Phase I Final Report

Issued: March 16, 2012

INDIRECT, DUAL-MEDIA, PHASE CHANGING MATERIAL MODULAR THERMAL ENERGY STORAGE SYSTEM

ACCIONA Proprietary

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Executive Summary

Work under this project has ultimately focused on the development and performance evaluation of a $100kWh_t$ prototype heat exchanger. The design utilizes a commercially available heat exchanger product to create a unique latent heat PCM storage module. The novel ideal associated with this technology is the inclusion of an agitation mechanism that is activated during the discharge process to improve heat transfer.

The prototype unit did not meet the performance goals estimated through modeling, nor did the estimated costs of the system fall in line with the goals established by DOE.

Project Objective

Design, validate at prototype level, and then demonstrate a full size, 800 MWh_t Thermal Energy Storage (TES) system based on Phase Changing Material (PCM) TES modules with round trip efficiency in excess of 93%. The PCM TES module would be the building block of a TES system which can be deployed at costs inline with the DOE benchmark of 2020.

The development of a reliable, unsophisticated, modular, and scalable TES system designed to be mass-manufactured utilizing the most advanced automated fabrication and assembly processes and field installed in the most cost-effective configuration could facilitate the attainment of the Levelized Cost of Energy (LCOE) of $.07/kWh by 2015. It is believed that the DOE targets can be attained by finding the best combination between the size of the TES module, its optimal integration in the power cycle, and the best PCM for the application.

The technology researched in this project utilizes latent in molten salt heat to store solar energy for later use. By using large, flat plate based heat exchangers, individual, welded pockets are formed. HTF is pumped though a series of pockets which have an internal pattern to manipulate flow and maximize the time HTF spends in an individual pocket. As the cycle is discharged, a vibration system is activated to shake loose solid particles deposited on the heat exchanger, causing them to separate and fall to the bottom of the tank. As the discharging concludes, the tank of salt will be fully solidified.

Background

In current thermal energy storage configurations, molten salt is held in two tanks, one for cold salt and one for hot salt. The system is charged by transferring cold salt through heat exchangers to gain sensible heat, and then deposited in a hot tank for storage. To discharge the system, salt is pumped from the hot tank through consecutive shell and tube heat exchangers into the cold tank. Conventional two tank systems utilize sensible heat exclusively. These systems are vulnerable to salt solidification on the heat exchanging surfaces during the discharge phase, resulting in a rapid decrease in heat transfer efficiency.

For comparison purposes, the proposed TES module concept is compared with what can be considered the current state of the art design reported by German Aerospace Center (DLR) Institute of Technical Thermodynamics in the DISTOR (Storage System for Solar Direct Steam Generation) Project. The basic design of the DISTOR latent and sensible heat storage system uses a parallel tube heat exchanger immersed in PCM placed into a non-pressured container. The tube heat exchanger is equipped with graphite fins (Steinman et al., 2008). The DISTOR project validated the concept of a fined heat exchanger immersed in a non-pressured nitrate salt bath as the most cost effective approach to PCM storage.

Results by Task

The following section provides a detailed account of the Phase I tasks as defined in the Statement of Project Objectives (SOPO). The detailed account highlights the approach for each task as well as the subsequent results.

Task 1.0 Heat transfer model and fluid dynamic analysis

The first task of this project was to create heat transfer and fluid dynamic models. For a system level feasibility study and initial system design, the TRNSYS software package was used. TRNSYS is a software package with built-in components such as pumps, tanks, heat exchangers, and has the ability to operate with user created components.

Further heat transfer and computational fluid dynamics modeling was performed with the MATLAB and COMSOL software packages. MATLAB was used to assist in sizing the system, designing the heat exchanger, and predicting its performance. COMSOL was used to evaluate the heat exchanger design from a fluid dynamics and finite element perspective. The phase change process was modeled to investigate the internal behavior of the PCM to visualize how heat will be transferred in the heat exchanger. A detailed modeling report was submitted to DOE and is attached in Appendix C.

Throughout the modeling process, the focus was to satisfy the performance requirements of this storage concept. Modeling results suggested this concept had the ability to reduce the amount of storage material required, and that the round trip efficiency of a PCM storage system has the potential to exceed 93%. Heat transfer and fluid dynamic analysis assisted in the design and modeling of the heat exchanger/storage tank. These analyses suggested that the 100 kWh_t prototype heat exchanger/storage tank would be capable of being charged in approximately 2 hours. Results from the experimental testing with the prototype unit were used to refine the models for larger scale predictions.

Task 1.1 PCM TES module design and the 100kWh_t lab unit fabrication

A commercially available product was used for fabrication of the heat exchanger surface walls as well as the vessel. The product utilized is described as a Flat-Panel Open Tank Heat Exchanger. This type of heat exchanger is made using two symmetric pieces of stamped sheet metal to form an enclosed plate heat exchanger. The 100kWh_t unit would require multiple heat exchanger sections and would ultimately be configured in a fashion similar to Figure 2.

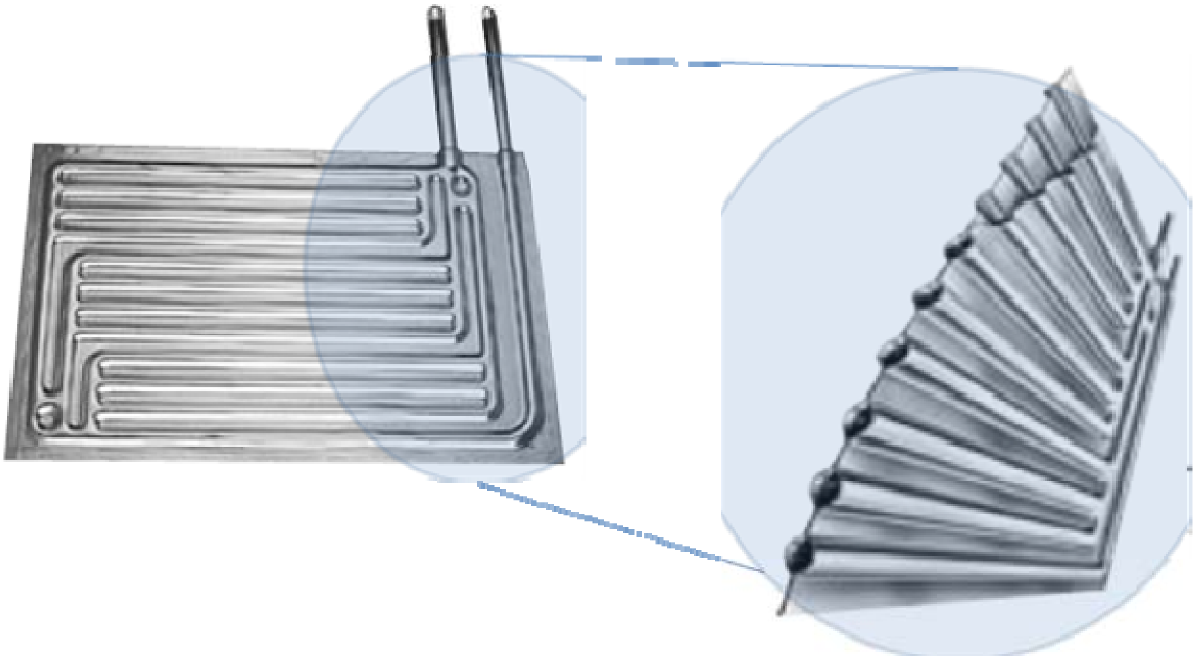


Figure 1 – Commercially available Flat-Panel Open Tank Heat Exchanger.

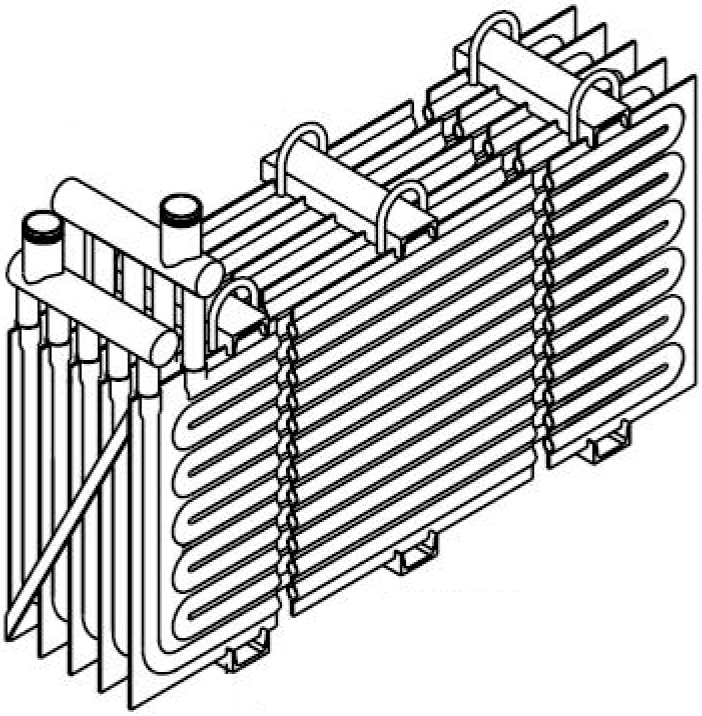


Figure 2 – Commercially available Flat-Panel Open Tank Heat Exchanger bundle.

The $100kWh_t$ prototype was developed through extensive collaboration with the heat exchanger manufacturer. Test loop operating parameters were shared with the manufacturer as well as lithium nitrate salt properties and mineral oil heat transfer fluid properties. The manufacturer then calculated a surface area needed to charge and discharge the $100kWh_t$ of latent heat within the unit at a heat transfer rate within the confines of the test loop equipment. For example, the heater skid purchased for the test loop provides HTF at a temperature of 550°F and a flow rate of 35GPM. These values limit the rate at which the PCM can be charged.

The end result from the heat exchanger manufacturer agreed with the calculation developed in house. The heat exchanger is comprised of a bank of double embossed plate heat exchanger sheets which are 42-7/8” x 47”, and have a surface area of 31.6 ft^2 each. The bank is hydraulically separated into two series halves, each using 6 plate heat exchanger units plumbed in parallel. This was done to maximize HTF time in salt and minimize pressure drop though the unit.

The rectangular tank was designed with a volume of 28.6 ft^3 with dimensions of 50” long x45” tall x 22” wide. The walls of the tank were fabricated using single embossed plate heat exchanger material, with the smooth surface facing inward. This extra heat exchanger surface area could be used to supplement heat transfer, however it has not be included in the surface area calculation for the design and will not be used as such for unit demonstration. Photographs of the heat exchanger and tank are inserted below as Figures 3 and 4.

Figure 3 – $100kWh_t$ prototype HEX bank made of 12 Flat-Panel Open Tank Heat Exchanger.

Figure 4 – 100kWh$_t$ prototype enclosure made of Flat-Panel Open Tank Heat Exchanger panels.

In order to evaluate the 100kWh$_t$ prototype, a test loop was designed and constructed. Design requirements for the test loop included safety, fitment on the test pad foot print, robustness, and budget constraints. A P&ID for the test loop is shown in Figure 5.

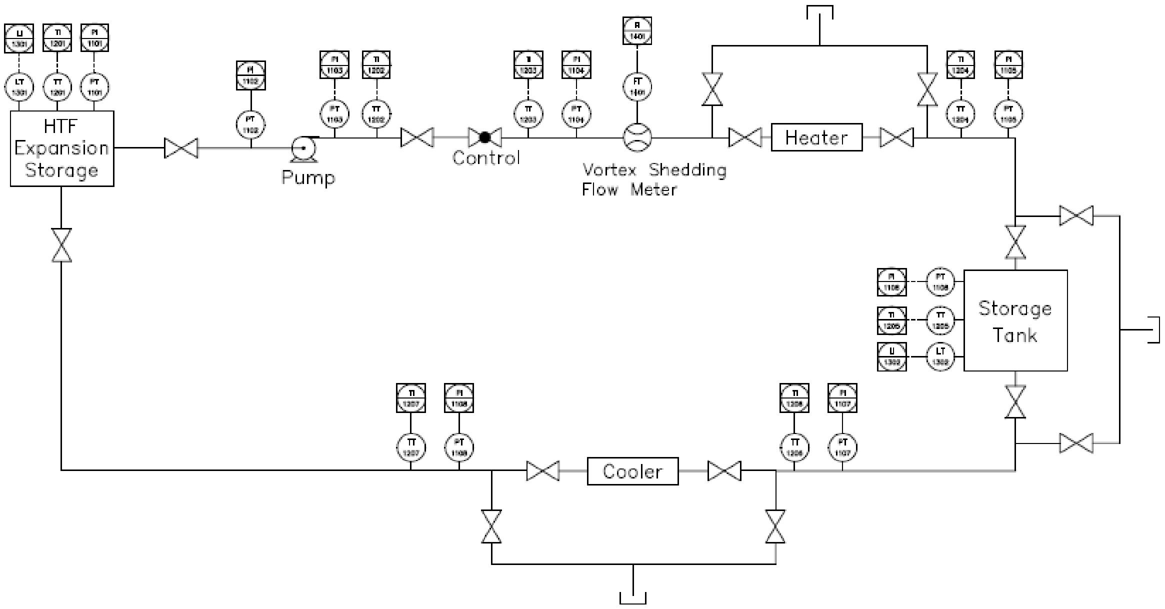


Figure 5 – Basic layout and instrumentation identification for 100 kWh_t unit test loop

The loop utilized a heater skid that consisted of: an HTF storage tank, a pump, a control valve to regulate flow, and an electric heater. The loop also included the thermal storage unit, and a liquid–to–air heat exchanger to serve as a cooler. The heat transfer fluid selected for this project was a pure mineral oil. This oil was selected because it has minimal effects on the environment and is very easy to work with. Lithium nitrate ($LiNO_3$) was selected based on its melting temperature of 254 °C (489 °F). Using a lower melting temperature salt required a smaller heater and placed less thermal stress on the pump seal. Although large scale installations will require a PCM with a higher melting temperature, $LiNO_3$ could still be used to simulate the freeze/thaw behavior being investigated. A 3D layout simulation of the test loop is shown in Figure 6.

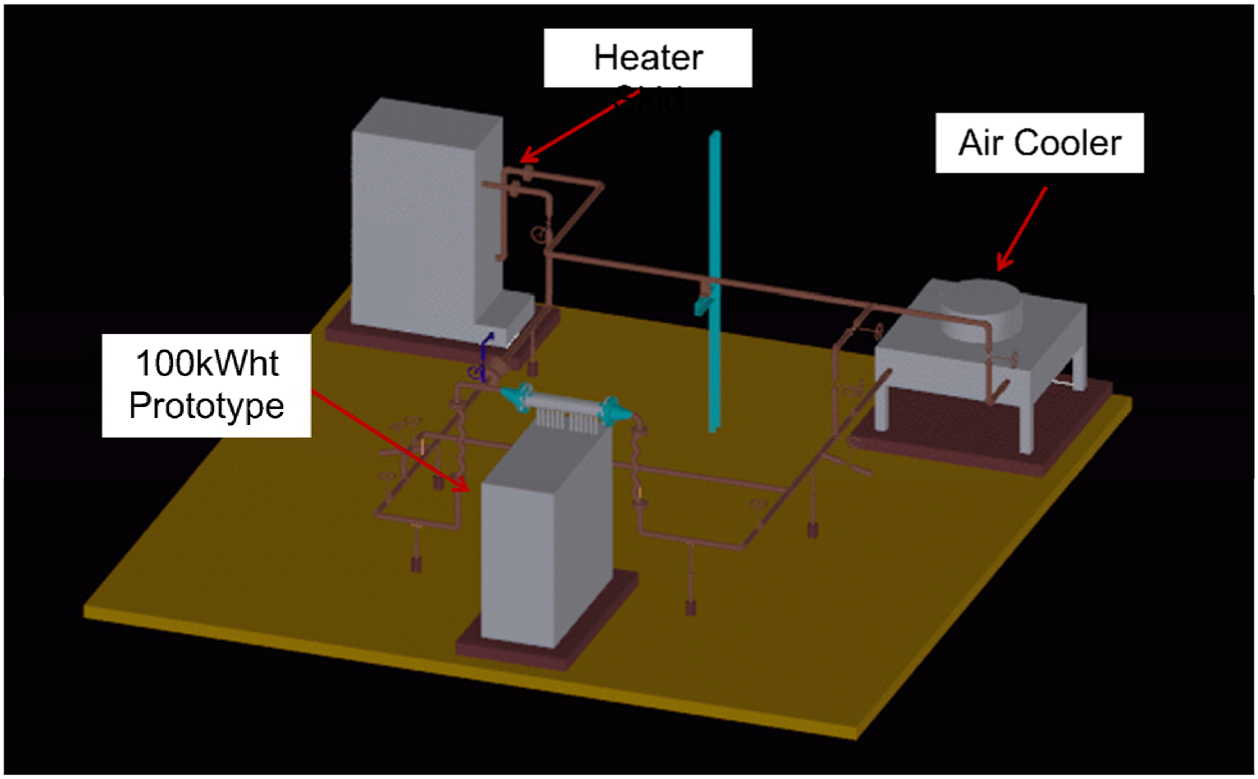


Figure 6 – 3D representation of the test loop equipment and layout.

This layout rendering was used to develop the final installation layout, which is show in Figures 6 through 12. Work included: anchoring of the heater skid and air cooler to the concrete containment pad, fabrication a vibration isolation foundation for the 100kWh$_t$ prototype, fabrication and installation of the pipe supports, field running of the pipe, sensor wells and valves, and fabrication of the heat exchanger lid.

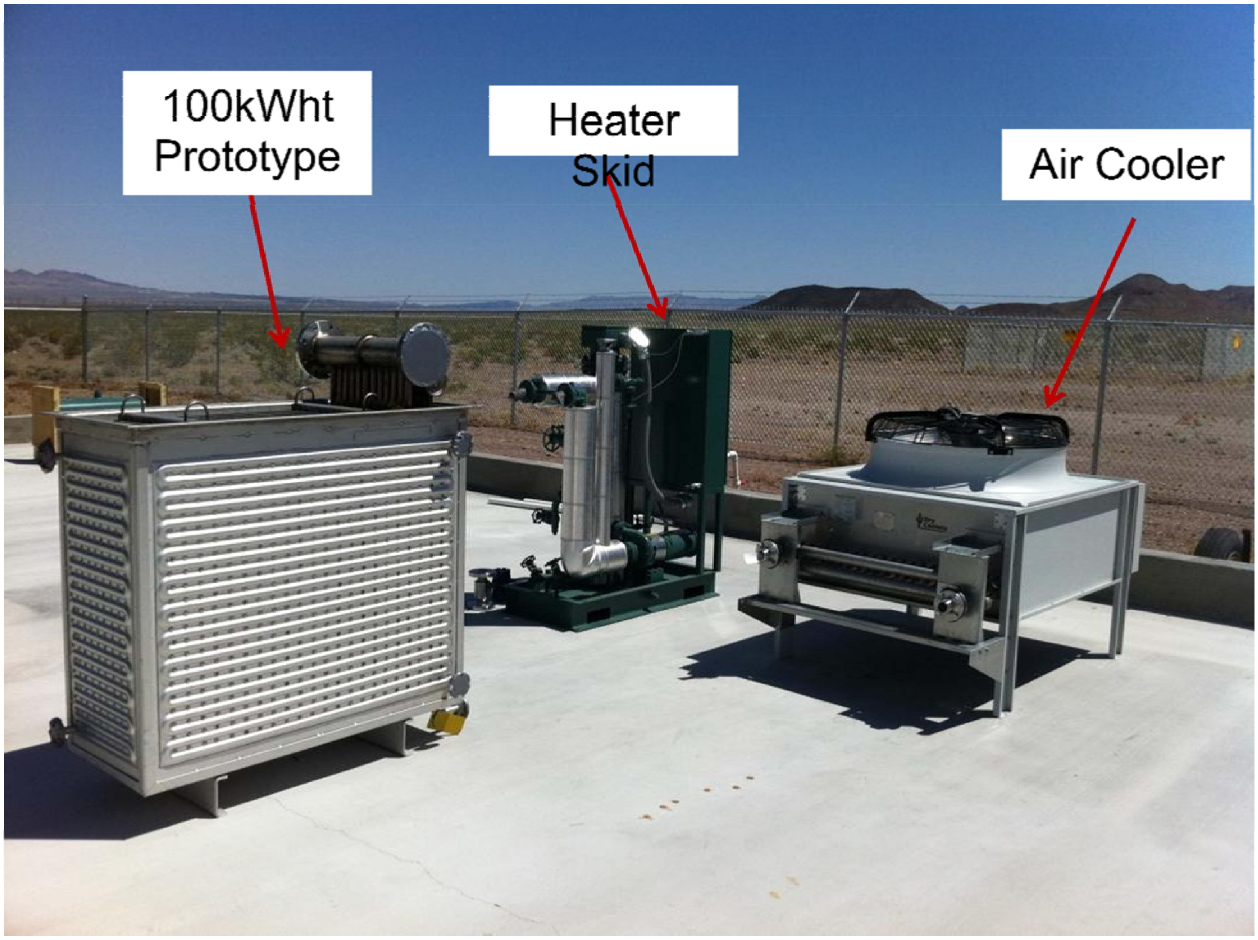


Figure 7 – Initial layout of the test loop equipment.

Figure 8 – Test loop equipment anchored with piping, valves, and instrument wells installed.

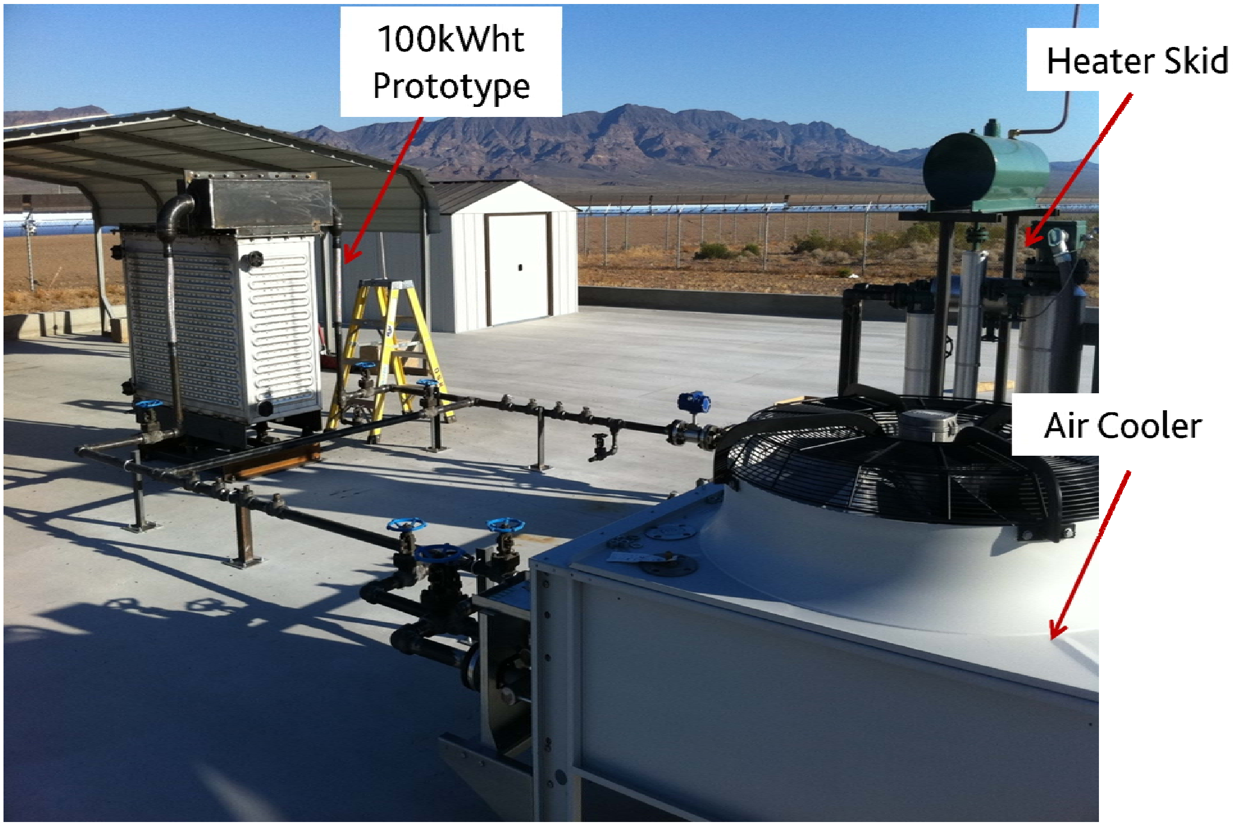


Figure 9 – Test loop equipment anchored with piping, valves, and instrument wells installed.

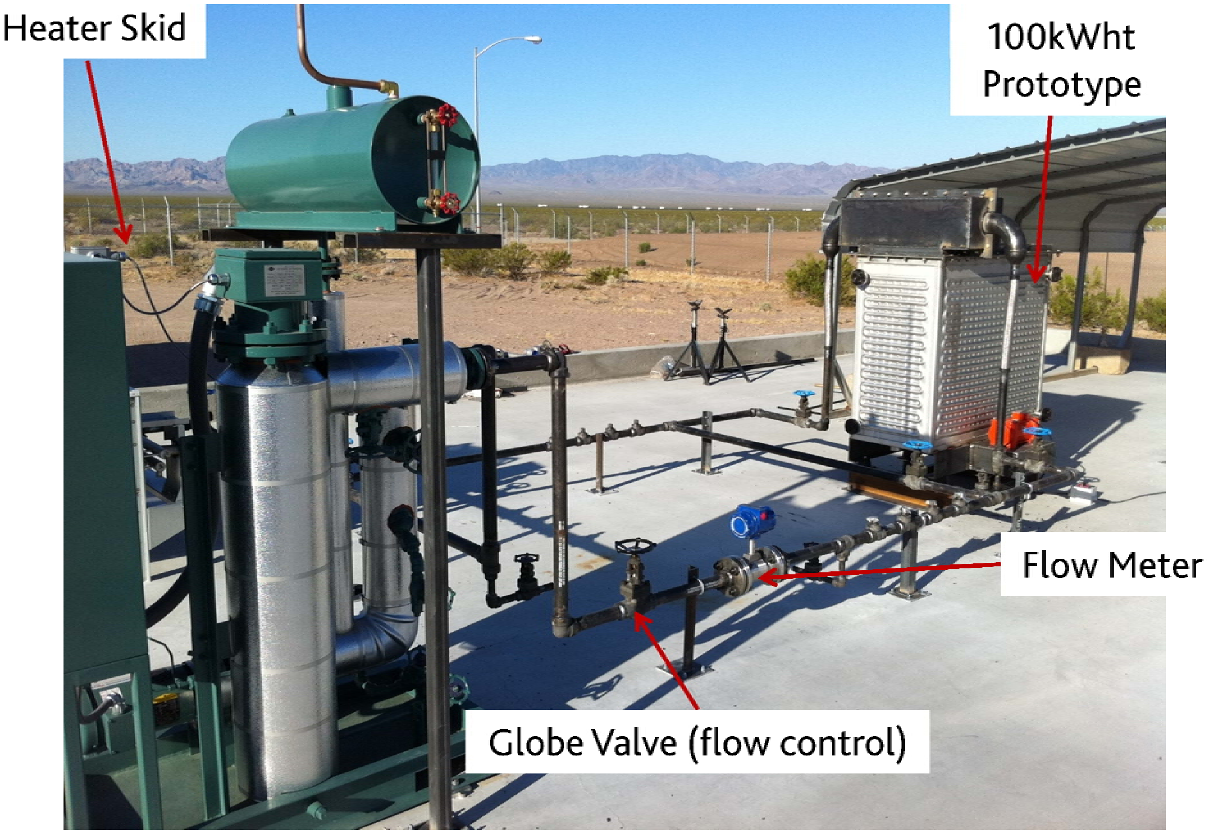


Figure 10 – Test loop equipment anchored with piping, valves, and instrument wells installed.

