Project Title: Improved Large Aperture Collector Manufacturing

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Executive Summary:

Solar Thermal Electric (STE) power generation is facing significant challenges from other sources of renewable energy; their advances have made it more and more difficult for solar thermal to remain a cost effective alternative in the United States. The primary advantage of STE is the thermal storage capability, which allows plants to continue producing electricity long after the sun has set. While it is necessary for the industry to fully develop this storage technology, it is also critical that significant cost reductions are found in the solar field construction and installation. If STE is to be competitive, these cost reductions must be recognized not only in the design and manufacture of the collectors, but also in the assembly and installation of the solar field. The goal of this project was to evaluate the current state of the art parabolic trough collector field and develop an improved field that can be installed for < $92/m^2$. Early in the project development it was recognized that the collector components, manufacture, assembly, and field installation are dependent on each other, and it is impossible to make changes to any of these without affecting the others. Therefore, a top down review of the collector was performed and each component was evaluated for performance, cost, manufacturability and assembly.

Phase I of this project was to perform a detailed analysis of the entire solar collector field and the associated manufacturing and assembly process. This included component redesign, assembly method development, and design of fixtures required to achieve the target assembly times and cost estimates. Detailed results of the Phase I work can be found in the continuation report for the same DOE award Number DE-EE00006357 submitted on the 30th of September, 2014. Phase II was a prototype scale physical demonstration to verify the design assumptions and conclusions developed analytically in Phase I and identify opportunities for further improvements, bringing this system to a technology readiness level 6.

The evaluation has resulted in the complete redesign of several of the key components in the collector module, as well as significant changes to the module assembly process and the solar field installation process. Design changes to the components were typically driven by reducing the component cost and to provide other downstream advantages to the solar field installation process. Key improvements include redesign of the mirror support structure and the upper receiver support. It is anticipated that the changes to these two components will result in a reduction of the installed solar field cost both in cycle time and labor required. Finally, parallel improvements in the field installation were also required so that the installation process could keep pace with the module assembly process.

In summary, the outcome of the project is a large aperture parabolic trough collector and associated assembly line and installation methods that will make parabolic trough collectors cost competitive with other renewable energy sources. During Phase II Abengoa was able to test many of the designs concepts and assumptions and the project installed cost of the solar field of $92/m^2$ is achievable.

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1 Background

The parabolic trough is the most established CSP technology and carries a long history of design experimentation dating back to the 1970's. This has led to relatively standardized collector architectures, a maturing global supply chain, and a fairly uniform cost reduction strategy. Many so-called "disruptive" design architectures have also been tested, but so far none have proven commercially advantageous.

During this time the cost reduction strategy has most commonly been to focus on the concentrator module; by experimenting with different structures, increasing the aperture area, and optimizing the design for efficient manufacture & assembly. More than three decades of R&D in these areas have led to markedly lower collector costs, improved component performance, and increasing competitiveness of CSP trough power plants with traditional gas and coal fired plants. To capitalize on this new market opportunity several large-aperture and cost-optimized collectors have recently been developed. However, in the experience of the authors these designs are not highly structurally efficient, nor are they fully optimized for volume manufacture, low-cost assembly, and flexible international deployment.

Abengoa has deployed more than 1500MWe of CSP troughs across several countries and has built and tested full-scale prototypes of many R&D concepts:

- Box-truss, torque tube, monocoque, and space frame trough structures
- Stamped and welded mirror arms, with both glass and sheet metal based mirrors
- Steel and aluminum space frames with precise and imprecise fabrication
- Jig-based and jig-free assembly alignment systems

These experiences, consolidated under the prior collector FOA award, resulted in a cost-reduction effort oriented toward large-aperture carbon steel space frame structures with glass mirrors. This led to development of the current state-of-the-art E2 collector as well as the next-generation 8.2 x 16m SpaceTube® (ST8.2). The E2 is a low-cost, assembly-optimized 5.8 x 12m steel space frame collector (RP-3 platform); while the SpaceTube® is an 8.2 x 16m space frame with a more material efficient frame design, higher optical rigidity, reduced part count, and better component standardization. Having benefitted from Abengoa's construction experience and robust R&D / DFMA program, the current SpaceTube® is comparatively low cost, and it incorporates many design features aimed to facilitate further cost reductions through automated manufacturing and assembly. This made it a unique candidate for SolarMat manufacturing study, and puts the end product within reach of the SunShot objectives

Figure 1: Diagram showing LS-2, E2, and ST8.2 (photos scaled by aperture dimension to highlight scale)

Abengoa's trough development efforts in both the US and Spain and other CSP industry developments also strongly influenced this development. This included

- Plant simulation of larger-aperture collectors which confirmed the potential for cost reduction previously identified by others in the field
- Design analysis of large-aperture torque tube and aluminum space frame structures, in which sub-optimal material efficiency and fabrication costs were found to result in higher costs compared to the SpaceTube® architecture.
- Design and testing of a sheet metal-based reflective film mirror replacement and development of commercial manufacturing designs for an optimized second version. This resulted in a marginal cost advantage, but not enough to justify commercializing
- Investigation of more sophisticated assembly and alignment strategies under development by Brightsource, Sener, and FlagSol, which showed potential especially if they could be expanded in scope and coupled to a highly cost-optimized structure like the SpaceTube®.

The prior trough R&D efforts also involved efforts to internalize non-CSP industry experience including a preliminary DFMA principles review done with Boothroyd Dewhurst, a construction literature review by the Arizona State University School of Construction Management, and two more focused manufacturing engineering subcontracts done by Ricardo Inc. and the nonprofit Edison Welding Institute.

The first two studies highlighted strong opportunities in lowering part count, standardizing components and fasteners, developing modular designs to support prefabrication and automation, and devising simple, error-proof manual assembly methods. These principles have delivered major new cost savings in otherwise "mature" products in analogous industries like automotive, truck trailer manufacture, metal building fabrication, and shipbuilding. For this reason, they were core in the design development of the SpaceTube® collector, and arguably key to its early successes.

The latter two studies were applied specifically to the first-generation SpaceTube® design and were important in setting the direction of the present SolarMat project. These studies developed a methodology to analyze the costs of manufacture and assembly, and identify new tooling concepts for more efficient manufacture. Among the main opportunities identified in these studies were the automated mirror arm manufacturing concept and the need for a less infrastructure-intensive assembly line, both of which now form central pillars of the SolarMat project strategy.

These new designs will be supported by new technology in the area of quality control inspection, in which state of the art photogrammetry and laser CMM inspection methods will be used to qualify parts and assemblies, and in which the recently-developed Absorber Reflection Method will enable in-line quality control inspection of modules produced by the new high-rate production line.

2 Project Objectives

The Solar MAT project addresses many of the issues that have faced the Solar Thermal Parabolic trough industry since its inception in the 1980's and many newer issues that have developed with the increased interest in renewable energy. There are many ways that the US can obtain its goals of green energy production, and all of these should have economic advantages for the US. As the technology of renewable resource energy production has increased, the market share for these competing technologies has become increasingly more competitive. As late as the early 2000's, it was believed that STE generation had an assured place in the renewable mix; however, with the exponential advances in photovoltaic generation the fate of STE is no longer assured. STE does have the advantage of thermal energy storage, allowing the energy to be dispatched to the grid on an as needed basis, but the ability to store solar thermal energy alone does not assure the survival of the industry. Systems that allow STE to be cost competitive with other renewable forms of electricity (PV, Wind, Bio Energy, etc.) and fossil fuel based generation (i.e. gas and coal) must be developed.

The project demonstrates a substantial reduction in the deployment cost of Abengoa's SpaceTube ® advanced large aperture parabolic trough collector. These reductions are obtained through application of high rate manufacture and fabrication and automated assembly techniques. The project scope includes manufacturing engineering development and pre-commercial feasibility demonstrations focused in three main areas; an aggressive manufacturing optimization of the collector sub-structures for lower input material costs & mechanized production, a low-investment-cost "lean" assembly line system, and a standalone quality control inspection applied to the installed collector.

The project was divided into 2 Phases. Phase I of the project was to develop conceptually the trough system and assembly line and perform detailed cost analysis as part of a feasibility study. Phase I was divided into 4 primary tasks. Each of these tasks had a value proposition developed and milestones and deliverables established. Additionally, at the end of Phase I there was a critical go/no-go milestone with 2 stage gates. A brief summary of each of the Phase I tasks is listed below.

Task 1 – Adapt structural components fabrication for automated manufacturing

Task 2 – Develop a highly automated re- deployable site assembly factory for the assembly of the collector modules.

Task 3 – Develop a non-contact quality control inspection system

Task 4 – Project management

Phase II of the project was the prototype demonstration of Phase I methods at a single module scale. This activity was oriented toward practical feasibility demonstration and design refinement of the Phase I "on paper" designs and serves to further identify and resolve the main practical challenges at each stage providing real world experience and establishing best practices in the following areas

- Experience with the form, fit, handling, and function of the new components

- Practical and ergonomic experience with the new assembly line / assembly stations
- Practical feedback and improvement ideas concerning assembly line layout, workflow, building shape, component storage and supply to the assembly line
- Steady-state workflow, laborers needed at each station, and pinch-points
- Experience and development of best practices for new in-field installation and alignment processes (pylons and mirror modules)
- 3rd party cross-check of costs provided by involving Abengoa Research innovation and Consulting SA (ARI&C) and EPC contractor(s) in the demonstration, and documentation of this 3rd party review useful to feed next steps in commercial implementation and related due diligence processes
- Important design improvements likely to be generated by multi-disciplinary demonstration team of R&D design engineers, manufacturing engineers, and experienced construction supervisors working together in a low-criticality R&D demonstration environment

It was not the intention of Abengoa to demonstrate every aspect of the Solar MAT Large Aperture manufacturing and assembly line, but rather to identify the “higher risk” operations and demonstrate those tasks. Higher risk tasks and operations were determined by performing a sensitivity analysis where a matrix was developed that evaluated each step and the consequences of failure or inability to meet cost and labor estimates.

Phase II was broken down into several sub tasks.

Task 5.1 – Procure and construct representative assembly line

Task 5.2 – Construct single module prototype using representative methods

Task 5.3 – Demonstrate standalone QC system and compare to results from conventional system (PG)

Task 5.4 – Project reporting

Task 6 – Project Management

3 Project Results and Discussion

Phase I included an “on paper” development of a semi-automated parabolic trough assembly plant, design and modifications to key collector components optimized for manufacture and assembly and optimization of some field installation steps. The plant layout included provisions for all module assembly steps, preassembly of several major subassemblies (mirror support structure and HCE sub assemblies), and the new inline real time non-contact QC station. Key optimized components were discussed in the Phase I continuation report, but a brief summary of the optimization process and the resulting cost reductions has been included below. The in-field process optimization developed in Phase I has been tested as part of Phase II and the results of this testing are reported below. Phase II was a physical demonstration of the assembly concepts developed in Phase I. Due to project time and budget constraints a full prototype of the entire system was never planned, it was intended that for mature processes, time and cost data could be drawn from current Abengoa installations.

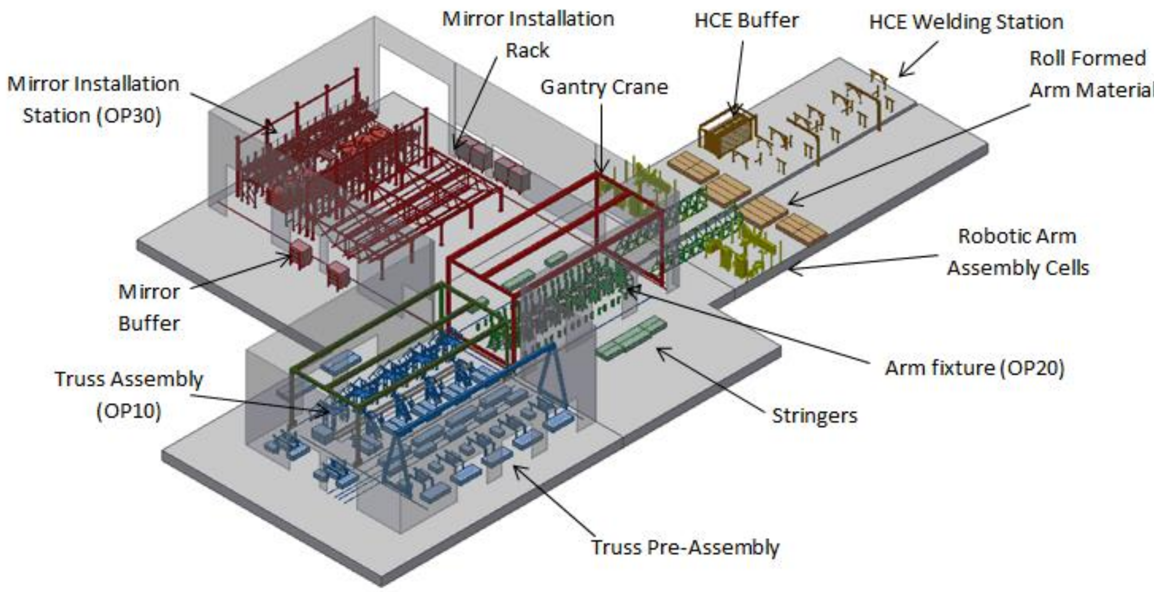


Figure 2: Phase 1 proposed semi-automated Solar MAT assembly line

3.1 Phase I projected cost savings

Optimization of a manufacturing and or assembly process often times requires that each component is evaluated using a DFMA (Design for Manufacturability and Assembly) methodology. Therefore the Solar MAT project not only evaluated the assembly of the collector module and installation of the field but also included a detailed review of the primary components to identify potential cost saving opportunities. Several components were identified through a cost sensitivity analysis in Phase I as having potential for significant cost savings. The components and their costs as estimated at the end of Phase 1 are shown in Table 1. These cost estimates were based on vendor's quotes.

