

RE<C: Heliostat Reflector Design

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Overview

The purpose of the heliostat reflector is to accurately focus sunlight onto a thermal receiver. The reflector must be weather resistant, relatively easy to position, and low cost to manufacture and maintain.

We faced two specific design challenges while trying to fulfill these requirements: weight and thermal expansion. Reflector weight is critical since it influences the sizing of other components: heavier reflectors require stronger structural support, more energy to position, and more complex positioning systems. These translate directly into increased costs.

Thermal expansion is also a challenge because these mirrors must accurately focus light outdoors over a wide range of ambient temperatures. Any time you have two different materials bonded together, shape distortion and structural failure are possibilities since the materials thermally expand at different rates. For example, steel and glass is a common pair of materials for mirror module design, and steel expands 30% more than glass for a given change in temperature.

Reflector Design and Construction

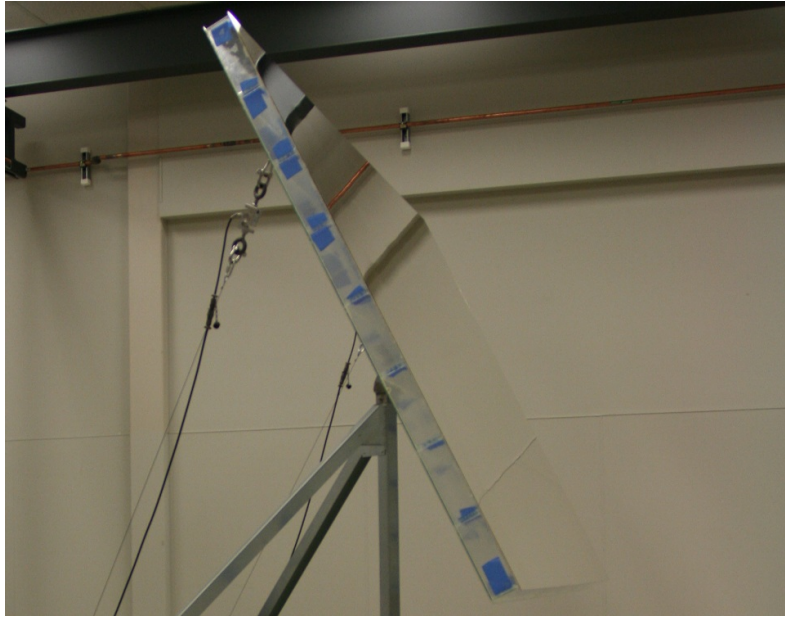
We experimented with hundreds of different reflector designs and sizes to address weight and thermal issues. Our experiments included mylar mirrors, concrete mirrors, foam-backed mirrors, steel supports, plastic frames, and different thicknesses of glass. We tested 1m x 1m square mirrors which could be easily shipped and mounted without additional equipment, and compared them to 2m x 3m rectangular mirrors, which would fit into a standard shipping container but would be more expensive in manufacturing and mounting. We also considered both flat and curved mirror shapes, balancing between increased manufacturing cost of curved mirrors with increased heat focusing abilities.

Our simplest design proved to be the best: A lightweight reflector made entirely out of glass. This design simplifies the assembly process, resolves the thermal expansion mismatch, and provides a high stiffness-to-weight ratio. We also decided that a larger curved mirror (2m x 3m) would be more effective than a smaller flat mirror in focusing light on a target.