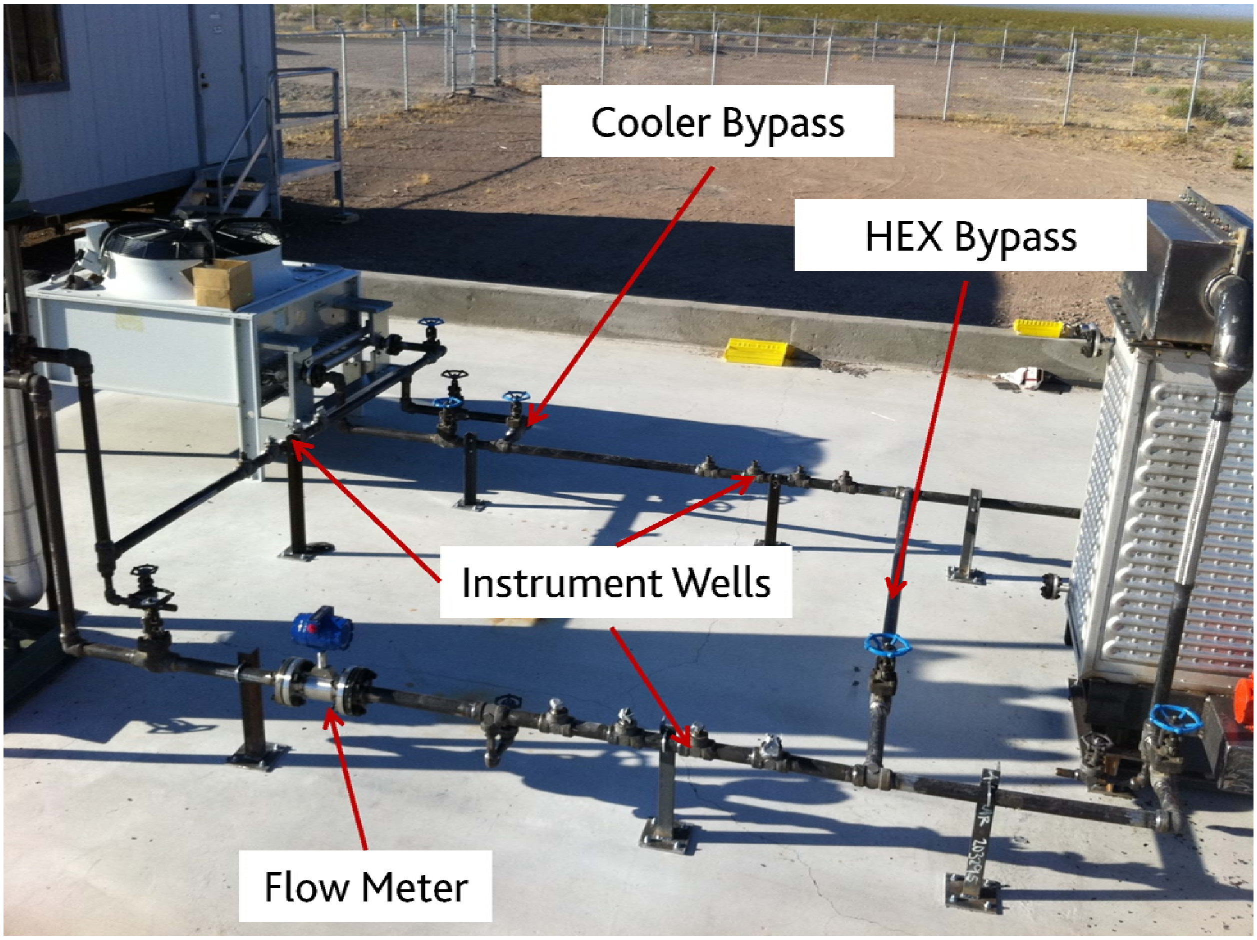


Figure 11 – Test loop equipment anchored with piping, valves, and instrument wells installed.

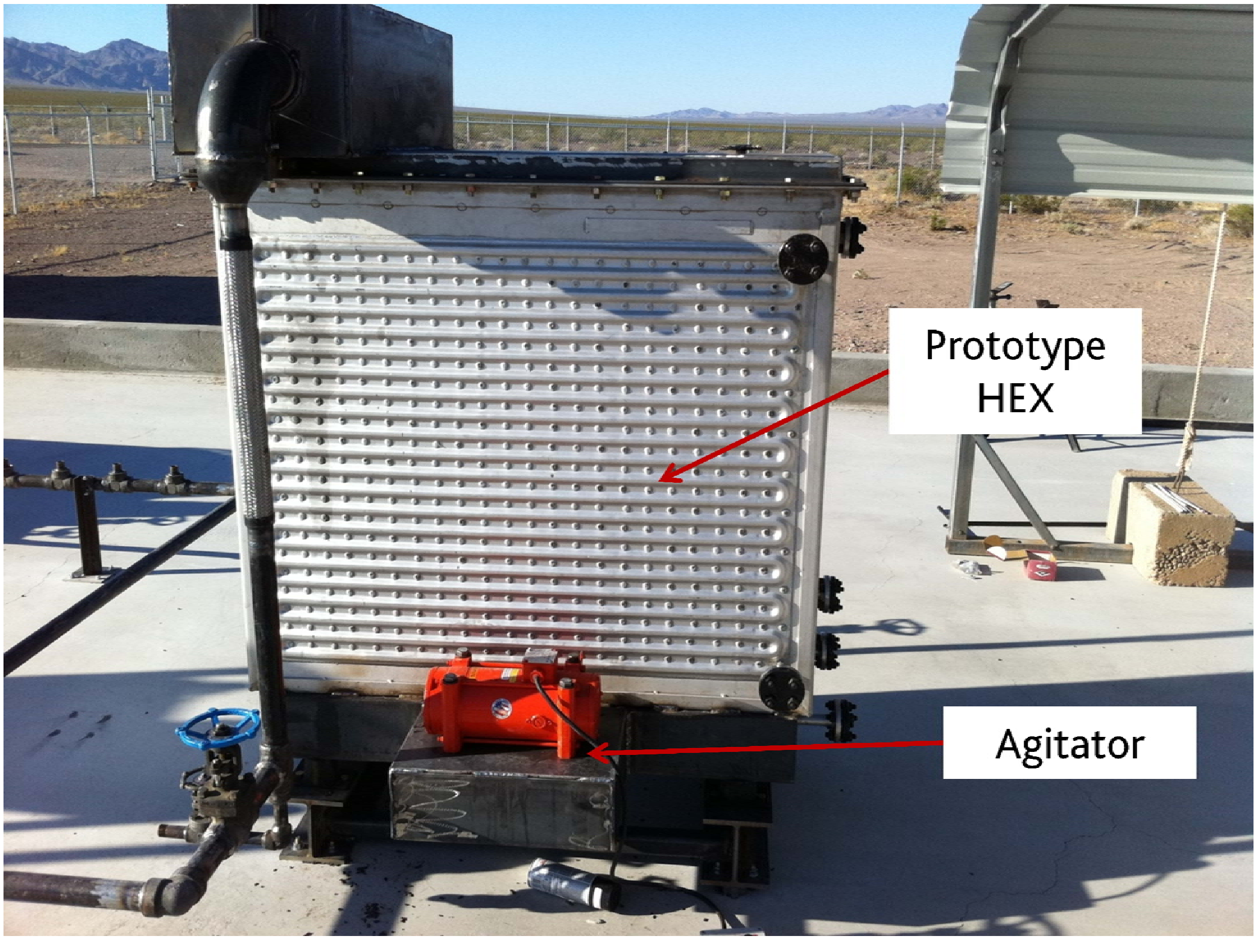


Figure 12 – Test loop equipment anchored with piping, valves, and instrument wells installed.

The instrumentation and data acquisition system purchased for the test loop is shown in Figures 13 through 15.

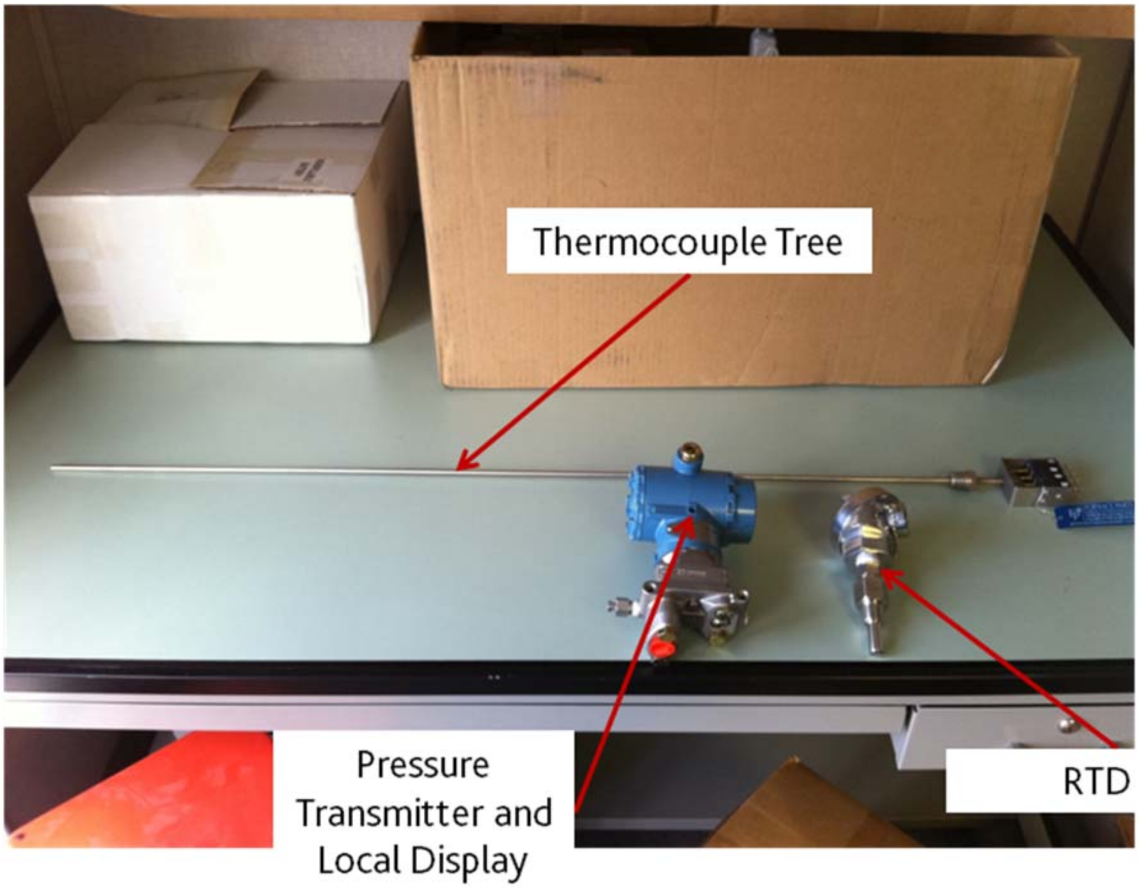


Figure 13 – Test loop instrumentation.

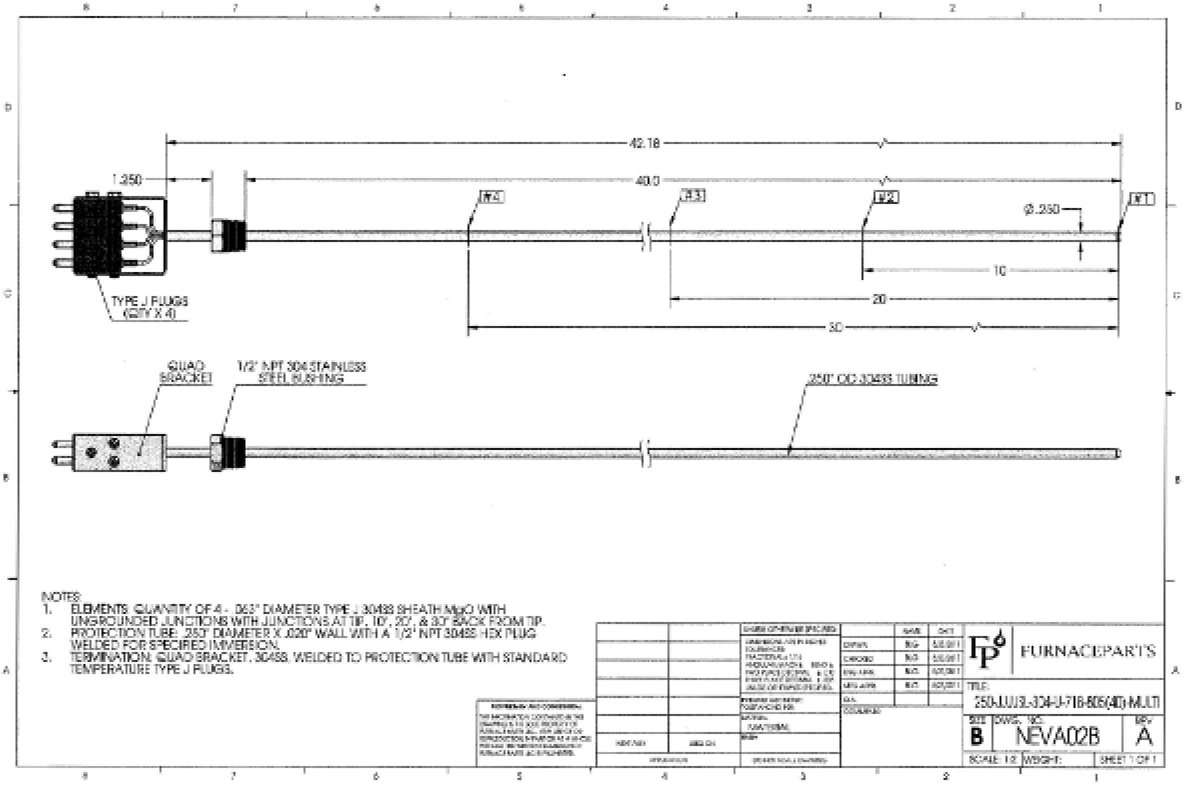


Figure 14 – Manufacturer drawing of the multi-measurement thermocouples.

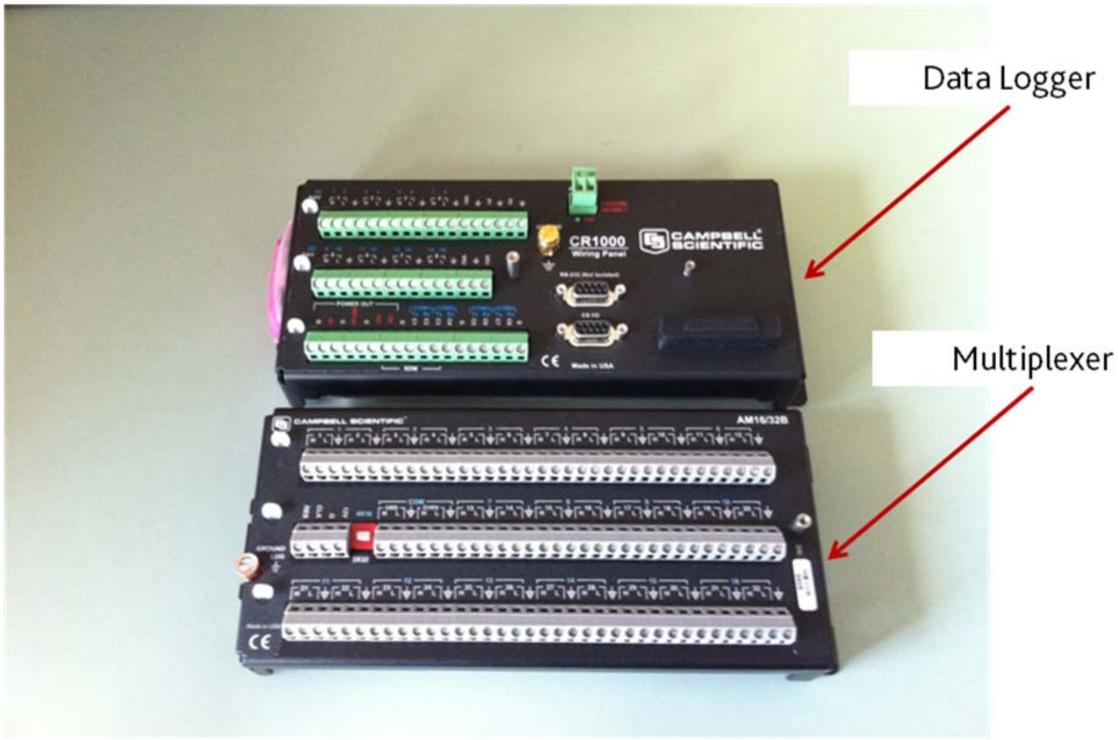


Figure 15 – Campbell Scientific CR1000 Data Logger and AM16/32B Multiplexer.

After the main equipment and piping were installed, instrumentation and insulation were installed. Figures 16 through 22 show the loop progress.

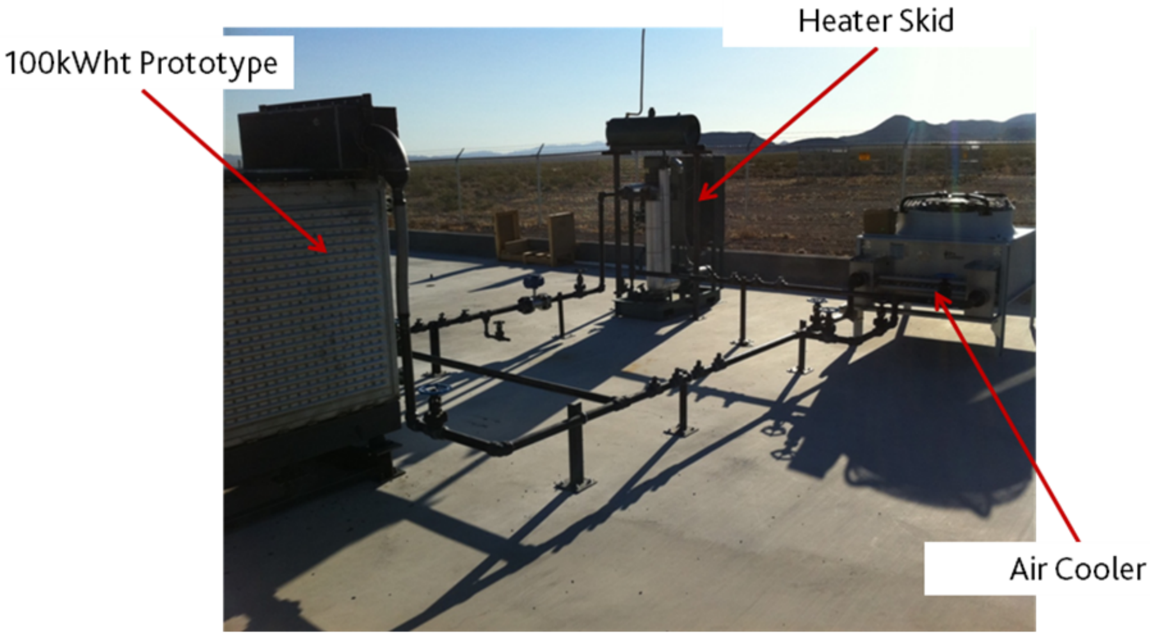


Figure 16 – The test loop before instrumentation and insulation.

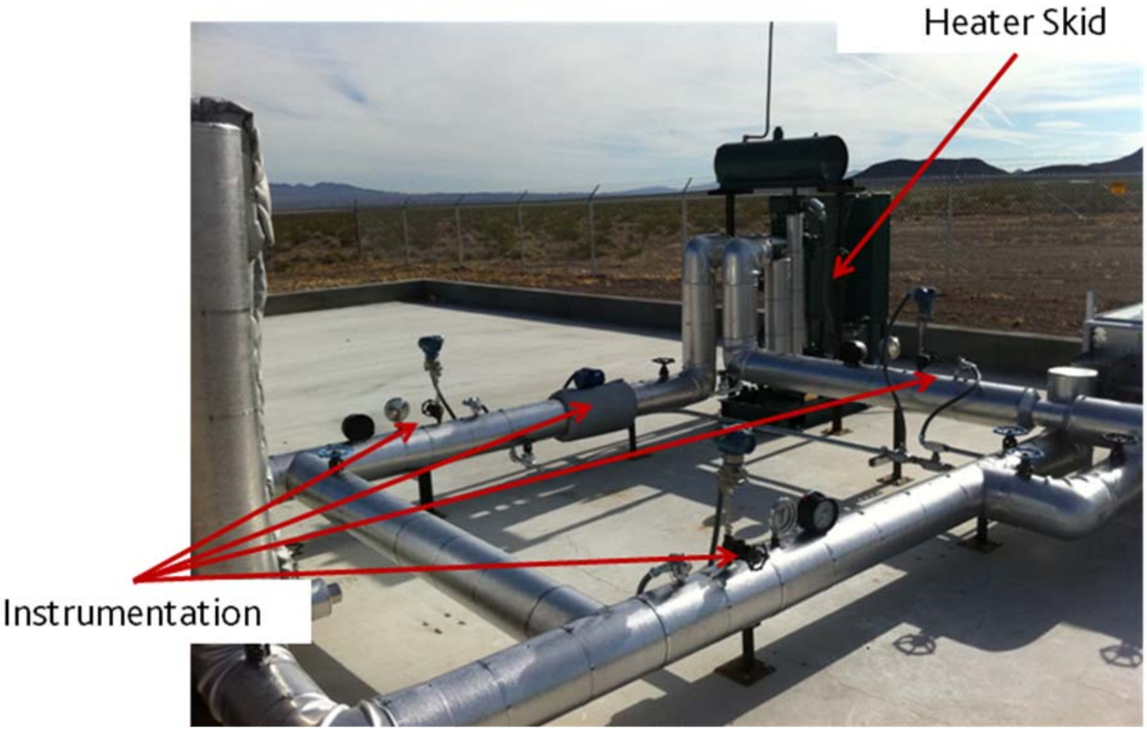


Figure 17 – The test loop after instrumentation and insulation.

Figure 18 – Another angle of the test loop before instrumentation and insulation.

Figure 19 – Second angle of the test loop after instrumentation and insulation.

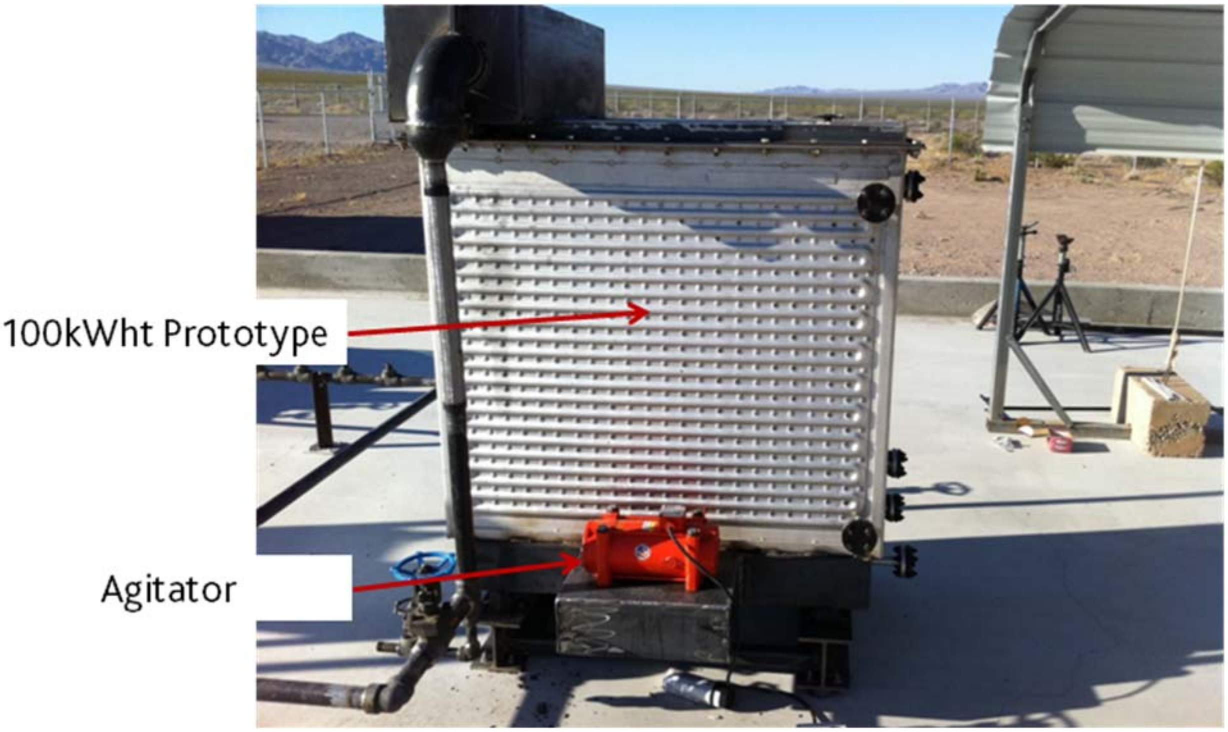


Figure 20 – The prototype heat exchanger before instrumentation and insulation.

