Metallic Mirror
A Solar Parabolic Trough

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I. Executive Summary

Objectives

The current glass-mirror parabolic trough technology is dead-weight on the structure, expensive to manufacture, complex to assemble, and sensitive to cracking during calibration. We aim to find a new metallic-mirror parabolic trough design that could alleviate all of these issues while decreasing deflection, increasing precision, increasing overall surface area, and providing a 25-50% cost reduction from current models. The goal of our design is to fulfill all of these requirements by replacing the burdensome silver-backed glass mirrors with a metallic mirror trough that not only provides the reflective surface, but also contributes to the structure of the system.

Background / Market

Parabolic solar reflectors capture solar energy in the form of heat. Current parabolic solar reflectors consist of silver-backed glass mirrors supported by an intricate substructure that provides the support for all of the components, and keeps the mirrors in correct orientation after assembly. Countless parts go into attaching and aligning the mirrors so that they are buffered from the torsion the trough experiences, yet stay focused on the heat collection element. The trough also is setup to track the sun throughout the day to maximize energy collection. The market for solar energy generation is always growing, and the government is always looking to invest in clean, inexpensive energy. Being able to create an effective solar trough at at 25-50% reduction in overall cost would greatly increase the demand for clean energy sources.

Overview

Our final design incorporates five mirrored aluminium sections joined by formed strips of aluminium with an adhesive—effectively restoring the structural integrity of a single sheet while also using the added stiffness to enforce the desired parabola. These strips will then be mounted to the truss structure with slip-fit joints secured with a bolt and nylock nut. The remainder of the truss structure will be welded with slip-fit joints for the horizontal linkages to achieve the final structure. This final structure features the incorporated metallic trough, a torque box based substructure, and an easy assembly design that keeps the number of parts and assembly procedure easy to manage. Implementation of this final design would require a physical prototype and 10+ years of testing prior to approval.

Future Recommendations

Future recommendations include continuing research of material finishes, films, or coatings for the metallic mirror to increase reflectivity. The scope of this project only included the initial design and analyses. Physical prototypes and real-world testing is required in order to ensure that the design is viable in efficiency and for production.

II. Background

Origin

Solar parabolic troughs are used to capture the sun's incoming radiation and turn it into usable energy. The first successful parabolic trough collector was made in 1913 generated about 45 kW of power with total aperture area of 1200 m^2. Despite of the success, it was shut down due to World War I. There was a radio silence until the 1980s about this idea. In the 1980s, there were nine solar parabolic power plants generating about 354 MW power called the Solar Electric Generating Systems (SEGS). Nowadays, most of these projects are present in the USA or Spain, but these kind of projects are in planning phase in the countries such as India, China, Australia, Algeria, Egypt, creating a huge market for such systems.

Objective

Current solar parabolic trough technology consists of a metal frame that supports silver-backed glass mirrors, a motor to rotate the system with the sun's movement, and a double-walled, vacuum collector tube filled with either molten salts or high temperature synthetic oil. As with most aspects of technology, continual improvement is vital in keeping a product relevant. In the case of the solar parabolic troughs, research has been done to move away from the heavy and complex glass mirror system, to a more lightweight and cohesive design.

For companies such as Arconic that are not currently in the solar parabolic trough market, research into a new and innovative mirror and structure system could help provide a path into the solar energy market. Since Arconic is not currently in the solar energy market, research on current technology had to be conducted. With that research, it was found that current solar fields could have a variance in metal support structure, but the glass mirror aspect of the system remains virtually the same. Each parabola has a set number of mirrors, all attached to the structure with connectors that not only isolate the mirrors from the structure, but are also easily misplaced or lost during construction. The angle of each mirror has to be positioned just right to allow for optimization of reflectance to the collector tube.

Through research, it was clear that the silver-backed mirrors were the main issue with current solar parabolic troughs. Arconic then set out to create a metallic-based system that could replace the glass mirrors with metallic mirrors and create a cohesive design that eliminates complications with construction. With that, Arconic set the goal of producing a design that has a 25-50% reduction in solar field costs without sacrificing the efficiency of the system.

Short and Long Term Goals

In order for a newly designed parabolic trough system to survive in industry, years of extensive and rigorous testing must be done. Energy companies are not willing to invest in a new technology until it has been tested and proven to be efficient for years. The system has to be completely functional before even proposing the testing phase of the product.