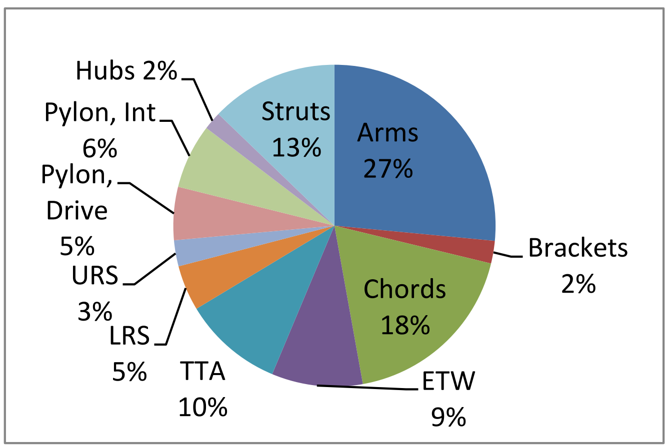


Figure 3: Phase I component cost breakdown

Table 1: Phase 1 projected component cost savings

Component	Starting Cost[1]	Phase 1 cost estimate[2]
Mirror Support Structure (MSS)	$14.93	$8.16

End Truss Weldment (ETW) Torque Transfer Weldment (TTW)	$6.02	$5.63
Upper Receiver Support (URS)	$2.19	$1.19
Lower Receiver Support (LRS)	$3.59	$2.19

[1]Starting prices and Phase I estimate taken from Phase I Continuation Report

[2]Based on quotation

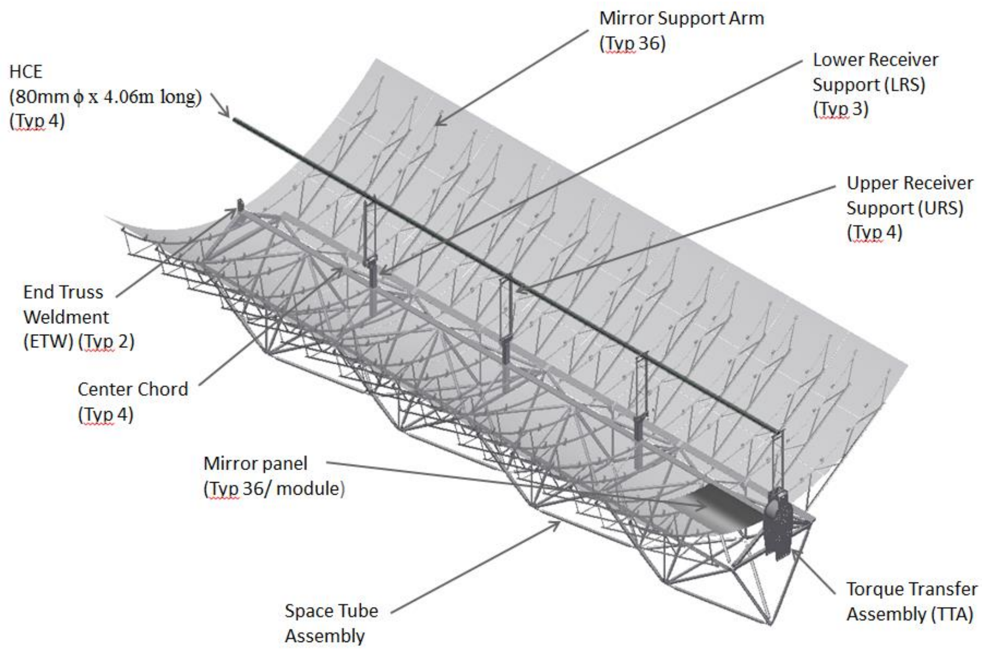


Figure 4: SpaceTube ® (ST8.2) large aperture parabolic trough solar collector mirror module

3.2 Mirror Support Structure (Arm)

Abengoa completed the physical installation of the robotic arm cell for the mirror support arm fabrication in our Lakewood CO facility. The robotic cell, designed by Grenzebach, consists of a multi-axis Kuka robotic arm with a Bollhoff self-piercing rivet tool. The current robotic cell must be manually loaded, but has been set up such that Abengoa can generate realistic time studies for the material handling and operation of the robotic cell. As noted in Phase I, it is anticipated that in order for these cells to keep up with mirror module assembly, it will be necessary to have two mirror arm assembly cells, each equipped with a rotating fixture that will allow one side of the fixture to be loaded while the other side is being riveted. Abengoa conducted time and motion studies on the robotic cell to verify these assumptions as part of Phase II Task 5.2.

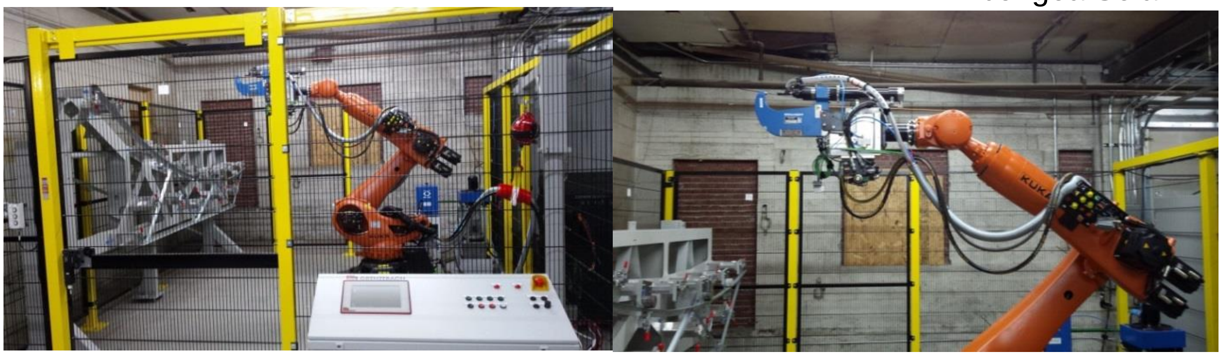


Figure 5: robotic arm shown with mirror arm fixture (left) with mirror arm components in place ready for riveting. Total cycle time for robot to make all riveted connections is under 2 min.

Table 2: Cost comparison of mirror arms (tooling amortized over 2 x 100MW plants)

	Current	Phase 1 Proposed
	Welded Arm (Eucomsa)	New Arm (Grenzebach)
Single arm weight, kg/unit	19 kg	13 kg
Raw Material, $/unit	$42.02	$22.53
Factory Processing Cost, $/unit	$2.28	$0
Site Labor + Tooling Amort., $/unit	$5.73	$4.66
Transportation Cost, $/unit	$2.22	$0.63
Single arm cost, $/unit	$52.25	$27.82
Total arm cost $/m^2	$14.93	$8.16

A detailed discussion of the mirror support structure and the operation of the arm cell will be included in the Task 5.2 summary section.

3.3 Upper Receiver Support (URS)

Phase I of the project identified the Upper Receiver Support as a component with significant potential for cost reduction through material selection and manufacturing techniques. Abengoa contracted with BATZ engineering to review the Upper Receiver Support design and provide recommendations regarding a reduced cost option. Batz returned with a recommendation that a stamped upper receiver arm could be implemented that would reduce the component cost by as much as 50%. A cost summary for the baseline welded URD and the proposed Phase I stamped URS design is included in Table 3. Pricing is based on vendor quotes.

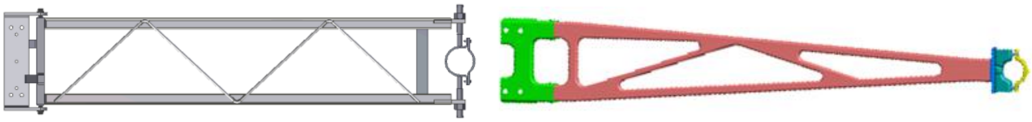


Figure 6: Final stamped Upper Receiver Support (URS) design (right) compared to baseline URS (left)

Figure 7: Batz stamped HCE support arm strength and stiffness test setup

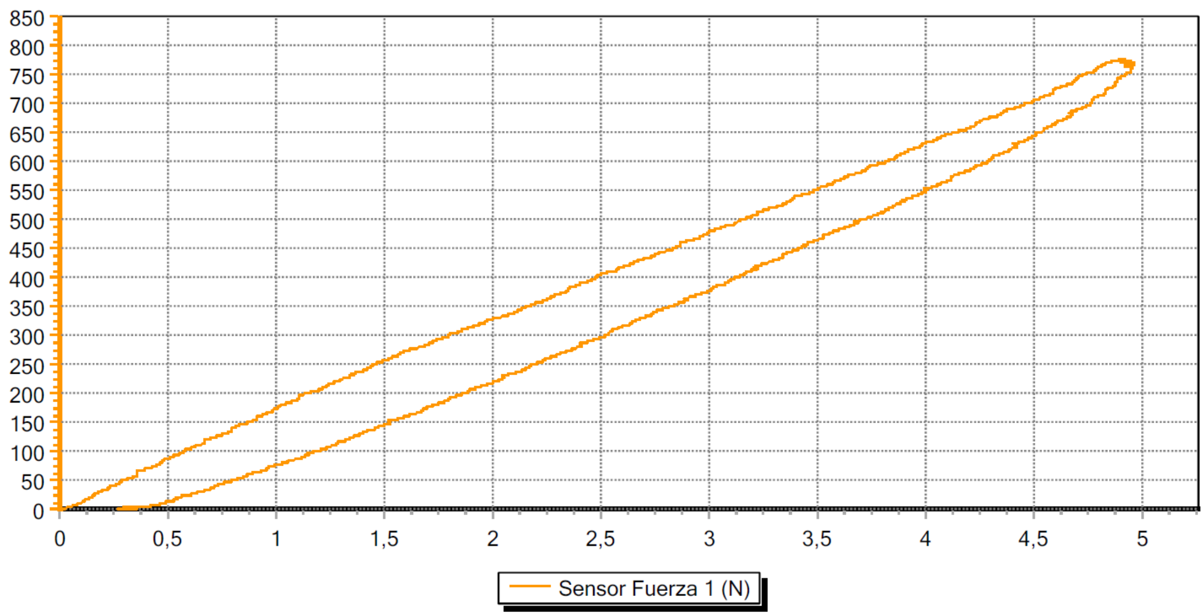


Figure 8: URS Loading test (Load in N vs. Deflection of receiver position in cm)

Table 3: Cost comparison of stamped HCE support arm

Upper Receiver Support (URS) Cost Reduction Summary		
Supplier	Cost (each)	Cost ($/m2)
Eucomsa welded (baseline design)	$71.93	$2.23
Batz (stamped part alone)	$25.00	$0.76
Batz w/ tooling amortized over 40k units (200MW)	$40.28	$1.19

3.4 End Truss Weldment (ETW) & Torque Transfer Assembly (TTA)

The current ETW that is used in the commercial version of the SpaceTube ® is expensive and difficult to fabricate for our in-house fabrication facility (Eucomsa). An alternate design has been proposed by Eucomsa but based on additional FEA performed outside this contract has shown that this design is not adequate (this design was used in the Phase II prototype and the results that were witnessed in the field validated the FEA results). The deflection was too great and the weldment did not have sufficient stiffness out of plan to resist the loading seen when lifting the module during the OP20 → OP30 transition.

Figure 9: Flipper attached to the TTA/ETW assembly. Shown while module is supported by crane (typical OP20-OP30 transition (note: excessive deflection in the TTA plates)

A new alternate design has been developed through a collaborative effort between AR I&C, Next Force Engineering (NFE), and Eucomsa. This design plays to Eucomsa's fabrication capabilities. A final design check has not been completed but is planned as part of the next steps/ commercialization plan.

Additionally, feedback from the Xina project construction has indicated that based on the fabrication tolerances of the drive bell crank, there is limited adjustment in the slots and the alignment of the modules across the drive is difficult.

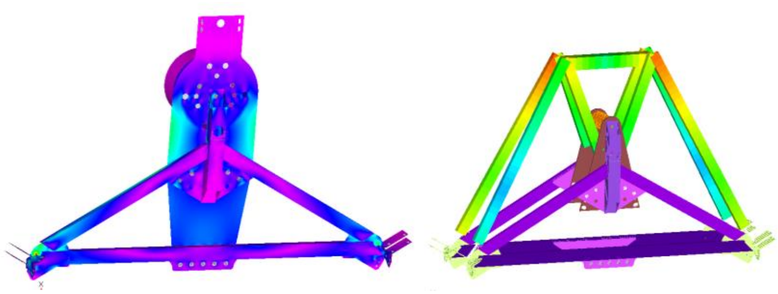


Figure 10: ETW and TTA cost saving concepts (pictured concepts replace both ETW and TTA)

3.5 Lower Receiver Support

Similar to the URS Abengoa worked with Batz to evaluate the Lower receiver support with an eye toward developing a stamping similar to the URS. The results of this effort resulted in a conclusion that a design utilizing a stamped section would be a viable alternative for a cost effective component.