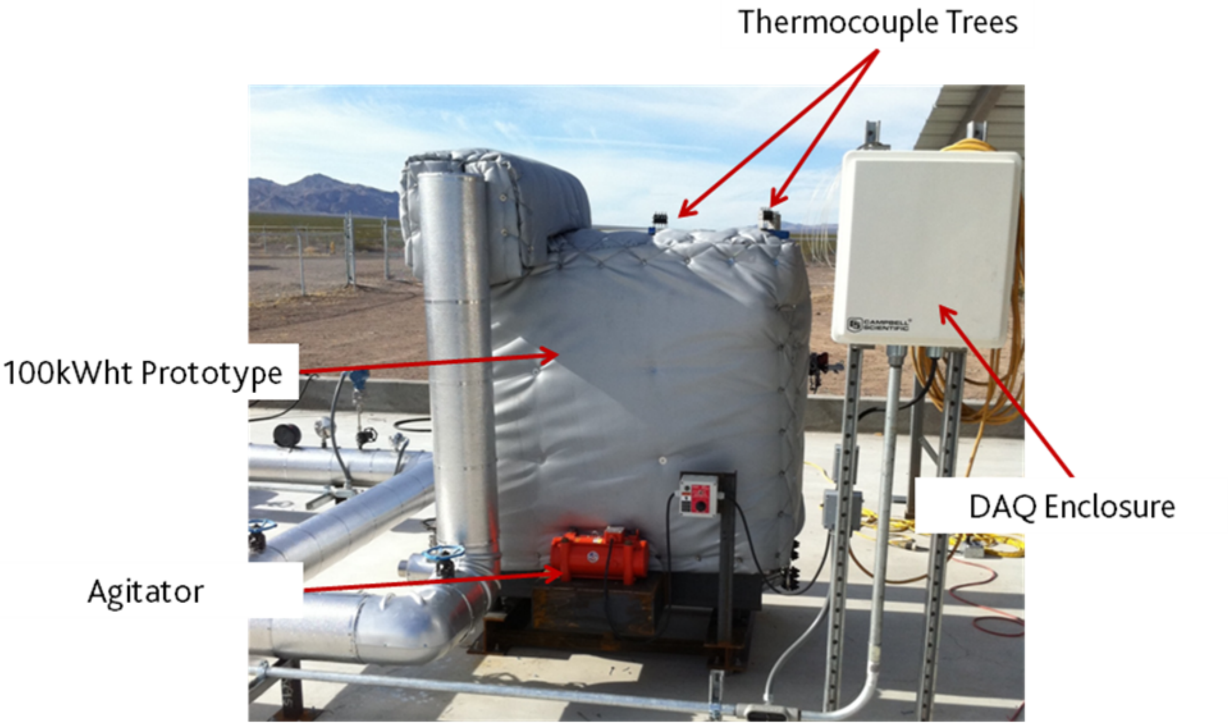


Figure 21 – The prototype heat exchanger after instrumentation and insulation.

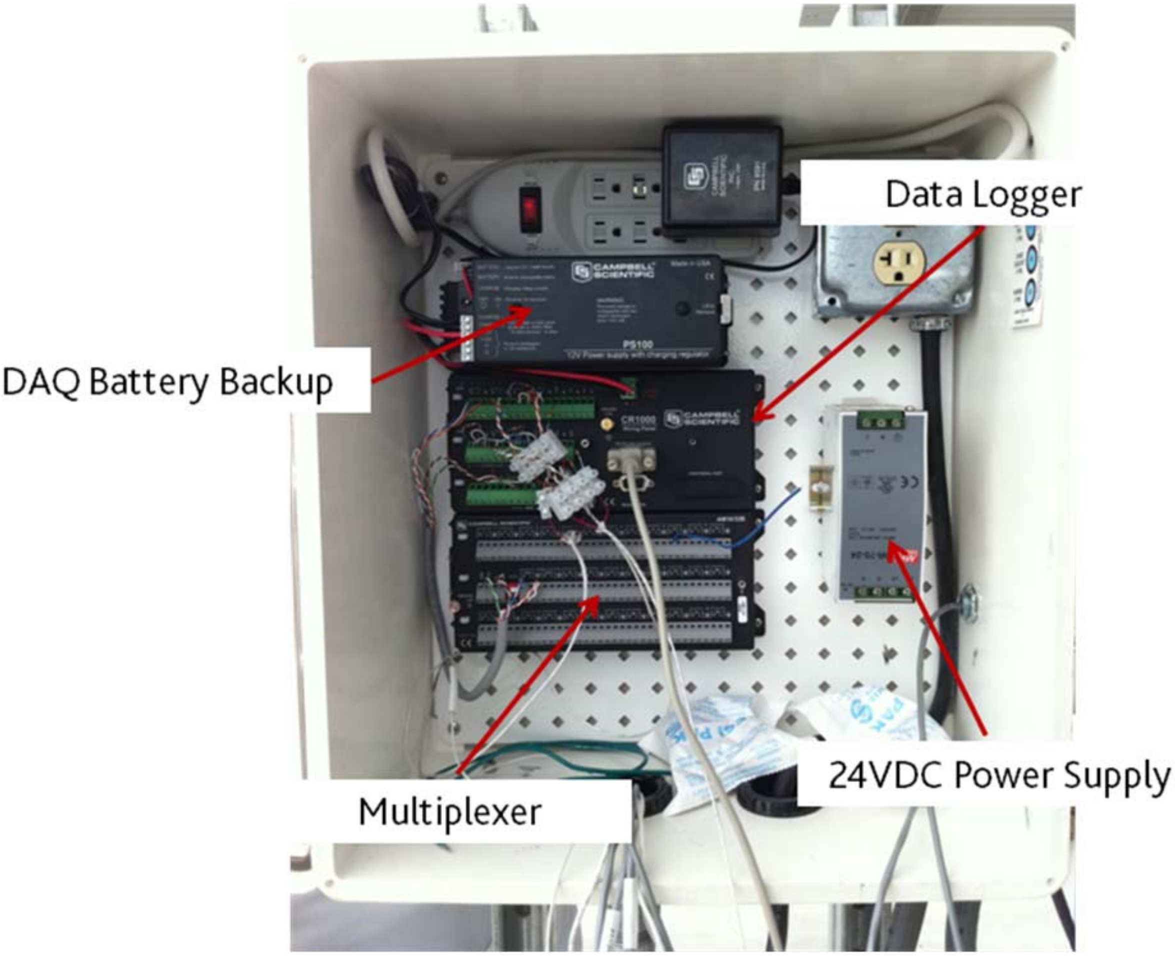


Figure 22 – The data acquisition system mounted in the enclosure.

With the installation of the instrumentation and insulation complete, oiling in the test loop and salting in the heat exchanger could begin. The first issue encountered involved clumping of the lithium nitrate. Discussions with the manufacturer revealed that this is a common issue due to the tendency of the product to absorb moisture in the air. The manufacturer suggested a couple of techniques to break up the clumps including striking the packaging with a mallet. These techniques proved to work very well and reduced the time require to add one drum from two hours to 30 minutes.

The next issue encountered involved moisture in the test loop HTF system. How the moisture ended up in the system is not clear but it is believed to have resulted from the prototype heat exchanger manufacturer using water to hydrostatically test the unit before shipping it. Regardless, the moisture in the system proved very difficult to remove. A couple of modifications were performed to the loop in an effort to reduce the volume of water and speed up boiling off any remaining in the loop. The loop was drained and force evacuated and new fluid was purchased. The expansion vessel was raised 12 inches and two high point vents were installed on the heat exchanger. Both sets of modifications are shown in Figure 23 though 26.

Figure 23 – Expansion vessel elevation before test loop modifications.

Figure 24 – Expansion vessel elevation after test loop modifications.

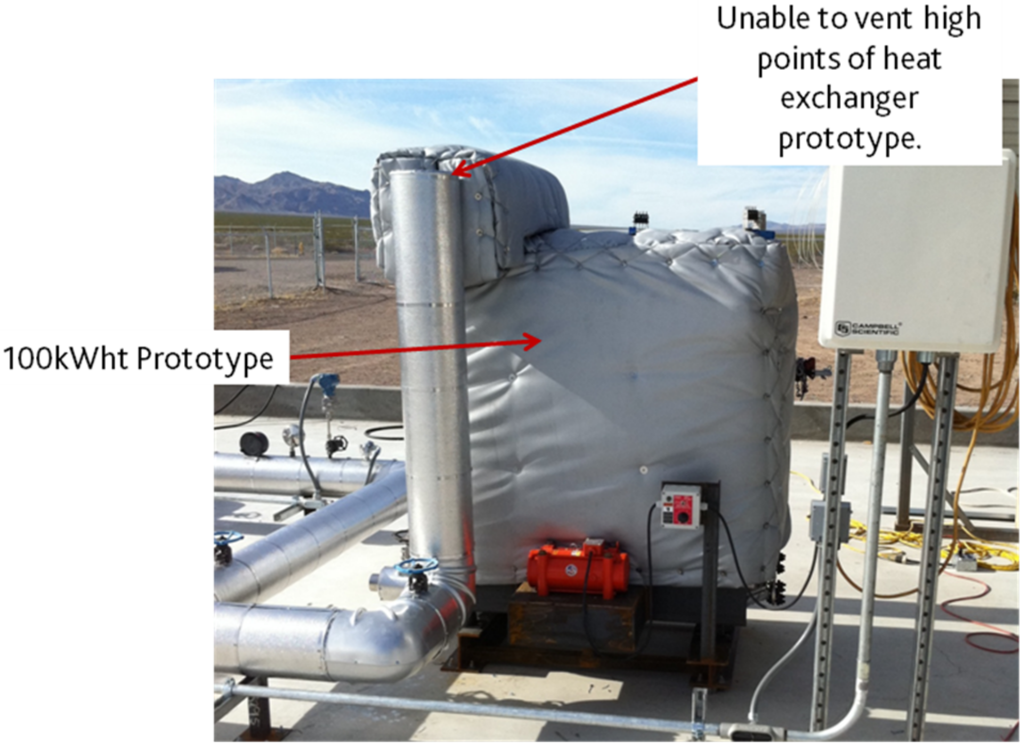


Figure 25 – Prototype heat exchanger before test loop modifications.

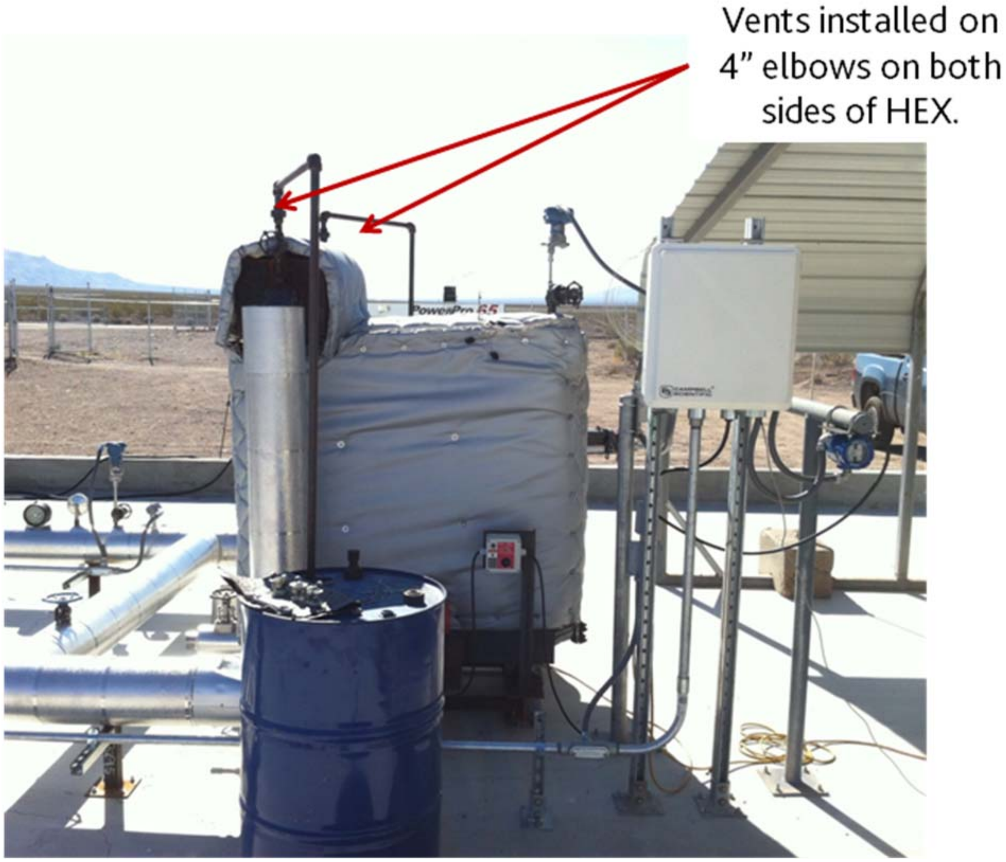


Figure 26 – Prototype heat exchanger after test loop modifications.

These physical modifications along with new HTF greatly increased the ability to boil off moisture in the system. Commissioning resumed followed by a complete melt of the initial salt inventory in the heat exchanger. This process was repeated two more times until the quantity of salt required for 100kWh$_t$ was present.

Prototype performance was tested by first making a baseline measurement. For the baseline test, the temperature of the test loop and prototype were raised uniformly until the salt had completely melted, reaching a temperature over 489° F. The heater was then turned off and HTF flow was diverted to the air cooler to remove heat from the system until the inlet to the cooler reached 462 °F. A cutoff temperature value is important because although energy could continue to be extracted from the prototype, the energy would be of little value due to its low temperature.

After the baseline measurement test was complete, an agitated performance test was conducted. The agitation test was performed using the same methodology as the baseline, with the addition of activating the heat exchanger agitator during the heat extraction phase (discharge). A summary of the results is shown below:

Table 1 – Test Results

Type of Test	**Baseline**	**Agitation**
Date of Test	12/2/2011	12/8/2011
HTF Outlet Start Temperature (°F)	493.7	490.8
HTF Outlet Temp at Finish (°F)	462.5	462.3
Duration of Test (min)	24	24.5
Total Energy Transferred (kWh_t)	33.5	36.5
Energy used for Agitation (kWh)	0	0.25
Average Heat Rate Salt to HTF (kW_t)	83.6	89.1

Agitation increased the heat rate from salt to HTF during the discharge phase from 83.6 kW_t to 89.1 kW_t. The total amount of energy extracted was 36.5 kWh_t, which is below the 100 kWh_t goal. This is likely due to uncertainty of thermal properties for the molten salt. The main focus of the test was to gather information regarding any performance gains due to agitation. As noted in the data above, agitation increased the total energy released by 9%. Data recorded during both tests are shown in Figures 27 and 28.

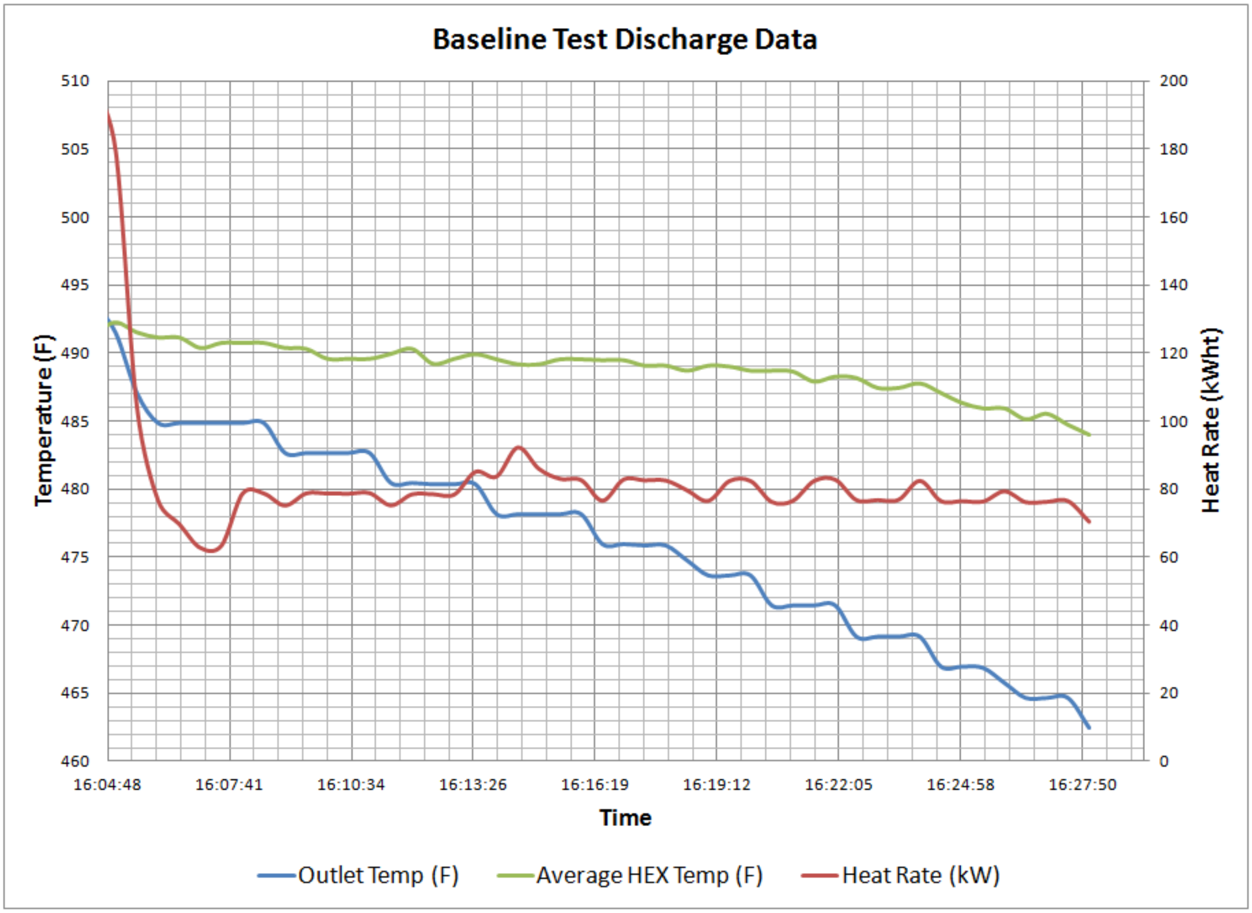


Figure 27 – Baseline performance test data.

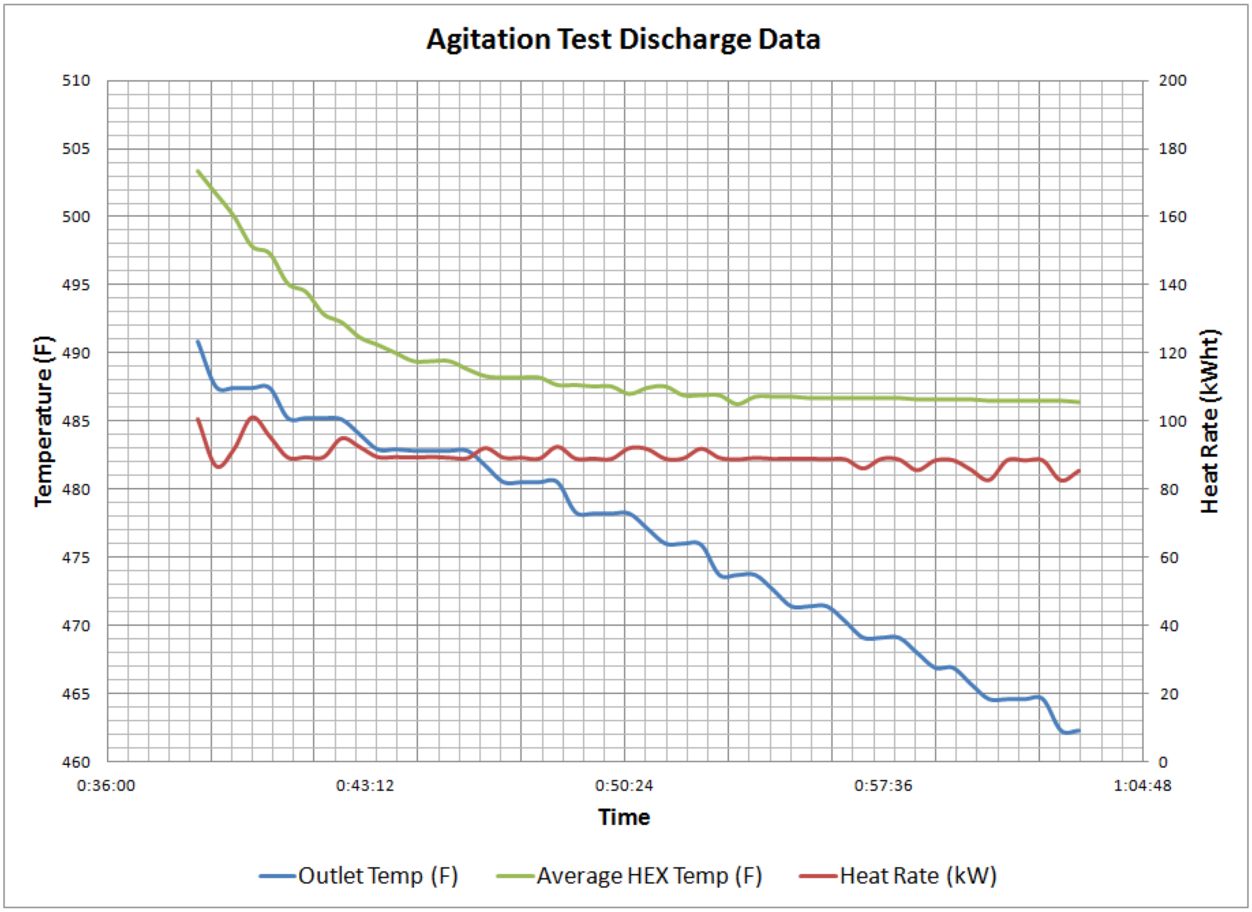


Figure 28 – Agitation performance test data.

Task 1.2 Salt selection and vibration system design

Four salt mixtures, Sodium Nitrate ($NaNO_3$), Potassium Nitrate (KNO_3), Potassium Hydroxide (KOH) and Lithium Nitrate ($LiNO_3$) were reviewed for their potential use in this project. All of these mixtures are readily available with the former three currently in use in the solar industry. Table 2 below highlights properties of these four salt mixtures.

Table 2 – Candidate Salt Properties.

Salt Type -	Melting Temp. °C	Density (at 20°C) kg/m^3	Specific Heat kJ/kg-K	Latent Heat kJ/kg	Cost $/kg
$NaNO_3$	306	2261	1.100	172	9.07
KNO_3	335	2109	0.953	95	11.77
KOH	360	2040	1.340	134	8.52
$LiNO_3$	254	2380	1.631	370	16.75

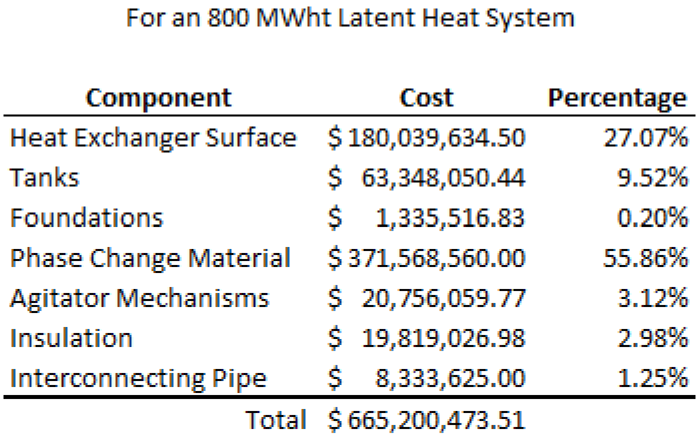
Of the four candidate salts $LiNO_3$was selected for testing with the 100kWh$_t$ prototype for several reasons highlighted in a detailed report submitted to DOE and attached in Appendix D.

Part of the technology theorized for this project was the inclusion of a mechanism to enhance heat transfer of the heat exchanger during storage system discharge. One issue that arises during the extraction of latent heat from a PCM is that the material begins to solidify on the heat exchange surface as it cools. Development of a solidified crust on the heat transfer surface has a direct impact on heat exchanger performance. By mechanically removing any solidified salt, it is theorized that an increase in heat exchanger efficiency can be achieved.

Two concepts were identified in research: mechanical agitation, and mechanical scraping. These two techniques were performed in a laboratory with the results being scalable to the 100kWh$_t$ prototype. The laboratory testing setup description as well as the methodology of determining agitation was the best choice were described in a detailed report submitted to DOE and attached in Appendix D.

Task 1.3 Final PCM TES System Basic Design

Utilizing the performance and cost data from the 100kWh$_t$ prototype, system performance and cost for a larger system on the order of 800MWh$_t$ could be extrapolated. The estimated cost of such a system is shown below:



For an 800 MWht Latent Heat System

Component	Cost	Percentage
Heat Exchanger Surface	$ 180,039,634.50	27.07%
Tanks	$ 63,348,050.44	9.52%
Foundations	$ 1,335,516.83	0.20%
Phase Change Material	$ 371,568,560.00	55.86%
Agitator Mechanisms	$ 20,756,059.77	3.12%
Insulation	$ 19,819,026.98	2.98%
Interconnecting Pipe	$ 8,333,625.00	1.25%
Total	$ 665,200,473.51	

The end result is a system cost of $831.5/kWh$_t$. It is believed that several measures could be taken to reduce this cost:

- Use a lower cost salt, $LiNO_3$ is one of the most expensive salts available ($7.60 per lb).
- Optimize heat exchanger design to reduce required surface area and increase heat transfer coefficient
- Increase the heat exchanger size to reduce the number of tanks required

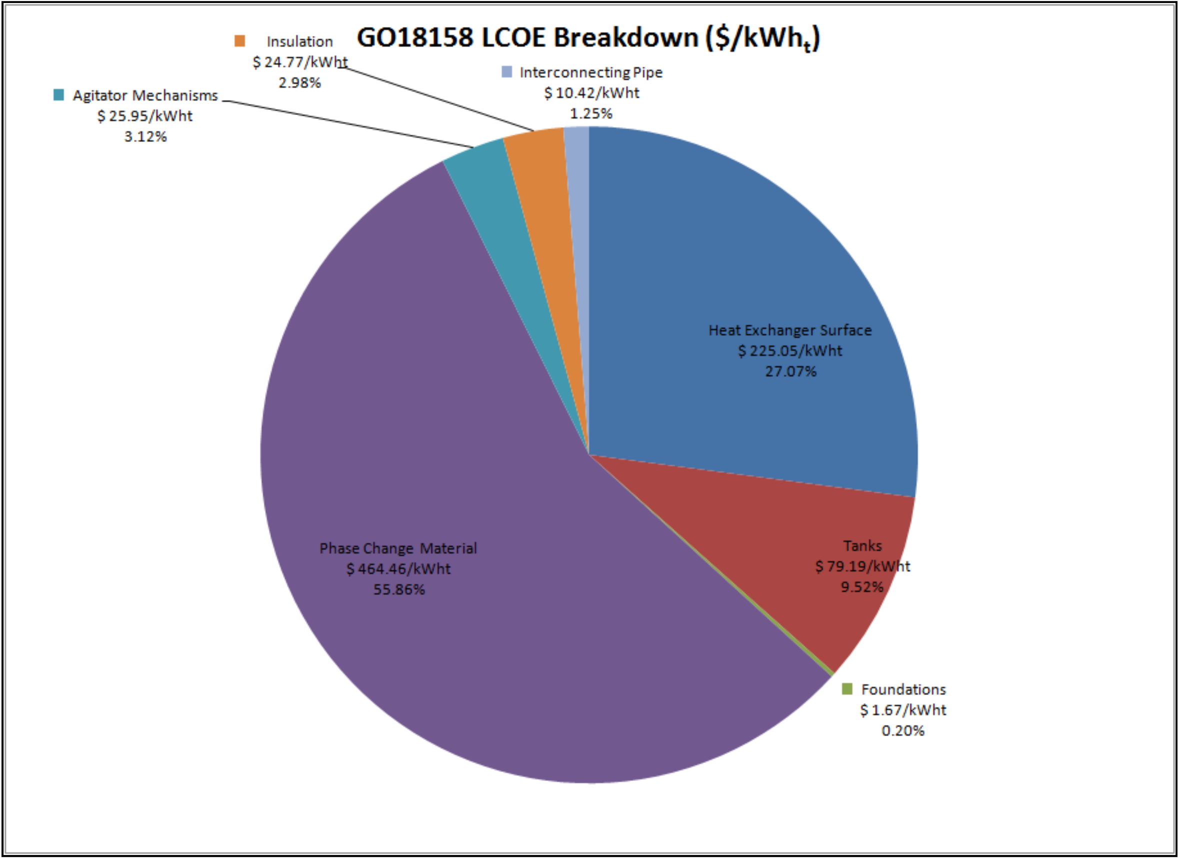


Figure 29 – Cost breakdown of 800MWh$_t$ system.

