FINAL TECHNICAL REPORT

Project Title: Next Generation Solar Collectors for CSP

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EXECUTIVE SUMMARY

The intent of "Next Generation Solar Collectors for CSP" program was to develop key technology elements for collectors in Phase 1 (Budget Period 1), design these elements in Phase 2 (Budget Period 2) and to deploy and test the final collector in Phase 3 (Budget Period 3). However, 3M and DOE mutually agreed to terminate the program at the end of Budget Period 1, primarily due to timeline issues. However, significant advancements were achieved in developing a next generation reflective material and panel that has the potential to significantly improve the efficiency of CSP systems.

A next generation solar mirror film was developed using the unique to 3M multilayer optical film (MOF) technology. Pilot line experiments were conducted to optimize the configuration of the MOF to produce a film with high reflectance over a specific wavelength region of the solar spectrum. MOF optimization included the defining of the number of layer pairs and resins to maximize the solar reflectance as well as the processing and adhesion of subsequent layers to the base MOF layer. Specular reflectance values in excess of 98% were achieved with values above 96% being more typical. With pilot scale equipment, uniformity of spectral response and reflectance was found to vary approximately 1%.

Surface protection with a UV absorber containing hardcoat as developed under Agreement DE-FC36-08GO18027 was optimized and modified to produce a coating to protect the base MOF layers from UV degradation and, at the same time, preserve a high degree of specular reflectance. Weathering chamber testing showed that an optimized MOF solar reflective film can withstand an estimated equivalent of 15+ years of outdoor weathering without measurable degradation of the reflectance spectrum. These weathering tests are being continued by 3M beyond the funding period of the agreement..

To maximize the solar reflectance of the MOF, supplemental reflection in the IR region using a silver layer is employed. Six metallization chambers were used to create samples and determine the process variables to maximize the solar reflectance. The sole production-ready metallization chamber did not achieve the reflectance level of the other chambers, and this gap in performance between the production scale material and the best samples is being investigated beyond the funding period to further optimize the MOF based solar mirror film. It was demonstrated that a fully stabilized and metalized MOF-based solar mirror reflector could be made on production-ready equipment that has an average SWHR of 95%.

Development work on a metal structured panel, the "mini-truss thin-sheet" (MTTS), to support the solar mirror film, has shown that the MTTS can be manufactured to a projected cost of less than \$30/m^2 while still meeting the overall slope error target of < 1.5 milliradians. A VSHOT (Video Scanning Hartmann Optical Test) was used to determine the slope errors of various metal and metal thickness configurations of the panels. Key sheet metal parameters were identified to ensure a durable and accurate MTTS panel at the lowest cost. These parameters have been translated into supplier specifications.

A key finding from the computational modeling is the high optical accuracy possible for heliostats with MTTS panels when compared to heliostats with 4 or 5 mm thick glass mirrors. This can be attributed to the high stiffness to weight ratio of these panels compared to glass mirrors. For example, at a tilt of 45 degrees, it was found that for a 40" x 40" glass reflectors, only 28% of the rays would hit a target 500 ft away, as compared to 100% for a MTTS reflector of the same size. This potentially has significant implications for overall heliostat field efficiency.

3M intends to pursue the optimization and possible future commercialization of the advanced mirror film as well as exploring the pairing of this with the MTTS panel for the deployment of highly efficient reflectors for CSP.

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1. BACKGROUND

In order for Concentrating Solar Power (CSP) to become an important contributor to utility scale base-load power, dramatic reductions in cost and increases in performance must be achieved. The proposed project is centered on delivering a step-change in solar collector technology aimed at transforming the economics and industrialization of CSP, thereby reaching the SunShot 6¢/kWh LCOE target.

The project objectives were aimed to address the "Topic 1: Advanced Collectors" as part of the SunShot Concentrating Solar Power (CSP) R&D Program. Project objectives for Phase 1 were to develop new solar collector base technologies: advanced reflective films, optically accurate reflector panels, low cost space frames, adaptive optics and accurate tracking drives. These new technology elements were be used in Phase 2 for the design of a next generation heliostat for power tower systems. In Phase 3 the heliostat was to be manufactured, assembled, installed and tested at the Sandia National Solar Thermal Test Facility.

This report covers the development of advanced solar reflective films and optically accurate reflector panels. This is due to 3M and DOE mutually agreeing to terminate the program at the end of Budget Period 1 (Phase 1). However, significant advancements were achieved during this program in developing a next generation reflective material and panel that have the potential to significantly improve the efficiency of CSP systems.

2. OBJECTIVES

The original objectives of the program can be summarized as:

- Develop a new set of technology elements, including reflective films, reflector panels, framing structural elements and dual axis drives that can be used as "open source" elements for next generation solar collector design
- Design and build a large format heliostat design incorporating these new technology elements, suitable for high and ultra-high concentrating power tower systems
- Install and field test the heliostat design at the National Solar Thermal Test Facility (at Sandia National Laboratories)
- Analyze the impact of new heliostat design on LCOE for multiple power tower receiver formats

The proposed project objectives consisted of several unique aspects, which when combined had the potential to impact LCOE more than if individual components were addressed separately. The reflective material targeted 97% or higher solar adjusted hemispherical reflectance (SWHR) and specularity measurements higher than 98% using unique-to-3M multilayer optical film technology. The panel technology would use the recently proven optically accurate structural panel technology used for the parabolic trough test loop in Daggett (SEGS I-II), and would be further developed for low cost and high performance. The "adaptive optics" concept and also a novel dual axis tracking concept would be explored to allow the reflector "facets" to continually be optimally positioned to focus the solar radiation onto the target. The combination of these elements into a "system" was expected to provide for a synergistic design that had overall an extremely high potential for high optical accuracy at lower cost per energy delivered. Overall, the project was not aimed at just cost reduction alone, but rather approached from the point of view of offering a system with the highest "on-target energy per dollar."

This report covers the development of advanced solar reflective films and optically accurate reflector panels. This is due to 3M and DOE mutually agreeing to terminate the program at the end of Budget Period 1 (Phase 1). However, significant advancements were achieved during this program in developing a next generation reflective material and panel that have the potential to significantly improve the efficiency of CSP systems

3. NOVELTY

The proposed project consisted of several unique aspects, which when combined was expected to enable a higher impact on LCOE than if individual components were addressed separately. The reflective materials aimed at a 97% or higher solar adjusted total hemispherical reflectance (SWHR) and specularity measurements higher than 98% using unique-to-3M multilayer optical film technology. The panel technology would use the recently proven optically accurate structural panel technology used for the parabolic trough test loop in Daggett (SEGS I-II), and would be further developed for low cost and high performance. The "adaptive optics" concept and also a novel dual axis tracking concept would be explored to allow the reflector "facets" to continually be optimally positioned to focus the solar radiation onto the target. The combination of these elements into a "system" was expected to provide for a synergistic design that had overall an extremely high potential for high optical accuracy at lower cost per energy delivered. Overall, the project was not aimed at just cost reduction alone, but rather approached from the point of view of offering a system with the highest "on-target energy per dollar."

As mentioned before, this report covers the development of advanced solar reflective films (MOF) and optically accurate structured reflector panels (MTTS). This is due to 3M and DOE mutually agreeing to terminate the program at the end of Budget Period 1 (Phase 1). However, significant advancements were achieved during this program in developing a next generation reflective material and panel that have the potential to significantly improve the efficiency of CSP systems.

4. TECHNICAL WORK PLAN

The outline of the technical work plan as originally submitted is provided below as a frame of reference. As mentioned previously, the accomplishments primarily cover tasks 1.1 and 1.2 since 3M and DOE mutually agreed to terminate the program after the phase 1 review (end of budget period 1).

BUDGET PERIOD 1 (15 months)

Task 1.0 Proof of Concept

The Task 1 period focuses on applied research of the individual solar collector components, namely reflective film, panels, support structure and dual axis drives. The team will enter this project at a technology readiness level (TRL) 2. The primary activities in this phase are to advance each of the new technology components with a focus on performance and cost metrics, thereby transitioning to a TRL 3.

Task 1.1: New reflective films development

We will develop and prototype new reflective films suitable for heliostat applications. Film development will focus on the use of a unique-to-3M multilayer optical film (MOF) technology.

Subtask 1.1.1: The film manufacturing runs will be conducted on a pilot scale. We are planning on the completion of at least three film manufacturing runs. Each run will incorporate product modifications and learnings from the previous run.

Subtask 1.1.2: Durability testing will include accelerated weathering with xenon arc lamps, salt spray (ISO 9227 NSS), thermal cycling (IEC 62108 section 10.6.3), damp heat (IEC 62108 section 10.7.3b) and humidity freeze (IEC 62108 section 10.8.3). Prototype films will be tested at NREL using the Ultra-Accelerated Weathering System (UAWS) and solar simulator. All these tests will be done on the film produced in the final film run of Subtask 1.1.1; however, it should be noted that most of these tests will be done on earlier runs for screening purposes. A statistically significant number of samples will be tested to ascertain representative performance data.

Subtask 1.1.3: Optical testing will be conducted on all the films produced from the manufacturing runs. Solar weighted total hemispherical reflectance measurements (SWTHR) will be quantified according to the ASTM E903 method at an air mass of 1.5. The specular reflectance will be measured using the D&S (Devices & Services Co.) model 15R using a 7.5 milliradian (mrad) ½ acceptance cone angle.

Milestone (Task 1.1): Produce $\geq$ 10 reflective film samples from various web positions of the final pilot manufactured MOF films, which meet the targets of an average SWTHR $\geq$ 97% and an average specular reflectance of $\geq$ 98%. The measurements will include standard deviation and an analysis of variance. These samples will have durability testing completed and show high market lifetime feasibility within the scope of known extrapolation correlations.

Task 1.2: New panel configurations and materials

We will develop and prototype new accurate reflective panel constructions with very high shape accuracy. We will use and adapt the MTTS panelization technology. Various material sets will be explored to provide the optimal performance-cost combinations.