Since such rigorous testing is required for investors to begin to work with the company, a few short term goals, such as further cost reduction and more efficient assembly may be developed. Therefore, in the short time following the initial designing of the new system, improvements on the small details and the structure will be made. With a set structure and metallic mirror already researched, small cost saving details such as shipping, construction or even nuts and bolts costs should be evaluated. Along with investigating further cost savings, the initial, small-scale prototype should be developed to test general reflectivity and functionality of the system.

After a small-scale prototype has been developed and any initial issues evaluated, a large scale prototype should be built and placed at a testing facility to begin solving any large scale issues with the system. As the large-scale prototype is being developed and built, further cost savings may be investigated.

With a large scale prototype built and being tested, the most important long term goal would be to collect enough data to prove to companies such as Nevada Solar One that this new metallic mirror system is just as efficient as the current system in place. What is lacking in reflective abilities is compensated for with price, ease of transportation, and simplified construction. Along with implementing the new system, research on potential surface coatings should be conducted to further enhance the metallic mirror surface. A coating to the metallic mirror could provide what was lacking in reflectivity with a metal as opposed to glass mirrors, which would make the system not only cost efficient, but also efficient in its function.

III. Market Opportunities

Opportunity

Current technology on the market for solar parabolic troughs varies from just metallic mirror surfaces to entire systems. An example of a metallic mirror surface would be the Almirr (Figure 1) multilaminar, mirrored aluminum system. Another example of an new type of metallic mirror is ReflecTech (Figure 2), produced by SkyFuel. ReflecTec differs from Almirr in the fact that it is a silver film that must be placed on a substructure to produce the parabolic shape. The material itself is not strong enough to be a stand-alone component of a parabolic trough structure.

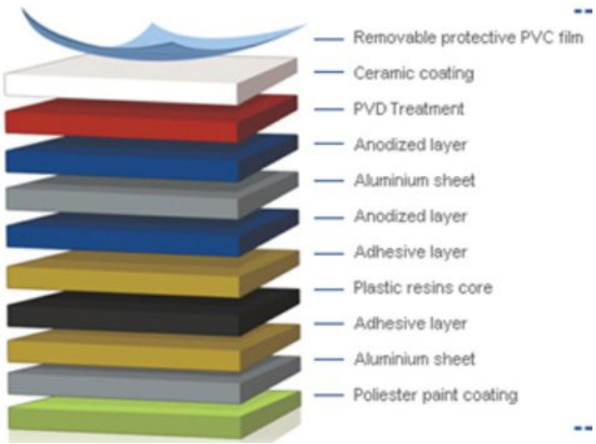


Figure 1: Breakdown of Almirr Structure

Figure 2: ReflecTech mirror film

SkyFuel also produces an entire solar parabolic trough system that includes the ReflecTec film along with an aluminum space frame, as opposed to a stainless steel frame. A company such as SkyFuel would be the main competitor to Arconic's new system due to the fact that both companies are working towards producing entire solar parabolic trough system, not just individual components.

Customers

Customers of a newly developed parabolic solar trough system would be energy generation companies such as Nevada Solar One, Solar Energy Generating Systems, or even Plataforma Solar de Almeria in Spain. Once a solar energy generation proceeds with using the new technology, the Department of Energy becomes the indirect customer because the DOE buys energy from companies such as Nevada Solar One and distributes it to homes across the designated region.

Success

The purpose of this project is to create a more inexpensive model of a parabolic solar collector. Since these models are already in use by energy collection facilities such as Nevada Solar One, this product would be particularly appealing to them, creating great opportunity for our team. For this project our success will be measured through comparing various features of our design to the current solution, including mrad error, intercept factor, surface area, deflection, and cost per square meter. Our goals for each of these features is to have similar or improved results than the current model—less than 8.00 precision error, greater than 0.96 intercept factor, greater than 45.0 m^2 of surface area, less than 2.00 inches in deflection, and a 25%-50% reduction in cost (less than \$265 per m^2).

IV. Project Description

Specifications

The functional specifications that our sponsor provided us were to have similar or improved effectiveness on the currently in place, silver-backed glass mirror design, as well as to reduce field costs by 25-50%. To further distill our definition of 'done' for this project, we decided the best measures of comparison for effectiveness were: deflection under a design torsional load, precision of the mirror's reflectivity, and surface area of the mirror. The lower cost requirement was quantitative enough because our sponsor provided us with the cost of the current design.

