- Exterior images of sites showing surroundings and any nearby solar obstructions.
- Photos of the interior workspaces, including furniture type, a view of the windows, any existing window treatments, and existing lighting fixtures.

- Hours of operation of building, or particular study sites.
- Full-time occupancy count for the space.
- Part-time / transient occupancy count of space. (Average and peak).
- Occupancy schedule.

In addition, if a site seemed promising, the team attempted to collect further information to support the analysis, such as:

- Electrical plans showing the location of lighting circuits and controls, types of lamps and ballasts, and controls.
- Furniture layouts and type of occupants (engineering, HR, financial, etc.).
- Data on the transmittance of windows and the reflectance of major room surfaces.
- Close-up photos of blinds, awnings, shades or other window treatments, showing color, size and operation type.
- Age of building, and date and information on recent retrofits.
- Section of building, showing ceiling type and height.
- Electric energy costs (kWh and demand charge schedules).
- Accessibility (security clearance required, distance from nearest airport or hotel, availability of staff and occupants for interviews and surveys, monitoring limitations, et cetera).

Ultimately, twenty DOD sites were contacted across the continental US and Puerto Rico, and 40 buildings screened. More detailed information, including plans and photographs, were collected on 14 locations. Seven sites were visited for further confirmation. Of these, only one was rejected as completely inappropriate for the study.

The rejected site was the Great Lakes Naval Station, classroom and office buildings 616 and 617, where it was found that existing high upper windows had been blocked via a retrofitted hung ceiling. There were no plans in place to return the ceiling to its original position, and thus the site was rejected.

Recruitment of study sites was challenging, and took longer than expected for a number of reasons, in descending order:

- Communication with DOD facility managers was often difficult. While a few were quite responsive, many never responded to initial inquires or failed to provide follow up information necessary for proper screening. Furthermore, staff turnover in this position was very high, such that for a given site, the project team often had a new facility manager contact every month or two.
- The number of DOD buildings meeting the most basic study criteria—high, unshaded windows—was much lower than expected. Based on the study team experience, it seems that a much larger proportion of the DOD building stock, compared to civilian buildings, includes exterior shading, or if they do have high windows, the buildings have been retrofitted with dropped ceilings, window tints, or other actions that make them poor candidates for a DRF retrofit.

- Many potential DOD sites were unavailable for the study, due to security concerns, extreme stress in meeting current troop rotation goals (Fort Bragg), or highly erratic occupancy patterns (Barstow).

To compensate for the limited number of available study sites, the study team pursued a diversity of conditions within each building when possible, such as including more than one orientations or space type within a selected building. Within the six study buildings, ultimately 27 different spaces were treated with the DRF, and 27 corresponding spaces were studied as controls.

4.3 SITE/FACILITY LOCATION, OPERATIONS, AND CONDITIONS

Field studies were conducted at six locations:

- Naval Station Norfolk, Norfolk, VA
- Naval War College, Newport, RI
- Fort Bliss, El Paso, TX
- Marine Corps Air Ground Combat Center, Twentynine Palms, CA
- Naval Postgraduate School, Monterey, CA
- Naval Hospital Bremerton, Bremerton, WA

Generally, sites will be referred to by the city and state they are located in. A subsection is devoted to each site below.

A quick summary of the sites is presented in Figure 5 below and shows that there were a range of building types and study conditions covered – from private offices with 1-2 windows to large open spaces with multiple rows of windows. Between the six sites, the study affected 123 workstations with DRF applied to 376 feet of windows and affecting around 262 building occupants.

State	Location	Building Name	Number of types of spaces	Number of treated spaces	Total study spaces (treated + control)	Number of treated window groups	Linear feet of treated window	Number of workstations in treated study spaces	Total potential study population (treated and control)
VA	Norfolk	Naval Station Norfolk	1	1	1	6	72	48	120
RI	Newport	Naval War College	2	5	9	19	88	24	40
TX	El Paso	Fort Bliss	2	7	15	7	60	12	24
CA	Twentynine Palms	Marine Corps Air Ground Combat Center	5	7	14	13	108	31	62
Ca	Monterey	Naval Postgraduate School	1	4	8	4	48	8	16
WA	Bremerton	Bremerton	2	3	6	3	14	6	12
		TOTALS	**6***	**24**	**47**	**49**	**376**	**123**	**262**

Figure 5: Summary of Spaces and Occupants Affected by the Demonstration Study

4.3.1 NAVAL BASE NORFOLK, NORFOLK, VA

The Naval Base Norfolk is located in Norfolk, VA with a humid subtropical climate which receives 46” of precipitation in an average year, and experiences 60% of possible sunshine annually[1].

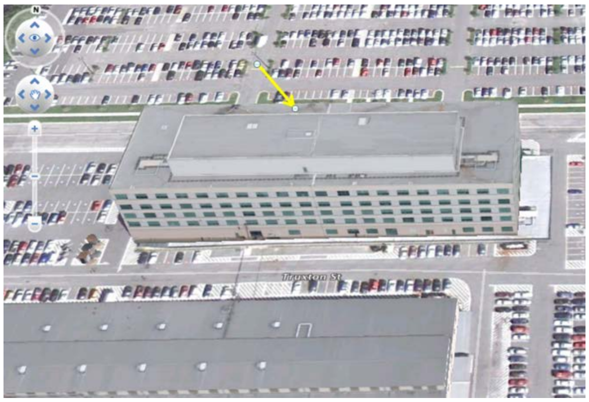

Figure 6. Building Z-133, front entrance on north side

Figure 7. Building Z-133 from the south east (study area 4^{th} floor)

Building Z-133 is a five story facility used primarily as administrative office space for base personnel. The building is more than forty years old, and was recently retrofited with new windows. The building’s front entrance is orientated due North (Figure 20), with the study spaces on the south facing façade (Figure 7). The final study spaces used were open offices; the six (6) west-most bays of south-facing facade were treated with the DRF product and the nine (9) east-most bays were used as the control spaces. No exterior obstructions block direct sunlight from reaching any of the study area windows. Perforated horizontal mini-blinds were installed on all windows for sun control, and observed to be generally deployed over the upper 1/2 or 2/3 of the windows (Figure 8). A 24” deep white counter runs continuously at the bottom of the windows, and along with 6” deep window recesses, which acts as a reflector of some sunlight into the space (see Figure 9 and Figure 10).

Figure 8. Perforated horizontal mini-blinds

[1] http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgsun.html

At the request of the building manager, a pilot occupant acceptance study was conducted in the fall of 2011 for a few months, with the DRF installed in two of the eastern most bays. (These were removed for the final study, when the treated area was moved to the eastern end of the open office space.) The study team requested that the blinds be re-mounted at the middle mullion, so that they could be deployed on the lower windows, however the site manager did not want to relocate the blinds for the purpose of the study. Instead, the perforated horizontal mini-blinds were retracted to the top of the treated windows for the duration of the study. Occupants in the control area, on the other hand, were allowed to adjust their blinds according to their preferences over the study period.

Upon the request of some of the occupants and the facility manager, 3M also installed a tinted window film (40% VLT) across all of the lower, view windows, in order to reduce the brightness of the view, especially for the treated windows, where deploying the blinds was no longer an option. Reflections of sunlight from car windows in a parking lot below and a white roof to the south of the study area were considered overly bright. For consistency, the tint was added to ALL windows in the open office space, the treated, the control, and those not studied.

Figure 9. Open office plan - Norfolk

Figure 10. Window geometry - Norfolk

The open office area (Figure 9) is 48’ deep with a sloped ceiling designed to disperse light down into the cubicle workstations. The sloped ceiling starts at 12’ above finished floor (AFF) near the windows slopes down to 8’ AFF at the rear of the cubicle area. The study space windows (Figure 10) consisted of groups of 3 double pane fixed windows per bay, for a total of 18 bays in the open office area. The DRF was applied in the upper panes, from 6’ AFF to 9’ AFF. The retracted blinds blocked the top 6” of this area. In Figure 10, two upper panels on left are treated with DRF while the panel on right of upper window is untreated.

There were approximately 15 occupants in the treated space and a similar number in the control space. The occupants of the study and control area primarily did IT work, programing computers, or processing information on their computers. Normal vacancy was observed to be about 33%. Cubicles either 4’ (opaque) or 5’ (clear top portion) tall are arranged in groups of eight, four deep by two wide, and held back from the windows by 5-feet, with a continuous work counter and walkway along the window wall. The occupants could generally see a small amount of the upper window from their cubical, but none of the lower view window. They tended to congregate along the work counter at the window for any work or social discussions. The occupants also reported that they enjoyed watching the airplanes practice landing and take offs on the landing strip to the south of the building. Standing by the windows, they enjoyed looking out to the waters of Norfolk Bay to the west of the building.

A detailed description of the study design, window type, HMG activities, and data collection issues for this site is provided in Section 5.7.

4.3.2 NAVAL WAR COLLEGE, NEWPORT RI

The Naval War College is located adjacent to Newport, RI on the Atlantic coast with a humid, continental climate. The area experiences annual precipitation averages of 46" and is distributed evenly throughout the year. According to NOAA, nearby Providence, RI (22 miles north) experiences 58% of possible sunshine annually[1], it is assumed Newport experiences a similar amount of sunshine annually. This site participated in both the pilot phase and the final phase of the study as outlined in Section 5.

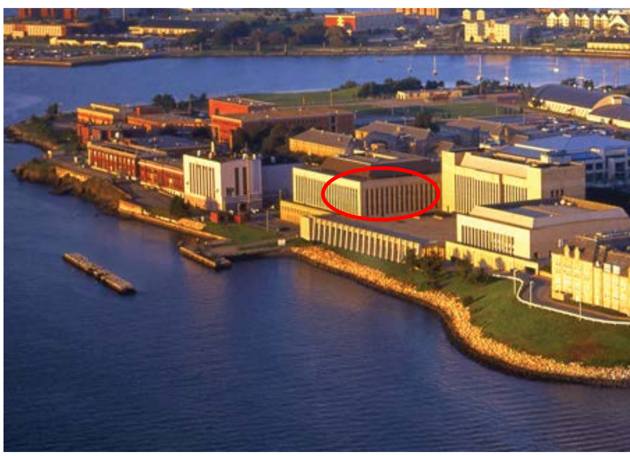

Figure 11. Hewitt Hall, study area circled in red.

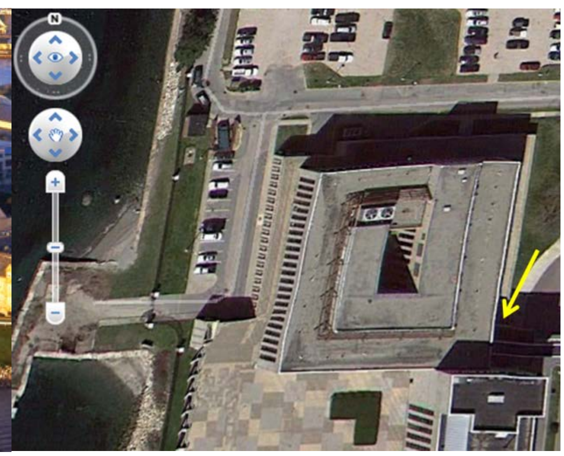

Figure 12. Hewitt Hall, front entrance indicated by arrow.

Hewitt Hall (Figure 11) is a four story building that houses the colleges' library and professors' offices and was used for both the pilot and main study. The building's entrance (Figure 12) is oriented approximately due east, and the study spaces were located on the west and south facades of the building. The building is over fifty years old.

[1] http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgsun.html

The windows have no exterior shading, but receive some minor shading from window recesses. In addition, a large building to the east created morning shade on some of the south-facing windows at various times of the year. A large roof deck below the study areas to the south, and the bay water to the west, often provided upwardly reflected sunlight into the study windows. The reflected sunlight from the roof deck was especially noticeable on sunny days, after a recent rain or snow.

Figure 13. Library, South facing windows

Figure 14. Private Office, South facing windows

There were two types of study spaces: a section of the second floor library (Figure 13) oriented primarily to the South, with a corner that also included western exposure; and private offices (Figure 14) located on either the second or third floors also oriented South, plus one pair of offices oriented to the West. Windows (Figure 15) in the study spaces were 8’ high x 4’ wide, mounted 3’ above the floor, and flush with the 11’ high ceiling (Figure 15). The top 6’ consisted of inwardly opening casement windows, and the bottom 2’ x 4’ section non-operable, both with clear, double pane glass.

Figure 15. Library, Window geometry

LIBRARY: The library is staffed by 3-4 librarians M-F, 7:30 a.m. to 4:30 p.m. and accessible to Naval personal from 6 a.m. to 11 p.m. all days of the week. The portion of the library used for this study is approximately 30’ deep x 200’ long with a variety of dark wooden furniture including: group desks, 4’ tall computer stations, sitting areas, and

4'-5' tall book stacks. Furniture (Figure 15) is located on the perimeter of the space near the windows and in the center of the study space with a walkway on each side. The south and west facing walls are white, and the back wall is cream in color. The electrical lighting system consisted of recessed 2x4 lensed troffers. The two rows of fixtures nearest the windows were operated on photocontrols. Other lights were left on whenever the space was open.

The fifteen treated windows of the library were originally provided with gold-colored curtains, which were occasionally closed to block direct sunlight. The casement windows were not actively used in the library. For the pilot, the DRF was installed on the upper 3' of the casement windows facing south, and then, for the full study, the DRF was installed in all fifteen windows in the library and the curtains removed. About two months after the DRF was installed, 1" horizontal blinds were installed below the DRF on the view portion of the windows. Thus the library windows had no operable shading for the two month period between initial installation of the DRF product and the subsequent installation of blinds on the view windows. Since a control space for the library was not possible, a six week period prior to the installation of DRF was used to collect data for purposes of 'controls' – the only space where this strategy was used.

OFFICES: Private offices are occupied by one or two professors each, who kept irregular office hours, or are frequently on assignment elsewhere. Each office is 14' x 25' with 11' dropped ceilings, and dark blue walls and carpeting. The furniture layout varies slightly in each office, but in general, occupant desks are located nearest the windows. Bookcases ranging from approximately 4' to 8' in height are a standard furnishing in each office and typically located away from the windows in each room. Other furniture consisted of couches and smaller working tables. The electrical lighting system consisted of recessed 2x4 lensed troffers installed in the t-bar dropped ceiling. Each room is controlled by an occupancy sensor.

The offices have two windows each and were also outfitted with curtains that remained for the duration of the pilot and final study periods. The office occupants were more active users of the casement windows, especially during the summer months. Installation of horizontal blinds would have prevented them from opening the windows, so the existing curtains remained.

Occupants did not make any unsolicited comments about the view from either the library or offices. However, all windows did have a distant view of other buildings on campus and the waters of the bay beyond.

A detailed description of the study design, HMG activities, and data collection issues for this site is provided in Section 5.7.

4.3.3 FORT BLISS, EL PASO, TX

Fort Bliss is located near El Paso, Texas in a hot desert climate with annual average precipitation of approximately 9" per year and experiences 84% of possible sunshine annually[1] making this an ideal location for a daylighting study.

[1] http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgsun.html

Figure 16. Building 20400, front entrance indicated by arrow

Figure 17. Building 20400, study windows (2nd floor)

Building 20400 is a three-story office building with the front entrance orientated south-east (approximately 170 degrees from due North) (Figure 16). Study spaces are located on the second floor and consisted of private and open office plans on the south-east façade (Figure 17). Façade faces 20 degrees east of south. The building is less than five years old.

Figure 18. Open office plan

Figure 19. Interior window geometry

For the open office spaces (Figure 18), the six bays of windows in the eastern wing of the building were treated with the product while the western wing was used as the control space. For the private office area, alternating perimeter offices in the east and west wings were treated with film in six of the twelve offices. Windows (Figure 19) are dual-glazed low-E with approximately 40% visible light transmittance. Windows are non-operable and approximately 2’ wide and 4’ high. Ceilings in the open and private office spaces are approximately 8’ high with white t-bar dropped ceilings.

In the treated spaces, the existing 1” horizontal mini blinds were lowered 18” below the ceiling to allow for the DRF to be installed in the top 2’ of the window. In the control spaces, the existing 1” horizontal mini blinds were left at the top of the window.

While the climate conditions make this site an ideal location for a daylighting retrofit, the specifics of the building do add to some complications in evaluating the full potential of the DRF technology. The roof overhang (see Figure 17) creates shading of the study windows in the summer time, and the central tower created morning shading for the control area to the west, and afternoon shading to the study area to the east.

OPEN OFFICE: During the study, the treated space had less than five occupants, while the control spaces had between 7-10 occupants. Each space has both long-term and short term occupants having a mix of full-time and part-time hours.

Lighting consists of 2x4 parabolic troffers with occupancy sensors and no wall switches for all spaces. It was observed in some of the unoccupied spaces occupancy sensors were covered up, to keep lights from turning on.

In the treated space, Wing C, some occupants sat next to the windows with 5' high cubicle partitions. All partitions were opaque and gray in color. Occupants seated away from the windows have restricted views of the windows. In the control spaces, Wing A and B, no furniture was located near the windows. The 5' high cubicle partitions are located approximately 13' from the windows.

All walls and the dropped ceiling are white in color in both the treatment and control spaces.

PRIVATE OFFICES: All offices are single-occupancy with two windows in each office. In each office, the occupant is seated near the window. Office furniture typically consisted of dark wood desks with book shelves and filing cabinets along the walls. Electric lighting consists of 2x4 parabolic troffers, controls are assumed to be wall switches or occupancy sensors.

All walls and the dropped ceiling are white in color in both the treatment and control spaces.

The view from the study spaces is of a vast open space with small, young trees providing no shading for the study facades. Most occupants disliked the view outside their windows and expressed issues with glare on work surfaces; as a result blinds were lowered most of the time. However, occupants did find the daylighting levels in their offices sufficient and could work with some of the electric lighting turned off.

A detailed description of the study design, HMG activities, and data collection issues for this site is provided in 5.7.

4.3.4 MARINE CORPS AIR GROUND COMBAT CENTER, TWENTYNINE PALMS, CA

The Marine Corps Air Ground Combat Center (MCAGCC) is located near Twentynine Palms, CA. The area experiences more than 300 days or 80% of possible sunshine annually and only about 4.5" of precipitation making it an ideal location for daylighting studies.

Figure 20 Building 1416, south corner

Figure 21 Building 1416, front entrance indicated by arrow

Building 1416 (Figure 20) is a two story facility containing administrative offices and medical offices in the form of a battalion aid station (BAS) which are part of this training facility used by the Marine Corps. This site participated in both the pilot phase and the final phase of the study as outlined in Section 5.

The building entrance (Figure 21) is oriented to the north-west (approximately 350 degrees from due North). The study spaces were located on the first and second floors on the south-east or south-west facades with the exception of a control space located on the north-east façade, and consisted of either open plan office layouts (Figure 22) or smaller single or shared office spaces. There were seven pairs of study spaces selected, each pair with different geometries, as detailed in Appendix A.

Figure 22. Open office layout, untreated, Weapons Company

Figure 23. Exterior window geometry

The study spaces are occupied by two Marine Corp battalions undergoing training which are rotated at least annually; consequently, there is little continuity in staff or occupancy. The windows in each space are sets of 4’ x 7’, non-operable double pane, high visible transmittance (VT), aluminum framed windows. Each window has a 5’ high view window and a 2’ high daylighting section above, separated by a grated metal awning to shade the exterior of the lower window (see Figure 23). Some rooms had only one such window, others had groups in two or three, on one or more facades (see Figure 20). The windows on the second floor also received some shading in the summer from the roof overhang.

Each window was fitted with a roller blind mounted below the mullion with the metal awning, but no operable shading devices were provided above the metal awning (see Figure 24). Thus, direct sunlight entered the spaces from the upper windows. This was clearly a problem for many occupants, as many of them had already taken some action to block this direct sunlight, placing cardboard or aluminum foil in the upper windows (see Figure 24).

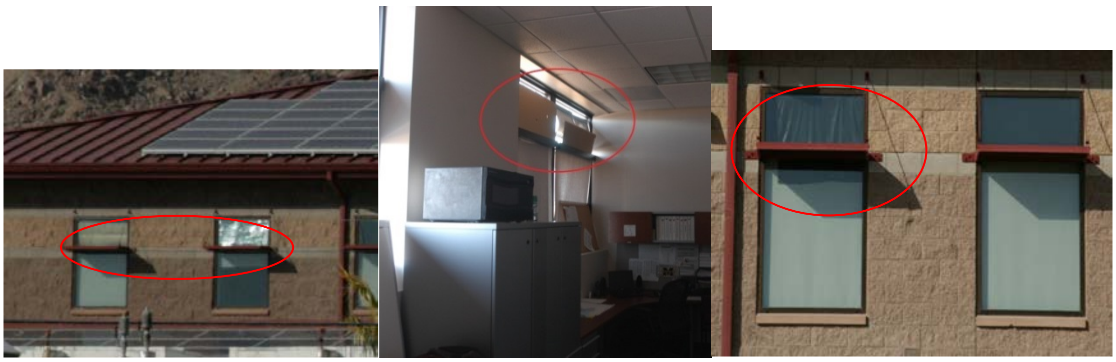

Figure 24. Upper windows blocked with cardboard, paper, dark plastic sheet, foil etc.

The view out of the windows was to other adjacent buildings, including a parking structure, and the sparsely vegetated desert. Many occupants commented that they did not like the view, and did not like the desert.

The electric lighting system was designed to comply with California’s Title 24 energy code. It consisted of 3-lamp T-8 parabolic 2x4 troffers placed 10’ x 10’ on center. Lighting controls include wall switches with bi-level switching, room occupancy sensors, and photo controls for fixtures within the ‘daylit zone’, i.e. within 10’ of a window. Even the emergency lighting was included on the photo control system.

Open office areas had 5’ high, grey colored partitions. Private offices and medical exam rooms had normal furniture for those space types. The record rooms had continuous shelving along the walls, with some work counters.

A detailed description of the study design, HMG activities, and data collection issues for this site is provided in Section 5.7.

4.3.5 NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA

The Naval Postgraduate School is located in Monterey, CA, a pacific coastal region that receives about 66% of possible sunshine annually[1]. Sunshine is often only present for

[1] Based off NOAA’s data for San Francisco, which has a similar climate. http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgsun.html

half of the day, with morning fog commonly burning off by noontime most of the year (January – August).

Figure 25. Halligan Hall, front entrance indicated by arrow

Figure 26. Halligan Hall, southwest-facing

Halligan Hall (Figure 25) is a two-story building built in the 1950s with the front entrance oriented to the northeast (approximately 80 degrees from due north). The study spaces are located on the southwest-facing façade (see Figure 26) and have black shade screens installed on the exterior of the windows. The building has two nearby buildings providing some late afternoon shading.

The building houses secretarial offices for administrative support staff; therefore, experiencing a consistent occupancy pattern.

Figure 27. Window geometry

Figure 28. Exterior window geometry with exterior screens

Eight private offices (Figure 27) were selected for the study; each containing two to three people and measuring 10’ wide by 20’ deep with southwest-facing windows. All offices have 10’ high ceilings with an HVAC unit hanging from the ceiling near the door and electrical conduits running in the ceiling. Typical office furniture was found in each office with some offices having 4' gray partitions with a view window on the top half of the partition. All spaces have light colored furniture with white acoustic ceiling tiles and walls, with some rooms having a darker two-toned paint on the upper portion of the wall. Lighting fixtures were lensed 2x4 troffers, suspended at approximately 10' with a 2' void above. Some fixtures had only one lamp and no lighting controls present, only wall switches. Each desk was equipped with an individual task light.

Office windows were made up of five single-pane floor to ceiling windows (Figure 27). One of the window panes, the second from the top, is an inward operating hopper window. With no central air conditioning in the building, these hopper windows are frequently opened. Black shade screens had been retrofitted some years ago on the exterior of all windows to reduce afternoon heat gain and glare (see Figure 28). Some of these were removed during the study.

Four rooms were treated with the DRF product, however exterior screens were removed from only two of the four rooms. Sun control window film (40% VT) was installed on the view windows in all of the treatment rooms. Previously, the windows had old sun control film that was tattered with visible signs of occupants' attempts at removing these. The old window film was only found on the upper windows and had to be scraped away to allow installation of DRF. Once the exterior shades were removed, occupants felt strongly about the solar heat gain from the lower view windows. The exterior screens obstructed the outdoor view if standing closer than 12' back from the window. The view to the outside was of two nearby buildings; the occupants did not have an obvious affection for the view.

Each office had existing 2.5" Venetian blinds mounted at top of each window; occupants frequently operated these. The top mounted blinds always interfered with the operation of hopper window. In the treated rooms, 1" horizontal blinds were installed below the hopper window. This resulted in the DRF installed on the top two windows (including the hopper window).

A detailed description of the study design, HMG activities, and data collection issues for this site is provided in Section 5.7.

4.3.6 NAVAL HOSPITAL BREMERTON, BREMERTON, WA

Bremerton Naval Hospital is located on Washington states Olympic Peninsula. On average, Bremerton receives approximately 8" of snow and 52" of rain annually. Seattle located just across Puget Sound from Bremerton, experiences 43% of possible sunshine annually[1], Bremerton is assumed to experience similar amounts of sunshine annually.

[1] http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgsun.html

Figure 29. Naval Hospital Bremerton, front entrance indicated by arrow.

Figure 30. Study areas located on top two floors

The Naval hospital is a three story building with the front entrance orientated to the southeast (approximately 20 degrees from due East) (Figure 29), with the study spaces located in the south-east wing (Figure 30) on the second and third floors. The study spaces experience some shading from nearby vegetation (see Figure 30), and afternoon shading from the western wing of the building. The building is less than ten years old.

Figure 31. Office layout and window geometry

The study spaces (Figure 31) consist of six private medical offices with intermittent occupancy, by various, rotating medical staff. All rooms are approximately 10' deep by 10' wide, with 9' high dropped ceiling. Offices contained non-operable, dual-glazed bronze anodized windows. Windows are 5' by 7'6" on average with a sill height of 30". Since the windows are continuous along the façade and the office layout does not always match the window sizes, the amount of window area per room varies.

All study rooms had existing cream colored roller shades. The occupants all noted that they highly valued the view out of the study space windows, of the trees and the sky, and liked the amount of daylight available in the spaces. However, patient privacy usually mandated that the window shades be completely pulled down while the space was occupied, reducing the clarity of the view and the presence of daylight (see Figure 30). In the treated study rooms, 1" cream colored blinds were installed below the DRF. Occupants were instructed not to operate the blinds and leave down for patient privacy.

Furniture in all rooms is considered normal for medical exam rooms. The two side walls were cream in color, and the back wall a light blue.

Lighting consisted of standard 2x4 recessed lensed troffers with bi-level controls with on/off wall switches

A detailed description of the study design, HMG activities, and data collection issues for this site is provided in Section 5.7.

5. TEST DESIGN AND ISSUE RESOLUTION

This chapter describes the process of the study. It explains the baseline characterization, operational data collection, equipment and instruments utilized, simulations, and occupant comfort assessment.

5.1 CONCEPTUAL TEST DESIGN

The bullet points in this section describe the test design, its associated components and the hypothesis proposed to evaluate the window film performances.

5.1.1 STUDY VARIABLES

- Independent variable(s):
  Several independent variables were modified, and varied depending on site conditions. The most common variable was the redirection of sunlight in the upper windows through application of the DRF product. In treated spaces, window film was installed on the upper windows; in un-treated (control) spaces, the upper window panes did not receive the DRF product. Most sites had existing full length blinds or shades attached at the top of each window. In treatment spaces, at sites with existing horizontal blinds, the blinds were repositioned just below the DRF application. While other sites, with vertical shades, were replaced with horizontal blinds, just below the DRF application, for the duration of the study. Additionally, at some sites sun control window film was installed in the lower view windows to help mitigate solar heat gain, previously controlled by existing blinds or exterior sun screens.
- Dependent variable(s):
  Dependent variables were daylighting illuminance levels and use of electric lighting within the treated spaces. Illuminance loggers were placed in transects to capture variations in illuminance at different distances from the windows. Electric lighting usage was also monitored to understand potential light switching behavior of the occupants.
- Controlled variable(s):
  The intent of the study was to control as many confounding variables as possible to isolate the effects of the window films. Site selection criteria ensured that general parameters such as latitude, climate conditions and building types are the same between each set of treated vs. control spaces. In addition, the study was replicated at sites with different latitudes and climates to ensure the results are more generally applicable to the continental United States.

  The team selected treated and control spaces to be nearly identical in size and orientation, usage, and located adjacent to one another. The study team screened the sites for consistent building operations over the study period, such as avoiding major furniture or occupancy changes, however some changes occurred anyway.

The project team gathered information of annual weather patterns, outside illuminance, blinds operation, and electric lighting operation schedule for each site.

5.1.2 Study Hypothesis

The team hypothesized that applying the window films to the treated spaces would increase daylight availability in the space, reducing the need for electric lighting, and enable the reduction in electric energy consumption via the use of photo controls. A secondary hypothesis was that the film would improve or at least not change occupant's visual comfort.

5.1.3 Study Phases

At the request of the ESCTP reviewers, the research study was split into two phases: a pilot phase with two monitoring sites, and a main study phase involving six monitoring sites. At each site, data was collected for calibration before the film was installed. Data was collected again post-intervention (film installation). Outlined below are the activities conducted for each phase:

- Pilot Site Phases: logger installation, calibration (pre-film) logging, film installation, post-intervention (post-film) logging, and logger removal.
- Main Site Phases: logger installation, calibration (pre-film) logging, film installation, post-intervention (post-film) logging, and logger removal.

The pilot phase study was conducted over a six-month period (Summer 2011 through the end of the year) at Twenty-Nine Palms, CA and Providence, RI with extensive and detailed monitoring. This was to ensure the team took full advantage of the pilot phase to discover and resolve potential study complications. The knowledge gained during the pilot was then applied to the design and execution of the main study phase.

The main study phase started after the conclusion of the pilot phase. It was conducted over a six month period from winter (January 2012) through the summer (June 2012). The main study phase included the Twenty-Nine Palms and Naval War College sites and four additional sites: the Naval Station at Norfolk, VA; Fort Bliss, TX; Naval Hospital, Bremerton, WA; and Naval Postgraduate School, Monterey, CA.

5.1.4 Test Design

The research study test design involves two types of data collection: collection of monitored physical data and collection of qualitative occupant visual comfort data. Collection of physical data involved monitoring illuminance levels at multiple locations throughout the study period. As illustrated in Figure 32, illuminance levels were measured at the following locations: inside and outside of the treated and control spaces, on the ceiling (facing lighting fixtures and facing down) and on the work surface. Occupant comfort data were collected via survey responses from occupants of these study spaces. Surveys were administered before and after window film installations to occupants in both the treated and control spaces.

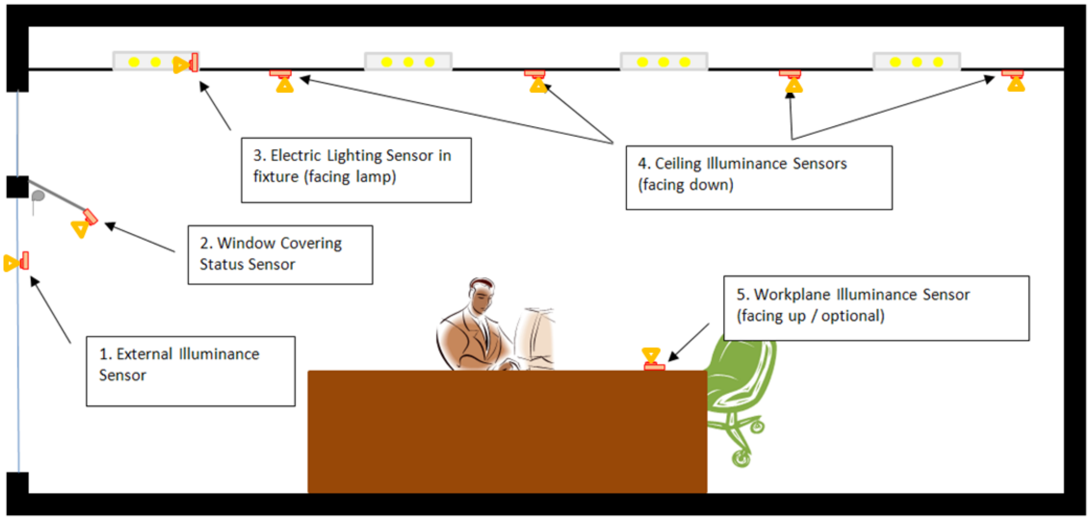

Figure 32. Cross section of study space showing locations of monitoring equipment

Figure 32 shows the cross- section of study space showing locations of monitoring equipment. The direction of view of each logger is represented by a triangle.

5.1.5 Pilot Phase - Lessons Learned

During the pilot phase conducted at Twenty-Nine Palms, CA and Providence, RI modifications were made to accommodate for lessons learned during the pilot phase of field monitoring, these are outlined below:

- Blinds/Curtain Placement and Operation monitoring:

  Modifying existing window blinds or shades was necessary in order to conduct the study. Existing window blinds or shades often cover the entire window and are either top-down blinds or curtains that close down the middle. In either case, applying the DRF to portions of the windows without modifying the blinds would have resulted in less than ideal daylighting performance. The study team worked with the site contacts to develop protocols for replacing existing blinds/shades with those that covered just the view portion of the windows while leaving the clerestory windows without internal shades.

- Occupant Surveys:

  The study team modified the occupant survey document based on the initial implementation of the survey. The changes were mostly aimed at making the form easier to read and less complex while asking for additional information directly instead of analysis of responses to general questions.

5.1.6 Site Monitoring Options

Site monitoring was done by one of two methods described below:

- **Side-by-side Comparison:**

This comparison entailed monitoring spaces with similar physical features and occupancy patterns. One space(s) would act as the “treatment” receiving the DRF product application, while the other space(s) would act as the “control” not receiving the DRF product. The two spaces were located on the same façade on the same floor or one floor above or below each other. It may be noted that the interior layout between the treated and control spaces was not always identical.

- **Before and After Comparison:**

  This comparison entailed monitoring a single space for a time period before the DRF product was installed and after installation. Ideally, monitoring would have occurred within 2 weeks of the summer or winter solstice events and each monitoring period, before and after, occur for six months to allow exposure to similar solar angles for both monitoring periods. However, this was not achieved due to delay in site identification and site access limitations.

5.1.6.1 DAYLIGHT PERFORMANCE METRICS USED FOR THIS STUDY

5.1.6.1.1 SPATIAL DAYLIGHT AUTONOMY (sDA)

Daylight performance metrics have evolved considerably in the few years that span the time period between the kick off and final report of this project. In that time, the Illuminating Engineering Society of North America (IES) has adopted and published a new set of metics describing a methodology to generate a comprehensive daylight illuminance performance metrics, named spatial Daylight Atuonomy, or sDA. It is fully described in IES publication LM-83[1], published in 2012. This methodology has been used to generate sDA values for this report.

sDA is a comprehensive performance metric, which synthesizes information from changes in daylight illuminance intensity over both time and space. It has been validated in some initial research projects, and is now being adopted by various building performance standards, such as LEED 2013.