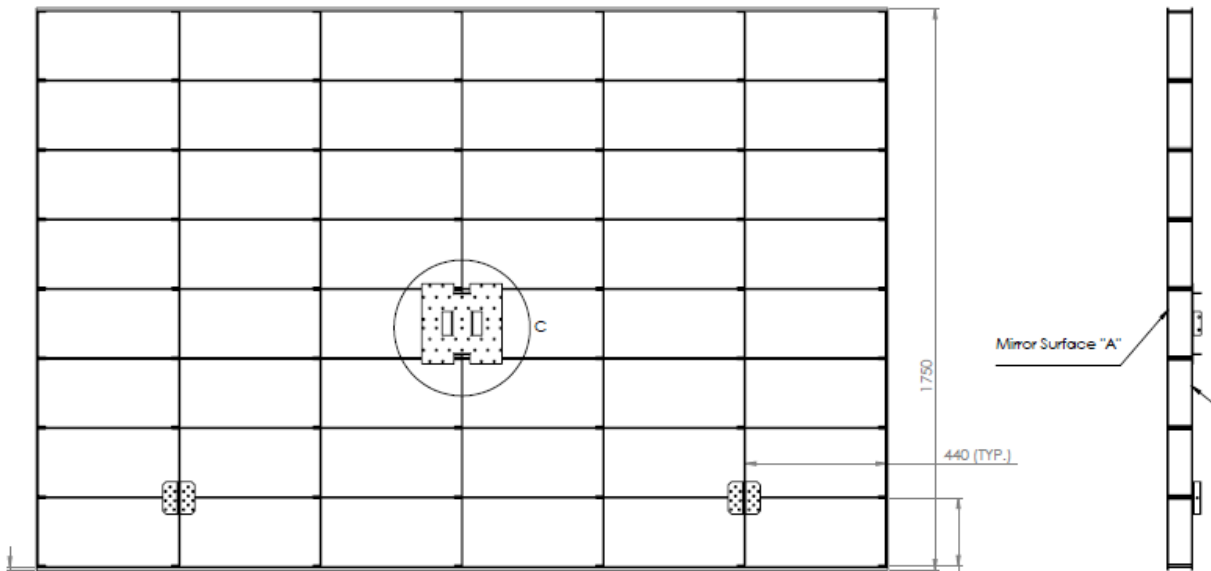


A 2m x 3m heliostat mirror

The reflector we designed is constructed out of a glass honeycomb-style matrix sandwiched between an optical quality mirror and a sheet of structural support glass. This reflector has a slight parabolic curve to focus and concentrate reflected sunlight 2-3 times over a 50m distance. The glass used for the construction is only two to three millimeters thick, reducing weight and cost while maintaining reliability.



2m x 3m heliostat reflector with mirrored front surface



Honeycomb matrix reflector design

To further reduce costs, we used annealed glass instead of tempered glass. A benefit of using annealed glass with a honeycomb support structure is that a local failure indeed remains local and does not propagate across the entire reflector.¹

Mounting pads for a central pivot and two actuator motors are attached with epoxy to the back of the reflector, directly behind cross-rib reinforcements. Placing the mounting pads on cross-ribs helps to distribute the loads and avoid stress concentrations that could warp the reflection or crack the mirror.

¹ We used a few other “matrix” shapes for connecting the two sheets of glass. Using wave-shaped pieces of glass instead of a square grid provided the most structural support with the least amount of material.



Mirror mounting points

Reflector Manufacturing, Shipping and Assembly

Manufacturing our reflector requires pre-cut glass pieces that are simple fractions of a typical glass sheet attached together with glass epoxy. The simple design enables the reflectors to be manufactured and assembled in a factory near where the heliostats are installed, reducing transportation costs. Due to the design of the reflector, and the materials chosen, the parabolic shape can be easily induced during the assembly process. One option we used was to place the mirror sheet over a pre-formed convex surface before attaching the honeycomb structure and rear shear pane. When the epoxy holding the glass cured, the parabolic shape is permanently set in the reflector.

The overall size of our reflector was partially chosen to enable simple and economical shipping. Eight to ten assembled reflectors can be loaded vertically into a reusable shipping container. Upon arrival at an installation site, vacuum lifters can be used to move the reflectors from the shipping containers onto an awaiting heliostat frame.