Initial Design

Our initial designs were primarily concerned with combating the tested torsional load, because that was the best quantitative measure of our design's structural integrity. Other design requirements, such as the surface area of the mirror, would be met or exceeded based on the fact that we were designing a parabola with the same dimensions as the current solar collector. To get low deflections, we originally experimented with having a large longitudinal beam with a cross section that was resistant to torsion. Revisiting our knowledge of mechanics, and recalling the equation for angle of twist (ø), we found that cross sections with a high St. Venant's Torsional Constant (J) were best for torsional resistance. Mathematically, the cross section with the highest J value is a circular tube; others include a hollow rectangular section and I-beam sections. We successfully met our deflection requirements with some designs using this central beam philosophy, however, the structures were quite heavy given the large beams and need to make some beams out of steel and not aluminum. We realized these designs would be expensive and that they were over engineered to counteract the extra deflection their self-weights were causing.

Evolution

While we were running FEA simulations on our initial designs, part of our project team began investigating usable materials for the mirrored surface of our structure. We all knew the parabolic trough had to possess some structural properties, but also had to have reflectivity and reflective precision that could compete with the silver-backed glass design.

Rather than just accept the literature values for the materials we were investigating, we decided to run an experiment of our own to test the reflectivity of different contenders. Through research, we found that silver polished aluminum, mirrored aluminum, and mylar would be the top three materials to consider in terms of reflectivity and cost. Ordering samples of each of these materials, we sectioned off an equal area of each (2” x 5”) for the experiment. Using a solar flat collector and a halogen lamp angled at 45 degrees pointed down at our material, we were able to measure the reflectivity of each material, as shown in Figure 1. From these experimental results, we were able to perform a chi squared test and then a t test between each sample to determine that the mirrored aluminum was the most reflective to a 99% confidence level. Although it should be noted that halogen lamps have a slightly different wavelength density than the sun, it was the most accurate repeatable setup. Because of these results, we decided to use mirrored aluminum as our metallic mirror.

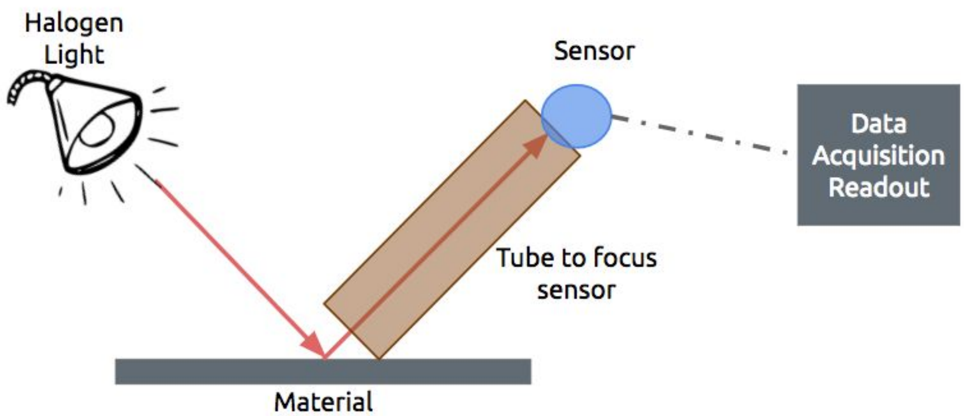


Figure 3: Experimental setup for determining metallic mirror material

Eventually, our design evolved to an all-aluminum truss structure not dissimilar to some of the current designs on the market. Given the drawbacks of our initial designs, we designed a truss that kept maximum deflection from torsion well under one inch, and was made of 1.5” aluminum square tube beams. We also discovered we could make the mirrored aluminum trough quite thin (0.075”) and adhere it to factory-formed parabolic straps to ensure it retained its shape.

Final Prototype

Given the product we were tasked with designing, a full scale prototype was never going to be possible within the scope of our semester. Even a scaled prototype would likely only prove useful as a visual aid, and not be accurate enough to perform experiments on. The closest we got to a physical prototype was a detailed 3D SolidWorks model of our final design, which accurately depicted our proposed connections between beams (slip-fit joints secured with bolts) as well as the parabolic mirror and supporting strips. We did not run FEA analysis tests on this SolidWorks model, because of issues were encountered due to the model’s complexity. However, we believe the FEA tests performed in STAAD.Pro on the same truss design provide ample evidence of our model’s structural integrity.

