Public Final Technical Report

Project Title: Development of Molten-Salt Heat Transfer Fluid Technology for Parabolic Trough Solar Power Plants

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1 Executive Summary

This Final Report for the "Development of Molten-Salt Heat Transfer Fluid (HTF) Technology for Parabolic Trough Solar Power Plants" describes the overall project accomplishments, results and conclusions. Phase 1 analyzed the feasibility, cost and performance of a parabolic trough solar power plant with a molten salt heat transfer fluid (HTF); researched and/or developed feasible component options, detailed cost estimates and workable operating procedures; and developed hourly performance models. As a result, a molten salt plant with 6 hours of storage was shown to reduce Thermal Energy Storage (TES) cost by 43.2%, solar field cost by 14.8%, and levelized cost of energy (LCOE) by 9.8% - 14.5% relative to a similar state-of-the-art baseline plant. The LCOE savings range met the project's Go/No Go criteria of 10% LCOE reduction. Another primary focus of Phase 1 and 2 was risk mitigation. The large risk areas associated with a molten salt parabolic trough plant were addressed in both Phases, such as; HTF freeze prevention and recovery, collector components and piping connections, and complex component interactions.

Phase 2 analyzed in more detail the technical and economic feasibility of a 140 $MW_{e,gross}$ molten-salt CSP plant with 6 hours of TES. Phase 2 accomplishments included developing technical solutions to the above mentioned risk areas, such as freeze protection/recovery, corrosion effects of applicable molten salts, collector design improvements for molten salt, and developing plant operating strategies for maximized plant performance and freeze risk mitigation. Phase 2 accomplishments also included developing and thoroughly analyzing a molten salt, Parabolic Trough power plant performance model, in order to achieve the project cost and performance targets. The plant performance model and an extensive basic Engineering, Procurement, and Construction (EPC) quote were used to calculate a real levelized cost of energy (LCOE) of 11.50¢/kWhe[1], which achieved the Phase 2 Go/No Go target of less than 0.12¢/kWhe.

Abengoa Solar has high confidence that the primary risk areas have been addressed in the project and a commercial plant utilizing molten salt is economically and technically feasible. The strong results from the Phase 1 and 2 research, testing, and analyses, summarized in this report, led Abengoa Solar to recommend that the project proceed to Phase 3. However, a commercially viable collector interconnection was not fully validated by the end of Phase 2, combined with the uncertainty in the federal budget, forced the DOE and Abengoa Solar to close the project. Thus the resources required to construct and operate a molten salt pilot plant will be solely supplied by Abengoa Solar.

[1] Financial assumptions for LCOE calculations are found in section 4.8.4.

2 Background

The original project proposal supported the DOE Solar Energy Technology Program goal to integrate advanced low-cost thermal energy storage with parabolic trough systems. The focus of this effort was to develop an R&D pathway for molten-salt heat transfer fluid (HTF) technology to be moved rapidly to a commercial status.

The goal of this effort was to develop the technologies required to allow the low freeze point molten-salts to be used in a parabolic trough solar field and to provide the opportunity to conduct the field testing necessary to allow this technology to be introduced into commercial solar plants at the end of this effort. The molten salt properties allow improvements in power plant efficiency and reduce HTF pumping parasitics. The molten salt HTF can be used in the solar field and thermal energy storage (TES) system, with a larger temperature difference than oil HTF, resulting in significantly lower cost of TES.

The focus of Phase 1 was to determine the concept feasibility. Abengoa Solar had to research and proposed solutions to all of the technical challenges associated with the use of molten salt HTF. The cost of a molten salt plant must be economically attractive when compared to state-of-the-art technology. The Go/No Go criteria to proceed to Phase 2 was a reduction in levelized cost of electricity (LCOE) of at least 10% or other attributes of similar value.

The focus of activities during Phase 2 included analysis and small scale testing of the new technologies required to operate with molten salt, with the ultimate goal to demonstrate that a 140 MWe Molten Salt, Parabolic Trough Power plant, using nitrate salts as the Heat Transfer Fluid (HTF) and thermal storage medium, can satisfy the DOE levelized energy cost goal of less than $0.12/kWhe. The following outlines the Statement of Project Objectives (SOPO) for the Project

Statement of Project Objectives (SOPO)

Task 1: Molten Salt Design Basis

- Develop draft of a design basis document for a parabolic trough plant using molten salt HTF
- Review existing molten salts
- Create a conceptual baseline plant design

Task 2: Parabolic Trough Collector Technology of Molten Salt HTF

- Identify and evaluate potential solutions for the interconnection of collectors
- Investigate the status of receiver tube selective coating temperature limits and performance
- Determine the optimized collector geometry for use with molten salt
- Investigate strategies for salt freeze prevention and recovery

Task 3: Molten Salt Plant Segment Design

- Investigate salt material compatibility issues for various plant components
- Identify appropriate valves, instrumentation, and other equipment for use with molten salt
- Investigate the systems needed for adding and removing salt from the plant
- Define the optimum solar field to minimize cost of energy
- Develop operations and maintenance procedures unique to the use of molten salt
- Design the thermal energy storage system including 2-tank and thermocline options.
- Identify pumps needed for the TES/HTF system
- Redesign turbine cycle and power block systems for use with molten salt
- Investigate wet and dry cooling

Task 4: Engineering Assessment of Molten Salt Plant

- Perform an engineering assessment of a molten salt HTF plant
- Perform a preliminary engineering design and cost estimation
- Calculate and analyze the performance of the plant using simulation tools

Task 5: Phase 1 Project Management & Phase 2 Planning

- Management of the project scope, schedule, and budget.
- Coordinate and assign tasks between team members
- Prepare and submit monthly technical progress reports
- Prepare and submit final report

Task 6: Molten Salt Component Testing

- Testing of molten-salt components identified during Phase 1 and 2 which need validation in molten salt.
- Includes testing collector interconnection designs freeze protection and recovery system, valves, instrumentation, and other equipment identified that requires additional testing in molten-salt.
- Material compatibility testing where necessary.

Task 7: Collector Design for Molten Salt

- Investigate changes to the mid-term design achieved in award DE-FG36-08GO18037, which are necessary to accommodate the use of molten salt HTF
- Address specific design elements such as interfacing with collector interconnects and freeze protection/recovery systems.
- Assemble Collector cost estimates to be used in economic calculations
- Collector performance metrics will be used in performance simulations

Task 8: Process Development –

- Address operational risks with the use of molten salt HTF
- Verification of published molten salt thermophysical properties
- Development of an initial salt melting procedure and development of a subsequent field filling procedure.
- Investigate salt plug detection methods.

Task 9: Performance and Economic Analysis –

- Improve component models to increase the fidelity of the software tools and, ultimately, the integrated plant model.
- Use software tools to predict the daily and annual performance of the baseline plant and various molten salt plant designs.
- Obtain a more in depth and detailed EPC cost estimation for the commercial molten salt plant
- Use the updated performance predictions and cost estimation to calculate the LCOE and other economic metrics.

Task 10: Project Management –

- Project management for Phase 2
- Includes detailed planning for Phase 3.
- Preparation for the critical milestone go/no-go decision at the end of Phase 2.

The Phase 2 Go/No-Go criteria are:

1) Demonstrate that all key risk areas have been addressed
2) The detailed economic and performance projections for a molten-salt HTF CSP plant show an LCOE of below $0.12/kWhe (real 2009 $), with a 10% ITC.

3 Introduction

Commercial parabolic trough projects using an organic fluid (a eutectic mixture of diphenyl oxide and biphenyl) as the heat transport fluid in the collector field and the steam generator. The fluid has an upper temperature limit of 393°C, which effectively sets an upper Rankine cycle efficiency limit of about 0.375. The high vapor pressure of the fluid (~ 8 bar at 390°C) requires the use of a separate fluid, in conjunction with a heat exchanger, for the thermal storage system.