Next Steps

Based on the performance of the 100kWh$_t$ prototype and the estimated full system costs, this technology is not feasible. Research should not continue.

Patents

No patent applications filed.

Government Property

No government owned property resulted from Phase I of this contract.

Publications

The following was submitted to and accepted by the American Society of Mechanical Engineers (ASME) for conference presentation and publication as part of the conference proceedings:

Title: DESIGN OF A MODULAR LATENT HEAT STORAGE SYSTEM FOR SOLAR THERMAL POWER PLANTS

Publication Location: Proceedings of the 5th Energy Sustainability Conference

Date: August 7-10, 2011, Washington, Washington D.C., USA

Paper Number: ESFuelCell2011-54426

Presentations during Phase I

Date & Location	**Presentation**	**Presenter**	**Purpose**
9/9/2009, Boulder City, NV	Kick-off Meeting	Newmarker	Initial kickoff meeting
2/9/2010, Albuquerque, NM	DOE CSP Program Review	Newmarker	Annual review meeting with DOE/NREL/SNL
5/26/2010, Washington, D.C.	Solar Energy Technologies Program Peer Review	Newmarker	DOE peer review meeting.
5/18/2011, Denver, CO	DOE CSP Program Review	Newmarker	Annual review meeting with DOE/NREL/SNL

Travel during Phase I

Date & Destination	Purpose	**P**articipant
9/9/2009, Boulder City, NV	Kick-off Meeting	George, Chris
11/9/2009, Boulder City, NV	TRNSYS Training	George, Chris
2/9/2010, Albuquerque, NM	DOE CSP Program Review	Newmarker, Marc Campbell, Mark
5/26/2010, Washington, D.C.	Solar Energy Technologies Program Peer Review	Newmarker, Marc
5/18/2011, Denver, CO	DOE CSP Program Review	Newmarker, Marc Campbell, Mark

Major Task Schedule – Phase I

Task #	Task Description	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	% Complete	
1.0	Heat transfer model and fluid dynamic analysis	2/1/2010	5/31/2011	5/31/2011	100%	Basic analysis complete.
1.1	PCM TES module design and the 100kWh lab unit fabrication	5/1/2010	3/31/2011	3/31/2011	100%	Unit Fabrication Complete
1.2	Salt selection and vibration system design	8/1/2010	3/31/2011	3/31/2011	100%	Agitator received
1.3	Final PCM TES System Basic Design	11/1/2010	12/31/2011	12/9/2011	100%	
1.4	Project Management and Reporting	-	-	-	100%	
1.4.1	The heat transfer model confirms that the system can store and discharge the necessary amount of heat with a size not to exceed the size of a 2 tank molten salt storage system when compared using a volume of storage material divided by MWe output.	9/1/2010	12/31/2011	12/9/2011	100%	
1.4.2	The lab scale prototype should function to at least the level predicted in the models, with a minimum goal of 93% round trip efficiency for heat storage and removal.	9/1/2010	12/31/2011	12/9/2011	100%	
1.4.3	Material performance and cost will be evaluated to determine if this design is feasible on a large scale.	9/1/2010	12/31/2011	12/9/2011	100%	Cost analysis shows this type of system is not feasible on a large scale.
1.4.4	NREL Solar Advisor Model (SAM) analysis will be performed to verify cost reduction.	9/1/2010	12/31/2011	12/9/2011	100%	Overall plant cost reduction cannot be realized using this technology.

Final Spending Summary – Phase I

Calendar Quarter	Year	From	To	Federal Share	Cumulative Federal Share	Recipient Share	Cumulative Recipient Share
Q3	2009	7/1/2009	9/30/2009	$12,329.63	$12,329.63	$3,083.07	$3,083.07
Q4	2009	10/1/2009	12/31/2009	$3,134.03	$15,463.66	$783.68	$3,866.75
Q1	2010	1/1/2010	3/31/2010	$4,319.29	$19,782.95	$1,080.06	$4,946.81
Q2	2010	4/1/2010	6/30/2010	$10,671.55	$30,454.50	$2,668.46	$7,615.27
Q3	2010	7/1/2010	9/30/2010	$32,048.73	$62,503.23	$8,013.91	$15,629.18
Q4	2010	10/1/2010	12/31/2010	$21,553.53	$84,056.76	$5,389.55	$21,018.73
Q1	2011	1/1/2011	3/31/2011	$36,521.69	$120,578.45	$9,132.39	$30,151.12
Q2	2011	4/1/2011	6/30/2011	$24,135.37	$144,713.82	$6,035.15	$36,186.27
Q3	2011	7/1/2011	9/30/2011	$70,336.19	$215,050.01	$17,587.85	$53,774.12
Q4	2011	10/1/2011	12/31/2011	$7,834.43	$222,884.44	$1,959.03	$55,733.15
Totals					**$222,884.44**		**$55,733.15**

Final Spending Summary SF424

Recipient:	Acciona Solar Power, Inc.
DOE Award #:	DE-FG36-08GO18158

Spending Summary for SF 424A Budget Forms

Object Class Categories	**Approved Phase 1 Budget**	**Project Expenditures**	
Per SF 424a		**This Quarter**	**Cumulative to Date**
a. Personnel	$371,195	$4,293	$72,236
b. Fringe Benefits	$92,799	$1,073	$18,059
c. Travel	$3,000	$0	$1,209
d. Equipment	$125,000	$1,855	$49,901
e. Supplies	$1,883	$2,572	$49,492
f. Contractual	$6,851	$0	$74,535
g. Construction	$24,300	$0	$0
h. Other	$0	$0	$13,183
i. Total Direct Charges (sum of a to h)	$625,027	$9,793	$278,615
j. Indirect Charges			
k. Totals (sum of i and j)	$625,027	$9,793	$278,615
DOE Share	$500,000	$7,834	$222,882
Cost Share	$125,027	$1,959	$55,733
Calculated Cost Share Percentage	20.00%	20.00%	20.00%

Final Cost Share Contributions – Phase I

Funding Source	**Approved Cost Share**		**This Quarter**		**Cumulative to Date**	
	Cash	**In-Kind**	**Cash**	**In-Kind**	**Cash**	**In-Kind**
ACCIONA		$125,027	$1,959		$55,733	
Total		$125,027	$1,959		$55,733	
Cumulative Cost Share Contributions					$55,733	

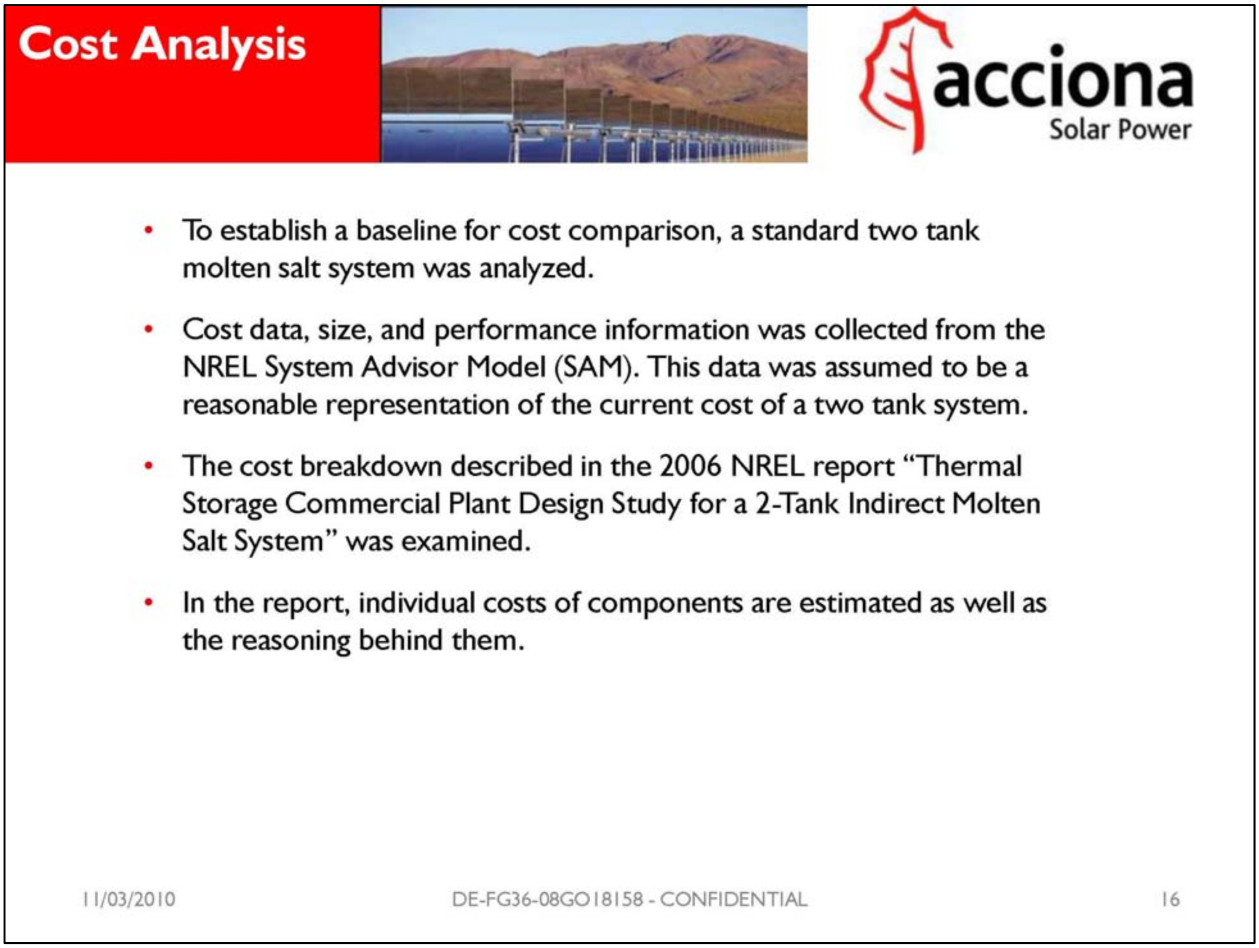
Appendix A

ACRONYMS

DOE	Department of Energy
HEX	Heat exchanger
HTF	Heat transfer fluid
kWh_t	Thermal kilowatt-hour
PCM	Phase Change Material
TES	Thermal energy storage
SAM	Solar Advisor Model

Appendix B

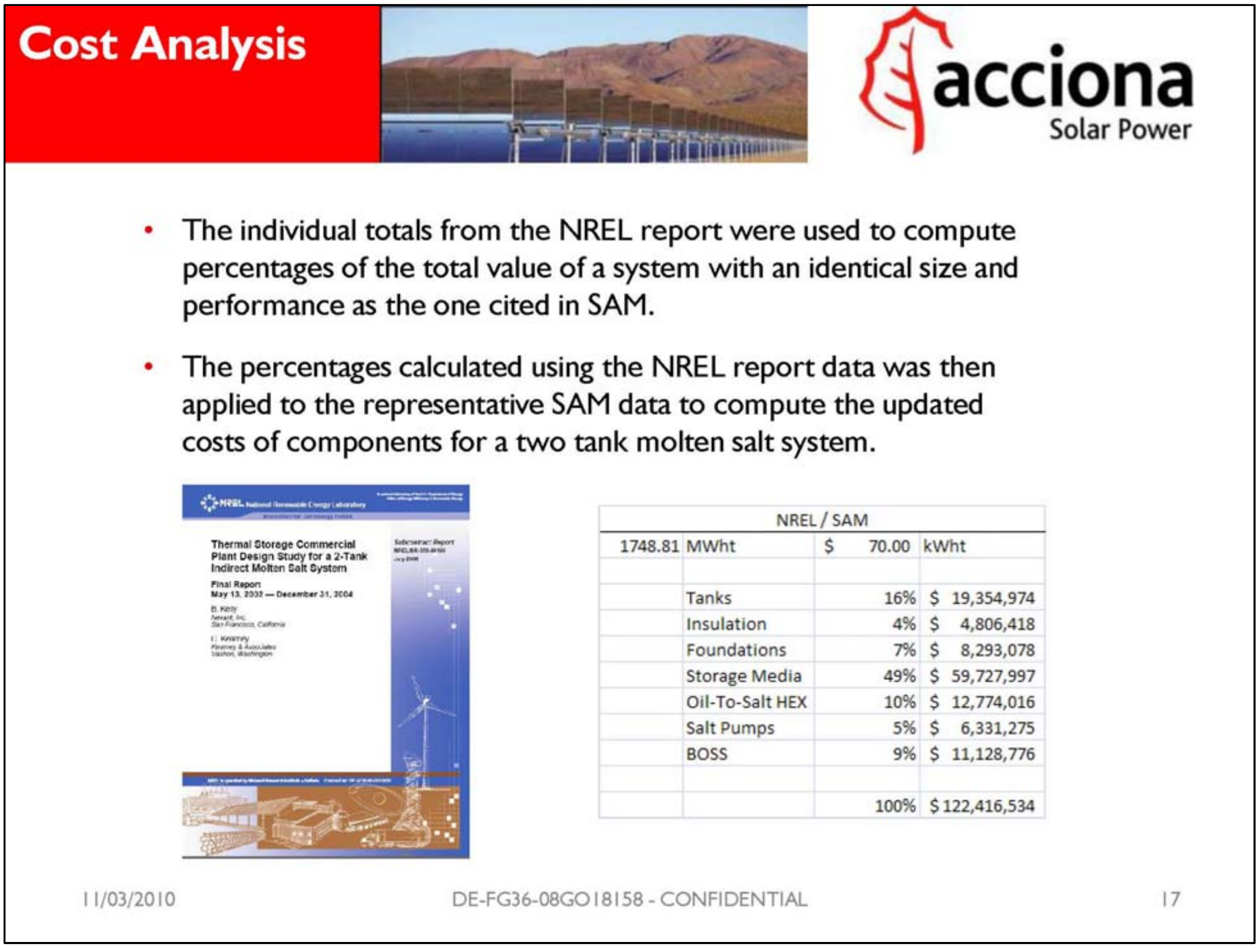
Molten Salt Two Tank System Cost Analysis



Cost Analysis

acciona
Solar Power

- To establish a baseline for cost comparison, a standard two tank molten salt system was analyzed.
- Cost data, size, and performance information was collected from the NREL System Advisor Model (SAM). This data was assumed to be a reasonable representation of the current cost of a two tank system.
- The cost breakdown described in the 2006 NREL report "Thermal Storage Commercial Plant Design Study for a 2-Tank Indirect Molten Salt System" was examined.
- In the report, individual costs of components are estimated as well as the reasoning behind them.



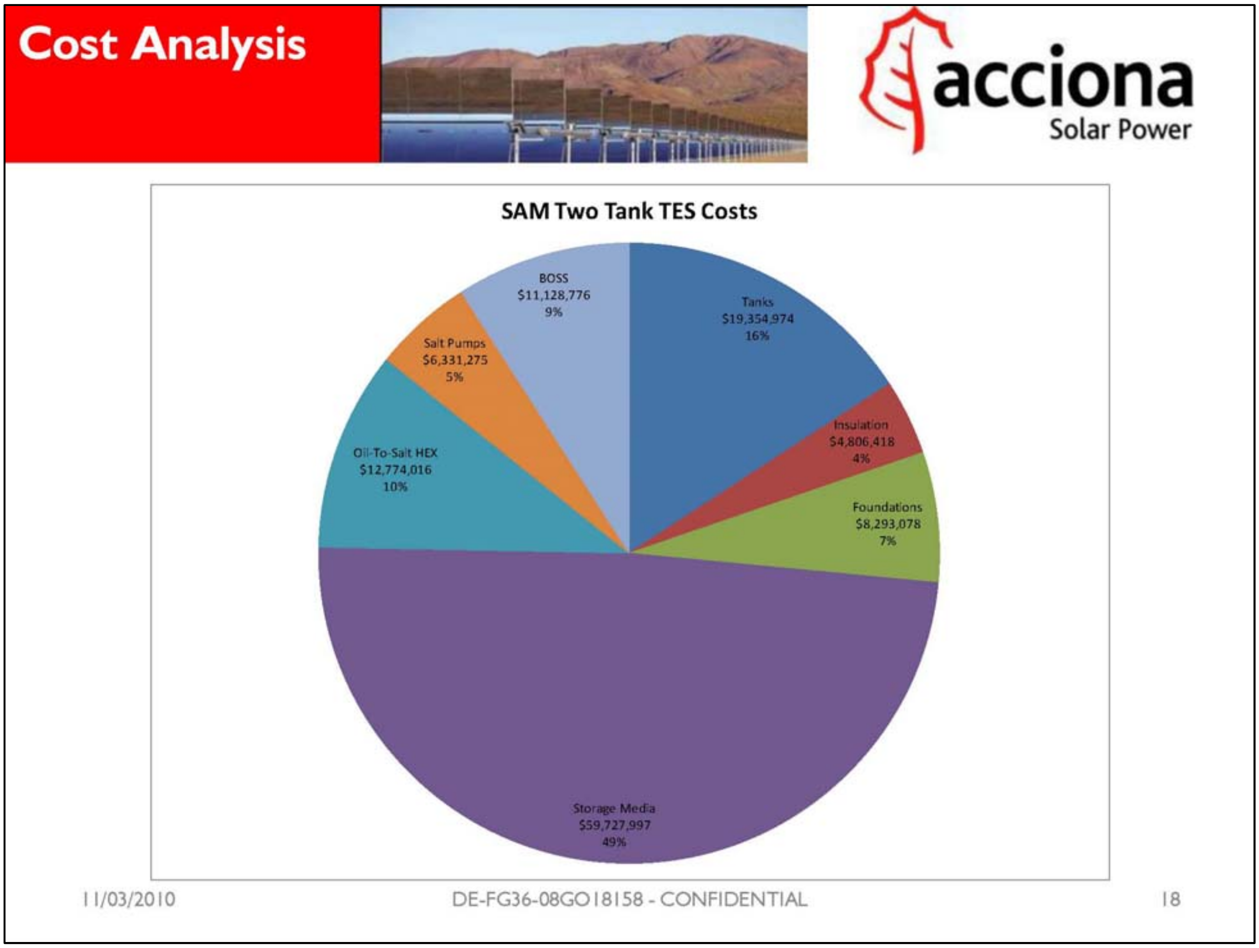
Cost Analysis

- The individual totals from the NREL report were used to compute percentages of the total value of a system with an identical size and performance as the one cited in SAM.
- The percentages calculated using the NREL report data was then applied to the representative SAM data to compute the updated costs of components for a two tank molten salt system.

Thermal Storage Commercial Plant Design Study for a 2-Tank Indirect Molten Salt System

Final Report
May 13, 2002 — December 31, 2004

NREL / SAM			
1748.81	MWht	$ 70.00	kWht
	Tanks	16%	$ 19,354,974
	Insulation	4%	$ 4,806,418
	Foundations	7%	$ 8,293,078
	Storage Media	49%	$ 59,727,997
	Oil-To-Salt HEX	10%	$ 12,774,016
	Salt Pumps	5%	$ 6,331,275
	BOSS	9%	$ 11,128,776
		100%	$ 122,416,534



Cost Analysis

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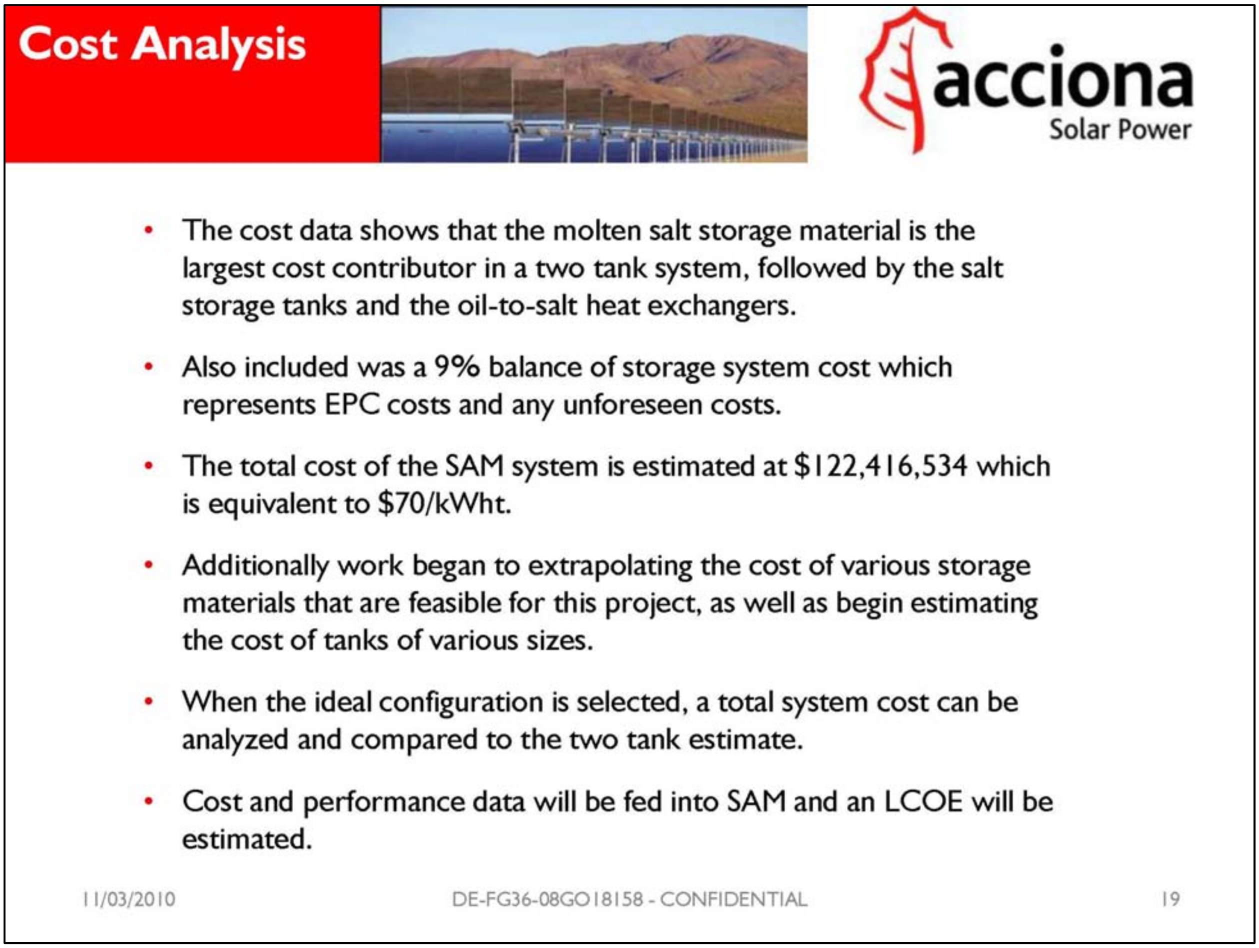

Cost Analysis

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- The cost data shows that the molten salt storage material is the largest cost contributor in a two tank system, followed by the salt storage tanks and the oil-to-salt heat exchangers.
- Also included was a 9% balance of storage system cost which represents EPC costs and any unforeseen costs.
- The total cost of the SAM system is estimated at $122,416,534 which is equivalent to $70/kWht.
- Additionally work began to extrapolating the cost of various storage materials that are feasible for this project, as well as begin estimating the cost of tanks of various sizes.
- When the ideal configuration is selected, a total system cost can be analyzed and compared to the two tank estimate.
- Cost and performance data will be fed into SAM and an LCOE will be estimated.

