FINAL REPORT

Architectural Daylighting System

ESTCP Project EW-201133

JANUARY 2015

John Olfelt
3M Company

Distribution Statement A

This document has been cleared for public release

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE *(DD-MM-YYYY)*
14/01/2015

2. REPORT TYPE
Final Technical Report

3. DATES COVERED *(From - To)*
7/1/11 – 12/31/14

4. TITLE AND SUBTITLE
Architectural Daylighting System

5a. CONTRACT NUMBER
W912HQ-11-C-0025

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
John Olfelt

5d. PROJECT NUMBER
EW-201133

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

3M Company
3M Center, Bldg 224-2S-25
St. Paul, MN 55144-1000

8. PERFORMING ORGANIZATION REPORT NUMBER
Lot 3010

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
ESTCP PROGRAM OFFICE
DR. JAMES GALVIN
4800 MARK CENTER DRIVE #17D08
ALEXANDRIA VA 22350-3600

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The project goal was to install the 3M architectural daylighting system with multiple sunlight collectors into an existing DoD facility to effectively reduce energy consumption and enhance the lighting quality and work environment. We expected The 3M architectural daylighting system would allow for active sunlight tracking, collection and concentration bringing more light into the building, penetrating light deeper into the core or below grade and allowing multiple discreet light extraction points. Overall performance was not as expected. The effect from the intensity of the sun on the hyperbola was greater than expected. 3M tried three different solutions but all were unreasonable to develop. The technology still needs improvement and the output was not as anticipated.

15. SUBJECT TERMS
Daylighting, reduce energy consumption, enhance work environment

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
UU					Guy Kallman
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	48	**19b. TELEPHONE NUMBER** *(include area code)*
UU	UU	UU			651 733-4113

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Table of Contents

List of Figures 3
List of Tables 3
List of Acronyms 4
Executive Summary 7
1 INTRODUCTION 9
1.1 Background 9
1.2 Objective Of The Demonstration 10
1.3 Drivers 10
2 TECHNOLOGY DESCRIPTION 11
2.1 Technology Overview 11
2.2 Technology Development 17
2.3 Advantages and Limitations of the Technology 19
3 PERFORMANCE OBJECTIVES 22
3.1 "Table 2" Summary of Performance Objectives 22
4 FACILITY/SITE DESCRIPTION 35
4.1 Facility/Site Location and Operations 35
4.2 Facility/Site Conditions 36
5 TEST DESIGN 37
5.1 Conceptual Test Design 37
5.2 Baseline Characterization 37
5.3 Proposed Design and Layout of System Components 39
5.4 Operational Testing 41
5.5 Sampling Protocol 41
5.6 Sampling Results 41
6 PERFORMANCE ASSESSMENT 42
7 COST ASSESSMENT 43
8 IMPLEMENTATION ISSUES 44
9 REFERENCES 46
APPENDICES 47
Appendix A: Points of Contacts 47

List of Figures

Figure 1: *Illustrates the sunlight collector tracking the sun* 11
Figure 2: *Illustrates the light traveling through the duct system* 12
Figure 3: *Illustrates 3M Reflective Film* 12
Figure 4: *Modeling of light output with LED lights on* 14
Figure 5: *Delivered illumination on 20' x 20' surface at 8 feet in Foot-Candles* 14
Figure 6: *Modeling of LED output within fixture cavity* 15
Figure 7: *Integrated Light Fixture* 15
Figure 8: *Integrated Lights installed in Office Space* 16
Figure 9: *Illustrates the output of daylight during normal sunny days* 16
Figure 10: *Illustrates the output of light from the artificial lighting on overcast days and shows sensor location* 17
Figure 11: *Design Phases for the Sunlight Collector* 18
Figure 12: *Energy analysts at global investment bank Citigroup (April 2013) expected results* . 31
Figure 13: *Site Map at Fort Bliss* 35
Figure 14**:** *Office space layout* 39
Figure 15**:** *Collector Placement and Duct Layout* 40
Figure 16**:** *Luminaries Placement* 40
Figure 17: *Hyperbola degradation* 44

List of Tables

Table 1: Lighting Technology Comparison 19
Table 2: Performance Objectives 22
Table 3: 3M Project Points of Contact 47
Table 4: Sub-Contractor Personnel 47
Table 5: Demonstration Site Contact 48
Table 6: Government Contacts 48

List of Acronyms

3M – 3M Company

AFF – Above Finished Floor

BLCC – Building Life-Cycle Cost

BP – British Petroleum

CT – Current Transformers

DoD – Department of Defense

DOE – Department of Energy

ECIP – Energy Conservation Investment Program

EO – Executive Order

ESTCP – Environmental Security Technology Certification Program

FY – Fiscal Year

GHG – Greenhouse gasses

GR&DC – 3M Government Research & Development Contracts Department

HDR – High Dynamic Range photography

HR – Human Resources

HVAC – Heating, Ventilation and Air Conditioning

IESNA – Illuminating Engineering Society of North America

IR – Infrared electromagnetic radiation

kW – Kilowatt

kWh – kilowatt hour

LBNL – Lawrence Berkeley National Laboratory

LPD – Lighting Power Density in watts / square foot

Lux – A unit of illuminance and luminous emittance. Illuminance is a measure of how much luminous flux is spread over a given area

MILCON – Military Construction

NRC – National Research Council (Canada), Institute for Research in Construction

NREL – National Renewable Energy Laboratory

NIST – National Institute of Standards and Technology

OSHA – Occupational Safety and Health Administration

PV – Photovoltaic

POC – Point of Contact

SDS – Sunlight Delivery System

SECNAV – United States, Secretary of the Navy

sf – Square feet

SIR – Savings to Investment Ratio

UBC – University of British Columbia

UGR – Unified Glare Rating

U.S. – United States of America

UV – Ultraviolet electromagnetic radiation

Acknowledgements

This work was performed under Project EW-201133 administered by Environmental Security Technology Certification Program (ESTCP) and funded by the U.S. Army Corps of Engineers, Humphreys Engineering Center Support Activity (HECSA) of the Department of Defense. We would like to thank ESTCP Energy and Water Program Manager, Dr. James Galvin for his support and guidance during the execution of this project. We are also grateful for the technical support provided by Mr. Scott Clark and Mr. Peter Knowles from HydroGeoLogic, Inc. The team is especially thankful for the support, patience, and understanding provided by our demonstration site contact, Mr. Don Vincent, Energy Manager at Fort Bliss.

Executive Summary

3M Architectural Markets Department developed the 3M™ Sunlight Delivery System and sought to validate this new technology in a larger field environment. This ESTCP project resulted in a full scale operational model designed, installed and tested at Fort Bliss, Texas. Results indicate that more developmental effort is needed in order to improve system reliability and performance.

The 3M Sunlight Delivery System actively tracks, captures and transports the sun's natural, full visible spectrum daylight into the interior space of the building where natural lighting is limited.

By harvesting free and abundant light from the sun, the 3M™ Sunlight Delivery System provides a more sustainable, energy efficient lighting solution that can result in reduced energy demand during high cost, on peak hours.

The 3M™ Sunlight Delivery System utilized a hybrid lighting solution option that incorporated additional artificial lighting and controls allowing for consistent light levels in overcast and night time situations.

The use of a system like this, utilizing daylight, has been shown to improve employee productivity, health, and morale and can also help contribute to green/sustainable building certifications across multiple credit categories.

The intent of this project was to build a full scale operational daylight harvesting system suitable for use at the Fort Bliss site after testing/validation was completed. Unfortunately a number of difficulties arose which halted the complete testing of the system as well as required it to be dismantled. These difficulties include:

- Unreliable tracking performance. Alignment is critical to the performance of this system. The tracking method included a feedback loop which fine tuned alignment based on sensors within the Collector. This loop was problematic due to software issues with the controller and physical changes in the optical path due to heat and dust.
- Poor hyperbolic reflector alignment and performance. This design depended on concentrated sunlight interacting with a hyperbolic reflector in order to deliver light long distances. Because of unanticipated heat build-up and concentrated sun energy, the team was not able to adequately protect the hyperbolic reflector from degradation ("tarnishing effect"). This greatly reduced the coupling of light into the ducts.
- Poor collector environmental protection. In this environment the project continually battled issues related to blowing sand. The clear Polycarbonate domes scratched almost immediately, though improved once a coating was applied. The collectors also collected a lot of dust internally, which necessitated frequent cleaning. A sealing system was never identified which could ensure a clean optical path.
- Too much dependence on remote support. Facilities management at Fort Bliss was not in a position to support the technical and mechanical requirements needed to keep the system operational. Given that the project never hit operational state, the team believed that continued monitoring and maintenance of the system would have been required even if successfully deployed. Tasks such as realignment of mirrors, replacing domes, cleaning equipment, updating tracking software, monitoring fail-safes, troubleshooting malfunctions, execution of system software, report generation and similar activities was beyond the job duties of personnel at the site. 3M was not in a position to provide long

term continuing support and the facility itself wanted as near a turn-key system as possible.

The following items were not completed:

- Balance of light output (interior spaces)
- Calibration of lighting (balance with LED lighting)
- Data Collection
- Lighting (lumen) levels
- Energy usage (reduction)
- Heat gain (included in energy saved)
- Human Factors – interviews/surveys

The Performance Objectives table in Section 2 provides details on individual objectives and results. To summarize, the installation was completed, but the 3M™ Sunlight Delivery System never finished final calibrations and final testing. Based on developmental elements needed to make the system operational, development cost were too great to proceed with the project.

Overall performance was not what was expected. The effect from the intensity of the sun on the hyperbola was greater than expected. 3M tried three different solutions to reduce this effect but all were unreasonable to develop. The technology still needs improvement and the output was not as anticipated.

1 INTRODUCTION

The goal was to install the 3M architectural daylighting system with multiple sunlight collectors into an existing DoD facility to effectively reduce energy consumption and enhance the lighting quality and work environment.