In principle, the organic fluid can be replaced with an inorganic fluid, such as binary, ternary, and quaternary nitrate and nitrite salt mixtures. The inorganic fluids have upper temperature limits in the range of 465°C to 600°C, which allows: 1) an improvement in the Rankine cycle efficiency to values in the range of 0.40 to 0.43, and 2) a direct thermal storage system, which avoids the need for intermediate heat exchangers. The principal liability to the inorganic fluids is a melting point between 100 and 220°C, and a corresponding requirement for electric heat tracing on all salt equipment. The project will determine whether the inorganic fluids offer a sufficient reduction in levelized energy costs to pursue further development, and to develop the components required for the use of molten salt use; i.e. valves, collector interconnections (joints), etc.

4 Project Results and Discussion

The following sections provide a brief description of the achievements and results during Phase 1 and 2 of the project. For brevity, the information is not presented in a scientifically thorough level of completeness.

4.1 Task 1 (Phase 1): Design Basis Document

A design basis document was prepared at the start of Phase 1 to establish an initial set of general criteria upon which a parabolic trough plant using an inorganic heat transfer/transport fluid could be designed. This document discussed the following system elements:

- Collector System
- Thermal Storage System
- Steam Generation System
- Electric Heat Tracing System
- Electric Power Generation System
- Balance of Plant
- Master Control System

4.1.1 Review of potential salt compositions

Many salt mixtures from various corporations and laboratories were investigated during Phase 1. At the time the Phase 1 Continuation Report was written, properties (or, in some cases, approximate/assumed properties) were only available for five different salts, listed in Table 1.

Table 1: Potential salt mixtures for HTF

	Solar Salt	Hitec	Hitec XL	(Sandia)	(Solar Millennium)
Composition (by weight)	60% $NaNO_3$, 40% KNO_3	40% $NaNO_2$, 7% $NaNO_3$, 53% KNO_3	7% $NaNO_2$, 45% KNO_3, 48% $Ca(NO_3)_2$	Quaternary (assumed %'s)	Quaternary nitrate/nitride (%'s unknown)
Freeze Point (℃)	220	142 [3]	120	100	80
Upper Temp Limit (℃)	585 [2]	450 - 538 [3]	480 - 505 [4]	475 - 500 [2]	450

[2] *Communication with R.W. Bradshaw at Sandia National Laboratory*
[3] *Coastal Chemical Co., L.L.C*
[4] *R. W. Bradshaw and N. P. Siegel, "MOLTEN NITRATE SALT DEVELOPMENT FOR THERMAL ENERGY STORAGE IN PARABOLIC TROUGH SOLAR POWER SYSTEMS", Energy Sustainability 2008, ES2008-54174, A.S.M.E.*

Density (kg/m^3 @ 300℃)	1899	1860	1992	1992[5]	N/A
Specific Heat (J/kg.℃ @ 300℃)	1495	1560	1447	1447[5]	N/A
Cost ($/kg)	1.30[6]	1.93[7]	1.66[7]	2.15[8]	N/A
Cost ($.℃/kJ)	0.87	1.24	1.15	1.49	N/A

During Phase 1 Hitec XL was chosen as the salt candidate for investigation and testing in phase 2 because the mixture exhibited a more desirable freeze-point temperature of approximately 120℃ and was thought to withstand a temperature limit of over 500℃. This temperature limit was thought to be contingent on a storage vessel ullage gas that was free of CO_2 to prevent or reduce calcium carbonate precipitation. During Phase 2 there were numerous indicators that Hitec XL was not a good candidate for commercial use. Hitec XL was difficult to work with in all of the thermophysical property test equipment and component test rigs, due to its hygroscopic behavior and lower thermal stability limit. Any salt mixture containing Calcium Nitrate was officially eliminated from further testing and possible commercial use in Phase 2 (summer 2012) after a 4,000 hour thermal stability test, in which the salt began decomposing at lower than expected temperatures.

4.2 Task 2 (Phase 1): Parabolic Trough Collector Technology for Molten Salt HTF

Many key solar field components were investigated during Task 2, to theoretically validate their use with molten salt HTF. The investigation of the components was outlined in the Phase 1 Continuation Report, which included details on:

- Molten salt collector joints
- Receiver tubes
- Optimizing the molten salt Collector size

[5] *Assumed values*

[6] *Abencs (March, 2009)*

[7] *Compiled from individual constituent prices from Univar (includes shipping) (March, 2009)*

[8] *Compiled from individual constituent prices from SQM (includes shipping) with assumed %'s (June, 2009) and LiNO3 created from LiCO3.*

4.3 Task 3 (Phase 1): Molten Salt Plant Segment Design

During Task 3, important systems of a molten salt commercial plant were examined in more detail. The goal was to refine the Phase 1 Design Basis of a commercial plant, make engineering design decisions based on detailed research, and identify risk areas of the key systems of a molten salt plant, such as:

- General Salt HTF systems
- Field HTF Layout and Optimizing
- Freeze Protection and Recovery designs and feasibility
    - Impedance heating and heat tracing
    - Optical melting of receiver tubes
- Loop Operation and Maintenance
    - Freeze recovery procedure
- Thermal Energy Storage System and Pumps
    - 2-Tank direct molten salt TES
        - Economics, performance, and specifications
    - Packed bed direct molten salt thermocline TES
        - Economics, performance, and specifications
- Power Generation System
    - Steam generator Specifications

4.4 Task 4 (Phase 1): Engineering Assessment of Molten Salt Plant

A conceptual system design was developed for a commercial molten salt plant. The generated specifications were used by Abengoa Solar's sister company, Abener, to develop an engineering, procurement, and construction cost estimate for the commercial plant. Refer to the Phase 1 Continuation report for further details of:

- Conceptual System Design
- Capital and O&M Cost Estimate
    - Plant Cost per category
- Plant Performance Analysis
    - Use of TRNSYS modeling software
    - Daily plant performance
    - Annual plant performance
    - Comparison of LCOE

All of the activities that were developed in Task 4 (phase 1) were greatly refined and improved in Phase 2, Task 9. With this in mind, reviewing further detail of the Task 4 findings is not necessary in this report because the Phase 2 results and conclusions are much more accurate and applicable to the goal of achieving competitive economic results for the commercialization of the molten salt trough technology.

4.5 Task 6 (Phase 2) – Molten-Salt Component Testing

There were multiple components that needed to be proven in molten salt service. Ideally, these components would have been tested in a flowing salt loop. However, construction of Sandia's Molten Salt Test Loop (MSTL), intended for this purpose, and was completed at the very end of the Phase 2 period of performance. As a result, Abengoa Solar (AS) reached an agreement with Madison Scientific LLC (MSLLC) and the University of Wisconsin-Madison (UWM) at the beginning of Phase 2 to construct equipment for and carry out testing of various components. Scheduling and financial constraints prohibited the purchase of a pump capable of molten salt service, so the tests were restricted to AS's design temperature and pressure with stagnant molten salt.

4.5.1 Collector Interconnection (Joint) Testing

Two test rigs were designed and constructed by University of Wisconsin, Madison to test collector joint assemblies, also sometimes referred to as collector interconnects. The rigs were fully instrumented for torque, force, temperature, pressure, and salt level measurements. In a solar field, interconnects are located on either end of the collector and allow the necessary degrees of freedom between the receiver tubes and the fixed process piping; rotation about the collector axis, linear thermal expansion at the receiver tube axis, and linear shift of receiver tube axis.

Test conditions were defined for mechanical cycle-life testing and thermal cycle-life testing. The mechanical cycle-life conditions evolved after some initial experiences. The final conditions are listed below.