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Appendix C

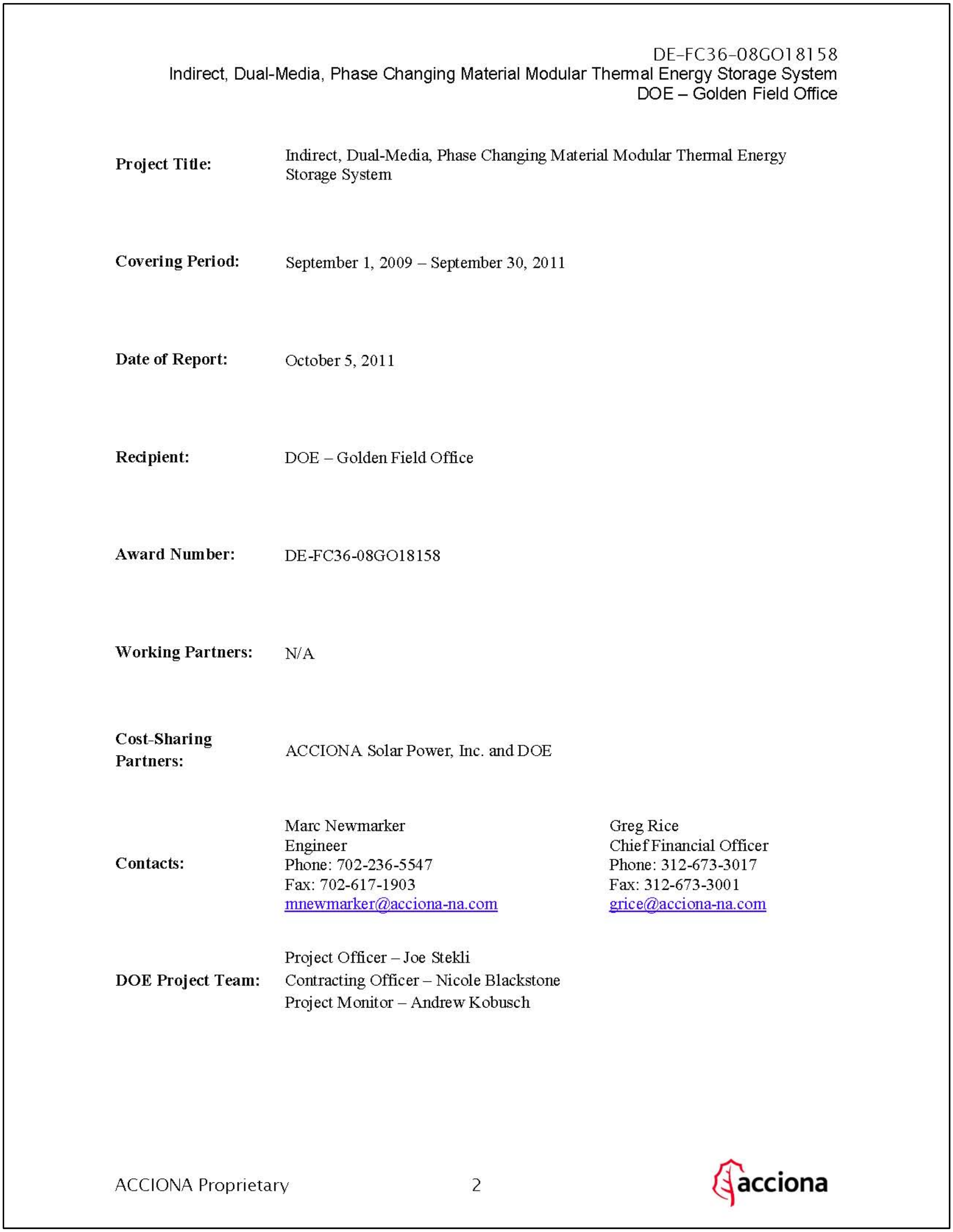
Modeling Report

Modeling Summary Report

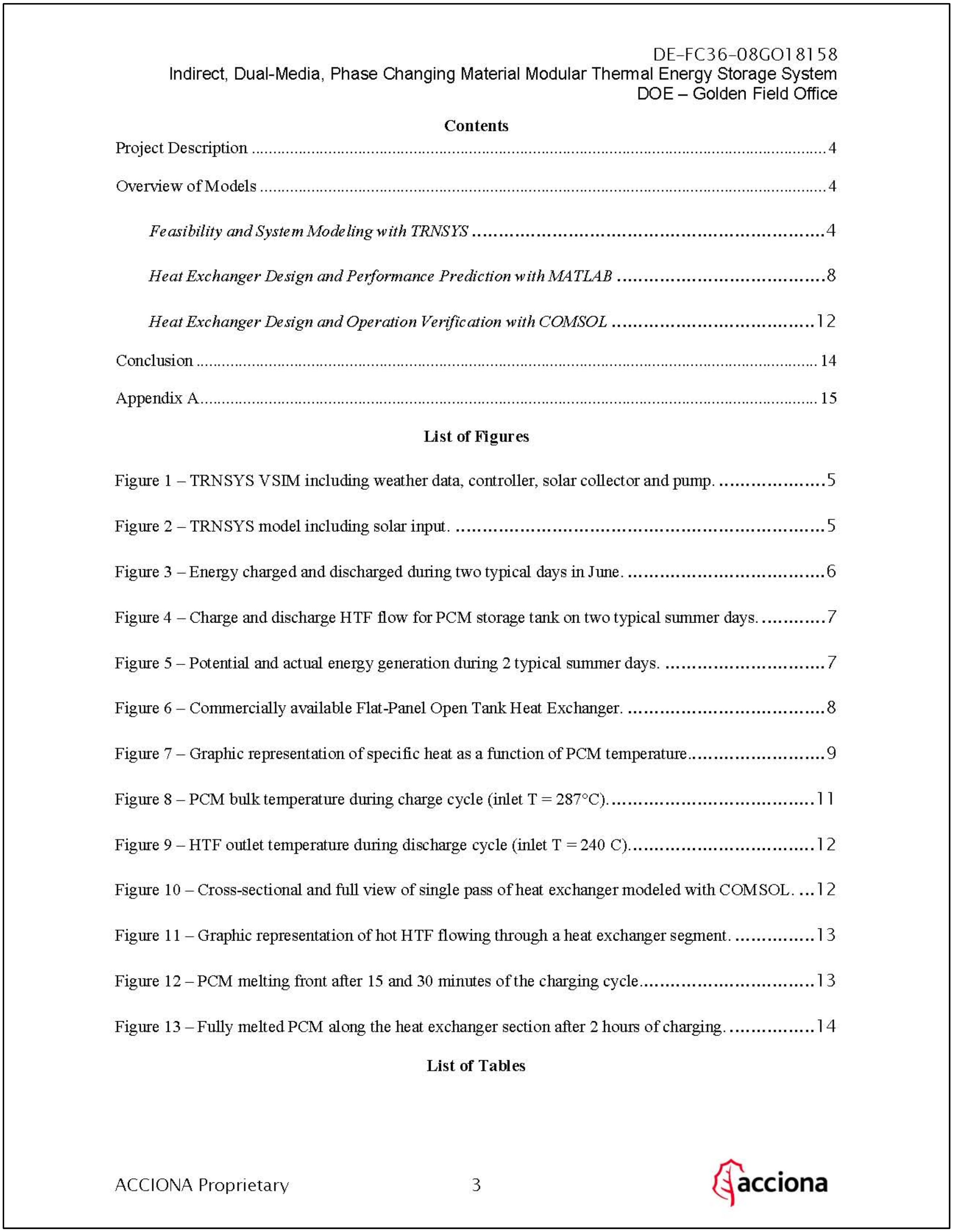
Issued: October 5, 2011

Indirect, Dual-Media, Phase Changing Material Modular Thermal Energy Storage System

ACCIONA Proprietary



Project Title:	Indirect, Dual-Media, Phase Changing Material Modular Thermal Energy Storage System	
Covering Period:	September 1, 2009 – September 30, 2011	
Date of Report:	October 5, 2011	
Recipient:	DOE – Golden Field Office	
Award Number:	DE-FC36-08GO18158	
Working Partners:	N/A	
Cost-Sharing Partners:	ACCIONA Solar Power, Inc. and DOE	
Contacts:	Marc Newmarker Engineer Phone: 702-236-5547 Fax: 702-617-1903 mnewmarker@acciona-na.com	Greg Rice Chief Financial Officer Phone: 312-673-3017 Fax: 312-673-3001 grice@acciona-na.com
DOE Project Team:	Project Officer – Joe Stekli Contracting Officer – Nicole Blackstone Project Monitor – Andrew Kobusch	



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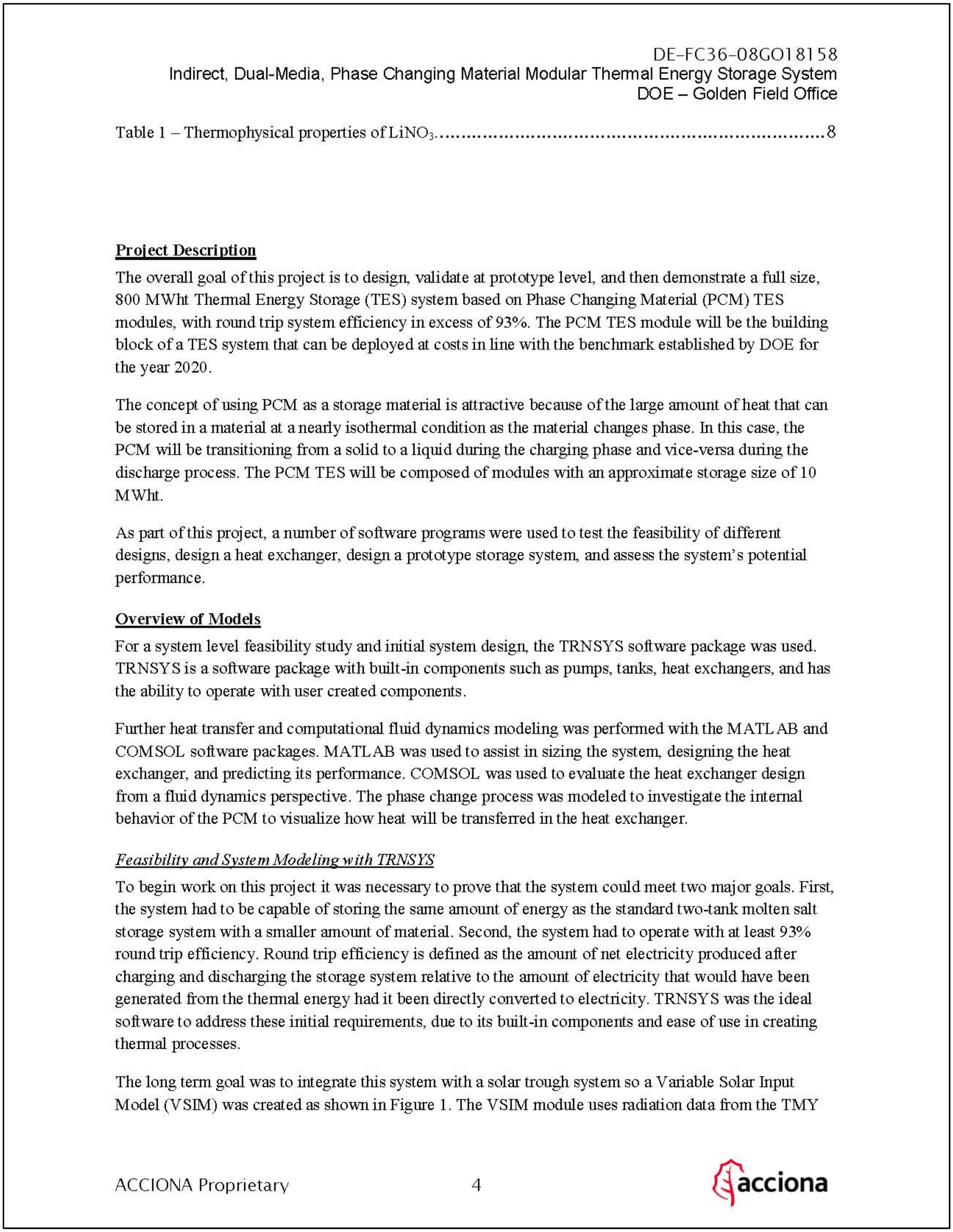

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Project Description

The overall goal of this project is to design, validate at prototype level, and then demonstrate a full size, 800 MWht Thermal Energy Storage (TES) system based on Phase Changing Material (PCM) TES modules, with round trip system efficiency in excess of 93%. The PCM TES module will be the building block of a TES system that can be deployed at costs in line with the benchmark established by DOE for the year 2020.

The concept of using PCM as a storage material is attractive because of the large amount of heat that can be stored in a material at a nearly isothermal condition as the material changes phase. In this case, the PCM will be transitioning from a solid to a liquid during the charging phase and vice-versa during the discharge process. The PCM TES will be composed of modules with an approximate storage size of 10 MWht.

As part of this project, a number of software programs were used to test the feasibility of different designs, design a heat exchanger, design a prototype storage system, and assess the system's potential performance.

Overview of Models

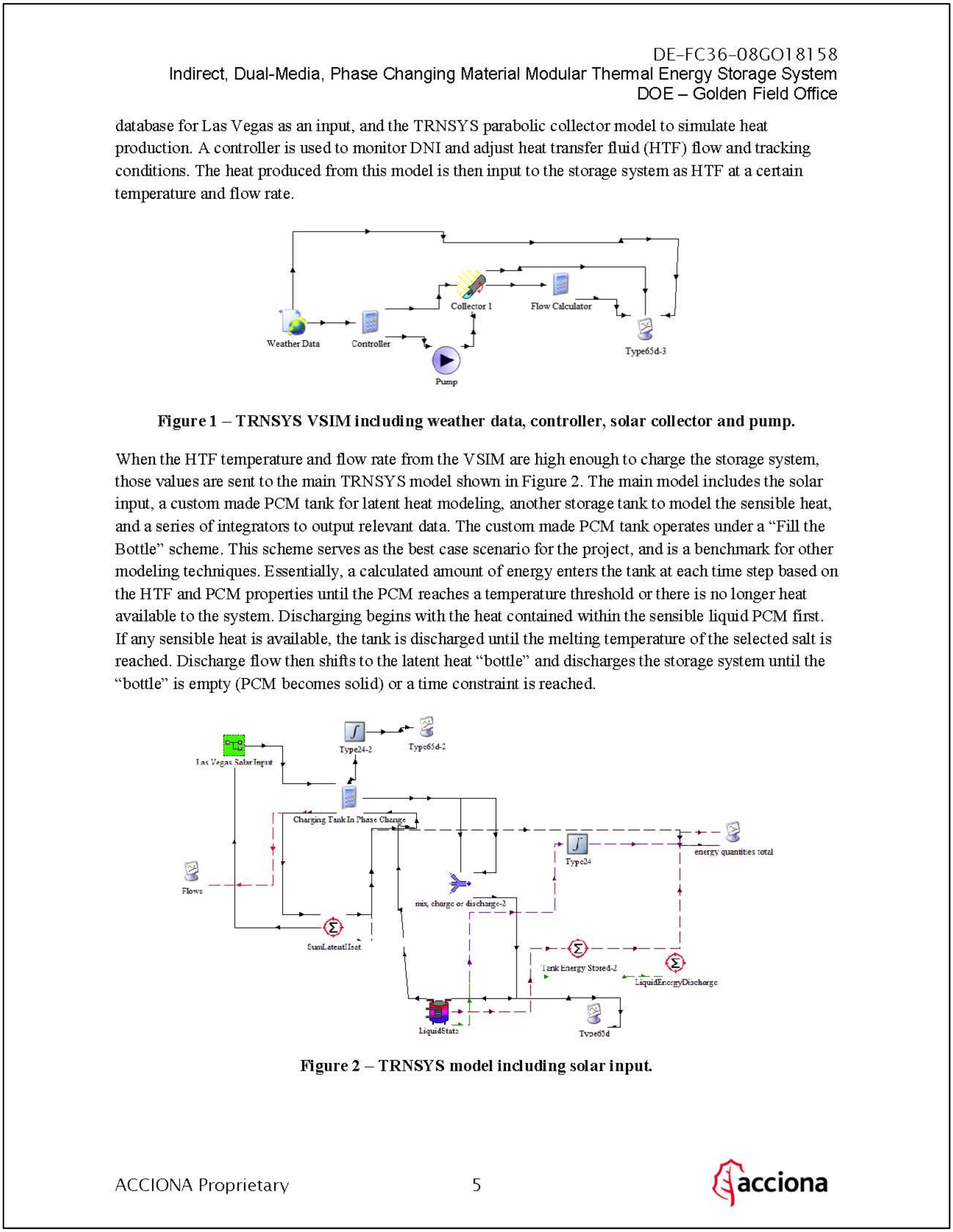
For a system level feasibility study and initial system design, the TRNSYS software package was used. TRNSYS is a software package with built-in components such as pumps, tanks, heat exchangers, and has the ability to operate with user created components.

Further heat transfer and computational fluid dynamics modeling was performed with the MATLAB and COMSOL software packages. MATLAB was used to assist in sizing the system, designing the heat exchanger, and predicting its performance. COMSOL was used to evaluate the heat exchanger design from a fluid dynamics perspective. The phase change process was modeled to investigate the internal behavior of the PCM to visualize how heat will be transferred in the heat exchanger.

Feasibility and System Modeling with TRNSYS

To begin work on this project it was necessary to prove that the system could meet two major goals. First, the system had to be capable of storing the same amount of energy as the standard two-tank molten salt storage system with a smaller amount of material. Second, the system had to operate with at least 93% round trip efficiency. Round trip efficiency is defined as the amount of net electricity produced after charging and discharging the storage system relative to the amount of electricity that would have been generated from the thermal energy had it been directly converted to electricity. TRNSYS was the ideal software to address these initial requirements, due to its built-in components and ease of use in creating thermal processes.

The long term goal was to integrate this system with a solar trough system so a Variable Solar Input Model (VSIM) was created as shown in Figure 1. The VSIM module uses radiation data from the TMY

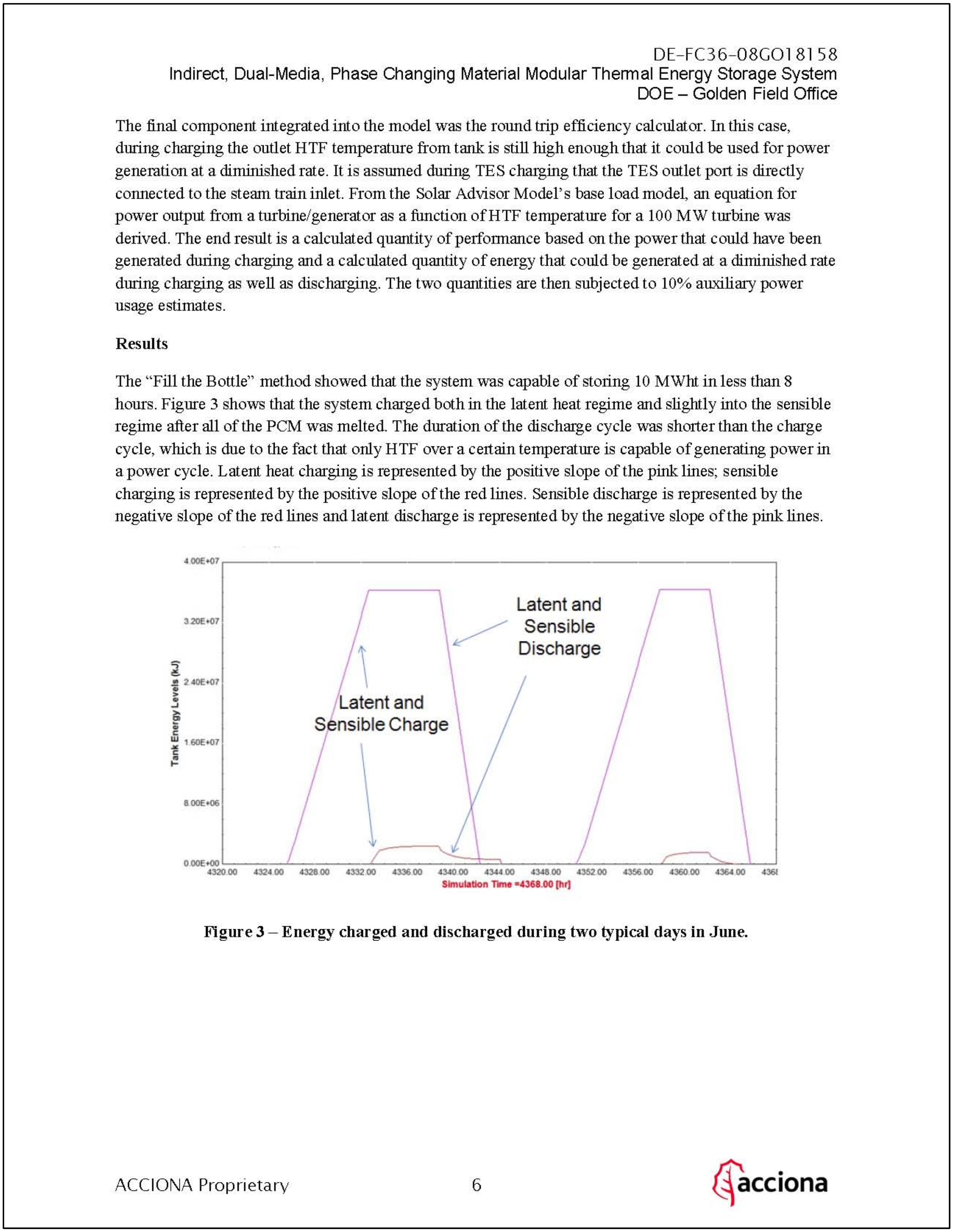


database for Las Vegas as an input, and the TRNSYS parabolic collector model to simulate heat production. A controller is used to monitor DNI and adjust heat transfer fluid (HTF) flow and tracking conditions. The heat produced from this model is then input to the storage system as HTF at a certain temperature and flow rate.

Figure 1 – TRNSYS VSIM including weather data, controller, solar collector and pump.

When the HTF temperature and flow rate from the VSIM are high enough to charge the storage system, those values are sent to the main TRNSYS model shown in Figure 2. The main model includes the solar input, a custom made PCM tank for latent heat modeling, another storage tank to model the sensible heat, and a series of integrators to output relevant data. The custom made PCM tank operates under a “Fill the Bottle” scheme. This scheme serves as the best case scenario for the project, and is a benchmark for other modeling techniques. Essentially, a calculated amount of energy enters the tank at each time step based on the HTF and PCM properties until the PCM reaches a temperature threshold or there is no longer heat available to the system. Discharging begins with the heat contained within the sensible liquid PCM first. If any sensible heat is available, the tank is discharged until the melting temperature of the selected salt is reached. Discharge flow then shifts to the latent heat “bottle” and discharges the storage system until the “bottle” is empty (PCM becomes solid) or a time constraint is reached.

Figure 2 – TRNSYS model including solar input.



The final component integrated into the model was the round trip efficiency calculator. In this case, during charging the outlet HTF temperature from tank is still high enough that it could be used for power generation at a diminished rate. It is assumed during TES charging that the TES outlet port is directly connected to the steam train inlet. From the Solar Advisor Model's base load model, an equation for power output from a turbine/generator as a function of HTF temperature for a 100 MW turbine was derived. The end result is a calculated quantity of performance based on the power that could have been generated during charging and a calculated quantity of energy that could be generated at a diminished rate during charging as well as discharging. The two quantities are then subjected to 10% auxiliary power usage estimates.

Results

The "Fill the Bottle" method showed that the system was capable of storing 10 MWht in less than 8 hours. Figure 3 shows that the system charged both in the latent heat regime and slightly into the sensible regime after all of the PCM was melted. The duration of the discharge cycle was shorter than the charge cycle, which is due to the fact that only HTF over a certain temperature is capable of generating power in a power cycle. Latent heat charging is represented by the positive slope of the pink lines; sensible charging is represented by the positive slope of the red lines. Sensible discharge is represented by the negative slope of the red lines and latent discharge is represented by the negative slope of the pink lines.

Figure 3 – Energy charged and discharged during two typical days in June.

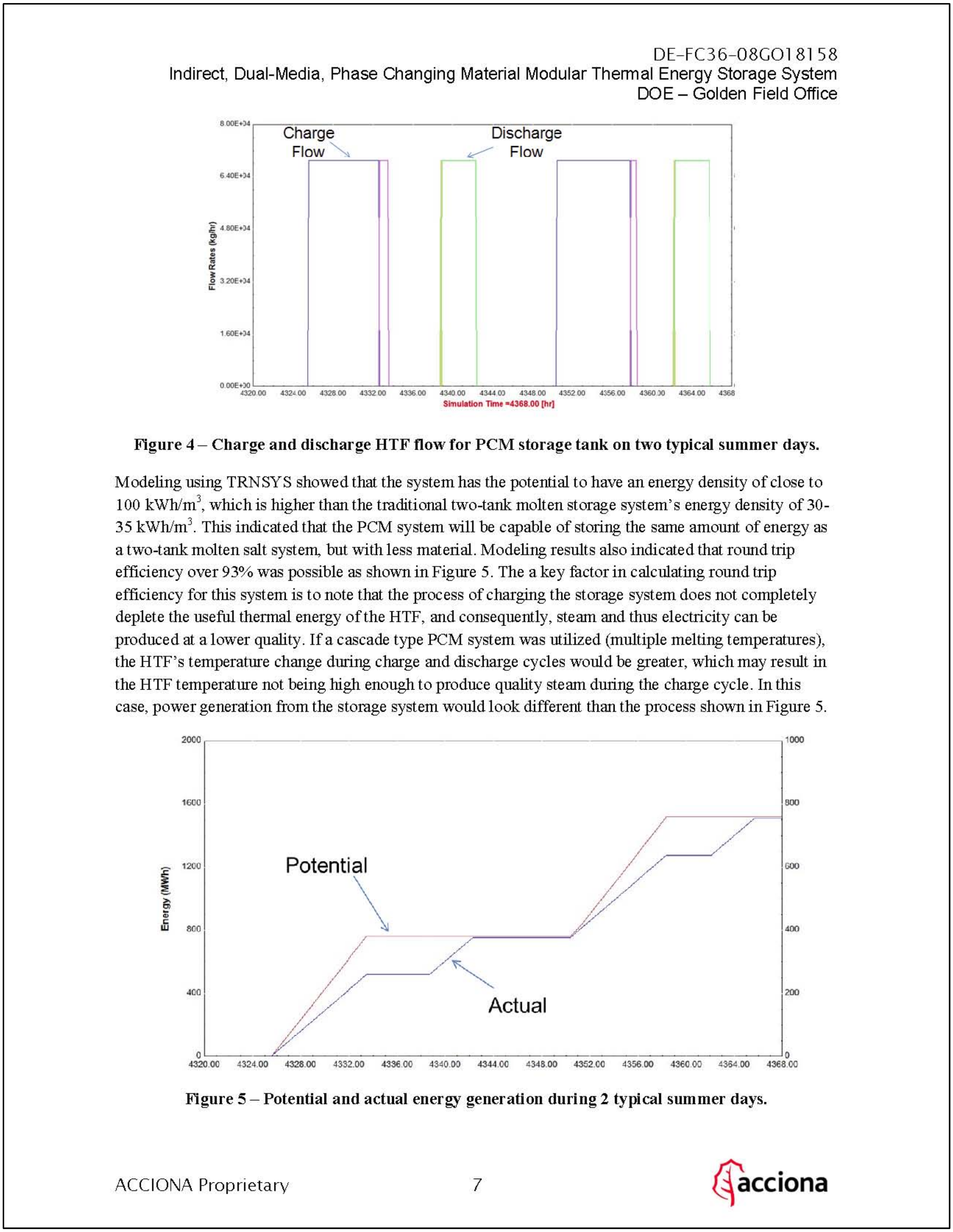


Figure 4 – Charge and discharge HTF flow for PCM storage tank on two typical summer days.