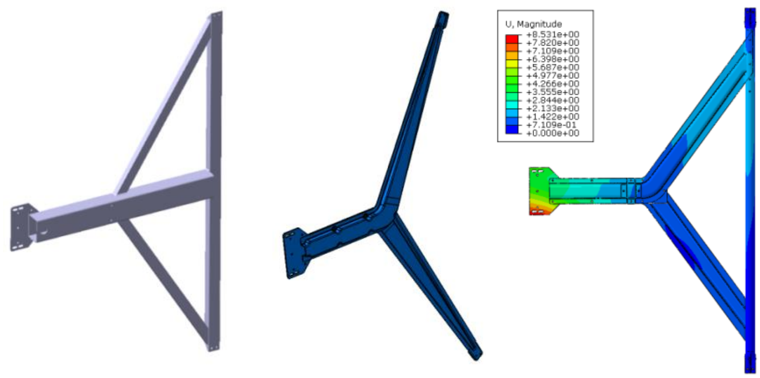


Figure 11: Lower Receiver Support (LRS) design progression and cost estimates

Lower Receiver Support (LRS) Cost Reduction Summary		
	Baseline Cost ($/m2)	Phase I ($/m2)
LRS	3.59	2.19

3.6 Component design optimization summary

The results of the component optimization have resulted in an anticipated cost reduction in the module component cost of approximately $21.27 /m^2. This cost savings is based on amortizing the tooling over 200 MWe installations and is based on US domestic fabrication and supply. Table 4 summarizes the anticipated cost reductions and identifies a supplier that has provided a written quote that was used for the cost basis.

Component	$ / collector	$ / m2	Supplier
Collector support structures	$ 56,681.52	$ 42.43	
Frame	$ 9,944.70	$ 7.44	
Hubs	$ 143.90	$ 1.08	Eucomsa
Struts	$ 568.05	$ 4.25	Eucomsa
Hardware	$ 282.53	$ 2.11	Eucomsa
MSS	$ 13,048.02	$ 9.77	
Arms	$ 801.00	$ 6.00	
Webs	$ 3.96	$1.07	OMCO
Arm Top and Bottom	$ 15.08	$4.06	OMCO
Brackets	$ 3.21	$0.86	OMCO
Chords / purlins	$ 503.80	$ 3.77	Eucomsa
Receiver Support	$ 4,436.30	$ 3.32	Batz
LRS	$ 117.65	$ 2.64	Eucomsa
URS	$ 22.67	$ 0.68	Batz
End Plate Structures	$ 9,831.51	$ 7.36	
ETW	$ 236.47	$ 3.54	Eucomsa
TTW	$ 510.21	$ 3.82	Eucomsa
Pylons	$ 9,492.50	$ 7.11	
Drive Pylon	$4,648.40	$ 3.48	Eucomsa
Interior Pylon	$ 484.38	$ 3.63	Eucomsa
Foundations	$ 9,928.49	$ 7.43	
Drive Foundation	$1,280.50	$ 0.96	SolarFrame
Int. Foundation	$ 864.80	$ 6.47	SolarFrame

Table 4: Total structural component cost, showing attainment of $45/m^2 target cost at 95% confidence (i.e. cost calculated from actual vendor quotations). Baseline E2 collector cost is $65/m^2

3.7 Balance of solar field assembly and installation

Phase I looked at multiple options for the assembly line / assembly plant for the solar field assembly and installation. Options included completely automated (High automation) assembly lines to semi-automated (low automation) to manual assembly lines. The figure below shows that until the installed solar field(s) exceed 300 MWe that the semi-automated options has the lowest assembly and installation cost. It is anticipated that as labor rates decrease (installations outside the United States) that the curve would be even more pronounced and that the cross over point would shift further to the right. Based on the results of this analysis Abengoa has pursued a low automation (semi – automated) assembly line approach.

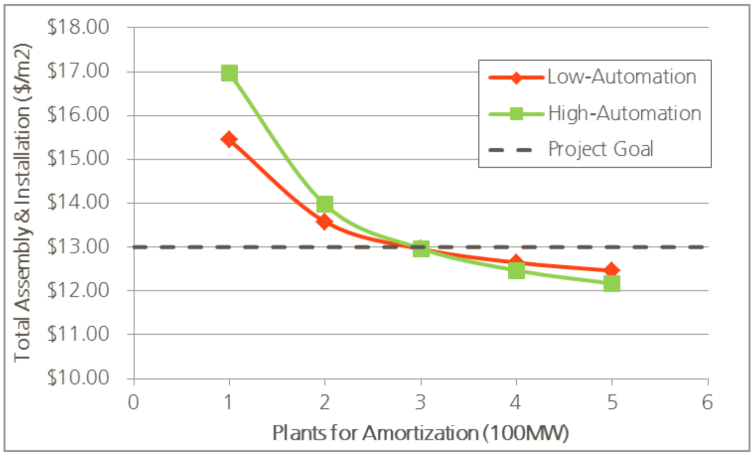


Figure 12: Cost of high and low automation options amortized over several plants

3.8 Performance Analysis Summary

The Phase I milestone for performance as defined in the SOPO is a >98% optical intercept @ 68% confidence, which is defined as "detailed engineering analysis." In order to verify this, the revised structural model was analyzed using Abengoa's proprietary Finite Element Ray-Tracing (FERT analysis code). The analysis not only took into account the structural behavior of the parts but also included Neumann CSR5 sunshape, FE-predicted deformation for mirrors and receivers (90mm diameter), and 1 mrad manufacturing / assembly error for the arms (Subtask 2.2). The zenith orientation intercept factor analytically determined in this ray tracing study was 98.4%, meeting the SOPO-defined Phase I goal. Its distribution on the mirror surface is shown below.

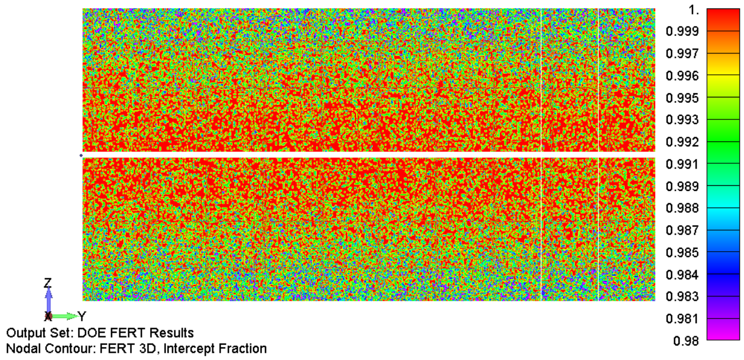


Figure 13: Ray-trace analysis of FEA design model using new mirror arm, showing local intercept factor versus position on reflector surface

4 Phase II – Single Module Scale Prototyping

4.1 Task 5.1 - Procurement and construction of prototype scale Manufacturing Assembly line

This task consisted primarily of procurement and construction of the fixtures and equipment required to test the Assembly line developed conceptually in Phase I. Therefore, much of what was completed in this task does not directly impact the performance of the SolarMat – Solar Field Assembly and Installation but was necessary to complete the testing required in Tasks 5.2 and 5.3.

An evaluation of the entire assembly process as proposed in Phase I (see Figure 2) was performed and activities that were identified as being “high risk” were scheduled for prototype testing in Phase II of the project. The analysis revealed that Operations OP20 and OP30 were considered the ‘highest’ risk and should be thoroughly tested. It should be noted that many of the perceived “low risk” processes are similar to what is currently being done at Abengoa commercial installations. Construction of the prototype assembly line was based on this analysis.

The assembly line has been optimized with task specific gantry cranes, but due to project budget and time constraints, the demonstration was developed with a single multipurpose crane that was used for all aspects of the testing. The figure below shows the modeled prototype assembly line.

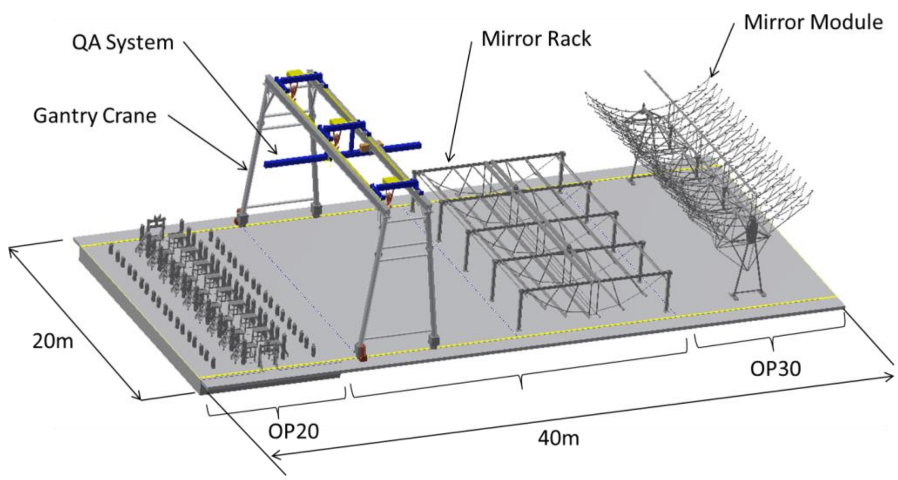


Figure 14: Propose outdoor demonstration layout - SolarTAC

4.2 Site Civil Works

The prototype assembly line was installed at the SolarTAC facility located in Aurora CO. site civil work consisted of extension of the security fence around the construction site, rehabilitation of the roads around the perimeter of the site, addition of the new electrical service required, and installation of a concrete pad. All this work was completed by Roche Constructors and Rodney Stein Construction.

In order to conserve project funds and time, Abengoa provided all engineering for the site civil works and provided a set of project drawings and specifications to the contractors for bidding and construction purposes. All field modifications required were approved by Abengoa engineering.

4.3 Foundations

One key feature of the foundation is the trench area in the OP20 station which accommodates the URS and the HCE installation. This was done so that comparisons could be made with the Xina site (a parabolic trough project currently under construction utilizing the SpaceTube ® near Uppington South Africa) to determine if the worker height significantly affects worker fatigue, safety and ergonomics.


Figure 15: Outdoor demonstration layout


Figure 16: Installation of OP20 fixture station over existing trench in the foundation (left) vs. elevation of the fixture assemblies to avoid installation of trench in the foundation – Xina (right)

4.4 Gantry Crane

Abengoa elected to utilize one generic crane on site that could be used to test all the different construction and assembly activities. Wazee Crane Company was selected to design, supply, and install the crane. The original concepts for the SolarMat assembly plant called for the gantry cranes to be manually operated and to be translated manually by personnel pushing. Based on the size of crane required for most of the operations it is apparent that the cranes must be designed with a drive. The hoists were powered and at fixed locations (again this was done to conserve budget) the same length as the trough, and did not require trolleys for operation, which worked well but limited some activities of the crane. Positioning of the trough using the simple controller provided by the crane manufacturer was accurate enough for all operations. Detailed crane pricing is included in the cost summary section of this report.

Figure 17: Gantry crane used for the SolarMat demonstration Prototype

4.5 Assembly Line Fixtures

The basic design of the assembly line fixtures was completed in Phase I of the project. Abengoa, through Abengoa Research Innovation and Consulting, completed the necessary fabrication drawings and these fixtures were fabricated by Eucomsa. The costs were based on quotes from Eucomsa. After installation of the fixtures, it was evident that a more thorough review of the fixture design for worker ergonomics and safety should have been performed. For the purposes of this project not all module assembly fixtures were supplied for this test and in some cases some modifications were necessary to accommodate the prototype testing plan. Below is a brief summary of each of the major assembly operation stations.

4.5.1 OP10 - SpaceTube ® assembly

OP10 is the SpaceTube main body assembly station. This station was not demonstrated in Phase II of the project. Abengoa has historical data from multiple commercial installations that demonstrate the time and labor estimates used for the SolarMat budget.

Figure 18: Outdoor demonstration layout

4.5.2 OP20 Mirror Support Structure and HCE Assembly

OP20 is the mirror support structure and HCE installation station. Historically it has been common practice to fully assembly the mirror module with mirror facets in a factory and transport the completed mirror module to the field, SolarMat Phase I proposed that the Upper receiver supports and the HCE also be installed on the module in the factory. This concept should result in a significant reduction of 'in-field' labor (primarily field welding) and double handling of the components, as well as serving a critical role for the new QC system. (Reference Task 5.3).

Figure 19: OP20 Mirror Arm & HCE Installation and Alignment Station

There were several lessons learned from the fabrication and assembly of the OP20 station. Several components, including the stair platforms and concrete stairways into the trench, were not designed to standard tread rise and run and did not meet minimum OSHA 29 CFR standards. In addition, the stair platforms were designed with several unique piece parts that could be redesigned as single parts for use in multiple places within the assembly (i.e. a "left" and "right" side support, instead of a reversible part).

Construction and Assembly of the OP20 station to the required tolerances is achieved using Photogrammetry (PG) in the same manner as a commercial installation. The alignment and calibration process for this station is iterative and took several days to complete. Each bracket was adjusted using a simple alignment tool according to feedback from the initial measurement. Another set of data is taken, and the process is repeated. This alignment achieved desired position and angle tolerance for each bracket. The results can be seen in Figure 20.