1.1 BACKGROUND

The DoD is seeking ways to achieve 10% of federal facility energy usage from renewable energy by the end of the decade.

Electric lighting accounts for 25% of a commercial building's total energy consumption and 40% of the electricity consumption in the United States. [1] In addition, the use of electric lighting results in substantial heat gain and cooling demands. Peak cooling loads are also increased as a result 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. [2]

As stated above, lighting accounts for a large fraction of the electricity consumption in facilities.

Natural daylight offers a sustainable, high-quality alternative to artificial lighting allowing electrical lights to be turned off or dimmed when not needed. Further, it is most effective during the peak electrical usage hours of the day when energy rates can be at their greatest.

In typical buildings, the penetration of daylight is limited to the zones very close to windows and as a result it is ineffective for daylighting the inner building core. Architectural daylighting, which is guiding daylight and transporting it into these difficult to reach interior spaces, is not a new idea; over the past few decades, there have been a number of daylighting demonstrations worldwide. Those installations showed that it is technically possible to transport daylight into the building interior.

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 rhythms, reduce stress, and improve productivity and attentiveness. [3, 4, 5]

The daylight availability is extremely dynamic due to the changing weather conditions from day-to-day and month-to-month. Building design and geographical location play an important role in determining the daylight availability.

Products that provide daylighting/sunlighting to the core of the building would be primarily skylights, tubular daylighting devices (Solatube™), and light fiber devices. Skylights and tubular daylighting devices are typically limited to top floor applications, they also need more access points in the roof, distribute limited amount of direct daylight access to all occupants, and the reflective material used is typically less efficient transporting light, then, for example, what could be realized using 3M's 99% Multi-Layer optical film. Effectiveness of light fiber devices is more constrained by distance due to material absorption. In order to address some of these needs 3M developed an active architectural daylighting system.

The 3M architectural daylighting system would allow for active sunlight tracking, collection and concentration bringing more light into the building, penetrating light deeper into the core or below grade and allowing multiple discreet light extraction points.

1.2 OBJECTIVE OF THE DEMONSTRATION

The main objective was to demonstrate that the 3M architectural daylighting system effectively reduces energy consumption and enhances the lighting quality and work environment in a selected DoD building. The 3M architectural daylighting system was installed at a selected building by qualified installers.

The objective of the field demonstration was to demonstrate that a core daylighting system can be integrated into existing buildings in a turn-key fashion with reliable performance and have architecturally-acceptable external collectors and internal light distribution systems.

The 3M architectural daylighting system is comprised of the following components:

- Sunlight collector/ concentrator- located on the roof
- Distribution System- to bring the light to the location intended
- Light Extraction System- Room lighting (to include LED for artificial light)

Despite several noteworthy attempts to alter the design/test configuration, the system did not perform as expected and further development is needed. The system was never tested after installation.

1.3 DRIVERS

Following legislations, executive orders and DoD 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 – Strengthening Federal Environmental, Energy, and Transportation Management
- Executive Order 13514 – Federal Leadership in Environmental, Energy, and Economic Performance
- 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.

2 TECHNOLOGY DESCRIPTION

The 3M architectural daylighting system was designed to allow for active sunlight tracking, collection and concentration to bring more light into a building, penetrating light deep into the core or below grade and allowing multiple discreet light extraction points. Optical components within the 3M sunlight collector direct sunlight through small openings on the roof or exterior walls, into the light ducts. Within the ceiling cavities, electric light fixtures are replaced with specially-designed dual-function light ducts that transport and distribute sunlight deep within the building. These light ducts can dually operate as efficient electric fixtures and they are controlled automatically to supplement the daylight when necessary.

2.1 TECHNOLOGY OVERVIEW

DESCRIPTION

The 3M architectural daylighting system pipes sunlight deep into buildings, thereby reducing electrical energy use in the building. The system has three major components: 1) An exterior sunlight collector (mounted on the roof), 2) light ducts which transport and distribute the sunlight into the building's core, and 3) specially-designed fixtures for delivery of daylight, combined with LED artificial lighting and controlled with sensors for optimum efficiency.

Sunlight is captured by an exterior collector: a sunlight collector mounted on the rooftop. The sunlight collector is programmed to follow the sun throughout the day whether it is shining or not and then resets at night. See *Figure* 1.

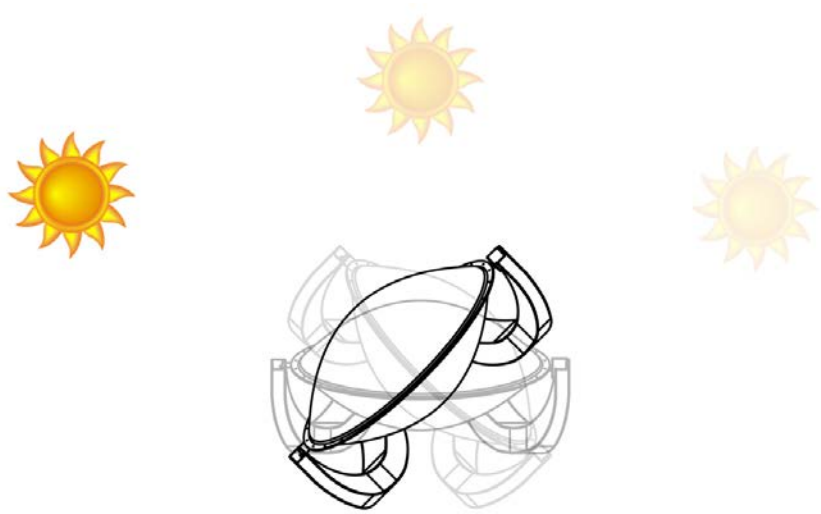

Figure 1: *Illustrates the sunlight collector tracking the sun*

The collected daylight is UV filtered then directed through the ducts into the core of the building utilizing 3M reflective film lined in the duct system. See *Figure 2*.

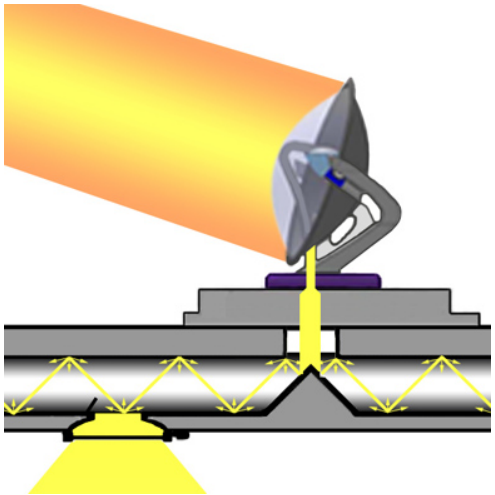

Figure 2: *Illustrates the light traveling through the duct system*

The 99+% reflective properties of the film (see *Figure 3*) used to transport and distribute the light (enabling a greater depth / distance that the sunlight can be piped into a building) plus the design of the sunlight collectors themselves (focusing on reliable performance and increased light concentration).

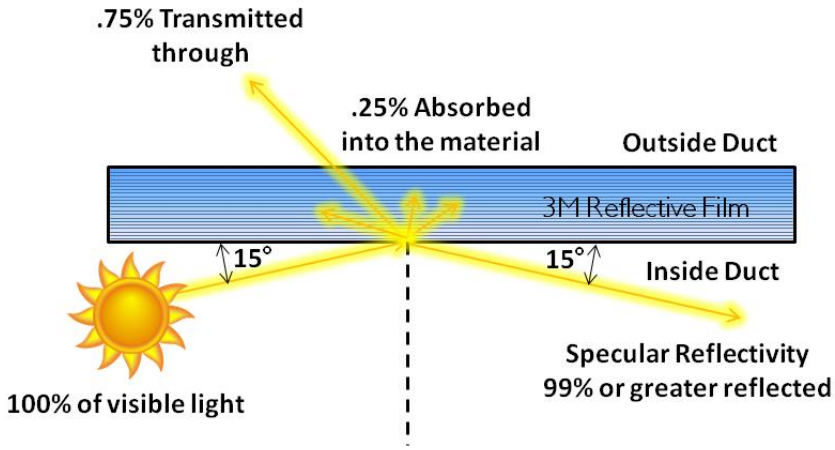

Figure 3: *Illustrates 3M Reflective Film*

Within the ceiling plenum, electric light fixtures are replaced with specially-designed fixtures for delivery of daylight, combined with LED artificial lighting.

The system could have delivered the sunlight in two ways.

- Separate illuminating fixtures - A daylight extraction fixture in addition to artificial lighting fixtures.

- Integrated illuminating fixtures - A fixture that integrated the supply of artificial light in combination with the extraction of daylight from the sunlight collector.

It was determined that due to the spacing, lack of ceiling space, and complexity of organizing two separate lighting systems, (along with all the other requirements in a ceiling – Diffusers, Fire protection, speakers, etc) that an integrated system was the only reasonable and practical approach for a long term solution.

Below is one example of the studies done to understand and model the integration of LED lighting and daylighting. This example below is one of the iterations used to design what became the standard installed fixture, which included both the daylight diffuser and LED light source.