Thus, even though the sDA metric was not part of the original table of performance objectives, sDA has been selected as the most meaningful measure of daylight illumination resulting from the installation of this product. It replaces the metrics previously listed in the Performance Objectives table, such as increase in illumination at 20’ from window and daylight uniformity (for which there is still no accepted measure).

5.1.6.1.2 GLARE

There are over twelve metrics of glare currently in use, with at least three specifically designed to evaluate daylit conditions. However, there is no professional consensus on which to use under what conditions. Indeed, recent research at the University of Idaho[2]

[1] IES LM-83-12, IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)Illuminating Engineering Society of North America, 2012

[2] Van de Wymelenberg, K 2012

found very poor correlation between the most commonly used metrics and subject's reported experience of glare under common office space conditions, using simple window and blinds technology. Furthermore, all of these metrics are only for evaluating instantaneous conditions, not conditions aggregated over time, thus raising the question about how to evaluate the overall glare performance of a product over the course of a full year's daylight cycle.

The IES LM-83 does describe a new annual daylight performance metric, Annual Sunlight Exposure, or ASE, which can be used as a proxy for glare, based on the same methodology to generate the sDA values described above. However, this annual metric also has two fundamental problems for the purposes of this project. First of all, it was not developed or tested against any advanced daylighting or complex glazing systems, but rather only simple windows, blinds and shades. Thus, it should not be considered appropriate for evaluating any conditions beyond those of the original test conditions. The second problem is that the currently approved methodology for generating ASE requires a simulation that is not compatible with a complex fenestration system, such as 3M's Daylight Redirecting Window Film (DRF), that requires a sophisticated BSDF file to describe its light distribution patterns. Thus, ASE is not an available option to describe the annual glare performance of the product. Given the lack of acceptable glare metrics for daylight glare, the project team choose to rely upon observations, interviews and survey results to assess any change in the glare conditions in the treated and control study spaces.

The study found <u>no</u> increased complaints of glare in any of the treated study spaces, and indeed, there were many reports from interviews of greatly reduced glare, with one exception. The one exception was the installation at the Naval Air Base in Norfolk, Virginia, where the film was mounted lower, only 6' above the floor, instead of the 7-8' above the floor elsewhere. The study team believes that by mounting the film closer to eye level, the frequency of extremely bright views of the film increased, resulting in the complaints of occasional glare. It should also be noted, that the deeper the space from the treated window, and the wider it is, the higher the risk of glare from the film, and thus the higher above eye level it should be mounted. The Norfolk space was about 40' deep, and over 200' wide, and thus also increased the risk of glare.

Overall, the study found that, if the product was appropriately mounted at 7-8' above the floor level, the installation reduced glare and created at least a neutral, and often a positive improvement, in visual comfort.

5.1.6.2 SIMULATION STUDY SETUP

A separate building energy simulation study was conducted to evaluate the effects of the DRF on illumination levels in the space and its resultant effect on lighting and whole building energy use. The simulation study was necessary in order to extrapolate the results and findings from the sites where we have data on a relatively limited amount of time (months) and to rationalize the energy savings numbers across sites. Daylighting is inherently dependent on the prevailing outdoor conditions (amount of sunshine, cloud cover etc) and on the specifics of a given space (window details, shading, massing, space dimensions etc). Thus using the raw data collected from each site is dependent on the specifics of each site. To project results from this raw data to a more rational comparison between sites and weathers, energy simulation studies were necessary.

HMG conducted two types of simulation studies:

- Daylighting analysis: Illuminance values were simulated with ray tracing in the Radiance software package using the Dynamic Radiance approach (also known as the three-phase method). This approach is described in more detail in Section 5.5.
- Whole Building analysis: The whole building analysis was built on top of the daylighting analysis using a process developed by HMG in prior research projects. This approach combines the accuracy of the dynamic radiance approach to predict illuminance in the space with the ability of the eQuest building energy analysis tool to take the outputs of the dynamic radiance analysis as inputs to a whole building and lighting energy use analysis. This approach is described in more detail in Section 5.5.

5.2 BASELINE CHARACTERIZATION AND OPERATIONAL TESTING

This section describes the monitoring of baseline conditions and operational testing used to quantify the effects of the DRF.

5.2.1 BASELINE AND OPERATIONAL DATA COLLECTION

Baseline conditions were needed to assess both non-energy related (visual comfort) and illuminance (daylighting) performance of the DRF. Control data was needed to account for seasonal changes in the sun's position above the horizon and weather.

To assess baseline visual comfort conditions, surveys were administered before the DRF was installed in both the treated and control spaces. After DRF installation, surveys were administered in two or three seasons to discern if DRF installation and blinds modification had adversely affected comfort. It was necessary to survey in multiple seasons to account for seasonal changes in the sun's position.

To assess the illuminance performance of the DRF, the research team collected baseline data at all sites for each activity type (e.g., private office vs. open office), and each window orientation. Onsite monitoring began before the DRF was installed to ensure the treatment and control rooms had reasonably similar operation. Onsite monitoring was conducted in treatment and control room pairs at each site whenever possible.

Monitoring was continued in both the treatment and control rooms for the operational testing phase of the study to control for changes in sun angles, weather, and occupant usage patterns.

For one study room a suitable control could not be found (the library at the Naval War College in Newport, RI). A before vs. after study was conducted instead. Monitoring was conducted before DRF installation to establish a baseline and monitoring continued for nearly a year as the operation testing phase of the study. It was not possible to fully account for changes in sun angles, weather, and occupant usage patterns at the Naval War College library though the study periods allow for comparing performance of the DRF at various sun angles representative of the location.

5.2.2 Baseline and Operational Data Collection Timeline

A baseline monitoring period for each site was conducted before the DRF was installed; the duration of this period varied by site as seen in Figure 33 depending on when the site agreed for participation in the study and driven by the desire to get as much time after the film installation as possible before the monitoring was to end in July 2012. The number of days of baseline monitoring does not affect the accuracy of the results since most sites included a side-by-side comparison with an untreated space during the entire study period. The baseline period was useful mostly to establish that the study space was similar to the control spaces.

Site Name	Baseline Monitoring Period
Norfolk, VA	2 days
Newport, RI	33 days
El Paso, TX	11 days
Twentynine Palms, CA	32 days
Monterey, CA	3 days
Bremerton, WA	28 days

Figure 33. Baseline Monitoring Period

The research team conducted multiple field visits to each monitored site to install monitoring equipment, oversee DRF installation, record space characteristics and conduct occupant surveys. After the installation of logging equipment, the team went back on site to conduct a number of post-DRF installation surveys. These post-installation visits served the dual purpose of collecting occupant survey data as well as allowing the team to make timely fixes and adjustment necessary for continuous and quality data collection from monitoring equipment. Operational testing of the DRF began when the DRF was installed, lasting for a period of 6-12 months, and varied by site. The dates of these activities are presented in Figure 34.

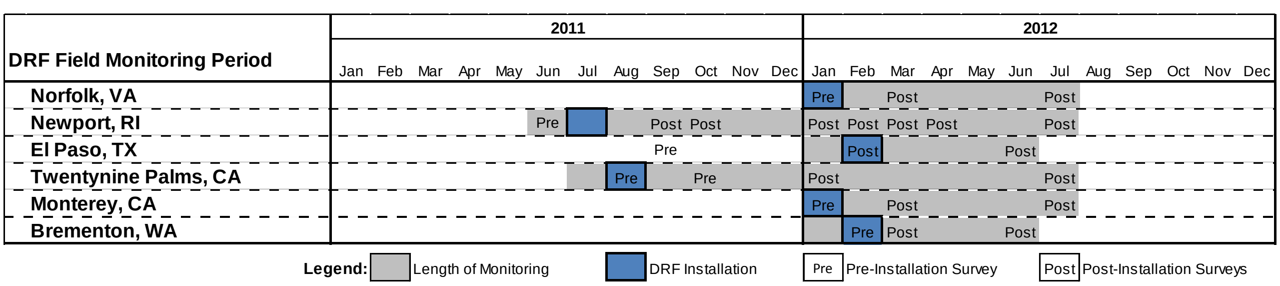

Figure 34. DRF Field Monitoring and Survey Timeline

5.2.3 Baseline Energy Use Estimation

The study team collected data on installed lighting fixtures using data loggers that recorded the lighting on/off state.

Weather conditions were an important variable to account for. Weather at the airport nearest each study sites was downloaded and used as a proxy for weather at the study site. Weather data were categorized into clear-, mixed-, and cloudy-weather categories. Interior illuminance data was analyzed separately for clear, cloudy and mixed days to help understand the impact of weather on product performance.

Information about HVAC equipment type, efficiencies, and usage was NOT collected on site. Subsequent simulation estimates of changes in HVAC usage are based on default system assumptions and Typical Meteorological Year (TMY) weather data.

5.2.4 DATA COLLECTION EQUIPMENT

The research team utilized off-the-shelf monitoring equipment. Interior illuminance was monitored with HOBO U12-12 loggers (Figure 35); outside illuminance was monitored with HOBO UA-002-64 loggers (Figure 36). In addition, a hand-held illuminance meter, a Minolta T-10, was utilized during site visits to obtain real-time illuminance readings. Time of illuminance readings were recorded so that they could be compared to data from the HOBO loggers to assess accuracy. Lighting circuits and blinds were monitored with DENT Lighting Loggers or Pacific Scientific Technology Lighting Loggers.

Figure 35. HOBO U12-12 for interior illuminance monitoring[1]

Figure 36. HOBO UA-002-64 for exterior illuminance monitoring[2]

[1] http://www.onsetcomp.com/products/data-loggers/u12-012

[2] http://www.onsetcomp.com/products/data-loggers/ua-002-64

Figure 37. Lighting Loggers for lighting and roller shade monitoring.

The angular response of the lighting sensor used for interior monitoring, the HOBO U12-12, is shown graphically by the area enclosed by the darker line in Figure 38. For the Minolta TL-1 hand-held illuminance meter employed for real-time illuminance reading, Figure 39 illustrates how the instrument accounts for the incidence angle effect on lighting level reading.

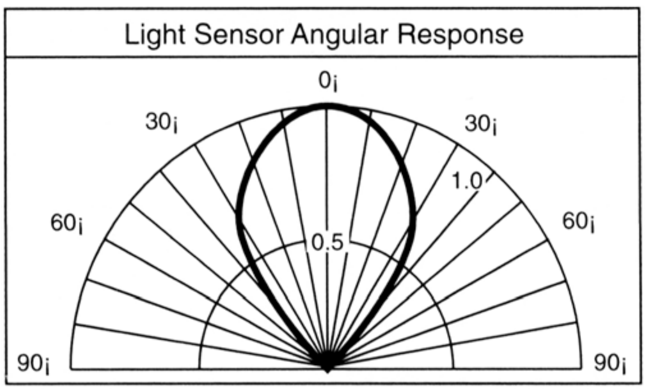

Figure 38. Angular response of the HOBO U12-12 illuminance sensor.

Cosine Correction Characteristics

Since the brightness at the measurement plane is proportional to the cosine of the angle at which the light is incident, the response of the receptor must also be proportional to the cosine of the incidence angle.
The graph above shows the cosine correction characteristics of Minolta Illuminance Meters **T-10**.
The cosine error of **T-10** are shown in the table right.

Incidence angle (deg.)	Cosine error (within)
10°	± 1%
30°	± 2%
50°	± 6%
60°	± 7%
80°	± 25%

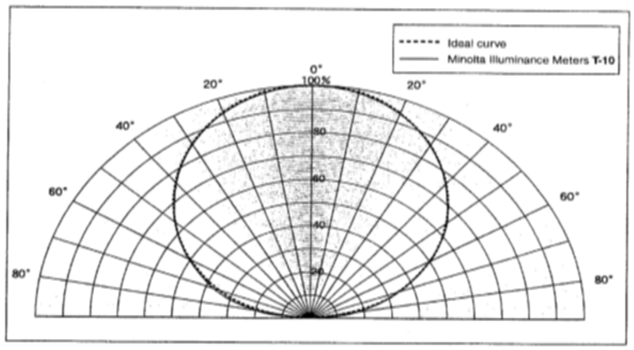

Figure 39. The Minolta T-10 illuminance meter's field of view is cosine corrected.

Other equipment used during the field observations included a digital camera equipped with a fisheye lens and software to enable high dynamic range imaging and visual field analysis.

5.3 SAMPLING PROTOCOL

This section provides specifications for the team's field data collection efforts, including data type, logging and data storage protocols.

5.3.1 DATA DESCRIPTION

Lighting circuit usage was monitored using DENT Lighting Loggers model TOU-L. One logger was installed on each electric lighting circuit in the space. Loggers attach magnetically and record on/off data through a photocell positioned directly adjacent to a lamp in the fixture. Care was taken to position loggers in a way which would not capture light redirected by the DRF.

Interior illuminance measurements were logged at 15-minute intervals via a HOBO U12-12 mounted at each logger point indicated on the research plan for each monitored space. The specific arrangement of the loggers was designed to capture the full-range of variation in lighting conditions in monitored rooms. Loggers were placed in similar configuration in each pair of monitored spaces to enable comparison between window film performance in the treated space and the baseline conditions in the control space.

Exterior illuminance measurements were logged at 15-minute intervals by a HOBO UA-002-64 positioned to look directly out the center of an un-shaded window.

5.3.2 DATA COLLECTORS

HMG staff collected data from all sites with help from the site contacts as necessary. For example, the site contacts collected surveys from occupants of the study spaces while HMG collected all of the illuminance, physical, photographic and electric lighting operation data.

5.3.3 DATA RECORDING

During each site visit, the study team retrieved monitored data from the loggers, administered occupant surveys and collected responses. Handheld illuminance readings were taken to aid in assessing visual lighting condition and illuminance levels reported from the monitoring equipment. Photographs were taken of the study space to document the visual conditions in the space. In additional High Dynamic Range (HDR) images were taken in the event glare analysis was needed. In the end, we decided that glare analysis was not needed since there were no complaints of glare from the DRF and the illuminance readings as well as other photographic evidence did not necessitate glare analysis. Overall, the research team conducted 3 to 5 visits per site, during which data was recorded for one-time measurements such as surveys and photographs. In additional illuminance monitoring was done on a continuous basis per Section 5.2.4

5.3.4 DATA STORAGE AND BACKUP

During site visits after data recording had begun, stored data was downloaded from loggers to a laptop for transfer to the research team's server. The research team's server employed mirrored hard drives for data security through redundancy, and data was backed up nightly for extra redundancy.

Some data was lost due to equipment failure and human error. Despite tests showing loggers were fully operational before deploying them in the field, some loggers still failed in the field. Moreover, some loggers simply disappeared from the sites during the study. Lastly, some equipment, including data loggers, was stolen from a car after it was removed from the sites, but before the data was downloaded.

5.3.5 DATA COLLECTION DIAGRAM

Figure 32 illustrates the basic approach for the location of data loggers. The specific locations of the loggers for each pair of monitored spaces is best represented by the "study areas" figures included each of the site study plans. The site study plans are included in Section 5.7 of the report. The study plan for each site marked the monitored space pairs, as well as noted the intended locations for the loggers. Occasionally, site adjustments in logger location were made to accommodate actual furniture conditions or ceiling tile layouts.

5.3.6 SURVEY QUESTIONNAIRES

The occupancy satisfaction survey used to solicit occupant's visual comfort in the study spaces and is included below for reference:

Bldg ID________ Room ID_________ **FILM? Y / N**

OCCUPANT SURVEY – Is this room visually comfortable?

1. Today's date _____day_______month______year   2. Time of day: ________Hour __am/ pm

   Cubicle Number: ________________

3. Your age:
❑ 10-19 ❑ 20-29 ❑ 30-39 ❑ 40-49 ❑ 50-59 ❑ 60-69 ❑ 70+

Please choose the closest correct answer

4. Your relationship to this space
❑ I am a regular occupant of this space ❑ I am an occasional occupant of this space

5. For about how long have you been using this space?
❑ just today ❑ a week ❑ a month ❑ 2-4 months ❑ 5-11 months ❑ a year or more

6. When you come here, how many hours per day to you generally spend in this space?
❑ an hour or less ❑ 2-4 hours ❑ 5-7 hours ❑ 8 or more hours per day

7. About how close are you currently located to a window?
❑ 2-8 feet from the window ❑ 10-15 feet from the window ❑ 20-30 feet (or more) from the window

8. If this room has windows with blinds or curtains, overall right now are they:
❑ fully closed ❑ ¾ closed ❑ ½ closed ❑ ¼ closed ❑ fully open ❑ no blinds or curtains

9. What are the weather conditions right now?
❑ It's a clear blue sky, sunny day ❑ It is variable, with big clouds moving by and occasional sun
❑ It's a lightly overcast day ❑ It's a foggy day ❑ Its a dark overcast day (and/or rain or snow)

10. Are patches of sunlight visible? (check all that apply) ❑ I can see patches of sunlight on my desk
❑ I can see patches of sunlight on the floor ❑ I can see patches of sunlight elsewhere inside this room
❑ I can see patches of sunlight outside of this room ❑ I cannot see any patches of sunlight anywhere

Please consider your experience of this room based on conditions in the last week as you fill out this form:	Worse <<								>> Better		
		1	2	3	4	5	6	7	8	9	n/a
11. I enjoy being in this room	Strongly Disagree	☐	☐	☐	☐	☐	☐	☐	☐	☐	Strongly Agree ☐
12. Temperature in the room is comfortable	Strongly Disagree	☐	☐	☐	☐	☐	☐	☐	☐	☐	Strongly Agree ☐
13. I like the view I have from the window	Strongly Disagree	☐	☐	☐	☐	☐	☐	☐	☐	☐	Strongly Agree ☐
14. I think the view out the window(s) is big enough	Strongly Disagree	☐	☐	☐	☐	☐	☐	☐	☐	☐	Strongly Agree ☐
15. I am happy with how the blinds (or curtains) operate	Strongly Disagree	☐	☐	☐	☐	☐	☐	☐	☐	☐	Strongly Agree ☐
16. The lighting conditions are comfortable	Strongly Disagree	☐	☐	☐	☐	☐	☐	☐	☐	☐	Strongly Agree ☐
17. I can/could work happily in this room with SOME of the electric lights turned off	Strongly Disagree	☐	☐	☐	☐	☐	☐	☐	☐	☐	Strongly Agree ☐
18. I can/could work happily in this room with ALL of the electric lights turned off (using only daylight)	Strongly Disagree	☐	☐	☐	☐	☐	☐	☐	☐	☐	Strongly Agree ☐
19. The daylight in this room is sufficient	Strongly Disagree	☐	☐	☐	☐	☐	☐	☐	☐	☐	Strongly Agree ☐
20. The daylight in this room is not too bright (i.e. not causing glare or discomfort)	Strongly Disagree	☐	☐	☐	☐	☐	☐	☐	☐	☐	Strongly Agree ☐
21. I am able to do my work here without any problems from glare or troubling reflections	Strongly Disagree	☐	☐	☐	☐	☐	☐	☐	☐	☐	Strongly Agree ☐

This survey is part of a study funded by Environmental Security Technology Certification Program (ESTCP). The results of this survey will be used to guide the development of better buildings. Your responses will remain anonymous. If you have any questions about the survey, please contact Tim Perry at Heschong Mahone Group, Inc. (916) 962-7001 or perry@h-m-g.com

OPTIONAL QUESTIONS:

22. Have you ever experienced glare from the windows? Yes / No

If you answered "No", skip to question 29 on the next page. Otherwise, continue.

23. How often do you experience glare problems? (Please circle all that apply)
   a. Non-stop, whenever I am in the space.
   b. At certain set times, every day.
   c. Irregularly, but every day.
   d. Intermittently, depending on the weather.
   e. Intermittently, depending on my location.

   Comments:____

24. When and where is glare a problem for you? (Please circle all that apply)
   a. In the morning (8 a.m. - 11 a.m.)
   b. Around noon. (11 a.m. – 1 p.m.)
   c. In the afternoon. (1 p.m. – 4 p.m.)
   d. Sitting in my cubicle
   e. Standing near my cubicle
   f. Standing in near the windows.

   Comments: ____

25. What visual problems does the glare cause for you? (Please circle all that apply)
   a. Reflections in my computer screen.
   b. Difficulty reading printed material.
   c. Difficulty looking at the window.
   d. Difficulty looking at people's faces in my cubicle.
   e. Difficulty looking at people's faces far away from my cubicle.
   f. Difficulty talking to people when standing near the window.

   Comments: ____

26. What does the glare cause you do do? (Please circle all that apply)
   a. Avoid looking out the window from your cubicle.
   b. Avoid looking out the window while walking around.
   c. Have eyestrain.
   d. Have a headache.
   e. Have a migraine.

   Comments: ____

27. From your experience, what are the most obvious sources of the glare? (Please circle all that apply)
   a. Direct view of the sun (solar orb).
   b. Sunlight reflecting off of the window sill or counter.
   c. Sunlight reflecting from car windows in parking lot below.
   d. Bright colored roofs or other buildings.
   e. Sunlight reflecting from wet surfaces, like parking lot or roofs.
   f. Bright sky and/or clouds.
   g. Contrast with shadowed or silhouetted elements inside of space.
   h. Brightness of diffusing film in upper window.

   Comments: ____

28. On a scale of 1-10, how bad is the glare you have been experiencing? An answer of 1 is the complete lack of glare, such as outdoors on a rainy day, and 10 is the worst possible condition, such as glare from looking at the low sun on a bright snowy day or out on the ocean.

No Glare 1☐ 2☐ 3☐ 4☐ 5 ☐ 6☐ 7☐ 8☐ 9☐ 10☐ Worst possible glare

OPTIONAL QUESTIONS:

29. What do you like most about the visual conditions in this room?

30. What do you like least about the visual conditions in this room?

32. If you could make any changes, how would you improve the visual conditions in this room?

33. Any other comments about the windows, view quality, electric lights, or other visual elements?

HMG is very interested in understanding what is causing visual discomfort in the room. We would like to conduct a short (10 minute) interview with anybody who would like to share their experience. If you are willing to talk to us, please call or e-mail Tim Perry. Tim's phone number is **(916) 962-7001**. Tim's e-mail address is perry@h-m-g.com.

Thank you!
Please return this survey to the person who gave it to you.

This survey is part of a study funded by Environmental Security Technology Certification Program (ESTCP), part of the Department of Defense's environmental research programs. The results of this survey will be used to guide the development of better buildings. Your responses will remain anonymous. If you have any questions about the survey, please contact Tim Perry at the Heschong Mahone Group, Inc. at (916) 962-7001 or perry@h-m-g.com

All surveys should be returned to
Daylighting Surveys
Heschong Mahone Group
11211 Gold Country Blvd #103
Gold River, California, 95670

5.4 EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES

This section discusses the equipment calibration and data sampling tasks that the team performed to ensure data quality.

5.4.1 EQUIPMENT CALIBRATION

To ensure data validity and accuracy, the HOBO loggers were calibrated against LI-COR sensors. The LI-COR sensors served as the standards in this case, and the sensors' calibration processes were performed following NIST standards by the manufacturer prior to their shipment. The research team then calibrated the HOBOs against the LI-COR sensor. The regression equations obtained from the calibration exercises were used to "correct" data obtained from the HOBO loggers back to the standard values.

5.4.2 QUALITY ASSURANCE SAMPLING

The HOBO loggers were calibrated against the LI-COR sensors both before and after their field deployment. The purpose of these calibration processes was to detect whether the logger sensitivity had drifted during the study period. One team member was tasked with reviewing and examining data for anomalies. No loggers experienced significant drift and data was deemed usable without adjustment.

Interior illuminance was graphed with exterior illuminance for select days. Results were compared to both hand-held measurements and simulation results and good agreement was found for both. Hand-held measurements were taken with a Minolta T-10 (which exhibits superior accuracy to the HOBO sensors).

5.4.3 POST-PROCESSING ANALYSIS

Post-processing of monitored data was necessary to account for study design and irregularities in data.

By design – To determine the impacts of daylighting in each space U-12 data loggers were placed in transects on the ceiling and workplanes. Two methods were used to estimate the electric lighting contribution based on data collected from U-12 Hobos' and DENT loggers. DENT loggers were placed in lighting fixtures to determine on/off state of electric lighting. However, data from these loggers was not used due to data quality issues. Alternatively, night-time illuminance values from the U-12 loggers were used as a proxy for the electric lighting contribution. Night-time illuminance values were determined to be between the hours of 10:00 PM to 6:00 AM. When electric lighting was on during these hours, a constant illuminance value was seen in the data set, resulting in the electric lighting contribution value. This value was then subtracted from the overall illuminance values in the data set to determine the impact of daylighting only.

Data issues – Several issues in the data set included: spikes in illuminance due to direct beams of sun, loggers falling down or placed incorrectly causing incorrect readings, and sudden increases or decreases in illuminance levels not explained by site conditions. Each issue was addressed after performing diagnostics on the data set, potential contributing site conditions, and HMG staff field observations.

Some loggers experienced direct beams of sunlight during the late afternoon resulting in spikes in the data set. These spikes were addressed by averaging several hours before and after the spike to determine more accurate daylighting levels for these periods of time. The averages were then applied to the affected data, resulting in data more representative of the illuminance typically observed in the space. Other issues in the data were found due to loggers positioned incorrectly or found out of place for a period of time. Data from these time periods was eliminated from the analysis due to inconsistency in the readings over time.

Sudden increases or decreases in illuminance levels not explained by a change in site conditions were observed in some instances. These could be a result of relocated loggers, changes in electric lighting operation, or unknown reasons. In most instances the data could be reconciled by observing the before and after illuminance levels and adjusting the increased or decreased values to these patterns.

5.5 MODELING AND SIMULATION

Simulation results were used to estimate energy savings for retrofitting DRF and photocontrols into office spaces. Generic open office models and TMY3 weather data was used to estimate annual impacts, rather than constraining the results to the specifics of the particular buildings and weather encountered during the field study.

First, daylight illuminance levels were calculated in using the Dynamic Radiance approach in Radiance. Second, a lighting schedule was created from the illuminance levels and whole-building energy usage was calculated using eQuest. The same TMY3 weather file was used in both simulations ensuring that incident solar energy and external heat loads were synchronized between the two simulations.

Daylighting simulations were conducted following IESNA LM-83 guidelines using the Dynamic Radiance approach, and whole-building energy simulations followed ASHRAE 90.1 2010 guidelines.

5.5.1 DAYLIGHTING SIMULATION ANALYSIS

The most important variables for daylight illumination simulation in radiance are building orientation, ceiling height, window glazing visual transmittance, office furniture layout, photocontrols, lighting schedule, blinds control, and office size. The range of these variables and detailed descriptions of how these were implemented are provided in this sub-section.

5.5.1.1 DAYLIGHTING SENSITIVITY ANALYSIS

We modeled an open office plan with a 60’ windowed façade. The model had a 70% reflective ceiling, 50% reflective walls, 20% reflective flooring and 50% reflective cubicle furniture.

Parametric runs compared relative savings for three latitudes, three orientations, two ceiling heights, two window visible light transmittance (VLTs), three blind control strategies, and seven space depths. Energy use in each daylit zone was plotted and analyzed to determine which variables had the most impact on total savings.

Sunlight redirecting products could logically be installed on façades oriented east, south-east, south, south-west, and west, which receive substantial direct sunlight over the course of the year. Savings per façade should logically be symmetrical around true south, with the exception of local climate conditions that vary between morning and afternoon, such as morning fog. For this analysis, savings were modeled for west, south, and east orientations to ensure the effects of morning fog are captured at all locations.

Two ceiling heights were modeled: a 9' ceiling and a 10' ceiling. All configurations had a 60' windowed façade with a lower window and an upper window. The lower window sill was 3'6" above AFF and the header was 7'2" AFF. The upper window sill was 7'6" AFF and the header was placed 3" below the ceiling (8'9" in the 9' ceiling model and 9'9" in the 10' ceiling model). An example of this façade is pictured in Figure 40 below. The 10' ceiling model had a net window-to-wall area ratio of 59% and the 9' ceiling model had a net window-to-wall area ratio of 54%. The net window-to-wall area ratio is the ratio of window to wall as seen from inside the room, from floor to ceiling. Building designers may be more familiar with gross window-to-wall area ratios which include plenum walls and structural area.

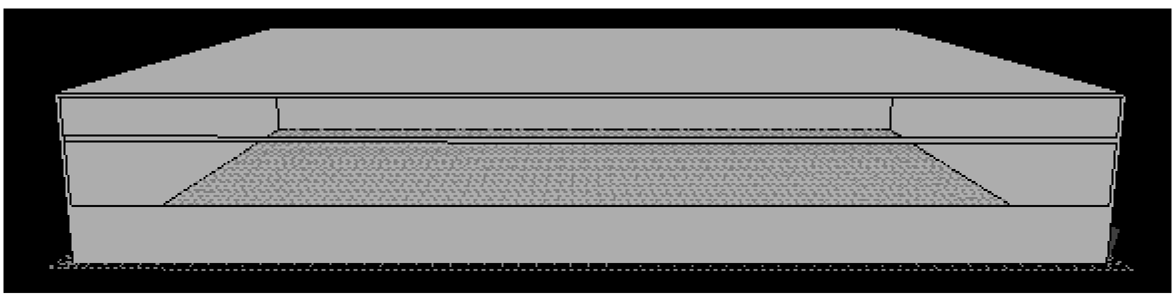

Figure 40: Office Façade for the 10' ceiling.

Clerestory height and area changed with ceiling height, but not with room depth. Consequently, as rooms grew deeper, the clerestory window-to-floor-area ratio declined. Larger clerestory window-to -floor-area ratios increase daylighting savings regardless of technology used.

		Room Size						
		60' x 16'	60' x 24'	60' x 32'	60' x 40'	60' x 48'	60' x 56'	60' x 64'
Clerestory Height	2.25'	13.9%	9.3%	7.0%	5.6%	4.6%	4.0%	3.5%
	1.25'	7.7%	5.2%	3.9%	3.1%	2.6%	2.2%	1.9%

Figure 41. Clerestory window to floor area ratio of each model configuration.

Two window visible light transmittances (VT's) were modeled: 40% and 70%. Dark tinted glass, such as 20% VT, was not modeled as buildings with dark glass are usually poor candidates for daylighting.

Windows blinds or shades (hereafter, referred to as `blinds'), and their operation play a critical role in determining the quantity of daylight in a space. In their Daylight Metrics report, the Heschong Mahone Group found operable blinds or shades were present in 84% of all the spaces studied[1]. The study also found that assumptions about modeling the operation of blinds had a significant impact on projected daylighting availability. This analysis uses the same optimal blinds operation assumptions that were developed by the PIER research group, and are consistent with the new IES LM-83 document describing procedures for modeling spatial daylight autonomy.

Optimal, or automatic, blinds operation in this study used the same standardized blinds operation trigger developed for the Daylight Metrics study – excess direct sunlight in the space. Blinds were closed for each hour when 2% or more of the sensors in the simulated space were in direct sunlight. Direct sunlight is defined as illuminance greater than 1000 lux (100 fc), excluding contributions from the sky or reflected sunlight—in other words, the illuminance in a sun patch. This 'auto' schedule is most similar to occupants who want to optimize their view and minimize their exposure to direct sunlight.

However, it is also observed that many occupants do not actively operate their blinds and leave them closed most of the time[2]. To capture this variation, results of this analysis are presented for both optimally operated blinds and for always closed blinds. The optimally operated blinds represent the upper-bounds of daylighting savings and the always closed blinds represent the lower bounds of daylighting savings. Actual savings will fall between these two bounds due to variations in occupant behavior.

In the base case model for this analysis, a single, full-height blind covered both the clerestory and view window entirely when closed. In the open condition, the blinds did not interfere with light entering the room from either upper or lower window. For the test products model, the clerestory had a BSDF file (discussed below) representing the test daylighting product, and the blinds only covered the lower, view windows when closed.

BSDF file for the DRF was created by Lawrence Berkeley National Lab (LBNL) and provided by the product manufacturer. The BSDF file was for DRF film and diffuser, both mounted on a 3mm clear glass. The glazing they would be mounted in front of in a retrofit project was not considered. The BSDF files from LBNL were combined with glazing layers in LBNL's WINDOW 7 software to create window assemblies representative of the products as they would be deployed in a daylighting retrofit project. Final simulation included the products mounted inside of 70% VLT, dual pane glazing and 40% VLT, dual pane glazing.

In order to model window blinds accurately, for the annual daylighting simulations, the project team used the WINDOW 6 software from LBNL to generate a model of 1" thick, off-white mini-blinds. The WINDOW 6 software generates a three-dimensional descriptive matrix of values of blinds transmittance in all directions, known as a Bi-Direction Scatter Distribution Function or BSDF. This BSDF is subsequently used in the

[1] Heschong, Lisa. Heschong Mahone Group. 2011. ***Daylight Metrics***. California Energy Commission. Publication number: CEC -500- 2012- 053.

[2] Senati, Leyla , 2013, ***The effect of window shading design on occupant use of blinds and electric lighting,*** Building and Environment, 64, pp 67-76.

Radiance simulations using the Dynamic Radiance Approach (Saxena, 2010)[1]. These window models including the glazing and mini-blinds were applied to the view windows (and upper window in the base case).

Electric lighting energy savings were based on illuminance results. The space was broken up into 8' deep daylit zones parallel to the windowed façade. Electric lighting savings were estimated for each zones based on illuminance levels within the zone. Each zone contained a row of 2' x 4' fluorescent troffer fixtures dimmed as a group.

Dimming photocontrols were modeled for this assessment. The dimming strategy modeled in this report is pictured in Figure 42. This system turns off once the target illuminance is reached to maximize energy savings. This type of system generally provides optimal daylight energy savings. Note the difference between light output and power consumption: fixture efficiency declines at lower light output levels due to loads within the ballast.