Results:

Reflector Retaining Slope Deviations [mrad]

	dSlX	dSlY
rms	**0.68**	**0.83**
mean	0.10	0.56
stdev	0.67	0.62
abs. max.	2.48	2.53

Reflector Retaining Points Coordinate Deviations [mm]

	dXYZ	dX	dY	dZ
rms	2.01	1.56	1.11	**0.64**
mean	1.41	0.00	0.00	0.00
stdev	1.43	1.56	1.11	0.64
abs. max.	8.50	8.10	-6.83	-2.46

Figure 20: OP20 station alignment results

4.5.3 OP20 – OP30 Transition

Transition of the module from OP20 to OP30 requires that the module not only be translated along the assembly line but also that the module is flipped from a pointing down to a pointing up orientation. The translation is achieved via the gantry crane and the rotation of the module is accomplished using a specially designed shaft and collar configuration (flipper). The design used was based on the design that is currently being used at the Xina installation in South Africa.

Figure 21: Flipper as used in Phase II. (left), flipper as modified and used at current installation in XINA, south Africa (right) an additional vertical stiffener was added to the flipper to provide additional bending stiffness to the TTA plates.

Figure 22: Module suspended from crane with flipper at each end

4.5.4 OP30 Mirror Installation fixture

OP30 is where the glass mirror facets are installed on the module. OP30 consists of two sets of permanent scaffolding (note: for the prototype only one set of permanent scaffolding was purchased) a transportation trailer with integral scaffolding and a “mirror rack”. For the purposes of this demonstration the proposed trailer was not utilized and the trailer mounted scaffolding was mounted directly to the concrete foundation. This decision was made based on project time and budget limitations.

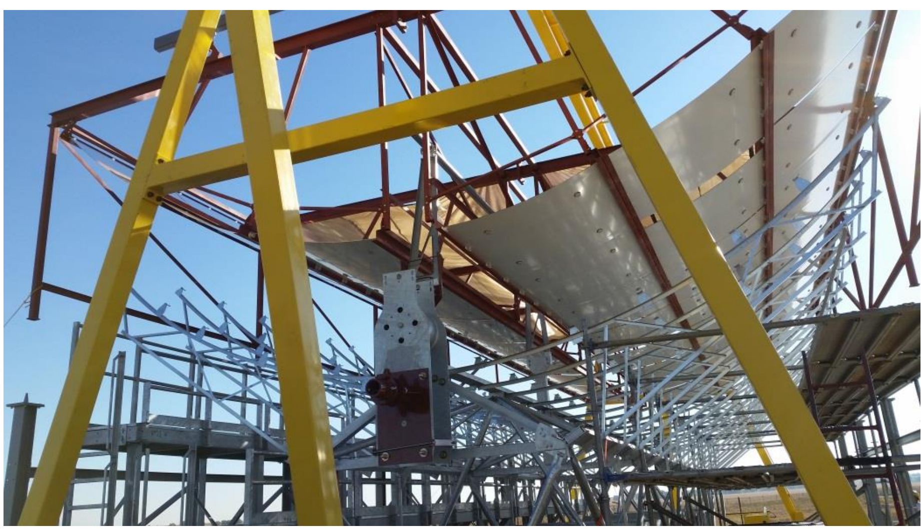


Figure 23: Mirror rack being lowered over SpaceTube module in OP30 station

The Mirror rack is a critical component in the operation of the OP30 station. The concept is that all of the mirror facets could be loaded on to a rack and then all 54 mirror facets could be located near the final installation position at the same time. As a result of a Critical Design Review, the mirror rack as originally proposed in Phase I was deemed to be inadequate so a new mirror rack was designed and fabricated for testing. The original mirror rack had lift points that were not compatible with the overhead gantry crane, the rack was too heavy for the crane and numerous rack/ module interferences were identified. The prototyped mirror rack addressed these issues, reducing the overall weight (~50%) and successfully providing the needed stiffness and stability while eliminating all interference issues.

Figure 24: Mirror rack being lifted from mirror installation position

The primary lessons learned from the OP30 fabrication and installation was a need for:

- reduction of weight of the pieces, such as smaller support legs, thinner decking,
- standard ladders and railings,
- review of scaffolding components for compliance with OSHA standards, pinch points, interferences, etc.

In general, the installation of the fixtures went well. Several fabrication issues were noted and some recommendations for changes were made based on construction and assembly of the fixtures. These recommendations typically were based on worker ergonomics or safety. Additionally, a critical final design review will be performed with representatives of the design engineers, the fabrication personnel, construction personnel and safety personnel.

4.5.5 Gripper Manipulator

Installation of the mirror modules on the pylons will be done using a “Gripper”. The gripper is a custom piece of equipment that has been designed to match the dimensions of the SpaceTube (ST8.2 x 16m). The gripper allows the setting of the mirror modules without the requirement of a crane and operator and allows for the continued setting of mirror modules in higher winds than would be allowed with a traditional crane setting operation. A gripper was purchased specifically for this project and was delivered with the assembly fixture components. The gripper design was based on an earlier design that was used for the assembly of a Heliostat field. The Heliostat gripper has been adapted for the SpaceTube ® and is currently being used in a commercial setting at the Xina project. The gripper unit tested for SolarMat was heavy, adding to the already significant load of a fully assembled module. A gripper redesign should include investigation into weight reduction.

Figure 25: "Gripper" unit used for module installation

5 Task 5.2 - Construct single module prototypes using representative methods

Following procurement and construction of the prototype assembly line actual testing of the assembly processes began. The purpose of this task was to test the fixtures equipment and processes developed in Phase I and to validate the labor and time assumptions made. As noted above all steps and processes were not tested or proven.

5.1 OP10 – SpaceTube (ST8.2 x 16m Module) assembly

The assembly of the SpaceTube ® is not considered a high risk operation and based on project schedule and budget it was determined that this part of the assembly process would not be prototyped. Abengoa is currently constructing a SpaceTube ® (ST8.2 x 16m) parabolic trough plant in South Africa, and are currently achieving a cycle time of 20 minutes.

5.2 OP 20 – Mirror Support Structure

The OP20 station includes several sub assembly processes and completion of the module up to installing the mirror facets. Below is a list of the major tasks associated with OP20.

- Mirror support structure (mirror arms) assembled (Mirror Arm Cell)
- Mirror Arms installed on the module
- HCE sub assembly welded
- URS installed on module
- HCE installed on module

5.2.1 Mirror Arm Cell

The mirror arm cell was developed during Phase I through a contract with Grenzebach. The general concept with the cell is that it would utilize a robot and a highly accurate fixture to assembly highly repeatable and accurate mirror arms using relatively low tolerance parts. The cell has been installed in Abengoa's facility in Lakewood, CO and is operational. To date we have been unable to assembly mirror arms with consistency or with the accuracy required to meet the optical performance criteria. A review of the entire process has been performed and several items have been identified that are contributing to the fabrication errors.

Comments and Observations

- Vendor parts out of specification
- The roll formed and roll bent top chord members are difficult to manufacture at prototype quantities. Samples from two vendors were purchased. One vendor consistently provided "better" parts but still out of tolerance.
- The fixture over constrains the components in the present clamping configuration
- Arm cell currently only functions in a semi-automated mode
- Some installations of the self-piercing rivet are not piercing the top layer.

Figure 26: (left) View of arms on the transportation cart (note: the top chord should align on all arms. (right) Non Typical self-piercing rivet joint at the mirror support bracket (note; the SPR did not penetrate the top layer - indicating incorrect joint design or implementation I.e. setting pressure, speed, etc.)

The current light weight mirror support structure utilizing light gauge pre coated steel, roll formed on or near site still appears to be the best and most economical option, and time and labor estimates from Phase I have been validated, for fabrication of the mirror support arms with the robotic arm cell, however there are several changes that are being considered that should allow the sub-assemblies to be fabricated with in tolerances.

Recommendations

- Redesign of the arm to eliminate the curved parts
- Additional work with Grenzebach or the cell component suppliers to get assembly cell fully operational
- Review of the cell to identify an appropriate component clamping scheme that does not induce stresses in the assembly during assembly
- A detailed review of the SPR joint - this is currently ongoing with two SPR vendors and pre-coated steel suppliers
- Additional research to identify Pre-coated steel (currently considering a Zn/Mg/ Al coating system) that will have a life expectancy of a minimum 25 years. This is done to eliminate the need for a secondary hot dipped galvanizing process

- Additional and or alternate Material suppliers should be identified

5.2.2 OP20 Station

The OP20 station is where the ancillary components of the SpaceTube ® are installed on the mirror module. During Phase II multiple tests were performed to establish a base line time and motion study for the installation of the mirror arms, URS and HCE weldment. In general, it was determined that the station performed well and the time per unit estimates from Phase I are achievable. The testing did highlight several items that will require correction before the station is placed in a commercial setting.

Figure 27: Module nearing completion on OP20 station

Comments and Observations

- The original PG alignment of the fixture had the end supports positioned such that the arms were approximately 50 mm off from the theoretical positions (see Figure 28) due to required position being outside the adjustable range.
- The HCE assembly is longer than gap between the end supports
- There is too much deflection in the TTA plates when using the flipper as designed (see Figure 9)
- The Arm carts were unacceptable –
  - the cantilevered support arms were not able to support the weight of the mirror arms
  - The fixed caster mountings were oriented incorrectly so the cart could not translate in the right direction
- General operation
  - Able to meet time and labor goals
  - Trench seems to work
  - Platforms do not meet OSHA recommendations

Figure 28: Arm cart (top left), HCE carts (middle left), HCE assembly (bottom left), mirror arm misalignment to OP20 station supports (top right), URS assembly (middle right), and mirror arm fabrication errors (bottom right)

In General, the OP20 station functioned as anticipated and testing was able to achieve the milestone cycle times of < 2x commercial times with the original man power estimated. Prior to commercial deployment of the fixture there are a number of design revisions that were identified during testing that should be implemented. These modifications should further reduce the cycle time required for this station.

Recommendations

- Some dimensional modifications to the fixture should be made to accommodate the HCE clearance issue. One or both of the end supports should be redesigned so that they can pivot out of the way when the module is being removed from the fixture.
- The TTA, ETW, and flipper design should be reviewed concurrently
- A redesign and CDR of the Arm carts should be performed
- HCE installation
    - The procedure should be revised to include the entire URS as part of the HCE sub-assembly
    - HCE carts should be modified to include
        - Higher quality wheels & bearings – with better control over position
        - Include a bracket for supporting the URS
        - Support for the URS
- Modify design of the LRS / URS connection so that the parts cannot be installed incorrectly
- A general CDR should be performed on the fixture and the assembly procedures with an emphasis on:
    - Ergonomics/ Safety / Material flow

OP20 Timed Tests	**Time**
Test 1	43 mins
Test 2	38 mins
Test 3	41 mins*
Test 4	52 mins*
*Using uncorrected procedure	

Figure 29: OP20 timed test results

The goal of the OP20 timed test was double the commercial timed goal of 20 minutes. If this 40-minute target could be demonstrated in just a few tests, it was assumed that commercial times would be achievable by implementing lessons learned from the demonstration. Since this was achieved by the second test, two more tests were performed using the assembly procedure as-written, with workers who had not yet performed the operations. This was done to give an idea of the learning curve requirements for this type of operation.

5.3 OP20 – OP30 Transition

This operation consists of lifting the partially assembled module off of the OP20 fixture (note at this point the module includes the SpaceTube ® and chords, all mirror support arms (36), the URSs (4) and the HCE assembly) translating the module from the OP20 to the OP30 fixture and at the same time rotating the module from the zenith down to a zenith up orientation. The timing of this operation was tested several times and compared with current commercial times of a similar method at the plant being constructed by Abengoa in South Africa. The first test took approximately 15 minutes, but was quickly reduced in subsequent tests to under a minute. This is a significant finding, as there was originally some concern about the cost of labor on an assembly line that requires this motion.

