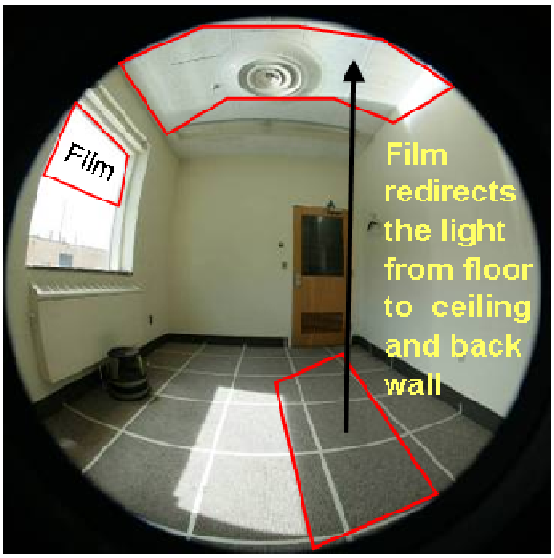

Daylight Redirecting Window Film

Daylight Redirecting Window Film
ESTCP Project No.: EW-201014
Cost and Performance Report

Raghu Padiyath (3M Company)

Contents

LIST OF FIGURES

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

ACKNOWLEDGMENTS

This work was performed under the project EW-201014 administered by Environmental Security Technology Certification Program (ESTCP) technology program of the Department of Defense(DoD). We would like to thank ESTCP program manager, Dr. James Galvin for his excellent support and guidance during the execution of this project. The support, patience and understanding of facility managers and other point of contacts at the six field sites where the program was carried out: Tom Giblin at Naval Station, Norfolk; Shawn Bogdan, Matt Siler and Kyle Hess at Naval War College, Newport; Marisela Leyva at Fort Bliss, TX; Clovis Vaughn and Andrew Burton at 29 Palms, CA; Doug Taber at NPS, Monterey; and Mitch Hailey at Naval Hospital, Bremerton; is greatly appreciated. We are grateful to the project team at Heschong Mahone Group (now part of TRC Companies): Lisa Heschong, Abhijeet Pande, Mudit Agarwal and Tim Perry for their immense contribution to this project. Finally, throughout the project, the guidance and counseling of Vern Novstrup at NAVFAC, Port Hueneme was much appreciated.

EXECUTIVE SUMMARY

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 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 Tables1 and 2. 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. With photocontrols alone, the savings are restricted to a lighting zone within 8 feet from the window wall and may be significantly reduced if the occupants keep the blinds closed, as frequently observed during this and 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.

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

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. Several studies have shown that better use of daylight can reduce energy demands by 20-40%, while reducing emissions and carbon footprint [1]. 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 [2,3,4]. 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 [5]. Most of these products are either not suitable or cost prohibitive for retrofitting to an existing window to make better the use of daylight.

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 demonstration, our goals were to verify the performance of daylight redirecting film, scale-up the prototype daylight redirecting film in a factory setting, quantify the potential for energy savings and qualitatively assess occupant satisfaction. We installed luminance monitors, utilized simulation techniques, and conducted surveys of the occupants. The surveys evaluated occupant comfort in terms of glare, light quality, and aesthetic quality of the installation. 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. Energy savings resulting from the DRF were not tracked during the project due to a number of reasons. Instead, a simulation exercise based on the measured optical characteristics is to predict the potential energy savings in three different climate and geographical regions.

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), FY 2008 (P.L. 110-181) and FY 2009 (P.L. 10-417)
- Executive Orders 13423 & 13514
- Executive Order Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding

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.