Subtask 1.2.1: Selection of material sets (front surface, structured panel, adhesive, and attachment components) will be evaluated on the basis of material properties, large volume cost, durability, corrosion resistance and surface smoothness (for surface material). All of the potential arrangements will be used to develop a selection matrix and help the team assess and determine which assembly can meet the design targets for this project.

Subtask 1.2.2: Prototypes will be assembled during this subtask. The top 3 strongest candidates from the selection matrix (Subtask 1.2.1) will be prototyped and tested. To assess the assembly methods and their impact on the quality, 2-5 small prototypes of each candidate will be fabricated. Each assembly process will be assessed for manufacturability.

Subtask 1.2.3: Shape accuracy will be quantified using VSHOT for each candidate. Hail impact testing (adapted from IEC 61646, Section 10.17) as well as neutral salt spray testing (ISO 9227, Section 5.2) will be done to evaluate the durability of the panels.

Milestone (Task 1.2): Complete assembly of at least 6 (up to 15) reflective panels of the various material sets will be done and a preliminary report on the manufacturability of each panel will be generated. The winning candidate will have an RMS slope error of $\leq$ 1.5 mrad relative to the best fit surface with a projected cost of $\leq$ $30/m^2. These measurements will include an analysis of variance (ANOVA) and the cost analysis will include a statistical analysis with high, low and most likely cost for the panels.

Task 1.3: New heliostat space frame element design

We will develop and prototype new support elements for high pointing accuracy heliostats. This will use a space frame technology along with a design that will incorporate “adaptive optics” to increase the total optical efficiency of the heliostat (and, ultimately, the solar field). Multiple design and material options will be explored and the most promising top 2 candidates will be prototyped and tested.

Milestone (Task 1.3): Produce at least 2 prototype support frame elements. At least one of these prototypes will demonstrate an average slope error budget of $\leq$ 0.5 mrad. This investigation will include an uncertainty analysis.

Task 1.4: New dual axis drive development

We will design and prototype new high accuracy drive/tracker system for heliostats. Hydraulic drives and Sunlock technology will be used as the basis for the new system. At least one prototype will be built and tested. Each step of the process will be examined and opportunities to improve the design and reduce assembly times will be sought out in order to reach the cost performance goals of the project.

Milestone (Task 1.4): Produce at least one dual-axis drive unit with a demonstrated average error budget of $\leq$ 0.75 mrad in both tracking axis directions within their respective tracking angle ranges. The measurements will include analyses of variance (ANOVA) in both tracking directions.

Task 1.5: Heliostat Design Concept Generation

Collaborate with the national laboratories (Sandia and NREL) to identify designs capable of meeting the performance metrics above.

> **Milestone (Task 1.5):** Based on the work conducted in Tasks 1.1-1.5, the group will identify at least 2 heliostat design concepts capable of meeting the performance metrics stated above while meeting a total installed cost of ≤ $\$75/m^2$. This cost analysis will also include a preliminary bill of materials.

Task 1.6: Preliminary heliostat optical design study

In this task, we will perform a preliminary optical analysis of the new heliostat designs, which may include analytical studies and/or preliminary FEA/optical ray tracing simulations to evaluate impact of gravity and wind loads on their performance. These analyses will be performed on single heliostats with the objective of demonstrating that gravity sag causes less than 10% variability of the beam centroid location in different orientations of the heliostat. Another objective will be to demonstrate less than a 2.5 mrad total tracking errors (azimuth and elevation directions, combined) under windy conditions. The optical error components from film (Task 1.1), and panel (Task 1.2) will be combined with the tracking errors to demonstrate a total optical error in calm winds of ≤ 3 mrad and total optical error in windy conditions of ≤ 4 mrad for the heliostat. Optionally, the optical efficiency of an idealized field of the new heliostats may be investigated with some standard assumptions on field and receiver configuration and evaluated in light of achieving a target of 65% peak field optical efficiency. The assumptions for the idealized field will be defined by the team.

> **Milestone (Task 1.6):** The optical design study shows that the variability of the beam centroid location is less than 10% at various orientations of the heliostat design with gravity sag. It will also be shown that at least one of the new heliostat designs will have a total tracking error of ≤ 2.5 mrad and a total optical error of ≤ 4 mrad under windy conditions. Optionally, a preliminary modeling of an idealized field/receiver system will be done to demonstrate the ability to reach a 65% peak field optical efficiency.

Go/No-Go Decision Point 1: Based on the individual heliostat sub-systems, a bottoms-up heliostat cost analysis showing total installed cost of ≤ $\$75/m^2$ will be completed. This cost analysis will include a bill of materials and vendor quotes. It will be shown that the heliostat system maintains the performance of total optical error in calm winds of ≤ 3 mrad and total optical error in windy conditions of ≤ 4 mrad.

Patents and Publications: File patents for relevant intellectual property. Publish results of research in high-visibility, high-impact, peer-reviewed journal(s). All publications resulting from the funded research are required to include an acknowledgement that the work was supported by the U.S. Department of Energy, SunShot Initiative, under the specific award number.

As a result of the go/no-go or stage-gate or continuation reviews, DOE may, at its sole discretion, make any of the following determinations: (1) continue to fund the project, depending on the availability of appropriations; (2) recommend specific direction or redirection of work under the project; (3) place a hold on the project pending further supporting data, funding, or to evaluate other projects concurrently; or (4) stop funding the project due to noncompliance, insufficient progress, inadequate business plan, schedule slip, change in strategic direction, or other factors.

BUDGET PERIOD 2 (9 months)

Task 2.0 Design

Phase 2 is focused on conceptual and detailed design work incorporating the technology elements (film, panel, space frame, drives, etc.) into a full heliostat design, taking the TRL from 3 to 5. Design(s) will be chosen to allow the evaluation and testing of the integrating concepts of the panel with the frame. Key manufacturing and performance challenges will be identified during this stage as well as possible panel integration strategies. An important focus during this stage will be reducing the frame manufacturing/material cost without compromising its function and performance. Another area of work will be to complete a detailed design of the tracking mechanism. Parallel to the design work, efforts will be placed on modeling performance evaluations of the various design options with accompanying manufacturing estimates. Key advantages and disadvantages will be listed and evaluated by the full team, including the national lab participants.

Task 2.1: Element Design

This task will focus on designing the individual elements of the heliostat for integration. The various components must be designed to flawlessly integrate with the technology element so that optical performance and cost determined in Task 1 are not compromised.

> Subtask 2.1.1: The reflective panel will be designed in this subtask. The reflective panel design will be reviewed and revised for its integration into the heliostat design. An optomechanical modeling study is to be completed. A CAD is to be done for the assembly and detailed drawings will be produced.
>
> Subtask 2.1.2: The focus of this task is to design the space frame. The space frame design will be reviewed and revised for its integration into the heliostat design. A 3D design will be completed and stress modeling for wind loads conducted. A CAD is to be done for the assembly and detailed drawings will be produced.
>
> Subtask 2.1.3: The drive-tracker will be designed and integrated into the heliostat. A 3D model will be developed to quantify system stresses under wind loads. CAD drawings will be completed for the heliostat components and assembly.
>
> Subtask 2.1.4: Tooling that is necessary for the manufacturing of the panel, space frame and drive-tracker will be designed. Tool drawings and shop drawings will be produced.
>
> **Milestone (Task 2.1):** A completed design package of the elements for the proposed collector will be provided. It will be shown that the redesign still meets the cost and performance metrics from Task 1.

Task 2.2: Full up Heliostat design

A full 3D design will be completed for the entire heliostat assembly. This model will be used to perform further stress analyses from wind loads. A CAD for the assembly and components will be completed. Cyclic fatigue analysis, where appropriate, will be done. Detailed parametric design analysis, such as an FMEA (failure mode and effects analysis), will also be conducted.

Task 2.3: Full up alternative collector design

Full 3D design and assembly for an alternative collector will be completed and used to asses component stresses during high and low winds. CAD for assembly and components will be completed. Cyclic fatigue analysis, where appropriate, will be done. Detailed parametric design analysis, such as an FMEA (failure mode and effects analysis), will also be conducted.

Task 2.4: Durability testing

Durability testing will be done on key components. Accelerated weathering tests, such as outlined in IEC 62108, will be selected and adapted as appropriate. Cyclic fatigue tests will be done on components which are expected to experience vibrations. Wind load testing, which may include wind tunnel testing, will be done on at least one collector design.

Milestone (Task 2): Demonstrate an operational wind load of ≥ 35 mph, a survival wind load of ≥ 90 mph, and a durability requirement of ≥ 30 years using a combination of testing and an appropriate analysis package.

Go/No-Go Decision Point 2: Based on the integrated heliostat system, a bottoms-up heliostat cost analysis showing total installed cost of ≤ $\$75/m^2$ will be completed. This cost analysis will include a bill of materials and vendor quotes. Results will be reported. It is expected that the heliostat system will maintain the performance of total optical error in calm winds of ≤ 3 mrad and total optical error in windy conditions of ≤ 4 mrad.

Patents and Publications: File patents for relevant intellectual property. Publish results of research in high-visibility, high-impact, peer-reviewed journal(s). All publications resulting from the funded research are required to include an acknowledgement that the work was supported by the U.S. Department of Energy, SunShot Initiative, under the specific award number.

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<u>BUDGET PERIOD 3 (8 months)</u>

Task 3.0 Prototype Build and Evaluation

Phase 3 is focused on the manufacturing, installation and assembly, commissioning, and testing of the new heliostat design at Sandia's National Solar Thermal Test Facility (NSTTF). All components will be made at prototype volumes, but with assessment for full manufacturing scale-up. In some instances, tooling will be made (e.g. for aluminum extrusions). Components will be test fit and integrated as they become available, e.g. the critical interconnections between the drives and frame and the frame and panels. The work described in this phase is focused on progressing this technology to TRL 7 by the end of this phase.