Run#1
(2x2 Passive DoD with Housing (V1))

Materials

New Housing = VM2000, 99% Reflective

Upper Shell = Clear Prismatic, 85% Transmissive

Bezel Collar = White Paint 86%R

Textured Portion of Lens = Pebbled Textured Acrylic 94%T

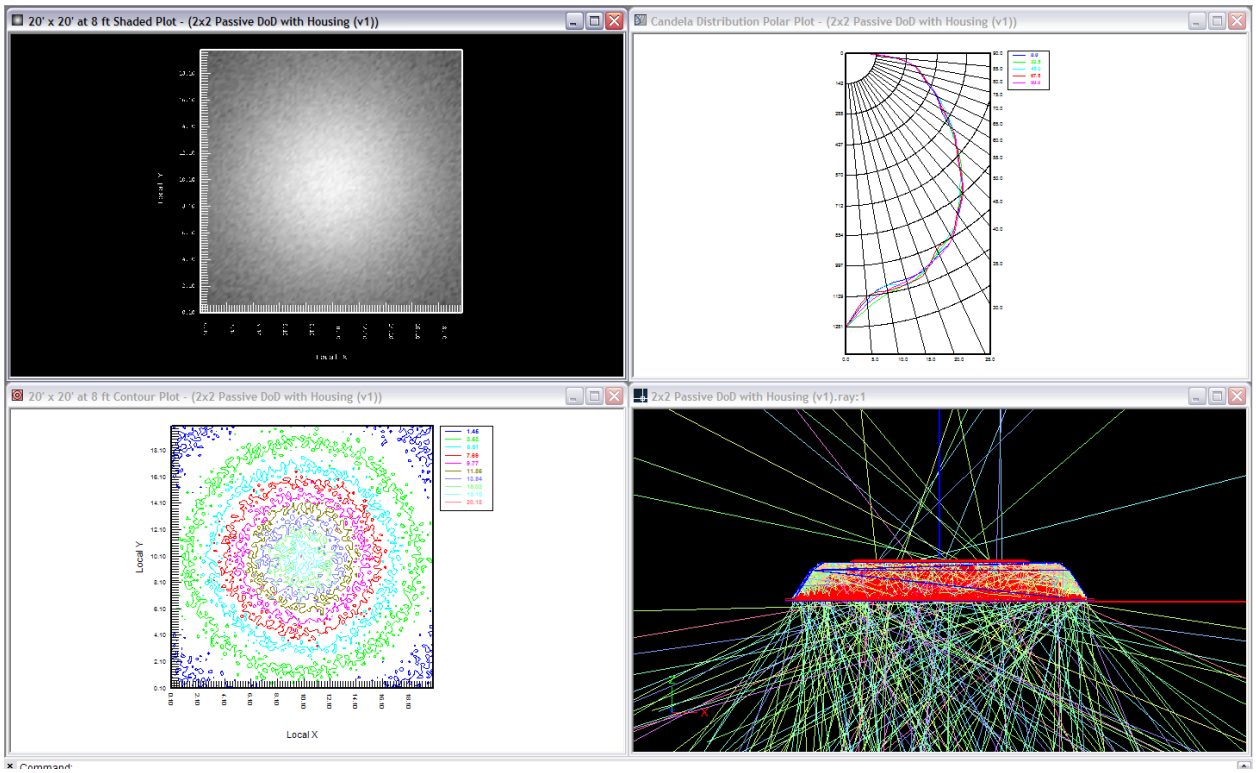

Figure 4: *Modeling of light output with LED lights on*

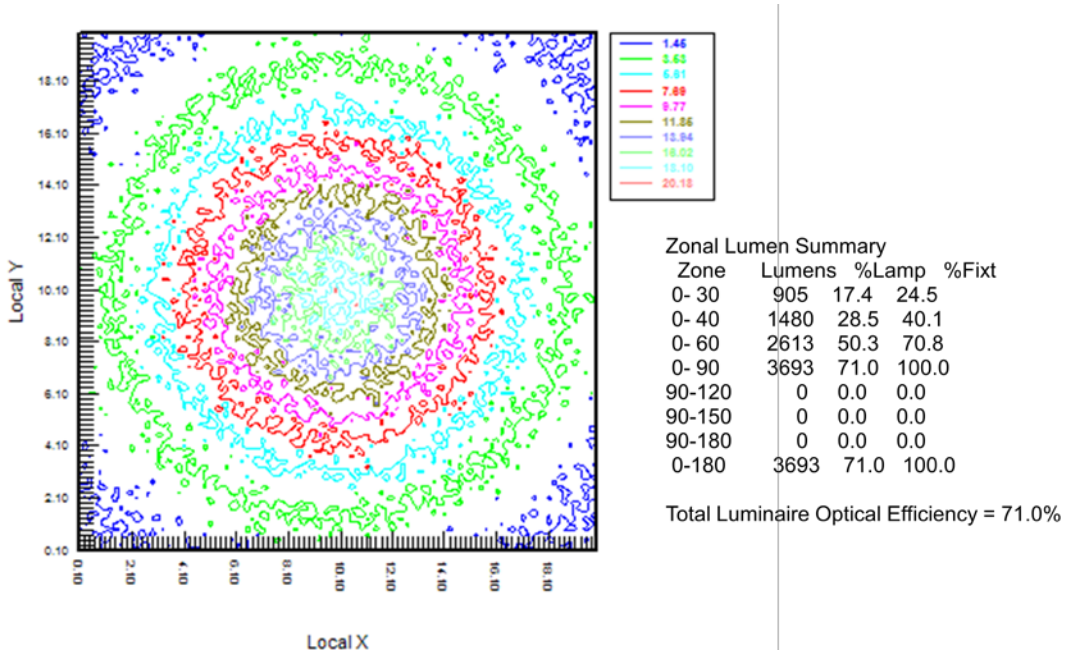

Figure 5: *Delivered illumination on 20' x 20' surface at 8 feet in Foot-Candles*

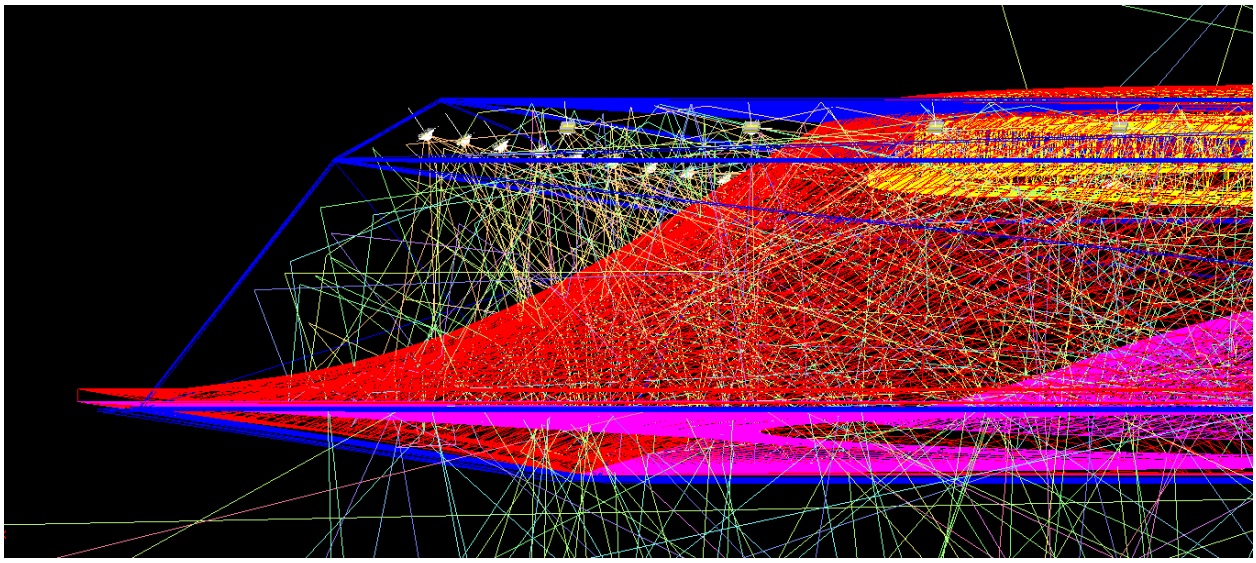

Figure 6: *Modeling of LED output within fixture cavity*

Additional modeling of the DOD Installation was completed showing a good room distribution of the LED artificial lighting (around the perimeter of the central daylighting duct) and the daylighting. The final integrated light fixture design and installation is shown below. See *Figure 7*

Figure 7: *Integrated Light Fixture*

Figure 8: *Integrated Lights installed in Office Space*

Individual sensors are assigned to each light fixture. When the daylight is limited, the sensor directs the increase in the artificial lighting from the LED portion of the fixture. See *Figure 9 and Figure 10*.