Modeling using TRNSYS showed that the system has the potential to have an energy density of close to 100 kWh/m^3, which is higher than the traditional two-tank molten storage system's energy density of 30-35 kWh/m^3. This indicated that the PCM system will be capable of storing the same amount of energy as a two-tank molten salt system, but with less material. Modeling results also indicated that round trip efficiency over 93% was possible as shown in Figure 5. The a key factor in calculating round trip efficiency for this system is to note that the process of charging the storage system does not completely deplete the useful thermal energy of the HTF, and consequently, steam and thus electricity can be produced at a lower quality. If a cascade type PCM system was utilized (multiple melting temperatures), the HTF's temperature change during charge and discharge cycles would be greater, which may result in the HTF temperature not being high enough to produce quality steam during the charge cycle. In this case, power generation from the storage system would look different than the process shown in Figure 5.

Figure 5 – Potential and actual energy generation during 2 typical summer days.

To model round trip efficiency, the turbine curve for a 100 MW cited in the DOE Solar Advisor Model (SAM) was selected. When utilizing the storage system under the actual case shown in Figure 5, it was calculated that the turbine could operate at an output of 62.5 MW, and was able to operate for a total of 12 hours. The system had the potential to output at 100 MW for 8 hours if the storage system was not used. The round trip efficiency in this case, accounting for parasitic loading was approximately 94%.

Heat Exchanger Design and Performance Prediction with MATLAB

To perform a more detailed analysis of the heat exchanger/storage tank in this system, the MATLAB software package was used. The analysis was focused on designing a prototype heat exchanger capable of storing 100 kWht. After the basic concept of a flat panel open tank heat exchanger was chosen for the prototype's design, shown in Figure 6, the heat exchanger was modeled and sized using conservation of energy principles and several assumptions.

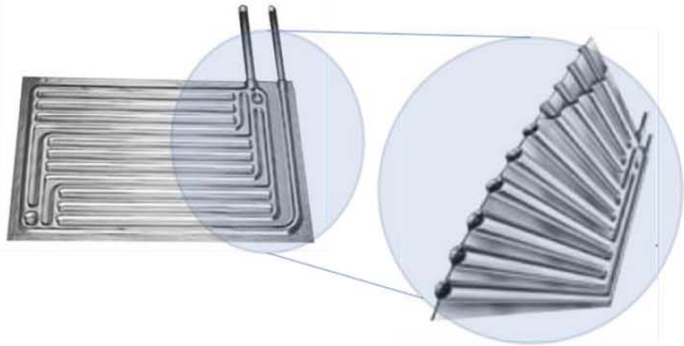


Figure 6 – Commercially available Flat-Panel Open Tank Heat Exchanger.

First, it was assumed that the PCM temperature was not dependent on location within the tank, that is to say the bulk temperature is representative of the entire mass. Second, it was assumed that the phase change process occurs over a small temperature range rather than at one specific temperature, as seen in Figure 7. Over the phase change temperature range, the specific heat of the phase change material is equal to the latent heat of fusion value divided by the value of the temperature range. Third, it was assumed that the main mode of heat transfer between the HTF and PCM is free convection. Fourth, during discharge, an additional heat transfer term in the form of conduction resistance was included to simulate PCM build up on the heat exchanger surface. Fifth, lithium nitrate ($LiNO_3$) was chosen as the PCM for this project, due to its lower melting point. The properties of $LiNO_3$ are shown in Table 1.

Table 1 – Thermophysical properties of $LiNO_3$.

Melting Temp.	254	°C
Density [12]	2380	kg/m^3
Specific Heat [11]	1.631	kJ/kg-K
Latent Heat [13]	373	kJ/kg
Thermal Conductivity	0.5	W/m-K
Coefficient of Thermal Expansion [10]	21.5	%

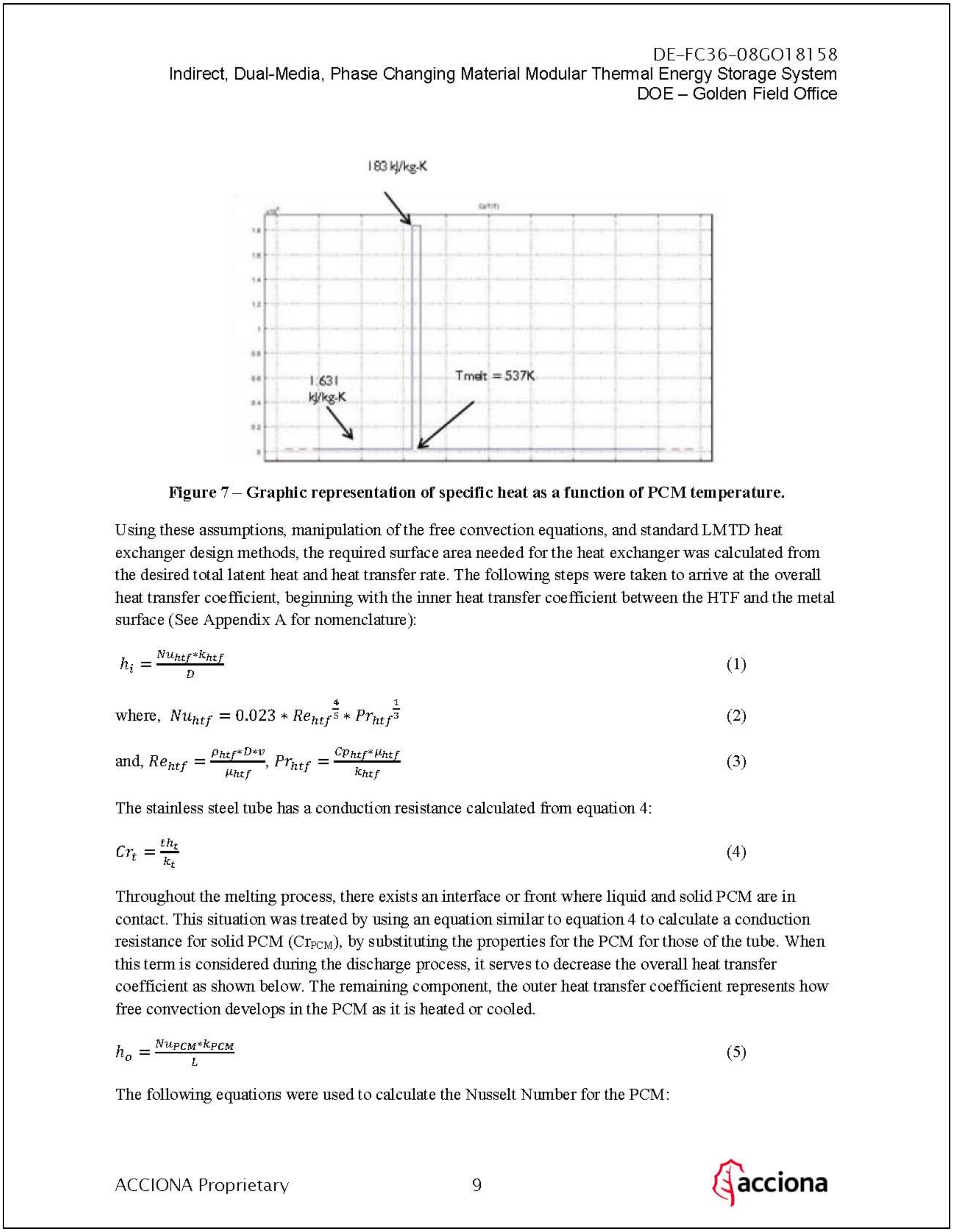


Figure 7 – Graphic representation of specific heat as a function of PCM temperature.

Using these assumptions, manipulation of the free convection equations, and standard LMTD heat exchanger design methods, the required surface area needed for the heat exchanger was calculated from the desired total latent heat and heat transfer rate. The following steps were taken to arrive at the overall heat transfer coefficient, beginning with the inner heat transfer coefficient between the HTF and the metal surface (See Appendix A for nomenclature):

$$h_i = \frac{Nu_{htf} * k_{htf}}{D} \tag{1}$$

where, $Nu_{htf} = 0.023 * Re_{htf}^{\frac{4}{5}} * Pr_{htf}^{\frac{1}{3}}$ (2)

and, $Re_{htf} = \frac{\rho_{htf} * D * v}{\mu_{htf}}$, $Pr_{htf} = \frac{Cp_{htf} * \mu_{htf}}{k_{htf}}$ (3)

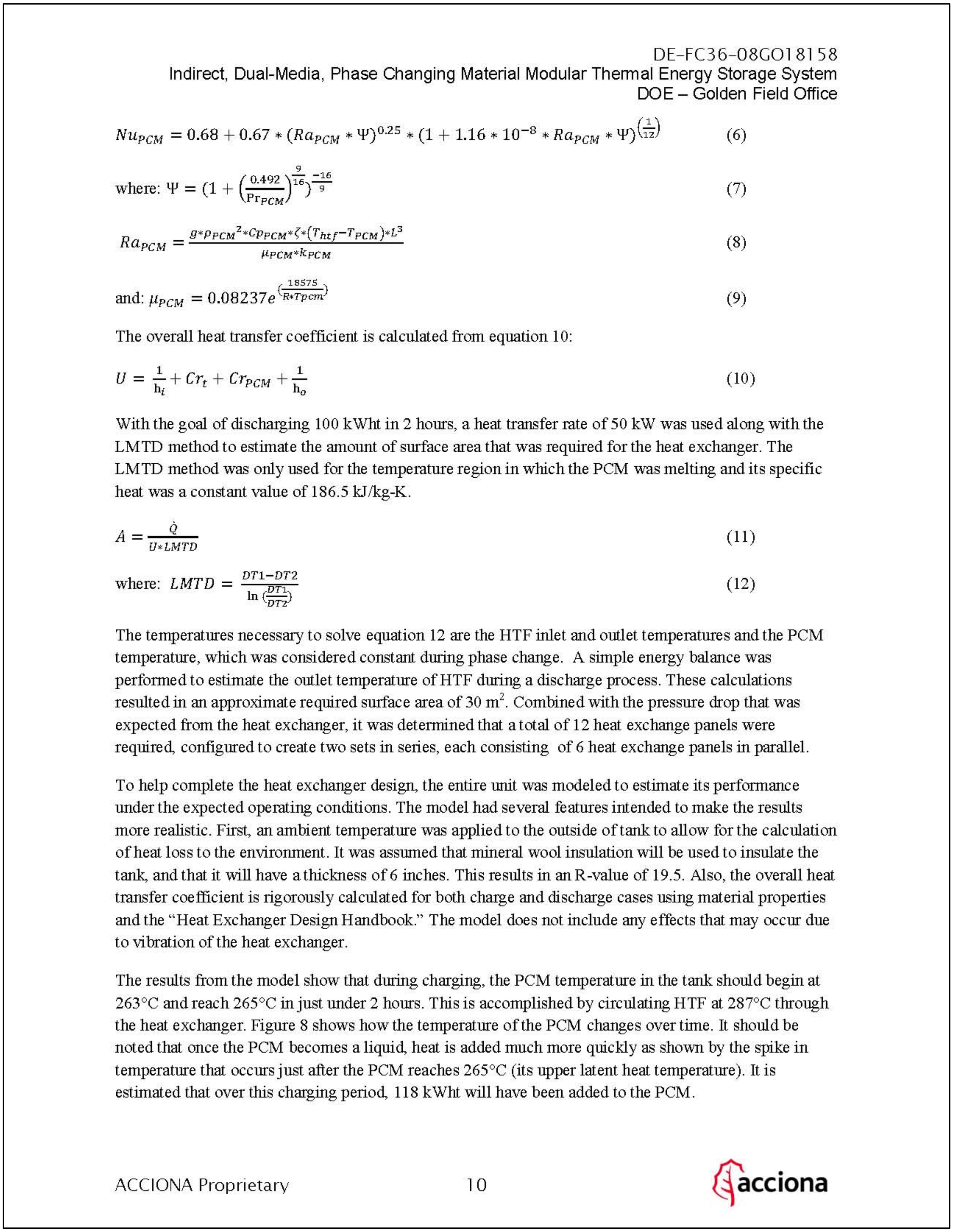
The stainless steel tube has a conduction resistance calculated from equation 4:

$$Cr_t = \frac{th_t}{k_t} \tag{4}$$

Throughout the melting process, there exists an interface or front where liquid and solid PCM are in contact. This situation was treated by using an equation similar to equation 4 to calculate a conduction resistance for solid PCM (Cr_{PCM}), by substituting the properties for the PCM for those of the tube. When this term is considered during the discharge process, it serves to decrease the overall heat transfer coefficient as shown below. The remaining component, the outer heat transfer coefficient represents how free convection develops in the PCM as it is heated or cooled.

$$h_o = \frac{Nu_{PCM} * k_{PCM}}{L} \tag{5}$$

The following equations were used to calculate the Nusselt Number for the PCM:



$$Nu_{PCM} = 0.68 + 0.67 * (Ra_{PCM} * \Psi)^{0.25} * (1 + 1.16 * 10^{-8} * Ra_{PCM} * \Psi)^{\left(\frac{1}{12}\right)} \quad (6)$$

where: $\Psi = (1 + \left(\frac{0.492}{\mathrm{Pr}_{PCM}}\right)^{\frac{9}{16}})^{\frac{-16}{9}}$ (7)

$$Ra_{PCM} = \frac{g * \rho_{PCM}{}^{2} * Cp_{PCM} * \zeta * (T_{htf} - T_{PCM}) * L^{3}}{\mu_{PCM} * k_{PCM}} \quad (8)$$

and: $\mu_{PCM} = 0.08237e^{\left(\frac{18575}{R * Tpcm}\right)}$ (9)

The overall heat transfer coefficient is calculated from equation 10:

$$U = \frac{1}{\mathrm{h}_i} + Cr_t + Cr_{PCM} + \frac{1}{\mathrm{h}_o} \quad (10)$$

With the goal of discharging 100 kWht in 2 hours, a heat transfer rate of 50 kW was used along with the LMTD method to estimate the amount of surface area that was required for the heat exchanger. The LMTD method was only used for the temperature region in which the PCM was melting and its specific heat was a constant value of 186.5 kJ/kg-K.

$$A = \frac{\dot{Q}}{U * LMTD} \quad (11)$$

where: $LMTD = \frac{DT1 - DT2}{\ln\left(\frac{DT1}{DT2}\right)}$ (12)

The temperatures necessary to solve equation 12 are the HTF inlet and outlet temperatures and the PCM temperature, which was considered constant during phase change. A simple energy balance was performed to estimate the outlet temperature of HTF during a discharge process. These calculations resulted in an approximate required surface area of 30 m^2. Combined with the pressure drop that was expected from the heat exchanger, it was determined that a total of 12 heat exchange panels were required, configured to create two sets in series, each consisting of 6 heat exchange panels in parallel.

To help complete the heat exchanger design, the entire unit was modeled to estimate its performance under the expected operating conditions. The model had several features intended to make the results more realistic. First, an ambient temperature was applied to the outside of tank to allow for the calculation of heat loss to the environment. It was assumed that mineral wool insulation will be used to insulate the tank, and that it will have a thickness of 6 inches. This results in an R-value of 19.5. Also, the overall heat transfer coefficient is rigorously calculated for both charge and discharge cases using material properties and the “Heat Exchanger Design Handbook.” The model does not include any effects that may occur due to vibration of the heat exchanger.

The results from the model show that during charging, the PCM temperature in the tank should begin at 263°C and reach 265°C in just under 2 hours. This is accomplished by circulating HTF at 287°C through the heat exchanger. Figure 8 shows how the temperature of the PCM changes over time. It should be noted that once the PCM becomes a liquid, heat is added much more quickly as shown by the spike in temperature that occurs just after the PCM reaches 265°C (its upper latent heat temperature). It is estimated that over this charging period, 118 kWht will have been added to the PCM.

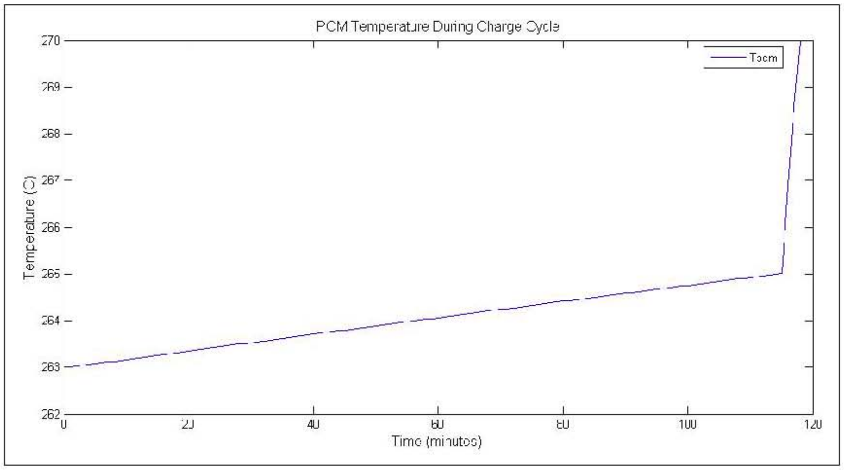


Figure 8 – PCM bulk temperature during charge cycle (inlet T = 287°C).

During the discharge cycle, the tank begins at 265°C and imparts energy to the HTF until the PCM temperature reaches 263°C. This is done by flowing HTF at a temperature of 240°C into the tank, and Figure 9 shows the HTF outlet temperature during the discharge cycle. The results from the model show that the HTF outlet temperature begins near 256°C and drops to 254.5°C by the end of the discharge cycle. Again, the steep drop at the end of the cycle represents the point at which the PCM has become fully solid. It is estimated that over the discharging period of 1.85 hours, 117 kWht will have been removed from the PCM. Realistically, it would not be desirable to take the PCM out of its latent heat region during charge or discharge. Therefore, the total amounts of energy that are charged and discharged from the PCM will be slightly lower than these results indicate.

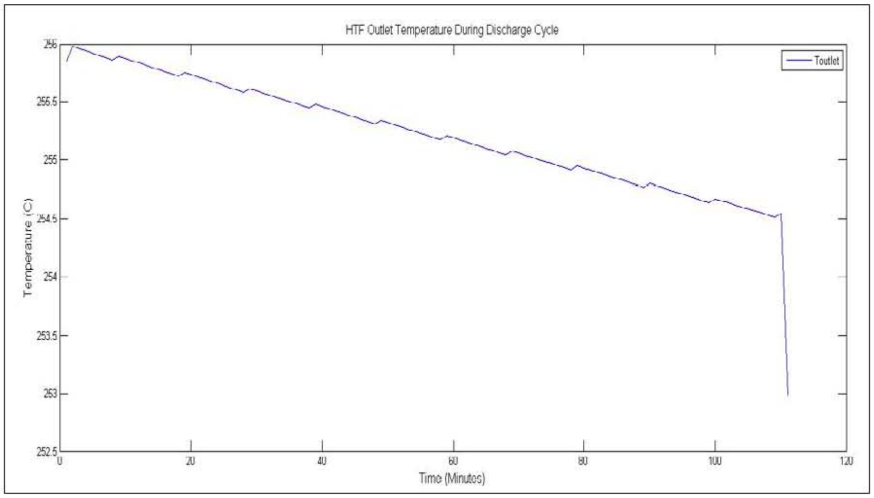


Figure 9 – HTF outlet temperature during discharge cycle (inlet T = 240 C).

Heat Exchanger Design and Operation Verification with COMSOL

Heat transfer and fluid flow calculations focused on the internal behavior of the heat exchanger were performed in COMSOL. The goal of this work was to visualize how the PCM melting and solidification processes occur inside the heat exchanger during the charge and discharge cycles. Figure 10 shows the section of heat exchanger that was used for this work.

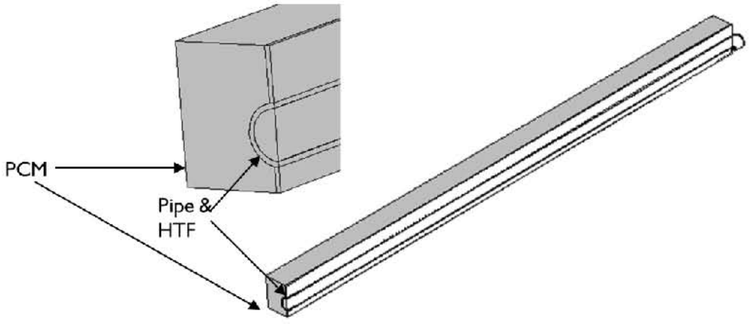


Figure 10 – Cross-sectional and full view of single pass of heat exchanger modeled with COMSOL.

A portion of the flat plate heat exchanger is surrounded by PCM material and filled with HTF. As the HTF temperature inside the tube is increased and fluid begins to flow, the temperature in the PCM can be monitored as shown in Figure 11.

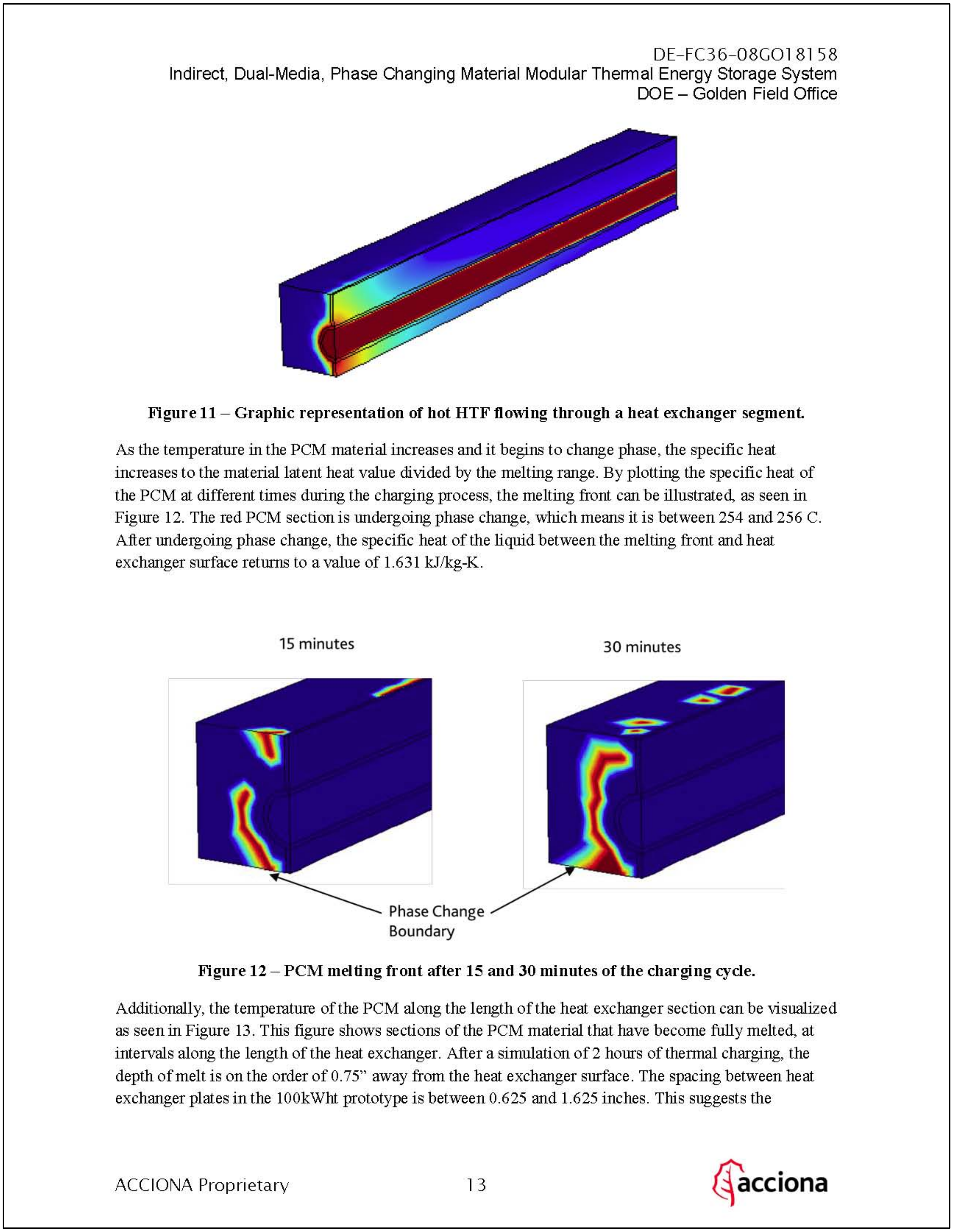


Figure 11 – **Graphic representation of hot HTF flowing through a heat exchanger segment.**

As the temperature in the PCM material increases and it begins to change phase, the specific heat increases to the material latent heat value divided by the melting range. By plotting the specific heat of the PCM at different times during the charging process, the melting front can be illustrated, as seen in Figure 12. The red PCM section is undergoing phase change, which means it is between 254 and 256 C. After undergoing phase change, the specific heat of the liquid between the melting front and heat exchanger surface returns to a value of 1.631 kJ/kg-K.

Figure 12 – **PCM melting front after 15 and 30 minutes of the charging cycle.**

Additionally, the temperature of the PCM along the length of the heat exchanger section can be visualized as seen in Figure 13. This figure shows sections of the PCM material that have become fully melted, at intervals along the length of the heat exchanger. After a simulation of 2 hours of thermal charging, the depth of melt is on the order of 0.75" away from the heat exchanger surface. The spacing between heat exchanger plates in the 100kWht prototype is between 0.625 and 1.625 inches. This suggests the

100kWht prototype should be capable of melting all of the PCM inside the heat exchanger in approximately 2 hours.