- Fluid = 60% NO_3, 40% KNO_3 (initially was 12% $NaNO_3$, 44% KNO_3, 44% $Ca(NO_3)_2$)
- Pressure = 40 bar[9] (gage)
- Temperature = 500 ºC
- Cover gas = air (initially was nitrogen)
- Rotation = 215 degrees
- Linear Translation (0mm = Ambient, 600mm = 500ºC)
    - Current: 200mm - 600mm position (normal operating range)
    - Initially: 0mm - 600mm (ambient to 500ºC)
- Frequency of motion (rotation and translation are simultaneous)
    - Rotation – 2 minutes per complete cycle
    - Translation – 2 minutes per complete cycle
- Success criteria – 11,000 cycles (30 years) with zero leakage

[9] This is 1.5X of the maximum operating pressure of a joint in the solar field, 1.5X is referenced from the ASME power piping code B31.3

During Phase 2, after numerous ball joint and rotary joint prototype failures, the test pressure and temperature combination was re-evaluated. Instead of testing joints at the maximum temperature and pressure that they could experience in a plant, plus a pressure safety factor (500ºC and 40bar), the testing plan changed to incrementally increase the pressure and temperature while the joint is being cycled and to test the joints at the “cold” side conditions and the “hot” side conditions. The temperatures and pressures that a collector joint will experience will vary from area to area within the solar field. For example, the joints on the “cold” side of the collector loops may experience 300ºC and 22 bar and the joints on the hot side may experience 500ºC and 10 bar.

Emerging from the Phase 1 investigation, variations of ball joint prototypes were acquired and tested at the beginning of Phase 2. Prototypes were procured from two ball joint manufacturers, Blue Sky Process Solutions and Advanced Thermal Systems (ATS). Although AS worked with multiple seal and ball joint vendors to try various injectable and rope packing seal combinations, no ball joint design was successful during high temperature molten salt testing. A detailed list of combinations that were tested can be found in the Phase 2 Continuation Report.

The second and more promising type of interconnect pursued during Phase 2 was a rotary joint and flexible hose assembly. AS began working with a preferred vendor of rotary flex assemblies and procured multiple molten salt joint prototype. After three prototype designs failed, AS decided to work with other vendors of rotary joints in order to find a solution. Expanding the investigation to all other known rotary joint companies yielded a number of promising prototype designs.

During the rotary joint research and development, two design categories were investigated; Dynamic seal rotary joints and Face seal rotary joints. Both design types were combined with flexhoses to accommodate the receiver tube growth. The dynamic seal design traditionally utilizes multiple bushings and seal rings, arranged in an alternating seal pack, to function as a combination of seal and bearing. Throughout the development of dynamic seal joints, AS was unable to obtain a design that sealed well, had sufficiently low torque, or was compatible with molten salt at 500℃.

The Face seal designs utilize a pair of precisely machined mating surfaces, pressed together with a spring or bellows in order to create a seal. The precisely machined sealing components are hard materials and can be made from a variety of materials in the carbide and ceramic families. The face seal concept allows for a wide variety of mechanical designs that can be created to seal molten salt at 500℃. By the time Phase 2 was complete at the end of 2012, Joint A, a face seal design, was the only rotary joint that showed partially successful results during high temperature testing. Table 2 summarizes the rotary joints that were tested during Phase 2 and concisely documents the results and conclusions. Following Table 2, are more detailed summaries of rotary joint tests that transpired after the Phase 2 Continuation report was submitted and before the end of the Phase 2 no cost extension period.

Table 2: Summary of rotary joint testing during Phase 2

Design Variant	Joint Design	Seal design	# of tests	Pass?	Results	Conclusions
1	Dynamic Seal	Graphite	3	No	Best results: Failed after 1,900 cycles	Due to oxidation of the graphite seal after 24 hours of testing
2	Dynamic Seal	Graphite	2	No	Best Results: Failed after 400 cycles	Due to oxidation of the graphite seal after 24 hours of testing
3	Face Seal	Carbide	2	No	Failed at 500℃ due to excessive leaking and bearing failure. 2 tests resulted in the same outcome	Joint design could not handle the higher temperatures. No sign of seal degradation
4	Double flexhose	none	1	No	Failed after 30 minutes (16 cycles) at 500ºC.	The bend radius was too extreme for the hose
5	Face Seal	Carbide	2	Partially	Successfully operated up to 480ºC, then failed at 490ºC. Follow-up test: the joint was held at 450ºC and successfully completed 2,855 cycles, until the leakrate surpassed the allowable level of 10 gr/hr. Continued	Need further testing to verify high temperature operating limit. It is a possible candidate for a pilot plant operating at 450ºC.

6	Face Seal	Ceramic	3	No	Prototypes failed soon after salt was introduced (at test temperature and low pressure) and rotation cycles began.	Seal design had dynamic instability issues because the leak rate increased substantially when the joint started rotating, which very quickly ended the test.
7	Face Seal	Ceramic		Did not test	Prototypes were not delivered before the end of Phase 2	
8	Dynamic Seal	Garlock		Did not test	Prototypes were not delivered before the end of Phase 2	

4.5.1.1 Joint A - Rotary Face Seal Joint

Testing Joint A was important because it was the first rotary joint design that was tested that utilizes a face seal. The joint was tested at 500º C and 25 bar for the first round of tests. The rotary joint failed the first and second tests because the leak rate steadily increased and the molten salt leaked out of a flanged connection that was not part of the designed leak path.

The manufacturer's engineers visited the lab and refurbished one of the joints that had failed. A plan was developed to heat the joint from the inside, with cartridge heaters, rather from the outside with heat tracing. The vendor claimed that the outer portions of the rotary joint were not designed to be at 500ºC. When the refurbished rotary joint was tested again, with the internal heating, the exterior surfaces were kept under 400ºC.

The next test consisted of cycle testing with a 10°C temperature increase at 2.5 hour increments, starting at 400℃ and ending at 500℃. The joint successfully survived testing up to 480℃, then at 490℃ the leak rate became excess ive and the test was officially labeled a failure because the joint did not operate at 500℃. In the temperature range of 460℃ to 480℃, the leak rate was less than 1.0 gram/hour. Figure 1 shows a graph of test data from the joint operating at 480℃ and the very good perf ormance and low leak rate that the Joint A was capable of.

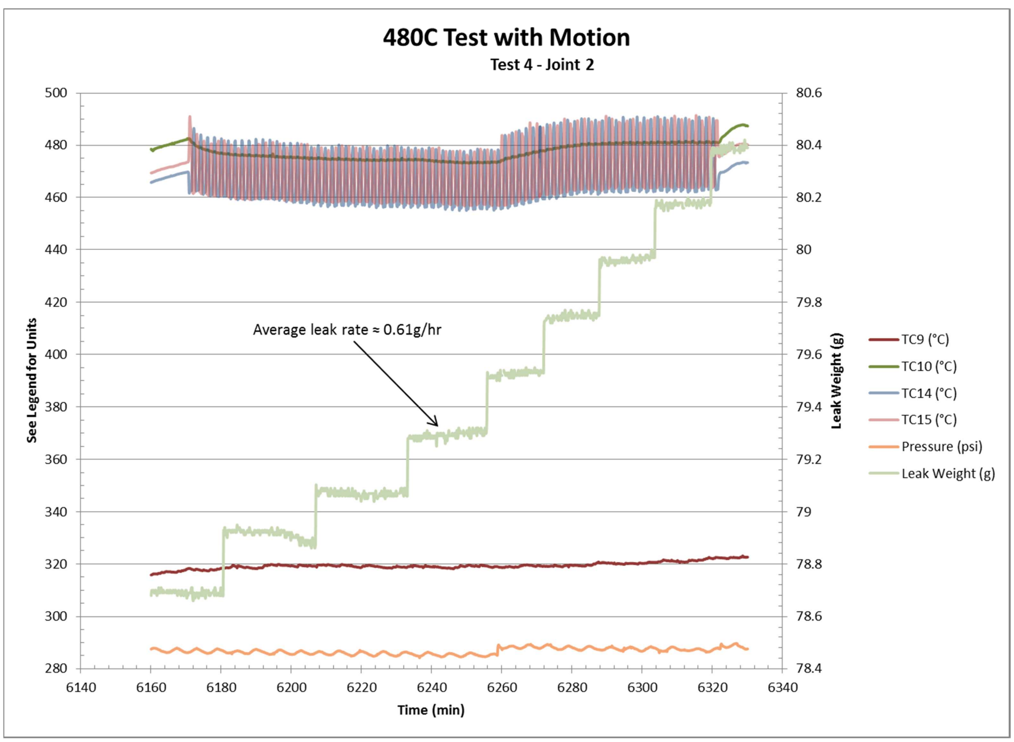

Figure 1: Graph of test at 480℃

After the brief success of testing at 480ºC, AS decided to perform a cycle life test at 450℃ to allow a 30℃ safety factor from the limiting operat ional temperature. If a joint design could perform well at 450℃, it would give the project a chance to move onto a pilot plant Phase.