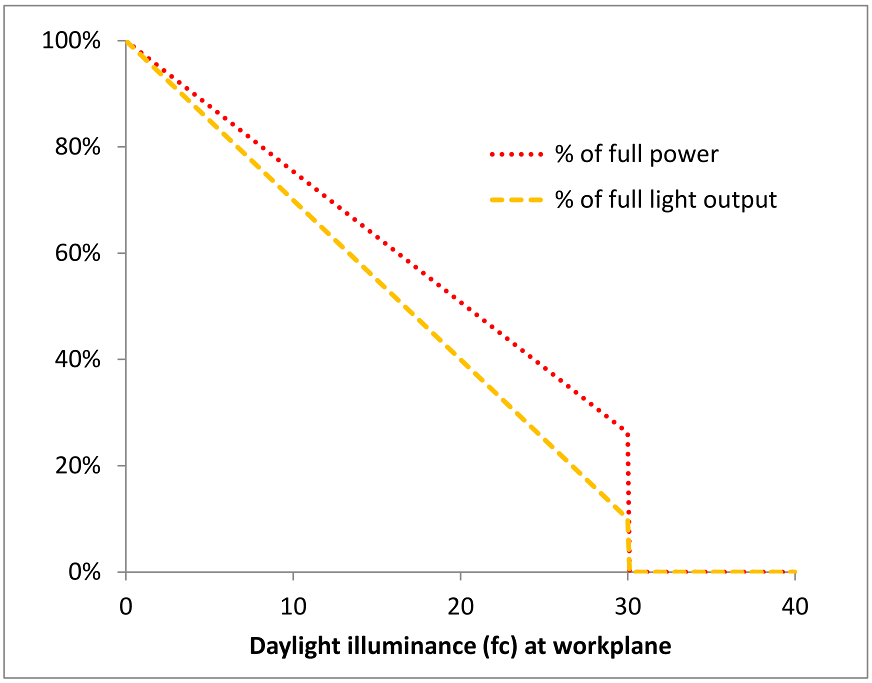

Figure 42. Simulated dimming system energy consumption and light output.

5.5.1.2 SPATIAL DAYLIGHTING AUTONOMY ANALYSIS

Following the sensitivity analysis conducted for illuminance measurements, analysis was conducted for calculating the difference in spatial Daylight Autonomy (sDA) made by the installation of the DRF versus the baseline conditions. This change was one of the performance objectives of the DRF demonstration study.

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[1] Saxena, Mudit (Heschong Mahone Group) 2010, ***Dynamic radiance – predicting annual daylighting with variable fenestration optics using BSDFs***, SimBuild 2010

Illuminance values were simulated with ray tracing in the Radiance software package using the Dynamic Radiance approach which is also known as the three-phase method (Saxena, 2010)[1]. While the buildings used as trial sites were valuable, they also had limitations for testing daylight redirecting products. Some of the buildings were shaded a significant portion of the day, some had small overhangs, and the variations in façade design and room size made it difficult to compare results between sites. In order to generate savings values closer to average office building design and allow comparison's across sites, a generic 'box' with flush mounted windows and no overhangs or fins was used in the simulations. As an added advantage, these results were comparable to savings estimates in a recent PIER report submitted to the California Energy Commission (Saxena, 2011)[2] as it utilized the same simulation methodology.

Analysis was conducted on a prototype office space (60'x40') with 10' ceiling height and windows with 70% visible light transmittance (VLT) which translates to a single pane window. The prototype office space was analyzed in three US locations to get three different climate conditions which represented a northeast US location (a mid-latitude, cloudy climate), southwest US location (a lower-latitude, sunny climate) and northwest location (a high-latitude, cloudy climate). The prototype design was also analyzed in three orientations – east, south, west. In addition, analysis was conducted with two operating conditions for blinds – automated blinds that are controlled based on glare and solar control, and blinds closed. The baseline had blinds on the entire window whereas the treated space was modeled with blinds only on the view windows and DRF on the clerestory windows.

Analysis was conducted using the same methodology as the daylight sensitivity analysis, except the results were processed to calculate sDA300, 50% -- representing percent of the study area that meets a minimum daylight illuminance level of 300 lux, for at least 50% of the operating hours per year.

5.5.1.2.1 THE DYNAMIC RADIANCE APPROACH (THE 3-PHASE METHOD)

The Dynamic Radiance approach was built on the annual daylight illuminance simulation capabilities previously developed in Daysim. It has extended the two-step Daylight Coefficient approach, which allows for faster simulation of annual weather conditions by reducing the number of hourly computations, into a three-step approach, which inserted an additional matrix describing fenestration light transmission properties into the calculation of room illuminance. This matrix consists of a three-dimensional description of how light moves through the plane of windows or skylights, as effected by blinds or special glazing optics. It is called a 'bi-direction scatter distribution function', or BSDF, described further below.

The three step process used by Dynamic Radiance is described by the equation: ***i* = *VTDs***, with the variables described below. It is also illustrated below in Figure 43.

---

[1] Saxena, Mudit (Heschong Mahone Group) 2010, ***Dynamic radiance – predicting annual daylighting with variable fenestration optics using BSDFs***, SimBuild 2010

[2] Saxena, Mudit. (Heschong Mahone Group). 2011. ***Office Daylighting Potential***. California Energy Commission. Publication number: TBD.

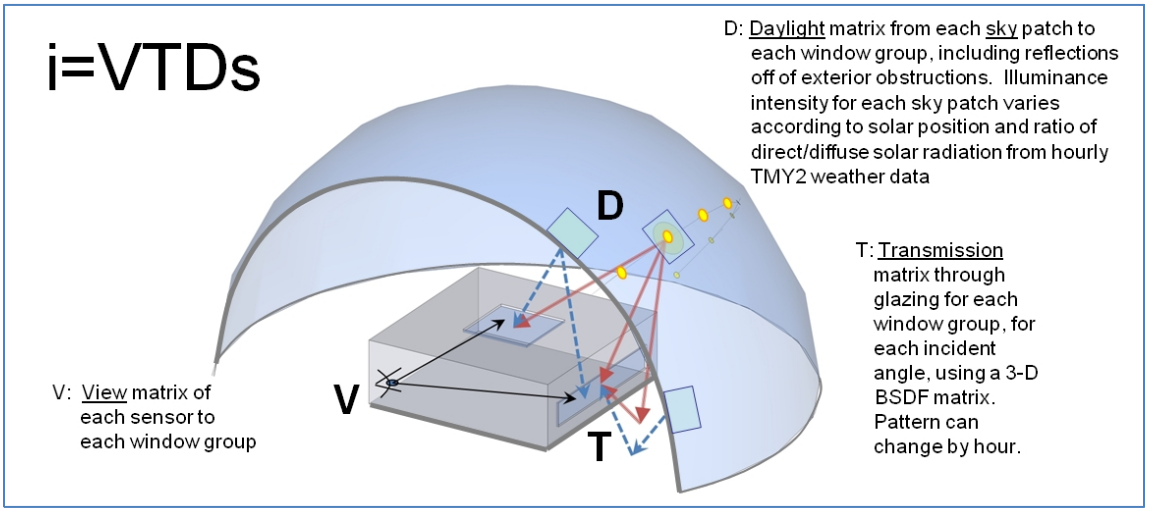

Figure 43. Dynamic Radiance approach

- where i = resultant illuminance vector,
- V = a "view matrix" that defines the relation between measurements and exiting window directions;
- T = the transmission portion of the BSDF;
- Ds = the "daylight matrix" that defines the relation between incoming window directions and sky patches, varied by ‘s’ = skypatch intensity

The use of a BSDF matrix gives Dynamic Radiance the capability to model angularly dependent, complex glazing assemblies and dynamic fenestration, which includes systems as simple as manually operated Venetian Blinds to sophisticated optically tracking skylights. As such, it is highly applicable to the advanced sidelighting product evaluated in this project: it has highly specular, anisotropic light redirecting properties that would be difficult or impossible to capture without the BSDF matrix.

For this project BSDF’s were used to represent all fenestration. BSDF’s represent the transmission of light through an assembly by creating coefficients describing light exiting the assembly in each of 145 outgoing patches (solid angles) for a light entering the assembly from each of 145 incoming patches (solid angles). The coefficients are stored in a 145x145 matrix inside an XML file. Due to the relatively large area of the patches in the BSDF, some amount of noise is introduced into the simulation. LBNL has estimated this introduces approximately ±5% noise into annual simulation results.

BSDF file for the DRF was created by Lawrence Berkeley National Lab (LBNL) and provided by the product manufacturer. The BSDF file was for DRF film and diffuser, both mounted on a 3mm clear glass. The glazing they would be mounted in front of in a retrofit project was not considered. The BSDF files from LBNL were combined with glazing layers in LBNL’s WINDOW 7 software to create window assemblies representative of the products as they would be deployed in a daylighting retrofit project. Final simulation included the products mounted inside of 70% VLT, dual pane glazing and 40% VLT, dual pane glazing.

5.5.2 LIGHTING AND WHOLE BUILDING ENERGY SAVINGS

HMG used eQuest version 3.64 to simulate the energy savings for a 60'x40' office space with the 3M film applied on clerestory windows and automatic daylighting controls. eQuest is an hourly building energy use analysis commonly used to estimate energy savings and conduct parametric analysis for multiple runs.

For this project, the difference in energy use between a 'base case' and an 'improved case' simulation runs were calculated and reported as energy savings (or increases).

All simulations were conducted using a simple 60'x40' space was modeled with two HVAC zones. The perimeter HVAC zone was sixteen feet deep. The core HVAC zone was 24 feet deep. The image below is a graphical representation screen capture of the building modeled for the analysis (Figure 44).

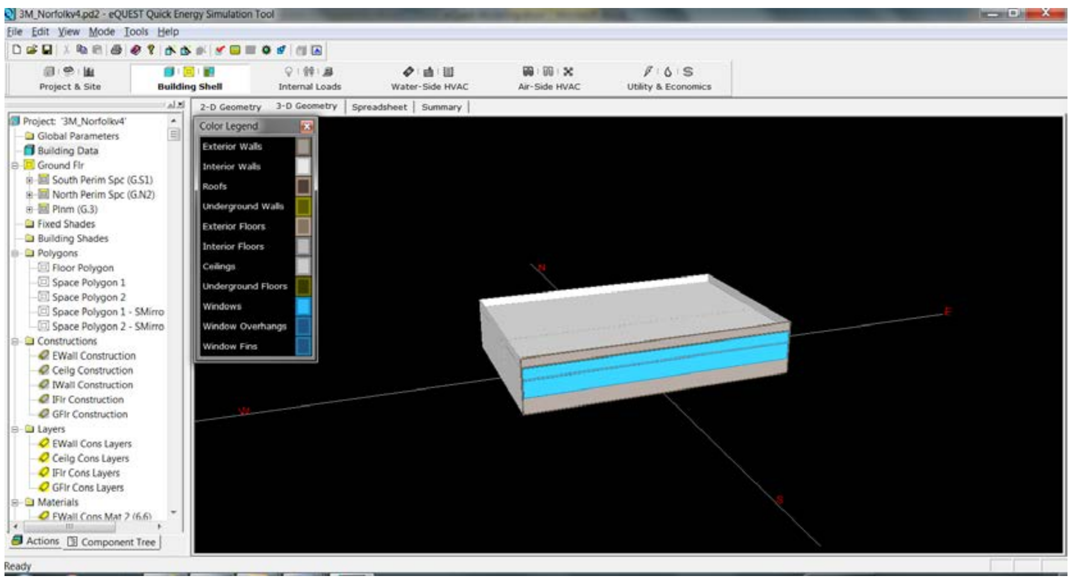

Figure 44. eQuest model for whole-building-energy use simulations.

Simulations were performed for east, south, and west orientations. Direct sunlight is required for the DRWF to provide daylighting benefits so north facing spaces were not modeled.

Simulations were performed for three locations. Two lower-latitude sites (Northeast and Southwest US) and one higher latitude site (Northwest US) were modeled. Two mixed-sky climates were modeled (Northeast and Northwest US) and one clear-sky climate (Southwest US) were modeled.

Base case and improved case runs were identical in all respects expect for glazing characteristics, window coverings, and electric lighting schedules. Glazing characteristics were changed for the in the improved case clerestory windows to reflect the thermal and SHGC properties of the DRWF. In the base cases, blinds covered the entire window while in the improved case blinds only covered the lower, view window. All electric lighting schedules were based upon the ASHRAE 90.1 medium office building prototype.

In spaces without daylighting (photocontrols), the ASHRAE 90.1 medium office building default schedule was used. When daylighting was modeled, the electric lighting was dimmed to maintain 30 foot-candles at the workplane. For example, if daylight was providing 10 foot-candles then the electric lighting would be dimmed to provide two-thirds of light output. If the daylight was brighter than 30 foot-candles then the electric lighting was switched entirely off. The 30 foot-candle set-point was based on IESNA's recommendation that 30 foot-candles of light be provided in open office environments.

The improved case was the same for all runs: DRF was installed in the upper, clerestory window; blinds covered only the lower, view window; and photocontrols dimmed the lights down in each daylit zone. As mentioned above, usage from the ASHREA 90.1 schedule was reduced to account for dimming of lights with photocontrols in each daylit zone (row of lights). Usage from daylit zones was averaged over HVAC zones imported into eQuest. The improved case represented the savings from a properly configured daylighting system in a room with DRF installed.

'Base Case 1' contained no photocontrols and a monolithic set of blinds covered both the clerestory and view windows. The ASHRAE 90.1 medium office building default lighting schedule was used without modification in all HVAC zones.

'Base Case 2' contained photocontrols in the front HVAC zone. Like 'Base Case 1', a monolithic set of blinds covered both the clerestory and view windows. The front HVAC zone contained two daylighting zones and simulated photocontrols dimmed the lights down from the ASHRAE90.1 schedule levels in these two daylit zones (row of lights). Usage from two daylit zones was averaged and imported into eQuest and used as the lighting schedule for the perimeter HVAC zone. No daylighting was performed in the core HVAC zone and so the ASHRAE 90.1 medium office building default lighting schedule was used without modification in this HVAC zone.

The wall with the windows was modeled as an exterior wall. All other walls, the ceiling, and floor were modeled as adiabatic. Windows were modeled without exterior overhangs.

Parametric runs were set up based on orientation and location. Parametric runs for east, south, and west orientations were done in three cities. EnergyPlus weather files for the three locations were converted to TMY3 weather files compatible with eQUEST.

A generic 'box' with flush mounted windows and no overhangs or fins was used in the simulations, in order to generate savings values closer to average office building design. This box was rotated through three orientations, and three climates, in order to describe the range of savings that could be expected. Parametric runs compared relative savings for three orientations, two ceiling heights, visible light transmittance (VLT) of glazing, two base-case photocontrol assumptions, three blind control options and seven office sizes. Values for each variable are shown in Figure 45.

The simulation study compared a base case model to an improved model, where the characteristics of window covering on the upper, clerestory window were varied. In base case runs both the upper, clerestory window and the lower, view window were covered with a monolithic mini-blind. In improved models, the mini-blind was moved down below the film and only covered the lower, view window. The DRF was applied to the upper, clerestory window and no interior or exterior moveable shading device was modeled for the upper window area.

Savings were calculated by subtracting energy use of the “improved” model from energy usage in the equivalent “baseline” model. Two baseline models were used: ‘BASE CASE 1’ assumed no pre-existing photocontrols in the space and ‘BASE CASE 2’ assumed photocontrols were already installed in the first two daylit zones (first two rows of fixtures) adjacent to the windowed façade. The “improved” case assumed photocontrols were added to all daylit zones in the space. Each daylit zone was an area 8’ deep, parallel to the windowed façade, and contained one row of light fixtures located along the midline of the zone. HVAC systems were modeled with the same default characteristics for all runs. The table below summarizes the main eQuest model inputs modified for the analysis.

Variable	**BASE CASE 1**	**BASE CASE 2**	**DRF**
Photocontrols	None *	Daylit zone 1 & 2*	All Lighting Zones*
Climate	Southwest US; Northwest US; Northeast US		
Orientation	E, S and W*		
Ceiling Ht.	9’ , 10’*		
Window VT	40%, 70%*		
Office Furniture	60” Cubicle*		
Lighting Schedule	ASHRAE 90.1*		
Blinds Control	Always Closed, Automated*, Always Open		
Office Size	60x16, 60x24, 60x32, 60x40*, 60x48, 60x56, 60x64		

*Figure 45: Parametric Simulation Variable Values. Values marked with a * were used in whole-building simulations.*

A key issue studied was how deep the DRF sent useful daylight into the space. This objective was not included in the original study plan, however onsite surveyors had observed the film redirected sunlight and created distinct shadows on walls about 60 feet from the windowed façade. They observed that the rear wall reflected daylight from the film into work areas near the back of the room and increased illuminance levels enough that electric-lighting-energy savings might be obtained if the area had photocontrols. Simulations with various model depths were run to determine if, for a given room depth, reflections off the back wall increased energy savings in shallower spaces compared to deeper spaces.

A second key issue studied via simulation was how climate affects savings. Because daylight energy savings will vary by latitude and climate, simulations were run for three climates, which represented a northeast US location (a mid-latitude, cloudy climate), southwest US location (a lower-latitude, sunny climate) and northwest location (a high-latitude, cloudy climate). The results of these simulations provide guidance on the likely range of energy savings achievable with the window films.

5.6 SAMPLING RESULTS

The site sampling met most, but not all objectives. The team did not find any available study sites in high-latitude with clear skies, but met their objectives for study sites in other sky types and latitudes (Figure 46).

	Predominantly clear skies (>60% clear)	Mixed skies (<60% clear)
High latitude	0	2
Low latitude	2	2

Figure 46. Actual geographic and climatic sample of study sites

The site data collection had some problems with loss of data from data loggers and logger theft on one site, but overall enough data was available to complete the study and make accurate recommendations. A snapshot of the data collected and missing is provided in Figure 47 through Figure 52.

Site	Space	Monitored Data Collected	Survey Data Collected
Twentynine Palms, CA	H&S Company	Yes *(1 logger stolen, 1 shield partially fell off. 2 lighting loggers failed. 2 curtain loggers failed)*	Yes
	Battery Company	Yes *(1 ceiling logger fell, partition top logger failed, PC lighting logger failed)*	Yes
	Weapons Company	Yes *(1 partition-top logger stolen, window shade logger failed)*	Yes
	Charlie Company	Yes *(one ceiling logger fell, two lighting circuit loggers failed, photocontrol logger data is unreliable)*	Yes
	Records Room (Treat)	Marginal study pair due to different orientations	Yes
	Records Room (Ctrl)		
	Dr. Office	Yes	Yes

	Psych. Office	Yes	Yes

Figure 47. Status of data collection from Twenty Nine Palms site

Site	Space	Monitored Data Collected	Survey Data Collected
Newport, RI	South Office 336 (Treat)	Yes *(One partition-top logger moved when the office occupant left.)*	Yes
	South Office 335 (Ctrl)	Yes	Yes
	West Office 330 (Treat)	Yes *(One ceiling logger fell 12/30/2011. Re-installed 1/6/2012)*	Yes
	West Office 329 (Ctrl)	Yes	Yes
	Library	Yes *(one ceiling logger fell 10/9/2011 and was re-installed 10/21/2011. Three ceiling loggers fell spring of 2012)*	Yes

Figure 48. Status of data collection from Newport site

Site	Space	Monitored Data Collected	Survey Data Collected
El Paso, TX	Open Office Area (Treat)	Yes *(Curtain logger failed after 3 days, 3 ceiling loggers fell and were replaced mid-way through study)*	Yes
	Open Office Area (Ctrl)	Yes *(Odd dates in curtain logger, lighting logger shows no lighting use for first 2 months of study, 1 ceiling logger fell, different furniture so no transect of loggers possible)*	Yes
	Private Offices	Not monitored	Yes

Figure 49. Status of data collection from El Paso site

Site	Space	Monitored Data Collected	Survey Data Collected
Bremerton, WA	Exam Rooms	Loggers Stolen	Yes

Figure 50. Status of data collection from Bremerton site

Note: There was a theft of dataloggers and other data collection equipment from a vehicle when our surveyor was in transit from this site. This resulted in loss of data from this site including data on illuminances, electric lighting, blinds operation and photographs. An incident report was filed per ESTCP procedures.

Site	Space	Monitored Data Collected	Survey Data Collected
Norfolk, VA	Open Office Area (Treat)	Yes	Yes
	Open Office Area (Ctrl)	Yes	Yes

Figure 51. Status of data collection from Norfolk site

Site	Space	Monitored Data Collected	Survey Data Collected
Monterey, CA	Private Office (Treat)	Yes *(sun-screen was never removed rendering the data quality marginal)*	Yes
	Private Office (Ctrl)	Yes	Yes

Figure 52. Status of data collection from Monterey site

Note: At Monterey, the building had external sun screens installed prior to this study which shaded the entire window including the clerestory. These screens were never removed from the site (as requested). Thus there was no direct sunlight on the clerestory limiting the performance of the film. The data collected on this site reflects this fact that there was not an appreciable increase in daylighting.

5.7 SITE MONITORING DETAILS

Monitoring was conducted at six study sites. A detailed description of the study design, window type, HMG activities, and data collection issues for each site is provided below.

The study sites and the name of the nearest city are listed here along with a short identifier of that site in parenthesis:

- Building Z-133 at Naval Station Norfolk in Norfolk, VA (Norfolk)
- Hewitt Hall at the Naval War College in Newport, RI (Newport)
- Building 20400 at Fort Bliss in El Paso, TX (El Paso)
- Building 1416 at MCAGCC in Twentynine Palms, CA (Twentynine Palms)
- Naval Hospital Bremerton, Bremerton, WA (Bremerton)
- Halligan Hall at the Naval Postgraduate School in Monterey, CA (Monterey)

5.7.1 BUILDING Z-133, NAVAL STATION NORFOLK, NORFOLK, VA

Study rooms are identified in Figure 53. Logger locations in Section A (Figure 54) and Section B (Figure 55) are indicated on the schematics below. A description of the logger locations is included in the subsections that follow.

Space ID	Purpose	Film	Monitoring	Survey Occupant Comfort
Section A	Treatment	Yes	One aisle of cubicles (4th window bay from west wall)	Yes
Section B	Control	No	One aisle of cubicles (4th window bay from east wall)	Yes

Figure 53. Norfolk Study Spaces

5.7.1.1 SECTION A

Logger locations are depicted in Figure 54 for Section A. In the figure, ceiling loggers are marked with blue dots and work surface loggers are marked with orange rings.

- One transect of five illuminance loggers each attached to the ceiling.
  - The first ceiling logger was placed in line with the center line of the fourth window from the west wall, equidistant between the first two rows of luminaires.
  - The subsequent loggers were placed in line with the center line of the fourth window equidistant between each subsequent pair of rows of luminaires.
- Three illuminance loggers were installed on top of furniture to serve as a proxy for work surface illumination. This placement reduced the chance of the sensors being accidentally covered by papers and other work materials. Work-surface proxy loggers were located on top of filing cabinets, book cases, and other equipment. The target locations are outlined in orange in Figure 54.

- An on/off lighting logger monitored each lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp. Installers turned each circuit on and off to ensure each logger monitored a different circuit and that all circuits were monitored.
- An illuminance logger was installed in a lower, view window to capture outside illuminance values to the south.
- Two loggers were installed on brackets facing towards the blinds to capture blinds operation schedules. The schedules of the two monitored blinds were generalized to create an operations schedule for this space.

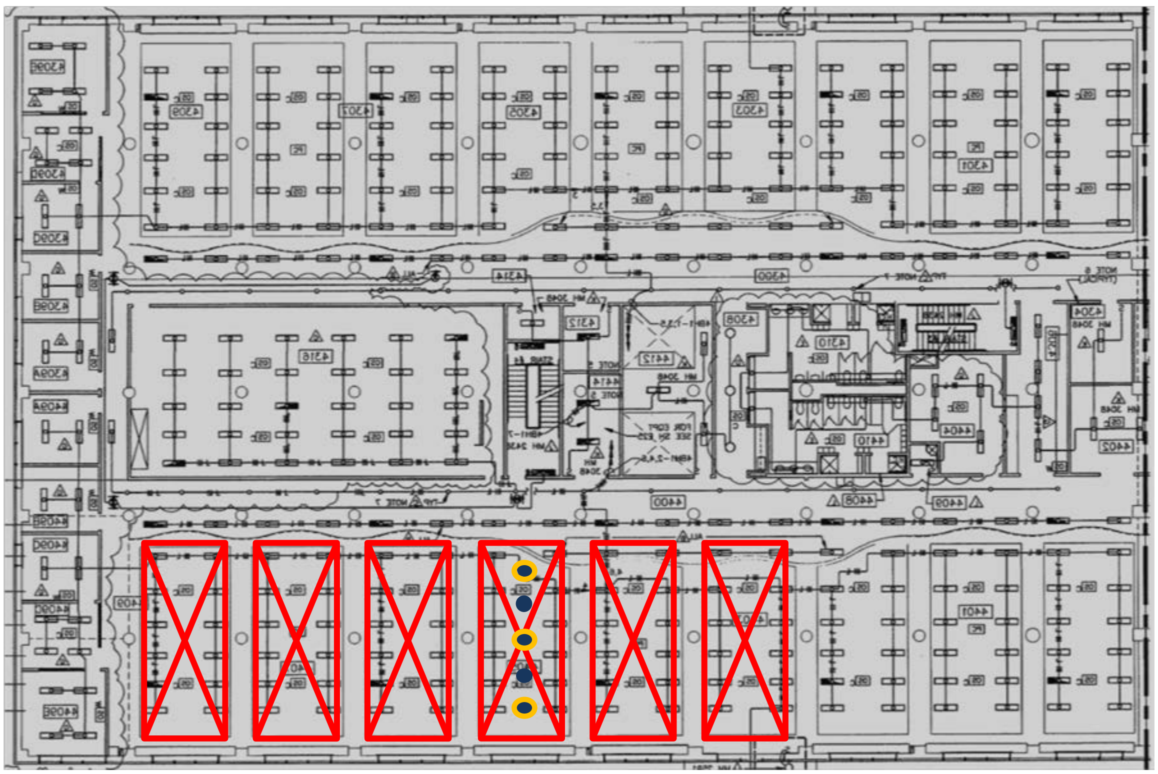

Figure 54. Norfolk - Z-133 Study Area, Section A -- Treated Areas

5.7.2 SECTION B

Logger locations in Section B will mirror those described in Section A, as Section A and Section B are practically mirror image of each other. Logger locations are shown in Figure 55 as well.

- One transect of five illuminance loggers each attached to the ceiling.
  - The first ceiling logger was placed in line with the center line of the fourth window from the east wall, equidistant between the first two rows of luminaires.
  - The subsequent loggers were place in line with the center line of the fourth window equidistant between each subsequent pair of rows of luminaires.

- Three illuminance loggers were installed on top of furniture to serve as a proxy for work surface illumination. This placement reduced the chance that the sensors would be accidentally covered by papers and other work materials. Work-surface proxy loggers were located on top of filing cabinets, book cases, and other equipment. The target locations are outlined in orange in Figure 55.
- An on/off lighting logger monitored each lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp. Installers turned each circuit on and off to ensure each logger monitored a different circuit and that all circuits were monitored.
- An illuminance logger was installed in a lower, view window to capture outside illuminance values to the south.
- Two loggers were installed on brackets facing towards the blinds to capture blinds operation schedules. The schedules of the two monitored blinds were generalized to create an operations schedule for this space.

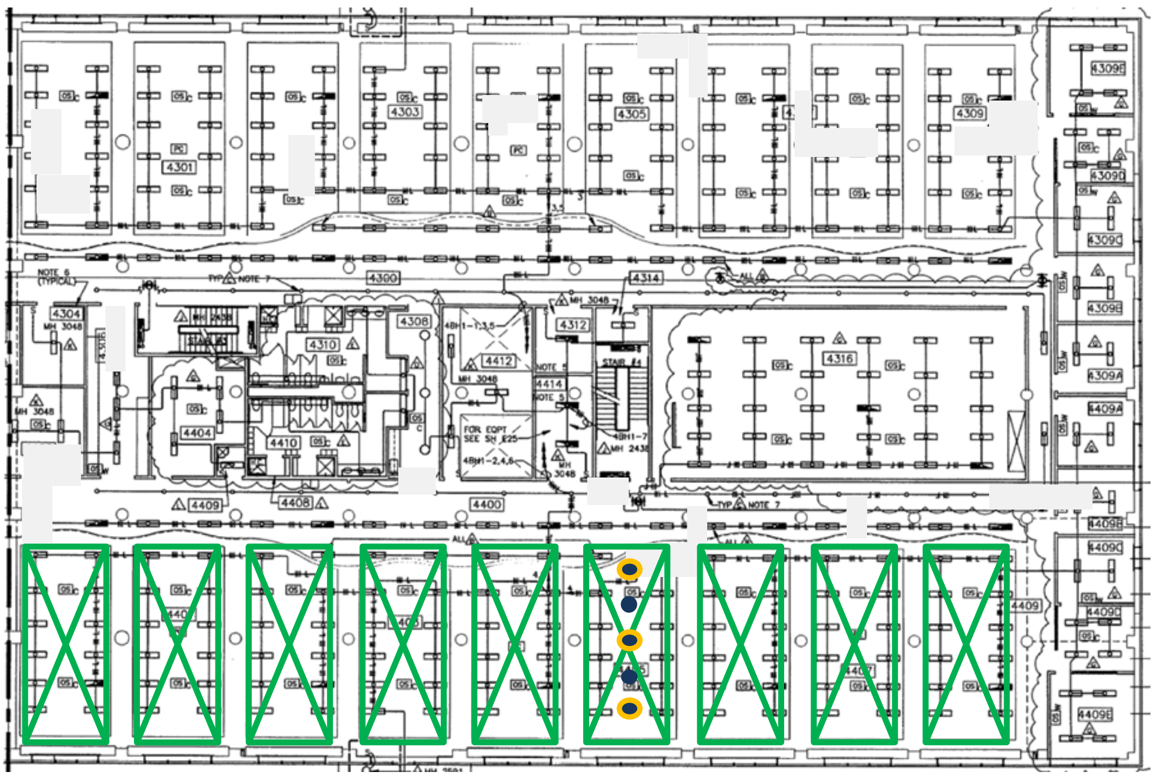

Figure 55. Norfolk - Z-133 Study Area, Section B -- Control Areas.

5.7.2.1 Data Collection Issues

Communications were directed to the space and naval warfare systems command (SPAWAR) building manager and base energy manager. They handled all necessary approvals at the base. A high turnover rate at the base energy manager position posed complications to maintaining communication throughout the study. Fortunately, the SPAWAR building manager ensured that each successive base energy manager received the necessary information to continue the study. The team would like to note that the SPAWAR building manager, Tom Giblin, went above and beyond what his job duties required of him and we are very thankful for his help.

The site personnel were concerned about drilling into the window frames to re-mount the blinds since the windows and frames had recently been renovated to stop leakage. Consequently, the occupants were directed to leave the blinds fully retracted and report any issues to the site staff, who relayed information to the study team. Issues with occupant comfort were reported at this site and it was impossible to determine if these issues could be avoided by remounting the window coverings (blinds) below the window film and allowing occupant control.

5.7.3 HEWITT HALL, NAVAL WAR COLLEGE, NEWPORT, RI

Study rooms are identified in Figure 56. Logger locations in the library (Figure 57) and the small offices (Figure 58) are indicated on the schematics below and show window IDs in red, ceiling logger locations as blue dots, and work-plane loggers as orange rings. A description of the logger locations is included in the subsections that follow.

	Room Number	Film	Monitored	Surveys
Library	Library	Yes	Yes	Yes
South Office	338	Yes	No	Yes
South Office	337	No	No	Yes
South Office	336	Yes	Yes	Yes
South Office	335	No	Yes	Yes
West Office	330	Yes	Yes	Yes
West Office	329	No	Yes	Yes
West Office	328	Yes	No	Yes
West Office	327	No	No	Yes

Figure 56. Newport Study Spaces

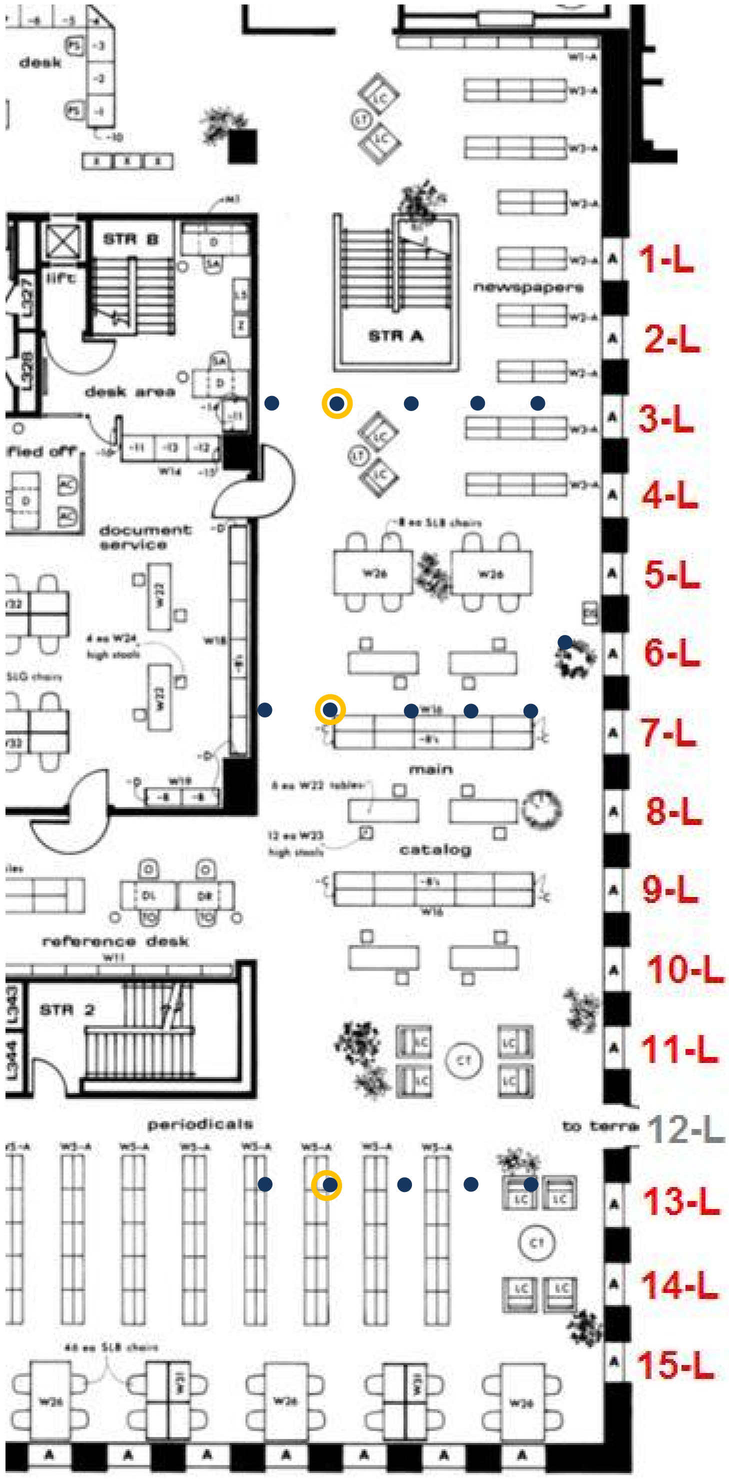

Figure 57. Newport - Library

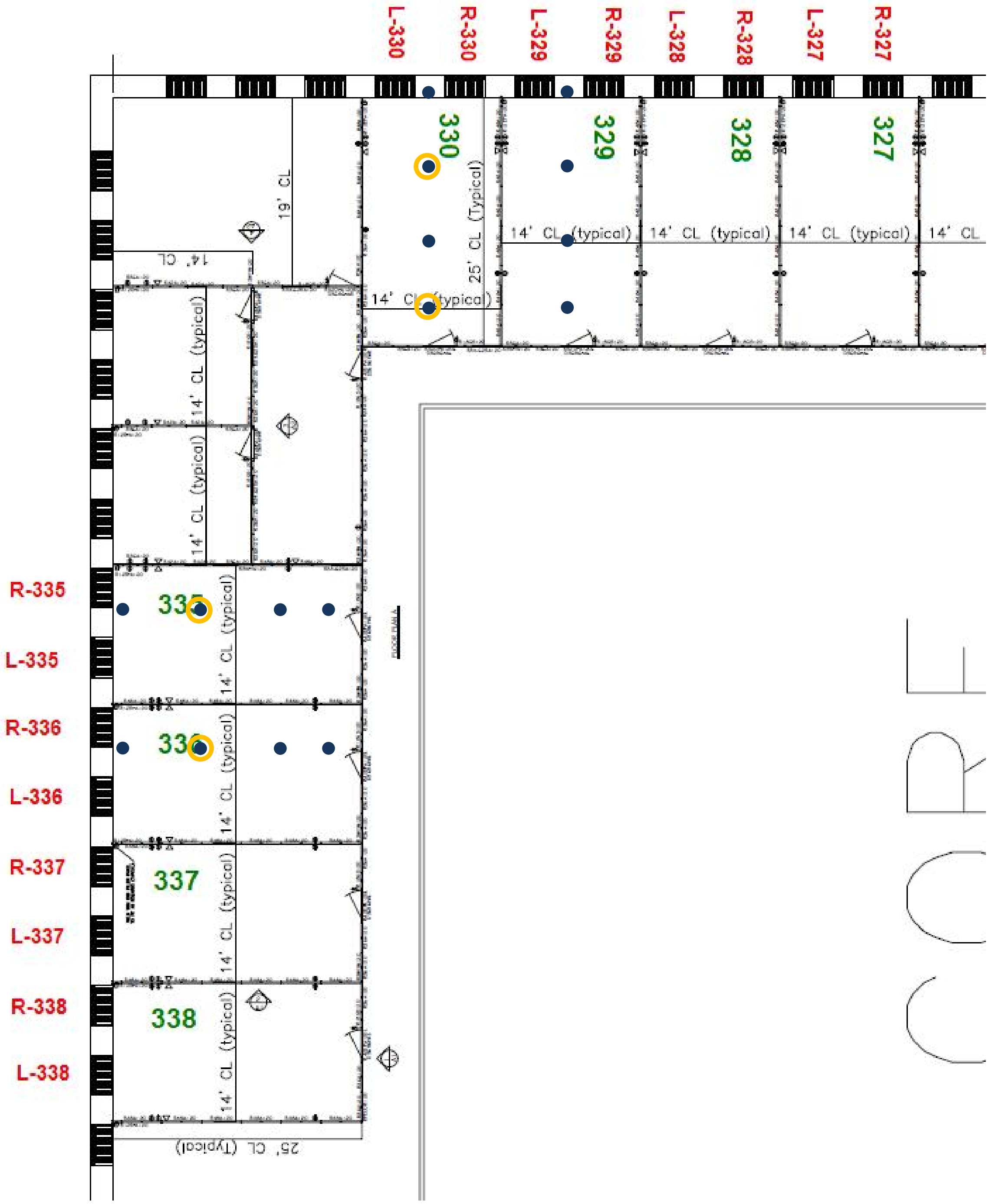

Figure 58. Newport - Offices

5.7.4 LIBRARY

Logger locations are depicted in Figure 57. In the figure, ceiling loggers are marked with blue dots and work surface loggers are marked with orange rings.