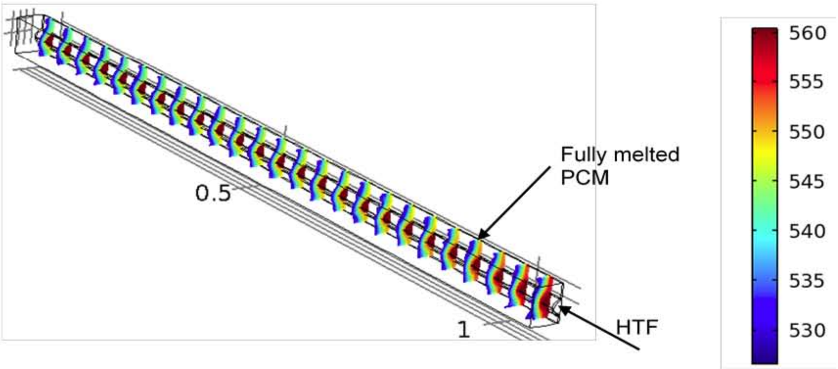
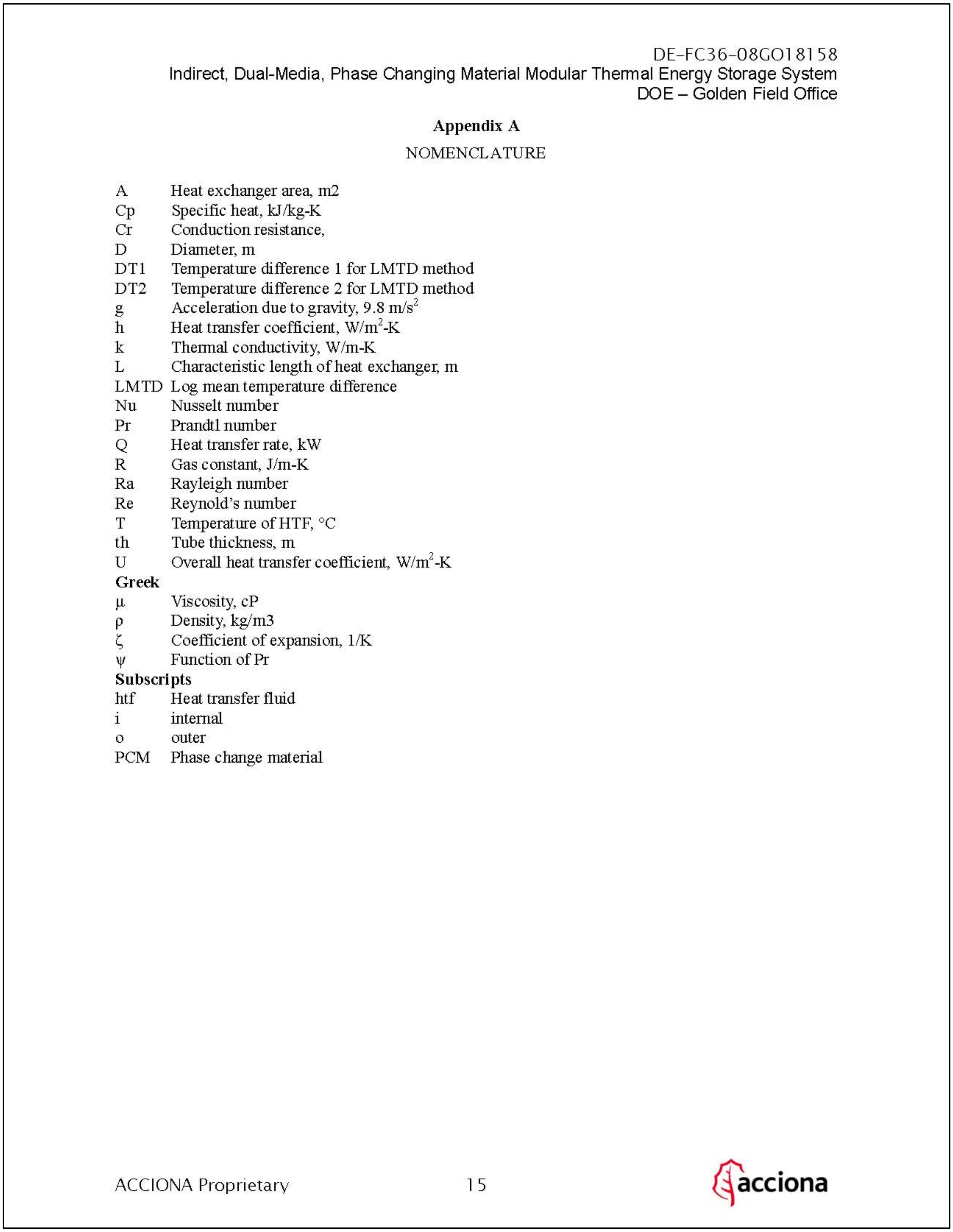


Figure 13 – Fully melted PCM along the heat exchanger section after 2 hours of charging.

Conclusion

Throughout the modeling process, the focus has been to satisfy the performance requirements of this storage concept. It has been shown that the system has the ability to reduce the amount of storage material required, and that the round trip efficiency of a PCM storage system has the potential to exceed 93%. Heat transfer and fluid dynamic analysis assisted in the design and modeling of the heat exchanger/storage tank. These analyses show that the 100 kWht prototype heat exchanger/storage tank should be capable of being charged in approximately 2 hours. Results from the experimental testing with the prototype unit will be used to refine the existing models for larger scale predictions. Additionally, the experimental results will show areas where the system can be optimized.



Appendix A

NOMENCLATURE

A	Heat exchanger area, m2
Cp	Specific heat, kJ/kg-K
Cr	Conduction resistance,
D	Diameter, m
DT1	Temperature difference 1 for LMTD method
DT2	Temperature difference 2 for LMTD method
g	Acceleration due to gravity, 9.8 m/s^2
h	Heat transfer coefficient, W/m^2-K
k	Thermal conductivity, W/m-K
L	Characteristic length of heat exchanger, m
LMTD	Log mean temperature difference
Nu	Nusselt number
Pr	Prandtl number
Q	Heat transfer rate, kW
R	Gas constant, J/m-K
Ra	Rayleigh number
Re	Reynold's number
T	Temperature of HTF, °C
th	Tube thickness, m
U	Overall heat transfer coefficient, W/m^2-K
Greek	
μ	Viscosity, cP
ρ	Density, kg/m3
ζ	Coefficient of expansion, 1/K
ψ	Function of Pr
Subscripts	
htf	Heat transfer fluid
i	internal
o	outer
PCM	Phase change material

Appendix D

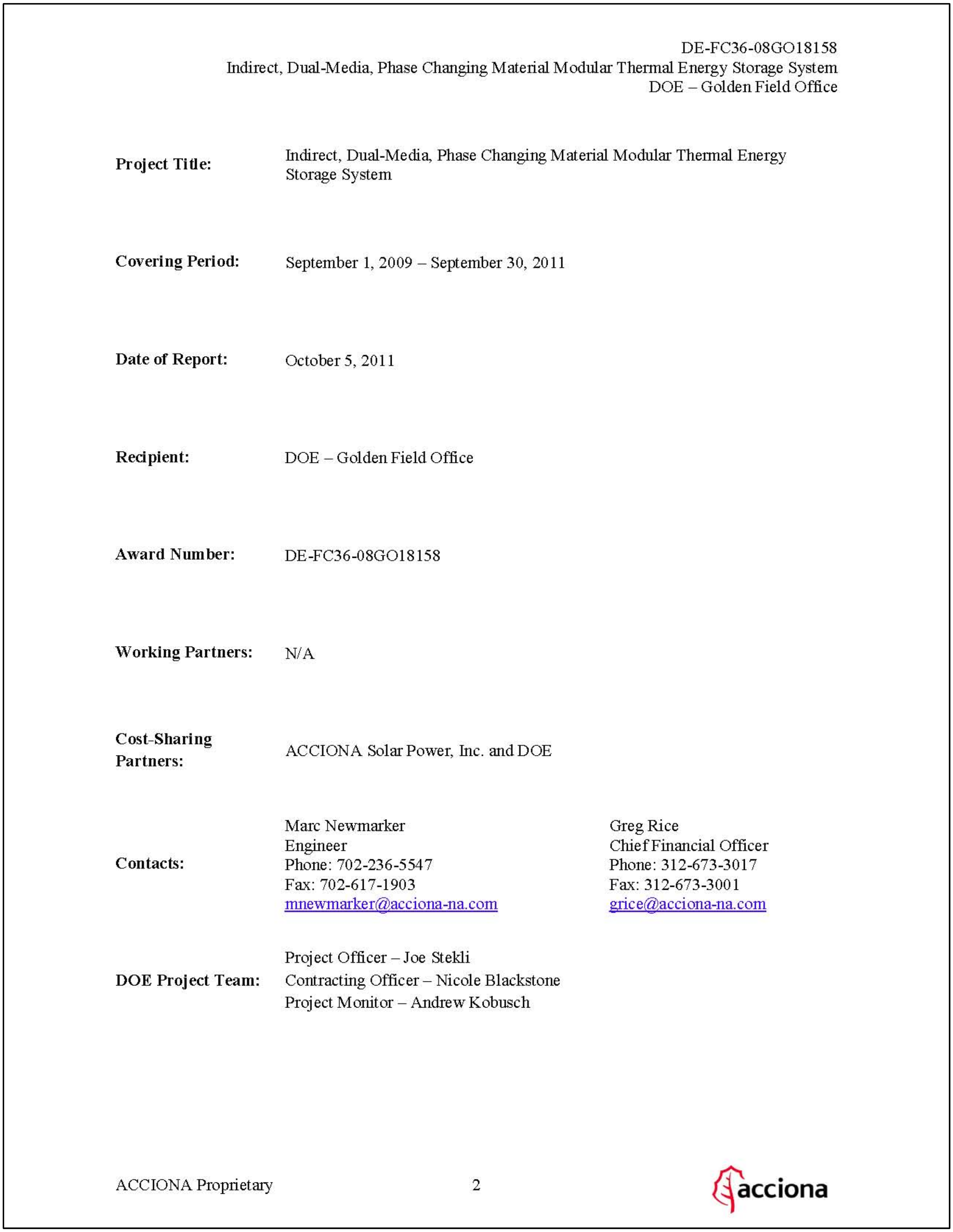
Salt Selection Report

Salt Selection Summary Report

Issued: October 5, 2011

Indirect, Dual-Media, Phase Changing Material Modular Thermal Energy Storage System

ACCIONA Proprietary



Project Title:	Indirect, Dual-Media, Phase Changing Material Modular Thermal Energy Storage System	
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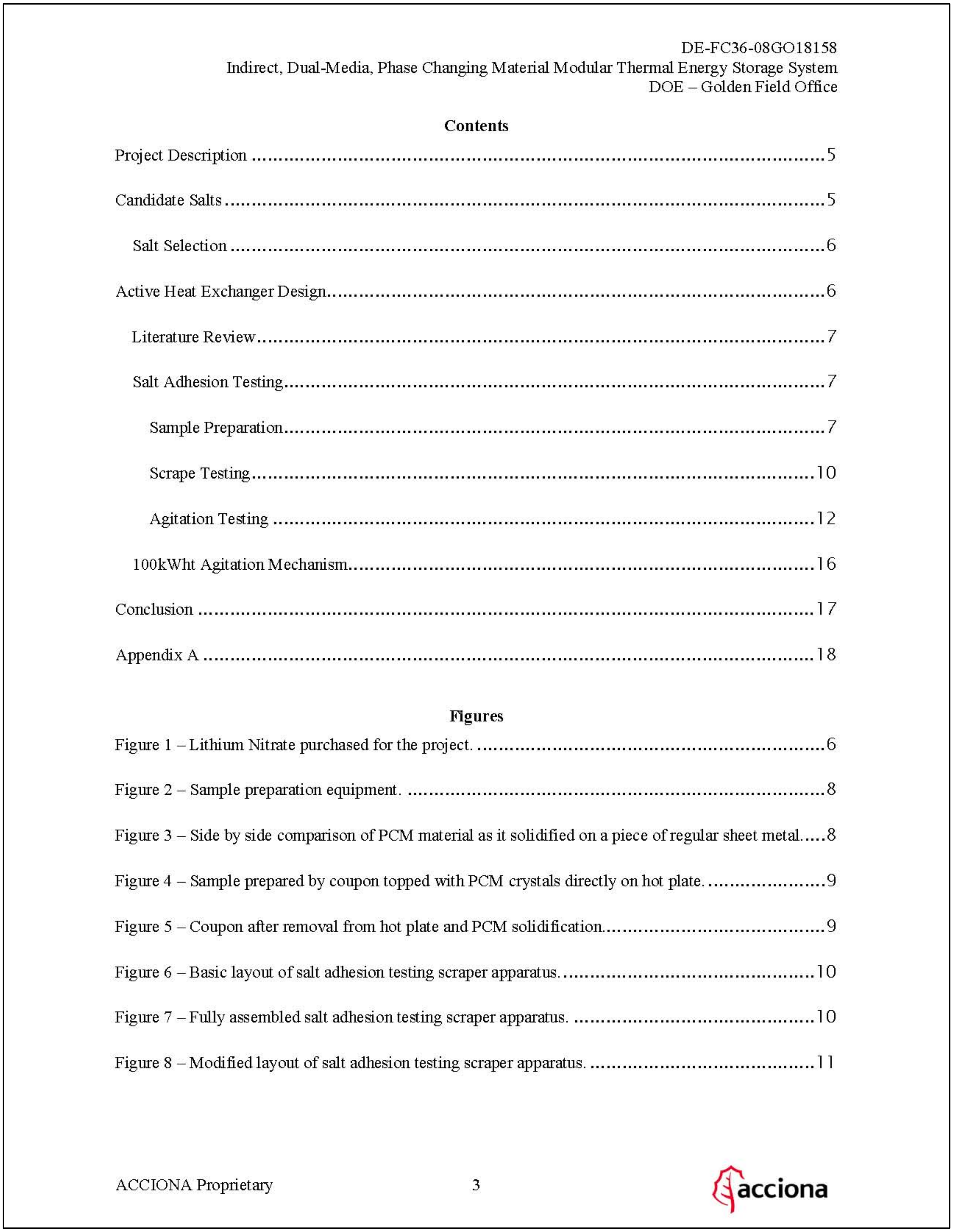

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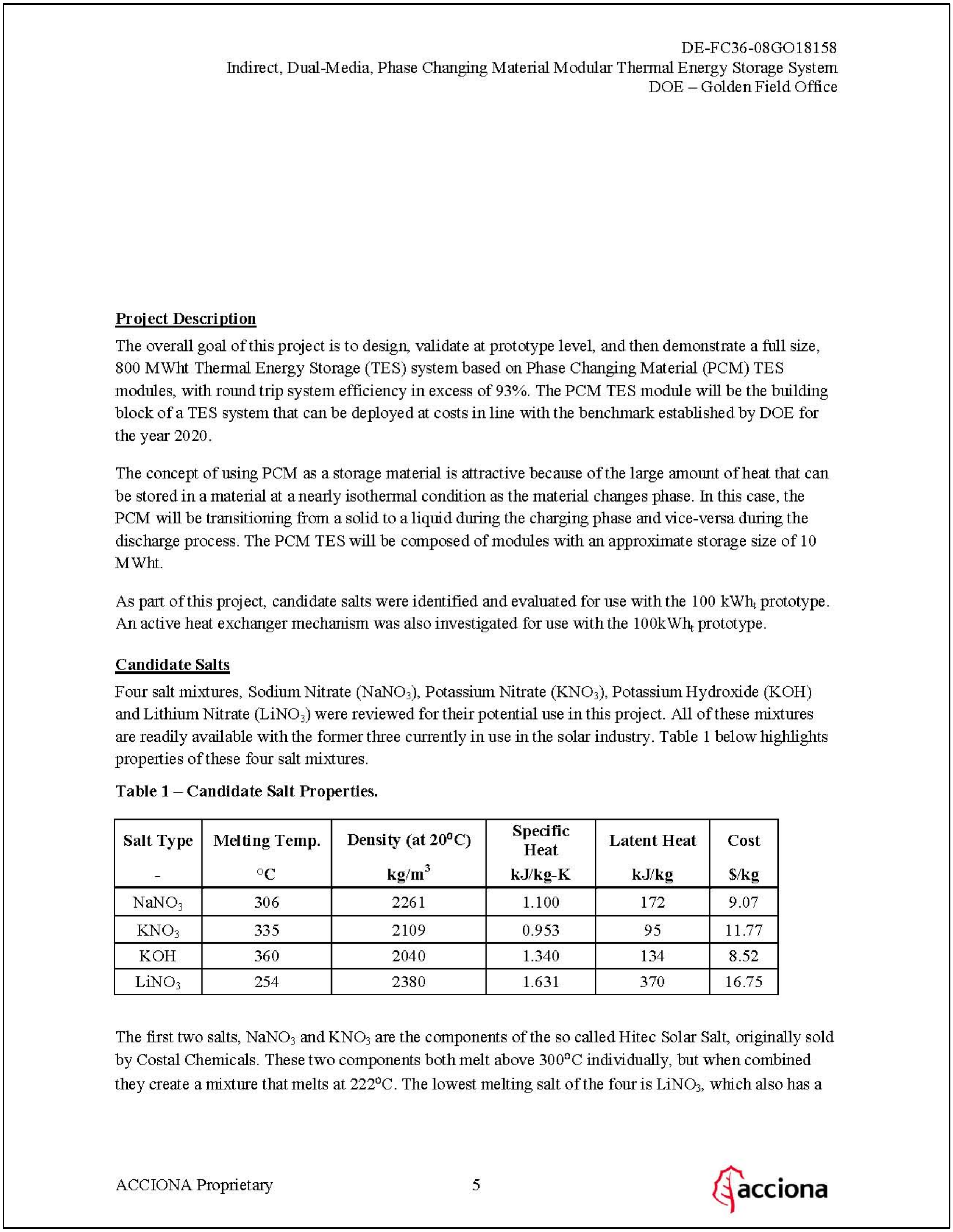


Project Description

The overall goal of this project is to design, validate at prototype level, and then demonstrate a full size, 800 MWht Thermal Energy Storage (TES) system based on Phase Changing Material (PCM) TES modules, with round trip system efficiency in excess of 93%. The PCM TES module will be the building block of a TES system that can be deployed at costs in line with the benchmark established by DOE for the year 2020.

The concept of using PCM as a storage material is attractive because of the large amount of heat that can be stored in a material at a nearly isothermal condition as the material changes phase. In this case, the PCM will be transitioning from a solid to a liquid during the charging phase and vice-versa during the discharge process. The PCM TES will be composed of modules with an approximate storage size of 10 MWht.

As part of this project, candidate salts were identified and evaluated for use with the 100 kWh_t prototype. An active heat exchanger mechanism was also investigated for use with the 100kWh_t prototype.

Candidate Salts

Four salt mixtures, Sodium Nitrate ($NaNO_3$), Potassium Nitrate (KNO_3), Potassium Hydroxide (KOH) and Lithium Nitrate ($LiNO_3$) were reviewed for their potential use in this project. All of these mixtures are readily available with the former three currently in use in the solar industry. Table 1 below highlights properties of these four salt mixtures.

Table 1 – Candidate Salt Properties.

Salt Type	Melting Temp.	Density (at 20°C)	Specific Heat	Latent Heat	Cost
-	°C	kg/m^3	kJ/kg-K	kJ/kg	$/kg
$NaNO_3$	306	2261	1.100	172	9.07
KNO_3	335	2109	0.953	95	11.77
KOH	360	2040	1.340	134	8.52
$LiNO_3$	254	2380	1.631	370	16.75

The first two salts, $NaNO_3$ and KNO_3 are the components of the so called Hitec Solar Salt, originally sold by Costal Chemicals. These two components both melt above 300°C individually, but when combined they create a mixture that melts at 222°C. The lowest melting salt of the four is $LiNO_3$, which also has a higher latent heat capacity and a significant increase in cost over the other materials. KOH has the lowest cost per unit mass, but has the lowest latent heat capacity of the group.

Salt Selection

Of the four candidate salts$LiNO_3$was selected for testing with the 100kWh$_t$ prototype. This salt was selected for several reasons. First, $LiNO_3$ has the best combined thermal properties of the group. This allows the prototype to be more compact thus reducing the required quantity of salt. Second, the melting temperature is below 300°C, which is highly compatible with the heater skid and heat transfer fluid selected for use in test loop. The HTF selected is Mobiltherm 603, a mineral oil that is capable of achieving 300°C without the need for a pressurized expansion vessel. Finally, a manufacturer/distributor was located that could readily provide the required quantity of $LiNO_3$. Figure 1 is a picture of the salt purchased for use in the 100kWh$_t$ prototype.

Figure 1 – Lithium Nitrate purchased for the project.

Active Heat Exchanger Design

Part of the technology theorized for this project was the inclusion of a mechanism to enhance heat transfer of the heat exchanger during storage system discharge. One issue that arises during the extraction of latent heat from a PCM is that the material begins to solidify on the heat exchange surface as it cools. Development of a solidified crust on the heat transfer surface has a direct impact on heat exchanger performance. By mechanically removing any solidified salt, it is theorized that an increase in heat exchanger efficiency can be achieved.

Literature Review

Research and design of the active heat exchanger component for the thermal storage system began with an investigation into technology that had been previously documented. Nathan Siegel of Sandia pointed out a Sandia report (SAND81-8184) which had the goal of designing a sodium hydroxide / sodium nitrate latent heat storage system for use with a saturated steam. In the report, several storage concepts were mentioned (approximately 37) and 9 were analyzed.

After review, two possible designs were selected from the report, and three from internal discussion, for a total of five designs that were evaluated.

- Fixed with Rotating Drum – salt sprayed on rotating drum with fixed scrapers (SAND81-8184)
- Fixed with Rotating Auger – auger rotates around HEX, removes salt and circulates liquid (SAND81-8184)
- Bubbles – compressed gas is injected into salt to create bubbles that washes the HEX surface
- Scraper – device physically removes salt from fixed position heat exchanger
- Harmonic resonance – device shakes the heat exchanger to remove particles

To aid in evaluating these designs, a salt adhesion testing scheme was developed. The concept behind this testing was to quantify the amount of work required to remove solidifying salt from a material surface, i.e. stainless steel.

Salt Adhesion Testing

Of the four active heat exchanger concepts, two commonalities can be identified: mechanical agitation, and mechanical scraping. These two techniques could be performed in a laboratory with the results being scalable to the 100kWh$_t$ prototype.

Sample Preparation

To perform the salt adhesion analysis, small quantities of KOH, $NaNO_3$ and KNO_3 were purchased from a laboratory chemical supply company. Next, material coupons of stainless steel in different finishes (brushed, polished and milled) were purchased. A laboratory hot plate was utilized to provide heat for phase change. An initial test plan was developed where salt would be melted in a crucible and droplets would be applied to the material surface. These samples would then be utilized in the scraping trials.

However, this method was not ideal due to several issues. First, the process of transferring molten salt from the crucible to the sample resulted in significant heat loss. This meant salt on the verge of solidification was contacting the material surface and consequently adhered poorly. To rectify this, the sample materials were placed on the hot plate until the moment of droplet deposition. This method worked modestly well.

Another method tried successfully was the direct deposition of solid salt crystals on the material surface, and the two items placed directly on the hot plate. After the salt melted, the sample was removed from the hot plate and allowed to cool.

Several lessons were learned during sample preparation. First, PCM is difficult to work with near its phase change temperature. Second, partially molten PCM is highly adhesive to materials near the melting point temperature. Third, liquid PCM does not bond to materials that are below the melting temperature, i.e. room temperature. Fourth, thermal expansion must be considered in tank design. Even with the small quantities used in this testing, expansion and contraction was noticeable.

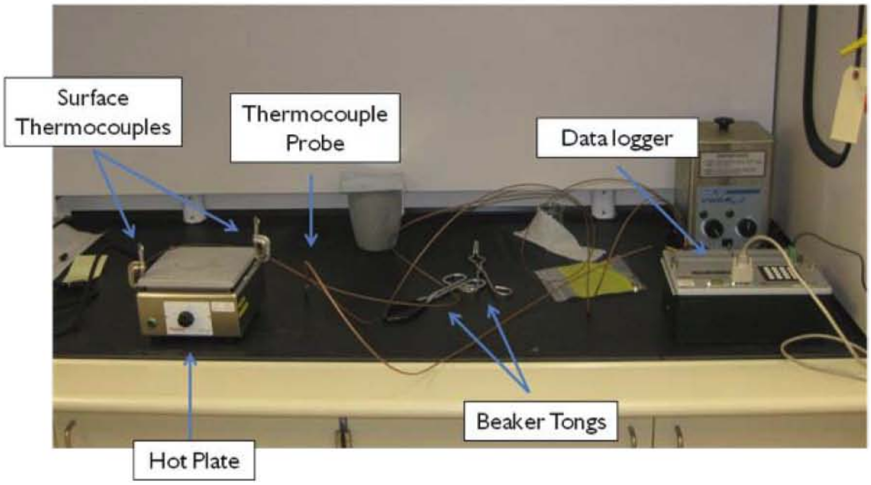


Figure 2 – Sample preparation equipment.

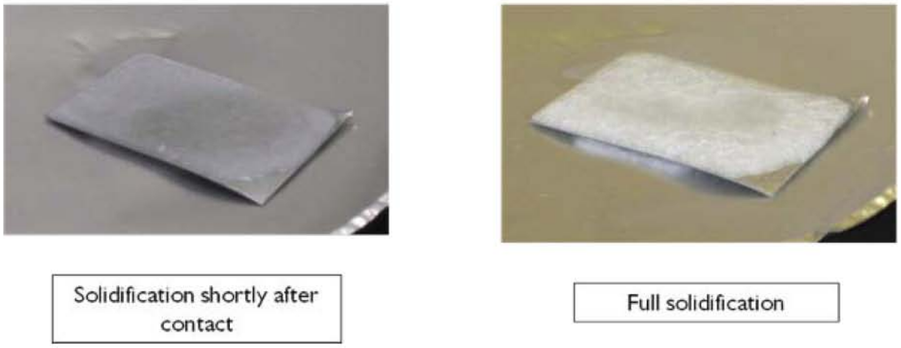
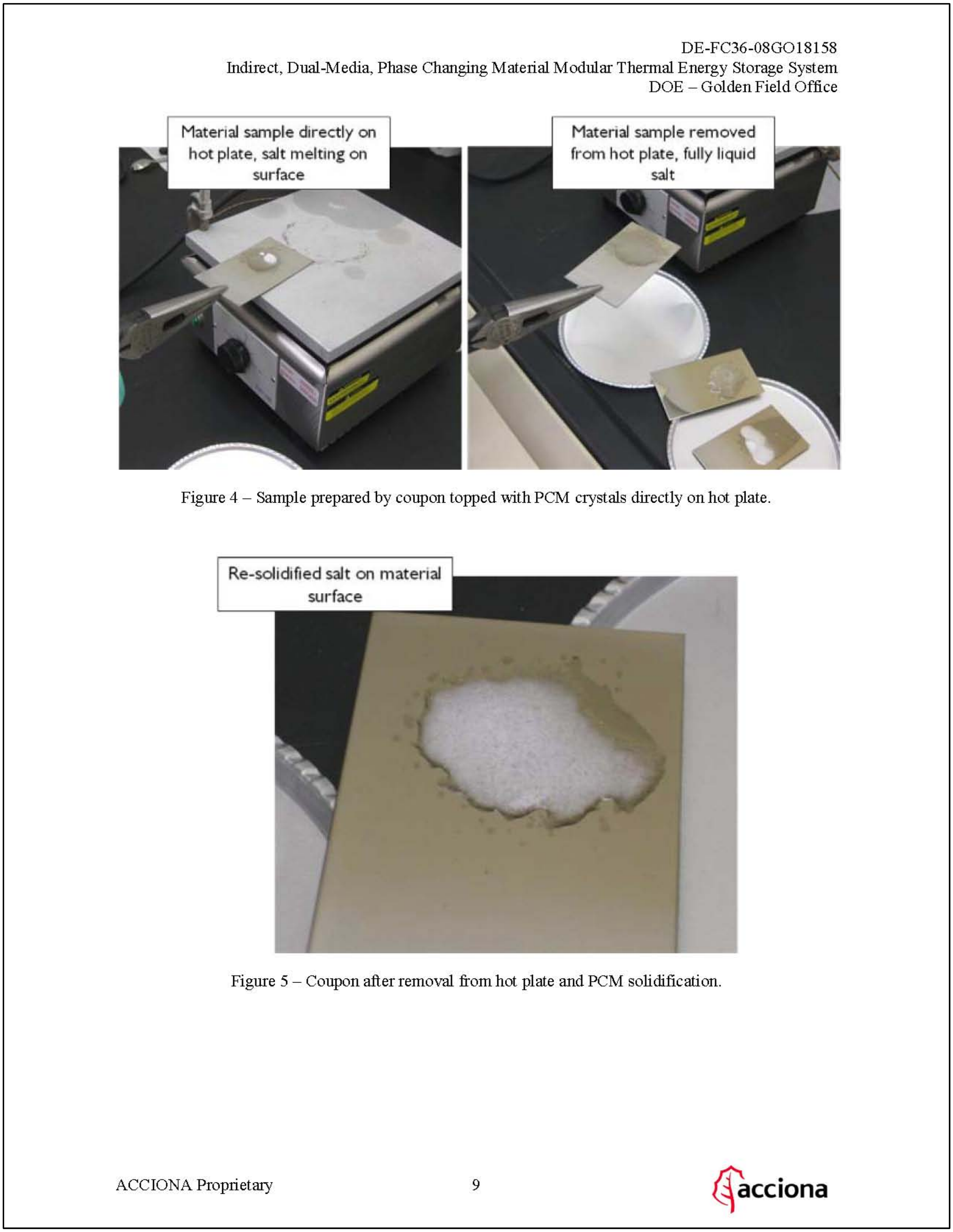


Figure 3 – Side by side comparison of PCM material as it solidified on a piece of regular sheet metal.