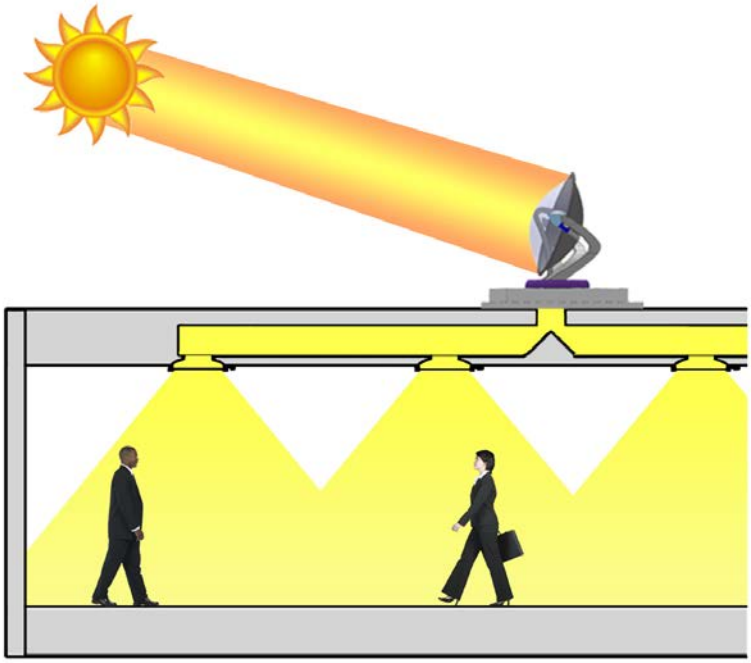

Figure 9: *Illustrates the output of daylight during normal sunny days*

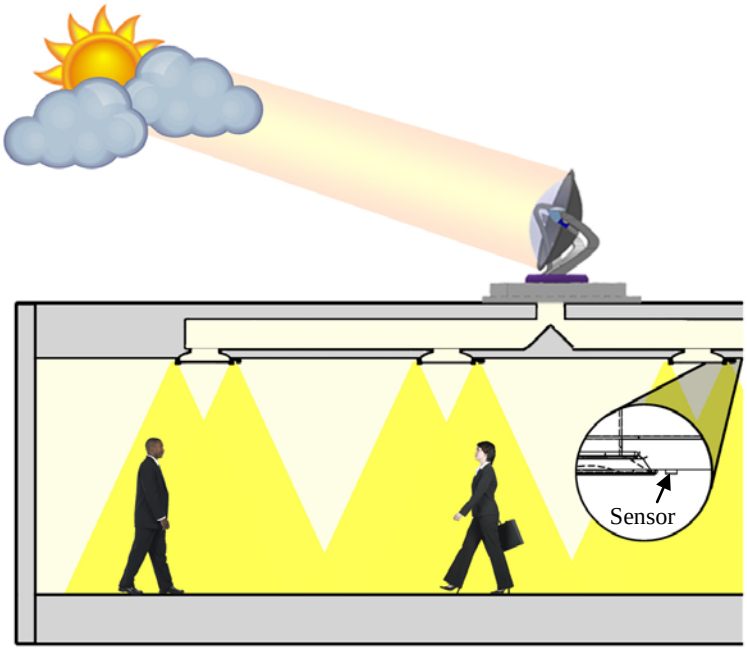

Figure 10: *Illustrates the output of light from the artificial lighting on overcast days and shows sensor location*

2.2 TECHNOLOGY DEVELOPMENT

3M was working to create a set of standard components which would reduce the cost of installation, engineering, and design as well as the cost of the 3M architectural daylighting system. It was 3M's intent to reach installed cost parity with high quality conventional lighting systems.

A key component to the success of driving daylight deep into a building through a series of duct works is the use of 3M's highly reflective mirror film. This core technology has been used for 15+ years in other applications, including passive daylighting systems. It was the intent of 3M to begin exploring ways of matching this 99+% reflector technology with a robust method of compressing, directing and extracting sunlight into building structures much deeper than what had been commercially demonstrated. This began with a series of small demonstration and on-campus developments, starting with the UBC (University of British Columbia) façade collector, which ultimately lead 3M to believe that a roof top collector was necessary. Below is a pictorial highlighting the progression of collectors to what was ultimately installed (3M2.0).

Design Phases for the Sunlight Collector

UBC Sunflower 3M1.0 3M1.5 (cost down version) 3M2.0

As the team worked through the various stages of development, the winning design had to demonstrate the right combination of cost and performance by maximizing light output and lowering system cost. The chart below shows this progression and why the 3M2.0 design was used for this installation.

Operational Effectiveness

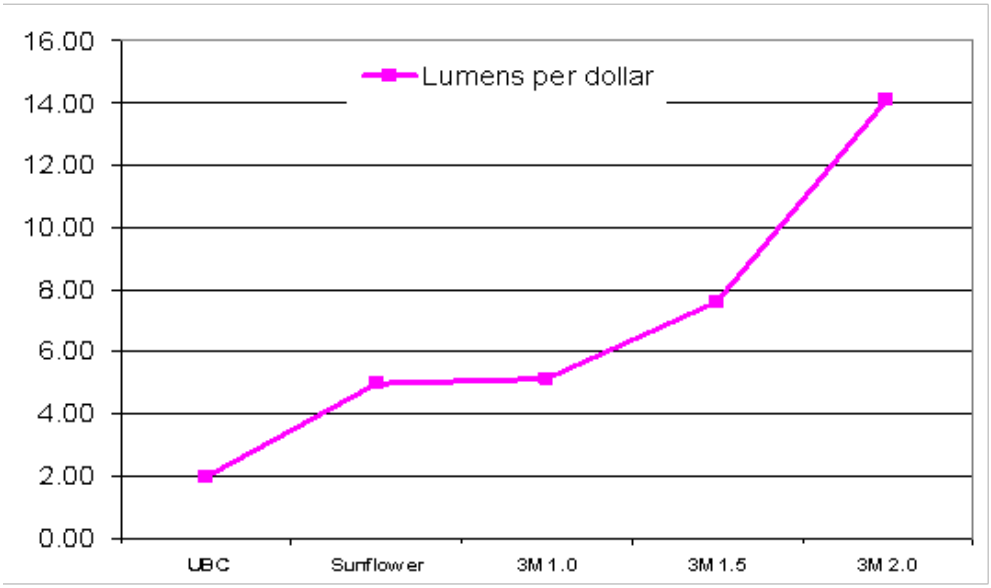

Figure 11: *Design Phases for the Sunlight Collector*

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

LIGHTING TECHNOLOGY COMPARISION

Table 1: Lighting Technology Comparison

Lighting Type	**Highlighted Attributes**	**Best Suited Conditions**	**Advantages/Disadvantages**
3M architectural daylighting system	Active sunlight tracking, collection and concentration bringing more light into a building, penetrating light deep into the core or below grade and allowing multiple discreet light extraction points.	Buildings requiring lighting deep within the core. Regions where sunlight is more prevalent.	Advantage: Uses sunlight for lighting of internal spaces during peak sunlighting hours and eliminates the need for any lighting power. Minimizes the generation of energy. Natural light can contribute to individual's well-being within the building. Disadvantage: Costly to install. Design needs further development. See performance limitations below.
Light tubes	Hollow structures that contain the light with a reflective lining for transport of light to another location, minimizing the loss of light.	Light transmission efficiency is greatest if the tube is short and straight. In longer, angled, or flexible tubes, part of the light intensity is lost.	Advantage: Offer better heat insulation properties and more flexibility for use in inner rooms. Provides natural light and saving energy. Light tubes do not require electric installations or insulation, and are thus especially useful for indoor wet areas. Disadvantage: Less visual contact with the external environment.
Skylights	Allow direct and/or indirect sunlight, via toplighting.	When allowing light to enter a room strictly from the roof. Toplighting works well with sidelighting to maximize daylighting.	Advantage: Daylight is available throughout the day from both ambient lighting from the sky and direct exposure to the sun. They can be fixed or operable. Disadvantage: Skylights are not overly energy efficient. A skylight in the roof will

			typically lose 35-45% more heat than the adjacent roof assembly. They are responsible for a large number of roof leaks.
PV + LED photovoltaic (PV)-powered, LED outdoor lighting system	Generates electrical power by converting sunlight into direct current electricity to power LED lights.	Mount anywhere so power panel is exposed to sunlight.	Advantage: PV installations can operate for many years with little maintenance or intervention after their initial set-up, so after the initial capital cost of building any solar power plant, operating costs are extremely low compared to existing power technologies. Significant energy savings. Disadvantage: Cost of purchasing. Cloudy areas may need more panels to produce electricity. Photovoltaic panels are made up of silicon and other toxic metals like mercury, lead and cadmium.
T8 Lighting	A fluorescent lamp or a fluorescent tube is a low pressure mercury-vapor gas-discharge lamp that uses fluorescence to produce visible light.	Commercial space. Low cost applications.	Advantage: Lower installation costs. Light can be more evenly distributed without point source of glare. Disadvantage: High usage ages lamp life rapidly. If broken, a very small amount of mercury can contaminate the surrounding environment. Light flickering. Disposal issues.

PERFORMANCE ADVANTAGES

The system is designed to use sunlight for lighting of internal spaces during peak sunlighting hours and eliminate the need for any lighting power and would assist in decreasing cooling load during those peak hours. This would increase the efficiency of any lighting system, and although it does not generate energy, it would offset the generation of energy.

The use of sun for light provides for a clean, renewable, and sustainable alternative to current lighting options.

The 3M architectural daylighting system reduces energy usage by utilizing natural daylight as a high-quality alternative to conventional artificial lighting allowing electrical lights to be turned off or dimmed when not needed.

The use of electric lighting contributes to substantial heat gain, due to inefficient light sources, resulting in increased cooling demands. Several studies have shown that better use of daylight can reduce energy demands by 20-40% while reducing emissions and carbon footprint.

The 3M architectural daylighting system was designed to deliver high quality; glare free, full spectrum lighting.

PERFORMANCE LIMITATIONS

Film performance – 3M did not have complete data on the life of the film in this application of concentrated sunlight. The effect from the intensity of the sun on the hyperbola was greater than expected.

Total system performance – The system was completely installed, but operation of the system was limited to days, not months or years.

Sunlight collector – The technical risks associated with the sunlight collector were twofold: weatherability and service life. (1) Weatherability –Light intensity proved to be a problem for the collectors (2) Service Life – the 3M sunlight collector that was used in the DoD installation was undergoing testing prior to installation. The initial proposal, noted that 3M was in development of this sunlight collector to increase efficiency, decrease cost and improve long term functionality. 3M tried three different solutions but all were unreasonable to develop. The technology still needs improvement and the output was not as anticipated.

Reflective Films – 3M reflective films have been used in commercial installations of tubular daylighting devices for more than 10 years. Based on our previous weathering results and real installations our film laminate meets tubular daylighting devices average photopically weighted reflectivity specifications of greater than 98% for 20 years when the tube is protected from UV radiation, provided that the light pipe tube remain fully scaled from both water and unfiltered UV light. The challenges encountered in this installation were with the increased concentration of sunlight and the complexity and difficulty in providing a complete airtight seal in the collector and overall duct system.

COST LIMITATIONS

Based on developmental elements needed to make the system operational, development costs were too great to proceed with the project.

3 PERFORMANCE OBJECTIVES

3.1 "TABLE 2" SUMMARY OF PERFORMANCE OBJECTIVES

Performance objectives are split into two sections: quantitative performance objectives and qualitative performance objectives. Both the quantitative and qualitative performance objectives for the 3M architectural daylighting system are summarized in the table. Text following the table discusses the metrics and provides supporting information necessary to interpret the results.