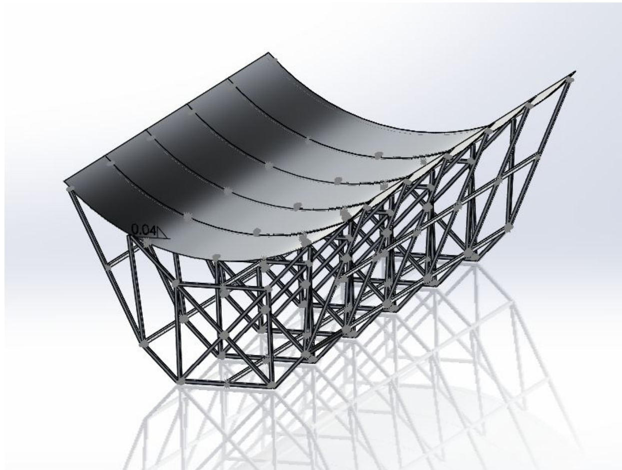


Figure 4: SolidWorks Model

Our new model focused on only major cost contributors i.e., Mirror and Metal Support structure. The different components used in our model are specified in Table 1 below.

Table 1: Bill of Materials

Name	Material	Dimensions (Inch)	Qty
Mirror	Mirrored Aluminum	63 x 0.075 x 220	5
Parabolic Sling	Aluminum	6 x 0.25 x 220	6
Square Tube	Aluminum	1.5 x 1.5 x 38 Wall-0.12"	12
Square Tube	Aluminum	1.5 x 1.5 x 39.5 Wall-0.12"	12
Square Tube	Aluminum	1.5 x 1.5 x 81 Wall-0.12"	6
Square Tube	Aluminum	1.5 x 1.5 x 101.3 Wall-0.12"	12
Square Tube	Aluminum	1.5 x 1.5 x 31.5 Wall-0.12"	12
Square Tube	Aluminum	1.5 x 1.5 x 63.7 Wall-0.12"	12
Square Tube	Aluminum	1.5 x 1.5 x 59 Wall-0.12"	24
Inner Connect Tube	Aluminum	1.25 x 1.25 x 1.5	80
Square Tube	Aluminum	1.5 x 1.5 x 59 Wall-0.25"	40
Square Tube	Aluminum	1.4 x 1.4 x 1.8 Wall-0.25	12
Square Tube	Aluminum	1.5 x 1.5 x 1.75 Wall-0.25"	24
Square Tube	Aluminum	1.4 x 1.4 x 1.55 Wall-0.25"	12
Screw	Steel	1/2"-13 UNC 2.5"	104
Nut	Steel	1/2"-13 UNC	104

One of our major objective was to reduce the solar field cost by 25-50%. Each component's price has been calculated and listed in Table 2. All our components are extruded, so an industrial extrusion rate is charged while doing the cost analysis. The rates of extrusion are $3.65 per lbs for mirrored aluminium and $1.65 per lbs for aluminium. These are the estimated quotes from our sponsor. Also, a 30% additional cost is added, which takes care for manufacturing, processing, and cutting expenses as required for new model.

Table 2: Cost Analysis

Name	Volume ($Inch^3$)	Density ($lb/inch^3$)	Weight (lb)	Material Cost ($)	Price (1 pc)	Qty	Total Cost ($)	Cost per m^2
Mirror	1039.5	0.1051	109.3	365.99	475.7 9	5	2378.95	59.47
Parabolic Sling	330.0	0.098	32.3	53.36	69.37	6	416.22	47.28
Square Tube	25.2	0.098	2.5	4.07	5.29	12	63.49	
Square Tube	26.2	0.098	2.6	4.23	5.50	12	66.00	
Square Tube	53.7	0.098	5.3	8.68	11.28	6	67.67	
Square Tube	67.1	0.098	6.6	10.85	14.11	12	169.26	
Square Tube	20.9	0.098	2.0	3.37	4.39	12	52.63	
Square Tube	42.2	0.098	4.1	6.82	8.87	12	106.44	
Square Tube	39.1	0.098	3.8	6.82	8.22	24	19.17	
Inner Connect Tube	2.3	0.098	0.2	0.38	0.49	80	39.41	
Square Tube	75.6	0.098	7.4	12.23	15.90	40	635.89	
Square Tube	2.1	0.098	0.2	0.33	0.45	12	46.80	
Square Tube	2.2	0.098	0.2	0.35	0.09	24	9.36	
Square Tube	1.8	0.098	0.2	0.29	0.44	12	5.22	
Screw					0.46	104	11.04	
Nut					0.37	104	4.50	