Task 3.1 Component Manufacture

> Subtask 3.1.1: Reflective film and panels will be manufactured to populate the heliostat, plus spare parts. A pilot manufacturing line will be developed and employed to produce panels sufficient for 1 heliostat plus spares.
>
> Subtask 3.1.2: This subtask will focus on manufacturing and assembling of the space frame for the heliostat. Space frame elements will be manufactured for 1 heliostat, plus spare

parts. All parts will be inspected and checked with special test tooling to ensure they meet the design tolerances. A pre-assembly of the parts will take place to verify that they meet the design intent.

Subtask 3.1.3: The tracker and drive sub-assembly will be manufactured for heliostat. All fabricated parts will be inspected, and cleared components will be used to construct the drive-tracker assembly.

Task 3.2: Heliostat Assembly, Installation and Commissioning

The teams will assemble and install a heliostat for a field test. The components will be shipped to the installation site (NSTTF, Sandia). The test site at NSTTF will be prepared and foundations will be laid. Once the heliostat components arrive to the site, it will be assembled and installed. The heliostat will be brought into service as soon as possible. Off-sun testing and characterization will be followed by on-sun tracking and operational cycling along with system debugging.

Task 3.3: Test and evaluate Heliostat at NSTTF

Optical performance and flux mapping will be done to validate the performance of the heliostats. This empirical data will validate the analytical ones calculated in the previous tasks.

Task 3.4: Alternative collector assembly and install

The teams will assemble and install a collector for a field test. The appropriate test site for this collector will be assessed and selected by the team. The components for the alternate collector will be shipped to the installation site, the test site prepared and foundations laid. Once the collector components arrive to the site, it will be assembled and installed. The collector will be brought into service as soon as possible. Off-sun testing and characterization will be followed by on-sun tracking and operational cycling along with system debugging.

Task 3.5: Alternative collector testing

Optical performance and flux mapping, or similar energy collection metric, will be done to validate the performance of the alternative collector. This empirical data will be used to validate the analytical ones calculated in the previous tasks. The alternative collector will also be assessed by the team in its potential to deliver high temperature thermal energy to the receiver.

Final Deliverables:

- **Final Deliverable 1:** Fully-integrated, field-tested heliostat with demonstrated total optical error in calm winds ≤ 3 mrad, total optical error in windy conditions ≤ 4 mrad, and gravity-induced variability of the beam centroid location of less than 10% at various orientations of the heliostat. Optionally, a preliminary idealized field/receiver system heliostat peak field optical efficiency of 65% will be shown.
- **Final Deliverable 2:** Demonstrate an operational wind load of ≥ 35 mph, a survival wind load of ≥ 90 mph, and a durability requirement of ≥ 30 years at a total installed cost of ≤ \$75/m^2. Demonstrate the highest flux/\$ when compared to existing heliostat fields.
- **Final Deliverable 3:** Performance comparison will be shown for the new heliostat design and the alternative collector based on a "solar energy flux on target per dollar" (flux/\$) basis.
- **Patents and Publications:** File patents for relevant intellectual property. Publish results of research in high-visibility, high-impact, peer-reviewed journal(s). All publications

resulting from the funded research are required to include an acknowledgement that the work was supported by the U.S. Department of Energy, SunShot Initiative, under the specific award number.

5. BUDGET PERIOD 1 (15 MONTHS)

5.1 TASK 1.0 PROOF OF CONCEPT

5.2 TASK 1.1 NEW REFLECTIVE FILMS DEVELOPMENT

All reflectance values reported were measured using a Lambda 1050 spectrophotometer with 150mm integrating sphere attachment. Solar-weighted hemispherical reflectance (SWHR) and average reflectance values were used to characterize the films. All specularity measurements reported are measured using Sesign & Services Co. (D&S) model# 15R with 7.5mrad half-angle of acceptance. Both measurements are consistent with SolarPACES Reflectance Measurement Guideline version 2.5 [ref.1].

A summary of accomplishments vs. objectives for Task 1.1 is shown below:

Task 1.1: New reflective films development	
Objectives	**Accomplishments**
Subtask 1.1.1: The film manufacturing runs will be conducted on a pilot scale. We are planning on the completion of at least three film manufacturing runs. Each run will incorporate product modifications and learnings from the previous run.	3 MOF runs, focusing on polymer extrusion and spectral response, were completed. The polymer characteristics for extrusion of the MOF were determined. 3 hard coat runs, focused on process window exploration, were completed. Formulation modifications were implemented to avoid surface haze. 4 metallization runs were completed. Process parameters were optimized for reflectance. Primers and plasma treatments demonstrated insensitivity of reflectance to most of the conditions.
Subtask 1.1.2: Durability testing will include accelerated weathering with xenon arc lamps, salt spray (ISO 9227 NSS), thermal cycling (IEC 62108 section 10.6.3), damp heat (IEC 62108 section 10.7.3b) and humidity freeze (IEC 62108 section 10.8.3). Testing of prototype films will be tested at NREL using the Ultra-Accelerated Weathering System (UAWS) and solar simulator. All these tests will be done on the film produced in the final film run of Subtask 1.1.1, however it should be noted that most of these tests will be done on earlier runs for screening purposes. A statistically significant number of samples will be tested to ascertain representative performance data.	Xenon arc lamp tests were completed to study UV absorbers and reflectance retention at a real-time 4yr equivalent. NSS tests were replaced by soak tests IEC 62108 testing was initiated and 1000hrs of testing completed. 2000hr results were obtained in mid-November. UAWS and solar simulator were not done due to program termination and late finalization of the multi-party CRADA
Subtask 1.1.3: Optical testing will be conducted on all the films produced from the manufacturing runs. Solar weighted total hemispherical reflectance measurements (SWTHR) will be quantified according to the ASTM E903 [ref.2] method at an air mass of 1.5. The specular reflectance will be measured using the D&S (Devices & Services Co.) model 15R using a 7.5 milliradian (mrad) ½ acceptance cone angle.	Testing completed per SolarPACES Reflectance Measurement Guideline version 2.5[ref.1] using Lambda 1050 Spectrometer and the D&S model 15R specular reflectometer.

As a philosophy, the solar spectrum is broken into four regions: ultraviolet, visible, near-infrared and infrared. These nominal regions are shown in the chart below (**Figure 1**). The exact locations of the uv/vis boundary and vis/N-IR boundary depend on the specifics of the design. The percentage of solar irradiance in each region is shown in **Table 1**.

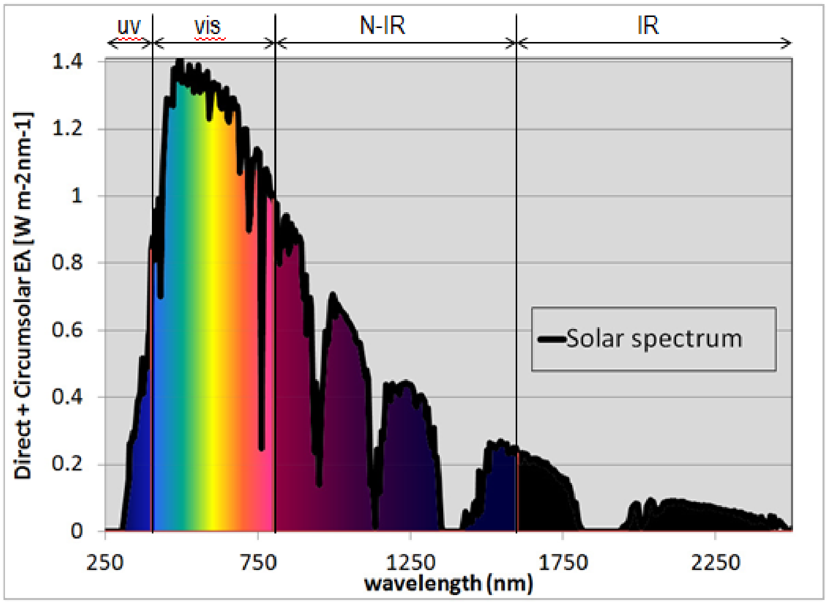

Figure 1. Solar spectral irradiance as given by ASTM G-173. Regions of interest are labeled as “uv”for ultraviolet, “vis” for visible, “N-IR” for near-infrared and “IR” for infrared.

Table 1. Percent of solar irradiance in regions of interest as defined by their wavelength range

Spectral region	Percent of G173 solar irradiance
uv (250-450nm)	9.0%
visible (450-750nm)	42.8%
near-IR (750-1600nm)	40.6%
IR (1600-2500nm)	7.6%
Total	100.0%

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In the UV region, the reflector spectral response is dominated by UV absorbers that serve to protect the polymer mirror from UV degradation. The reflectance is low in this region. The lower wavelength boundary is 250nm as defined by the solar spectrum. The upper wavelength boundary is defined by the absorbance of the UV protection. In the visible region, the reflector spectral response is dominated by the Multilayer Optical Film (MOF). The reflectance in this region is high. The lower wavelength boundary is defined by the UV absorbers. The upper wavelength boundary is defined by extent of the MOF reflection band. The reflection band is determined by the number of layer pairs and the choice of materials for high and low index layers. The total optical power in the reflection band can be distributed to give a wide band with low reflectance, narrow band with high reflectance of anywhere between. The peak of the solar spectrum is in the visible region and therefore a high priority was placed on increasing the reflectivity in this region.

In the near-IR region, the reflector spectral response is dominated by the supplemental metal reflection layer. The reflectance in this region is high. The lower wavelength boundary is defined by the MOF reflection band. The upper wavelength boundary is 1600nm. In the IR region, the reflector spectral response is dominated by the supplemental metal reflection layer in combination with material absorption. The reflectance in this region is moderate. The lower wavelength boundary is 1600nm. The upper wavelength boundary is 2500nm as defined by the solar spectrum.

5.2.1 *SUBTASK 1.1.1*

MOF development has been on-going at 3M since the 1990s. The experience and expertise of these many years of developments were leveraged in this program. In addition, the work done on the development of current products at 3M for other markets was also leveraged.