- Three transects of five illuminance loggers each was attached to the ceiling.

- A transect of five illuminance loggers were installed perpendicular to window 3-L. All loggers were located equidistant from surrounding luminaires. The approximate locations of these loggers are marked with dark-blue dots in Figure 57.
  - The first logger was located between the two rows of luminaires closest to the windows.
  - The second logger was located between the second and third rows of luminaires.
  - The third logger was located between the third and fourth rows of luminaires.
  - The fourth logger was located between the fourth and fifth rows of luminaires.
  - The fifth logger was located between the wall and the row of luminaires furthest from the window.
- A transect of five illuminance loggers were installed perpendicular to window 7-L. All loggers were located equidistant from surrounding luminaires except the last logger. The approximate locations of these loggers are marked with dark-blue dots in Figure 57. Loggers will have the same position relative to surrounding lights and walls as those in transect described above. This transect is based off the window with the photocontrol for the two rows of lights closest to the window.
- A transect of five illuminance loggers were installed perpendicular to window 13-L. All loggers were located equidistant from surrounding luminaires except the last logger. The approximate locations of these loggers are marked with dark-blue dots in Figure 57. Loggers have the same position relative to surrounding lights and walls as those in transect described above.
- Three illuminance loggers were installed on top of furniture to serve as a proxy for work surface illumination. This placement reduces the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located below ceiling loggers for calibration purposes where possible. Otherwise the horizontal displacement was noted. The target locations are outlined in orange in Figure 58.
  - The first logger was located under the fourth logger of the 3-L ceiling transect on top of the magazine case.
  - The second logger was located on top of the computer workstation partitions under the fourth logger of the 7-L ceiling transect.
  - The third logger was located on top of the case under transect 13-L.
- An illuminance logger monitored sample lighting circuits. The loggers were installed inside a fixture with the light sensor pointed towards the lamp.

- Three loggers were installed in a lower, view window to capture outside illuminance values to the south. These loggers were installed in windows ***3-L***, ***7-L*** and ***13-L***. Illuminance to west was captured by a logger in third-floor office.
- Three loggers were installed on brackets facing towards the curtains to capture curtain operation schedules. Not all curtains were monitored and a generalized schedule for this space was estimated for those that were not monitored. Loggers were installed on windows ***3-L***, ***7-L*** and ***13-L***.

5.7.4.1 **SMALL OFFICES**

5.7.4.1.1 OFFICE 336 – SOUTH TREATED

Specific Loggers

- One logger was installed in window ***L-336*** to capture outside illuminance.

General Loggers

- One transects of four illuminance loggers each was attached to the ceiling. The first logger was located between the two rows of lights closest to the windows. The second logger between the next two rows of lights. The third logger between the two rows of lights closest to the door and the last logger was located between the last row of lights and the wall containing the door.
- Two illuminance loggers were installed on top of furniture to serve as a proxy for work surface illumination. One was placed in the back half of the room and the other near the center of the room on convenient work surfaces. The surface was chosen to minimize the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located below ceiling loggers for calibration purposes where possible. Otherwise the horizontal displacement was noted. The target locations are outlined in orange in Figure 58.
- An illuminance logger monitored the lighting circuit operation. The loggers were installed inside a fixture with the light sensor pointed towards a lamp.
- Two loggers were installed on brackets facing towards the curtains to capture curtain operation schedules. Loggers were installed on windows ***L-336*** and ***R-336***.

5.7.4.1.2 OFFICE 335 – SOUTH CONTROL

General Loggers

- One transects of four illuminance loggers each was attached to the ceiling. The first logger was located between the two rows of lights closest to the windows. The second logger between the next two rows of lights. The third logger between the two rows of lights closest to the door and the last logger was located between the last row of lights and the wall containing the door. Loggers were equidistant from surrounding fixtures

- Two illuminance loggers were installed on top of furniture to serve as a proxy for work surface illumination. One was placed in the back half of the room and the other near the center of the room on convenient work surfaces. The surface was chosen to minimize the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located below ceiling loggers for calibration purposes where possible. Otherwise the horizontal displacement was noted. The target locations are outlined in orange in Figure 58.
- An illuminance logger monitored the lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp.
- Two loggers were installed on brackets facing towards the curtains to capture curtain operation schedules. Loggers were installed on windows ***L-335*** and ***R-335***.

5.7.4.1.3 Office 330 – West Treated

Specific Loggers

- One logger was installed in window ***L-330*** to capture outside illuminance.

General Loggers

- One transects of four illuminance loggers each was attached to the ceiling. The first logger was located between the two rows of lights closest to the windows. The second logger between the next two rows of lights. The third logger between the two rows of lights closest to the door and the last logger was located between the last row of lights and the wall containing the door.
- Two illuminance loggers were installed on top of furniture to serve as a proxy for work surface illumination. One was placed in the back half of the room and the other near the center of the room on convenient work surfaces. The surface was chosen to minimize the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located below ceiling loggers for calibration purposes where possible. Otherwise the horizontal displacement was noted. The target locations are outlined in orange in Figure 58.
- An illuminance logger monitored the lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp.
- Two loggers were installed on brackets facing towards the curtains to capture curtain operation schedules. Loggers were installed on windows ***L-330*** and ***R-330***.

5.7.4.1.4 Office 329 – West Control

General Loggers

- One transects of four illuminance loggers each was attached to the ceiling. The first logger was located between the two rows of lights closest to the windows. The second logger between the next two rows of lights. The third logger between the two rows of lights closest to the door and the last logger was located between the last row of lights and the wall containing the door. Loggers were equidistant from surrounding fixtures

- Two illuminance loggers were installed on top of furniture to serve as a proxy for work surface illumination. One was placed in the back half of the room and the other near the center of the room on convenient work surfaces. The surface was chosen to minimize the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located below ceiling loggers for calibration purposes where possible. Otherwise the horizontal displacement was noted. The target locations are outlined in orange in Figure 58.
- An illuminance logger monitored the lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp.
- Two loggers were installed on brackets facing towards the curtains to capture curtain operation schedules. Loggers were installed on windows ***L-329*** and ***R-329***.

5.7.4.2 DATA COLLECTION ISSUES

One issue encountered was that curtains were not removed from the private offices. Part of the issue was that new blinds needed to be purchased. However, after mini-blinds were purchased and installed, the curtains still remained in place reducing the window aperture and daylight levels in the room. This made interpreting project results difficult.

A few data loggers in isolated locations were either moved by accident or fell from their mountings – however these were corrected within a reasonable amount of time.

5.7.5 BUILDING 20400, FORT BLISS, EL PASO, TX

Study rooms are identified in Figure 59. Logger locations in Wing A (Figure 60), Wing B (Figure 61), and Wing C (Figure 62) are indicated on the schematics below. A description of the logger locations is included in the subsections that follow.

Wing	Space ID	Purpose	Film	Monitoring	Survey Occupant Comfort
A	Open-Office	Control	No	Yes	Yes
B	Open-Office	Control	No	No	Yes
C	Open-Office	Treatment	Yes	Yes	Yes
A	Chaplains Office	Treatment	Yes	No	Yes
A	S6’s Office	Control	No	No	Yes
A	S4’s Office	Treatment	Yes	No	Yes

Wing	Space ID	Purpose	Film	Monitoring	Survey Occupant Comfort
A	S1's Office	Control	No	No	Yes
A	Commander's Office	Treatment	Yes	No	Yes
A	Executive Officer's Office	Control	No	No	Yes
C	Executive Officer's Office	Treatment	Yes	No	Yes
C	Commander's Office	Control	No	No	Yes
C	S1's Office	Treatment	Yes	No	Yes
C	S4's Office	Control	No	No	Yes
C	S6's Office	Treatment	Yes	No	Yes
C	Chaplain's Office	Control	No	No	Yes

Figure 59 . El Paso Study Spaces

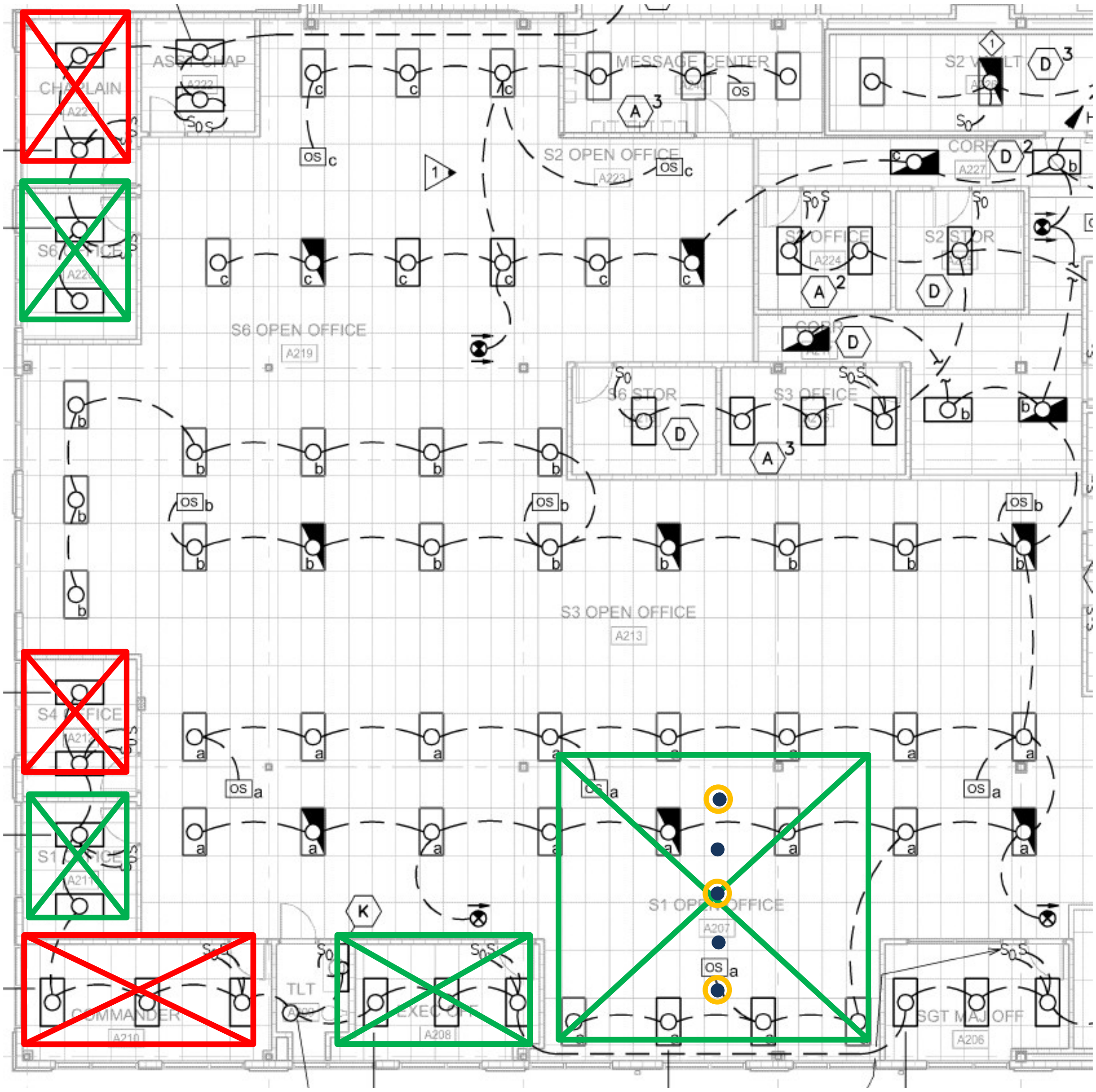

Figure 60. Wing "A", Study Area -- Treated areas (Red) and Control Areas (Green)

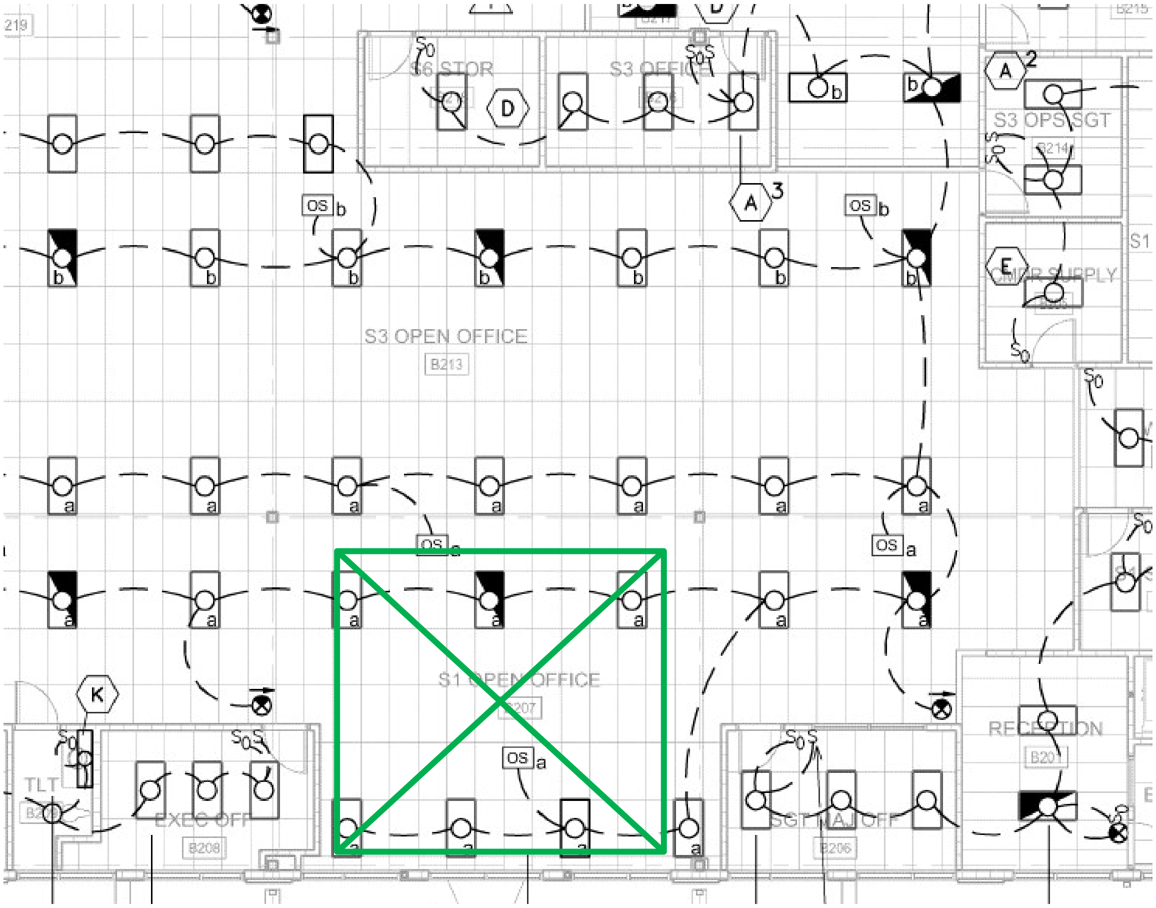

Figure 61. Wing "B", Study Area -- Control Area (Green)

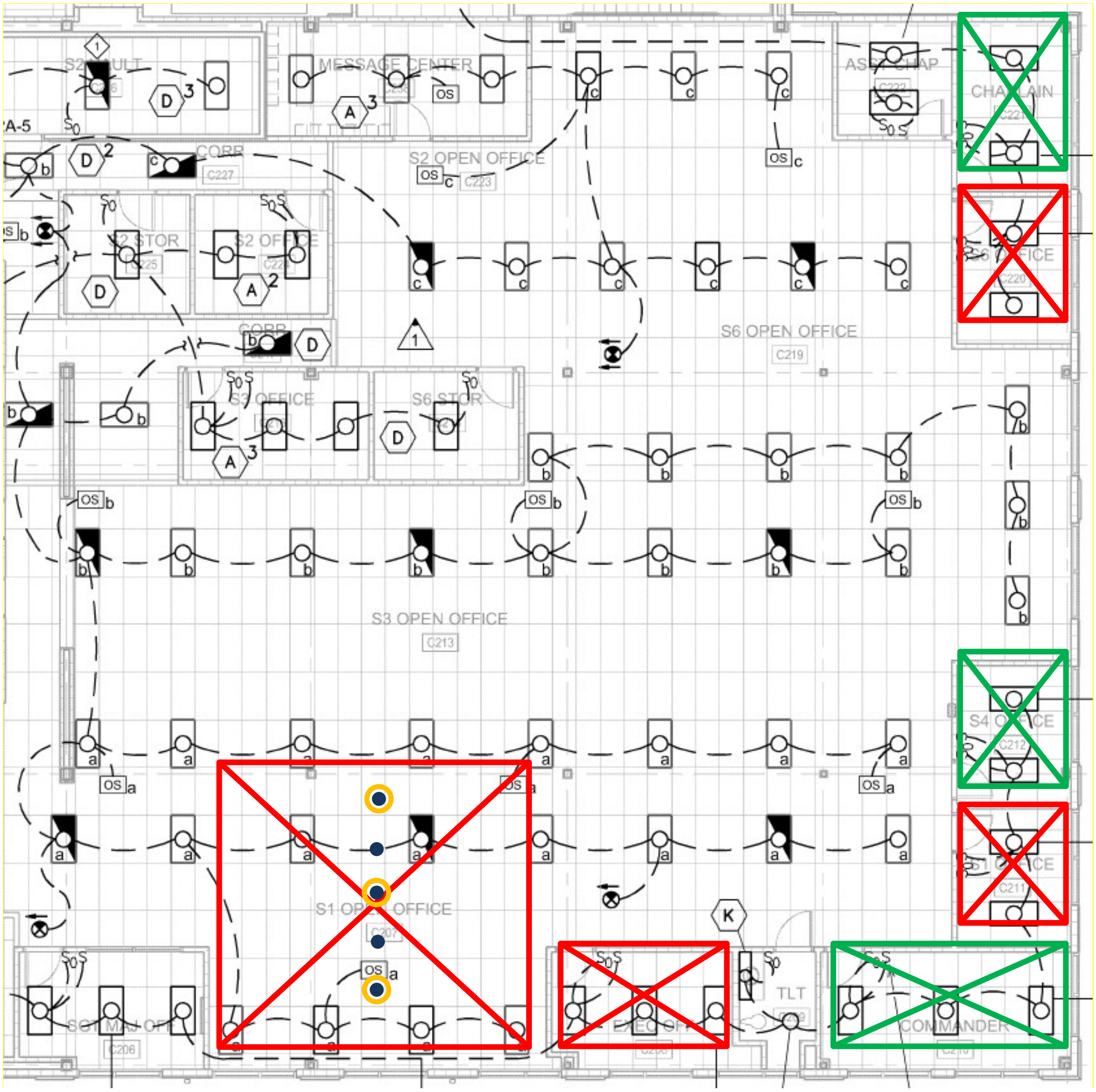

Figure 62. Wing "C", Study Area -- Treated areas (Red) and Control Areas (Green)

5.7.5.1 **Wing "A" Open-Office**

Logger locations are depicted in Figure 60. In the figure, ceiling loggers are marked with blue dots and work surface loggers are marked with orange rings.

- One transect of five illuminance loggers each was attached to the ceiling.
  - The first ceiling logger was placed on the centerline of the room equidistant from the two fixtures closest to the south-facing windows.
  - The last ceiling logger was placed on the centerline of the room equidistant from the two fixtures further away from the south-facing windows.

    - The middle three ceiling loggers were placed between the first and last ceiling loggers and equidistant from the first and last loggers and one another.
- Three illuminance loggers were installed on top of furniture to serve as a proxy for work surface illumination. This placement reduced the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located on top of filing cabinets, book cases, or other equipment. The target locations are outlined in orange in Figure 60.
- An on/off lighting logger monitored each lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp.
- An illuminance logger was installed in a lower, view window to capture outside illuminance values to the south.
- Two loggers were installed on brackets facing towards the roller shades to capture roller shades operation schedules. All roller shades were monitored and a generalized schedule for this space was estimated for those that were not monitored.

5.7.5.2 **WING "C" OPEN-OFFICE**

Logger locations are the same as in Wing "A" Open-Office. Logger locations are depicted in Figure 62. In the figure, ceiling loggers are marked with blue dots and work surface loggers are marked with orange rings.

- One transect of five illuminance loggers each was attached to the ceiling.
    - The first ceiling logger was placed on the centerline of the room equidistant from the two fixtures closest to the south-facing windows.
    - The last ceiling logger was placed on the centerline of the room equidistant from the two fixtures further away from the south-facing windows.
    - The middle three ceiling loggers were placed between the first and last ceiling loggers and equidistant from the first and last loggers and one another.
- Three illuminance loggers were installed on top of furniture to serve as a proxy for work surface illumination. This placement reduced the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located on top of filing cabinets, book cases, or other equipment. The target locations are outlined in orange in Figure 62.
- An on/off lighting logger monitored each lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp.
- An illuminance logger was installed in a lower, view window to capture outside illuminance values to the south.

- Two loggers were installed on brackets facing towards the roller shades to capture roller shades operation schedules.

5.7.6 BUILDING 1416, MCAGCC, TWENTYNINE PALMS, CA

A table of study spaces (Figure 63) and schematics with logger locations are provided for first floor (Figure 64) and second floor study rooms (Figure 65).

Treatment	Control
ER / Triage (1037)	ER / Triage (1137)
Exam 2 (1036)	Exam 2 (1136)
Exam 1 (1035)	Exam 1 (1135)
BAS General Office (1034)	BAS General Office (1134)
Medical Office (1032)	Psych. Office (1031)
Weapons Company Office (1026)	Charlie Company Office (1015)
H&S Company Office (2031)	Battery Company Office (2131)

Figure 63. Twentynine Palms Study Spaces

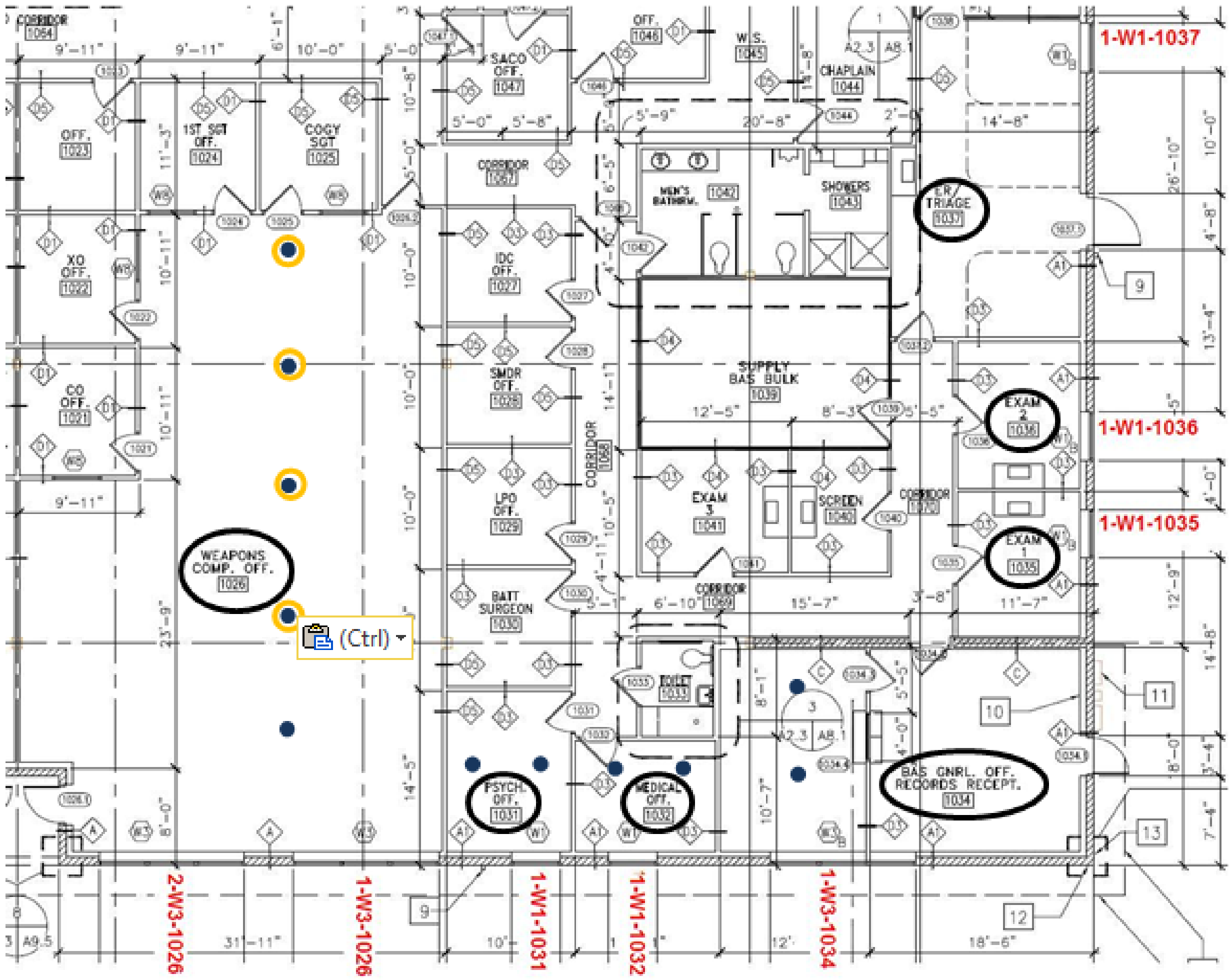

Figure 64. Twentynine Palms First Floor

Study spaces not shown in Figure 64:

- Charlie Company Office (1015) - Study space is located on the south-west façade and is mirror image of Weapons Company Office.
- BAS General Office (1134) - Study space is located south-east corner of the first floor, and is mirror image of BAS General Office (1034).
- Exam 1 (1135), Exam 2 (1136), and ER/Triage (1137) - These three study spaces are located on the same façade (south-east) and mirror images of Exam 1 (1035), Exam 2 (1136), and ER/Triage (1137) shown in above figure.

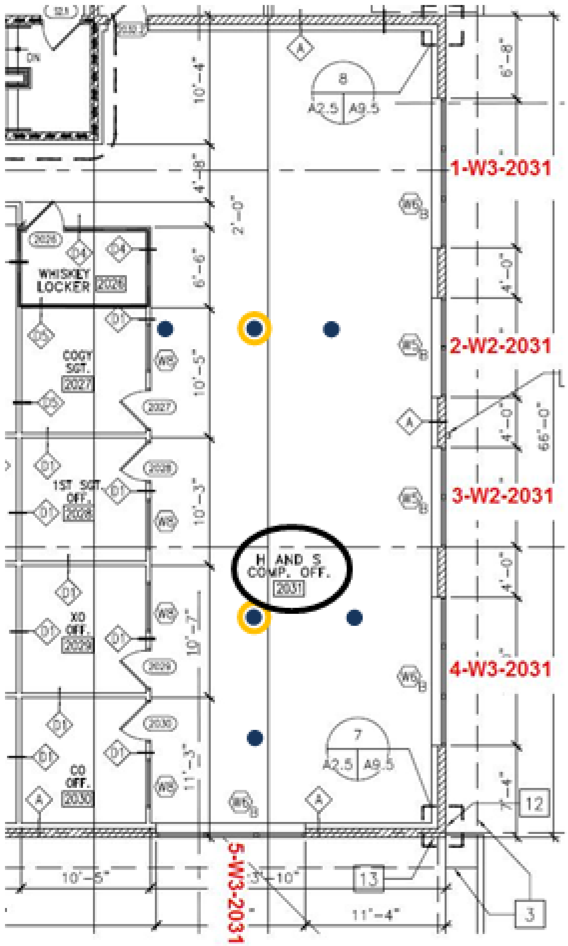

Figure 65. Twentynine Palms Second Floor

Battery Company office (2131) is not shown in Figure 65; this space is located on the north-east façade of the building and is similar in layout to H&S Company office (2031).

5.7.6.1 H&S Company Office (both halves of building 1416)

Logger locations are depicted in Figure 65. In the figure, ceiling loggers are marked with blue dots and work surface loggers are marked with orange rings.

- Six illuminance loggers were attached to the ceiling. A transect of three illuminance loggers was installed perpendicular to window 2-W2-2031. All loggers were located equidistant from surrounding luminaires. The approximate locations of these loggers are marked with dark-blue dots in Figure 85.
  - The first logger was located between the two rows of luminaires closest to the windows.
  - The second logger was located between the second and third rows of luminaires.
  - The third logger was located between the third row of luminaires and the wall.

  - A transect of two loggers started from the left-most pane of window 4-W3-2031. The approximate locations of these loggers are marked with dark-blue dots in Figure 65.
  - The first logger was located between two rows of luminaires closest to the windows.
  - The second logger was located between the second and third rows of luminaires.
  - The remaining logger is located between the second transect and window 5-W3-2031. The logger should fall on a line which is perpendicular to window 5-W3-2031 which passes through the end of the second transect. The approximate location of this logger is marked with a blue dot in Figure 65.
- Two illuminance loggers were installed on top of existing partitions to serve as a proxy for work surface illumination. This placement reduced the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located below ceiling loggers for calibration purposes where possible. The target locations are outlined in orange in Figure 65.
  - The first logger was located under the mid-point of the ceiling-logger transect perpendicular to window 2-W2-2031.
  - The second logger was located under the sensor closest to the XO Office.
- An illuminance logger monitored each lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp.
- One logger was installed in a lower, view window to capture outside illuminance values to the south-east. This logger was installed in window ***2-W2-2031***. Illuminance to the south-west was captured by a logger in the Weapons Company Office.
- Three loggers were installed on brackets facing towards the roller shades to capture roller shade operation schedules. Not all roller shades were monitored and a generalized schedule for this space was estimated from the shades which are monitored. Loggers were installed on windows ***2-W2-2031, 4-W3-2031*** and ***5-W3-2031***.

5.7.6.2 **RECORDS ROOM (BOTH HALVES OF BUILDING 1416)**

Logger locations are depicted in Figure 64. Ceiling loggers are marked with blue dots.

- Two illuminance loggers were installed on the ceiling, along the midline of the window, at third points in the room. The sensor locations are marked with blue dots in Figure 64.
- Outside illuminance was monitored in the nearby Weapons Company Office with the same orientation.

5.7.6.3 MEDICAL OFFICE

The medical office was treated with the film. The adjoining psychologist's office served as the control. Loggers were installed as follows:

- Logger locations are depicted in Figure 64. Ceiling loggers are marked with blue dots. Two illuminance loggers were installed on the ceiling, along the midline of the room, at third points in the room. The sensor locations are marked with blue dots in Figure 64.
- Outside illuminance was monitored in the nearby Weapons Company Office with the same orientation.

5.7.6.4 PSYCHOLOGIST OFFICE

In a deviation from the original plan, no film was installed in the psychologist's office. Instead, it served as a control for the adjoining medical office.

- Logger locations are marked in Figure 64. Ceiling loggers are marked with blue dots. Two illuminance loggers were installed on the ceiling on a virtual line from the loggers in the adjoining medical office.
- Outside illuminance was monitored in the nearby Weapons Company Office with the same orientation

5.7.6.5 WEAPONS COMPANY OFFICE

Logger locations are depicted in Figure 64. Ceiling loggers are marked with blue dots. Work surface loggers are marked with orange rings.