General result summary: The installation was completed, but the 3M™ Sunlight Delivery System never finished final calibrations and final testing. Based on developmental elements needed to make the system operational, development costs were too great to proceed with the project. The result is many of the final tests were never completed as shown in the results column.

Table 2: Performance Objectives

Performance Objective	**Metric**	**Data Requirements**	**Success Criteria**	**Results**
Quantitative Performance Objectives				
Facility Energy Usage	Percentage	Meter readings of energy used in area before and after installation; 5000 sf test space	75% reduction in daytime lighting power	Never measured- not stable enough, to be tracking for long periods
Emissions	Conversion of energy usage into CO_2 equivalents	CO_2-equivalent conversion factor for national level usage	Net reduction in CO_2 emissions	Never calculated.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Facility Metering	Number	(1) 5000 sf space Heat Gain	Sub-metered; allow confirmation of the energy savings due to the daylight dimming system compared to an all-on operation Heat gain will be monitored in three locations (1) inside the sunlight collector where it attaches to the duct (2) 3-5ft away from the duct in the ceiling plenum (3) next to the duct wall. Measurements will be taken before system start-up and then monitored after the system is up and running.	Never metered. A period of time greater than 3 days was needed to provide meaningful data. This was not achieved.
System Maintenance	Change in maintenance practices	Interviews with site maintenance staff	System does not create significant maintenance needs	Maintenance would have been required long term and would have added to the cost and further diminish any overall cost saving.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
System Performance over Distance and Time	Number	Lumen Levels gathered over time at different locations	Less than 20% light loss (1%/meter) from entrance to beginning of light extraction. And less than 2% light loss over 1 year time period.	Never measured.
System Integration	System cost Contractor analysis of installation efficiency System performance tracking: cost/ time between repairs, material performance over time due to degradation over time or by external factors such as a deflection of the sunlight collector from excessive wind loads Meets building code	Post-installation building inspection Monthly testing of the light output of the system to test quality and levels	Contractor sign-off and building owner receipt of completion. Light output performance of the system remains at least 90% intensity over a 20 year period	No other testing was completed on the project. System was successfully installed, and integrated with the lighting. The quality of the duct installation required to have an airtight seal was not achieved. It was determined to be too difficult to economically achieve.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
System Economics	Life-Cycle Cost, Full-load equivalent hours provided by 3M system Peak lighting load intensity (kW/sf) reduction Net kWh impacts on lighting and HVAC	Life-Cycle Cost, Full-load equivalent hours provided by 3M system Peak lighting load intensity (kW/sf) reduction Net kWh impacts on lighting and HVAC	Savings to Investment Payback period < 20 years resulting from reduction in need for electrical lighting and whole building energy use 75% reduction in daytime lighting power	None available- Determined to be not cost effective to other energy savings methods.
Availability	Hours	10 hours per day, or 3,650 hours per year of light	Data gathered with loggers will output how much natural light vs artificial light was used to know approximate how many hours of sunlight was achieved	Never measured.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Light Quality	Likert scale and open response questions about glare and visual comfort Frequency of use Glare index (UGR) and user ratings of glare (DeBoer scale) Absenteeism as one measure of occupant productivity	Evaluations, Surveys of occupants before and after installation of the 3M architectural daylighting system Luminance maps ("high dynamic range photographic images") of the space from typical viewpoints User survey data with DeBoer scale response Record of absenteeism before and after installation	Maintenance or Reduction in glare, Increase in perception of visual comfort, Positive subjective usability satisfaction, Absenteeism remains stable or reduces No or negative change in glare index ($\Delta <= 0$) Maintenance or reduction in subjective glare ratings	Surveys never conducted. The observations over the short period of operation demonstrated some color shift and difficulties in balancing the system from light fixture to light fixture.
Reliability	Hours	3,650 hours per year of available time, assuming 5% downtime you'd have 3,468 hours Hours of maintenance time	Data gathered with loggers will output how much daylight was achieved No adjustments after original installation	Never measured, too many moving parts and systems for long term reliability.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Usability	Likert scale and open response questions about quality of occupant engagement with system via controls Operation of controls (usage frequency) Ease of installation by installation technicians, measured against number of concerns/frustrations	Survey of occupants before and after installation of the daylighting system Operation observations Evaluations measuring comments about the system to count the number of positive comments and negative concerns about the system, space/fixture modifications over time by occupants, questions about the method of installation, and speed and effort of installation by installation technicians	Increase perception of control quality due to improvement in usability and engagement with system Maintenance of or Increase in subjective usability satisfaction ratings Positive comments > Negative concerns by occupants, few installation questions, and installation completed in or under designated timeframe	Collectors went through ongoing changes and troubleshooting issues. Dust collected within collectors due to inadequate seals in the ducts, roof collectors not being adequately sealed and the difficult and inadequate interface between the collector and ducts.

Qualitative Performance Objectives				
User Satisfaction	Acceptance of light adequacy by occupants of building, satisfaction by building owners, and ease of use by installation technicians, measured against number of concerns by each group	Evaluations measuring comments about the system to count the number of positive commendations, neutral comments, and negative concerns about the system, space/fixture modifications over time by occupants, questions about the method of installation, and speed of installation by installation technicians	Positive commendations > Negative concerns by occupants and owners, space modifications not due to cope with unwanted effects of the system, few installation questions, and installation completed in or under designated timeframe	Survey never conducted.
Behavior Change	Number	Survey and/or interview results describing small/large behavior changes	Surveyed occupants list no behavioral changes or positive behavior changes	Survey never conducted.
Security	Level	Expert opinion	3M sunlight collector remains functional while installed on the roof during all normal situations.	Never in operation.

FACILITY ENERGY USAGE

Energy savings, and the ability to reduce building energy lighting usage, were to be monitored with equipment that would log hourly energy usage patterns on each lighting circuit and task light. 3M was also trying to achieve complete reduction in the overall building energy usage with the daylighting system.

Result

The system was not stable enough to be tracked for long periods.

EMMISSIONS

Part of the project was to study if a reduction in CO_2 emissions was possible. By converting whole-building-energy savings into CO_2 emission savings the net reduction in CO_2 emission could be calculated.

Results

Reduction in CO_2 emissions was never calculated after system was installed.

FACILITY METERING

Heat gain was to be monitored in three locations (1) inside the sunlight collector where it attached to the duct (2) 3-5ft away from the duct in the ceiling plenum (3) next to the duct wall. Measurements were to be taken before and after the start up. By metering heat gain, the team hoped to confirm the energy savings due to the daylight dimming system compared to an all-on operation.

Results

Facility metering was never conducted after system was installed. A period of time greater than 3 days was needed to provide meaningful data. This was not achieved.

SYSTEM MAINTENANCE

The maintenance staff would have given the best input into the system, after installed, and what it required for ongoing maintenance.

Result

Maintenance would have been required long term and would have added to the cost and further diminish any overall cost savings.

SYSTEM PERFORMANCE OVER DISTANCE AND TIME

It was necessary to the project to get a real world experience on system performance. The system performance was to be measured at the beginning of the duct and again at the first point of light extraction. System performance needed to be measured over time to understand what factors contributed to loss of light, such as dust and contaminants.

Results

Loss of light over a set time frame was never measured after system was installed.

SYSTEM INTEGRATION

System was successfully installed, and integrated with the lighting. The quality of the duct installation required to have an airtight seal was not achieved. It was determined to be too difficult to economically achieve.

Results

Based on developmental elements needed to make the system operational, development cost were too great to proceed with the project.

SYSTEM ECONOMICS

One method used for evaluating the long term value of the daylighting system is a Building Life Cycle Cost Program. There were two primary reasons this (or any other cost justification analysis) was never completed:

1. Product Development Costs was not completed to a level acceptable to the market. Because of the cost required to make this system economically feasible from an energy savings model, 3M made the decision to terminate the program.
2. Building Modification Costs were a substantial portion of the project and would never be consistent from project to project… a) in either the Sunlight collect installation, or b) in the duct distribution system.

The following paragraphs will explain the challenges and issues the Sunlight Collection and Distribution System went through and why the cost projections were never realized or completed and the system was discontinued.

Product Development Costs.

To go into more detail on reasons for the discontinuation of the 3M Sunlight program, from the product perspective, there are two areas that can be broken down in more detail. First, is long term material performance, and second, is the cost of the collector system.

- Material Performance. For an architectural application on the exterior of a building, the designer, architect, or engineer will expect a minimum performance (or life expectancy) of 20 years. Warranties are not always available for 20 years, but a reasonable expectation for 20 year life is expected, at a minimum. Because of the concentrations of sunlight (100:1) needed to justify the component cost downstream of the collector (ducts, light extractors, etc), the materials were exposed to concentrations previously not tested in long term testing and did not perform at levels needed to make this successful. Developments of products that will have the ability to withstand these extreme sunlight concentrations are not available within 3M or in the market at this time. Photos of the parabolic reflector (in the report) are one example of this. Another is the ducts themselves- especially lengths close to the sunlight collector.

Cleaning of the reflective material was also a concern. The initial goal of the system was to have a sealed system - without the ability of dust and debris to collect. The 3M reflective material is susceptible to surface abrasion in the cleaning process and to add a hard coat to improve this performance adds costs and reduces the reflectivity a small percentage. In reality, a sealed

system is not realistically achievable over a system due to the various trades installing the duct system and the air tightness of the sunlight collector itself.

- Cost of the Sunlight Collector System. As shown previously in this report, our anticipated goals were a continual development path of cost reductions for the collector system costs. Some initial system changes demonstrated promising results, but then were hindered by material deficiencies (that added costs) and the true realized costs of mechanical, structural, and development costs, that did not provide a path to economic viability.