The pilot plant would begin operations at 450℃ wit h the hope that a joint could be obtained to operate at 500℃ and eventually 550℃.

The next test was a sustained 450℃ and 20 bar cycl e life test. As can be seen in Figure 2: joint test data from hour 35 at 450℃Figure 2 , the performance of the joint was very stable during long periods of the test, even at hour 35 of the mechanical cycle test. The joint successfully completed 2,855 cycles, until the leakrate surpassed the allowable level of 10 gr/hr. The joint then successfully completed another 2,000 cycles until the leak rate became too large to continue, approximately 30 g/hr. It should also be mentioned that the torque specification for the rotary joints is ≤ 750 N*m and the joint never exceeded 68 N*m during the entire duration of the test.

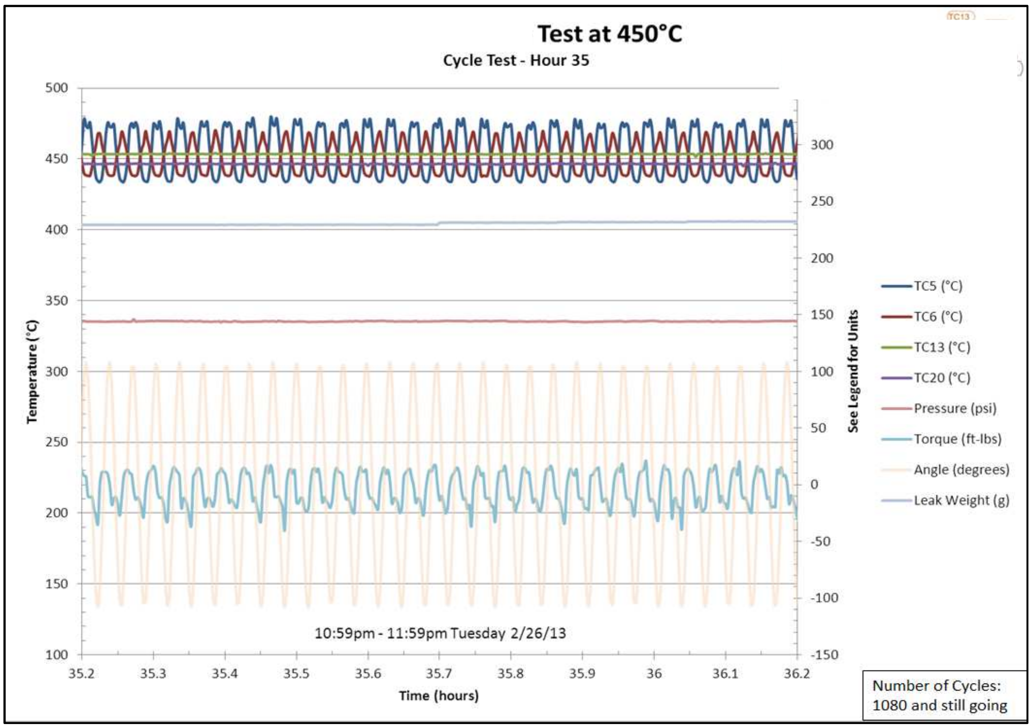

Figure 2: joint test data from hour 35 at 450℃

Although test results from 450℃ and 480℃ were ver y promising, it was not sufficient enough to call the joint development program a complete success and move onto Phase 3. This was due to the fact that Joint A could not operate at 500℃, which was the ultimate goal, and the Abengoa Solar team had multiple prototype rotary joints in the testing pipeline.

4.5.1.2 Joint B - Rotary Face Seal Joint

A second rotary joint manufacturer supplied Abengoa Solar with a customized face seal rotary joint. The first prototype was tested and failed while it was being brought to operating temperature and pressure. The manufacturer concluded from their post mortem failure analysis that the joint needed a redesigned guide bushing with improved tolerances and clearances for the large thermal expansion. The vendor was able to redesign and rework one of the previously manufactured joints, which really helped reduce the lead time in between prototypes. The second prototype was delivered it survived the test conditions of 500℃ and 4 bar, with a fairly high leak-rate (30 g/hr). Unfortunately once the test rig started rotating, the joint failed and salt began pouring out of the joint. The test was immediately stopped and the joint was removed and sent back to the manufacturer for failure analysis. Figure 3 shows a picture after the joint failure.

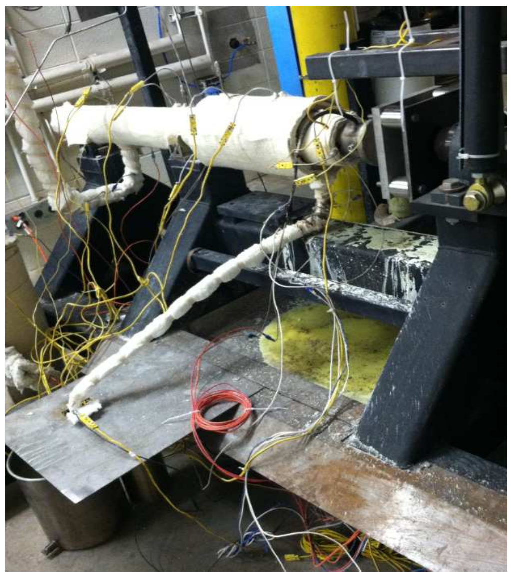

Figure 3: Picture after the second prototype test

Unfortunately by the end of Phase 2, the Joint B vendor was not able to supply a design that could handle pressurized 500℃ molten salt. Abengoa Solar is continuing to work with this particular vendor to improve their rotary joint design for the next round of prototype tests.

4.5.1.3 Double Flexhose Assembly

A third vendor delivered a collector interconnect assembly that did not include a rotary or ball joint. The design consisted of 2 flexhoses and a torque transfer arm. The double flexhose design had potential for success due to the completion of encouraging cycle life testing under pressure at the vendor's facility. The assembly successfully completed more than 10,000 cycles without salt or at high temperatures. After testing at the UWM facility, AS found that elevated temperature and small bend radius were the biggest factor in the demise of the double hose design. The design failed 30 minutes into the test. It is suspected that the corrosive qualities of salt did not influence the failure because the test was too short in duration to have corrosion be a contributing factor.

4.5.1.4 Joint C - Dynamic seal and Joint D - Face seal joint prototypes

A fourth manufacturer who specializes in custom rotary joint applications, in industries such as deep water oil and gas and the defense industry, proposed two rotary joint designs. One with a face seal design, similar to that of Joints A and B, and another design with a more traditional seal pack, making use of a newly developed seal material.

This manufacturer had a design feature on some rotary joints that utilizes compressed gas to pressurize the non-working fluid side of the seal, which balances the pressure differential across the seal and allows it to work at higher pressures. This feature is called gas-padding and it had great potential to work well in a molten salt rotary joint.

Regrettably this vendor was never able to deliver either prototype by the time Phase 2 was completed. Both designs have been wrought with delays and manufacturing problems that kept pushing back the delivery schedule. Abengoa Solar will still test these prototypes when they are delivered in mid-2013.

4.5.2 Pressure Sensor Testing

During Phase 2 a test rig was fabricated for valve and pressure sensor testing, which is shown in
Figure 4: . The pressure sensor test was performed using the upper reservoir of the rig. The first pressure transducer tested was a capillary-style pressure transmitter with a sodium-potassium (NaK) fill. Tests were conducted over a range of temperatures between 200℃ and 500℃ and over a pressure range of 0-40 bar gauge p ressure.