To enhance its performance, the mirror film will receive a coating on each surface. The sun side will receive a hardcoat for abrasion resistance and UV stability as developed under Agreement DE-FC36-08GO18027. The side opposite the sun will receive a metal coating to supplement solar reflectance at wavelengths greater than the MOF reflection band.

3M had previously developed a test to evaluate the adhesion of the metal coating to mirror films. The protocol required soaking strips of mirror film in de-ionized water then performing peel test. Silvering experiments were performed in two different silver coating chambers on the different MOF films to evaluate adhesion by means of this wet peel adhesion test.

5.2.2 *SUBTASK 1.1.2*

Ultraviolet (UV) protection for the MOF was incorporated into the hardcoat layer which was developed under Agreement DE-FC36-08GO18027

Absorption of the UV absorber (uva) in the hardcoat not only affects the reflectance in the UV region, as desired, but also impacts the visible region. The combination of uva concentration and coating thickness determine the optical density of the coating. **Figure 2** plots the transmittance through a coated PMMA film for three thicknesses of uva-t3 at a constant concentration (2.5%). The location and slope of the band-edge increases with uva content. It was found necessary to balance the UV protection with absorption of desirable radiation. For a mirror film, the UV protection is related to the coating transmittance while the effect on reflectance is related to passing through the coating (hardcoat) twice.

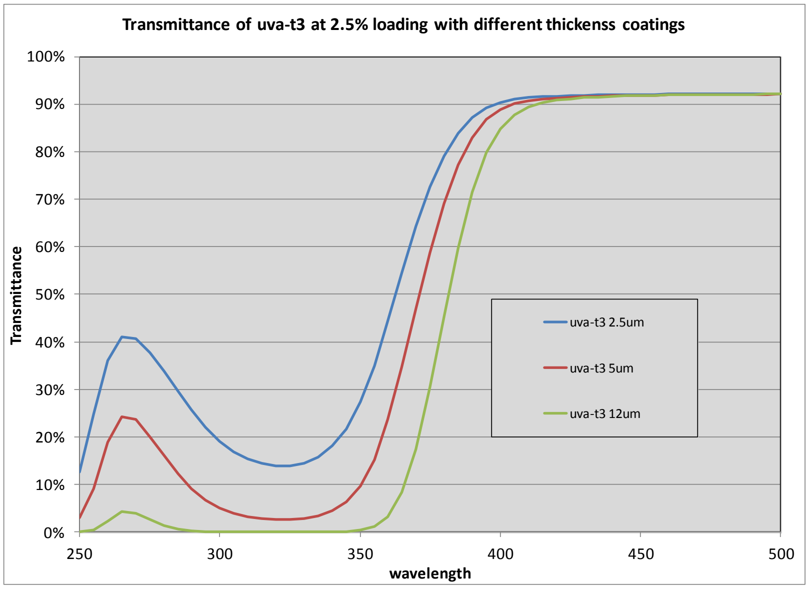


Figure 2. Spectral transmittance of a 2.5% uva-t3 concentration at three coating thicknesses.

Hardcoat formulations using the absorbers shown in **Figure 2** were coated onto durable substrates (PMMA and ETFE) and MOF film. These samples were aged in accelerated weathering chambers.

Samples of uva-doped hardcoat using 11 candidate absorbers coated onto durable substrates completed 2 to 4 year-equivalents of weathering. Evaluation of the strength of absorber retention was characterized by dividing the measured absorbance by the initial absorbance at 350nm. These evaluations can be done at any wavelength or integrated over a wavelength band with similar results. 350nm was used for convenience.

Samples of uva-doped hardcoat using 8 of the candidate absorbers coated onto an MOF substrate completed 4 year-equivalents of weathering. Evaluation of the protection of the absorber was characterized by dividing the measured average reflectance by the initial average reflectance.

To further identify the requirements for UV protection, a study based on ASTM G178 [ref. 3] was conducted. Sharp cut-on filters were placed between the source and samples of mirror film to determine the relative actinic effects of the spectral regions.

5.2.3 *SUBTASK 1.1.3*

The non-sun side of the MOF was coated with a metal layer to yield full solar coverage. While it is possible to coat various metals, silver is the metal of choice for high solar reflectance

To minimize mirror cost the thickness of the silver should be minimized without a penalty in SWHR. Film samples with a range of silver thicknesses were fabricated in a pilot metallization chamber.

In order to maximize the reflectance from the reflectance of the silver layer, six different metallization chambers were used to generate mirror samples

Priming layers have been used in metallization to change characteristics of the metal layer. An experiment to screen priming layers and glow discharge treatment of the surface was conducted to evaluate the effect on reflectance using pilot scale equipment. Four priming conditions were created both with and without the glow discharge treatment. Samples were evaluated for average reflectance in the N-IR band.

An experiment was conducted on production scale equipment to evaluate process variables.

Figure 3 shows a plot of specularity at 7 equally spaced locations across the film width. The range in specularity follows reflectance variations as previously described. All film samples were fabricated on combinations of pilot and production scale equipment. Improvement of crossweb uniformity is expected with production equipment.

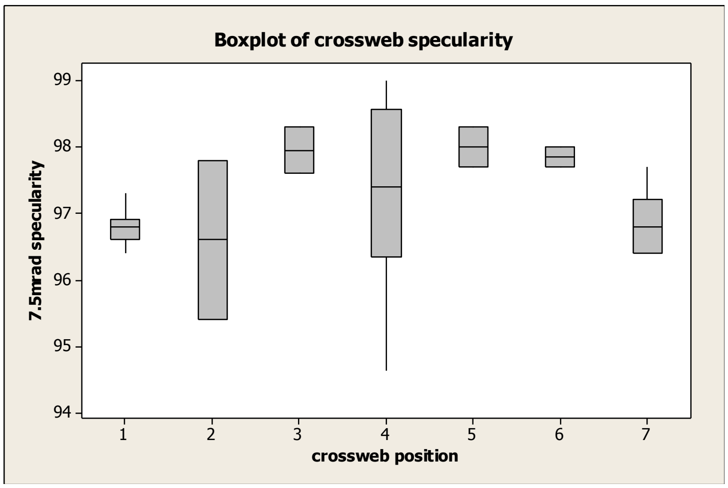


Figure 3. Crossweb plot of specularity of film made with combinations of pilot and production equipment.

Hardcoat and metal layers were applied to the MOF mirror to produce a mirror film for full pilot scale testing. Initial performance measurements of SWHR and specularity were made on 5 samples

Table 2. Initial testing results for pilot scale mirror film from 2 metallization chambers. 5 film samples are averaged for performance values.

Initial performance	C1	C2
Specularity (7.5 mrad)	97.4	97.1
SWHR	95	94.2
Salt Soak	3wks - No change	3wks - No change
Wet Peel (lbf/0.5")	0.58	2.12

Outdoor weathering under natural conditions and accelerated (concentrated) conditions was initiated at three field locations and is continuing beyond program termination. Samples had completed three calendar months of testing up to program termination. Each location and weathering configuration had received a different level of solar exposure ranging from 0.21 to 2.10 year-equivalents. These tests were continued beyond program termination.

The samples were also tested per IEC 62108 [ref.4], a protocol for Concentrator Photovoltaic (CPV) modules and assemblies. These stress tests are included to understand potential limitations of the solar mirror film. These tests are not indicative of the suitability of the film for the intended application. Further investigation for appropriate testing is required. These tests were continued beyond program termination.

5.2.4 *MILESTONE (TASK 1.1)*

Milestone (Task 1.1): Produce ≥ 10 reflective film samples from various web positions of the final pilot manufactured MOF films, which meet the targets of an average SWTHR ≥ 97% and an average specular reflectance of ≥ 98%. The measurements will include standard deviation and an analysis of variance. These samples will have durability testing completed and show high market lifetime feasibility within the scope of known extrapolation correlations.	Optical characteristics of the next generation solar reflective film: SWTHR: 94.2-95%; Specular Reflectance: 97.1-97.4% An equivalent 13+ years of MOF durability demonstrated in the weathering chambers. Effectiveness of hardcoat with UV absorbers to increase durability has also demonstrated and is ongoing beyond program termination.

5.3 TASK 1.2 NEW PANEL CONFIGURATIONS AND MATERIALS

A summary of accomplishments vs. objectives for Task 1.2 is shown below:

Task 1.2: New panel configurations and materials	
Objectives	**Accomplishments**
Subtask 1.2.1: Selection of material sets (front surface, structured panel, adhesive, and attachment components) will be evaluated on the basis of material properties, large volume cost, durability, corrosion resistance and surface smoothness (for surface material). All of the potential arrangements will be used to develop a selection matrix and help the team assess and determine which assembly can meet the design targets for this project.	Cost analysis and material set matrix was completed and optimal material sets chosen for further study. A projected cost of < $30/m^2 for the panels was achievable. Impact of substrate smoothness was measured using scatterometry and shown that electro galvanized steel was the best candidate for the reflector sheet.
Subtask 1.2.2: Prototypes will be assembled during this subtask. The top 3 strongest candidates from the selection matrix (Subtask 1.2.1) will be prototyped and tested. To assess the assembly methods and their impact on the quality, 2-5 small prototypes of each candidate will be fabricated. Each assembly process will be assessed for manufacturability	Over 30 prototype panels were assembled an evaluated for quality and manufacturability. Panels were tested for optical properties and manufacturability was assessed and specifications discussed with sheet metal vendors.
Subtask 1.2.3: Shape accuracy will be quantified using VSHOT for each candidate. Hail impact testing (adapted from IEC 61646, Section 10.17) as well as neutral salt spray testing (ISO 9227, Section 5.2) will be done to evaluate the durability of the panels.	Shape accuracy was measured on the selected prototypes and shown that < 1.5 mrad of slope can be obtained. Materials & panels were shown to pass salt spray testing and be able to withstand up to 19 mm diameter hail

The objective of the panel development effort for next generation solar collectors is driven by two main factors: (1) successful deployment of the MTTS panel with the 3M-Gossamer LAT 73 parabolic trough at Daggett (SEGS I-II), and (2) the current limitations of glass based reflectors. The MTTS (mini-truss thin-sheet) is a Gossamer Space Frames innovative panel structure (US

Patent No. 8,132,391, [ref. 5]) and was optimized and engineered by 3M and Gossamer for to enable a 7.3 m wide aperture parabolic trough with the highest geometric concentration factor (100+) of any operating parabolic trough today. This is possible because of the high shape accuracy of these panels. These panels also open up the possibility of using polymer-based reflectors over the front sheet. This combination of materials allows for an accurate reflector that is not subject to breakage and is lead free.