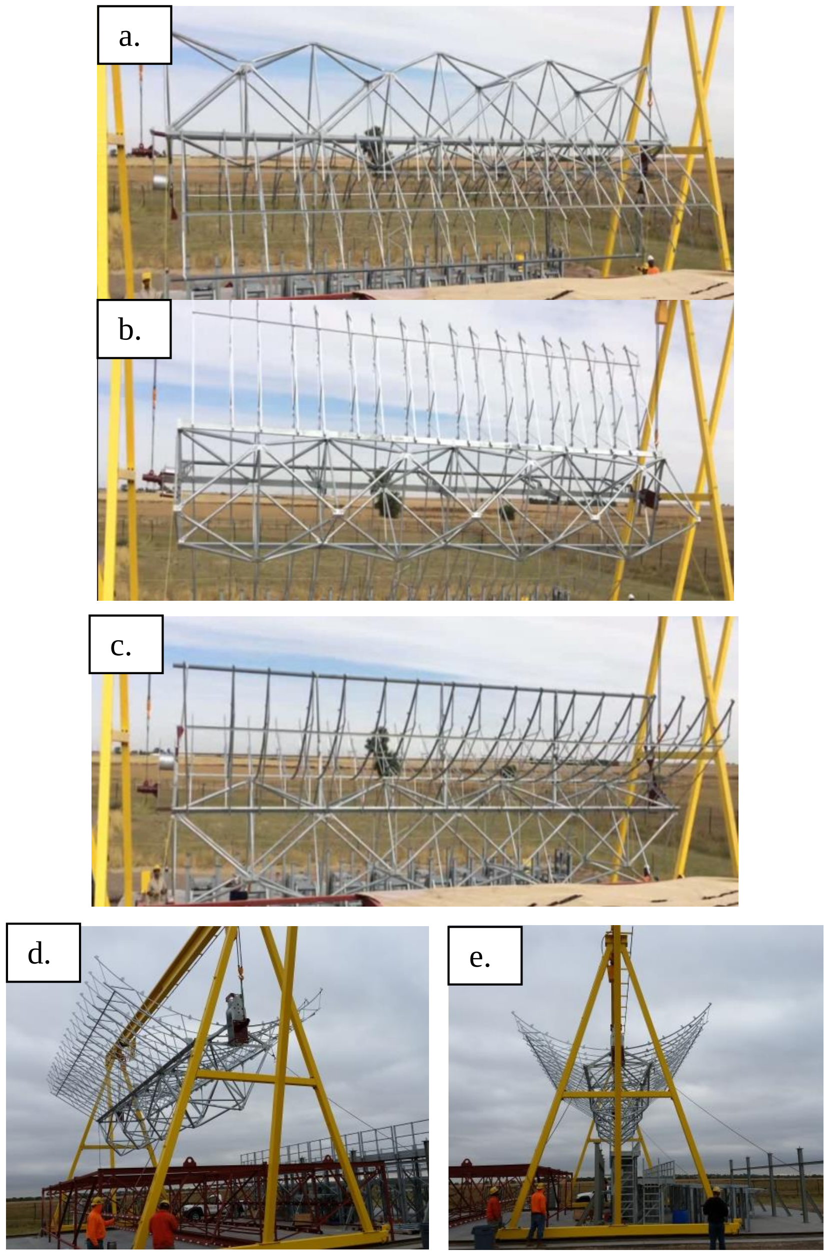


Figure 30: Module transition from OP20 to OP30

Comments and Observations

- Center of Gravity (CG) location very important for controlled rotation
- Similar process currently being used in Xina
  - Very controlled
  - Manual
  - Location of rope seems to be very important
- Current mounting scheme of flipper is not stiff enough too much deflection in the TTW (see above section)
- Access to the anti-rotation pins on the flipper is difficult.

Recommendations

- Modification to the ETW so it can carry out of plane loads – See above section OP20
- Consider crow's nest on the crane to provide access to the flipper for installing and removing the anti-rotation pins; or fixed platform

5.4 OP30

Final assembly and QC testing is done in station OP30. Most operations associated with the OP30 station were prototyped as part of this project. Operations in OP30 Include

- Loading of the mirror facets in the mirror rack
- Lifting the mirror rack on the mirror rack supports (mirror rack is over module)
- Place mirror from rack on the module
- Install mirror facet fasteners (4 fasteners/ mirror facet)

Figure 31: Mirror rack resting in mirror installation position

Comments and Observations

Mirror Rack

- Loading of mirror rack worked but could be improved – unable to push mirrors onto the rack
- Vertical support members of the mirror rack track were located such that they interfered with mirror installation
- HCE clearance at the cross beam splice was very tight
- Lost one mirror due to crane location very tight access
- Interference between mirror rack and the URS at the TTW

Installing Mirrors

- Platform height with respect to mirror installation point influenced installation time.
- Fastening of mirror facets to the arms with the small bolts very time consuming

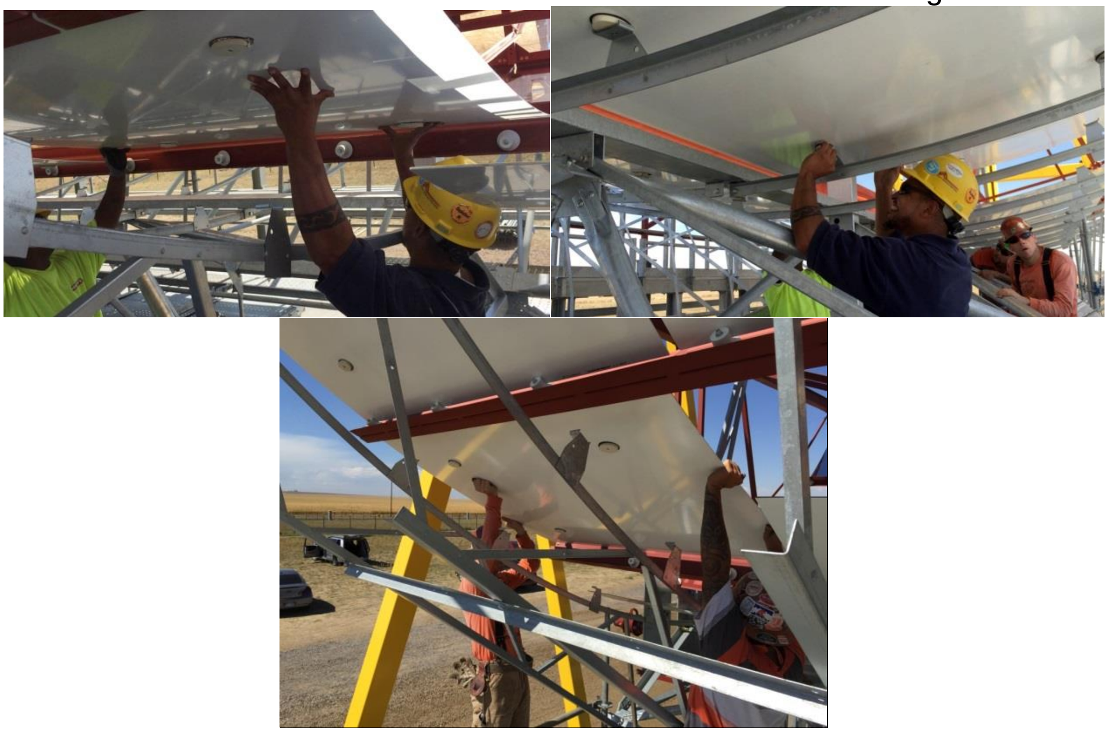


Figure 32: Mirror installation from mirror rack to module

General

- Scaffolding tripping hazards
- Lifting frame out of the scaffolding was difficult not much clearance
- Access in and around the frame was limited
- Access to the center platforms required climbing over frame and down from fixed scaffolding
- Final design on a truck bed. (trailer mounted scaffolding) - reduces the number of lifts by one in the assembly line process - adds complexity to the trailer and module lift in the field
    - This will require pretty precise location of the trailer so that the mirrors are in the correct position for installation on the frame

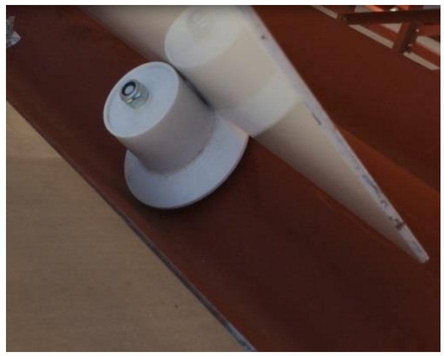



Figure 33:OP30 station as mirror rack is lowered into place (top), walkway for workers to install mirrors (middle left), interference between mirror rack and URS (middle right), and flanged downhill rollers (bottom)

Recommendations

Mirror Rack

- Redesign of the mirror rack features
    - Cross members with no splice
    - Need more rollers with bearings
    - Need better flange on downhill rollers to prevent mirror from riding up
    - Move vertical track supports to land in between the mirrors
    - Design to minimize head room loss
    - Redesign the cone alignment feature
    - Design in coordination with crane for this station
    - Need method of securing the mirror facets to assure that they will not be dropped

Installing Mirrors

- Workers should use a vacuum gripper to lift mirrors – in test sides of mirror was accessible but in commercial application the gap between mirrors is much smaller

General

- Critical design review of the fixture
    - Safety and ergonomics
    - Sharp edges
    - Open spaces

- Programmable crane with preprogramed moves
- Lifting frame out of the scaffolding was difficult not much clearance
- Access in and around the frame was limited
- Access to the center platforms required climbing over frame and down from fixed scaffolding
- Final design on a truck bed. (trailer mounted scaffolding) - reduces the number of lifts by one in the assembly line process - adds complexity to the trailer and module lift in the field
    - This will require pretty precise location of the trailer so that the mirrors are in the correct position for installation on the frame. Lifting frame out of the scaffolding with gripper will be more difficult than lifting straight out of the scaffolding with a crane.
- Due to timing may want to redesign this station with two cranes and two mirror racks so that the mirror racks can be loaded in parallel with other operations
- In testing the time metric was not quite achieved. This can be overcome with additional labor or with improvement to the fixtures.

Table 5: OP30 and mirror rack timed test results

	1st attempt (minutes)	**2nd attempt (minutes)**	**3rd attempt (minutes)**
Loading mirror rack with mirrors	19	15	15
Placement of the mirror rack on OP30 (with mirrors)	11	9	8
Installation of the mirrors	52	37	29
Removal of the mirror rack to its home position (no mirrors)	5	3	3
Total time	**87**	**64**	**55**

5.5 In field Activities

5.5.1 Pylon Installation and Pylon Alignment

The first step in the pylon installation process was to install two pylons, one at each end of a collector, using a traditional surveying method. The intermediate pylons are then installed using high intensity lasers and laser distance meters. First, the pylon is lifted in to place using a flatbed crane truck and secured loosely to the anchor bolts. An attachment holding two lasers and a distance meter is placed on the surveyed pylon and the lasers are aligned to a target on the other surveyed pylon. A target is then placed on the pylon being installed, where the distance from the centerline created by the laser to the intended installation location can clearly be seen. The pylon is moved on the anchor bolts using screw jacks, to assist in the fine movements required for accuracy. The distance meter is used to ensure that the axial position (parallel to the laser) is set correctly. Once in the proper location, the pylon anchor bolts are tightened and the next pylon is installed. (Figure 34)

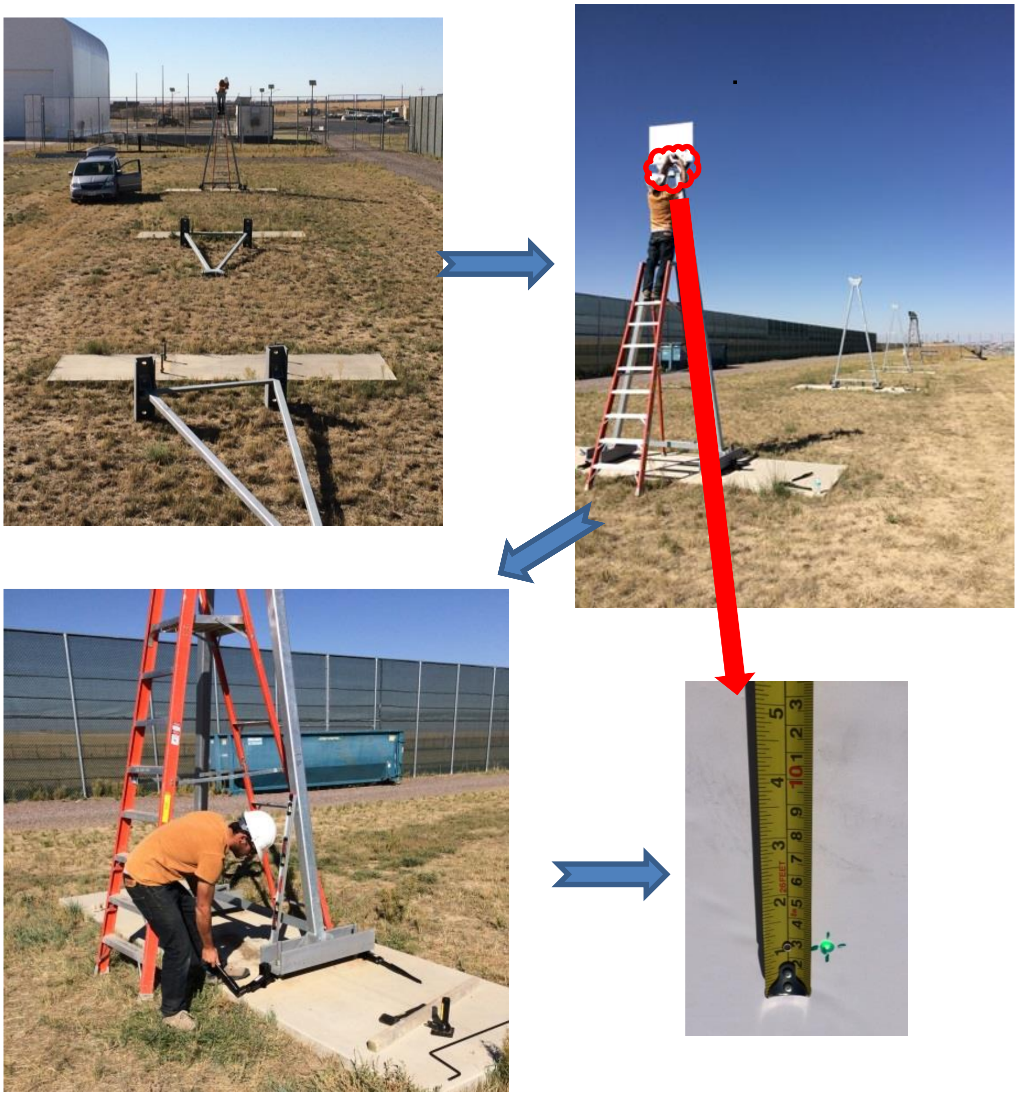


Figure 34: Pylon installation and alignment steps

This method was tested at SolarTAC using existing pylons and foundations on site. Performing the steps described above was simple, although the height of the pylons for a SpaceTube would require a significant ladder, and could potentially be replaced with a lift. The screw jacks provided the necessary control, and the pylons held their position upon tightening of the anchor bolts. To verify correct alignment, a total station was used to measure the position of two locations on each pylon top, and the center point between the two points was compared to a straight line drawn between the center points of the surveyed pylons. The results of these measurements showed a deviation average from the center line of approximately 10mm. However, the uncertainty in the total station measurement (standard deviation of 1.6mm) was larger than the desired tolerance. A discussion after the completion of the test led to an agreement that the original tolerance was tighter than necessary. It is believed that this method would be successful in a commercial deployment. The results of the total station uncertainty calculations are shown in Table 6. Two points on a single pylon were measured, twice each, from 4 separate locations of the total station.