It was found that the transducer had a very large temperature dependence that agreed with the manufacturer specifications of 1% Full Scale/10℃ at a maximum drift of 0.87% Full Scale/10^{o}C. This translates to 0.5 bar/10℃. However, if an appropriate offset (zeroing the pressure transducer) was calculated at each temperature, the transducer was found to measure the pressure with an accuracy of ±0.19% to ±4.87%, at 200℃ and 500℃ respectively. This range is significantly larger than the manufacturer specified ±0.5% accuracy. Despite the inaccuracy, temperature-dependent equations were found that could correct the pressure readings as the temperature increased.

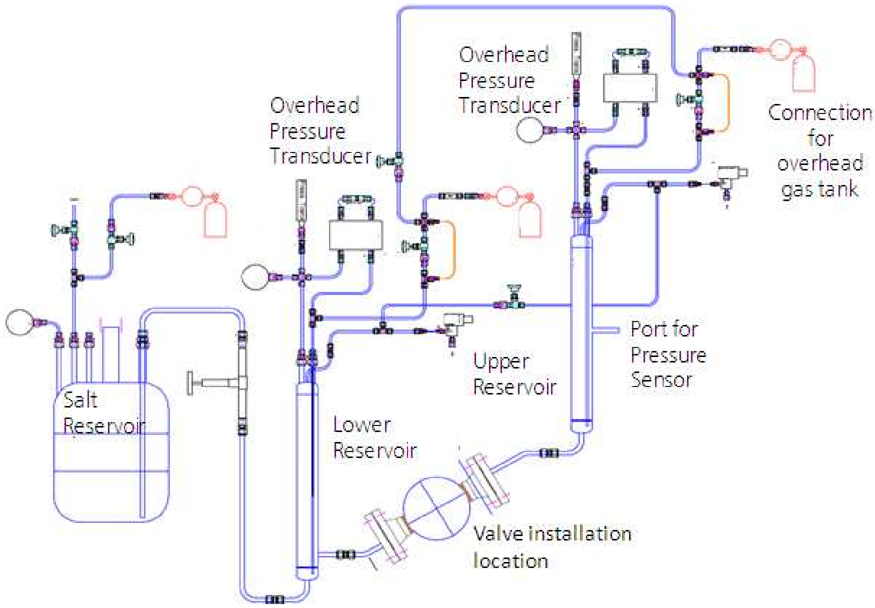

Figure 4: Schematic of Valve/Pressure Sensor Cart (Left), Constructed Apparatus (Right)

A second pressure transducer was obtained from the same manufacturer that had an internal temperature compensation feature. This transducer was specified to have a 5% full scale drift from the temperature where it is zeroed. A preliminary test of this sensor was performed, with the zero point at 25℃ and the operating temperature at 250℃. The drift was found to be approximately 1 bar at this temperature, which was consistent with the manufacturer's claims. The problem arose from the fact that the internal thermocouple output was not accessible in this model, which means that the inaccuracy could not be corrected with the Data Acquisition (DAQ) system. From these results it was concluded that the most accurate pressure readings will be acquired by using the original pressure transducer, with no internal temperature correction factor, and allow the DAQ system to calculate the correct pressure drift using the output of the internal thermocouple measurement.

In summary, a NaK based pressure sensor design has been identified that is compatible with molten salt. Care, however, must be taken to maintain accuracy and minimize drift over the commercial plant operating temperature range.

4.5.3 Valve Testing

Valves for use with molten salt HTF have been proven in the CSP industry with molten salt power tower projects and lower temperature Thermal Energy Storage systems coupled with oil HTF. Abengoa Solar wanted to test and prove that multiple valve designs exist for different applications within a commercial molten salt trough plant operating at 500℃ and 40 bar. There were two series of valve tests that were developed: one series for shut-off valves and one series for flow control valves.

Table 3 : Shut-off Valve Test Plan

	Test Type	Test Parameter	Pressure [bar (psi)]	Temperature [℃]
Test 1	Mechanical Cycling	200 open/close cycles	40 (580.2)	300
Test 2	Mechanical Cycling	200 open/close cycles	16 (232.0)	500
Test 3	Internal Leak Test, Closed	24 hours	20 (290.1)	500
Test 4	Thermal Cycling, Freeze/Thaw	4 full range temperature cycles, followed by 10 open/close cycles	40 (580.2)	500 → 105 → 500
Test 5	Thermal Cycling, Freeze/Thaw	3 sets: 1 temperature cycle followed by 10 open/close cycles	40 (580.2)	160 → 105 → 160

Table 4: Flow Control Valve Test Plan

	Test Type	Test Parameter	Pressure [bar (psi)]	Temperature [℃]
Test 1	Mechanical Cycling	4 full open phase cycles (10%, 30%, 50%, 70%, 90% open, hold 20 minutes each)	40 (580.2)	500
Test 2	Thermal Cycling, Freeze/Thaw	3 full range temperature cycles, followed by 1 open phase cycle	40 (580.2)	500 → 105 → 500
Test 3	Thermal Cycling, Freeze/Thaw	5 sets: 1 temperature cycle followed by 1 open phase cycle	40 (580.2)	160 → 105 → 160

The primary concerns for shut-off valves are internal leakage and external leakage. Two 6" diameter triple offset valve were purchased and tested. With the correct heating strategy for the lab scale testing, the triple offset valve performed very well at the test conditions and was proven to be a good candidate for shut-off valve applications. AS decided to purchase prototype 3" gate valves from a domestic manufacturer, in order to verify that a gate valve would also be a valid option for shut-off valves.

Again, the valves performed well under the test conditions and also proved to be another valve option for shut-off applications. The gate valves were substantially more expensive and larger than the triple offset valve; therefore it is unlikely that a gate valve would be used, in place of a triple offset valve.

For flow control valves, the primary concern is external leakage. Globe valves were purchased from two different manufacturers. A 3" globe valve was tested with Hitec XL-eutectic salt as the fluid. The test sequence for flow control valves is shown in Table 4. The valves appeared to pass the external leak test, but on further inspection, the bolted bonnet had allowed a small amount of salt to leak out. A lot of effort was spent reworking the valves and using different gaskets to get the bonnet to be leak-free. Eventually one valve was modified with a welded-bonnet and put back through the test sequence. The welded bonnet valve passed the tests and confirmed that welding components together is better than using gaskets and bolted connections when it comes to molten salt service. The only downfall of welding valves together is the inability to disassemble them easily and replace inner components.

The Globe valve from the other manufacturer was a classic case of lenient quality control at the vendor. After a 45 week lead time, the valves were finally delivered to the AS test facility. It was soon discovered that the valves were incorrect. The bonnet was not extended and the body casting was the wrong material. After months of negotiations and replacement, the valves were finally tested with molten salt. These globe valves passed the test sequences and were validated as another viable option for commercial service.

In conclusion, there are multiple different valve options for a commercial molten salt trough plant operating at 500ºC. The important lesson learned during the valve test campaign was the need to oversee the valve vendors more closely and leave ample lead time in the schedule for procurement and delivery of molten salt valves.

4.5.4 Flow Meter

As mentioned in section 4.1, the one disadvantage of the UWM test facility was the inability to have flowing salt. Therefore, a direct test of flow meter technology at the design conditions set for the molten salt trough solar field was not possible. Fortunately due to the commissioning of the Sandia Molten Salt Test Loop (MSTL), Abengoa Solar will be able to test flowmeters in a collector joint test rig, which will be shipped, integrated into the MSTL, and tested during the summer of 2013.

4.5.5 Corrosion Testing

Two different types of corrosion tests were performed to test the behavior of 316Ti and 321 Stainless Steels (SS), which are the common steels used in trough receiver tubes: salt fog testing and salt bath testing. For both tests, four coupon types were tested: as-received, tension, compression, and welded. The samples were obtained from receiver tube vendors.