- A transect of five illuminance loggers was attached to the ceiling. The transect started between the two rows of luminaires closest to the windows and formed a line perpendicular to the right hand edge of windows ***1-W3-1026***. Subsequent loggers were positioned between rows of luminaires. All loggers were located equidistant from surrounding luminaires. Logger locations are marked with blue circles in Figure 64.
- Three loggers were installed on partition tops to serve as a proxy for work surface illumination. This placement reduced the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located below ceiling loggers for calibration purposes where possible. Otherwise the horizontal displacement was noted. One logger was located beneath the three ceiling-transect loggers furthest from the windows. The target locations are outlined in orange in Figure 64.
- An illuminance logger monitored each lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp. Installers will manipulate lighting circuits to ensure each logger monitors a different circuit.
- One logger was installed in a lower, view window to capture outside illuminance values to the south-west. This logger was installed in window 1-W3-1026.

- Two loggers were installed on brackets facing towards the roller shades to capture roller shade operation schedules. Loggers were installed on windows 1-W3-1026 and 2-W3-1026.

5.7.6.6 Charlie Company Office

The Charlie Company office was monitored to serve as a control for the adjoining Weapons Company office. Logger locations are the same as those in the Weapons Company office.

5.7.6.7 Data Collection Issues

On several site visits one of the battalions was out in the field training with only a skeleton crew remaining present in their section of the building. This made it difficult to obtain enough survey responses to fully evaluate occupant comfort. Public Works (PW) staff attempted to administer the surveys on our behalf but also obtained a poor response rate.

Marine Corps officers and the public works department staff were supportive of the project. When a new battalion arrived, many hours of site visit time were spent introducing the new officers to the project and receiving their permission to proceed with the plan.

5.7.7 Naval Hospital Bremerton, Bremerton, WA

Study rooms are identified in Figure 66. Second floor (Figure 67) and third floor logger locations (Figure 68) are indicated in the schematics below. A description of the logger locations is included in the subsections that follow.

Space ID	Purpose	Film	Monitoring	Survey Occupant Comfort
3370	Treatment	Yes	Yes	Yes
3372	Control	No	Yes	Yes
2187	Treatment	Yes	No	Yes
2189	Control	No	No	Yes
2191	Treatment	Yes	No	Yes
2193	Control	No	No	Yes

Figure 66. Bremerton Study Spaces

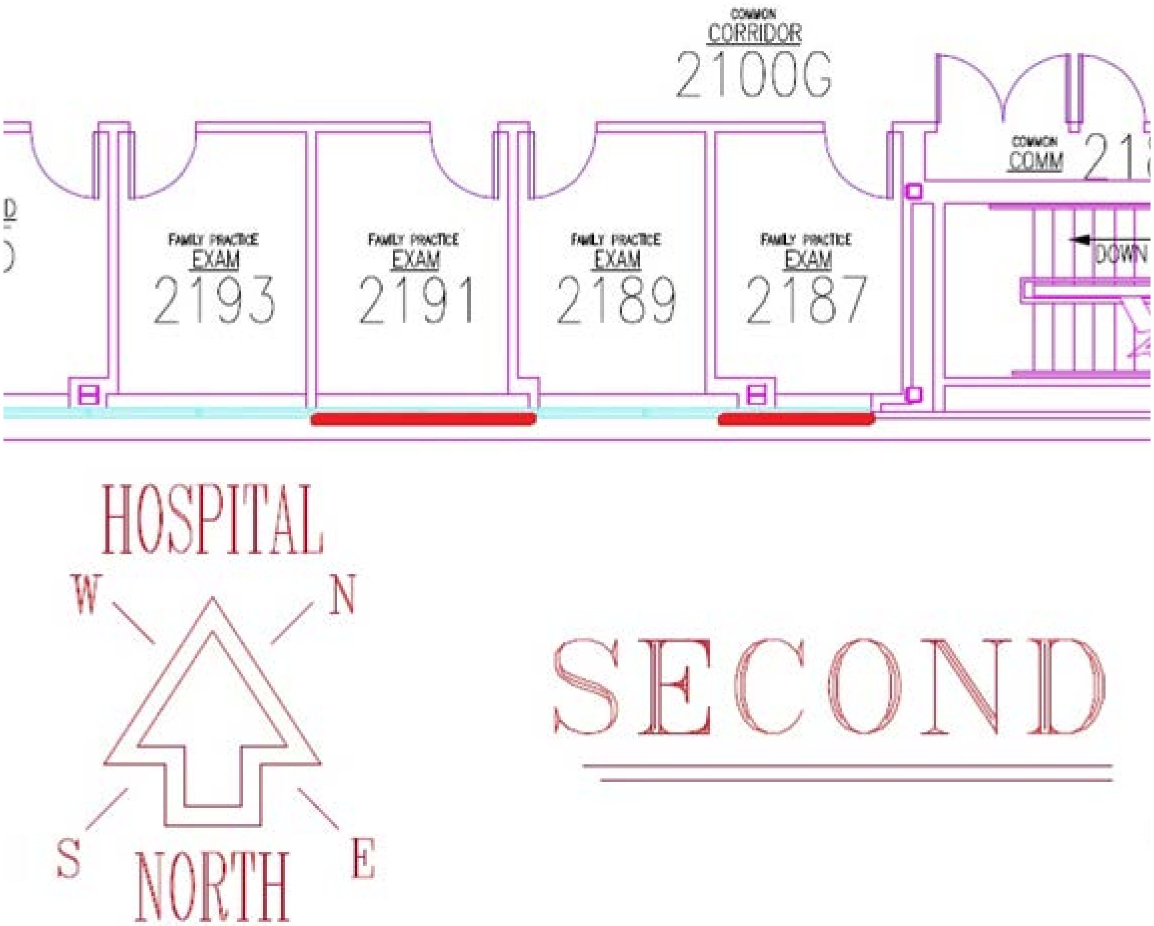

Figure 67. Second Floor study rooms -- red lines indicate treated space

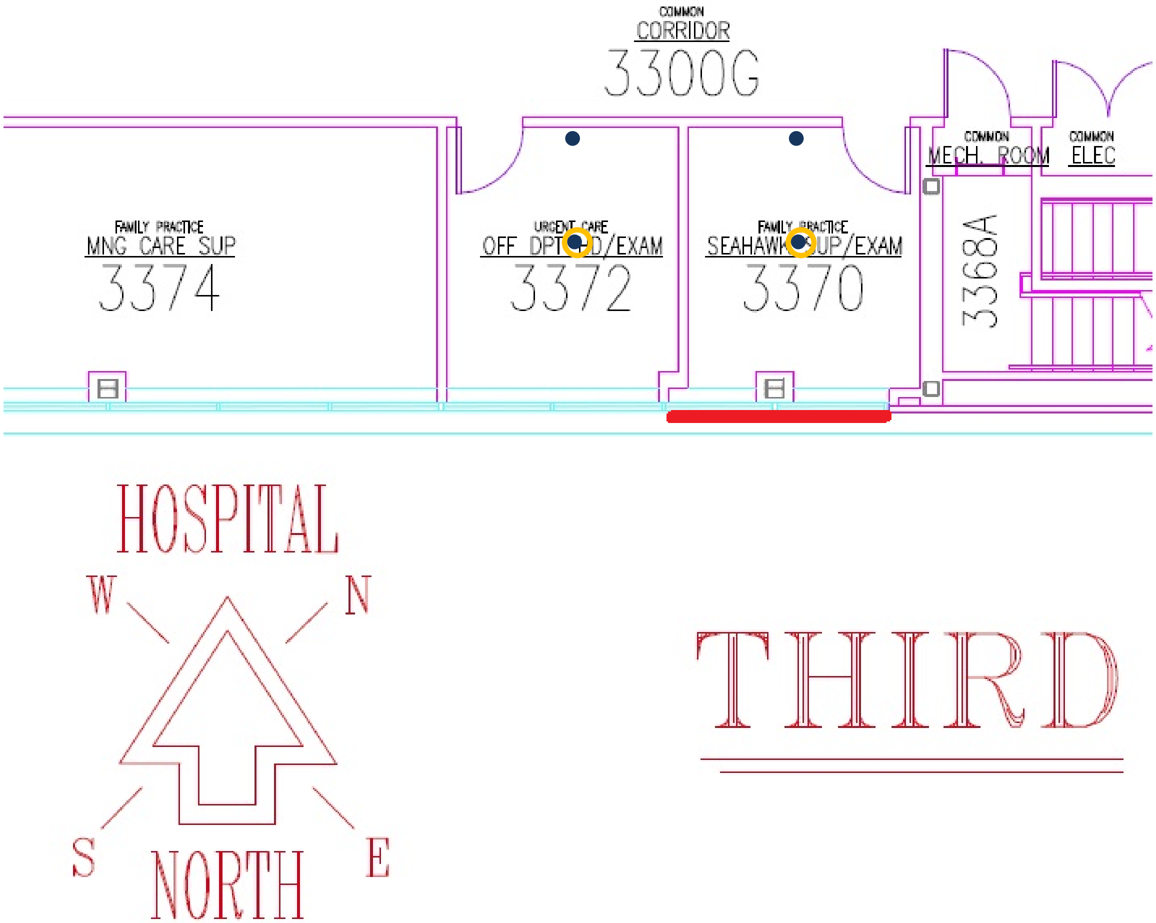

Figure 68. Third Floor study rooms

5.7.7.1 Office 3370

Logger locations are depicted in Figure 68. In the figure, ceiling loggers are marked with blue dots and work surface loggers are marked with orange rings.

- One transects of two illuminance loggers each was attached to the ceiling.
  - The first ceiling logger was placed on the centerline of the room equidistant from the two fixtures.
  - The second ceiling logger was placed between the last fixture and the wall.
- One illuminance loggers was installed on top of furniture to serve as a proxy for work surface illumination. This placement reduced the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located on top of filing cabinets, book cases, or other equipment. The target locations are outlined in orange in Figure 68.

- An on/off lighting logger monitored each lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp.
- An illuminance logger was installed in a lower, view window to capture outside illuminance values to the south-east.
- Two loggers were installed on brackets facing towards the roller shades to capture roller shades operation schedules. All roller shades were monitored and a generalized schedule for this space was estimated for those that were not monitored.

5.7.7.2 **OFFICE 3372**

Logger locations are the same as in office 3370 except that outside illuminance will not be monitored in room 3372. Logger locations are depicted in Figure 68. In the figure, ceiling loggers are marked with blue dots and work surface loggers are marked with orange rings.

- One transects of two illuminance loggers each was attached to the ceiling.
  - The first ceiling logger was placed on the centerline of the room equidistant from the two fixtures.
  - The second ceiling logger was placed between the last fixture and the wall.
- One illuminance logger was installed on top of furniture to serve as a proxy for work surface illumination. This placement reduced the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located on top of filing cabinets, book cases, or other equipment. The target locations are outlined in orange in Figure 68.
- An on/off lighting logger monitored each lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp.
- Two loggers were installed on brackets facing towards the roller shades to capture roller shades operation schedules. All roller shades were monitored and a generalized schedule for this space was estimated for those that were not monitored.

5.7.7.3 **DATA COLLECTION ISSUES**

Survey responses were difficult to interpret because staff members worked in multiple offices on a daily basis.

5.7.8 HALLIGAN HALL, NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA

Study rooms are identified in Figure 69. Study area (Figure 70) and logger locations (Figure 71) for the second floor are indicated in the schematics below. A description of the logger locations is included in the subsections that follow.

Space ID	Purpose	Film	Monitoring	Survey Occupant Comfort
222	Treatment	X		X
224	Control			X
226	Control			X
228	Treatment	X		X
230	Treatment	X		X
232	Control		X	X
234	Treatment	X	X	X
236	Control			X

Figure 69. Monterey Study Spaces

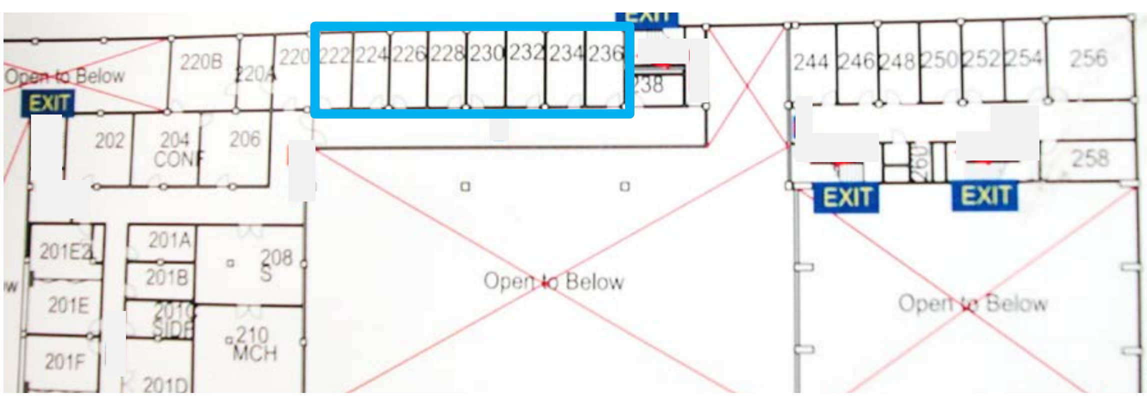

Figure 70. Halligan Hall Second Floor Study Area – Study Area (Blue Box)

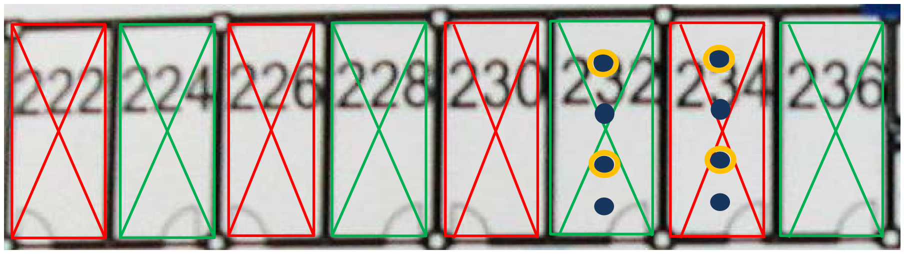

Figure 71. Monterey Study Area - Ceiling and Work Station Loggers

5.7.8.1 **ROOM 232**

Logger locations are depicted in Figure 71. In the figure, ceiling loggers are marked with blue dots and work surface loggers are marked with orange rings.

- One transect of four illuminance loggers each was attached to the ceiling.
  - The first ceiling logger was placed on the centerline of the room and 2.5' feet away from the southwest-facing wall (with the window).
  - The subsequent loggers were place also on the centerline of the room and 7.5', 12.5', and 17.5' feet away from the southwest-facing wall respectively.
- Two illuminance loggers were installed on top of furniture to serve as a proxy for work surface illumination. This placement reduced the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located on top of filing cabinets, book cases, or other equipment. The target locations are outlined in orange in Figure 71.
- An on/off lighting logger monitored each lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp.
- An illuminance logger was installed in a lower, view window to capture outside illuminance values to the south-west.
- Two loggers were installed on brackets facing towards the roller shades to capture roller shades operation schedules. All roller shades were monitored and a generalized schedule for this space was estimated for those that were not monitored.

5.7.8.2 **ROOM 234**

Logger locations are exactly the same as in Room 232. Logger locations are shown in Figure 71 as well. Note that even though the monitoring configurations in Room 232 and Room 234 are the same, only the top window in Room 234 was treated with the daylighting redirecting film.

- One transect of four illuminance loggers each was attached to the ceiling.
  - The first ceiling logger was placed on the centerline of the room and 2.5' feet away from the southwest-facing wall (with the window).

- The subsequent loggers were place also on the centerline of the room and 7.5’, 12.5’, and 17.5’ feet away from the southwest-facing wall respectively.

- Two illuminance loggers were installed on top of furniture to serve as a proxy for work surface illumination. This placement reduced the chance that the sensors were accidentally covered by papers and other work materials. Work-surface proxy loggers were located on top of filing cabinets, book cases, or other equipment. The target locations are outlined in orange in Figure 71.
- An on/off lighting logger will monitor each lighting circuit. The loggers were installed inside a fixture with the light sensor pointed towards a lamp. Installers will turn each circuit on and off to ensure each logger monitors a different circuit and that all circuits are monitored.
- An illuminance logger was installed in a lower, view window to capture outside illuminance values to the south.
- Two loggers were installed on brackets facing towards the roller shades to capture roller shades operation schedules. All roller shades were monitored and a generalized schedule for this space was estimated for those that were not monitored.

5.7.8.3 DATA COLLECTION ISSUES

The site energy manager was very supportive of the project. The energy manager handled all internal scheduling with other affected departments and obtained all the necessary internal approvals. There were some difficulties scheduling removal of exterior sun-screens on the study rooms.

The screens were scheduled to be removed immediately after film installation in the treatment rooms. However, when the screens were removed two of the four study rooms, the occupants developed thermal comfort issues. The 3M Company addressed thermal issues to the occupants’ satisfaction by treating the windows with Prestige 40, a solar-heat-gain control film. Despite successfully resolving the thermal comfort issues the site energy manager was unable to convince public works staff to remove the screens from the remaining two treatment rooms. Unfortunately, the illuminance monitoring equipment was installed in rooms which retained the sun-control screens, rendering the monitoring data unusable for the study.

6. PERFORMANCE RESULTS

This section describes the results of the performance objectives (PO) tested and discuss their significance in contributing to DoD energy and water savings goals. The performance assessment methodologies are described in Section 5 and in Appendix A. Following is a quick summary of the performance results:

- Energy and Water Security: Well daylit spaces can continue to be fully functional even if the power goes off during daytime hours. Well daylit spaces can also enable emergency reduction in electric power consumption by turning off most overhead lights, if there is a demand or power supply emergency in the building, thus saving power for other essential functions. Daylight spaces provide important visual orientation clues, so that occupants do not get disoriented in an emergency.
- Cost Avoidance: This item will be provided by 3M.
- Greenhouse Gas Reduction: Addition of the DRF to existing office spaces along with enabling daylighting controls results in a net reduction in greenhouse gas emissions from building energy use. There are direct electric energy use reductions due to less use of lighting energy and secondarily due to lower cooling loads. As with many strategies that reduce cooling loads in the space, there is a slight increase in heating load in the space and thus higher natural gas consumption. Since the DRR reduces electric lighting energy use, there is a resultant decrease in the heat that the electric lighting adds to the space which in turn results in slightly higher heating loads in the space. But the balance of the electric energy savings and gas use increase is overwhelmingly positive in the direction of overall energy savings and CO2 emissions reductions.

6.1 SUMMARY OF PERFORMANCE OBJECTIVES AND OUTCOMES

This section provides a summary of all performance objectives (POs) evaluated as part of the technology demonstration.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Key Quantitative Performance Objectives				
Increase daylight illuminance levels	spatial Daylight Autonomy (sDA) See discussion in section 5.1.6.1.1	Grid of horizontal illuminance measurements, measured and/or simulated under controlled sky conditions	At least a 10% increase in spatial Daylight Autonomy	**Fully met.** sDA in the treated spaces increased between 3%-24%, averaging 11% per simulation results. Further details in Section 6.3.2
Economic Payback	Life-Cycle Cost	Cost of energy impacts, cost of labor and materials for installation, cost of maintenance and replacement (provided by others)	Savings to Investment Ratio greater than 1.0; Net-present-value; Payback period < 10 years.	**Frequently met.** Simple payback averages 10 years but dependent on electricity rates and climate (range of 3-35 years).
Potential to reduce lighting energy use	Full-load equivalent hours (FLE) electric lights can be turned off (dimensionless) Peak lighting load intensity (kW/sf)	Lighting circuit current, task lighting power consumption; hourly operation schedules	At least 200 annual FLE and 25% reduction in daytime peak electric lighting need for the zone 15' to 25' from the windows;	**Partially met.** 184-270 FLE depending on blinds operation. Average peak demand reduction of 13%.
Other Desirable Quantitative Performance Objectives				
Reduce whole building energy use	Net kWh impacts on lighting and HVAC	Information on building envelope, HVAC equipment, and operation sufficient for simulation modeling	Net reduction in annual whole building energy use at least 1.05 times the direct lighting energy savings.	**Frequently Met.** Average annual whole building savings 1.30 times direct lighting savings. Range of 0.93-1.62 depending on climate.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Green-house Gas Emissions	Conversion of energy usage into green-house gas equivalents based on national averages	Green-house-gas-equivalent conversion factor for national level usage. Embedded costs of GHG in film production	Net reduction in greenhouse gas emissions over 10 years are at least twice the greenhouse gas cost of manufacturing.	**This item will be provided by 3M**. CO2 emissions reductions due to the whole building energy savings are 0.59-3.26 lb/sf/yr.
Key Qualitative Performance Objectives				
Maintain or increase visual comfort	Likert scale and open response questions about glare and visual comfort	Survey of occupants before and after installation of the daylight redirecting window film	Maintenance of or increase in occupant visual comfort	**Frequently met.** Occupant comfort was preserved or increased in all but one installation where the product was not installed high enough above eye level.
Other Desirable Qualitative Performance Objectives				
Improve preservation of views out from the building	Likert scale and open response questions about quality of view Operation and openness of window blinds (percent open)	Survey of occupants before and after installation of the daylight redirecting window film Blinds operation observations	Increase perception of quality of available view Increase amount of time blinds can be left open to preserve views.	**Partially met.** Increase in occupant ranking of view quality. No discernible change in blinds operation
Reduce glare	Current quantitate glare indices are inadequate to task of rating new innovative products.	Glare assessment based on occupant surveys and informal interviews.	Maintenance or reduction in subjective glare ratings	**Frequently met.** Glare was unchanged or reduced in all but one space where DRF installed too close to eye level.
Maintainability of System	Change in maintenance practices	Interviews with site maintenance staff	Film does not create significant film-maintenance needs	**Fully met.** Staff did not report any maintenance concerns with DRF installation.

Figure 72. Performance Objective Outcomes

Detailed performance results by site and by study methodology are presented in the following sections of the report.

6.2 PERFORMANCE RESULTS BY SITE

6.2.1 NAVAL BASE, NORFOLK, VA

6.2.1.1 BACKGROUND

The south facing open office space on the fourth floor of Building Z-133 of the Naval Air Base in Norfolk Virginia proved to be the best study site of the project, providing the most robust dataset and easily interpreted findings, for a number of reasons. First of all, the geometry of the space studied is very similar to many common office spaces with simple, strip windows, and cubical layouts. Secondly, the treatment and control study areas had nearly identical geometries, and were large enough for sufficient data collection. Also importantly, the study space was continuously occupied by the same people throughout the study period, and the data monitoring equipment remained in place for the full study period, with only a few inadvertent data losses.

However, there were some peculiarities of the Norfolk site that should be noted in evaluating the findings from the site. First of all, the office occupants were not typical administrative or professional workers, but rather were mostly IT specialists, who spent a majority of their time programming computers. In general, previous work has suggested that IT workers are the least interested in daylight and views, as the majority of their focus is on the computer screen and they often prefer very low ambient illumination levels. This observation is reinforced by a comment from one of the survey responses: "Go back to the blinds! We are computer users. Wrong place to experiment with using natural light."

Secondly, due to existing window geometry, with a center dividing mullion, the film was mounted above the center mullion, starting at 6' above the floor (Figure 73). This mounting height is lower than recommended, as it is more likely to bring redirected sunlight within eye level to the back or sides of the space, creating more potential for glare problems.

Figure 73. DRF installed on top three panes, Blinds retracted to top of treated window

Thirdly, the existing blinds were not relocated at this site, but rather simply retracted (Figure 73). This created about a 6" opaque band at the top of the treated window, effectively reducing the treated area by 17%. The occupants were instructed to keep the blinds fully retracted for the duration of the study, but the study team cannot completely confirm that this request was always followed. The occupants in the control area, on the other hand, were allowed to operate the blinds at will, and based on observations and photos, generally left them 50% to 75% closed. From the occupant survey, there was clear dissatisfaction about blinds control in the treated area: "I would make it possible to lower and raise the blinds as needed."

Finally, the lack of blinds on the lower windows in the treatment area raised a concern about glare from the lower windows, which ultimately led to the installation of a low VT tinted film on the lower portion of ALL windows (18 bays) in the study space. Before installing the film on the six western window bays, 3M first installed the film in two test windows at the far eastern end of the study area. At that time the facility manager was a strong proponent of tinted glazing to reduce heat loads[1], and strongly argued that tinted glazing would be needed to improve thermal and visual comfort in the space. The facility manager also refused to relocate the blinds for the duration of the study. After the two month test period, 3M agreed to make two changes to the final test installation: increasing the diffusion layer for the DRF from 50% to 100%, and adding tinted film to all the lower windows. The initial film installation in the eastern two bays were removed, and replaced with the six bays to the west. Low VT tinted film was added throughout the space.

It is not known how the addition of low VT tinted film on the lower windows affected visual comfort or occupant operation of the blinds in the control area. It is easy to know that the low VT film greatly reduced the available daylight throughout the space, proportional to the area (50% of all window area) and the reduced VT (40%).

6.2.1.2 OCCUPANT AND MAINTENANCE FINDINGS

At Norfolk, 43 surveys were received from treated areas and 17 from control areas, and were sufficiently distributed in time and space to allow limited statistical comparison.

As discussed earlier, the facility manager at Norfolk was particularly concerned about mounting anything to the frame of the existing windows. As a result, the blinds were not relocated, and the film was installed using a magnetic frame attachment (Figure 74). This type of concern for not wanting any un-reversible changes to a space is a likely barrier to retrofitting spaces with the DRF, and should be addressed in future product attachment options.

[1] note quote from occupant survey: "blinds are hard to operate. I usually close them to reduce heat, not brightness."

Figure 74. Magnetic frame attachment for DRF application

A number of occupants preferred the operable blinds over the fixed film for a variety of reasons. In the treated area, a few occupants complained about lack of control of the blinds: "I would make it possible to lower and raise the blinds as needed." The survey results confirmed a significant difference, with respondents in the treated area less happy with the blinds operation, by 1.5 points on a 9 point scale (p=0.05).

The view from window was rated neutral in the treated area (5) but positive in the control area (6), with a significant difference (p=0.05). There are two likely explanations. First in the control area, occupants could raise blinds fully at times when direct sun was not a problem, plus the perforated blinds supported a limited view even when closed. Secondly, the new DRF in the upper windows obscured the previous view of the sky and landing airplanes, which the occupants found particularly entertaining: "Opaque window panels have blocked my view of the sky, but it is only a minor inconvenience." Another occupant noted: "Film on the window makes it look grey outside all the time;" but it is not clear if this occupant was referring to the DRF or the low VT tinted film.

The survey results suggested some modest problems with glare and excessive daylight in the treated areas. Occupants in the treated area were more likely to report that 'the daylight is never too bright' (4.3) during equinox (p=0.03), but not in the summer. The occupants in the treated area were neutral on glare problems during equinox (5), but positive in the control areas (6.5) (p=0.03). The written complaints noted glare on their monitors: "Occasionally there is a glare on my computer. I have to move my monitor to avoid;" and also noted too much light in general.

Only one occupant clearly addressed the new low-VT film in their comments: "I think a tinted film on all the windows would help better with glare." Thus, it is unclear if the addition of the tinted film to the lower windows impacted the occupants' visual comfort.

6.2.1.3 MONITORED FINDINGS

Monitoring at the Naval Base in Norfolk, VA took place for a period of six months from January 2012 through June 2012 in both the treated and control spaces. This monitoring period captured winter, spring equinox, and summer sun angles. Of the monitored data, the workplane loggers placed in a transect on the partitions at 8.5', 22', and 35' from the windows, in both the treatment and control area, proved to be most useful in understanding the impact of daylighting in the study spaces. From this analysis, DRF shows the greatest impact during winter months with low sun angles and during clear sky conditions. Under these conditions the DRF was effective in redirecting daylight in the space for approximately eight hours between 7:30 AM and 3:30 PM. While the DRF had the greatest daylighting impact during winter months with low sun angles, there was also a noticeable impact during the spring equinox; whereas, the impact is negligible during months with high sun angles (i.e. summer).

Figure 75 shows the difference in raw illuminance values (includes electric lighting contribution) between the treated and control spaces. These findings also support the conclusion that the DRF has the greatest impact during winter months with low sun angles. The illuminance levels below are reported by distance from the window; the DRF has the greatest impact nearest the windows (8.5'), while still seeing increased daylighting levels 22' and 35' deep into the space. Note in Figure 75 the vertical axis of the three graphs remains constant. In the subsequent series, the vertical axis varies to provide greater detail at low light levels at the back of the room.

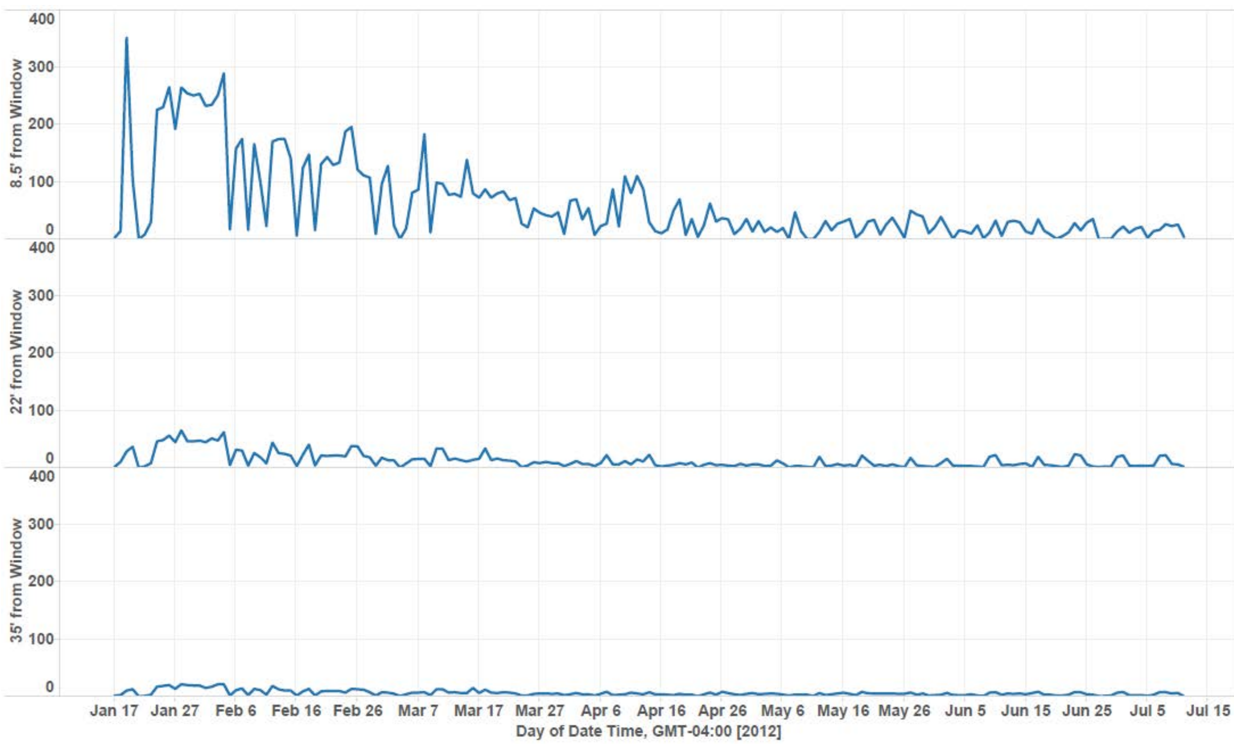

Figure 75. Increased Illuminance from DRF

The three graphs below represent the difference in daylighting between the control and treatment spaces plotted by the solar azimuth during three seasons. The general trend is one of greater daylighting contribution from the DRF during winter months when the sun angles are lower, and reduced contribution with higher sun angles increase during the summer months. Note that the vertical axes of the three sets of graphs vary by location in the room.

During winter months, peak daylighting levels are most significant closest to the windows around solar noon as seen in Figure 76. However, even 35' deep into the space, up to a 20 fc increase in daylighting levels was observed in the treated space. This indicates the DRF is performing as predicted to increase the daylighting availability in the space, especially during months with low sun angles.

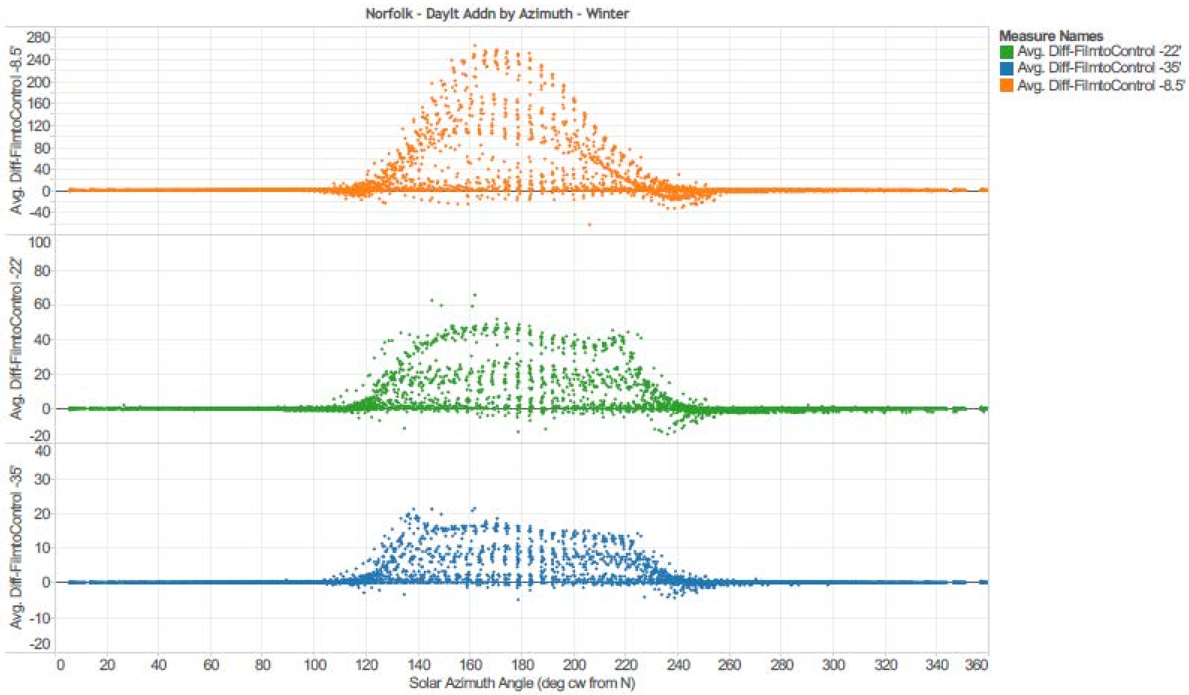

Figure 76. Added Daylight by Azimuth - Winter

As the seasons change and approach spring equinox, daylighting contributions from the DRF are significantly less than seen during winter. The impact of the DRF once again was most noticeable closest to the window (8.5'), which saw a contribution of up to 100 fc in the treated space. Daylighting contributions of up to an additional 20 fc and 10 fc can be seen at 22' and 35' deep in to the space, respectively.