Table 6: Total Station uncertainty calculations

	Coordinate Position			
Position, Point	X	Y	Z	Calculated Distance (m)
Position 1, A	0	0	0	(broken)
Position 1, B	0.4712	-21.6619	-0.1249	
Position 1, A	-2.7171	-21.8831	1.0751	3.412
Position 1, B	0.4705	-21.6821	-0.1248	
Position 2, A	3.651	-19.2783	1.1601	3.411
Position 2, B	6.7932	-19.8579	-0.0345	
Position 2, A	3.6511	-19.2781	1.1599	3.411
Position 2, B	6.7934	-19.8579	-0.0343	
Position 3, A	-0.61	-2.0221	0.8038	3.388
Position 3, B	2.4881	-1.3401	-0.3851	
Position 3, A	-0.61	-2.0224	0.8038	3.388
Position 3, B	2.488	-1.3399	-0.3851	
Position 4, A	5.1651	-8.7818	0.7264	3.415
Position 4, B	3.5319	-6.0298	-0.4645	
Position 4, A	5.1654	-8.7818	0.7264	3.415
Position 4, B	3.5319	-6.0297	-0.4645	

(meters)	Mean	Std Dev
With all points	3.4056	0.0114
With red sections removed	3.4127	0.0016

5.5.2 Module installation and Alignment

Module installation on the pylons was not performed in Phase II. It was originally proposed as part of the Phase II work, but due to time constraints it was not possible to install new pylon foundations at the correct spacing to facilitate this test. Therefore, limited operational testing of the gripper was performed and information was obtained from the current parabolic trough construction project where a similar gripper is being used in a commercial application.

Comments and Observations

- Gripper is heavy (>7000 lbs.) therefore load with module is >10000lbs. Requires a 15-ton lift to operate
- Clamping system did not fit the module correctly
- Controls
  - Movement axially is smooth (1:1 movement)
  - Rotational movements tend to be jerky (1:10 movement)

- No operator training or documentation received with unit
- Comments from witnessing similar system at Xina
    - Operated smooth after some operator training
    - Required 16MT unit
    - Could install module on pylons well within time allotment

Recommendations

- A design review should be performed with the vender to verify design and weights
- Review clamping and frame dimensions with vendor
- Request vendor supply documentation and training

Table 7: Cost breakdown of traditional and new SolarMat in-field tasks

		Traditional ($/m^2)	SolarMat ($/m^2)
Pylon Installation and Alignment	**Labor**	0.58	0.24
	Equipment	0.02	0.05
Module Installation	**Labor**	0.92	0.47
	Equipment	0.11	0.13
	Wind Shutdowns	0.94	0.47
Module Alignment	**Labor**	0.28	0.09
	Equipment	0.00	0.00
TOTAL		2.86	1.46

*Cost estimates based on labor values obtained at current parabolic trough installations and testing performed as part of this project.

6 Task 5.3 - Demonstrate standalone QC system and compare to results from conventional system

The evaluated loss mechanisms attributed to the module structure are the geometric imprecision of the structure itself, the final installed slope error of the reflector surface, and the HCE position. Of these, the slope of the reflector surfaces provides the largest effect, and so must be measured with the highest accuracy. The current state of the art quality control system is a semi-automated photogrammetry (PG) unit on a track that measures mirror inclination via manually-installed targets. This has two important pitfalls: it requires a large amount of labor, and must approximate, rather than measure directly, the actual surface shape of the reflectors.

Additionally, because this method requires manual installation and removal of more than two hundred targets per concentrator tested, it is only practical to test a small sampling of the overall production. It also requires a module to be pulled out of production and placed on a large, dedicated test pad inside the assembly hall.

Abengoa has developed a concept to eliminate these drawbacks using the Observer Method, a process which uses the reflection of an object in the mirrors themselves to directly measure slope. The Abengoa process uses the absorber tube directly. It uses a similar track mounted camera, but measures the mirror surface of each assembled module as it leaves the assembly building. This not only allows all modules to be measured, but could provide real-time alignment feedback to the assembly team. This method has 4 basics steps, outlined below.

Steps	Description
Measurement of the geometry	Photogrammetric reconstruction of 3d coordinates and camera positions, interior and exterior orientation via bundle adjustment of the mirror edges
Image distortion and perspective	Correct lens effects and perspective of the images
Segmentation and Edge Detection	Segmentation of the Region of Interest (ROI) and Edge Detection of the absorber tube reflection
Absorber position and Reflector Slope	Calculation of the absorber position and the reflector slope

Figure 35: Observer Method process steps

Below is a figure showing the measurements that can be taken using this method. It also has the advantages of being in-line and fast enough to be used on 100% of modules during the assembly process.

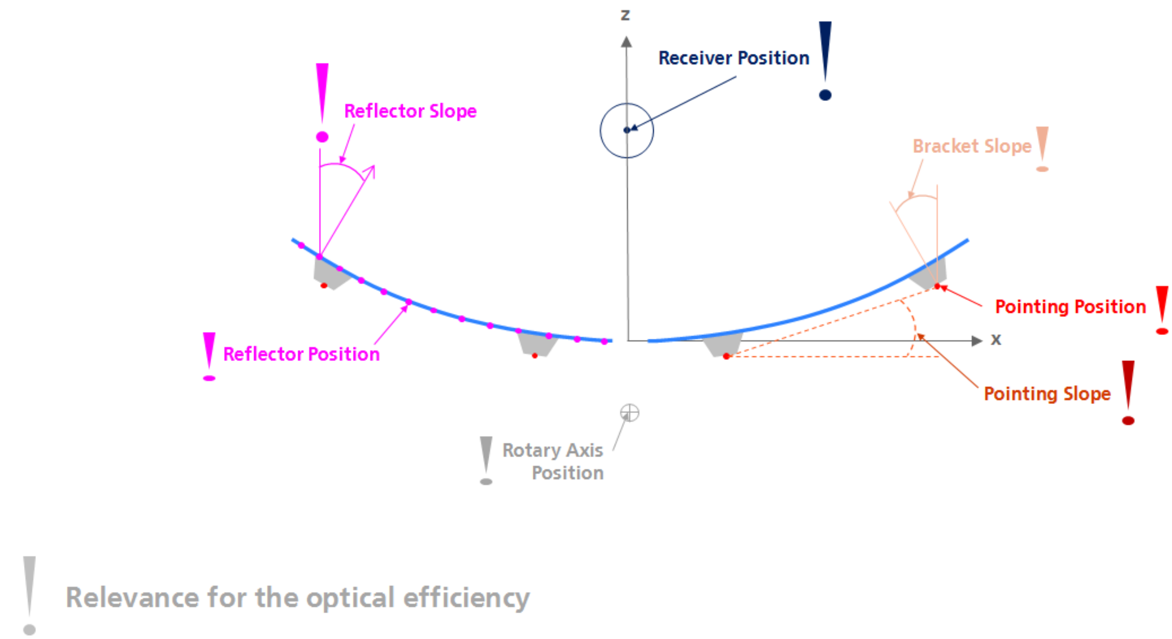
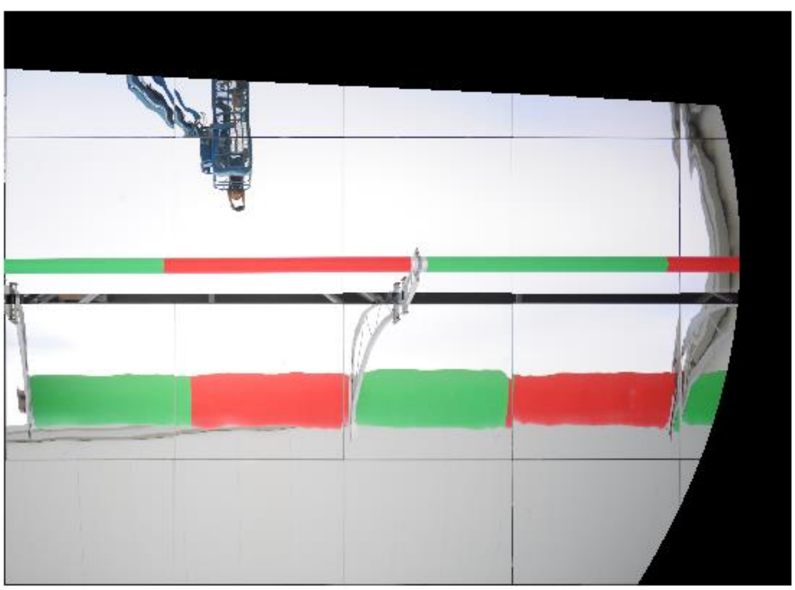


Figure 36: Measureable values with the Observer Method

The software has been developed over the course of both Phases of the project, and tested extensively on modules with known optical accuracy values in Spain. Since the detailed methodology of the system was described in the Phase I Continuation Report, this section is focused on results of physical testing performed in Phase II. Figure 37 shows a distortion corrected image of the module and painted receiver, and the software's calculation of the region of interest, segmentation of the receiver, and detection of each edge of the receiver.



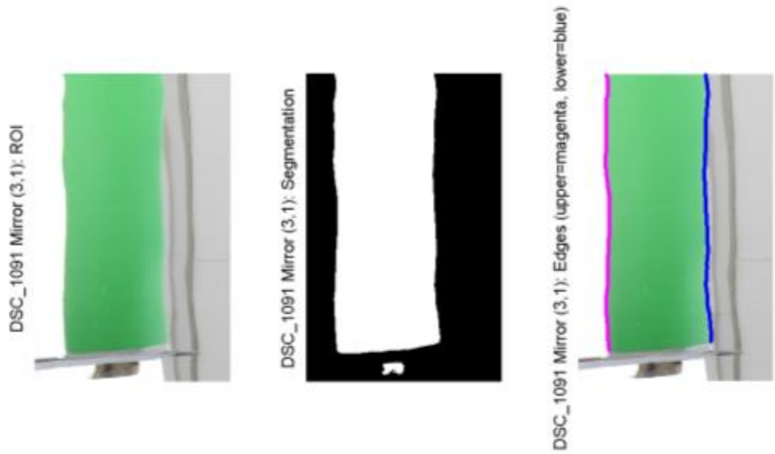


Figure 37: Distortion-corrected image of receiver reflection (top) and receiver image segmentation and edge detection (bottom)

Utilizing this method on each photo, a compilation of the receiver edges from the various positions can be made, and the surface irregularities can be seen, as show in Figure 38.

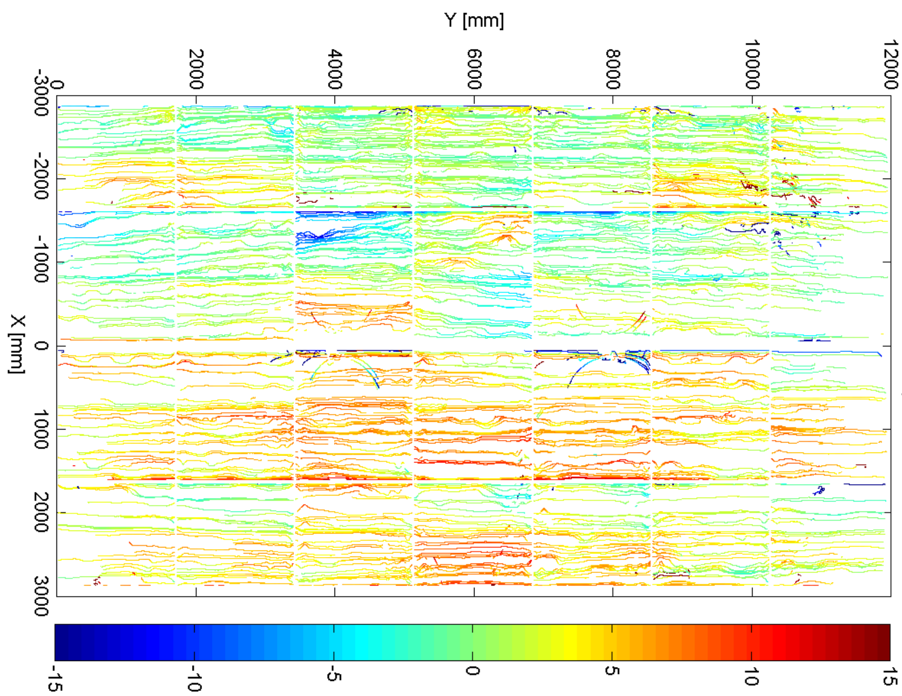


Figure 38: Composite layout of receiver edges in mirror reflections

This is used to calculate slope error. A visual comparison between this QC method and the previous standard, Deflectometry, can be seen in Figure 39. In addition, a table showing the calculated Optical Intercept using both methods is show in Figure 40.