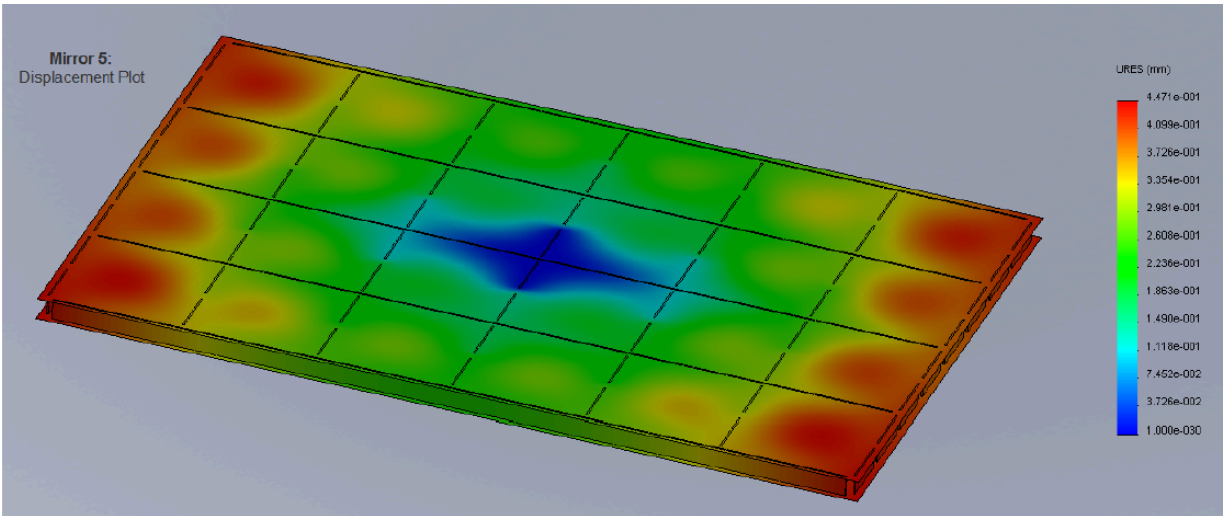


Heliostat reflector mounted on a test platform

Reflector Testing

The reflector design was novel, so we knew it was critical to qualify it for use. Our tests included:

- Preliminary stress calculations
- Load versus deflection testing
- Environmental conditions testing
- Reflection quality testing



FEA displacement of candidate mirror design

Finite Element Analysis (FEA) was performed to analyze stress and displacement under expected loading conditions. The reflector design showed modest stresses and only 0.5 mm of displacement under standard operating load conditions.

The stress and deflection analysis model was validated by loading a prototype reflector and measuring the resulting displacement. For a load of ~1200 N, the measured deflection was 0.55 mm. This results in a reflector stiffness of approximately 2000 N/mm.



Reflector stiffness testing

We tested the initial environmental robustness of our reflector by subjecting it to controlled temperature and humidity cycling and performing a simulated hail test. Cycling temperatures between 0°C (32°F) and 50°C (122°F) showed no problems, since the mirror, structural components, and back panel of the reflector are all made of the same material.

The hail test used a “hail gun” to fire an ice ball at the reflector. The glass reflector survived the standard 25mm hail test, in accordance with the IEC standard (IEC 61215A), which approximates marble-sized hail. It was only when we increased the hail kinetic energy to 9 times past the standard that we were able to crack the reflector. Even at this high energy impact, the damage is retained locally due to the matrix support structure construction.



[Video: Hail Tests of reflectors](#)

Ultimately, what we care about on the performance side is the quality of the optical image produced by the reflector, under a range of conditions, and in volume manufacturing. While testing different prototypes, we performed qualitative tests by focusing sunlight onto targets and inspecting the image quality.