Salt fog test under ASTM B117 was run for 1000 hours. During this test, the coupons were exposed to a 5% NaCl solution at 30 ℃. This test i s an accelerated test that proves to be harsh on steel. Neither set of coupons showed pitting or intergranular stress corrosion cracking.

The other test performed in conjunction with the salt fog test was a salt bath test at 500ºC. This test was run for 3000 hours at Sandia National Laboratory. Samples were removed at 1000, 2000, and 3000 hours. One set of samples were thermally cycled before submersion in the salt bath. The removal of heat treatment oxidation did not show a significant difference in corrosion, as was observed in the salt fog test. Grain boundary oxidation of approximately 10 microns was found after only 1000 hours, but quickly slowed and did not exceed 15 microns after 3000 hours. This intergranular corrosion was expressed as shallow wedge-shaped structure rather than the more typical narrow oxide filaments. Even with the intergranular corrosion, no intergranular stress corrosion cracking was observed nor any pitting. During the salt bath test, a black film appeared on the coupons and spalled off once cooled. This film was tested and proved to be iron oxide and calcium oxide. Over time, calcium carbonate precipitated out of the salt bath. The salt also decomposed into a mixture with much less calcium nitrate than the original mixture. This was another indicator that any salt containing calcium nitrate has a lower than expected thermal stability limit.

Overall the corrosion tests indicated that 316Ti and 321 stainless steel would be acceptable for Hitec XL molten salt service up to 500ºC. However, since Hitec XL was eliminated as a candidate for the commercial molten salt HTF, the corrosion study results do not validate the corrosion resistance of 316Ti and 321 stainless steels with other advanced ternary nitrate salts.

4.5.6 Freeze Protection/Recovery

In order for a direct storage molten salt HTF trough plant to be a viable solution, there must be a system and plan in place for freeze recovery and protection (freeze P/R). This system is also needed for initial heating of process equipment and piping during initial plant fill. A major commercial vendor was contracted to design this freeze recovery system for the collector field. This is for a 140 MWe_{gross} plant located in Phoenix, AZ. Details of the TES piping was not available at the time, so only the solar field piping was considered. The field was broken into two systems: heat trace system and impedance heating system. Two types of molten salt heat transfer fluids with significantly different melt points were also considered; Hitec XL eutectic (T_{melt}~120ºC) and Solar Salt (T_{melt}~220-238ºC).

All piping included in the heat trace system is heated using mineral insulated (MI) cable. This is the only known type of heat trace cable that can withstand exposure temperatures over 250 ºC. The receiver tubes are heated with an impedance heating system. This is one area that AS will investigate in the future in order to significantly reduce the freeze P/R system costs. A system for Hitec XL or Solar Salt with 89 mm O.D. receiver tubes of 2mm wall thickness would be able to operate within the NEC code, secondary voltage restrictions of 30 volts for a non-ground fault interrupted or 80 volts for a ground fault interrupted design.

Cross-over piping and ball joint assemblies were designed for MI cable heating. If flexhoses were used in place of ball joint assemblies, tests at University of Wisconsin-Madison proved that sustained impedance heating of flexhoses is possible up to 500ºC.

Engineering, procurement, and construction (EPC) cost estimates of the solar field freeze P/R systems we provided with an uncertainty of ± 25%. The quoted costs did not include insulation or power distribution to the systems. An important finding is the minimal increase in EPC cost for a significant increase in melt point temperature. This confirms that majority of the freeze P/R system costs result from the fact that the system exists at all. As such, reduction in salt melt point has more impact on risk reduction than EPC cost.

4.6 Task 7 (Phase 2) – Molten-Salt Collector Analysis

The goal of this task was to determine all design modifications to the large aperture collector, developed under DOE project DE-FG36-08GO18037, necessary to use the collector in a solar field with a molten salt HTF and solar field outlet temperature of 500ºC. Design requirements for both projects (GO18037 and GO18038) were gathered and compiled into a single document as a way to ensure any design changes resulted in a collector that stayed within all of the design constraints. The molten salt HTF required changes to the collector due to increased operating temperature, increased mass at receiver tube axis, and the need for an impedance heating system. These efforts included the following:

- Selection of 89mm outer diameter receiver tube
- Receiver support design that could account for the increased thermal expansion of the receiver tubes
- Electrical isolation of the receiver tubes from the rest of the collector
- A design for cable placement of the impedance heating system
- Methods to connect the receiver tubes to the impedance heating system circuit
- Positioning of the added impedance heating system components in relation to the collector
- Adjustment of the center of gravity of each module due to increased mass in the receivers and increased torque of the joints
- Structural analysis of the collector due to increased mass in the receivers and increased torque of the joints

4.7 Task 8 (Phase 2) – Process Development

The following sections describe process related topics investigated during Phase2.

4.7.1 Salt thermophysical properties

To improve the accuracy of plant performance, design, and cost estimates, thermophysical properties of the selected heat transfer fluid, Hitec XL, were needed. The only data available was from unknown sources, so the goal was to fully characterize Hitec XL including the eutectic mixture. As mentioned above, Hitec XL (more specifically Calcium Nitrate) was very difficult to work with and caused unreliable results from more than one lab that was contracted to work on salt properties, and was ultimately discarded as a candidate for commercial operation. During the thermophysical property testing campaign, AS attempted to obtain the following properties of Hitec XL:

- Eutectic mixture composition
- Melt point (confirmation with differential scanning calorimetry)
- Freeze point[10]
- Heat of fusion
- Specific heat vs. temperature
- Viscosity vs. temperature

[10] Freeze point and melt point can be different depending on each salt mixture. This is due to differing melt points for the individual constituents and the possibility of a glassification stage that has an indistinct freeze point.

- Density vs. temperature
- Thermal conductivity vs. temperature

Due to the fact that any salt composition that contains Calcium Nitrate was removed from the investigation of commercially viable salts, it eliminated the importance of obtaining more reliable and accurate property data for Hitec XL. Abengoa Solar will continue to investigate advanced ternary molten salt compositions, thus continuing the need to obtain reliable thermophysical property data from vendors and laboratories.

4.7.2 Salt Freeze Detection

A Stage-Gate™ process was used to identify and evaluate methods and/or equipment to identify salt plugs within process piping and receiver tubes. For conciseness, the complete list is not included here, but the result was the selection of a gamma-ray detector and a distributed temperature sensing (DTS) system for testing.

A gamma-ray detector passes gamma rays through the piping or receiver tubes (and any associated cladding, insulation, or glass envelope) to detect density variations. It is an active method in which a technician must scan each section of pipe in question. The hypothesis was that the density variation between liquid and solid phase of nitrate salts would allow the identification of frozen salt in a cross-section of piping. Testing carried out at Sandia NL with Solar Salt filled receiver tubes showed that the uncertainty in the gamma-ray detector was on the same order of magnitude as the density variation from the liquid to solid phase of the salt. As such, frozen salt could not be definitively distinguished from liquid salt. However, the detector was able to identify void space (i.e. air pockets) created when the salt freezes.

A distributed temperature sensing (DTS) system uses optical fibers to sense temperature along the length of the fiber by analyzing the backscatter light. All process piping would be traced with the fiber to provide a nearly continuous temperature profile along the length of each pipe. This would be a passive method in which cold spots (indicative of a freeze event) are detected automatically by the DTS system. The glass fiber is available in several commercial grades depending on the maximum operating temperature. Cables capable of withstanding sustained temperatures above 300℃ req uire copper or gold coatings which are prohibitively expensive. Tests were conducted at NREL and a DTS supplier to confirm the functionality of the technology and validate a novel use of cheaper, lower temperature fiber on piping above 300℃. While this technology is ideal for feeder and header piping, it would be difficult, though not impossible, to employ on receiver tubes due to the evacuated annulus.

4.7.3 Freeze protection/recovery procedure

Given the design of the solar field freeze protection/recovery system, procedures were developed for various situations which are likely to occur:

- Heating of the field for initial salt fill
- Freeze prevention for loops or process piping
- Freeze recovery for loops or process piping

The freeze protection and recovery procedures take into account the available data from sensors in the field and plant auxiliary transformer capacity. In an emergency power outage scenario, collector loops would be allowed to freeze while the back-up diesel generator would power the heat tracing of feeders and header piping. This decision was made based on reasonable sizing of the diesel generator and the amount of time required to recover from a freeze event in various pipe diameters.