In Figure 6, we showed the potential cost per lumen from an initial 3M collector at 5 lumens/ dollar to 14 lumens per dollar. This was over a relatively short period of time and the hope was that through further development, this trend would continue. (This was for cost of the Sunlight Collector only). This trend did not continue, and as mentioned earlier, additional material development activities were required as well as a very large reduction in overall component and assembly costs.

Another factor 3M had to compete against in competitive energy savings product offerings. The major indirect competition was the reduction in costs for LED's and Photovoltaic systems. Below is a chart (See *Figure 12*) demonstrating the continuing progress Photovoltaic systems have made and continue to make in regards to reducing costs per delivered watt.

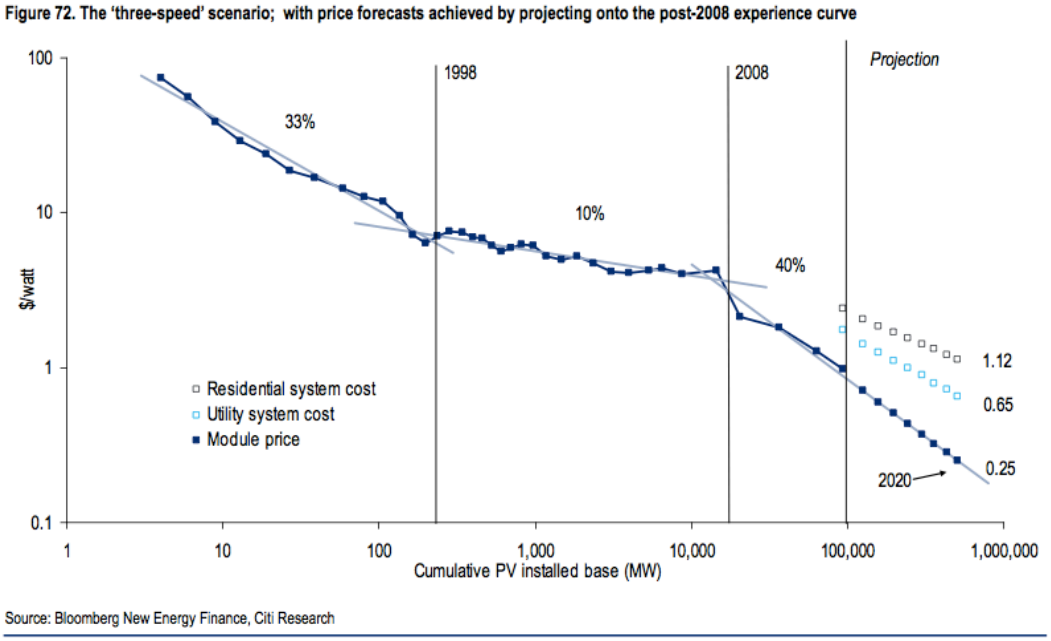

Figure 12: *Energy analysts at global investment bank Citigroup (April 2013) expected results*

Any Sunlight Collecting system has the inherent disadvantage of requiring a backup lighting system. In effect, the Sunlighting system is a redundant system. For nighttime use, or use during overcast or cloudy conditions, an alternative lighting system is required, most likely an LED system. Since an alternative lighting system is required, the only component needed (or added) would be the energy source - a photovoltaic system. All these system costs are continually being improved and reducing in costs. The PV system also has the advantage of

working, collecting energy, (albeit to a lesser extent), during overcast/ cloudy conditions - providing a longer term of operation that the concentrating sunlight collecting system.

Building Modification Costs (for Sunlight Collector and Distribution System):

The biggest impact on the installation of the system will be if the installation is in new construction (or deep retrofit) or in an existing structure. Existing buildings are an important aspect and will be the majority of opportunities for any new product development. In New York City, over 90% of the buildings today will still be existing and used in 2030. This means that a system that does not have a cost effective option for existing buildings, will have limited opportunities in the market.

- Sunlight Duct Installation. This process was more difficult than anticipated due to the various trades and work done in the ceiling plenum space. Un-like mechanical ducts, which use pressure to push air through the system, lighting ducts are required to have straight runs whenever possible because any turn or deviation results in a great reduction in the amount of delivered light. In existing building, there is limited locations for straight runs due to all the systems already in place - lighting, mechanical, and fire protection – plumbing, electrical, and roof drains can also provide challenges for light ducts.

As demonstrated in the project, the installation costs of over $350,000 are an impediment /obstacle to any energy cost justification. Assuming we were able to collect and distribute 50% of the 80,000 theoretical lumens/ collector and using the 5 collectors installed at Fort Bliss, the installed cost alone would be approx. $1.50/ lumen or 0.66 lumens/$. This in installation costs only, in an existing building that had relatively good ceiling clearances for adequate duct passage. The structural reinforcement was slightly more than the majority of buildings, since this was a Butler Metal Building and roof system. (Metal Buildings are quite flexible and much higher deflection limits than conventional construction).

Overall new construction would have a substantial reduction in the installation costs, but would need to be determined uniquely on each project, and would still be substantially more than the alternative PV + LED system only.

AVAILABILITY

One outcome of this project was to better understand the amount of time and the period of time during the day sunlight was available and useful to the system. Sunrise and sunset data would have determined the hours of available sunlight. Data loggers would have been used to track how many hours of sunlight was received and useful to the system.

Results

Data loggers were never used to log the amount of available light during the day after system was installed.

LIGHT QUALITY

Understanding how the light affected occupants in their individual stations as well as the quality of light and consistency from station to station would be measured by conducting surveys with the occupants to evaluate the quality of the illumination, visual-comfort, and perception of glare in their work space.

Results

Surveys were never conducted after system was installed. The observations over the short period of operation demonstrated some color shift and difficulties in balancing the system from light fixture to light fixture.

RELIABILITY

Logging operational hours (full light and low light) with data loggers would show how much daylight was achieved.

Results

The system was never measured. Too many moving parts and systems for long term reliability.

USABILITY

One study was to monitor ease of installation. Receiving input from the installation technicians would be important information to collect and apply towards installing new projects into future new building construction or retrofitting into existing buildings.

Results

During installation, collectors went through ongoing changes and troubleshooting issues.

Dust collected within collectors due to inadequate seals in the ducts, roof collectors not being adequately sealed and the difficult and inadequate interface between the collector and ducts.

USER SATISFACTION

The goal when installing the system was to exceed more than 30-foot candles in the test office space which would provide adequate daylight illuminance levels. Acceptance of light adequacy by occupants of the building, satisfaction by building owners, and ease of use by installation technicians, measured against number of concerns by each group would have allowed us to compare positive and negative comments and calculate user satisfaction.

Results

Surveys were never conducted after system was installed.

BEHAVIOR CHANGE

It was our intent to interview occupants to determine any behavioral changes from before and after the system was installed. Some of the feedback we were looking for from the occupants was reduction in absenteeism, and an increase in occupant productivity.

Results

Surveys were never conducted after system was installed.

SECURITY

System was never in production to observe long term weather related problems.

Results

During installation dust collected within collectors and the hyperbola was seeing degradation within the collector from the intensity of the sun.

CONCLUSION

The project was fully installed but did not perform as expected. The testing measurements and survey results were never conducted. Based on developmental elements needed to make the system operational, development cost were too great to proceed with the project.

4 FACILITY/SITE DESCRIPTION

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The site selected to implement the demonstration plan of the 3M architectural daylighting system is Building B-20137: Stryker Vehicle Maintenance Building, Fort Bliss, TX. The space within the building being renovated is 5000 sf located on the top floor. This building was selected as a good candidate for the Sunlight Delivery System demonstration because:

Building B-20137 Vehicle Maintenance building-

- Large open office area (meets program requirements) approx. 5,000 SF.
- Good access for installation
- Good southern exposure

- Building 'owned' by DPW- (Directorate of Public Works)
  - Occupants have changed since original selection
  - Occupant deployment now expected late November 2012- returning August 2013.
  - New occupants are expected to use the space.

A total of five collectors were installed on the roof of building B-20137. Four of the collectors delivered sunlight to 76 fixtures in the renovated office space (see Figure 13) on the second floor. The fifth collector delivered sunlight to 6 fixtures in the hallway on the first floor between the vehicle maintenance bays.

<u>LOCATION/SITE MAP</u>

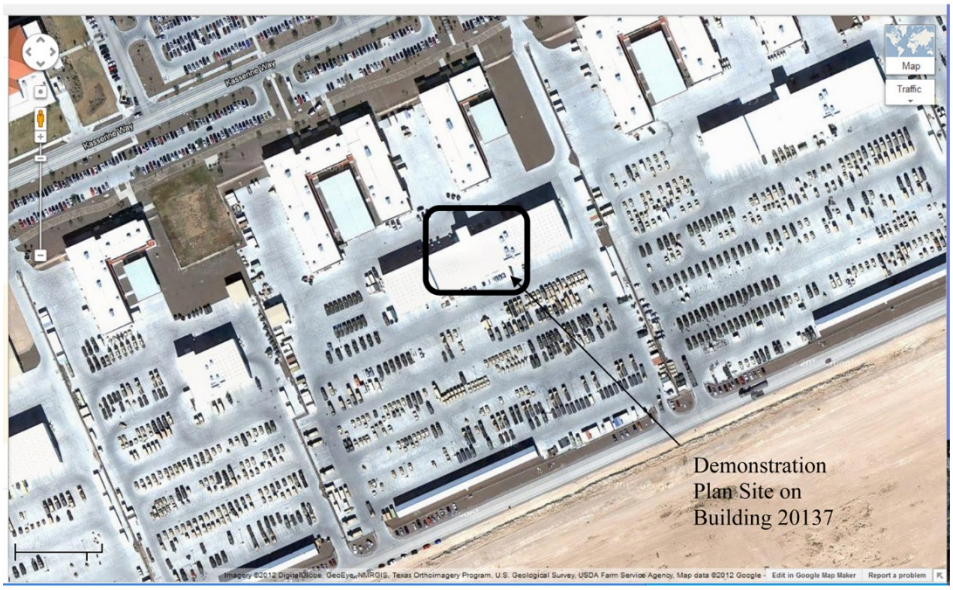

Figure 13: *Site Map at Fort Bliss*

4.2 FACILITY/SITE CONDITIONS

Fort Bliss - El Paso, TX

Fort Bliss receives an average of 302 days of clear skies and is located outside of major earthquake zones. The fort is currently motivated in targeting net zero resource use by 2015. The southwestern United States is an ideal location for the Sunlight Delivery System. With the 300 plus days of clear skies, the system is more effective than being located in a northern location. To receive the biggest advantage of sunlight, interior rooms without any windows would be preferred.