DE-FC36-08GO18158
Indirect, Dual-Media, Phase Changing Material Modular Thermal Energy Storage System
DOE – Golden Field Office

Figure 4 – Sample prepared by coupon topped with PCM crystals directly on hot plate.

Figure 5 – Coupon after removal from hot plate and PCM solidification.

Scrape Testing

The first salt adhesion test developed was the scrape test. This test was performed by pulling a coupon with solidified PCM adhered to it through a fixed jig and measuring the force required to fully remove the attached material. The jig was constructed of off –the-shelf angled steel clamped to a metal table. A load cell was attached to the coupon and used to pull the sample through the jig. A diagram of the system is shown in Figure 6 and a picture of the actual apparatus is shown in Figure 7.

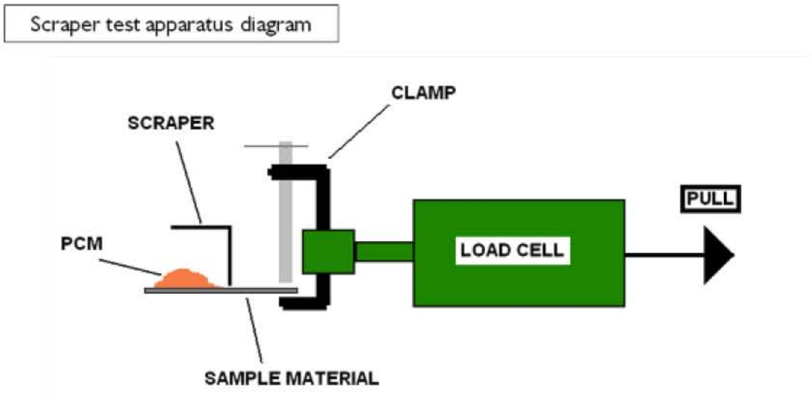


Figure 6 – Basic layout of salt adhesion testing scraper apparatus.

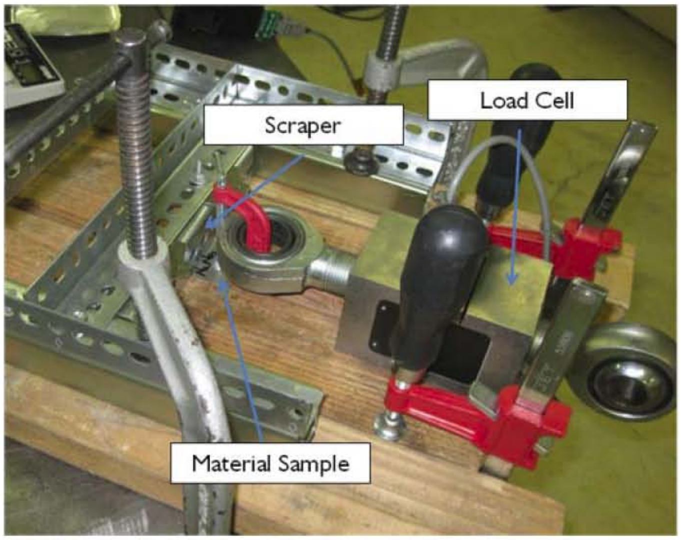


Figure 7 – Fully assembled salt adhesion testing scraper apparatus.

Table 2 – Scrape Test Results.

Salt Type -	Mill Finish lb_f	Brushed Finish lb_f	Polished Finish lb_f
$NaNO_3$	33	34	32
KNO_3	30	32	34

The values of force required to remove the solidified PCM were very high. Designing a mechanism and heat exchanger capable or surviving these forces is not feasible. However, it was concluded that these results do not represent a real life scenario because the tests occurred at room temperature. To gain a better grasp on the forces required the tests would be repeated with the material coupons near the PCM melting point to better represent heat exchanger conditions.

The testing apparatus from the first iteration was modified to incorporate a hot plate beneath the scraper. This would allow the samples to be tested near the melting point of the PCM. Figure 8 is a diagram of the modified system and Figure 9 is a picture of the actual system.

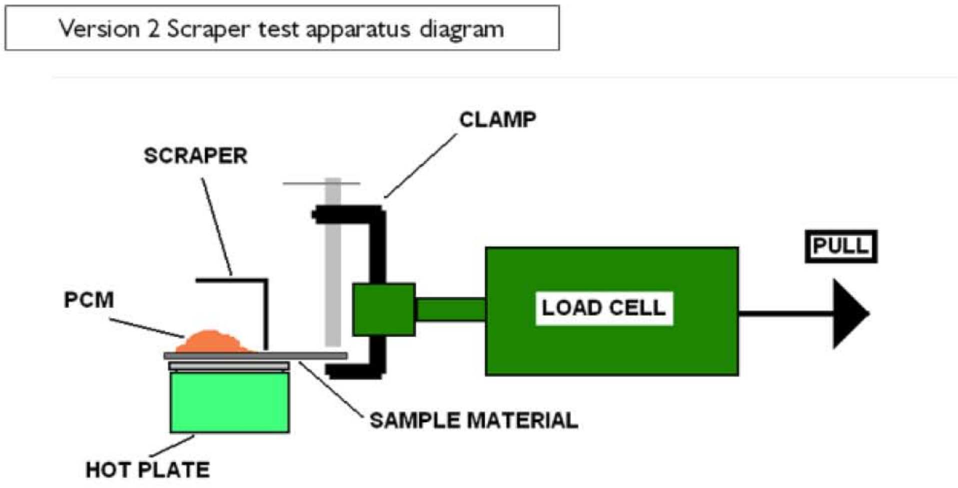


Figure 8 – Modified layout of salt adhesion testing scraper apparatus.

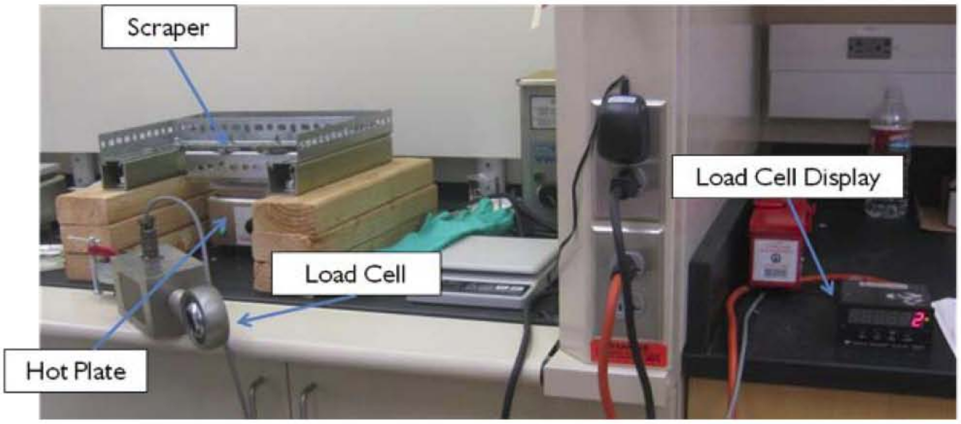


Figure 9 – Fully assembled salt adhesion testing scraper apparatus.

The modification to the testing apparatus and method resulted in a significant reduction in the amount of force required to remove solidified salt from the sample coupons, Table 3. However, it was noted that the residue remaining on the coupons was significantly thicker than the residue on the samples from the first iteration performed at room temperature. This residue is solidified PCM that has rigidly adhered to the coupon surface. Any residue on the heat exchange surface would have a negative impact on heat transfer efficiency. Thus, scraping is not a feasible option for the 100kWht test unit.

Table 3 – Second Iteration Scrape Test Results.

Salt Type -	**Mill Finish** **lb_f**	**Brushed Finish** **lb_f**	**Polished Finish** **lb_f**
$NaNO_3$	2	1	1
KNO_3	1	1	1

Agitation Testing

The next sets of tests performed were agitation tests. These tests were designed to evaluate the benefits of agitating the heat exchange surface during discharge as compared to a stationary surface. The first test simply compared between submerged stainless steel coupons, one of which was agitated and removed, and one which was not agitated. Both coupons were dipped in fully molten salt and removed after one minute. Photos of each type coupon are shown in Figure 10. A summary table from the first iteration is seen in Table 4. It is estimated that agitation reduced salt build up by nearly 14%.

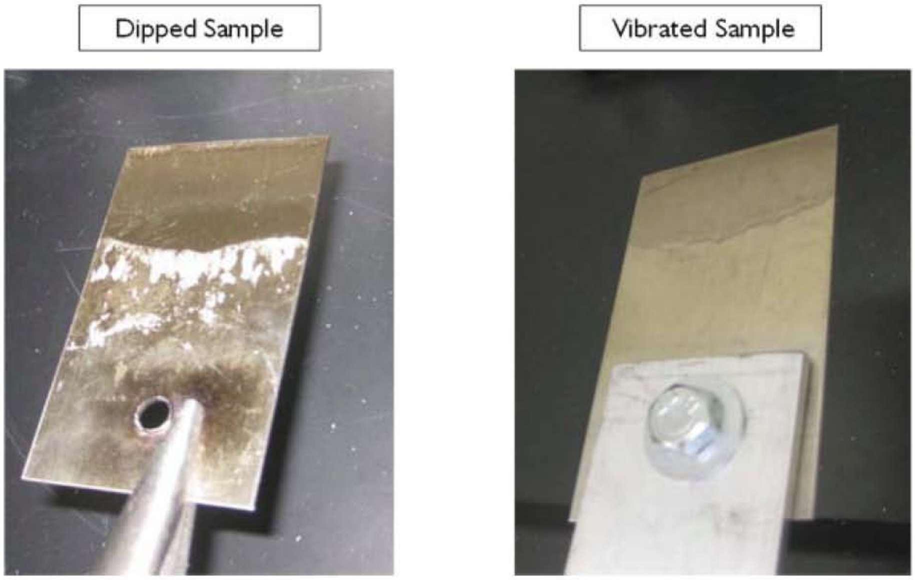


Figure 10 – Results from first iteration of agitation testing.

Table 4 – Results from Agitation Testing.

-	Coupon Thickness in.	Min. PCM Thickness in.	Min. PCM Thickness in.	Film Reduction %
Dipped	0.024	0.025	0.037	
Agitated	0.024	0.025	0.032	14

A second agitation test was performed to better simulate a heat exchanger. This test also compared a submerged and removed stainless coupon against an agitated and removed coupon. During this iteration the salt was allowed to fully solidify. A diagram of the agitation apparatus is shown in Figure 11.

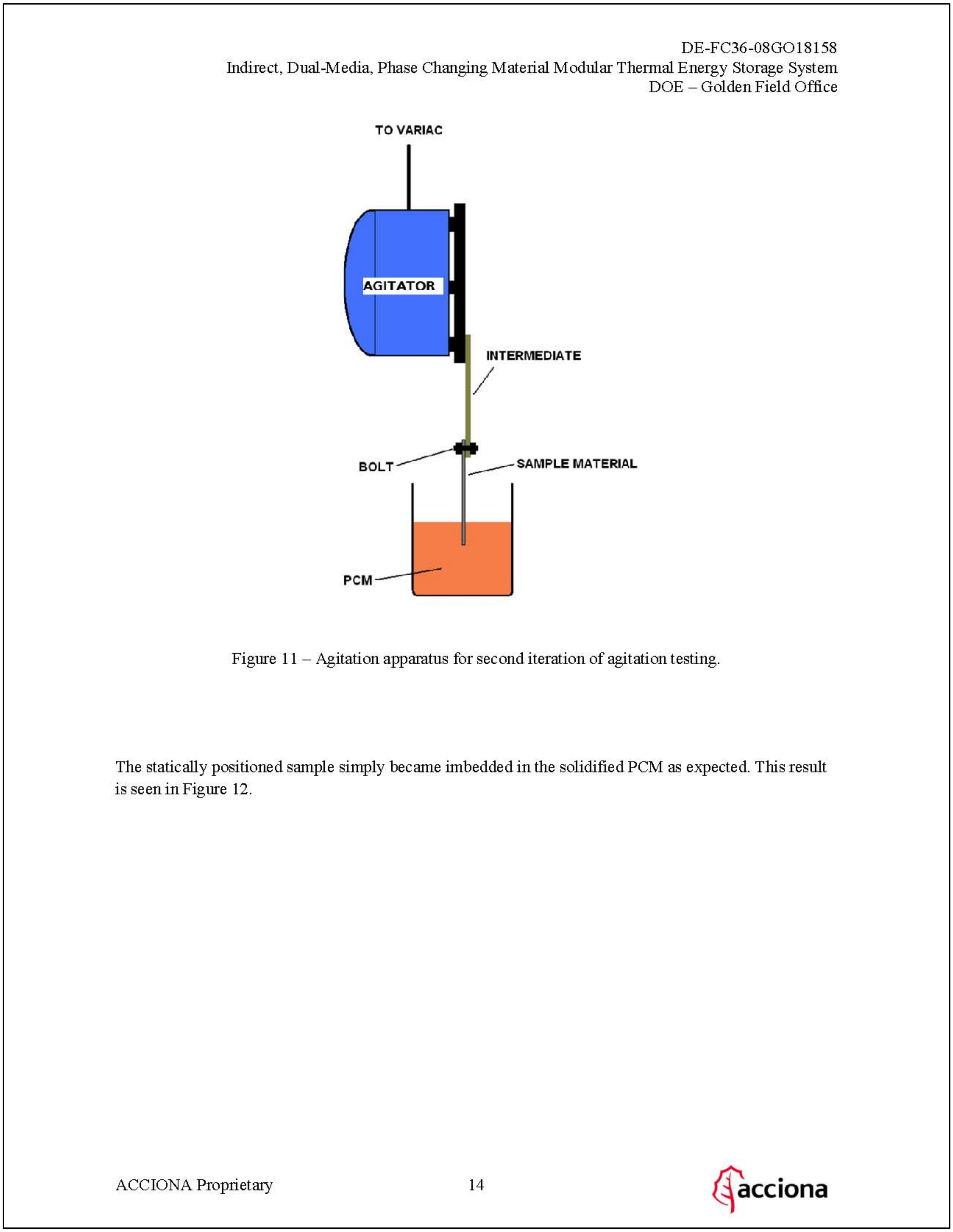


Figure 11 – Agitation apparatus for second iteration of agitation testing.

The statically positioned sample simply became imbedded in the solidified PCM as expected. This result is seen in Figure 12.

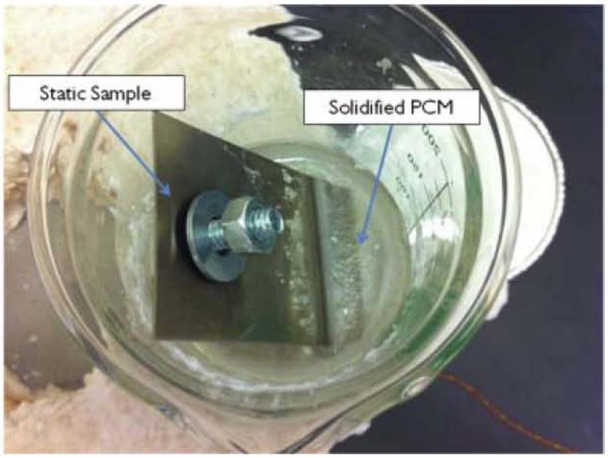


Figure 12 – Statically positioned sample.

The agitated sample had very favorable results. As seen in Figure 13, very little solidified salt build was documented which suggests that heat exchanger agitation will have a very beneficial impact on heat transfer during discharge.

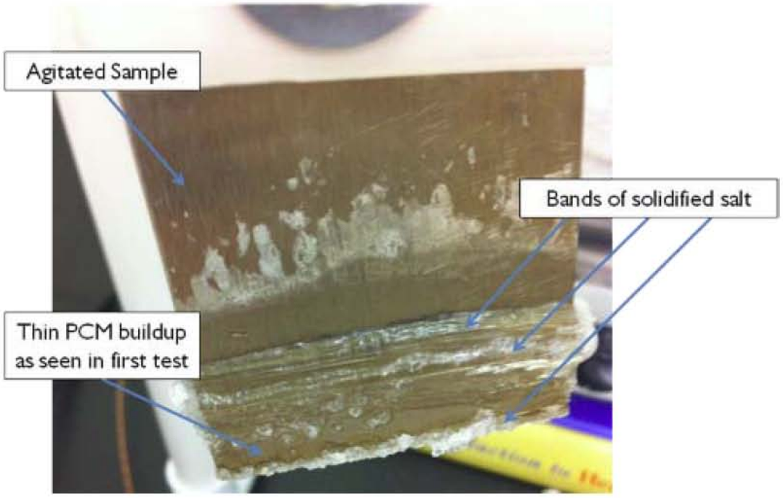


Figure 13 – Agitated sample.

Several lessons were learned during this round of salt testing. First, agitation during solidification caused solid salt particles on the exposed upper liquid level to fall to the bottom of beaker. Second, agitation during solidification resulted in minimal salt build up on the sample coupon. After evaluating the work performed, it has been concluded that agitation is the preferred solution for the 100kWht test unit. Design of an agitation unit was performed using off-the-shelf parts.

100kWht Agitation Mechanism

As discussed, lab scale salt adhesion testing led to the conclusion that agitation is the preferred solution for the 100kWht test unit. Design of the agitation unit relied on the use of off the shelf parts. There are many electric and compressed air powered solutions available from suppliers. For the 100kWh$_t$ prototype, an electric unit was selected Air powered units could reduce the overall cost of such a thermal storage system by requiring power for only a central air compressor.

The unit selected was purchased from McMaster-Carr. It is a Vibco SCR-1000. This unit is typically used in industries with vibration hoppers, such as packaging or concrete manufacturing. The unit has four bolt-though mounting tabs that can be used to secure the unit to the prototype. This model has adjustable counterweights and a user controlled speed selector. This means both agitation amplitude and frequency can be manipulated. The unit purchased is shown in Figure 14. The installed unit is shown in Figure 15.

Figure 14 – Adjustable electric agitator.

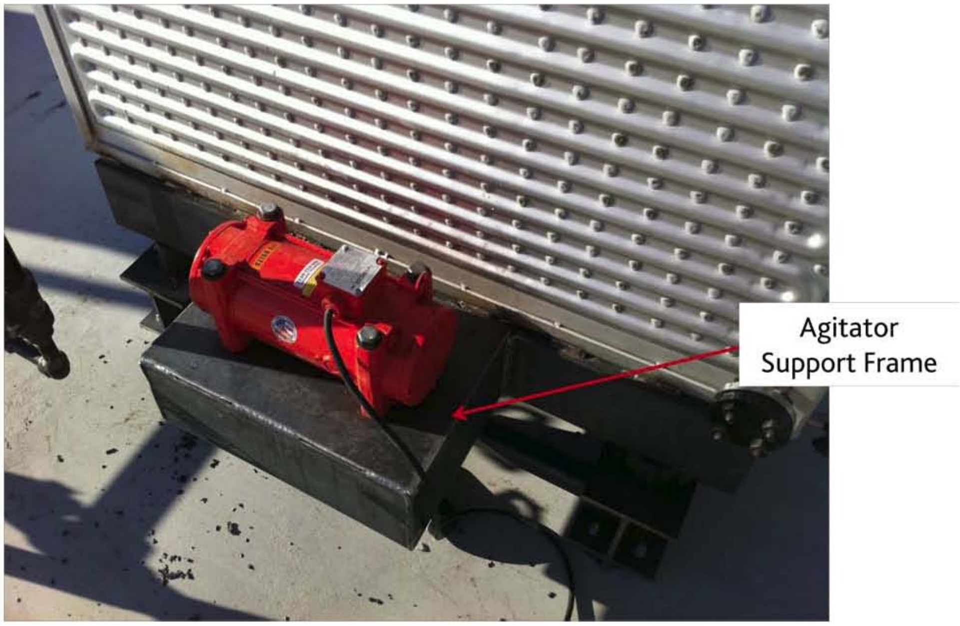
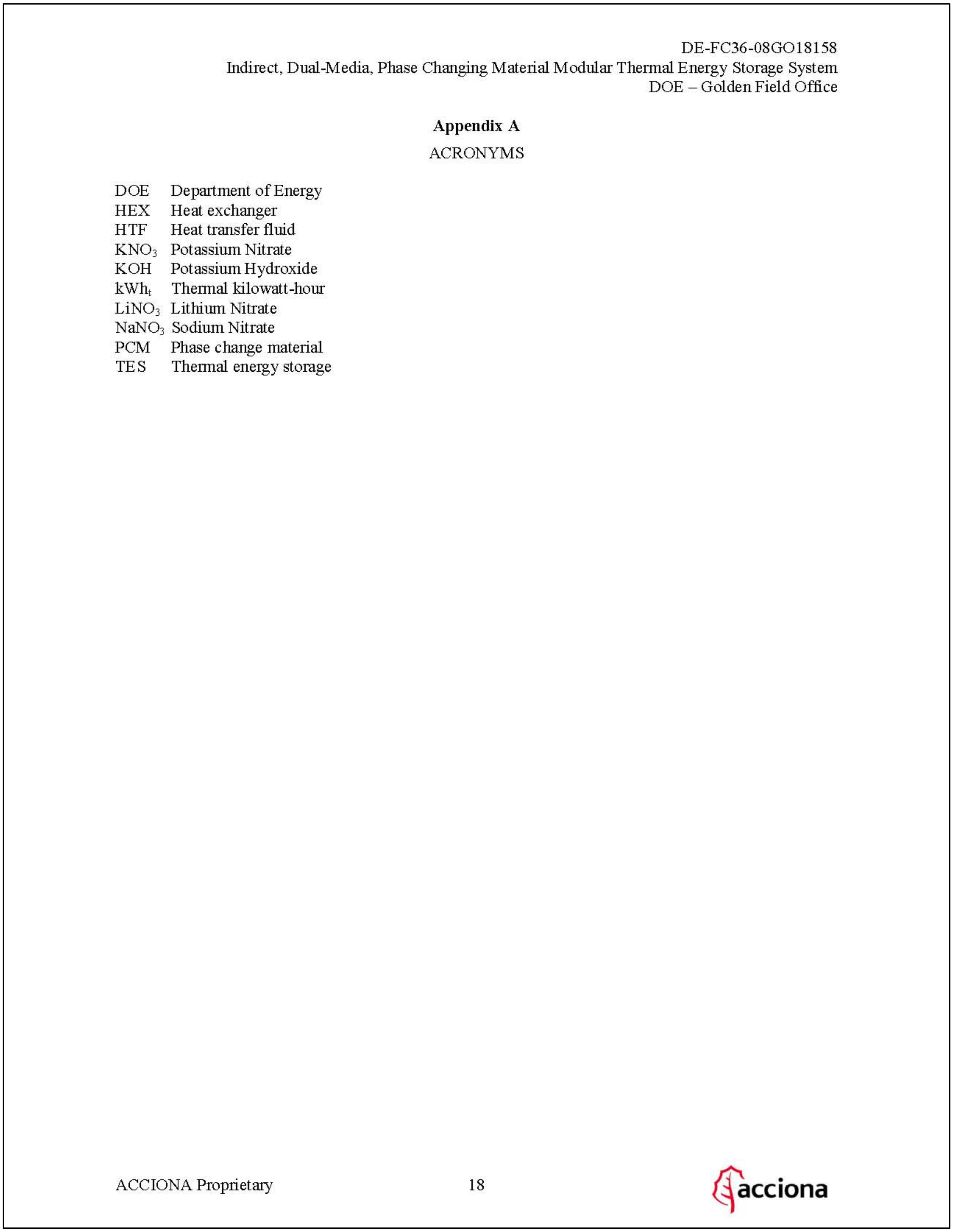


Figure 15 – Adjustable electric agitator installed on 100kWh$_t$ prototype.

Conclusion

Throughout the modeling process, the focus has been to satisfy the performance requirements of this storage concept. It has been shown that the system has the ability to reduce the amount of storage material required, and that the round trip efficiency of a PCM storage system has the potential to exceed 93%. Heat transfer and fluid dynamic analysis assisted in the design and modeling of the heat exchanger/storage tank. These analyses show that the 100 kWht prototype heat exchanger/storage tank should be capable of being charged in approximately 2 hours. Results from the experimental testing with the prototype unit will be used to refine the existing models for larger scale predictions. Additionally, the experimental results will show areas where the system can be optimized.



Appendix A

ACRONYMS

DOE	Department of Energy
HEX	Heat exchanger
HTF	Heat transfer fluid
KNO_3	Potassium Nitrate
KOH	Potassium Hydroxide
kWh_t	Thermal kilowatt-hour
$LiNO_3$	Lithium Nitrate
$NaNO_3$	Sodium Nitrate
PCM	Phase change material
TES	Thermal energy storage