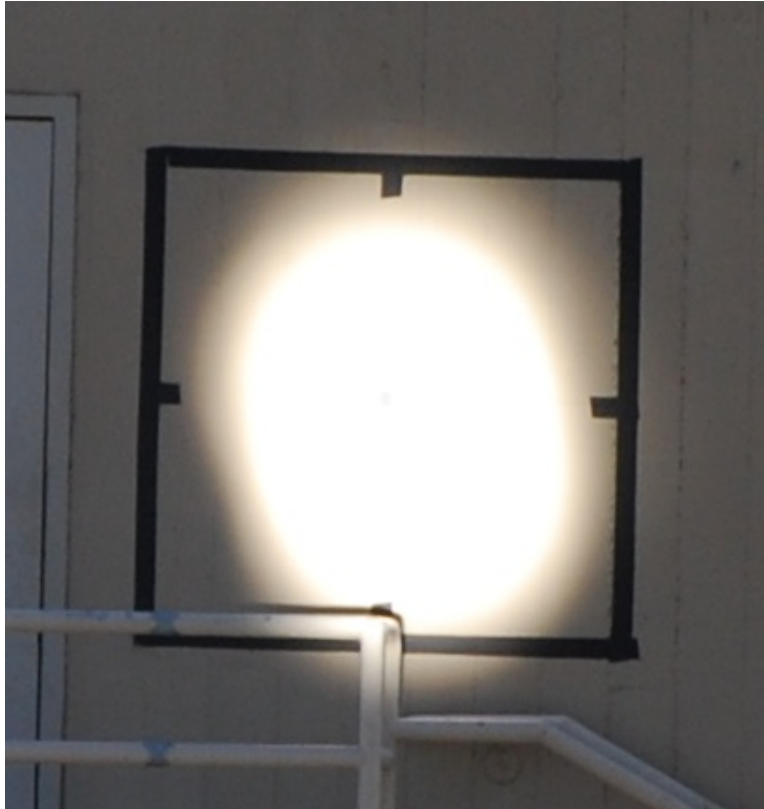


Image from a 1m x 1m prototype mirror onto a 1m x 1m box target.



Solar reflection from a 2m x 3m prototype mirror on a 1m x 1m target, showing a bright 1m diameter focused spot but also some light spillage. Improvement may be required depending on the target requirements.

Over the course of building and testing about 100 different mirrors, we learned several lessons in mirror design and shipping:

- It's important to support the glass uniformly during mirror shaping - uneven support can affect the reflector shape during manufacturing, leading to uneven light-spots on the target.
- Handling large glass sheets safely without breaking them is challenging. We had good results using commercial "vacuum lifters" combined with custom transport and testing carts.
- In some prototypes of our honeycomb reflector design, we observed water collecting in one of the pockets between the glass sheets after a heavy rainstorm. Future designs would benefit from using good edge sealing or an intentionally unsealed design that allows water to drain out of the pockets.
- Working with glass has its challenges. Several times, we observed substantial glass breakage in transport from suppliers, especially when a crate of glass that specified transport in an air ride truck was transported on a standard truck. We had less problems transporting fabricated reflector modules, but it was a challenge during the prototyping stage when packing standards weren't in place. We had one assembled reflector module fail overnight with significant breakage; it was stationary and not in use at the time. It was not under observation, so it we could only speculate over the failure conditions.

Conclusions

The unique reflector we designed, while not perfect, accomplished our design goals. Through the design and testing process, we learned the following lessons:

- Designing a thick mirror module composed of thin glass sheets and internal ribs provides a very high reflector stiffness with low material usage.
- It is possible to build a fully glass mirror module, minimizing issues with shape distortion and change of mirror focus due to differential thermal expansion.
- Selecting glass sizes and thicknesses that are readily available and easy to handle leads to significant cost reductions in manufacturing, assembly, and labor.
- Designing holistically leads to reduced total manufacturing cost. Minimizing the cost of the reflector module alone is not enough. A careful balance must be made in design tradeoffs between reflector size and quality, thermal receiver aperture size and temperature, manufacturing costs and installation costs.
- Rapid iteration is critical, especially early in the design process. In the case of mirror design, the value of specialized mirror handling tools and the tools and processes to do rapid (even qualitative) tests of mirror image quality shouldn't be underestimated.

Potential areas for future work include:

- Performing additional field reliability tests to address possible failures, including sandstorms, rain storms, damage to reflector edges, and long-term lifetime analysis.
- Exploring glass slumping as a method for curved mirror fabrication. This has been tried by many groups with mixed success.
- Conducting further manufacturing cost analysis and optimization of multilayer glass mirrors. While we did a preliminary analysis and worked with major glass manufacturers

to explore possible high-volume manufacturing methods, it's difficult to know the real cost in very high volume without more data.