The material cost of the MTTS panel can be broken down into five components: (1) reflector sheet, (2) structural sheet, (3) structural adhesive (4), edge protection, and (5) attachment hardware. The current high volume manufacturing cost for the MTTS panel manufactured from aluminum sheets can be reasonably estimated to break out into:

- Material components [(1) to (5) above] – 80%
- Overhead / Profit – 20%

The edge protection is only a small fraction of the total material cost. The focus for meeting the panel cost of $30/m^2 therefore was focused on the sheet metal used for the reflector and structured backer, the adhesive used to join the two sheets, and the attachment materials to attach the panel to the supporting frame. The effort in this task was therefore focused on reducing the material cost components while meeting the performance metrics of the reflector panel.

5.3.1 ***SUBTASK 1.2.1***

Material selection for the MTTS were primarily driven by cost considerations and then by performance. The approach taken was that of taking every element of the MTTS and then exploring material options that would drive the cost down as far as was thought reasonable. The experience of the team in this process was key so that material options were not explored that did not fit with (a) the expected performance of the final product and (b) with the eventual ability to manufacture the product in a cost effective way. The four material components of the MTTS will be discussed in three sections and a final cost analysis table:

1. Sheet Material Selection: selection of material for the reflector sheet and for the structured sheet. These two materials are dealt with in one section because the mechanical performance of the MTTS is dependent on both sheet material properties.
2. Adhesive Material Selection: selection of the structural adhesive to join the reflector sheet to the structured sheet.
3. Attachment Material Selection: selection of materials that would allow the panel to be attached to the supporting frame.
4. Projected Cost: table projected cost for material components of MTTS and final product

Sheet Material Selection

Material Type and Thickness Selection: The selection of the material for the reflector and structured sheets limited these primarily to metals. Metals in general have the highest modulus of elasticity per dollar. Exceptions to this can be found, such as glass or FRP (fiber reinforced plastics). For the MTTS, the structured sheet needs to be made of metal due to the stamping process used to make the structure. For the reflector sheet, it is possible to use any flat sheet material (such as glass), but, as discussed later, thermal expansion coefficient and other material property differences between the front reflector sheet and the rear structured sheet are likely to cause performance losses.

For the material evaluation, aluminum and steel were considered the primary candidates. High volume quotes for coils of these materials were obtained and it was found that for a 5052-H32 grade of aluminum and for AZ50 Galvalume® coated steel, the price is in general about $2/lb and $0.60/lb for these two metals. Variations can be found in this pricing based upon market fluctuations and coating, finishing requirements, etc. but these values afforded a good baseline for initial evaluations.

A "quasi" design of experiment was done to explore the area of interest. It is called a "quasi" design because the thickness levels for the design could not be adjusted to optimal design points as this was dictated by sheet metal thickness availability.

Table 3. Structural and reflector sheet thicknesses for the design space along with cost reduction potential for each set.

			REFLECTOR SHEET			
			Steel	Steel	Steel	Steel
		thickness	0.0200	0.0150	0.0100	0.0085
STRUCTURAL PANEL SHEET	Steel	0.0180	48	55	62	64
	Steel	0.0157	51	58	65	67
	Steel	0.0130	55	62	69	71

The table above shows the material sets that were explored. The cost reduction potential is shown for each set. The VSHOT measurement of slope error was the primary selection criteria used in selecting the material sets. The stamped structured steel samples were purchased from the existing supplier of the stamped aluminum structured panels for the parabolic trough application (i.e. using the existing stamping die). The sheet metal used for this were all 55% Zn Al coated steel meeting ASTM A792 [ref. 6] specification with coating designation of AZ50 (minimum of 0.50 oz/ft^2, both sides). The three thickness sheets were as shown in the table. The fact that the stamping die was not optimized neither for steel mechanical properties nor for the steel sheet thicknesses resulted in the bent structured "feet" and "tabs" not being bent to specification. These were manually corrected before prototype assembly (see "1.2.2 Prototype Assembly" section for details) to minimize the influence of these on the panel performance. The metal for the reflector sheet was a CS 1010 which is a plain carbon steel with nominal 0.10% carbon content. This sheet was used without corrosion protection for the 0.020", 0.015" and 0.010" thicknesses. The 0.0085" thick steel sheet did however have an electro-galvanized coating on both sides. These metal reflector sheets were all laminated with 3M solar mirror film (SMF 1100) prior to assembly in order to obtain a reflective surface for VSHOT testing.

Initial results for the slope errors for the 12 sample set did not show meaningful trends, as can be seen from the contour plot below.

Table 4. Initial sample set slope error results

Str.thick in.	Refl.thick in.	dz/dx mrad	dz/dy mrad	dz/(dx dy) mrad
0.018	0.020	2.118	1.384	2.530
0.018	0.015	1.412	0.811	1.628
0.018	0.010	1.702	0.930	1.939
0.018	0.0085	1.514	0.854	1.738
0.015	0.020	2.109	1.066	2.363
0.015	0.015	1.581	0.986	1.864
0.015	0.010	1.880	0.980	2.120
0.015	0.0085	1.966	0.782	2.116
0.013	0.020	3.853	1.157	4.022
0.013	0.015	0.990	0.862	1.312
0.013	0.010	1.507	1.375	2.040
0.013	0.0085	1.441	0.765	1.632

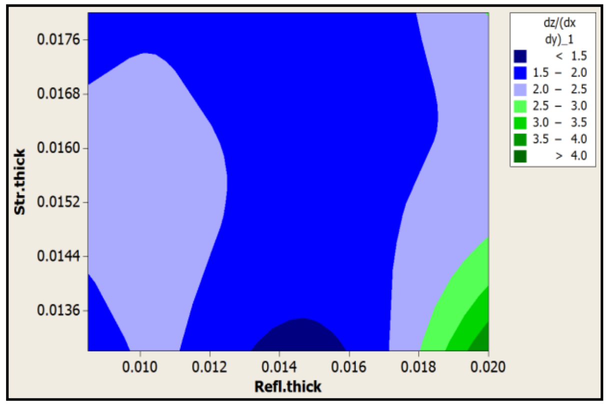


Figure 4. Contour plot of slope error

Some representative heat plots of slope errors from the VSHOT test are shown in **Figure 5**.

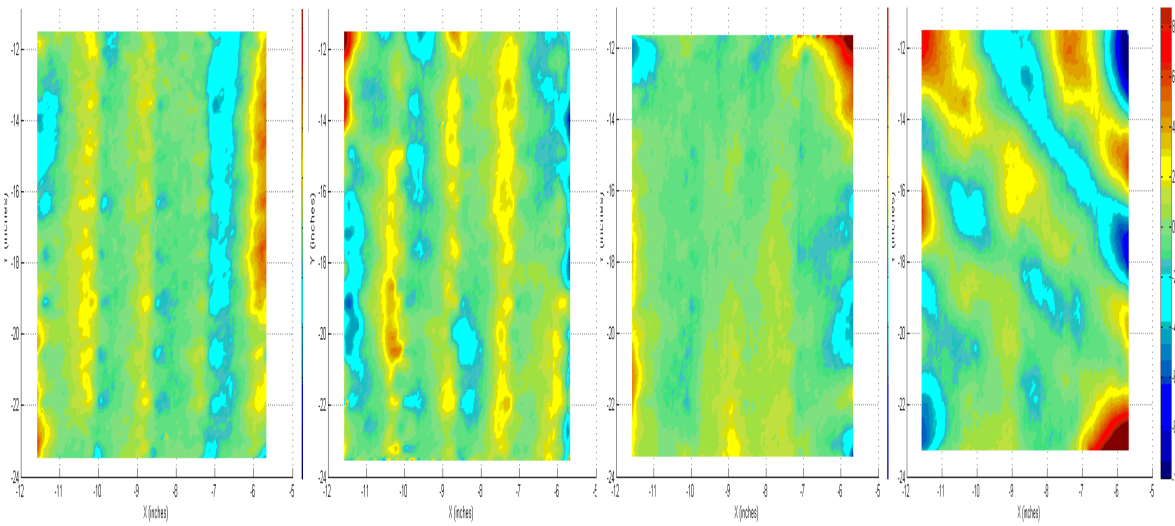


Figure 5. Heat-plots of slope error (dz/dx) from VSHOT measurements for MTTS reflector sheet thicknesses of (L to R) 0.085", 0.010", 0.015" and 0.020". The structured sheet thickness for all above samples was 0.013".

Some observations can be made: (1) "read through" is occurring for reflector steel sheet thicknesses that are equal to or less than 0.015" and (2) the prototypes with 0.020" thick reflector steel sheet are not flat. This prompted a systematic investigation into the reasons for the variation of the slope error for the 0.020" thick sample. 8 different theories were proposed of which 3 could be matched with observations. One of these was eliminated by testing. The two causes were (1) inherent unevenness of the sheet (high coil set) and (2) assembling the MTTS with the structured sheet aligned at 90 degrees to the machine direction of the reflector sheet. Investigation into "flatness" specifications for sheet metals ensued. It was found that, among the three flatness specifications of ASTM A568 [ref. 7], the "I-unit" was the most commonly used expression of flatness in the industry. The I-unit of a strip of sheet metal is determined using the formula:

$$I = \left[\left(\frac{\pi}{2} \right) \left(\frac{H}{L} \right) \right]^2 \times 10^5$$

Where H is the wave height and L is the wave interval, as measured according to ASTM A568 [ref.7]. It was determined that the I-unit for the 0.020" thick reflector sheet used for the prototypes was 55. A new steel sheet was procured and I-unit determined to be in the <1 range. These were assembled into MTTS panels as before, but with the structured panel aligned with the machine direction of the metal. Substituting these results into the table of data and reanalyzing, gave a significant improvement, as can be seen in the contour plot of **Figure 6**.

