PHASE 2 CONTINUATION REPORT

SANDSHIFTER SUBPROJECT
PROTOTYPE PHASE

Project Title:	CSP Energy Storage - Multiple Technologies Compared
Covering Period:	Sep 30, 2008 – Feb 28, 2012
Date of Report:	Mar 6, 2012
Recipient:	US Solar Thermal Storage LLC
Award Number:	DE-FC36-08GO18155

Contacts: **Principal Investigator**
Jake Stephens
Phone: (520) 981-7303
Fax: (520) 514-8001
Email: jstephens@greensunenergy.com

DOE Project Team: Joe Stekli, Tommy Rueckert, Levi Irwin, Mark Mehos, Cliff Ho

Abstract: This report summarizes the work of the US Solar Thermal Storage LLC ("USSTS") team on **SandShifter subproject** for **Phase 2** of U.S. Department of Energy's FOA #DE-FC36-08GO18155.005. This subproject develops a new-to-the-world, disruptive technology which leverages an abundant, inexpensive, and benign material, *Sand*, for application in Thermal Energy Storage (TES) in association with power generation from Concentrating Solar Thermal (CST) systems. Sand, as a standalone TES media, has a 10 to 25X cost per unit of storage capacity cost advantage over the prevailing technology, molten salt. The work summarized herein suggests that SandShifter, which has a non-linear cost curve favoring higher hours of storage, could likely achieve economics of $15 per kWh-th or less for several hours of storage in high temperature steam- or salt-as-HTF configurations with further technology development.

During Phase 2, this subproject successfully demonstrated a 50 kW-th, working prototype of the SandShifter system, having moved toward that result while innovating new design approaches, advanced supporting science, and vetting or quantifying numerous critical issues. Most specifically, the promise of Sand as an economical, high-temperature, TES media has been initially validated for the first time in history. Most broadly, a new knowledge platform has been founded in sand-metal heat transfer and sand-HTF heat exchange which will inform the evolution of a promising technological area. The Phase 2 work will specifically inform the execution of Phase 3 of the project for a nominally 1 MW scale demonstration project, the next major milestone in further development of this technology.

Table of Contents

List of Appendices:

Section 1
Executive Summary

Introduction: The SandShifter is a new-to-the-world Thermal Energy Storage (TES) technology being developed by US Solar Thermal Storage which offers the potential to leverage sand, a benign, low cost material, as a thermal storage media – and an alternative to the prevailing TES options in Concentrating Solar Thermal (CST) power generation systems. Sand is unique for TES not only in its low material costs per unit of energy storage (10X to 25X advantage relative to molten salt), but in its broad temperature range applicability. This wide temperature range suitability offers the potential for application in a variety of potential CST plant formats, including Parabolic Troughs and Power Towers, and potential for use at very high temperatures (e.g., 550C and beyond), and high delta-Ts, and broader approach temperatures, allowing it to benefit proportionally from the associated higher plant, storage-per-unit-of-TES-material efficiencies, and heat exchanger compaction, respectively.

Objectives: Use of sand for TES, however, requires the development of a cost-effective sand-to-HTF heat exchanger design. The purpose of this FOA project is to advance a novel concept – the rotating drum SandShifter, a two-tank style system which achieves high thermal efficiency by moving sand in counterflow to a Heat Transfer Fluid (HTF) – from an early stage concept to a initially demonstrated working design while simultaneously addressing key design challenges, vetting potential fatal flaws, demonstrating a favorable economic potential compared to alternative TES technologies, and pointing to paths for future technological development and cost reductions.

During Phase 2, specifically, the team's objective was to advance supporting science and an initial technology design into an integrated, small-scale, working prototype which would serve as a platform for direct examination, qualitatively and quantitatively, of the SandShifter technology. As such, the team sought to design, construct, and testing a 50 kW SandShifter prototype. This work collectively would then serve as a basis for updating the potential technology cost model, provide an expanded knowledge platform for future technology development, and inform the Phase 2I medium-scale demonstration project effort.