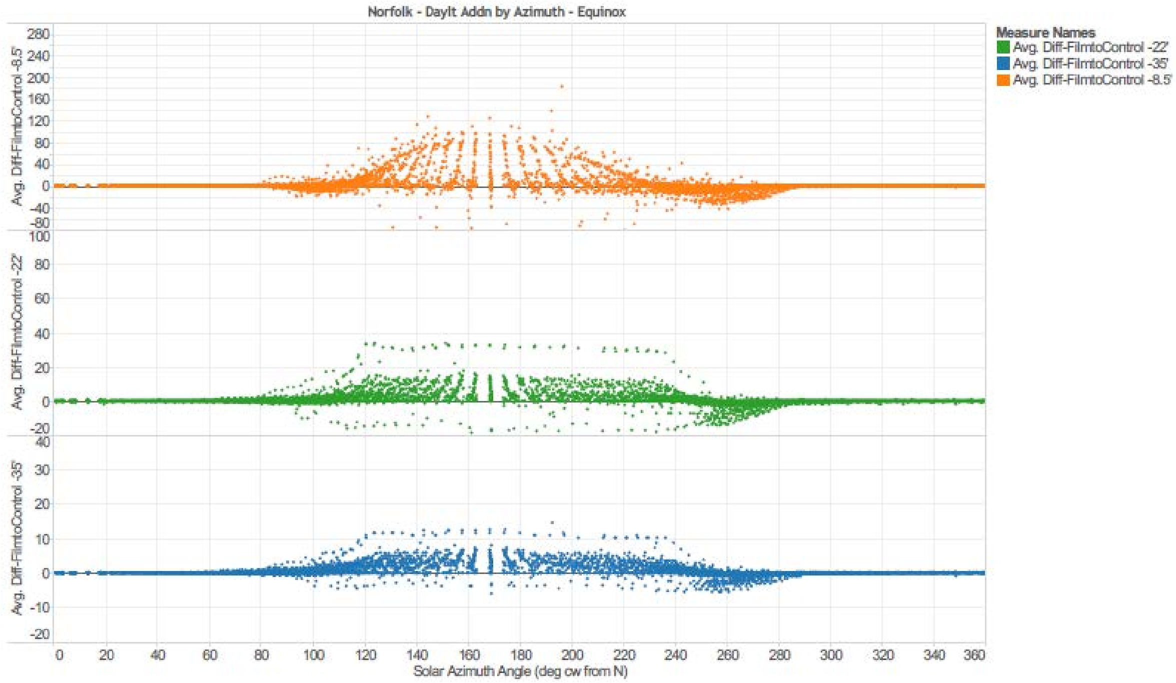

Figure 77. Added Daylight by Azimuth - Equinox

The DRF has negligible effect on daylight availability in the space during summer months. As seen in Figure 78, the daylight contribution from DRF varies with both positive and negative values during the summer, resulting in little, if any, average change..

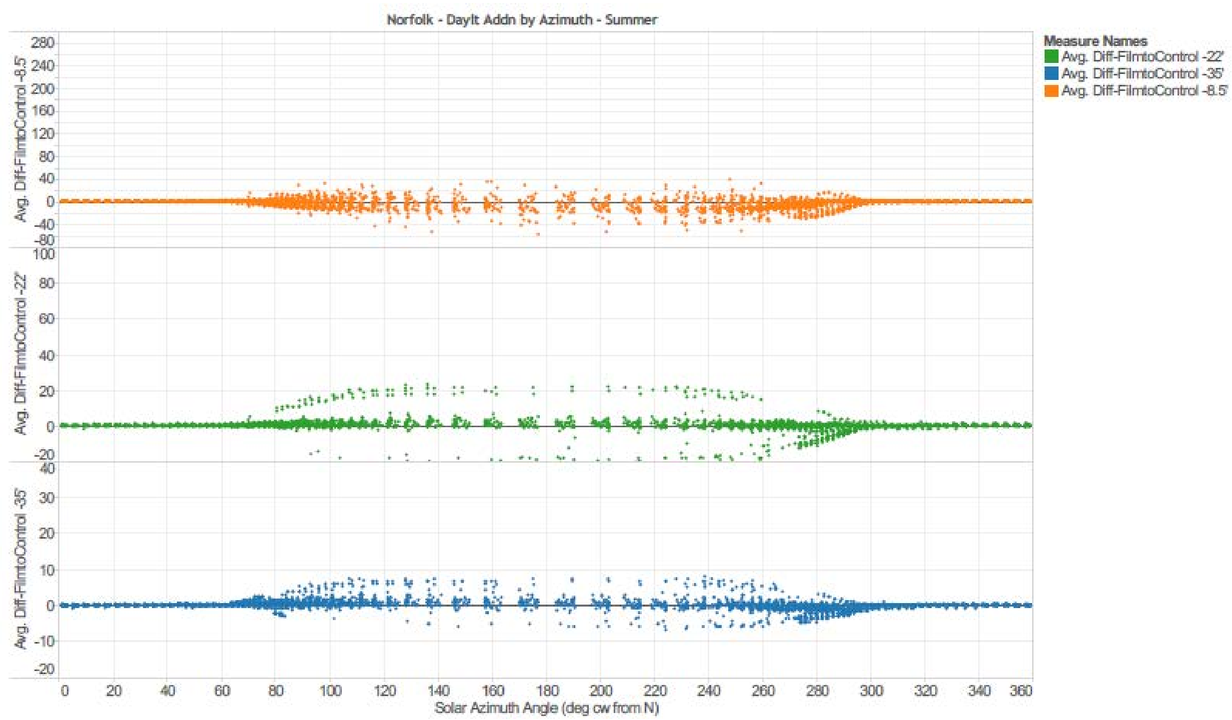

Figure 78. Added Daylight by Azimuth - Summer

The second conclusion from the monitored findings at Norfolk, VA is that increased daylighting contribution in the space due to DRF peaks at about 30-35 degrees of solar elevation, as seen in Figure 79.

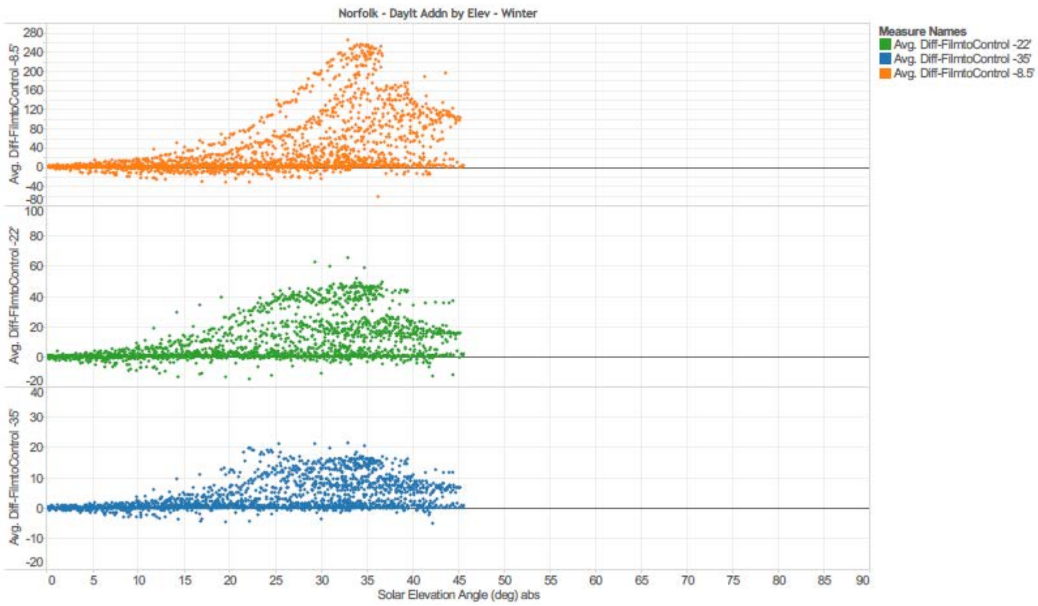

Figure 79. Added Daylight by Elevation - Winter

The daylighting contribution is much higher closer to the window, although still about 20 foot candles higher at the back of room (35’). This profile continues through the spring equinox, where the DRF adds useful daylight throughout the room but at much lower values. The daylight contribution is again highest closest to the window, but now peaks at about 45 degrees of solar elevation.

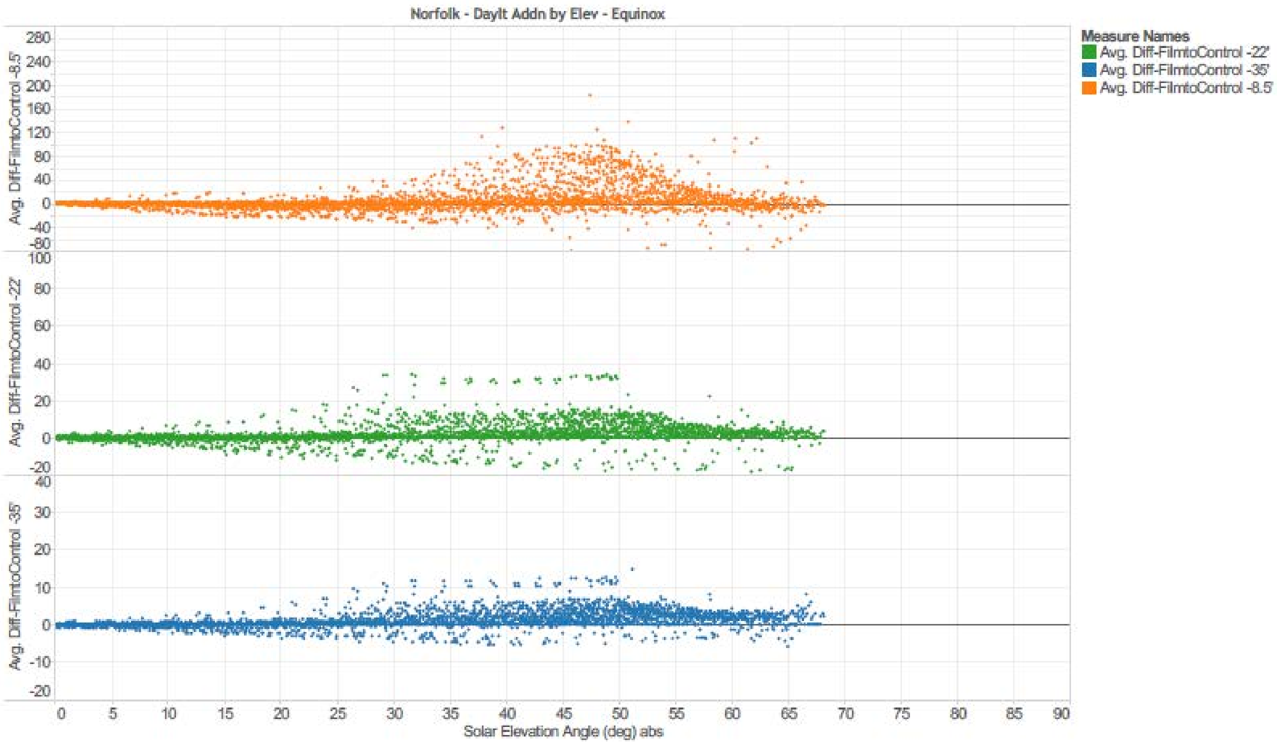

Figure 80. Added Daylight by Elevation - Spring equinox

During the summer months with high sun angles, the DRF does not provide any additional daylighting to the treated space, as seen in Figure 81.

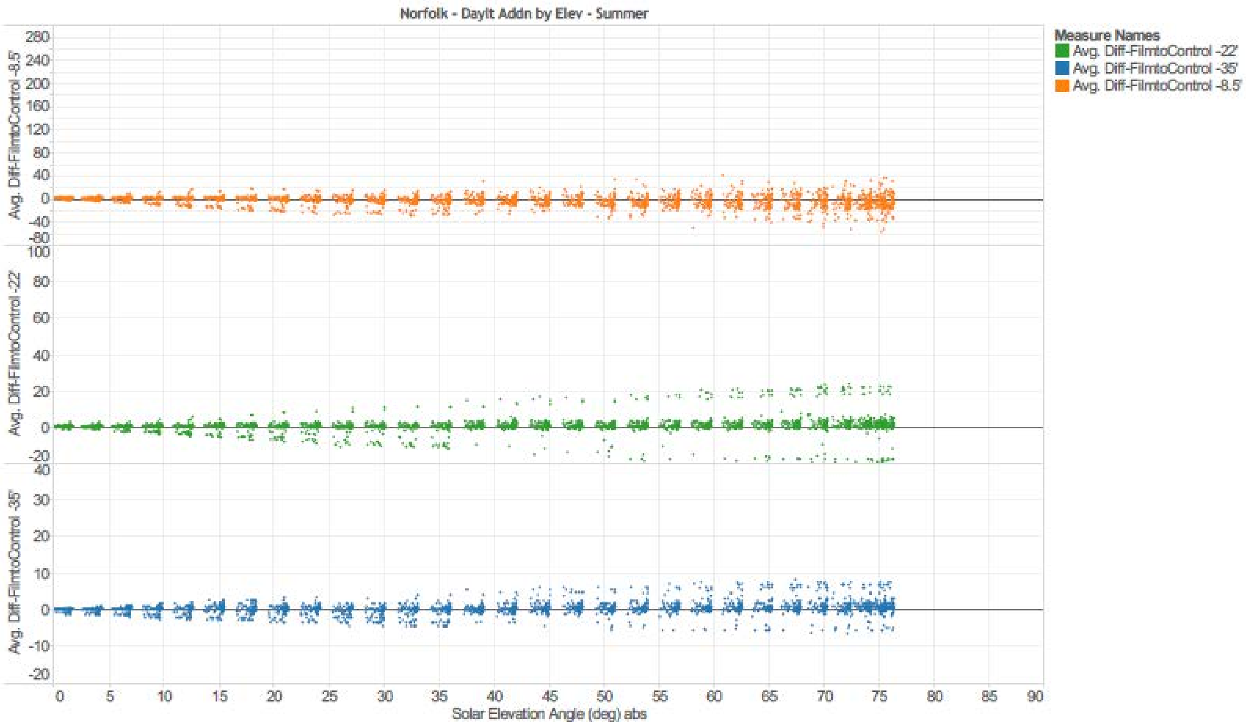

Figure 81. Added Daylight by Elevation - Summer

Monitored findings also indicate the DRF only increased daylighting in the treated space on mostly clear days, regardless of season, and saw no impact on cloudy days. The figures below indicate the impact on daylighting from the DFR with clear and cloudy sky conditions for a typical day during the winter, spring equinox, and summer.

Figure 82 and Figure 83 represent the impact of the DRF during low sun angles (i.e. winter) during clear and cloudy sky conditions, respectively. During clear sky conditions, nearest the windows, the DRF increased daylighting levels in the treated spaces (red lines) by up to 100 fc during 11 AM - 12 PM compared to the control spaces (blue lines). Deeper in the space an increase in daylighting levels of up to 10 fc was also observed during the same hours. During cloudy sky conditions however, the DRF (red lines) did not have any effect on increasing daylighting levels and follows the daylighting pattern seen in the control space (blue lines), as seen in Figure 83.

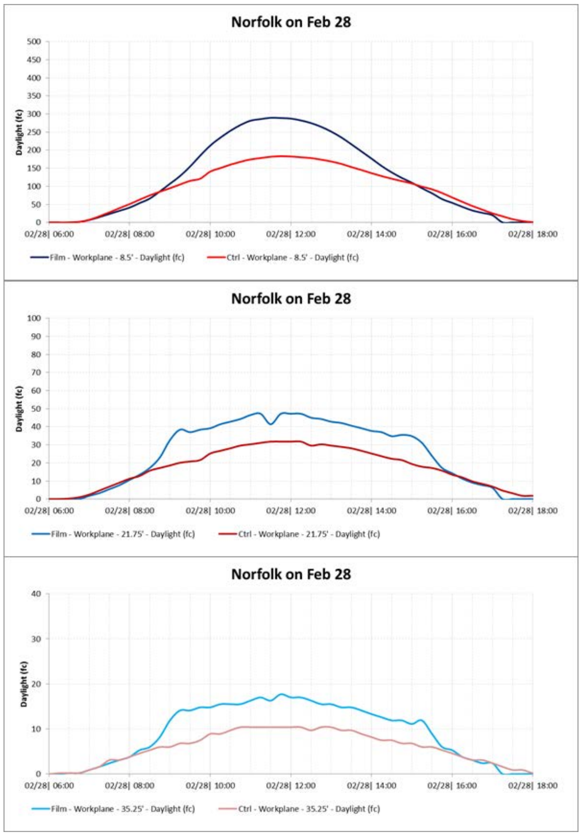

Figure 82. Daylight (fc) Clear Sky Conditions - Winter

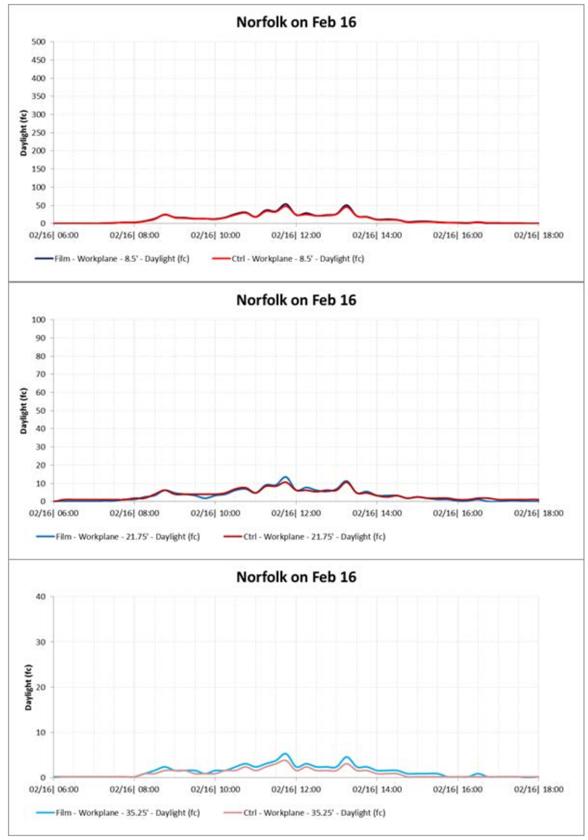

Figure 83. Daylight (fc) Cloudy Sky Conditions - Winter

As sun angle increases, the impact from the DRF becomes almost negligible, regardless of sky conditions. Figure 84 and Figure 85 represent a typical day with clear and cloudy sky conditions in the spring. While the performance of the DRF (red lines) to the control space (blue lines) during high sun angle’s (i.e. summer months) are shown in Figure 86 and Figure 87. Once again, the impact from the DRF is insignificant.

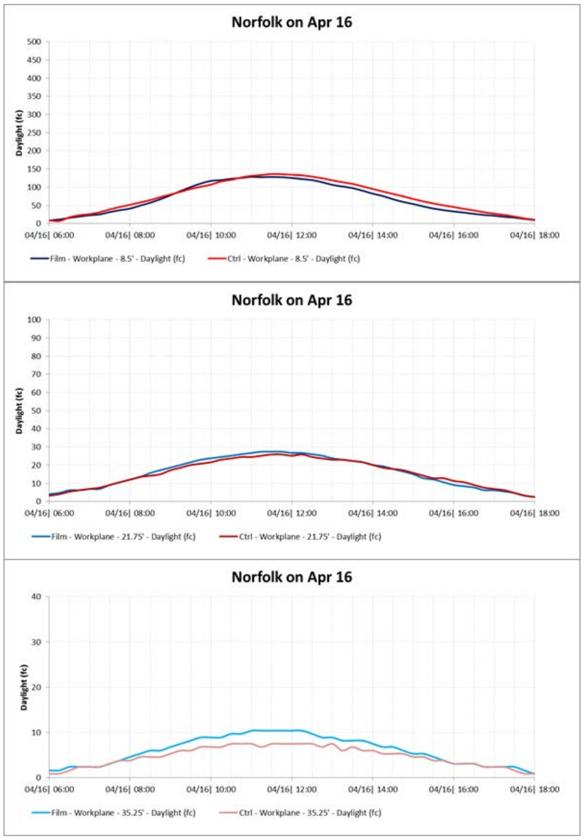

Figure 84. Daylight (fc) Clear Sky Conditions - Spring

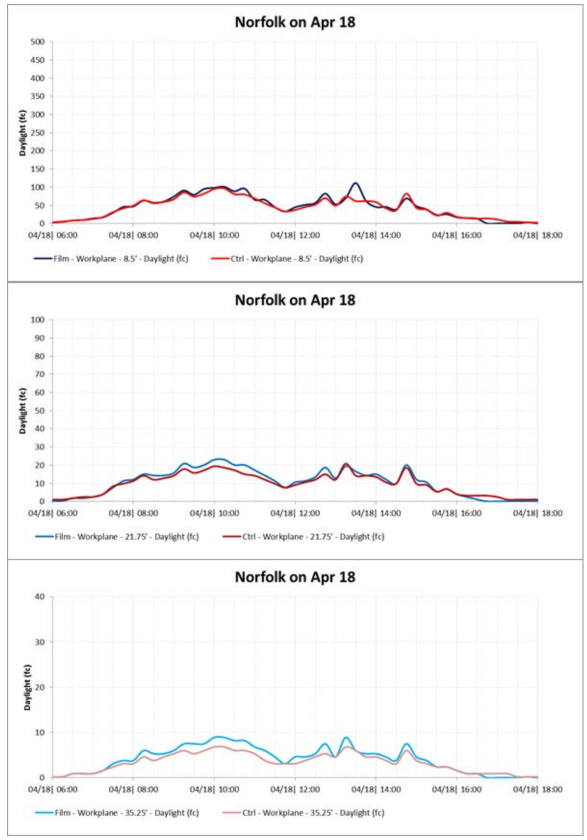

Figure 85. Daylight (fc) Cloudy Sky Conditions - Summer

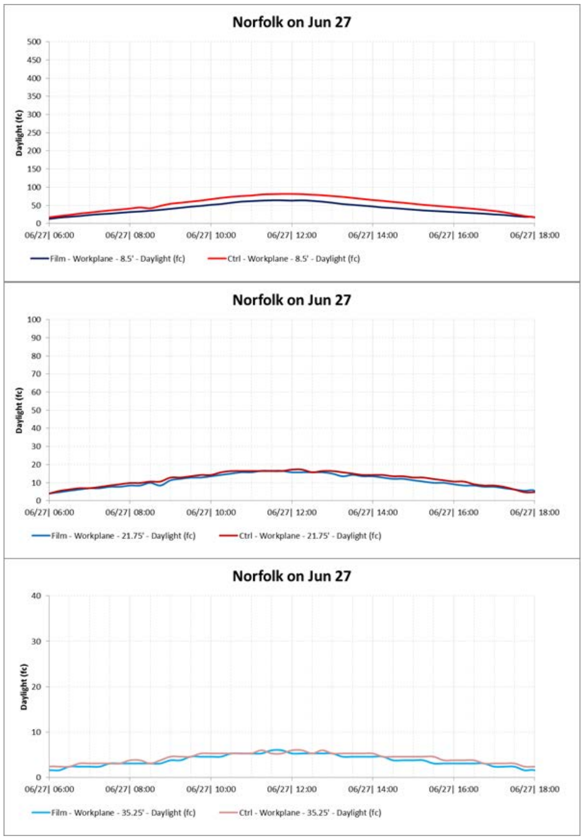

Figure 86. Daylight (fc) Clear Sky Conditions - Summer

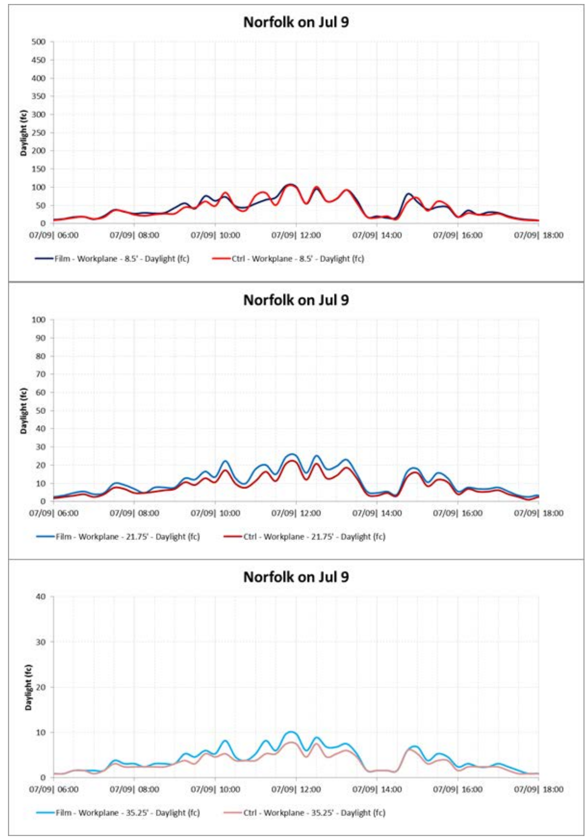

Figure 87. Daylight (fc) Cloudy Sky Conditions - Summer

The Norfolk monitored findings conclude the DRF had the greatest impact during months with low sun angles and clear skies. As the sun angles increase during the spring and summer, the impact of the DRF becomes negligible.

6.2.2 NAVAL WAR COLLEGE, NEWPORT, RI

6.2.2.1 BACKGROUND

The library and offices studied at Hewitt Hall, at the Naval War College, in Newport Rhode Island presented some interesting challenges for the study. The tall windows with clear glass provided daylight deep into the spaces, and the opportunity to add the DRF to the upper portion of those window areas. The DRF film was added to ALL south facing windows in the library, and two pairs of windows in two south facing, and two west facing, two-person offices upstairs. The offices each had an un-treated control pair for study, making for a total of eight offices in the study. The library, however, did not have a control space. Therefore, the library was planned to be a before and after study.

All of the windows were casements, opening inward, which meant that when they were opened, the geometry of the DRF would be changed substantially, usually for the worse. Sunlight penetration through the tall windows was controlled via full length curtains, hung from the top of the windows. The curtains were never relocated, or removed, in the eight study offices. In the offices, the windows were capable of being opened throughout the study, but it is believed that they were only operated during the summer and early fall months. In addition, even when fully open the curtains still blocked approximately 25% of the glazing as seen in Figure 88.

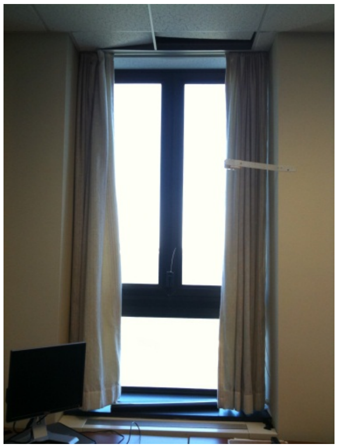

Figure 88. Private office, curtains fully open

Figure 89. Library, blinds installed below DRF

In the library, the curtains were removed in anticipation of installing horizontal mini-blinds below the DRF film application as seen in Figure 89. However, there was a period of over two months before the new blinds were installed. Thus, the library data is broken into three periods: 1.) 'Pre', before the DRF was installed, with curtains; 2.) 'Post-w/o blinds', after the DRF was installed, but with no window coverings; and 3.) 'Post-blinds', after the DRF was installed, and with horizontal blinds below the film. Unfortunately, these three periods spanned different seasons (summer, fall, winter); therefore, the angles of the sun and the performance of the DRF is very different. Once the horizontal blinds were installed, the casement windows could no longer be opened more than a crack. However, the project team was told that the windows in the library were never operated.

6.2.2.2 OCCUPANT AND MAINTENANCE FINDINGS

At the Naval War College, occupant surveys were received from treated areas and from control areas, but they were not distributed in space or time to allow useful statistical comparison. In general, responses to the lighting and visual conditions in the treated spaces were all positive, averaging 1-2 points above neutral, indicating that visual conditions were acceptable. There is one marked exception, in the survey responses to the question "I like how the blinds operate", with very low ratings for the treated space of (1.5-4). Otherwise, positive responses included such remarks as: "Awesome view," " Great view of bay and bridge," "The lighting is fine," " We have lots of windows that let in lots of light and a pretty view of the bay," and "I like the view & natural light." Overall, occupants liked the view from their windows and were not negatively impacted during the study period.

In the library, occupants did experience glare issues during the period after the DRF was installed and curtains were removed, but before the blinds were installed. Occupants mentioned “Some of the terminals facing the windows are subject to glare.” However, once the blinds were installed just below the DRF, occupants did not express any glare issues and had positive comments about the visual quality of their space. These included: “The lighting is good, not too bright, no glare,” and “It is bright and open throughout the room. The windows offer a nice view. There is not anything that I dislike.”

6.2.2.3 MONITORED FINDINGS

Monitoring at the Naval War College in Newport, RI took place for a period of twelve months, from June 2011 through June 2012, including both a pilot and a final study phase. Of the monitored data, the library workplane loggers placed in three transects on computer terminals and book stacks proved to be most useful in understanding the impact of daylighting in the study space. Details on the transects are provided in Section 5.7.2 of this report. The monitored findings from transect 7L (daylight from south-facing window) and 13L (daylight from south and west facing windows) will be discussed below. For a number of reasons, data from the private offices was not useful in determining the impact of the DRF on daylighting in the space.

Note: The modification of the window coverings, from original full height curtains, to horizontal blinds only below the DRF, was delayed for a few months after the DRF installation. Hence, the monitored data is broken into three distinct periods:

1.) ‘Pre’ or ‘control’, before the DRF was installed, with curtains (6/2011-7/2011)

2.) ‘Post-w/o blinds’, after the DRF was installed, but with no window coverings (7/2011-9/2011)

3.) ‘Post w/blinds’, after the DRF was installed, and with horizontal blinds below the film (10/2011-7/2012)

The monitoring of transect 7L is a before and after scenario with the three monitoring periods, outlined above, graphed separately in Figure 90. Transect 7L has a southern exposure. It is evident the DRF increases the amount of daylighting in the space compared to the control period. Difference in daylighting levels between the two periods after the DRF was installed – without blinds (or curtains) and with blinds – clearly shows the seasonal nature of the DRF performance. The DRF performs best during the winter months with low sun angles that is reflected in the fact that overall illuminance levels were higher in winter even when the blinds on the view windows were added.

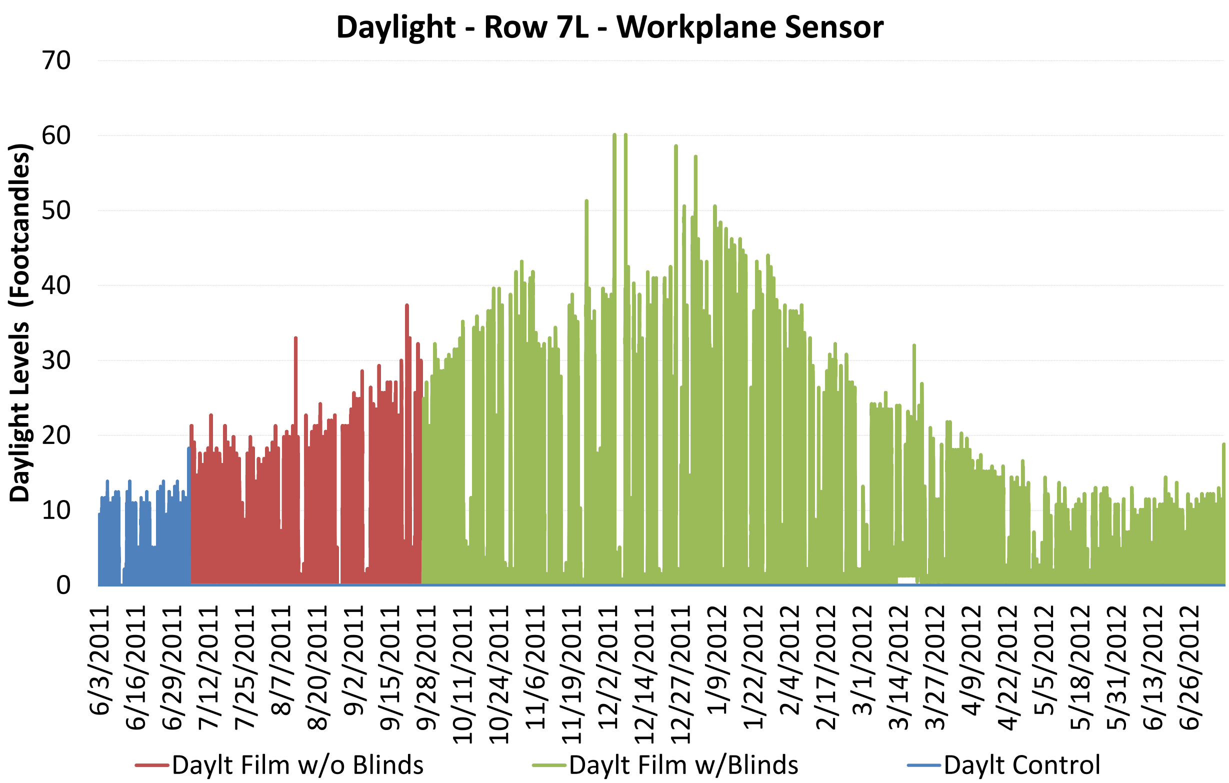

Figure 90. Library - Transect 7L, Daylight Measurements

From this analysis, DRF again shows the greatest impact during winter months with low sun angles and during clear sky conditions. Under these winter conditions the DRF was effective in redirecting daylight in the space for approximately six hours between 10:00 AM and 4:00 PM. In addition, the DRF (with blinds) increases the daylighting contribution (footcandle) most in the space between 20-35 degrees of solar altitude, as seen in Figure 91 (a period covering fall and winter of 2011 and spring/summer of 2012). Conversely, during the study period when the DRF was installed but no blinds or curtains were in place, the combined clear windows and DRF had an impact on the space up to an elevation of 70 degrees (a period covering summer of 2011).