Table 5. Initial sample set slope error results

Str.thick in.	Refl.thick in.	dz/dx mrad	dz/dy mrad	dz/(dx dy) mrad
0.018	0.020	0.718	0.937	1.181
0.018	0.015	1.412	0.811	1.628
0.018	0.010	1.702	0.930	1.939
0.018	0.0085	1.514	0.854	1.738
0.015	0.020	0.915	1.064	1.403
0.015	0.015	1.581	0.986	1.864
0.015	0.010	1.880	0.980	2.120
0.015	0.0085	1.966	0.782	2.116
0.013	0.020	1.078	1.361	1.736
0.013	0.015	0.990	0.862	1.312
0.013	0.010	1.507	1.375	2.040
0.013	0.0085	1.441	0.765	1.632

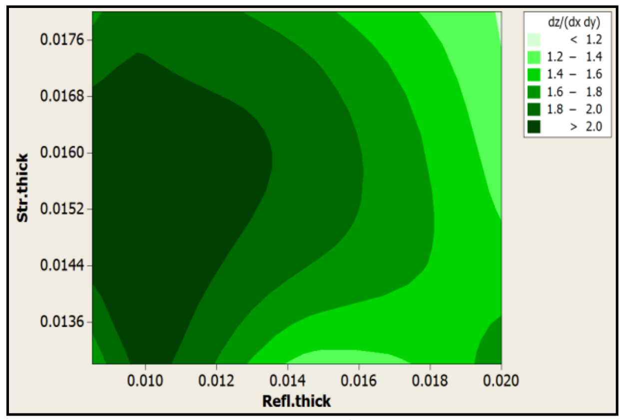


Figure 6.Contour plot of slope error

Discussions with various sheet metal converters, distributors and mills it was found that the industry can relatively easily provide sheet metal to an I-unit specification range of 4 to 7, when requested. Requiring an I-unit = 1 seemed possible with some processors (with tension leveling equipment), but the implications on cost still needs to be fully explored. Through literature search and discussions with processors it was also learned that, in order to get a flat steel sheet, stringent specifications are needed at both the steel mill as well as at the converter, where leveling would take place.

The contour plot of **Figure 6** indicates that the reflector sheet should be 0.020" thick to meet the RMS slope error target of < 1.5 mrad. The thickness of the structured sheet, on the other hand, appears to have minimal impact on the measured slope error. An area of concern with thin sheet metal is the potential for buckling under load. To test the potential impact of buckling under wind load, a computational model was used to predict the upper limit for wind speed, for front and rear winds, before non-linear deformation was noted (for details see section "1.2.3 Prototype Testing"). The result for the various MTTS constructions is shown in the table below.

Table 6. Maximum wind loads to buckling

Str.thick in.	Refl.thick in.	Front Wind mph	Rear Wind mph
0.018	0.020	156	140
0.018	0.015	156	131
0.018	0.010	116	124
0.018	0.0085	94	123
0.015	0.020	156	125
0.015	0.015	156	114
0.015	0.010	114	113
0.015	0.0085	95	111
0.013	0.020	156	103
0.013	0.015	156	100
0.013	0.010	113	94
0.013	0.0085	91	92

The result shown in **Table 6** suggests that all thickness configurations would meet the SunShot target of 85 mph survival wind speed. Therefore, for a reflector sheet thickness of 0.020", the structured sheet thickness may have a thickness of > 0.013" and still meet both the wind load and slope error requirements.

The work above suggested that the reflector sheet and structured metal sheets could be made of steel of 0.020" and 0.018" thickness, respectively, to meet the slope error target of the project. To verify that the performance targets could be met, and to enable a preliminary evaluation of three different adhesives, prototype panels were assembled using 0.020" reflector sheets with I-unit < 1. The VSHOT tests shown in the table below were very encouraging.

Table 7. Results for prototypes with 0.018" structured sheet (low I-unit) and 0.020" reflector sheet with various adhesives.

Prototype #	Adhesive	dz/dx mrad	dz/dy mrad	dz/(dx dy) mrad
1	DP 8410 NS	0.443	0.402	0.599
2	DP 810 NS	0.616	0.504	0.796
3	DP 8810 NS	0.567	0.484	0.745

Corrosion Resistance: Corrosion of metals is a key aspect of metals. This is especially the case when exploring steel as a material. Various options exist for the corrosion protection of thin steel sheet and this problem has been explored by the automotive industry over many decades. Today, the most cost-effective option for cars is still mostly galvanized steel.

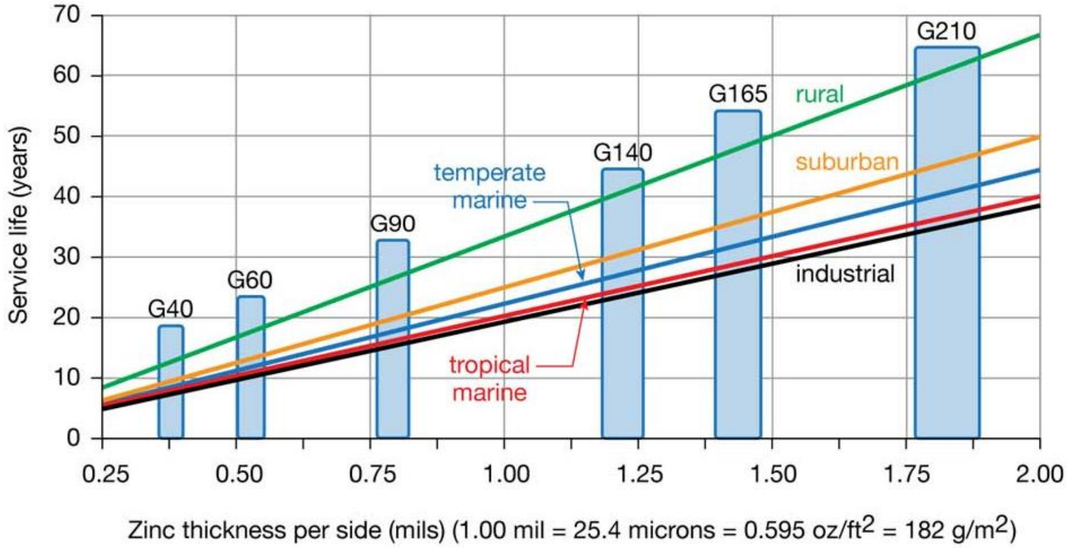


Figure 7. Service life of hot-dipped galvanized sheet: time to 5% red rust-outdoors-fully exposed; (source: GalvInfo Center: GalvInfoNote 1.6, www.galvinfo.com [ref. 8])

Other corrosion protection coating options for steel include electro-galvanizing, galvanneal, 55% aluminum-zinc alloy and aluminized steel. All of these have the option of further being painted. The painting of coated steel provides additional corrosion protection by slowing the penetration of water and oxygen to the underlying metal and by containing corrosion inhibiting agents. Depending on the paint system used the literature reports examples of almost doubling the service life of a G90 corrosion protected steel from 12 to 15 years to 20 to 25 years with a high quality paint (GalvInfoNote 4.2 p.2 [ref. 9]).

55% Aluminum-Zinc alloy coated steel (Galvalume® being a registered trademark of BIEC International Inc.) has proven to be better at corrosion resistance than galvanized steel. A study by Townsend and Borzillo (“ 55% Al-Zn Alloy Coated Sheet Steel: The Versatile, Long Lasting Building Panel Steel”, 5th International Conference on Zinc Coated Sheet Steel, Birmingham, England 1997 [ref. 10]) shows that AZ50 Galvalume can outlast a G90 galvanized steel by 2 to 4 times.

The structured panel sheet is a stamped part with many cut edges. With cut edges there is concern with corrosion occurring at the exposed steel edge. The manufacturer of the stamped part suggested that some “smearing” occurs during the stamping operation over the cut edge, providing protection. To test whether the stamped structured panel would be protection by smearing, structured panels of (1) 0.024” aluminum, (2) 0.018” G90 galvanized steel and (3) 0.0157” 55% Al-Zn coated steel was placed into a neutral salt spray chamber (ISO 9227:2006 section 5.2) [ref. 11]. Three samples of each material were tested (observation results in **Table 8**).

Table 8. Neutral salt spray testing for 7 days of structured panels

	Thickness	Corrosion/red rust	Salt Deposit
5052-H32 Aluminum	0.024”	none	minimal
G90 Galvanized Steel	0.018”	~1 %	significant
55% Al-Zn Coated Steel	0.0157”	none	significant

Many literature sources have pointed to the deficiency of the salt spray test in predicting the real-life performance of materials; however it does provide a useful first test. Further evaluations will be done on full prototypes. Initial indications are that the 55% Al-Zn coating on steel for the structured panel may be a good choice.

Surface Smoothness: The smoothness of the reflector sheet is an important that can influence the specular reflectance of the final product. Surface smoothness of the various substrates has been investigated using scatterometry, Keyance confocal and a Zygo interferometer. One of the challenges in measuring of surface roughness of the reflector sheet is the correlation of this measurement with the ultimate specular reflection of the polymeric mirror film once it is laminated onto the reflector sheet. The study is still ongoing and it is desired that a industry specification on roughness could be provided (or a relevant smoothness / gloss spec developed).