5 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

Tests were performed during installation to measure product feasibility and performance. All proposed testing after installation to support performance objectives was never conducted since the control system caused a malfunction and the systems needed to be shut down. After installation, the collectors never ran long enough without manual interact to perform the tests and collect pertinent data.

5.2 BASELINE CHARACTERIZATION

The following were the test results conducted during installation.

Hyperbola Temperatures (from system software):
This test was used to determine if the system temperature for the hyperbola matched an external temperature probe.

- Collector #1 = 122C
- Collector #2 = 153C
- Collector #3 = 138C
- Collector #4 = 124C (while tracking the sun)
- Collector #5 = 55C (this was just at the start of tracking. It was increasing at the same rate as the other collectors at approx. 0.1C/second)

Conclusion: After comparing the system temperatures for the hyperbola versus an external temperature probe, it was concluded that the hyperbola thermocouples were operating appropriately. This was very important to ensure that the closed loop control system was working properly.

Office Space Light Measurements
This test determined the light distribution from the collectors after we were able to get them running.
Time: 1500
Exterior conditions: Hazy
Collectors: #3 and #4 ONLY (Collectors #1 and #2 were not operational)
Interior conditions: Shades open, LEDs on, and SDS #3 and #4 (Total Light)
Conclusion: The light distribution from each collector was not evenly distributed among the luminaires which required balancing the system.

Collector	Luminaire	Lux	Luminaire	Lux
#3	50	n/a	60	n/a
#3	51	410	61	530
#3	52	501	62	720
#3	53	398	63	600
#3	54	642	64	804
#3	55	605	65	700
#3	56	580	66	n/a

#3	57	560	67	620
#3	58	530	68	523
#3	59	470	69	391

Collector	Luminaire	Lux	Luminaire	Lux
#4	70	n/a	80	614
#4	71	n/a	81	788
#4	72	908	82	990
#4	73	642	83	890
#4	74	1004	84	1103
#4	75	771	85	977
#4	76	831	86	826
#4	77	799	87	870

n/a = cube not available
Luminaire number refers to the fixture location in the office space. Reference Figure 10 for the location of each fixture.

Office Measurements
Once all the collectors were running, we were able to collect the following data from select fixtures (fixture output, LUX):

May 8th, 1225	10	19	#1	40	49	#2	60	69	#3	80	87	#4
SDS Only	104	132	332	49	147	252	125	38	118	138	370	195
SDS & Window	138	133	298	39	160	245	117	48	256	192	476	556
SDS & LEDs	591	646	905	449	584	673	613	704	670	720	1128	743
Total Light	583	651	746	465	574	684	776	646	766	832	1170	992

SDS Only: Sunlight Delivery System (SDS) only being used in the office space (LEDs turned off and window shades drawn closed
SDS & Window: Sunlight Delivery System with the window shades open
SDS & LEDs: Sunlight Delivery System with the LEDs turned on and window shades drawn closed
Total Light: Sunlight Delivery System, LEDs turned on, and window shades open

Luminaire number refers to the fixture location in the office space. Reference Figure 10 for the location of each fixture.

Conclusion: There was a wide distribution of light output from each collector and across the collectors. When the LED's were turned on, their output was much greater than the output of the collectors. Ducting needed to be balanced from each collector to have a more even distribution.

5.3 Proposed Design and Layout of System Components

SYSTEM DESIGN

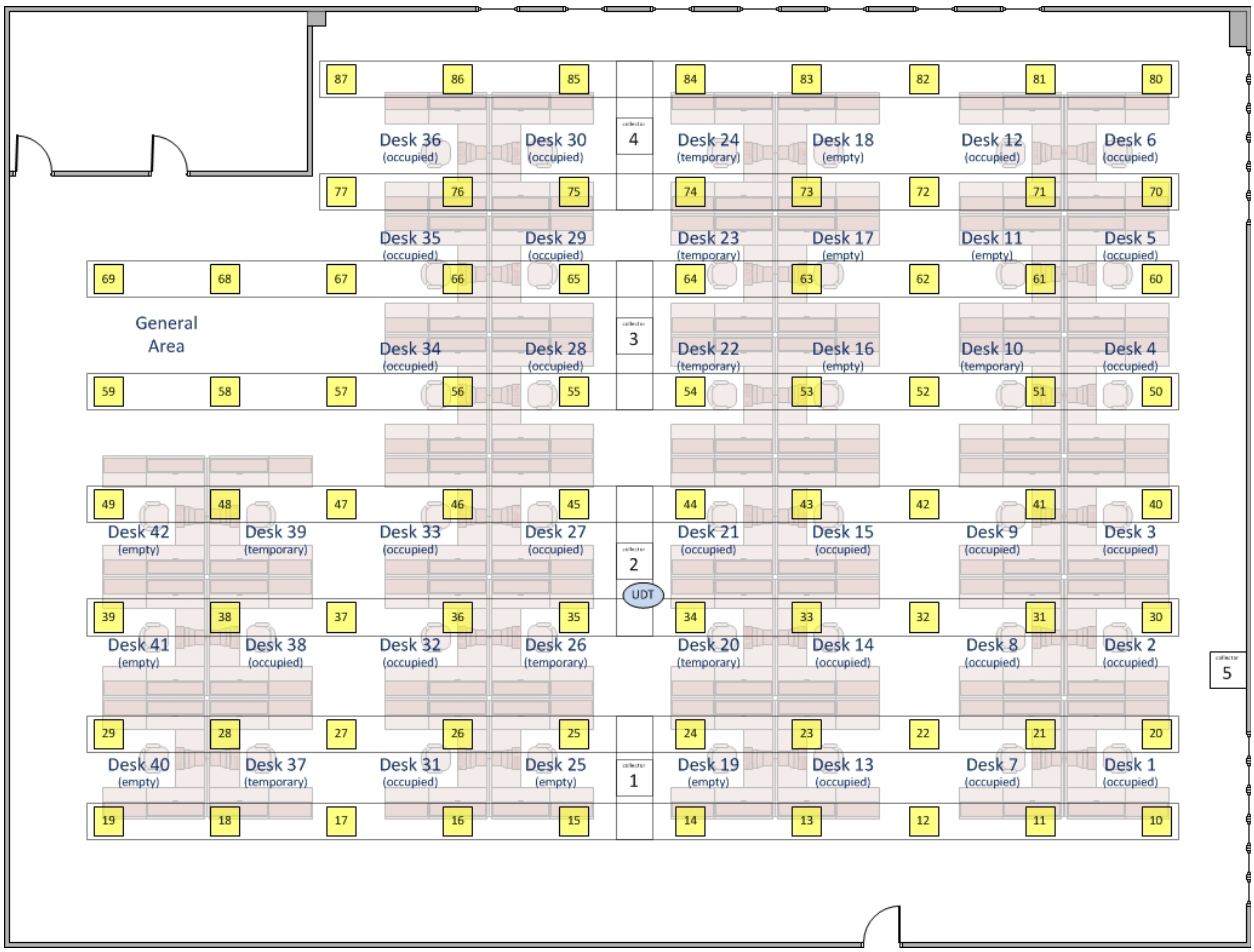

Figure 14**:** *Office space layout*

Four Sunlight Delivery System collectors (Figure 15) were used to distribute light to 76 fixtures in the second floor office space of Building 20137. Each collector distributed sunlight to 20 fixtures, except collector #4 which distributed light to 16 fixtures (reference Figure 16). The collector was designed to track the sun throughout the day and direct the sunlight into the ducts to evenly distribute the sunlight. Tracking the sun was performed using an open loop control system based on the position of the sun during the day for the building location and a closed loop control loop developed by 3M. Referring to Figure 10, collector #1 splits the sunlight into two different duct runs. Each duct run supports ten fixtures, either 10-19 or 20-29. Each fixture

distributed the sunlight through the center portion while the perimeter of the fixture was lined with LEDs. Unfortunately, the Sunlight Delivery System never performed long enough to enable the LED balancing function; dim the LEDs when there is strong sunlight output and increase the LED brightness as the sun went down.