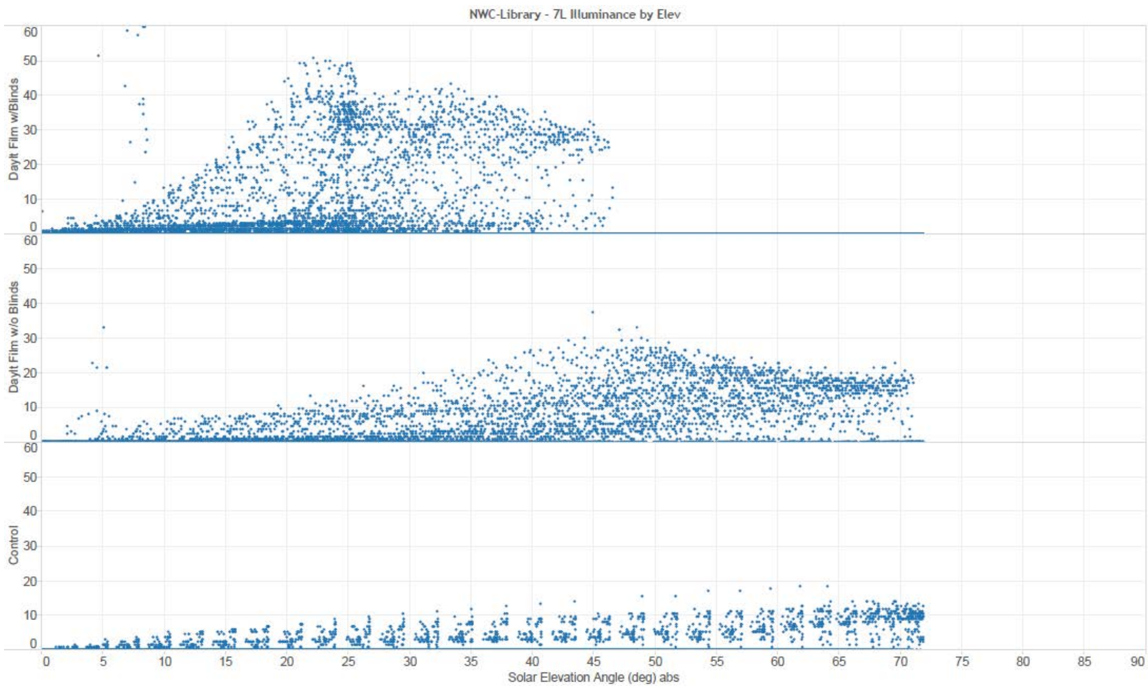

Figure 91. Library - Transect 7L, Added Daylight (fc) vs. Solar Elevation- Clear Sky Conditions

Of the two treated monitoring phases, the monitored data again shows the DRF is only effective during clear sky conditions. The figures below show hourly profiles with maximum and average values for the daylighting contribution from DRF for a typical clear day and typical cloudy day. As seen in Figure 93, the DRF has an insignificant impact on the daylighting in the space during cloudy sky conditions.

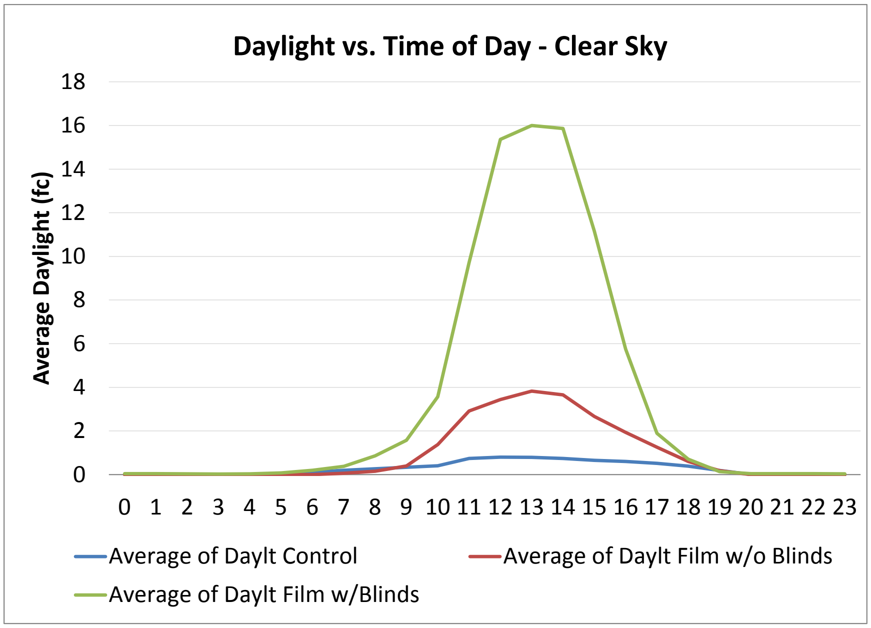

Figure 92. Library - Transect 7L, Daylight vs. Time of Day - Clear Sky Conditions

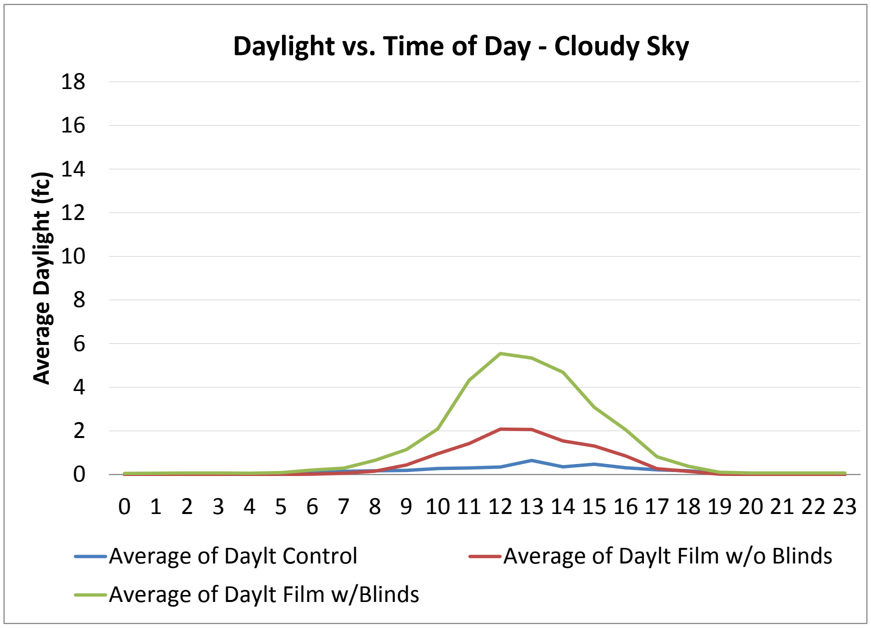

Figure 93. Library - Transect 7L, Daylight vs. Time of Day - Cloudy Sky Conditions

The monitoring of transect 13L, graphed separately in Figure 94, is also a before and after scenario with the three monitoring periods, outlined above. Transect 13L has a south and western exposure. Similar to transect 7L, the DRF shows the greatest impact during low sun angles and during clear sky conditions.

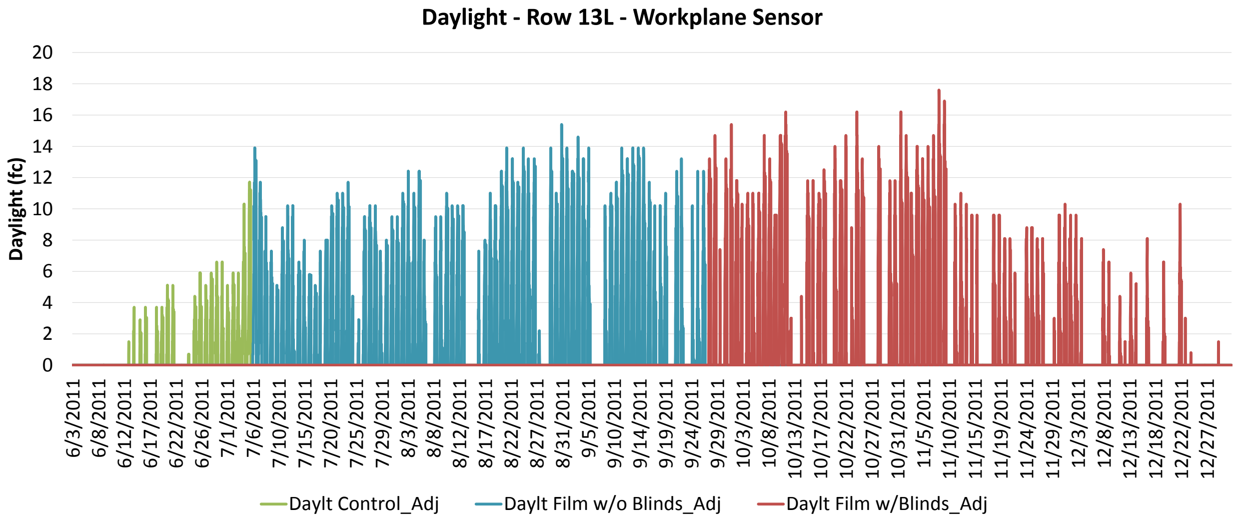

Figure 94. Library - Transect 13L, Daylight Measurements

Similar to transect 7L, increased daylighting levels occurred during clear sky conditions (Figure 95). While daylighting conditions improved during cloudy sky conditions (Figure 96) the increase was not as significant as during the clear sky conditions.

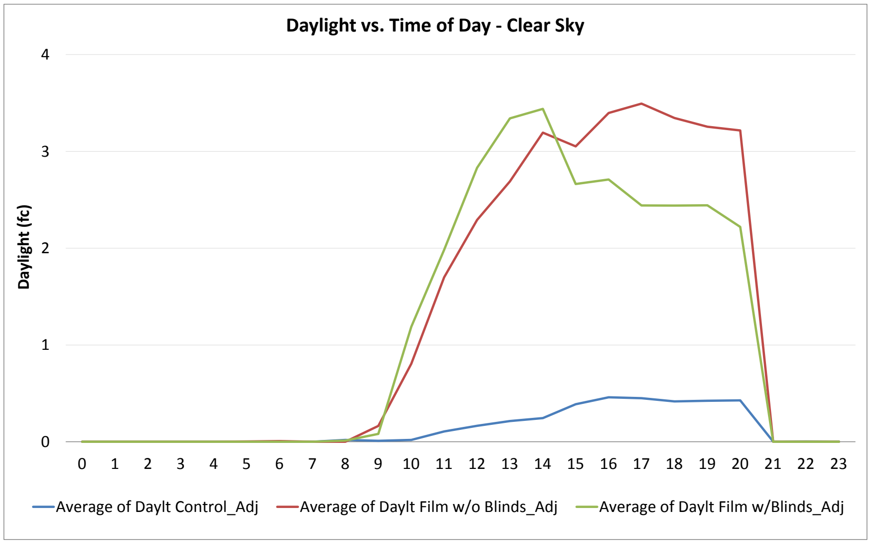

Figure 95. Library - Transect 13L, Daylight vs. Time of Day - Clear Sky Conditions

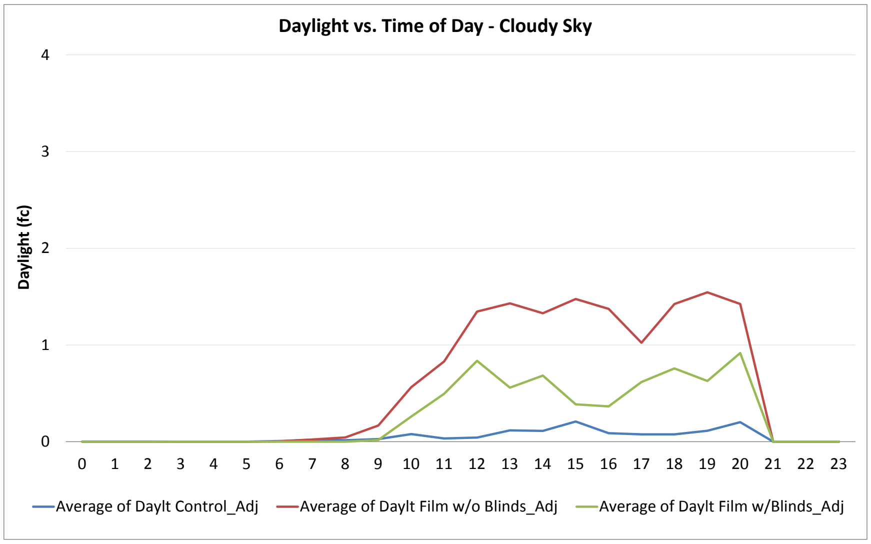

Figure 96. Library - Transect 13L, Daylight vs. Time of Day - Cloudy Sky Conditions

Overall, the occupants experience with the visual appearance of the DRF at the Naval War College was positive and they also commented positively on the increased daylighting in the treated spaces. They also liked the new horizontal blinds which replaced the full height curtains. The increased daylighting levels experienced by the occupants were verified through the monitoring findings presented above, showing the greatest impact during low sun angles and clear sky conditions.

6.2.3 FORT BLISS, EL PASO, TX

6.2.3.1 BACKGROUND

At Fort Bliss, south-facing open and private office spaces were used for the study; the DRF was installed in the south-facing open office area and half of the private offices in Wing A and C. The open office treatment areas had less than five occupants with varying schedules throughout the study, while the control areas had more occupants with part- and full-time schedules. The private offices had more consistent occupants, but also had inconsistent hours.

6.2.3.2 OCCUPANT AND MAINTENANCE FINDINGS

The study team interviewed the ranking non-commissioned officer in the area to get a sense of both his experience and the experience of others with in the study spaces. The officer said that occupants kept the blinds closed to control heat and glare before the film was installed. However, once the film was installed they did not experience nearly as many thermal issues. In addition, the officer felt that the AC worked better as well stating "it has been better in every regard" since the film was installed, and applied both to his office and the open office areas which received the film. Lastly, the officer observed the occupants use the electric lighting less after the film was installed.

6.2.3.3 MONITORED FINDINGS

Monitoring at Fort Bliss located near El Paso, TX took place for a period of six months from January 2012 through June 2012. Of the monitored data, the workplane loggers in the open office areas in one transect on the work partitions 5.5’, 13.5’ and 21.5’ from the windows, proved to be most useful in understanding the impact of daylighting in the study space. From this analysis, findings indicate the DRF increases daylighting levels during months with low sun angles (i.e. winter) with clear sky conditions, similar to findings from Norfolk, VA and Newport, RI.

Note: In the figures below there is no control workplane logger for distance 5.5’ from the window due to the furniture layout which provided no work surface until further back in the space. Thus the baseline illumination condition close to the window is not available for comparison at this site.

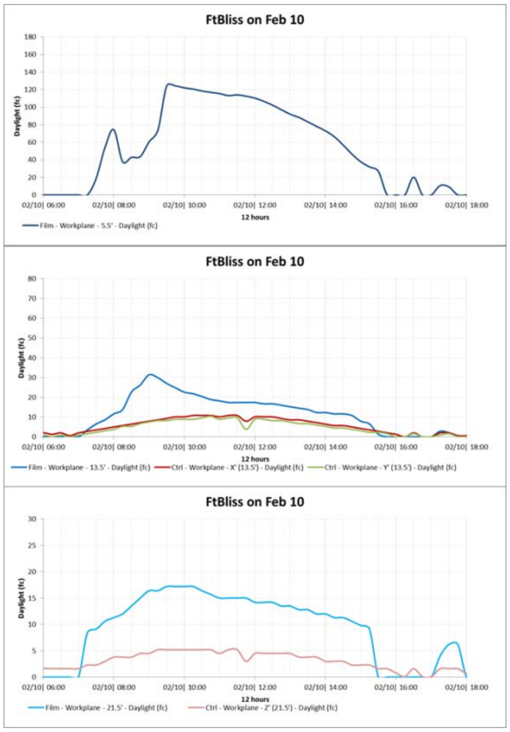

Figure 97. Winter - Daylight Contribution by Time of Day - Clear Sky Conditions

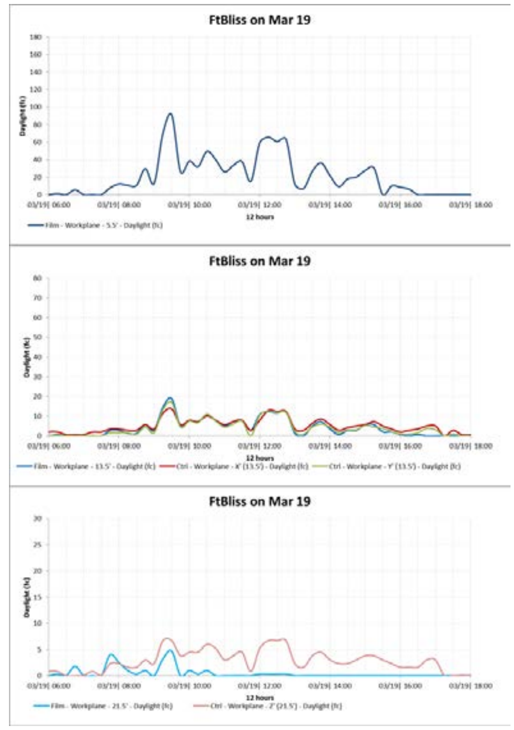

Figure 98. *Daylight Contribution by Time of Day - Cloudy Sky Conditions*

Figure 97 represents a day in February with clear sky conditions, and Figure *98* represents cloudy sky conditions. While the workplane logger at 5.5' does not have a control comparison, daylighting levels in the space nearest the window experienced up to 120 fc from the DRF application during clear sky conditions. A noticeable increase in daylighting from the DRF of up to 10-15 fc can be seen even 21.5' deep into the space. This again indicates the DRF is most effective in redirecting daylighting during low sun angles and clear skies. When the sky is cloudy the effect of the DRF is marginal at best.

As seen in Figure 99 (clear sky conditions) and Figure 100 (cloudy sky conditions) the DRF has insignificant impact on increasing daylighting levels during mid-level sun angles of the Spring months, regardless of sky conditions. Similar findings can be seen for months with high sun angles (i.e. summer).

Occupant feedback about the daylighting conditions in the treated spaces was positive and also noted a reduced need for electric lighting with the DRF in place.

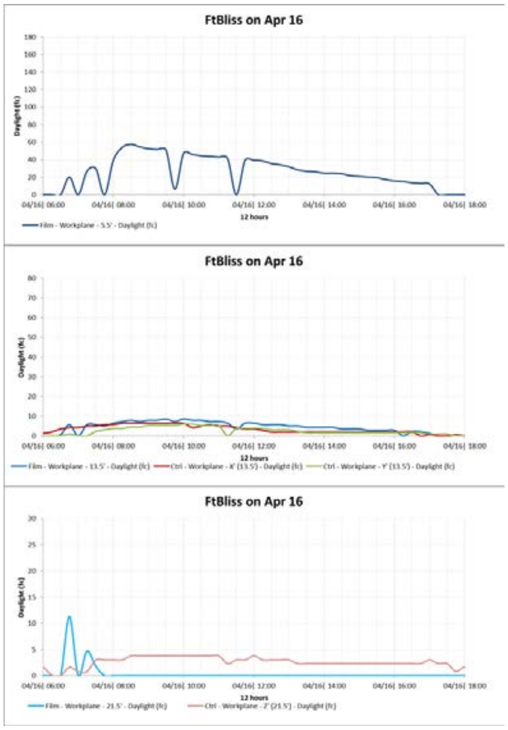

Figure 99. Spring - Daylight Contribution by Time of Day - Clear Sky Conditions

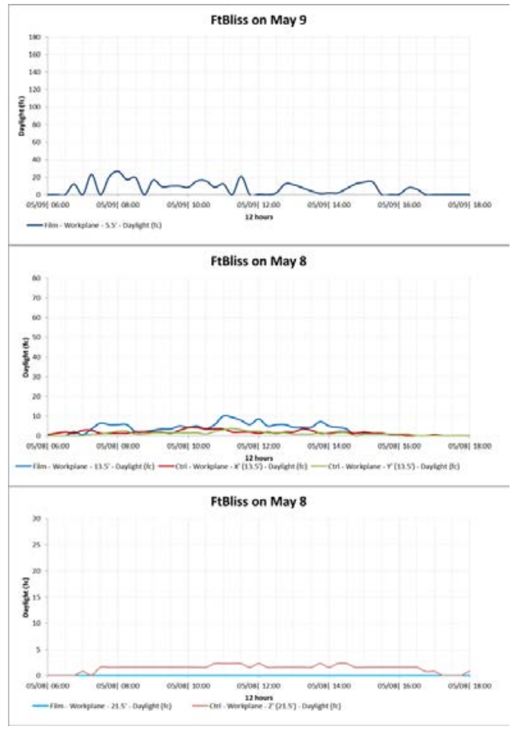

Figure 100. Spring - Daylight Contribution by Time of Day - Cloudy Sky Conditions

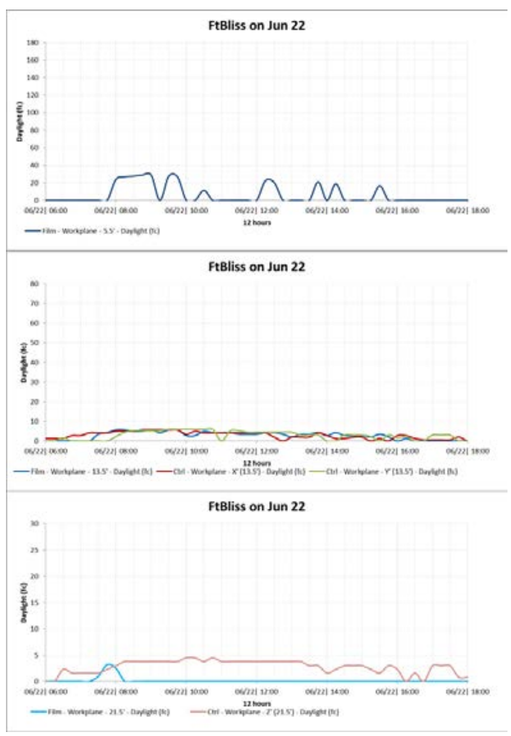

Figure 101. Summer - Daylight Contribution by Time of Day - Clear Sky Conditions

6.2.4 MARINE CORP AIR GROUND COMBAT CENTER, TWENTYNINE PALMS, CA

6.2.4.1 BACKGROUND

Building 1416 at the Marine Corp Air Ground Combat Center (MCAGCC), in Twentynine Palms, California, in the high, dry California dessert, was perhaps the second most productive study site for the project. The very clear, sunny climate was ideal for utilization of the test product, and the two potential study buildings had many geometrically identical spaces, that had a clear problem that needed to be solved with unwanted sun penetration and resulting glare.

Building 1416 and 1436, are two mirrored-imaged, two story buildings, oriented approximately 40 degrees east of south. The buildings offered the opportunity to find sets of identical spaces that could be easily compared between treated and control conditions. Both buildings provide office space and services for a number of Battalions while they were based at the MCAGCC for 6-12 months of training. Each Battalion was assigned a nearly identical office layout in one of the two buildings. However, while the geometries of the spaces were perfectly matched, the schedules of the Battalions was not, and the changing schedules provided an unexpected challenge for this study.

For example, one Battalion was suddenly shipped to Korea with little notice, leaving a quarter of one building empty, and forcing the project team to create a new study plan on short notice. Other Battalions had very erratic occupancy of the buildings, resulting in inconsistent occupant surveys. Ultimately, Building 1436 was dropped from the study due to poor occupancy patterns during the study period.

Figure 102. Window interior, showing sunlight

Figure 103. Window exterior, showing shading

Figure 102 illustrates how the roller blinds were mounted below the upper mullion and exterior shading device (Figure 103), leaving the upper portion of the window unshaded. Direct sunlight could come into all the windows, often at a very low sun angle. Some occupants had tried to block these upper windows with cardboard or aluminum foil. This problem created by the unshaded upper windows on the southeast and southwest facades, with their high VT glass, also created a perfect opportunity for application of the DRF.

The study team selected this building for one of the two pilot studies, to install the film and monitoring equipment in a variety of locations for six months in advance of the main study, in order to learn more about installation issues, and the range of occupant responses. Because of this pilot phase, the study team spent relatively more time on-site in this building, and were able to conduct more informal interviews with occupants compared to other sites.

For the pilot phase, eight pairs of rooms were selected for study to represent a range of sizes, orientations, and use types. These included:

- two pairs of company offices
  - Charlie/Weapons—deep spaces from one windowed façade
  - Battery/H&S—shallow space from two windowed facades
- two pairs of exam rooms
- two pairs of medical offices
- one pair of triage rooms
- one pair of records rooms

Despite up to twenty assigned occupants in each of the company offices, very few occupant surveys were returned at any given point in time, nor were they submitted consistently between the treatment and control conditions. Thus, statistical comparison of the occupant surveys is not supported.

6.2.4.2 OCCUPANT AND MAINTENANCE FINDINGS

The occupants of the deep open office spaces (Charlie/Weapons) gave very high ratings to the lighting conditions in the treated space, both in winter (8.0) and in spring (8.7), and felt that the daylight in the room was sufficient both in winter (7.7) and in spring (8.0), compared to the control room, which was judged as neutral for both seasons (5.0 and 5.4). The respondents agreed that the treated room was not too bright (8.0 and 8.0) and there were no problems with glare or troubling reflections (8.7 and 8.0). Importantly, these differences in survey ratings disappear in the summer, when conditions between the control and treated rooms were most similar.

Most of the occupants were appreciative of the view, especially when asked what they liked the most about the control spaces: “open view of outdoors,” “ I can still see the Mt. view,” “The light from the sun has an open feel to the room,” and “At dawn and dusk you have a great view.”

However, from written comments in the control areas, they also clearly identified the problem with the unshaded upper windows: “Add shades to top portion of windows,” “To be able to close the very top layer of the windows,” and “Blinding light in the afternoon that comes through the top window.”

In the treated area, the written comments start to reflect greater comfort; “No need for extra lighting”, “Visual conditions are conducive to work.” However, a few occupants still noted that there were limited conditions when problems persisted: “At times it (DRF) allows too much light in the room,” “Morning (early) light is bright and distracting," and "Yes, early in the morning there is a lot of glare coming in from the top windows."

6.2.4.3 MONITORED FINDINGS

Monitoring at Twentynine Palms, CA took place from July 2011 to June 2012. The first six months, July 2011-December 2011, were part of the pilot period. The monitoring period captured a full year's worth of sun angles. However, the data analysis from the monitored data revealed a problem: the location of the 'workplane' loggers (see Figure 104) on top of the high partitions resulted in very spotty and unreliable data. Many sensors were covered, moved, disabled, or lost. Furthermore, a number of ceiling sensors fell off and/or stopped recording for extended periods for unknown reasons. Thus, there was not sufficient data to establish clear patterns of performance, or support rigorous analysis.

Figure 104. Open office, Ceiling (circled) and Partition (arrows) locations

6.2.5 NAVAL HOSPITAL, BREMERTON, WA

6.2.5.1 BACKGROUND

Four south-facing exam rooms in the Naval Hospital at Bermerton, WA, were selected for this study. Occupants were intrigued by the promise of the film because while they loved the view and daylight that their windows provided them, they needed to keep the roller screens down most of the day in order to provide patient privacy. The DRF offered an option to preserve daylight while also allowing the shades to remain down for privacy concerns.

The hospital was recently constructed and had high performance windows. The roller shades were mounted at the top of the windows. In the treated rooms, the DRF was installed in the top 2' of the windows, and a new set of blinds installed below the film. Mature trees and a wing of the building to the west provided considerable shading on the windows.

6.2.5.2 OCCUPANT AND MAINTENANCE FINDINGS

Occupants in both the control and treated rooms expressed how much they enjoyed the outdoor scenery from their windows.

In the control spaces, occupants had issues with glare and solar heat gain, reporting that they would like to "lower the blinds to allow more daylight, but still have patient privacy. Also I would try to lower the heat in those rooms," and "We get glare on the computer screens and my eyes hurt from the glare."

In contrast, the occupants in the treated rooms had positive experiences in their rooms stating: "I would love to make all the rooms with windows like this," "I think the daylight brings energy to my work day," "It is bright without using lights in the room," "It makes me feel like I don't work in a box," and "I like that we can have sunlight shining in and still maintain patient privacy."

Based on occupant responses in the treated spaces, the DRF was effective in allowing more daylighting into the space compared to the control spaces, without causing glare or other negative comfort issues. It should be noted that these were all fairly small, shallow spaces, and so the redirected daylight was always well above eye level at the back of the rooms.

Furthermore, this was the only site that requested information about purchasing the DRF film indicating the level of satisfaction with the product.

6.2.5.3 MONITORED FINDINGS

Monitored data was collected at this site for a period of six month between January and June 2012. However, immediately after the loggers were removed from the site, the data loggers and associated equipment were stolen from the surveyor's car. Thus, unfortunately, no monitored findings are available to report for this site.

6.2.6 NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA

6.2.6.1 BACKGROUND

Halligan hall at the Naval Postgraduate School in Monterey California proved to be the least successful study site of the six. The eight (8) study rooms, narrow deep offices, each with 2-3 occupants, and tall, west facing windows, had been previously retrofitted with an exterior three-dimensional shade screen to block high angle sunlight. On the inside of the windows, a 3" deep Venetian blind was mounted at the top of the window head, interfering with the operation of the hopper windows in the middle of the assembly. Occupants complained of extra heat in the un-conditioned building, and blinding sunlight in the afternoon. The DRF retrofit for four of the offices included: adding DRF to the upper-most panes, plus adding a low-e film to the hopper window, and replacing the existing Venetian blinds with horizontal mini-blinds mounted below the hopper window. However, the existing exterior shade screen was only removed from two of the four treated rooms. The exterior shade screen effectively blocked high angle sun from the

DRF on these two windows, limiting its functionality to only those few hours of low angle sun that made it past the screen.

6.2.6.2 OCCUPANT AND MAINTENANCE FINDINGS

The occupants returned 7 surveys for the control conditions, either before DRF installation or from untreated spaces, and 12 surveys for post-treated spaces, under two seasonal conditions. Given the low numbers of surveys, statistical analysis is not supported. However, it is clear from the surveys that the treated rooms provided mixed results for the occupants. A few were very enthusiastic about the film, but others still found the western orientation very challenging both visually and thermally. The previously installed exterior shade screen was still appreciated for its ability to cut out the hot summer and afternoon sun, and the inward opening hopper windows created major problems for blinds operation, that were only partially addressed with the newly installed blinds system.

In the control spaces, written notes included complaints about glare and heat: "Afternoon sun blinds my guests if blinds are not fully closed.", but generally noted that the visual and thermal conditions with the existing shade screen was acceptable.

A few occupants in the treated spaces appreciated the new film: "I like brightness of diffusing film on the upper window," and blinds operation: "The new mini blinds (installed halfway down) are better than the old wooden blinds that were installed at the ceiling."

However, they were hesitant to give up the shade screens: "Installed screens work perfectly." Occupants provided <u>more</u> complaints about glare and heat in the treated spaces than under the control condition: "Have to close the blinds, constantly adjusting the blinds depending on the time of day." "Right now it is 10 am and it is already too bright in my room. I have to close my blinds in order to see my computer screens. In the afternoon when I enter my office I have to make sure to protect my eyes and not look directly at the windows in order to avoid sudden glare." "Please do not remove the black screens..The new film is not bad when used IN ADDITION to the black screen."

"The room is too bright, the glare on my computer screens is really distracting. The temperature in the office in the afternoon is too high, on sunny days it reaches up to 75! The closed blinds are hot to the touch in the afternoon."

Thus, it appears that the DRF retrofit assembly was not sufficient to solve the discomfort from the low angle western sun on these windows, especially in comparison to the pre-existing shade screen.

The analysis is further complicated by the fact that this building had no air conditioning making the occupants more sensitive to the thermal comfort issue.

6.2.6.3 MONITORED FINDINGS

Of the eight study rooms, data was collected from two each of the control and treated rooms, Unfortunately, the two treated rooms with monitoring equipment installed were also those where the exterior screens was never removed. Thus there was no appreciable increase in daylight from the installation of the DRF over the control condition, based on the monitored data.

6.3 SIMULATION FINDINGS

This section of the report outlines key findings from the simulation analysis.

6.3.1 SENSITIVITY ANALYSIS FOR ILLUMINANCE DUE TO DRF

Simulation results for 3M Window Film, applied in a generic office spaces with no external shading, are presented in the in following sections. Results show the product significantly increases available daylighting savings in the first three daylit zones (first 24’ from the 8’ high windows).

Savings were calculated for electric lighting energy use, reported as both an annual reduction in full-load-equivalent ON hours (FLE ON hours), and percent reduction in FLE hours. Savings were calculated for each 8’ deep daylit zone separately. In the following plots, daylit zones are numbered 1-8, representing luminaire rows starting 4’ from the windowed façade and then each subsequent 8’ through the center of each daylit zone. The last row of luminaires is 4’ from the rear wall, 60’ back from the windows.

All energy savings are reported for not just one, but two changes: (1) adding photocontrols and (2) adding 3M Window Film to the clerestory. Figure 105 compares a room 64’ deep, with photocontrols in all lighting zones, but no film, to the same room with photocontrols and the 3M Window Film applied to the clerestory window. In the left-hand graph, dashed lines indicate savings from photocontrols alone and solid lines indicate savings from adding the 3M Window Film. The right-hand graph isolates the incremental savings resulting from the 3M Window Film. Incremental savings are concentrated away from the windows due to the daylight redirecting nature of the film. In effect, the film enables sufficient daylighting savings to pay for photocontrols in the third and fourth daylit zones, ie. zones that were previously considered marginal or poor candidates for daylighting.

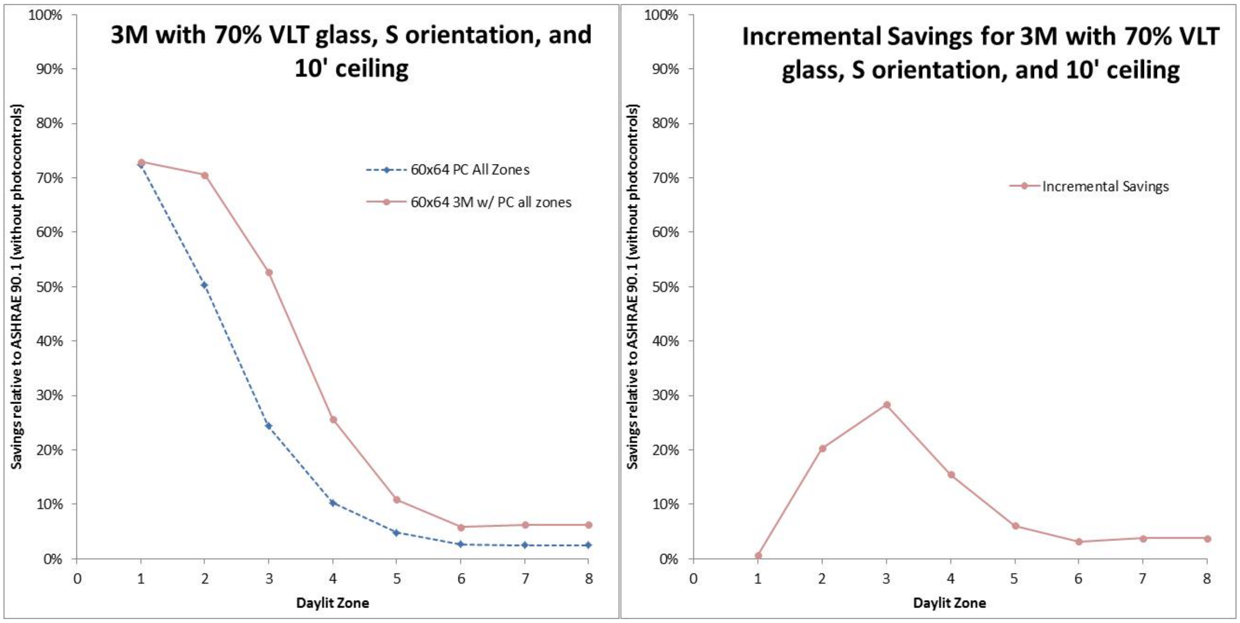

Figure 105. Potential daylighting savings with and without DRF for Southwest US

The savings presented in Figure 105 assume optimal operation of the blinds: the blinds are closed as soon as direct sun enters the window and re-opened as soon as the sun leaves the windowed façade[1]. This control strategy is likely to preserve occupant comfort and maximize energy savings. However, this strategy is a 'technical potential' and realizing this potential requires careful design and investment in automated and integrated window shade and electric lighting controls.