The corrosion protection coatings of traditional G90 galvanized and AZ50 Galvalume®, for instance, are unacceptable as reflector sheets due to the inherent spangle of these coatings. Earlier work (pre award) using scatterometry illustrates this. These show the large beam broadening for samples laminated to Galvalume®.

The table below shows some of the challenges with scattering properties of surfaces before and after lamination with a reflective film. Substrate samples of glass, electro-galvanized (EG) steel and painted aluminum were taken for a study of the impact of surface roughness (scatter) of the substrate on the final scatter of the reflector once the polymeric reflector is laminated onto it. This time some experimental films (#1 and #2) were used. The substrates (bare) were coated with a thin layer of silver through vapor deposition in order to render them reflective for the scatterometry measurements.

While EG steel appears to provide sufficient smoothness, the level of corrosion protection afforded by EG steel, by itself, is not sufficient. For instance, AK Steel offers electro-galvanized steel with a zinc coating up to 0.32 oz/ft^2, which is about an 0.5 mil zinc thickness per side (see **Figure 7** for expected life). The investigation of painted EG steels is currently being pursued with Material Sciences Corporation (Elk Grove Village, IL). Other substrates that were considered were aluminized steel, spangle free galvanized steel and painted steels.

Adhesive Selection

3M’s Industrial Adhesives and Tapes Division (IATD) has recently developed structural adhesives for commercialization that are targeted to meet or exceed the performance of the ScotchWeld DP 810 NS. The cost of these adhesives is expected to be considerably lower than the current DP 810 NS. Initial testing on these new adhesives has shown it to meet and exceed the performance of the current DP 810NS for the MTTS application. One of these new adhesives (DP 8810) is designated as a low odor (LO) product, while the other (DP 8410) as a MMA containing product with superior impact properties and at a lower cost.

Durability testing of the new adhesives was conducted by placing test samples made from the two new adhesives as well as a set with the current DP 810 NS, into an Atlas SUNTEST XLS+ (Ametek Measurement and Calibration Technologies). The weathering chamber was run dry and used with a daylight filter. The samples were exposed for periods of 1200 and 1800 hrs. Sets (10 each) were removed and tested for peak load to failure in a tensile testing jig. The jig was designed to mimic the failure mode (shear/tensile) of the MTTS. The boxplot for the results is shown in **Figure 8**. Both adhesives perform the same or better than the DP 810 NS. Prototype MTTS samples have been prepared mostly by using the new DP 8810. Comparative evaluation of prototype panels with the three adhesives was also done.

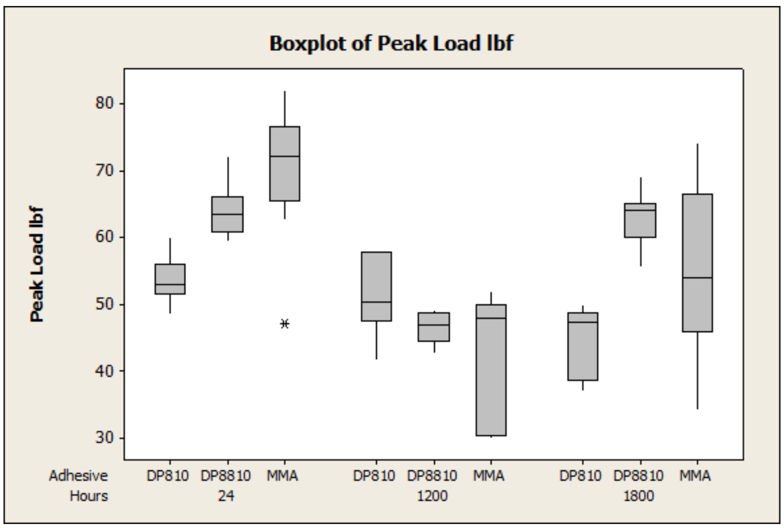


Figure 8. Boxplot of "Peak Load" for the structural adhesives after various exposure times.

So far, the new adhesives have not shown any performance disadvantages compared to the DP 810NS. The presence of spacer beads in the new adhesives (8 – 12 micron) is seen as an advantage with the new adhesives since they ensure a minimum bond thickness. Initially, the 1:10 mix ratio of the new adhesives proved challenging (vs. the 1:1 ratio of the DP 810), but was overcome by changing mixing nozzles and dispensers. Ultimately, the manufacturing processing equipment has to be adapted to ensure good mixing of the catalyst for these adhesives.

Attachment Material Selection

One of the significant cost components of the MTTS panels is the attachment hardware needed to attach it to the supporting frame. This could be as much as 23% of the material cost of the MTTS. The use of 3M Solar Acrylic Foam Tape (SAFT) was explored to replace the attachment hardware. The SAFT technology has been used by 3M for several decades in outdoor applications and some of the benefits of using this type of tape for bonding the MTTS are: immediate handling strength, tolerance to thermal mechanical stresses, weather resistance, long-term durable performance with a proven track record in outdoor industrial applications, and a cost effective approach [ref.12].

Projected Cost:

High volume vendor quotes were obtained for the projected material thickness needs and estimates of quantity and price of adhesive and SAFT 2204 tape.

5.3.2 *SUBTASK 1.2.2*

The prototype assembly process was fixed early on in the project in order to eliminate as many of the variables that can influence the material selection process. To optimize the assembly the following variables were held constant:

- Use of a vacuum chuck (> 20 in Hg) to hold the reflector sheet flat during assembly
- Adhesive strips , ¼" wide and 0.010" thick, laid down using a template
- The "feet" and "tabs" of the structured panels were aligned

By initially holding these variables constant, the impact of these on the material selection process was minimized. **Figure 9** shows how the panels were prepared for assembly. The vacuum chuck and assembly sequence is shown in **Figure 10**.

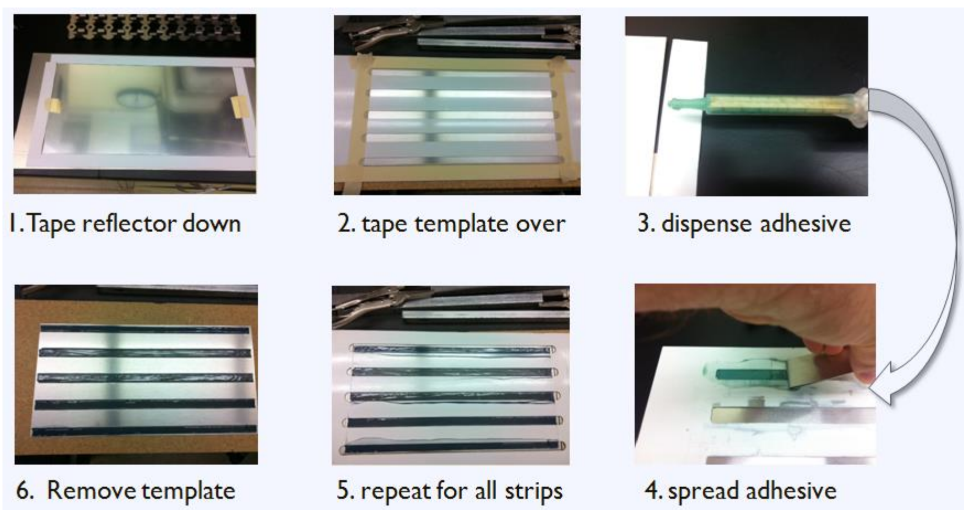
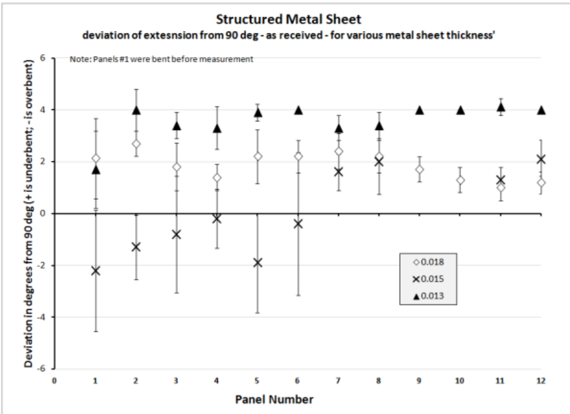


Figure 9. Photos of the assembly sequence used to assemble the MTTS panel candidates.

The "feet" and "tabs" of the structural panels were aligned before assembly to eliminate any high pressure points and possible impact on the panel performance. The measurement of the alignment of the "feet" for the panels before and after alignment is shown in **Figure 9** (a) and (b) below.

(a)


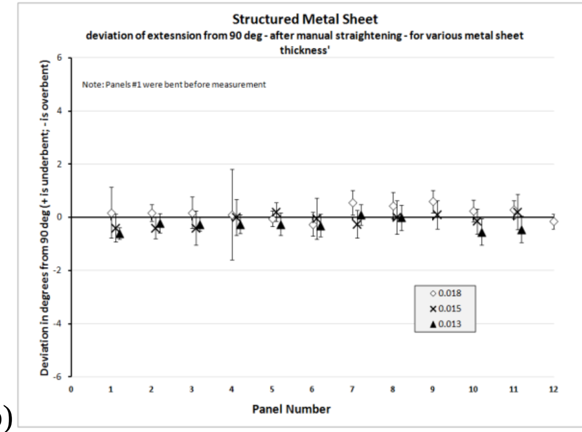
(b)


Figure 9: (a) alignment of the "feet" as received and (b) after alignment.

The assembly sequence for the prototypes is shown below. The need for vacuum, the pressure (weight) during curing, adhesive profile & type are variables that are still being explored. Some of these variables could impact the ultimate manufacturing process.