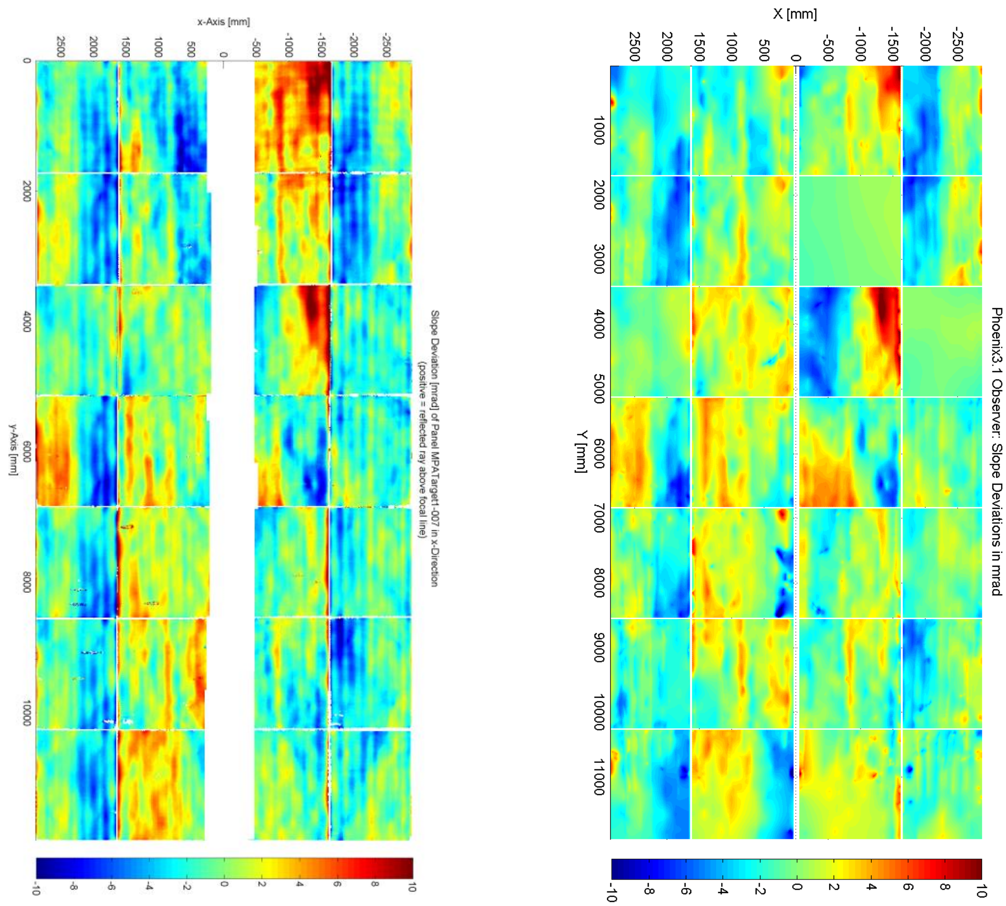


Figure 39: Slope error results using Deflectometry (left) and the Observer Method (right)

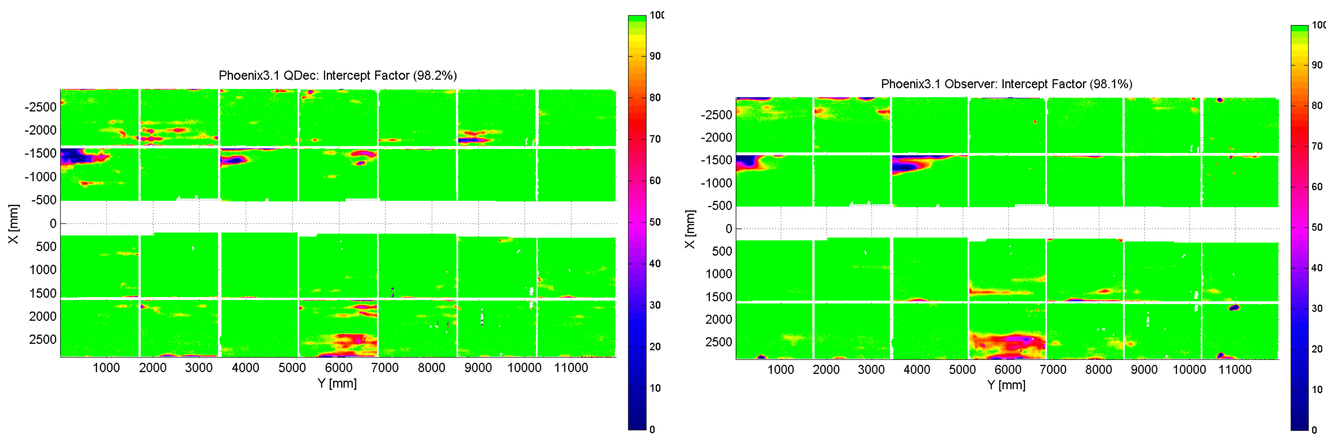


Figure 40: Optical Intercept calculation using deflectometry (98.2%, left) and the Observer Method (98.1%, right)

In performing the measurements at the SolarTAC test site, several key lessons were learned. First, the software is sensitive significant color deviations from what is expected. For example, in our test, the mirror gaps were large enough to cause confusion to the software, so we attempted to cover the gaps with tape. However, the blue color of the tape was too close to sky reflection color in the mirrors, and the software was unable to detect the mirror edges. In a similar way, since the photos were taken outside, sun glare in the receiver surface and the mirror reflections caused issues in the edge detection software (see Figure 41). While many of these issues are corrected in a commercial plant (smaller mirror gaps, photos taken indoors, etc.) it is clear that it is important to make the software more robust to be able to handle the inconsistencies that could be seen during assembly.

Figure 41: Observer method photos with sun glare (left) and appropriate for the software (right)

7 Task 5.4 - Final technical and economic feasibility analysis including path to commercialize

Abengoa has completed the prototyping and field testing for the SolarMat project. The results of the testing indicate that it is possible to achieve an installed parabolic trough solar field cost of $92/m^2. This installed cost is based on a semi-automated assembly line / factory that is transportable and can be amortized over a minimum of 200MWe installation. The prototyping of the “high risk” processes was able to highlight several areas where further refinement of the fixture and procedures will result in improved worker safety and ergonomics and time reductions. Additionally, the prototyping was useful in the time and motion studies in validating the number and location of the workers, tooling, and material supply required.

Table 8: Detailed assembly and installation cost breakdown for Phase I and Phase II

	Phase I prediction		Phase II Completion	
Description	Total	Total ($/m2)	Total	Total ($/m2)
Eqipment	$ 1,610,199.08	$ 2.38	$2,315,460.59	$3.42
Photogrametry	$ 82,200.00	$ 0.12	$109,335.00	$0.16
QC System	$ 52,745.00	$ 0.08	$85,470.00	$0.13
QC System maintenance	$ 29,455.00	$ 0.04	$23,865.00	$0.04
Tools	$ 325,851.58	$ 0.48	$346,821.85	$0.51
General tools	$ 34,930.62	$ 0.05	$56,602.91	$0.08
Tool Consumables	$ 69,861.25	$ 0.10	$56,602.91	$0.08
Rivet gun	$ 67,277.21	$ 0.10	$109,018.54	$0.16
Riveting gun (spare)	$ 153,782.50	$ 0.23	$124,597.50	$0.18
Assembly Work Stations	$ 138,112.44	$ 0.20	$243,782.64	$0.36
Work stations	$ 123,042.44	$ 0.18	$210,482.64	$0.31
Mirrors lifting fixture	$ 15,070.00	$ 0.02	$33,300.00	$0.05
Factory Equipment	$ 708,021.13	$ 1.04	$1,217,512.85	$1.80
Generator	$ 25,200.00	$ 0.04	$25,200.00	$0.04
Air Compressor	$ 17,920.00	$ 0.03	$17,920.00	$0.03
Water Tank	$ 350.48	$ 0.00	$700.95	$0.00
Expenses	$ -	$ -	$4,384.50	$0.01
Porch Crane Op10-Op20	$ 20,550.00	$ 0.03	$33,300.00	$0.05
Porch Crane Op20-Op30	$ 20,550.00	$ 0.03	$33,300.00	$0.05
Porch Crane Op30	$ 20,550.00	$ 0.03	$179,820.00	$0.27
Crane assembly and transport	$ 71,445.50	$ 0.11	$57,886.50	$0.09
Robotic cells - Arm Pre-Assembly (OP40)	$ 513,750.00	$ 0.76	$832,500.00	$1.23
Column crane 500 kg	$ 7,665.15	$ 0.01	$12,420.90	$0.02
Material Trolleys	$ 10,040.00	$ 0.01	$20,080.00	$0.03
Vehicles	$ 356,013.93	$ 0.53	$398,008.25	$0.59
Crane 30t	$ 45,500.00	$ 0.07	$45,500.00	$0.07
Gripper	$ 23,975.00	$ 0.04	$38,850.00	$0.06
Boomloader for Gripper	$ 28,770.00	$ 0.04	$23,310.00	$0.03
Truck for module transportation	$ 19,995.15	$ 0.03	$16,200.45	$0.02
Module trailer	$ 68,500.00	$ 0.10	$111,000.00	$0.16
Pylons trailer	$ 13,871.25	$ 0.02	$22,477.50	$0.03
Column crane 500 kg	$ 3,832.58	$ 0.01	$6,210.45	$0.01
Car for personel in field	$ 19,995.15	$ 0.03	$16,200.45	$0.02
Car for foremen	$ 16,111.20	$ 0.02	$13,053.60	$0.02
Boomloader	$ 57,540.00	$ 0.08	$46,620.00	$0.07
4x4 forklift	$ 18,221.00	$ 0.03	$14,763.00	$0.02
CCP field erection manlift	$ 8,439.20	$ 0.01	$6,837.60	$0.01
Pylons alignment manlift	$ 16,878.40	$ 0.02	$13,675.20	$0.02
Field tubes welding manlift		$ -		$0.00
Pylons erection crane vehicle	$ 14,385.00	$ 0.02	$23,310.00	$0.03
Expenses	$ 217,613.76	$ 0.32	$214,043.76	$0.32
Mobile Office	$ 25,326.00	$ 0.04	$25,326.00	$0.04
Mobile Restoroom	$ 2,867.76	$ 0.00	$2,867.76	$0.00
Drinkable water	$ 8,820.00	$ 0.01	$5,250.00	$0.01
Recycling containers	$ 2,800.00	$ 0.00	$2,800.00	$0.00
Fuel for machines and generators	$ 177,800.00	$ 0.26	$177,800.00	$0.26
Assembly building	$ 638,840.68	$ 0.94	$705,847.00	$1.04
Building Structure	$ 632,315.39	$ 0.93	$665,847.00	$0.98
Concrete Pad	$ 293,947.20	$ 0.43	$238,161.60	$0.35
Building structure	$ 125,105.77	$ 0.18	$202,726.14	$0.30
Building erection	$ 95,310.90	$ 0.14	$77,222.70	$0.11
Other Building Costs	$ 64,390.00	$ 0.09	$104,340.00	$0.15
Tent	$ 53,561.52	$ 0.08	$43,396.56	$0.06
Installations	$ 6,525.29	$ 0.01	$40,000.00	$0.06
Electrical	$ 3,688.46	$ 0.01	$20,000.00	$0.03
Air pressure	$ 2,836.83	$ 0.00	$20,000.00	$0.03
Personel	$ 5,361,234.80	$ 7.91	$5,812,788.67	$8.58
Assembly in Factory	$ 3,155,244.44	$ 4.65	$3,606,800.00	$5.32
Management	$ 374,779.00	$ 0.55	$374,779.00	$0.55
Logistics	$ 617,259.00	$ 0.91	$617,259.00	$0.91
Structure Erection	$ 745,068.36	$ 1.10	$745,066.67	$1.10
Pylon erection	$ 367,284.00	$ 0.54	$367,284.00	$0.54
HCE welding and installation	$ -	$ -		$0.00
Auxiliary	$ 101,600.00	$ 0.15	$101,600.00	$0.15
Total Cost	**$7,827,888.32**	**$ 11.55**	**$9,048,140.02**	**$13.35**

As part of this project, a path to commercialization is considered one of the key deliverables by the DOE and Abengoa management. Commercialization of this system can only move forward with buy-in/ acceptance by Abengoa sister companies. As a result of the testing a complete design / specification document package is being developed. These documents are necessary to transfer the information required and gain acceptance with Abengoa sister companies. These documents include:

- Module and collector documents
    - Design basis
    - Revised fabrication drawing and specifications for all trough components
    - Cost estimates
- Assembly line documents
    - Drawings and specifications for the assembly line fixture
    - Installation and alignment procedures for the assembly line fixtures
    - Operation procedures for the fixtures
    - Assembly procedures for the module using the assembly line
    - Ancillary tooling required
    - Cost and labor estimates
- Assembly plant – infrastructure
    - Building requirements and specifications
        - Building footprint
        - Utilities
    - Cranes
    - Tooling
    - Labor and cost estimates
- Field assembly documents
    - Detailed list of tooling with drawing and specifications if fabrication is required
    - Detailed procedures for installation
    - Labor and cost estimates

8 Task 6 – Project Management

The primary milestones and metrics of Phase II are listed in Table 9. This section will go through each milestone, describe the spending and discrepancies, and discuss Abengoa's success or failure to meet the stated goals.