4.8 Task 9 (Phase 2) – Plant Performance & Economic Analysis

Ultimately the designs, location, and operational strategies of CSP plants must be reduced to annual performance, EPC cost, and O&M cost to determine their economic viability based equally influential financing assumptions. Significant effort was given to Task 9 to improve accuracy of these input values for the calculation of LCOE, particularly in the area of commercial plant modeling and analysis. The following sections will briefly review the significant efforts given to performance model improvements, analyses of plant performance, EPC cost estimation and O&M cost. The results of these efforts are then paired with three different financial conditions to show the possible outcomes for LCOE.

4.8.1 Performance Model Development

The TRNSYS modeling environment (based on the Fortran programming language) is used for annual performance predictions of the solar power plants. During the course of Phase 2, a group of engineers developed new and improved subroutines to increase accuracy, fidelity, speed, and/or flexibility. While dozens of improvements were made, a list of the significant improvements is given below.

- Discretized receiver tube heat loss to improve heat loss accuracy
- Integration of a preprocessor and the performance model to facilitate parametric runs for optimization
- Power block improvements including addition of dry cooling and separation of turbine performance and steam generation modeling
- Development of a heat exchanger model to allow a broader range of plant designs
- A stand-alone insulation optimization tool which accounts for heat tracing cost
- Improved architecture of control implementation

In addition to improvements, software bugs were corrected when identified. The net annual performance was reduced from Phase 1 to 2, however the capital cost of the molten salt commercial plant was greatly reduced, and consequentially obtaining a much better Cost/Performance value that is 25% lower than the Phase 1 value.

4.8.2 Performance Analysis

In this task, the TRNSYS modeling environment was used to analyze various aspects of molten salt CSP trough plants. While many such investigations were performed, the annual performance of the reference molten salt plant is the focus of this section.

Four plant designs were simulated to obtain performance data for determination of LCOE. The first was a 140 MWe_{gross} plant with 6 hours of storage and a solar multiple of 2 with a 490ºC maximum field outlet temperature. This plant is referred to as the “Reference 490 Plant”. Analysis results indicate this increase in storage capacity and solar field will yield a more reduced LCOE. Specifications of the reference 490ºC plant are summarized in Table 5.

The first two plants are based on the assumption that a ternary salt with a lower freeze point also has a lower thermal stability limit, which allows a maximum field outlet temperature of 490ºC. If a company is willing to assume the increased freeze risk of Solar Salt as the HTF, the maximum field outlet temperature of 540ºC could be achieved based on assumed receiver tube coating limits.

Table 5: Reference molten salt (490ºC) CSP plant specifications

Component	Molten Salt Plant (2-Tank)
Turbine Name Plate Capacity (gross)	140 MWe_gross (nominal)
Solar Multiple	2.0
Power Cycle	Superheated steam Rankine cycle (480℃, 125 bar)
Cooling	Dry
Solar Field HTF	Ternary salt composition
Field Outlet Temperature	490 ℃ (nominal)
Field Inlet Temperature	300 ℃ (nominal)
Storage Size	6 equivalent full load hours
Storage Type	2-tank molten salt direct
Collectors	Abengoa’s Large Aperture Collector
Receiver Type	PTR-90
Receiver Diameter	88.9 mm (O.D.)
Receiver Length	4.7 m

Annual performance data was calculated at 15 minute increments based on the location of Gila Bend, AZ using DNI data from SolarAnywhere (this new TMY data is approximately 5%

higher than TMY data used in Phase 1). The annual DNI for the Reference plant is 2,731 kWh/m^2-yr.. To account for plant outages, an availability of 96% is applied to the annual electric production.

4.8.3 Basic EPC quote for Commercial CSP Plant

Obtaining a Basic Engineering, Procurement, and Construction package for Reference 490 ºC Plant was a large portion of the work done in Task 9 of Phase 2. The EPC package of documents consisted of, but was not limited to, the following:

- process flow diagrams
- piping and instrument diagrams
- equipment lists
- piping line lists
- piping specifications
- equipment specifications
- heat tracing designs
- insulation specification
- electrical design
- plant layout
- collector design and foundation
- equipment foundations
- bids on all major equipment/systems

Cost estimate categories include direct costs and the indirect costs associated with the project. Direct capital cost categories include line items such as Equipment, Foundations, Steel, Piping, Electrical, Insulation, Site Preparation, Buildings, and Roads and Landscaping. Indirect costs included items such as Engineering, Construction and Engineering Management, Construction Utilities, Site Supervision, Quality and Document Control, and Insurance.

An uncertainty of ±10% was requested by contract for this work. Gila Bend was used as the location to determine the solar resource, site preparation, water quality, labor costs, shipping, and other location based expenses. A detailed breakdown of cost estimates allowed for scaling the EPC cost of plants with different field sizes, TES sizes, and/or maximum operating temperatures.

4.8.4 Levelized Cost of Energy

Using the System Advisor Model (SAM ver. 2011.12.2), the above cost estimate and performance predictions for the reference plant were converted to a real LCOE using the Generic System, Independent Power Producer model. Values are in 2012 US Dollars as opposed to the 2009 US Dollars documented in the SOPO. The financial assumptions are listed below, in Table 6, which summarizes the LCOE parameters that are discussed in this Final Report. It is important to list all of the financial assumptions due to the large range of possible values that greatly affect the LCOE output. Explicitly tabulating the values allows for LCOE comparisons of different "projects".

Table 6: SAM Input Assumptions

	Financial Term Group	
Financial Terms	Phase 2 DE-FC36-08GO18038	Comments
Analysis Period	30 years	
Inflation Rate	2.30 %	
Real Discount Rate	8.00 %	
Federal Tax	34%/year	
State Tax	6%/year	
Property Tax	0%	
% of Installed Costs subject to Property Tax	100%	
Assessed value decline (Property tax)	0%	
Sales Tax	7.75%	
Insurance	0.21%	
Loan term	20 years	
Loan Rate	8.00 %	
Loan (Debt) fraction	-	Selected to minimize LCOE
Fed. Depreciation Rate	5-yr MACRS	
State Depreciation Rate	5-yr MACRS	
PPA Escalation Rate	-	Selected to minimize LCOE
Minimum Required IRR	12.00%	No positive cash flow constraint
Minimum Required Debt Service Coverage Ratio (DSCR)	1.40	
Federal Investment Tax Credit (ITC)	10%	
Investment Based Incentive (IBI)	0%	No taxable incentive, Reduces Depreciation & ITC Bases (state & federal)
Cost assumptions		
Contingency	5.0%	
Engineer, Procure, Construct	16.0%	

Project, Land, Misc.	3.5%	
% of Direct Costs subject to Sales Taxes	80.0%	
Performance Assumptions		
System Degradation	0%	
Availability	96% included in Performance data	

Operations and maintenance (O&M) costs were based on operational experience of Therminol based CSP plants, with modifications for plant design changes and the switch to direct storage with molten salt HTF.

Table 7 lists the real LCOE's calculated for the 140MWe$_{gross}$ plant with two different field outlet temperature limits. In both cases the LCOE$_{real}$ satisfies the Statement of Project Objectives requirement for a maximum real LCOE of <12.0¢/kWhe (2009 $). The size of the reference plant (140MWe$_{gross}$ with 6 hours equivalent full load (EFLH) TES) was selected at the beginning of the project without knowledge of the optimum solar multiple and storage capacity. Using TRNSYS and scaling of the reference plant EPC costs, it has been shown that a 140 MWe$_{gross}$ plant with more hours of TES will result in a reduced LCOE.