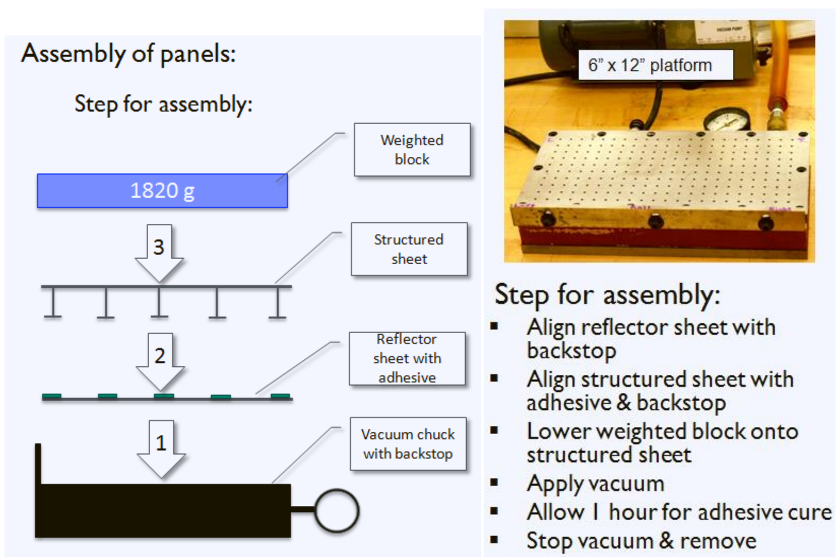


Figure 10. Prototype assembly sequence; the vacuum chuck is shown at top right.

5.3.3 *SUBTASK 1.2.3*

<u>VSHOT Testing</u>

The 3M VSHOT testing apparatus was used to test the root mean square (RMS) slope error of the prototype MTTS panels. The RMS slope error was recorded in both the x-direction (dz/dx), the y-direction (dz/dy) and the overall RMS slope error (designated as dz/(dx dy), where dz/(dx dy) = SQUARE ROOT [$(dz/dx)^2 + (dz/dy)^2$]. The samples were mounted on a specially constructed alignment jig to minimize the alignment coefficients B10 and B11. The analysis of the panels was done by allowing the focal length in both directions to be optimized for the samples. This mode of analysis was verified with NREL (Allison Gray) as the best analysis methodology. Along with the slope errors, best fit focal lengths (both directions), number of points used for the analysis and number of outliers was recorded. These were all used as checks to ensure that no sample anomalies were occurring.

To check the capability of the VSHOT, a statistical analysis was done on the measuring system using 3 samples of expected RMS slope error ranges of 0.5 – 1.5 mrads, 3 operators and with each operator taking 3 measurements per sample (in random order and different days). The results yielded a study gage R&R of just under 30%, which generally indicates a capable method.

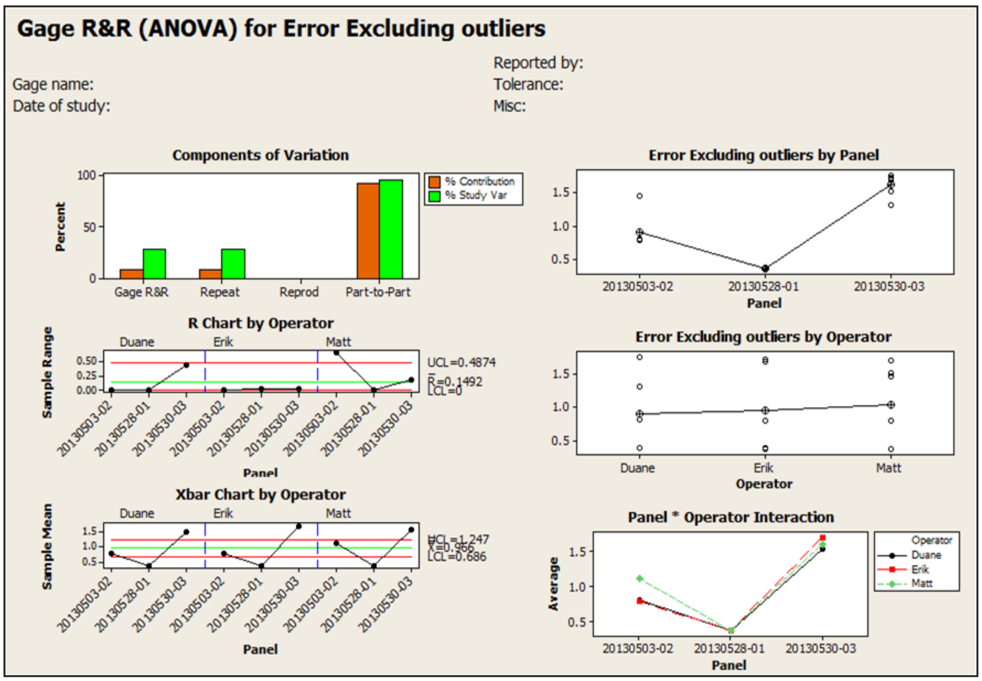


Figure 11. Gage R&R study for the VSHOT in measuring prototype MTTS panels.

Computational Modeling

A Finite Element model was generated using Abaqus CAE 6.12-1 to predict the behavior of MTTS and 5 mm glass under static pressure loads (like wind loads) in a simply supported beam configuration. Linear elastic material properties where defined for aluminum, and glass constructions. Shell elements where used to model the thin sheet metal structures in the MTTS while 3D brick elements where utilized to model the thick glass construction. A global seed size of 0.13-inches was used to ensure accuracy of modeling results. A symmetry boundary condition was used to simplify the modeling effort. A proprietary nonlinear adhesive model was used to predict the adhesive behavior (ScotchWeld DP810 NS) in the MTTS. Model results were evaluated with Abaqus Standard.

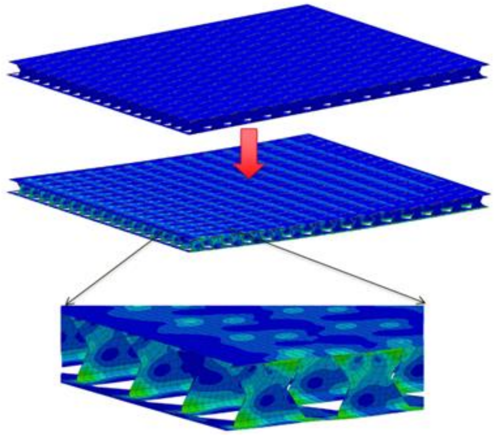


Figure 12. Computational model of the MTTS showing loading of the panel and resulting stress.

The MTTS and glass sheets in the model were set to span a 40 inch length (1 m) and initially a plot of maximum displacement with applied pressure was developed. The Uniform Building Code Wind Specification (Jones 2-5) was used to translate the pressures into wind velocities. The result for the various steel panel constructions was plotted vs. maximum displacement, as shown.

Hail Testing

Hail testing was done by generally following the procedure described in IEC 62108 (2007-12) [ref.4] and hail velocities chosen as described in IEC 61646 (2008), table 2, page 34.

Procedure for hail testing has been to impact the panels with the smallest hail pellets first, and then move to progressively larger sizes. Visual recording as well as VSHOT characterization is used to evaluate the samples. So far we have noted that the front-side impact of hail leads to slight permanent deformation with 19 mm (3/4") hail when the reflector panel is 0.020". For the panels with 0.0085" reflector sheet, permanent deformation is noted with 12.5 mm (1/2" hail). The tests are still continuing to enable a full assessment of front and rear hail impact on performance.

Neutral Salt Spray Testing:

Neutral salt spray (NSS) testing was done according to ISO 9227 Section 5.2 [ref. 11]. 4" x 4" samples were cut out of larger sheets for the test. Some brown sealing adhesive was placed along the sheared edges to prevent corrosion and skew results.

(a)  (b)  (c) 

Figure 13. 7 days of NSS testing of a (a) aluminum, (b) 55% Al-Zn coated steel (0.0157" thick) and (c) G90 galvanized steel (0.018" thick) structured panel. No

rust is visible on cut edges of stamped sheets of (a) and (b), but for (c) some rust is visible, but not necessarily along stamped edges.

5.3.4 *MILESTONE (TASK 1.2)*

Milestone (Task 1.2): Complete assembly of at least 6 (up to 15) reflective panels of the various material sets will be done and a preliminary report on the manufacturability of each panel will be generated. The winning candidate will have an RMS slope error of ≤ 1.5 mrad relative to the best fit surface with a projected cost of ≤ \$30/m2. These measurements will include an analysis of variance (ANOVA) and the cost analysis will include a statistical analysis with high, low and most likely cost for the panels	Over 30 panels were assembled and over 60 optical measurements were which allowed the isolation of significant variables in the manufacturing of optically accurate MTTS panels. A combined RMS slope error of < 1.5 mrads was achieved repeatable with some values as low as 0.8 mrad. Projected cost of these panels was < \$30/m^2, using preliminary vendor quotes. A measurement capability of the VSHOT optical tester was completed and ANOVA used to analyze the data.

5.4 GO/NO GO DECISION POINT 1

The intent of "Next Generation Solar Collectors for CSP" program was to develop key technology elements for collectors in Phase 1 (Budget Period 1), design these elements in Phase 2 (Budget Period 2) and to deploy and test the final collector in Phase 3 (Budget Period 3). However, 3M and DOE mutually agreed to terminate the program at the end of Budget Period 1. However, significant advancements were achieved in developing a next generation reflective material and panel that has the potential to significantly improve the efficiency of CSP systems (Tasks 1.1 and 1.2).

3M intends to pursue the optimization and possible future commercialization of the advanced mirror film as well as exploring the pairing of this with the MTTS panel for the deployment of highly efficient reflectors for CSP.

5.5 PATENTS AND PUBLICATIONS

- A. Molnar and M. O'Neill, SunShot CSP Program Review 2013 – April 23-25, "Advanced Reflective Films and Panels for Next Generation Solar Collectors" *- **Uploaded** to OSTI (Office of Scientific and Technical Information)* ***on October 7, 2013.***
- Provisional Patent Application No. 61/947,238 "Durable Solar Mirror Film with Asymmetric Construction", M. B. O'Neill, D. North; Filed March 3, 2014

5.6 DELIVERABLES

Since the program was terminated after the Phase 1 review, it was not possible, or expected for the final deliverables of the program to be met.

5.7 REFERENCES

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