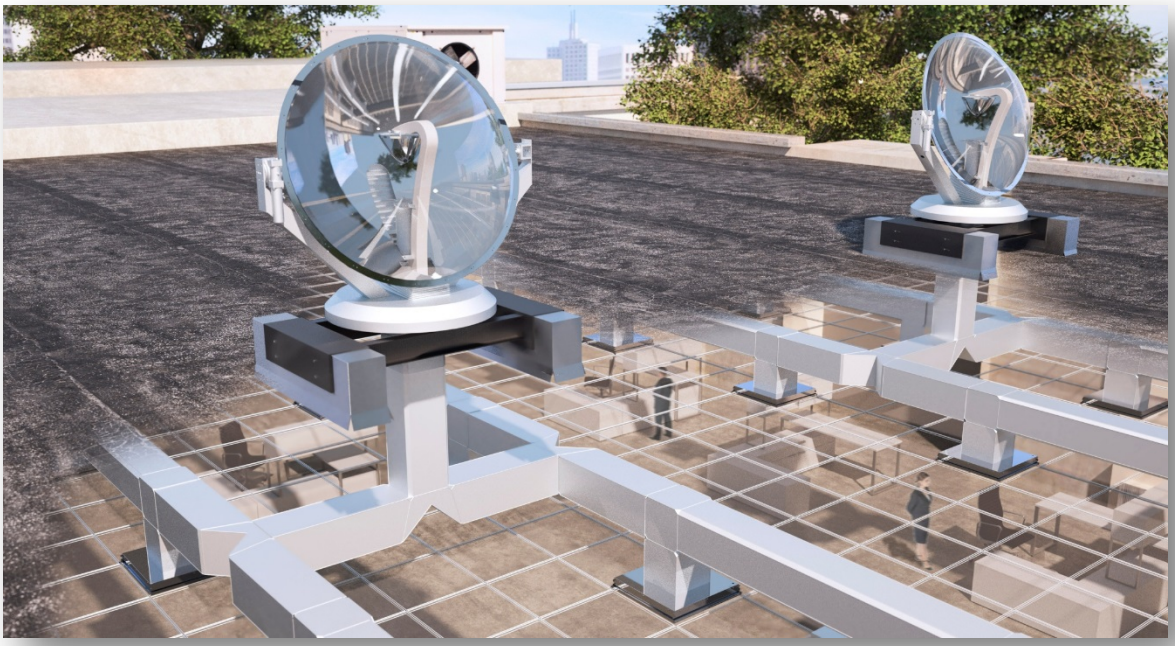

Figure 15**:** *Collector Placement and Duct Layout*

Figure 16**:** *Luminaries Placement*

5.4 Operational Testing

Operational testing was not applicable after product installation. Based on developmental elements needed to make the system operational, development cost were too great to proceed with the project.

5.5 Sampling Protocol

Protocols were not written since sampling will not be conducted after installation.

5.6 Sampling Results

No sampling results.

6 PERFORMANCE ASSESSMENT

CONCLUSION

To summarize, the installation was completed, but the 3M™ Sunlight Delivery System never finished final calibrations and final testing. Based on developmental elements needed to make the system operational, development cost were too great to proceed with the project.

Overall performance was not what was expected. The effect from the intensity of the sun on the hyperbola was greater than expected. The concentrated intensity of the sun on the hyperbola caused the hyperbola to tarnish prematurely. The tarnished hyperbola significantly reduced the reflectively of the system which drastically reduced the sunlight output at the fixtures in the office space. This intensity only caused issues with the hyperbola and had no affects to the building or its occupants. 3M tried three different solutions but all were unreasonable to develop. The first solution involved creating the hyperbola out of blown glass and coating the inside with silver. The glass would provide the environmental barrier to project silver from tarnishing. Besides being extremely fragile to work with, a precise glass hyperbola could not be created. The second option that was investigated involved polishing the aluminum hyperbola to a mirror finish. The polished aluminum surface could not achieve the required reflective characteristics need. The last option investigated involved outsourcing the hyperbola silver and protective coating. While the outsourced protective coating showed promise, the coating process cost over $2,500 per hyperbola, making this option cost prohibitive. The technology still needs improvement and the output was not as anticipated in a timely manner.

7 COST ASSESSMENT

To summarize, the installation was completed, but the 3M™ Sunlight Delivery System never finished final calibrations and final testing. Based on developmental elements needed to make the system operational, development cost were too great to proceed with the project.

Due to the uncertainty around any estimation related to capital, operational and cost/benefit analysis, costs will not be included in this report other then what was highlighted in section 3 of this report (System Economics).

8 IMPLEMENTATION ISSUES

As discussed in numerous sections throughout the report, multiple issues arouse such that continuation of the project became difficult in light of a rapidly decreasing value proposition due to developmental costs and uncertainty.

These difficulties include:

Alignment is critical to the performance of this system. The tracking method included a feedback loop which fine tuned alignment based on sensors within the Collector. This loop was problematic due to software issues with the controller and physical changes in the optical path due to heat and dust.

Poor hyperbolic reflector alignment and performance, was a show stopper in moving forward. This design depended on concentrated sunlight interacting with a hyperbolic reflector in order to deliver light long distances. Because of unanticipated heat build-up and concentrated sun energy, the team was not able to adequately protect the hyperbolic reflector from degradation ("tarnishing effect"). This greatly reduced the coupling of light into the ducts. Below is a sample of this defect.

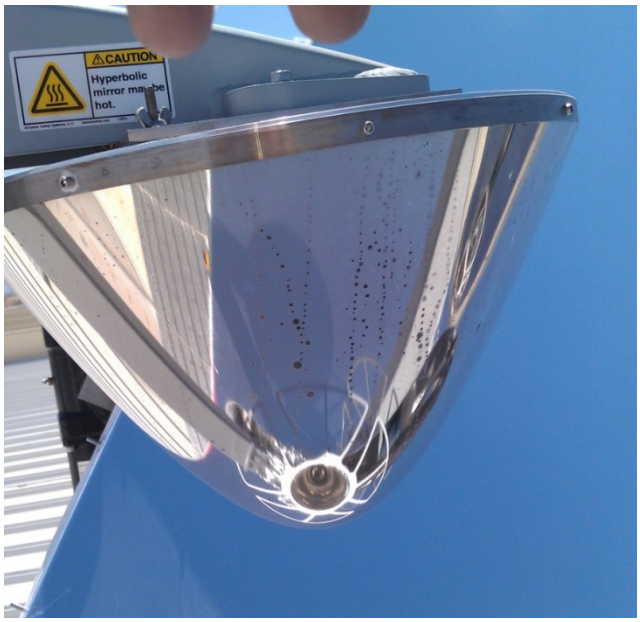

Figure 17: *Hyperbola degradation*

Hyperbola Temperatures (from system software):
Collector #1 = 122C
Collector #2 = 153C
Collector #3 = 138C
Collector #4 = 124C (while tracking the sun)
Collector #5 = 55C (this was just at the start of tracking. It was increasing at the same rate as the other collectors at approx. 0.1C/second)

In this environment the project continually battled issues related to blowing sand. The clear Polycarbonate domes scratched almost immediately, though improved once a coating was applied. The collectors also collected a lot of dust internally, which necessitated frequent cleaning. A sealing system was never identified which could ensure a clean optical path.

Facilities management at Fort Bliss was not in a position to support the technical and mechanical requirements needed to keep the system operational. Given that the project never hit operational state, the team believed that continued monitoring and maintenance of the system would have been required even if successfully deployed. Tasks such as realignment of mirrors, replacing domes, cleaning equipment, updating tracking software, monitoring fail-safes, troubleshooting malfunctions, execution of system software, report generation and similar activities was beyond the job duties of personnel at the site. 3M was not in a position to provide long term continuing support and the facility itself wanted as near a turn-key system as possible.

9 REFERENCES

1. U.S. Department of Energy. 2006 Building Energy Databook. Available for download at http://buildingsdatabook.eren.doe.gov.
2. 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.
3. J. Veitch, "Task lighting effects on office worker satisfaction and performance, and energy efficiency" . Leukos, 2(2), 85-96, 2005.
4. A.R. Webb, "Considerations for lighting in the built environment: Non-visual effects of light", Energy and Buildings, 38, 721-727, 2006.
5. Heschong-Mahone Group, Inc. 2003.

APPENDICES

APPENDIX A: POINTS OF CONTACTS

Table 3: 3M Project Points of Contact

Name	Organization	Phone	Email	Role in Project
John Olfelt	3M Architectural Markets Division 3M Center 220-7W-07 St. Paul, MN 55144	Phone: 651-737-1995	John.olfelt@mmm.com	Principal Investigator
Greg Visich	3M Architectural Markets Division Laboratory 3M Center 236-1D-15 St. Paul, MN 55144	Phone: 651-733-8527	gwvisich@mmm.com	Co-investigator, product development
Gina Albanese	3M Display and Graphics Business Laboratory 3M Center 235-S-46 St. Paul, MN 55144	Phone: 651-733-7241	galbanese@mmm.com	Co-investigator, design and performance
Ruth Charles	3M Govt. R&D Contracts 3M Center 224-2S-25 St. Paul, MN 55144	Phone: 651-736-7939	rpcharles@mmm.com	Contract Manager

Table 4: Sub-Contractor Personnel

Name	Organization	Phone	Email	Role in Project
Chris Baker	The Weidt Group	Phone: 952.938.1588 Fax: 952-938-1480	ChrisB@TWGI.com	Energy Consultation
Leo Ramos	SWGC EP Inc.	(915)892-4333	lramos@southwest-gc.com	Project Manager
Andrew Osborne		(952)356-6687	aosborne@ptnet.com	Parallel
Doug Sheldon		(949)857-6000	doug.sheldon@icsys-inc.com	IC Systems

Table 5: Demonstration Site Contact

Name	Organization	Phone	Email	Role in Project
Don Vincent	Fort Bliss DPW Bldg 777 / Rm 300 Ft. Bliss	Desk: 915-568-5172 Cell: 915-861-7503	donald.e.vincent.civ@mail.mil	Energy Engineer / Energy Manager

Table 6: Government Contacts

Name	Title	Phone	Email
Jim Galvin	Energy and Water Program Manager, Contracting Officer Representative	O: 571-372-6397 C: 913-636-8285	james.j.galvin.civ@mail.mil
Scott Clark	SERDP/ESTCP Support Office Senior Energy Engineer HydroGeoLogic, Inc.	O: (518) 877-0390 C: (703) 862-4229	clarks@hgl.com
Pete Knowles	Energy & Water PMA SERDP/ESTCP Support Office HydroGeoLogic, Inc.	(703) 736-4511	pknowles@hgl.com
Nancy Hilleary	Contracting Officer, USACE Humphreys Engineering Center	703-428-6120	nancy.l.hilleary@usace.army.mil