Table 9: SOPO Milestones

Sub-tasks Evaluated	Metric Definition	Success Value	Assessment Tool	Milestone Budget	Achievements
5.1	Procure and install assembly line to meet Phase I cost objectives	<20% deviation from Phase 1 estimates	Purchase orders (invoices) for key components tested, labor, and quotes for all other components.	$809,431 50% DOE cost share: $404,715 20 mos.	Achieved: not within 20% alone, but equipment allows for labor reduction
5.2	Module assembly (w/ mirror support arms, mirror facets and HCE) module installation, and alignment on the pylons demonstrated to meet cost and assembly time objectives	<20% deviation from Phase 1 estimates (<20min/module for assembly time, >30% labor cost reduction @ 68% confidence)	Recording and analysis of test operations (time and motions studies, development of best practices and procedures), Abengoa Research Consulting (ARC) and EPC contractor reports evaluating design for commercial readiness.	$491,210 50% DOE cost share: $245,605 22 mos.	Achieved: (within 8.5% of Phase I estimates) Prototype timing + learning curve estimates within 20min cycle time
5.3	Optical performance of test module	>98% optical intercept @ 95% confidence	Photogrammetry results plus vendor-sourced mirror slope data will be ray-traced, accounting for sun-shape, concentrator slope, and receiver placement errors	$113,260 50% DOE cost share: $56,630 23 mos.	Not Achieved: Unable to measure SolarMat module Likely would not have met target even if measured

5.3	Accuracy of Absorber Reflection Method QC system in measuring optical intercept and cycle time achieved	+/- 0.5% @ 68% confidence, <20min cycle time	Comparison to the HPC deflectometry measurement system on a known trough in conjunction with physically validated optical model predictions	$113,260 50% DOE cost share: $56,630 23 mos.	Achieved: ARM system within 0.1% of Deflectometry method in calculating optical intercept
5.4	Cost savings of collector components, labor, and amortized site infrastructure	>$45/m^2 @ 95% confidence, relative to $137/m^2 baseline value	Composite of results from representative assembly line test and investment quotations	$116,569 50% DOE cost share: $58,285 24 mos.	Achieved: $45.17 / m^2 reduction

8.1 Milestone 5.1

Table 10: Milestone 5.1 Spending

	5.1
Personnel	$133,332.29
Travel	$4,754.41
Equipment	$251,410.06
Contractual	$490,307.24
Indirect	$232,558.03
TOTAL	**$1,112,362.03**
SOPO approved	$809,431.00
Deviation	($302,931.03)

Table 11: Milestone 5.1 Budget Justification Discrepancies

Item	Budget Sheet	Task	Category	Actual (Sep 30)	Difference
General Contracting labor for station installation	$-	5.1	Contractual	$155,707	($155,707)
Concrete pad	$32,500	5.1	Contractual	$144,433	($111,933)
Electrical service to test pad	$45,000	5.1	Contractual	$83,670	($38,670)
OP20 stations, fixtures, tools	$40,000	5.1	Equipment	$62,629	($22,629)
Build up roads	$7,000	5.1	Contractual	$23,000	($16,000)

Eucomsa design work	$-	5.1	Contractual	$15,541	($15,541)
Drive & drive pylon	$35,000	5.1	Equipment	$-	$35,000
Surveying of outermost pylons for alignment	$35,000	5.1	Contractual	$-	$35,000
ARC - station assembly and oversight	$65,000	5.1	Contractual	$5,194	$59,806

Milestone 5.1 is related to the assembly line equipment & installation cost, as well as supporting infrastructure and building costs. Through procurement and installation of the prototype line, several key findings led to cost increases from previous estimates. In addition, through quotations and real plant costs from current Abengoa plants under construction, the numbers were refined to a higher degree of confidence. Table 12 shows the key cost differences and reasoning.

Table 12: Key cost differences for Milestone 5.1

Item	Change	Note
QC System	$ 0.05	Improved camera, higher resolution
Work stations	$ 0.13	New OP20 supports + HCE carts
Mirrors lifting fixture	$ 0.03	Roller improvements
Porch Crane Op30	$ 0.23	Must be motorized
Robotic cells	$ 0.47	More detailed design, riveting system
Module trailer	$ 0.06	Suspension and supports
Building structure	$ 0.11	More detailed floorplan, material supply area
Other Building Costs	$ 0.06	More detailed floorplan, material supply area

Overall, the final cost estimate for these items is $4.77 / m^2, (compared to the Phase I estimate of $3.64 / m^2) an increase of 31%. This does not meet the stated Milestone goal of <20% deviation from Phase I estimates. However, the final equipment design supported a significant reduction in labor, as explained in Milestone 5.2, and the overall cost reduction at the end of Phase II for assembly and installation is within the 20% range.

8.2 Milestone 5.2

Table 13: Milestone 5.2 Spending

	5.2
Personnel	$17,949.02
Travel	$1,064.30
Equipment	$63,637.60
Contractual	$322,298.50
Indirect	$80,013.59
TOTAL	**$484,963.01**
SOPO approved	$491,210.00
Deviation	$6,246.99

Table 14: Milestone 5.2 Budget Justification Discrepancies

Item	Budget Sheet	Task	Category	Actual (Sep 30)	Difference
Contracted labor for all station operations	$ 5,000	5.2	Contractual	$225,871	($220,871)
16m SpaceTube frames	$ 30,000	5.2	Equipment	$53,461	($23,461)
ARC - planning and oversight of each station	$ 25,000	5.2	Contractual	$8,586	$16,414
ARC - pylon alignment operations	$ 40,000	5.2	Contractual	$9,222	$30,778
Site and equipment maintenance	$ 45,000	5.2	Contractual	$10,000	$35,000

Milestone 5.2 is related to the labor and time required to assembly, install, and align the various components of the solar field. Through repeated testing, timing, and functionality reviews, many estimates from Phase I were validated, with a cost increase at two assembly stations. It was discovered that one extra worker was required at each of two arm cells to assist with material handling, and 4 extra workers were required for removing the mirrors from the mirror rack to install on to the module. This represents a cost increase of $0.67 / m^2 from the Phase I estimate, an increase of 8%, which meets the goal of <20% deviation. In addition, video timing and learning curve estimates lead to a <20min cycle time per module for all assembly, installation, and alignment operations.

8.3 Milestone 5.3

Table 15: Milestone 5.3 Spending

	5.3
Personnel	$13,447.43
Travel	$0.00
Equipment	$8,051.38
Contractual	$22,260.00
Indirect	$15,809.22
TOTAL	**$59,568.03**
SOPO approved	$226,520.00
Deviation	$166,951.97

Table 16: Milestone 5.3 Budget Justification Discrepancies

Item	Budget Sheet	Task	Category	Actual (Sep 30)	Difference
QC hardware	$18,000	5.3	Equipment	$8,155	$9,845

QC Labor: OP20/30 alignment	$45,000	5.3	Contractual	$-	$45,000
QC Labor: alignment and testing in OP20 and OP30	$70,000	5.3	Contractual	$-	$70,000
QC Labor: testing, interpretation, and adjustment of ARM system	$30,000	5.3	Contractual	$22,260	$7,740

Milestone 5.3 contained two parts, relating to the accuracy of measurement for the new QC system as compared to the current measurement standard, as well as the optical performance of the constructed module in the Phase II demonstration. While two measurements were taken on the constructed module (PG and ARM methods), no results were able to be obtained, as explained in the Task 5.3 section. Therefore, this milestone was not achieved.

However, several tests were performed on the ARM QC method comparing it to Deflectometry on a module with known characteristics at Abengoa's facilities in Spain. These tests resulted in an agreement on calculation of the Optical Intercept within 0.1% (see section on Task 5.3) meeting the goal of +/-0.5% stated in the SOPO.

8.4 Milestone 5.4

Table 17: Milestone 5.4 Spending

	5.4
Personnel	$0.00
Travel	$0.00
Equipment	$0.00
Contractual	$9,848.52
Indirect	$1,674.25
TOTAL	**$11,522.77**
SOPO approved	$116,569.00
Deviation	$105,046.23

Table 18: Milestone 5.4 Budget Justification Discrepancies

Item	**Budget Sheet**	**Task**	**Category**	**Actual (Sep 30)**	**Difference**
ARC - Data compilation, final reporting	$40,000	5.4	Contractual	$-	$40,000
Travel to Spain, meetings with Abengoa Research	$9,000	5.4	Travel	$2,980	$6,020

Milestone 5.4 is related to the final reporting and cost tabulation of the overall solar field assembly. After considering the achievements of the SolarMat project alone and the current state of parabolic trough technology at Abengoa, three primary values cost estimates are displayed in Table 19: the original cost goals at the beginning of the

project, the Phase II closing cost estimates due to achievements in this DOE award, and the Phase II closing cost estimates including changes in other categories unrelated to specific tasks within this project.

Table 19: Solar field cost estimates

	Original goals	SolarMat achievements	Current estimates
Manufacturing Facility	$4.12	$4.56	$4.56
Mirrors	$24.98	$25.00	$27.50
Drives	$3.38	$3.38	$2.46
Pedestal, Mirror Support Structure, Foundation	$44.24	$44.24	$38.52
Controls	$4.56	$4.56	$1.18
Power	$2.06	$2.06	$4.17
Installation and Check Out	$8.67	$8.04	$8.08
Total Capital Costs	$92.00	$91.83	$86.47

Overall, the SolarMat project was able to achieve a cost of $91.83 / m^2, successfully reaching the Milestone goal.

8.5 Overall Phase II Project Spending

Table 20: Overall Phase II Project Spending

	Actual						
Overall Spending	Q4-2014	Q1-2015	Q2-2015	Q3-2015	Total	SOPO Value	Difference
Subtask 5.1	$39,731	$74,040	$354,343	$644,248	$1,112,362	$809,431	$(302,931)
Subtask 5.2	$48,012	$ -	$ -	$436,951	$484,963	$491,210	$6,247
Subtask 5.3	$ -	$ -	$ -	$59,568	$59,568	$226,520	$166,952
Subtask 5.4	$11,523	$ -	$ -	$ -	$11,523	$116,569	$105,046
Task 6	$2,573	$2,730	$11,505	$7,387	$24,194	$54,221	$30,027
Total	$101,838	$76,770	$365,848	$1,148,154	**$1,692,610**	$1,697,951	$5,341

9 Significant Accomplishments and Conclusions

Completion of Phase II of this project has resulted in the demonstration of a parabolic trough assembly line and field installation methodology that can achieve installed solar field cost targets of $91.83/m^2. This installed cost represents a reduction of 33% over current state of the art parabolic trough installation previously completed by Abengoa. These cost reductions were achieved through improved component design, semi - automated assembly processes, optimized material flow and handling, improved worker ergonomics, etc. The demonstration of the assembly line at a single module scale facilitated the identification of numerous minor issues that are easily remedied prior to a commercial installation, but would have proved very costly if allowed to propagate to an actual commercial installation. Major accomplishments resulting from this project include:

- Significant reduction in module component cost ($15.39/m^2)
    - Reduction in ETW TTA
    - MSS
    - LRS and URS
- Development of assembly line resulting in reduced installed cost
    - Reduced labor cost
    - Reduced capital cost lower infrastructure over previous State of the Art
    - Reduced construction period
- Test plat form for future testing and training development
- Demonstration of new QC system (100%, faster direct optical)
- Some equipment can be transferred directly to the field for immediate commercialization
- Improved field installation techniques - immediate commercial applications

10 Inventions, Patents, Publications, and Other Results

At this time Abengoa is not pursuing any patents for the equipment developed in the course of this project and no publications or conference papers are planned.

11 Path Forward

The goal of the project was to go from TRL 3 to TRL 6. Through the efforts of this project and the support of the US DOE Abengoa has developed a Semi automated parabolic collector field assembly plant and installation methodology that can be shown to approach the installed cost targets as defined in the DOE Sun Shot. The system that has been developed was based on a specific set of data that assumes an installation in the Southwest United States. In reality there next parabolic trough plant to be installed by Abengoa will most likely not be in the United States therefore some allowances for the site specific installation will be based on local labor rates, shipping cost, local fabrication and manufacturing capabilities etc.

Abengoa has recently completed a parabolic trough field installation using the E2 collector in South Africa and is installing a second parabolic trough plant utilizing the SpaceTube ® collector next door. Some of the assembly concepts that were developed in the course of the SolarMat project have already been implemented in the module assembly, additionally it has been possible to compare the installation methods of the two different trough designs and develop a better understanding of the differences. While some of the assembly techniques have been already implemented many of the concepts will require additional development and “buy-in” by Abengoa’s construction and EPC divisions before a wholesale acceptance of the SolarMat assembly and installation concepts.

At the completion of this DOE project Abengoa Solar (US) in coordination with AR I&C (Spain) will be working together to develop a complete solar field assembly installation package that can then be provided to Abengoa sister companies for greater global acceptance. This documentation package will include

1. complete design, fabrication and assembly documents and support documents for the Solar Collectors
2. complete design fabrication and assembly documentation required for all assembly tooling
3. complete set of assembly / operation instructions
4. updated field installation procedures
5. cost and labor analysis.

Additionally, the infrastructure that was developed during this project will be used to continue refining procedures and possibly to test new equipment and concepts along with hosting construction and EPC personnel at the SolarTAC site for in house training.

12 References

List literature references cited in the report, using the format provided in the RPPR-2 form submitted with the quarterly reports.

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