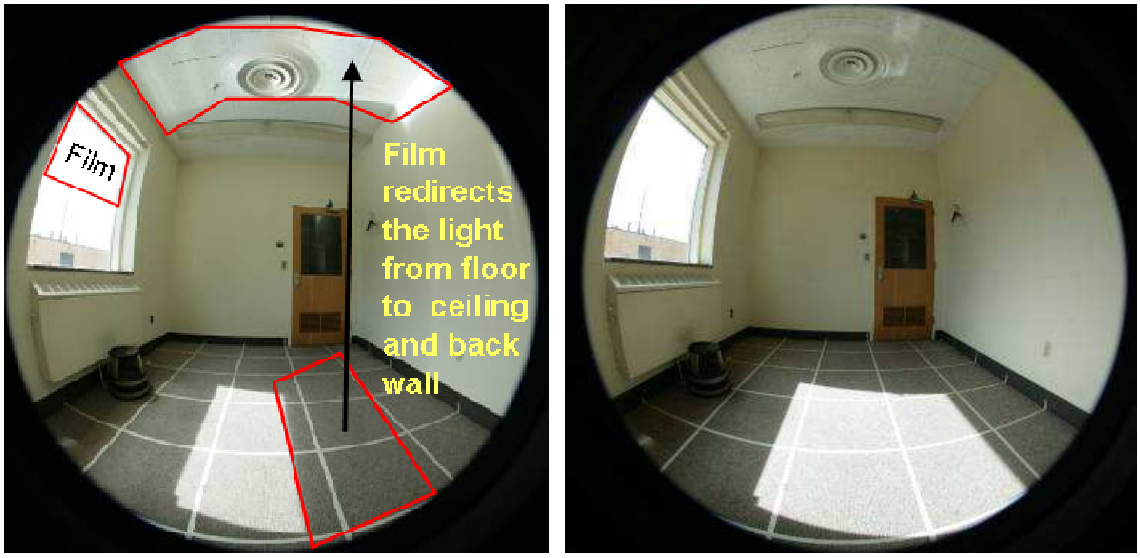

Figure 1. Photographs taken with a fisheye lens demonstrates the effectiveness of the daylight redirecting film.

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 Figure 1, the light incident on the upper portion of the window is redirected towards the ceiling and the back of the room.

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). 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, building and 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

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.

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 film also rejects 99.9 % of UV incident on the window resulting in longer lasting furnishings within the building and contributes 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 2. A detailed narrative for each of the performance metrics are presented in Section 6.

3.1 QUANTITATIVE PERFORMANCE OBJECTIVES

3.1.1 INCREASE DAYLIGHT ILLUMINANCE LEVELS

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. 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.[2]

3.1.2 ECONOMIC PAYBACK

Various costs related to the implementation were considered in the life cycle cost analysis to determine simple payback, and other related economic metrics.

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

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.

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.

---

[2] 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: 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. 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. *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

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Key Quantitative Performance Objectives				
Increase daylight illuminance levels	spatial Daylight Autonomy (sDA)	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%.
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 quantitative 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 2. Performance objectives outcomes

4. SITE/FACILITY DESCRIPTION

4.1 SITE/FACILITY LOCATION, OPERATIONS, AND CONDITIONS

Field studies were conducted at six locations. A quick summary of the sites is presented in Figure 3 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 3: Summary of spaces and occupants affected by the demonstration study

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. 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 still important.

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. Figure 4 shows the sample frame achieved for the study.

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

Figure 4. Climatic sample achieved

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 six final study sites do represent a range of build types and vintages, but are understood not to be perfectly representative of the general population of all DOD buildings.

4.2.3 FACILITY REPRESENTATIVENESS

The chosen sites encompass a variety of climates, 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. Of the 20 potential sites evaluated, 14 were rejected for one or more reasons.

4.3 RECRUITMENT AND SCREENING

Facility contacts were suggested to the study team by ESTCP liaison, 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 describing the purpose and conditions of the study was then sent to the facility managers. If they responded positively, they were then sent a request to provide additional information for further screening including but not limited to floor plans, photographs of workspaces, occupancy count and schedule, close-ups of the windows, blinds, awnings, etc. Ultimately, twenty DOD sites were contacted across the continental US and Puerto Rico, and 40 buildings were screened.

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).

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).

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. 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.

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.

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)[3]. 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. 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.

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. 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.

Two types of simulation studies were conducted:

- **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).
- **Whole Building Analysis:** The whole building analysis was built on top of the daylighting analysis using a process developed by HMG in prior research

[3] 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

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.

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.

Onsite monitoring began before the DRF was installed to ensure the treatment and control rooms had reasonably similar operation. 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.

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 was different for each site as seen in Figure 5.

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 5. Baseline monitoring period

The research team conducted multiple field visits to each 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 6.

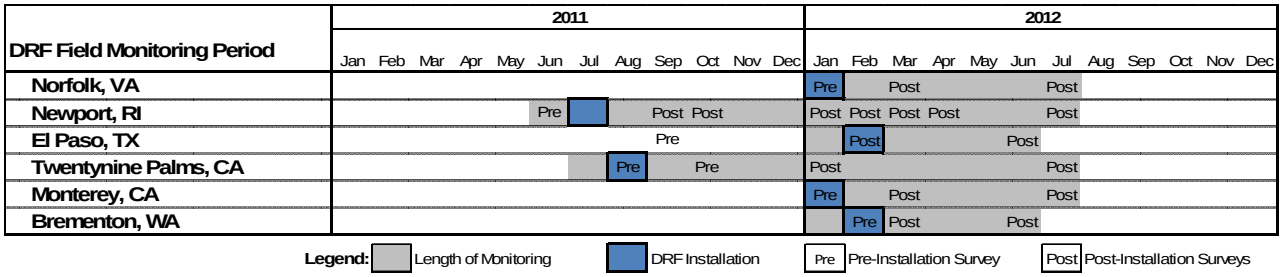

Figure 6. DRF field monitoring and survey timeline

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.