The minimum possible electric lighting energy savings occur when the occupants leave the blinds closed all the time. Figure 106 shows savings with blinds always closed. Examination of the graphs shows absolute savings are considerably reduced compared to the optimal blinds control model above. However, the relative contribution of the daylighting film increases when the blinds are always closed (Figure 105 vs. Figure 106). Overall, the daylighting film preserves a large percentage of the optimal savings, even when the window blinds are left always closed.

[1] The blinds trigger is direct sun landing at least one foot into the space and create illuminance levels in excess of 100 fc (1000lux).

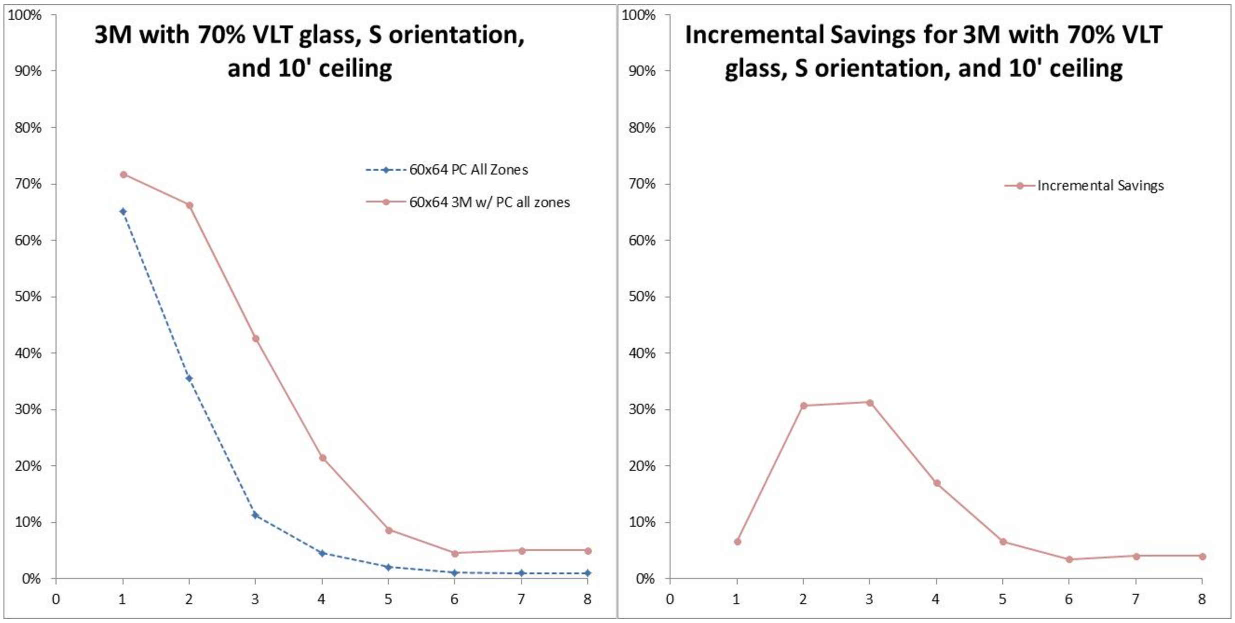

Figure 106. Daylighting savings with and without DRF and blinds always closed.

Re-plotting the savings for the models with the film installed shows the difference between optimal blinds control (automatic) and worst-case blinds control (closed) is small relative to the total savings obtained (Figure 107).

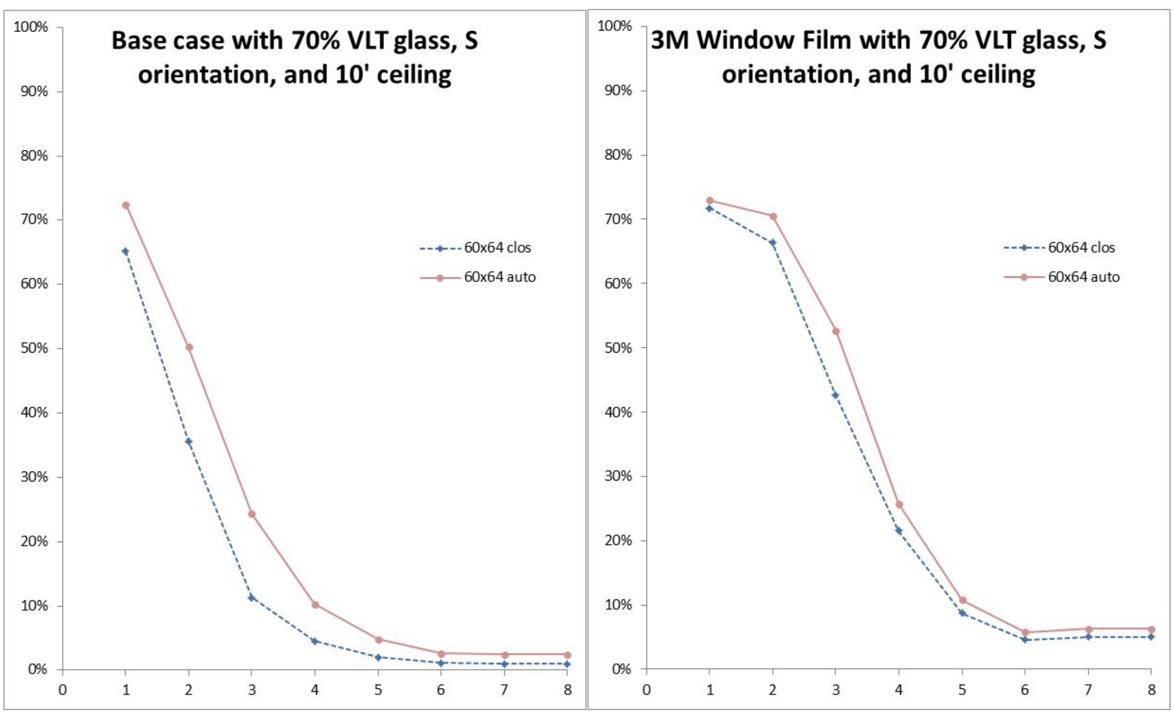

Figure 107. Effect of blinds operation on daylight savings: Base case on the left, and 3M film on the right

The data presented graphically in Figure 105, Figure 106 and Figure 107 are presented in tabular form in Figure 108, for the two cases: Auto=optimal blinds operation, and

Closed=blinds always closed. PC=photocontrols only; PC & 3M=photocontrols plus 3M DFRF; 3M savings= relative change in daylighting savings due to DRF. If the blinds are always closed, adding 3M Window Film increases savings by more than 30% in the second and third daylighting zones and by 17% in the fourth daylighting zone. However, if the blinds are controlled optimally (automatically), percent improvement in savings is reduced. Aggregate savings for a large number of spaces is likely to fall somewhere in the middle between these two boundary conditions, assuming a normal variation in occupant behavior. It is important to note that ease of access to blinds controls is a key factor in how actively blinds are adjusted by occupants.

	Auto			Closed		
Zone	PC	PC & 3M	3M Savings	PC	PC & 3M	3M Savings
1	72%	73%	1%	65%	72%	7%
2	50%	71%	20%	36%	66%	31%
3	24%	53%	28%	11%	43%	31%
4	10%	26%	15%	5%	22%	17%
5	5%	11%	6%	2%	9%	7%
6	3%	6%	3%	1%	5%	3%
7	2%	6%	4%	1%	5%	4%
8	2%	6%	4%	1%	5%	4%

Figure 108. DRF: lighting energy savings sensitivity analysis

The most important observation from this simulation exercise is that the electric lighting savings with the test products under worst case conditions (blinds always Closed) is better than the electric lighting savings potential for the same windows with no test product under best case conditions (Auto). Thus, the test products completely eliminate the downside risk of poor blinds operation, and greatly increase the upside opportunity for daylight savings.

6.3.2 SPATIAL DAYLIGHTING AUTONOMY RESULTS

Analysis was conducted using the same methodology as the daylight sensitivity analysis, except the results were processed to calculate spatial Daylight Autonomy, $sDA_{300, 50\%}$, which represents the percent of the study area that meets a minimum daylight illuminance level of 300 lux, for at least 50% of the operating hours per year.

Overall, the study found a substantial increase in sDA across the three climates and three orientations considered in the simulations, regardless of the window blinds operation.

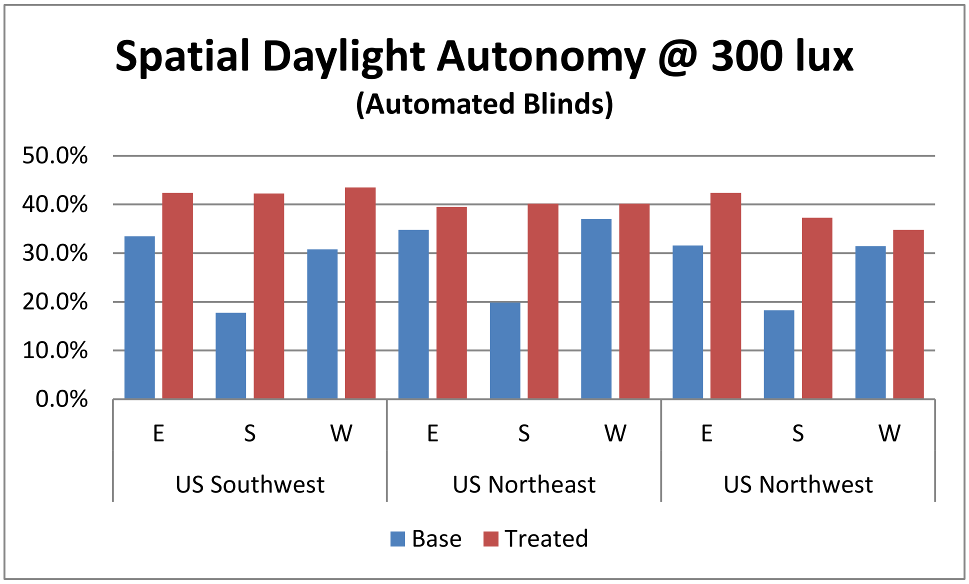

Figure 109. sDA Increase from DRF – with Automated Blinds Operation

With the blinds operated with automated controls, across the nine conditions considered, the DRF increased sDA on average by 11%. The average sDA for the baseline was 28%, which increased to an average of 40% sDA for the space treated with DRF. The amount of increase in sDA varies by climate zone and orientation as seen in Figure 109. The largest percent increase in sDA is seen for the southern exposure in the southwest climate.

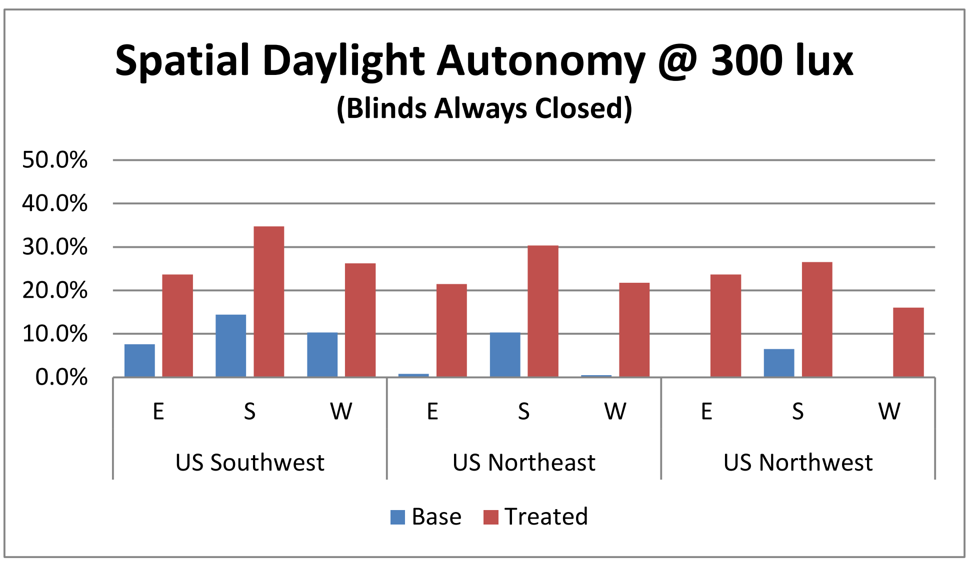

Figure 110. sDA Increase from DRF – with Blinds Always Closed

With the blinds Closed at all times, the increase in sDA averages even higher at 19%, since the sDA for the baseline averages a low of 5.5% whereas the average sDA for the treated space with DRF is 25%. This is expected since the baseline has blinds covering the entire window, not an unusual scenario for spaces with high glare or direct sunlight penetration potential. Since the treated area has blinds only on the lower view window and the upper clerestory section lets in daylight due to DRF, there is much higher illuminance in the treated space. Thus, one can say that the DRF (along with relocation of blinds) provides a hedge against a complete loss of daylight due to failure of operation of window blinds. Results for blinds all Closed, by climate zone and orientation, are seen in Figure 110. Also it should be noted that these sDA results are for a deep space and the sDA values will be much higher for spaces that have shallow depth.

6.3.1 LIGHTING AND WHOLE BUILDING ENERGY ANALYSIS RESULTS

Lighting and whole building energy analysis was conducted by comparing the energy simulation analysis procedures described in Section 5.5. Two levels of energy savings were established:

- Minimum Savings - reduction in energy use when baseline building has photocontrols in the areas closest to windows, and treated model adds photocontrols for lighting over the entire space and adds DRF to the clerestory. Blinds were assumed to be operated in an optimal (automated) manner.
- Maximum Savings - reduction in energy use when baseline building does not have photocontrols, and treated model adds photocontrols for lighting over the entire space and adds DRF to the clerestory. Blinds were assumed to be operated in an optimal (automated) manner.

Comparing the annual results using these two criteria, lighting energy savings are estimated to range between **a low of 0.41 kWh/sf** (~20% of baseline lighting energy use) for the east facing space located in the US Northwest, to **a high of 1.48 kWh/sf** (~52% of baseline lighting energy use) for the west facing space located in the US Southwest as seen in Figure 111.

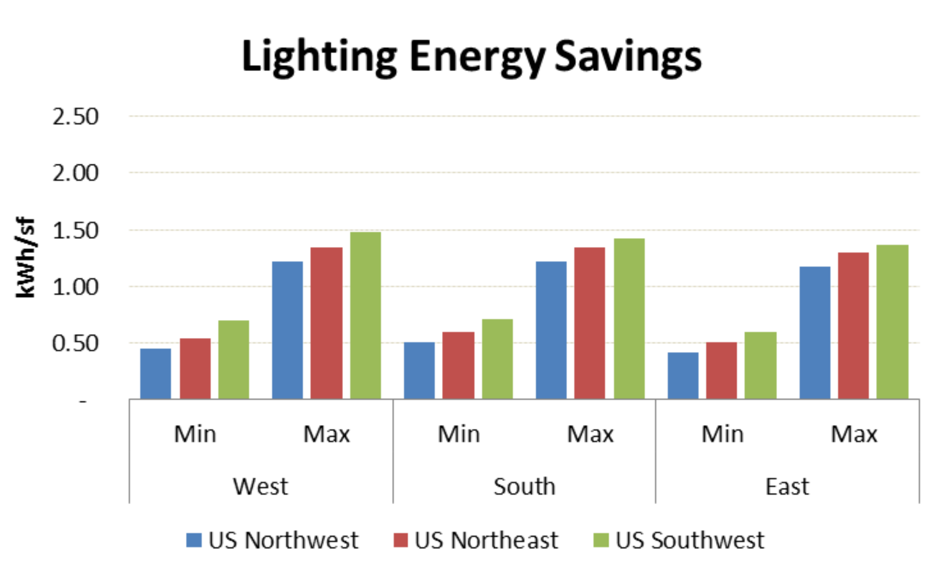

Figure 111. Predicted Lighting Energy Savings

Accounting for the impacts of the lighting energy savings on overall building energy use, i.e. including both cooling and heating impacts in addition to electric lighting energy savings, the whole building energy savings (for the 40' wide by 64' deep space studied) are estimated to be between **a low of 0.39 kWh/sf** (~4% of baseline energy use) for the east facing space located in the US Northwest to **a high of 2.11 kWh/sf** (~13% of baseline energy use) for the west facing space located in the US Southwest as seen in Figure 111.

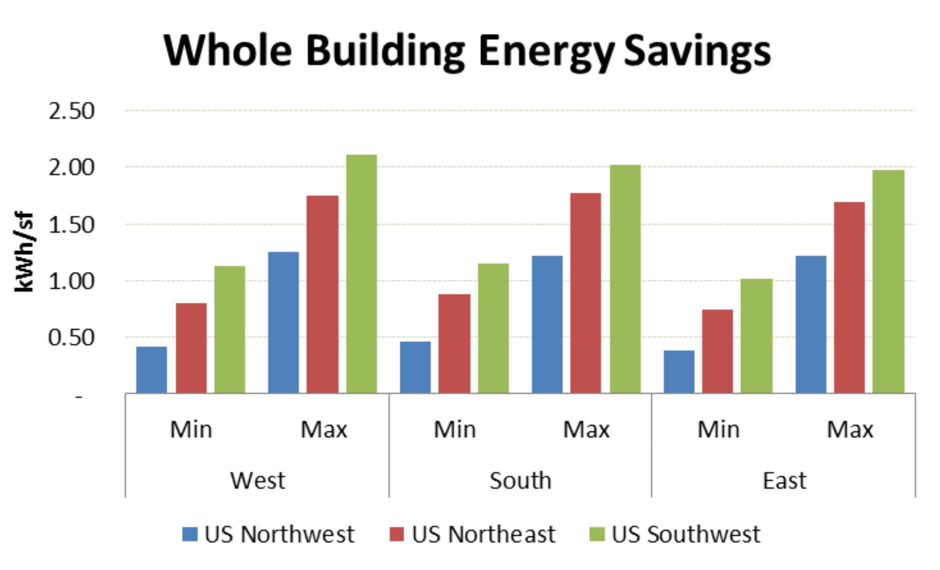

Figure 112. Predicted Whole Building Energy Savings

6.4 PERFORMANCE RESULTS BY OBJECTIVE

Outcomes of individual Performance Objectives (PO's) are described in detail below.

6.4.1 INCREASE DAYLIGHT ILLUMINANCE LEVELS

Success in increasing daylight illuminance levels is achieved if there is an increase in the spatial Daylight Autonomy (sDA) due to the installation of DRF. The sDA metric is described in detail in Section 5.1.6.1.1 .

The purpose of this performance objective is to show the new technology increases daylight in the space and distributes it more uniformly throughout the space. Increased daylight availability allows electric lights to be turned off, and more uniform distribution of light reduces glare potential, as occupants are exposed to less contrast in the visual enviroment. The DRF technology was shown to both increase daylight illuminance levels and uniformity.

As described in detail in Section 5.5.1 and 6.3.2 simulations of prototypical spaces were performed with a grid of sensors arrayed in the spaces to capture fine-scale variations in lighting levels that would be cost-prohibitive to collect in the field. Daylight levels were validated against field results and then illuminance levels, and spatial daylight autonomy were calculated.

As summarized in Figure 109 and Figure 110 the **DRF installation increases sDA between 11% to 19%**, which exceed the performance objective target of 10%.

6.4.2 POTENTIAL TO REDUCE LIGHTING ENERGY USE

This performance objective was to reduce electric lighting usage 15’ to 25’ from the windows by at least 200 hours and reduce annual daytime usage by at least 25%. The purpose of meeting these goals would indicate the technology can provide significant electric lighting energy savings deep in the space from daylighting. Daylighting typically is not cost effective more than two window head heights from the windowed façade[1]. The window head height is defined as the height of the window header (or top) above the finished floor.

Electric lighting usage was measured in Full-Load-Equivalent (FLE) On hours. For example, if half the lights are on for eight hours (50%*8hr), then this is reported as 4 FLE On hours. This metric is especially relevant to the dimming system that was simulated here. Partial hours of usage are summed up into an easily digestible number that directly reflects changes in usage measured at the electric meter.

This performance objective was met for most typical conditions observed in DoD facilities:

The first objective, **reducing FLE On hours by at least 200 hours was fully met** both when blinds are operated optimally (Figure 113) and when blinds are always closed (Figure 114).

		West		**South**		**East**	
		40% VLT	**70% VLT**	**40% VLT**	**70% VLT**	**40% VLT**	**70% VLT**
Northwest	Hours	735 hrs.	1158 hrs.	761 hrs.	1183 hrs.	656 hrs.	1076 hrs.
	% Change	26%	41%	27%	41%	23%	38%
Northeast	Hours	842 hrs.	1376 hrs.	883 hrs.	1342 hrs.	774 hrs.	1279 hrs.
	% Change	29%	48%	31%	47%	27%	45%
Southwest	Hours	1110 hrs.	1638 hrs.	1095 hrs.	1570 hrs.	924 hrs.	1452 hrs.
	% Change	39%	57%	38%	55%	32%	51%

Figure 113. Lighting energy savings with optimal blind control

Figure 113 shows lighting energy savings 16 to 24' from the windowed façade with the addition of optimal blind control, DRF and photocontrol expressed as Full Load Equivalent (FLE) ON hours.

Figure 114 shows lighting energy savings 16 to 24' from the windowed façade with the addition of blinds that are always closed on the view portion of the window, DRF on clerestory and photocontrol expressed as Full Load Equivalent (FLE) ON hours.

[1] Heschong Mahone Group, Inc., “Sidelighting Photocontrols Field Study”, consultant report to Southern California Edison, Pacific Gas and Electric Company and Northwest Energy Efficiency Alliance, 2005

		West		South		East	
		40% VLT	**70% VLT**	**40% VLT**	**70% VLT**	**40% VLT**	**70% VLT**
Northwest	Hours	498 hrs.	750 hrs.	614 hrs.	972 hrs.	410 hrs.	643 hrs.
	% Change	17%	26%	21%	34%	14%	23%
Northeast	Hours	551 hrs.	868 hrs.	715 hrs.	1081 hrs.	492 hrs.	788 hrs.
	% Change	19%	30%	25%	38%	17%	28%
Southwest	Hours	804 hrs.	1088 hrs.	926 hrs.	1279 hrs.	626 hrs.	910 hrs.
	% Change	28%	38%	32%	45%	22%	32%

Figure 114. Lighting energy savings with always-closed blinds

The second objective, reducing annual lighting energy usage by 25% is achieved in all climate zones and orientations modeled when the baseline does not have existing photocontrols. When the baseline building has photocontrols in the first two zones, the 25% target is achieved on a consistent basis in the Southwest and Northeast climate conditions but not for the Northwest climate conditions as seen in Figure 115.

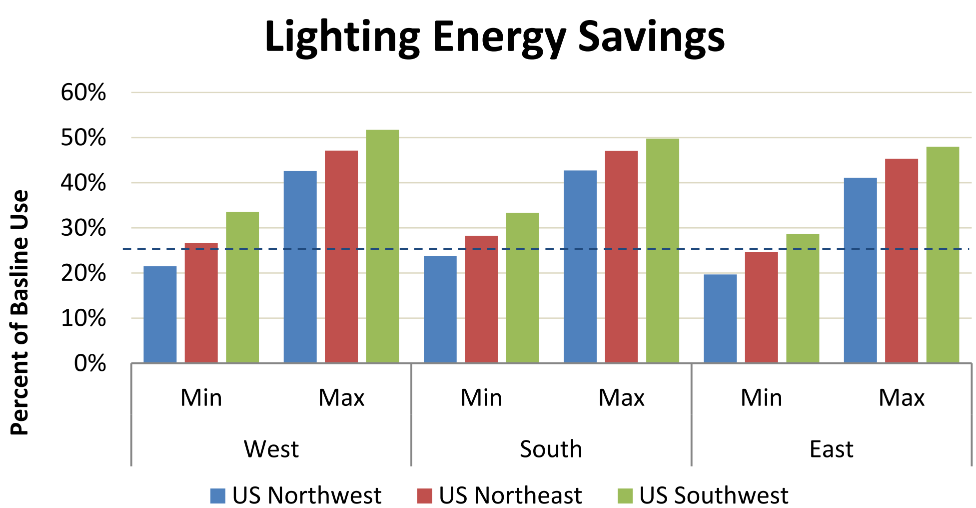

Figure 115. Percent Lighting Energy Savings for DRF and Daylighting Controls

6.4.3 REDUCE WHOLE BUILDING ENERGY USE

The success criteria for performance objective "reduce whole building energy use" was that whole-building energy savings be at least 5% greater than the electric-lighting energy savings alone. The purpose was to show that adding the film and photocontrols can have a net positive annual impact energy savings, reducing both energy demand and costs for DOD buildings.

Based on the lighting energy savings numbers presented in Figure 111 and whole building energy savings from Figure 112, one can calculate the additional whole building savings from HVAC impacts. This **additional impact is on average 30% across all building models** (orientations, climates etc). Thus the performance objective is met on average. The only exception is the US Northwest where the cooling loads are not high and thus HVAC impacts are negligible.

6.4.4 GREEN-HOUSE GAS EMISSIONS

Total electric and natural gas energy savings were converted to carbon equivalents and are presented in Figure *116*. To develop the carbon equivalents, we used the US Environmental Protection Agency estimates[1].

CO2 Savings lb/sf/yr	**West**		**South**		**East**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
US Northwest	0.65	1.83	0.76	1.86	0.60	1.76
US Northeast	0.89	2.20	1.02	2.33	0.74	2.13
US Southwest	0.66	2.21	0.84	2.26	0.51	2.13

Figure 116. *CO_2 savings from DRF and photocontrols. (pounds of CO2 / sq. ft. / year)*

Carbon emissions reductions due to whole building energy savings from DRF installation range from 0.51 lb/sf/yr to 2.13 lb/sf/yr depending on climate and window orientation.

6.4.5 MAINTAIN OR INCREASE VISUAL COMFORT

This performance objective was to at least maintain, or even increase, the visual comfort of occupants in the spaces where DRF was installed. This is a subjective assessment based on occupant feedback to the DRF installation.

As detailed in the individual site findings in Section 6.2, the DRF installation was largely seen as a success from the perspective of visual comfort. **Occupant visual comfort was preserved or increased in all but one installation**. In the installation where visual comfort decreased (Norfolk), the product was not installed high enough above eye level. In the installation at Twenty Nine Palms, the DRF dramatically improved the visual comfort of the occupants.

[1] (EPA 2012). eGRID2012 Version 1.0, U.S. annual non-baseload CO2 output emission rate, year 2009 data, U.S. Environmental Protection Agency, Washington, DC.

6.4.6 IMPROVE PRESERVATION OF VIEWS OUT FROM THE BUILDING

The goal of this performance objective was to increase perception of quality of available view due to improvement in overall visual comfort. This is a subjective metric based on occupant feedback to the DRF retrofit. Based on this subjective feedback, the performance objective is largely met across the sites. **An increase in occupant ranking of view quality was observed when the DRF was installed**. There is antidotal evidence in a few of the small study spaces, that blinds where left open more often in the spaces treated with DRF.

The impacts of blinds operation on daylight availability or energy savings potential could not be analyzed based on the data available. The existing, and reconfigured, blinds operation was less than ideal in many of the study sites. Written responses from the occupants indicate that they clearly preferred having control of the blinds. Many of the strongest written complaints about visual and thermal discomfort were lodged when the occupants did not have control of blinds operation.

6.4.7 REDUCE GLARE

This performance objective is also a subjective assessment of the impacts of DRF installation on at least preserving visual quality, or even better, reducing glare from windows. Based on occupant surveys, **glare conditions were unchanged or improved in five out of six locations**. In Norfolk, installation of the DRF at 6’ AFF -- too close to eye level -- resulted in some glare complaints.

6.4.8 MAINTAINABILITY OF SYSTEM

This performance objective aims to document that the DRF installation does not create significant new maintenance needs. While the study was a relatively short period (6-8 months per site), **site staff did not report any maintenance concerns with final product installation**. Nor is the study team aware of any safety or maintenance concerns related to this product. Thus we consider this performance objective to be met.

7. IMPLEMENTATION ISSUES

7.1.1 PILOT PHASE LESSONS LEARNED

Some facility managers were concerned about mechanical attachments of a secondary diffuser to existing window frames. Over the course of the study 3M tested a number of different installation methods and developed a new version of the DRF film with an integral diffuser, which requires no mechanical attachments.

Most sites had existing window blinds, roller shades or curtains which covered the entire window, blocking the function of the DRF. The study team worked with the site contacts to devise various ways to modify existing blinds/shades so that they would only cover the lower, view portion of the windows while leaving the upper, clerestory windows unobstructed. This effort to relocate window coverings was not fully successful at all sites, and although technically easy, seems to constitute the most challenging social barrier for a DRF retrofit project.

7.1.2 MAIN STUDY SITE SELECTION

Appropriate study sites meeting the research design criteria were difficult to find. Ultimately, the study team selected six study sites, out of 20 candidate sites, with the goal of testing the product under a variety of field and climatic conditions.

These six study sites were representative of the standard civilian building types that this product was designed for, with large un-shaded windows. However, from the screening process it became clear that these types of buildings are more the exception and the rule among the population of DoD buildings, where a higher percentage of buildings seem to have climatically sensitive designs, and thus carefully shaded windows. Furthermore, low occupancy at some sites and high security concerns at others made them inappropriate as study locations.

The six sites represented three of the desired four climate conditions for the study. The team was not able to find any available study sites in high-latitude with clear skies, but met their objectives for study sites in other sky types and latitudes.

7.1.3 SITE DATA COLLECTION ISSUES

The site data collection had some problems with loss of data from dataloggers and logger theft on one site, but overall sufficient monitored data was available to compare to simulation findings, and provide insight to SRF operation under site conditions. Standard occupant survey forms were not particularly successful at the DoD study sites, due to sporadic and rotating populations. Sustained observations of occupant comfort were difficult under these conditions. Additional insight to occupant comfort was gained via personal interviews, where permitted.

7.1.4 Product Installation

Choosing daylight redirecting products involves aesthetic, safety, installation, maintenance, occupant comfort, and economic considerations. The team discussed these considerations with all potential sites during recruitment and has observed the outcome of product installation in 23 rooms spread over six sites.

7.1.4.1 Aesthetics

The product changes the appearance and aesthetics of the space. The brighter appearance of the rooms was welcomed by most occupants. However, the film also eliminates the view of the outside through the upper, clerestory window. This study found occupants tolerated this well with one exception: at Norfolk the study one of the occupants reported lack of ability to watch the planes take off and land and was mildly irritated by the inability to see the planes through the film.

7.1.4.2 Safety, Installation and Maintenance

Compared to other products, such as light shelves or louvers, available to enhance daylighting in side-lit spaces, the 3M Window Film has fewer maintenance and safety issues. The film does not extend into the room making it easier to clean the windows, and in the event of a fire, the film would not obstruct the flow of water from fire suppression sprinklers, as might internal light shelves. Compared to louvers, the DRF does not collect dust and is easier to clean.

7.1.4.2.1 Occupant Comfort

The product should be installed on windows no less than 7' above floor level to prevent excessive brightness at standing eye level at the back of a room.

In some study sites where the existing blinds were disabled or exterior sun screens were removed, occupants expressed thermal discomfort from additional solar heat gain. This was mitigated by installing an additional sun control film on lower panes.

7.1.4.3 Economics

The economics of a retrofit are complex and the benefit cost ratio will be sensitive to many variables including product cost, labor costs, climate and sun exposure, glazing type and area, blinds operation, room size, photo-controls and wiring costs, the cost of electricity, and the room's occupancy schedule.

Consequently, this report provides benefit cost guidance for a generic condition. The electric lighting and HVAC savings attributable to retrofitting the DRF and photocontrols into a room use default ASHRAE schedules and equipment. 3M estimates the current (2013) cost of installation of the DRF and associated hardware to be $20/ft of window area covered by the DRF.

8. TECHNOLOGY TRANSFER

The following sections describe completed, ongoing, and future efforts to influence the DoD energy and water community through appropriate technology transfer.

8.1 RESULTS PRESENTATIONS

HMG was invited to present on emerging daylighting technologies at the California Emerging Technologies Coordinating Council meeting September 19, 2012. HMG presented field observations and data from field trials of the DRF. Attendees were excited to see new products poised to enter the marked and stated they were interested in tracking further development of the product. In addition, attendees were particularly intrigued by the daylighting simulation results as these surpassed those they had seen presented elsewhere.

Results have also been presented to the ESTCP at poster sessions and in annual reviews.

Results were also presented at the fifth international Daylighting Symposium, hosted by Velux in Copenhagen, Denmark, May 2013, attended by about 400 daylighting educators, practitioners and policy analysts.

8.2 DESIGN COMMUNITY IMPACTS

Simulations in this report used the Radiance three-phase method (a.k.a. the Dynamic Radiance approach) to estimate daylight availability in the spaces. The three-phase method was recently developed by Greg Ward of Anyhere Software in collaboration with HMG. Financial support was provided by Southern California Edison and Lawrence Berkeley National Labs (LBNL). This approach to modeling daylight availability built on the development of BSDF representations of complex optical systems by LBNL. The three-phase method has now been added to EnergyPlus by the National Renewable Energy Laboratory (NREL).

LBNL and NREL are working to make the tools for analyzing complex optical systems more widely available. LBNL is developing a library of BSDF files representing complex optical systems. NREL is drawing on this library to provide state-of-the-art simulation capabilities in EnergyPlus. Consequently, the simulation method used in this report is no longer restricted to a small group of researchers. Instead, due to LBNL and NREL's ongoing work, building science professionals will be able to simulate the energy savings in their buildings for 3M's DRF and other complex systems in the near future.