In addition, the thermal stability limits of various salts are still being confirmed through testing. Table 7 presents conservative cases assuming that Hitec XL molten salt HTF has a thermal stability limit which allows a maximum field outlet temperature of 490ºC. The table also presents a more optimistic case which assumes Solar Salt as the HTF. This case has been limited to 540ºC field outlet temperature based on assumed receiver tube coating limits.

Table 7: LCOE$_{real}$ summary for molten salt plants (2012)

	LCOE$_{real}$ (¢/kWhe)
Maximum Field Outlet Temperature (ºC)	Phase 2 DE-FC36-08GO18038
490	11.50
540	10.94

4.9 Technical risks

The main technical risks were the focus of the efforts in Phase 1 and Phase 2. Some of these risks are listed below and discussed in more detail in the paragraphs which follow. Several other minor risks are also being addressed but are not discussed here for brevity:

- Thermal stability limit of a ternary salt.
- Attaining a leak-free collector joint that will have a 30 year operational lifetime.
- Attaining leak-free valves that will have a 30 year operational lifetime.

- Risk of freezing salt and damage it may cause.

In a solar power plant, the solar-to-electric efficiency is, to a first order, the product of the field efficiency times the Rankine cycle efficiency. Increasing the field outlet temperature allows an increase in the steam pressures and temperatures in the Rankine cycle, which leads to an increase in the cycle efficiency and decrease in storage costs. The two limiting technical factors on field outlet temperature are the receiver tube selective coating and the salt thermochemical stability limit. Development of selective coating is outside the scope of the DOE project, but investigation of thermochemical/electrochemical stability is being investigated. There are long lists of reactions or processes (some reversible and some not) which can result in degradation of the salt.

Due to the lack of a collector design that rotates around a stationary receiver, joints are needed to give current collectors the rotational and linear degrees of freedom needed for operation. While solutions have been found for heating of various joint options, the search continues for a rotary joint or ball joint compatible with molten nitrate salts.

Similar to joints, valves are needed with compatible seal materials or technologies. For valves AS feels confident about commercial solutions for the various types needed, and are focusing on engineering details such as material combinations, torque specs, geometry, and heat tracing placement.

Finally, freezing of salt HTF's is still a concern. While substantial design effort and modeling has been devoted to predicting and preventing freezing of the salt in the plant piping and equipment, physical testing is still needed. Freeze/thaw cycles have been successfully carried out on some valves, but this must be done for all components. This testing is better suited for pilot plant testing with flowing salt and system geometry which is more representative of the commercial design. While salts with lower freeze points reduce the risk of a freeze, vendor cost estimates have confirmed that the freeze point temperature has lower impact on the direct costs of the commercial plant. With this in mind, the success of a commercial molten salt CSP plant is not reliant on finding the perfect, low freeze ternary or quaternary salt mixture.

5 Project Conclusions

Although the Molten Salt Trough project is being closed, the majority of the key objectives were achieved during Phase 1 and Phase 2. As a result of Abengoa Solar's extensive effort and research of molten salt HTF technologies, obtaining commercial plant EPC quotes, and testing key molten salt components, the technology is much closer to becoming a commercial reality than it was at the beginning of the project. One of the primary goals in Phase 2 was to identify and address all of the key risk areas involved with using molten salt as a HTF. The identified risk areas were; thermal stability limit of a ternary salt, attaining a leak-free collector joint and leak free valves that will have a 30 year operational lifetime, and the risk of salt freezing and the damage it may cause. Refer to section 4.9 for further details on technical risks.

Another primary goal of the project was to develop a molten salt commercial plant design that achieved the LCOE goal of <0.12¢/kWhe. This was accomplished by creating a very powerful and accurate performance model and obtaining a comprehensive basic EPC cost estimate in Phase 2 that was much lower than original expectations. The expectations were based on a low resolution EPC quote that was obtained in Phase 1. As discussed in section 4.8.4, moderately optimistic LCOE financial and cost assumptions can produce an LCOE in the range of 11.50¢/kWhe for a 140 MWe_{gross} CSP plant with molten salt HTF. With very aggressive and optimistic LCOE assumptions, a similar 140 MWe_{gross} plant can produce a LCOE substantially lower. The work completed in Task 9: Plant Performance and Economic Analysis (section 4.8) validated the business case with performance and capital cost values that are substantially better than an oil HTF CSP trough plant. The 140 MWe_{gross} molten salt plant has a capex/performance value that is 22% to 28% better than a baseline plant that uses oil HTF and 6 hours of molten salt storage.

Given the convincing results from the project, Abengoa Solar strongly recommended proceeding to Phase 3 and advancing the development of the SpaceTube Collector CSP pilot plant with the use of molten salt HTF. There was high confidence that the primary risk areas had been addressed and a commercial plant utilizing molten salt is economically and technically feasible. However, a commercially viable collector interconnection was not fully validated by the end of Phase 2, combined with the uncertainty in the federal budget, forced the DOE and Abengoa Solar to close the project. Even so, Abengoa Solar is dedicated to continued development and testing of the molten salt trough technology and will continue to work towards commercialization of a parabolic trough CSP plant with molten salt as the primary HTF.

6 Budget and Schedule

The total approved budget was not spent during the project performance period. The budget for the project is summarized in the table 10 below:

Table 8: Overall budget for the entire project period

Object Class Categories - Per SF-424a	Approved Budget	Cumulative Total Spent
a. Personnel	$931,120	$947,940
b. Fringe Benefits	$39,079	$39,079
c. Travel	$57,272	$34,146
d. Equipment	$481,162	$374,540
e. Supplies	$11,344	$2,116
f. Contractual	$1,571,179	$1,357,033
g. Construction		$0
h. Other		$1,799
i. Total Direct Charges (sum of a to h)	$3,091,156	$2,756,654
j. Indirect Charges	$947,193	$618,119
k. Totals (sum of i and j)	**$4,038,349**	**$3,374,773**
DOE Share	$3,230,679	$2,699,818.46
Cost Share	$807,670	$674,954.62
Calculated Cost Share Percentage	20.0%	20.0%

Refer to the SF-425 form for complete details of the final project finances. The project budget was underspent because plans changed in the middle of the different phases and there was not time or resources to go through a budget and contract modification with the DOE, to allow Abengoa Solar to redirect funds that were slated for specific tasks or in certain budgetary categories.

The overall Project schedule was delayed a number of times from the original baseline project schedule. There were delays in getting subcontractors and vendors to supply services and molten salt equipment in the agreed upon timeframe. There was also a large delay of 6 months, due to paperwork and processing time required for transitioning from Phase 1 to

Phase 2. Finally, the schedule was delayed to the point of needing a no cost extension because the project team was not able to obtain a rotary flex joint that functioned successfully in high temperature nitrate salts. All of these delays added up to a total project delay of 10 months from the original Phase 2 end-date of February 28, 2012 to the new end date of December 31, 2012.

7 Path Forward

Given the convincing results from the project, Abengoa Solar strongly recommended proceeding to Phase 3. There was high confidence that the primary risk areas had been addressed and a commercial plant utilizing molten salt is economically and technically feasible. However, a commercially viable collector interconnection was not fully validated by the end of Phase 2. Even so, Abengoa Solar is dedicated to continued development and testing of the molten salt trough technology, especially perfecting a rotation joint for molten salt use. Abengoa Solar will continue to invest resources towards the commercialization of molten salt parabolic trough technology is confident that a commercial solution for the technology can be achieved in the coming years.

8 Acronyms

AS – Abengoa Solar, LLC

ATS – Advanced Thermal Systems

CSP – Concentrated Solar Power

DAQ – Data Acquisition

EFLH – Equivalent Full Load Hours

EPC – Engineering, Procurement, and Construction

HTF – Heat Transfer Fluid

ITC – Investment Tax Credit

LCOE – Levelized Cost of Energy

MI – Mineral Insulated

MSLLC – Madison Scientific, LLC

MSTL – Molten Salt Test Loop (Sandia National Laboratories)

O&M – Operation and Maintenance

SS – Stainless Steel

TES – Thermal Energy Storage

UWM – University of Wisconsin, Madison