5.5 EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES

To ensure data validity and accuracy, the HOBO loggers were calibrated against LI-COR sensors. 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.

5.5.1 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. 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. 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

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. The site data collection had some problems with loss of data from data loggers and logger theft on one site. A snapshot of the data collected is provided in Figure 7

Site	Space Type	Monitored Data Collected	Survey Data Collected
Newport, RI	Small private offices, Library (open space)	Offices and Library	Yes
El Paso, TX	Small private offices, open office space	Open space	Yes
Bremerton, WA	Small private offices (exam rooms)	Exam rooms	Yes
Norfolk, VA	Open office area	Open office	Yes
Monterey, CA	Private offices	Private office	Yes
29 Palms, CA	Open office area, small offices (exam room, records room)	Open office	Yes

Figure 7. Status of data collection at demonstration sites

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 5.2.1.

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. Illuminance levels and spatial daylight autonomy were calculated via simulations.

DRF installation increases sDA by 11% to 19% which exceeded the performance objective target.

6.2 ECONOMIC PAYBACK

Several different economic payback analyses were conducted since the savings are a strong function of building location, orientation and most importantly, the energy price. Simple payback analysis shown Figure 14 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 8) and when blinds are always closed (Figure 9).

		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 8. 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 9. 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 10.

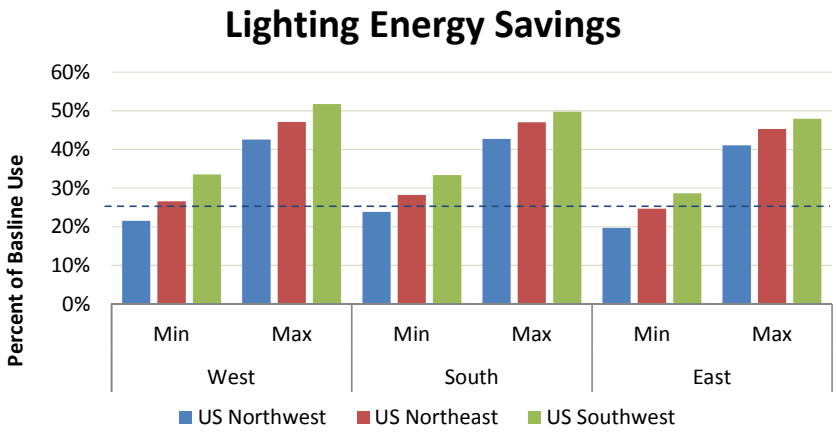

Figure 10. Percent lighting energy savings predicted from DRF and daylighting controls

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. 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.

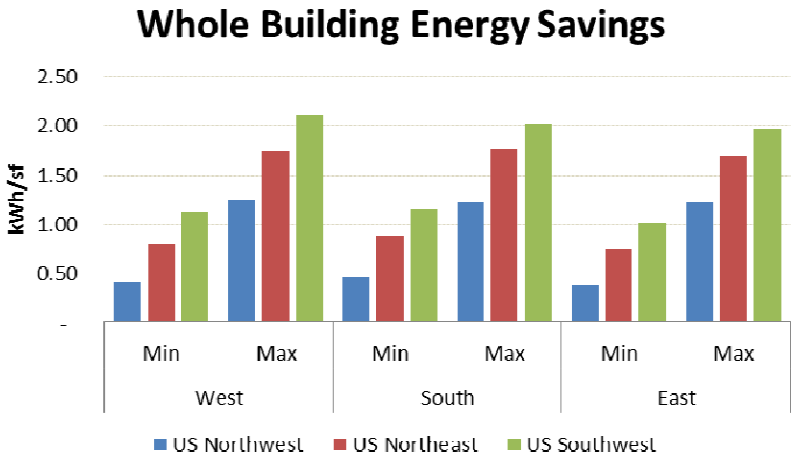

Figure 11. Predicted whole building energy savings

6.5 GREEN-HOUSE GAS EMISSIONS

Total electric and natural gas energy savings were converted to carbon equivalents and are presented in Figure 12. To develop the carbon equivalents, we used the US Environmental Protection Agency estimates[4].