V. Conclusions

Summary

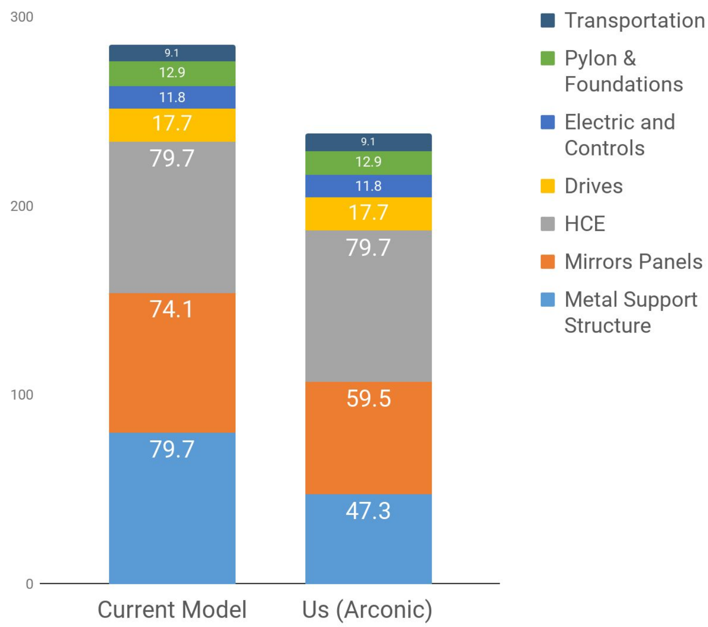
In this project, we were able to design a parabolic solar trough, made entirely of aluminum that meets all of our objectives. By using a thin mirrored aluminum as our reflector, and integrating this surface into the structure, we were able to eliminate a large amount of the deadweight acting on the structure. Additionally, our design has minimal assembly steps compared to the current design, so it will decrease error opportunity in field assembly, in addition to decreasing risk of time delays such as losing parts in field, allowing for a quicker setup time that will maximize financial return on investment.

Comparison

To compare our structures results to our project objectives, we met all performance goals or improved upon the current structure, with decreased overall cost. The surface area of our design came out to be 45.92 m^2, greater than our objective of 45 m^2. This increase in surface area, which was achieved by designing a mirror structure comprised of less pieces and fewer gaps than the current model, will significantly impact the amount of energy reflecting off of our mirror into the collection tubes. Precision error and intercept factor are two parameters we can use to gauge the performance of our solar collector. Precision error is measured as the standard deviation of light reflected off a surface. Our sponsor's goal for us was have precision error under 8.0 milliradians (an arc length equal to 1/1000 of the radius), because after this value, solar collector performance decreases rapidly. Though we did not have the time, funding, or equipment to test for precision error, we are fairly confident that our mirrored aluminum structure, with far fewer mirror parts than the current glass mirror design, would be calibrated to have similar or improved precision performance. Intercept factor is a calculation for the ratio of the radiation that hits the mirrored surface to the radiation that the target (collector tube) receives. Our sponsor recommended a minimum of a 0.96 intercept factor. Again, this calculation is beyond our scope since we did not have access to the materials or equipment to find our intercept factor. However, we argue that because our overall structure will be stiffer and have a more accurate parabola due to the assembly procedure, our intercept factor should match or exceed 0.96. Our design also has a greater surface area, which in combination with the intercept factor will produce significantly more power per trough to the original. Our design's maximum deflection is 0.68", much lower than our 2" target. When we compare major cost factors from the current model which was given by our sponsor at beginning of the project, we have reduced mirror cost by $14.60 per square meter, and metal support structure by $32.40

per square meter. Including all other solar field costs, our design costs $238 per square meter, which is a 31% cost decrease on the current design. This meets our project goal of at least a 25% decrease in cost. A cost comparison graphic can be seen below in Figure 3.

Figure 5: Cost comparison from current model



Product Development Process

In order to achieve these results, our team began by researching various metallic mirrors, selecting three options to text in an experiment. After testing the reflectivity of mirrored aluminum, silver polished aluminum, and mylar, it was found that mirrored aluminum was the most effective reflector to a 99% confidence level. After selecting our reflective surface, we began designing the structure of the parabolic trough, with the goal of achieving less than 2” in deflection. Through many iterations in STAAD.Pro, we were able to find a design using minimal materials to minimize cost, while achieving our deflection goal. Finishing off the project, we took this design into Solidworks where we modeled each attachment method to achieve an accurate bill of materials to factor into a finalized cost analysis.

Recommendations

For future projects, we would like to recommend furthering research on various materials used, including looking into the concept of layering grades or finishes of aluminum to reduce cost and increase torsional stiffness. Additionally, research could be done on potentially using various alloyed materials, different coatings or films in order to increase spectral reflectivity in metallic mirrors.

In terms of cost analysis, future projects could explore more in depth into various other components of the overall system including receivers, heated transfer fluid, and reducing transportation to decrease overall cost. Including these considerations may show that our system is an even greater cost reduction from the current design being used in industry.