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

The success criterion 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.

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 occupant feedback to the DRF retrofit. Based on this subjective feedback, the

[4] (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.

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 drivers 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 13. 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[5]	$11/ft^2
Installation costs	Labor and material required to install[6]	$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[7]	15 years
Operator training	Estimate of training costs	None

Figure 13. Cost model for the DRF technology

[5] 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.

[6] 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.

[7] 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 14). 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 14. Simple payback based on calculated energy savings.

In a related study, Lawrence Berkeley National Laboratory (LBNL) found that "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."

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 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[8] 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.

8.1 COMMERCIALIZATION PLAN

A number of different ways to make the technology available globally are being worked on. These include insulated glass units (IGU) with the daylight redirecting film laminated to the inside surface of the outer pane and a diffusing glass as the inner pane, triple pane windows with removable sash where the redirecting film is laminated to the outer surface of the inner pane of IGU and diffusing film on the removable sash, and redirecting film applied to a single pane window of buildings designed with monitor roof. Several commercial projects have already been completed using one or more of the configurations described above and many others are in various stages of implementation.

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

In addition, the DRF film with integrated diffusing film is currently under final stages of product development.

The demonstration project funded by DoD under the ESTCP project was immensely helpful in all aspects of commercialization of this technology. The project succeeded in demonstrating that the luminance away from the window is indeed increased significantly and the occupants value the additional light. The wide range of building types, weather and occupant profile evaluated in this project helped the team develop effective communication and sales tools to demonstrate to potential customers the value of increased daylight. Finally, the modeling and simulation demonstrated in this project is being extended to develop a generic tool to help architects and designers with achieving reduced energy consumption in the most effective way.

REFERENCES

1. V.H.C. Crisp, P.J. Littlefair, I. Cooper and G. McKennan, “Daylighting as a passive solar energy option: an assessment of its potential in non-domestic buildings”, Report BR129, BRE Press, UK.
2. J. Veitch, “Task lighting effects on office worker satisfaction and performance, and energy efficiency”. *Leukos*, 2(2), 85-96, 2005.
3. A.R. Webb, “Considerations for lighting in the built environment: Non-visual effects of light”, Energy and Buildings, 38, 721-727, 2006.
4. Heschong-Mahone Group, Inc. 2003.
5. Daylight in Buildings. A source book on daylighting systems and components. A report of IEA task 21 / ECBCS Annex 29, 2000.
6. R. Sullivan, L. Beltran, M. Rubin and S. Selkowitz, “Energy and daylight performance of angular selective glazings”, Proceedings of the ASHRAE/DOE/BTECC Conference, Thermal Performance of the Exterior Envelopes of Buildings VII, Clearwater Beach, FL, December 7 – 11, 1998.

APPENDIX A: MANAGEMENT AND STAFFING

Name	Organization	Phone	Email	Role in Project
Raghu Padiyath	3M Renewable Energy Division 3M Center 235-3D-02 St. Paul, MN 55144	Phone: 651-733-8952 Fax: 651-733-4289	raghupadiyath@mmm.com	Principal Investigator
Charles Marttila	3M Corporate R&D 3M Center 201-2E-23 St. Paul, MN 55144	Phone: 651-733-1667 Fax: 651-737-2590	camarttila@mmm.com	Co-investigator, optical modeling
Ruth Charles	3M Govt. R&D Contracts 3M Center 224-2S-25 St. Paul, MN 55144	Phone: 651-736-7939 Fax: 651-736-4777	rpcharles@mmm.com	Contract administrator
Lisa Heschong	Heschong Mahone Group 11211 Gold Country Blvd. Suite. 103 Gold River, CA 95670	Phone: 916-962-7001 Fax: 916-962-0101	lheschong@h-m-g.com	Sub-contractor, Consultants - building & energy
Tim Perry	Heschong Mahone Group 11211 Gold Country Blvd. Suite. 103 Gold River, CA 95670	Phone: 916-962-7001 Fax: 916-962-0101	perry@h-m-g.com	Sub-contractor, Consultants - building & energy
Abhijeet Pande	Heschong Mahone Group 11211 Gold Country Blvd. Suite. 103 Gold River, CA 95670	Phone: 916-962-7001 Fax: 916-962-0101	APande@h-m-g.com	Sub-contractor, Consultants - building & energy