Methodology: The approach adopted by the team recognized the new nature of this technology and the corresponding needs to a) accommodate a continuous expansion of knowledge based on experimental work, new knowledge, and trial-and-error; and, b) breakdown the proposed system into its primary components, in terms of sub-systems, technical areas, and potential fatal flaws. The resulting philosophy therefore prioritized investigational areas on needs-driven basis while adopting a highly-observant and adaptive learning modality which could adjust strategies and tactics based on real-time knowledge development during the project. This investigative approach was overlaid with a multi-disciplinary team which incorporates several key perspectives to ensure the technology evolved in a way that was both reality-based and which captured the type of creative thinking only possible when experts from multiple fields simultaneously contribute to a process. Here, these include the expertise of power engineering experts, financial analysts, steel fabricators, general contractors, civil contractor specialist, materials handling equipment experts, a utility, and power project developers, among others – a range including academia, construction, and end-customers.

In practice, the team listed the critical areas for the technology's technical and cost performance and divided these into discrete analytical, experimental, and/or engineering tasks. Such key issues included, among others, the erosive effects of sand on metal, sand flow through a tube bundle, heat loss to the external environments, auxiliary load quantification, structural integrity and fabrication approaches, and sand-to-metal heat transfer performance. As such, the chapters of this report are organized to focus on the primary, critical investigation areas:

System Design
Prototype
Thermodynamic Modeling
Heat Transfer
Heat Exchanger Design
Sand Erosion
Auxiliary/Parasitics
Heat Loss
Sand Kinematics
Operations & Maintenance
Cost Estimate

Each of these areas has a number of sub-tasks, supporting analyses, experiments, and design issues to confirm assumptions, quantify performance potential (positive or negative), develop qualitative understanding of key issues, and to inform design strategies.

<u>Results Overview</u>: The team has successfully achieved its objectives to design, construct and build a 50 kW-th prototype; to vet key technological issues; to develop a platform for knowledge development; to develop supporting knowledge; and to quantify the SandShifter's economic potential.

Specifically:

1) A 50 kW-th prototype of the SandShifter was developed and tested, allowing demonstration and examination of the both the larger technological concept and a number of critical supporting concepts and related technical issues, and achievement in practice of a new-to-the-world system which exchanges heat between sand and HTF.

2) Extensive lab work examined several sub-systems, proving key concepts, examining supporting critical issues, and documenting achievable performance.

3) Various design options were vetted to advance the Preferred Design Approach, particularly as relates the heat exchanger sub-assembly.

4) Cost estimates were updated to analyze the economic potential of the technology.

5) Numerous learnings were achieved as relates all aspects of the technology, ranging from fabrication strategies, to sand kinematic behavior, to potential sand-to-metal heat transfer rates, to auxiliary loads.

6) Thermodynamic model for SandShifter technology updated, incorporating various learnings and analyses, and cases were examined to look at the technology's performance in alternate CST configurations.

Some key findings of note:

A) Achievable sand-to-metal heat exchange performance of 450-600 W/K-m2.

B**) Cost performance potential (12 to 4 hours of TES), with further technology development, of:**

i) Conventional Trough: $29-39/kWh-th;

ii) Molten Salt as HTF: $15-29/kWh-th; and

iii) Steam as HTF: $13-$31/kWh-th.

Looking Forward: Future work on the SandShifter technology must:

1. **Examine the system at larger scale, and with the full configuration** (including MHE and sand storage vessels), to learn from the experiences which will be derived in the areas of fabrication, O&M, and configuration for optimal future design. This is intended work for Phase 3, pursuing a 1 MW demonstration project.

2. **Examine application of the SandShifter for molten salt and steam as HTF options**, and the corresponding CST configurations.

    a. Phase 3 work might be modified to focus on these applications.

    b. Optimize the system design by more intensive investigation and development of design options, in terms of available technologies and development of new technologies and configurations, particularly in the context of alternative CST plant configurations.

Other comments on 'Looking Forward' elements pertaining to the project's various areas of investigation are found in the respective sections.

Recommendations:

1. **Fund and pursue Phase 3** of the project, allowing adaptations for higher temperature and alt-HTF applications, as manageable given the available Phase 3 budget.

2. **Expand the R&D program** to more fully examine and demonstrate the potential of the SandShifter technology with alternate CST plant configurations, in order maximally cultivate and demonstrate the potential of sand as TES. This would ideally leverage additional engineering and analytical resources to systematically examine and cultivate the design options and their corresponding cost outcomes. Several options are proposed to expand Phase 3 to develop these areas.

Section 2
Objectives

1. Executive Summary

During Phase 2, the objective was construct an integrated, working SandShifter prototype, while examining various design options, quantifying performance and cost potentials, advancing the related fundamental science. Work would thereby further demonstrate the technology's feasibility, provide important learnings, and inform Phase 3 work, a 1 MW scale demonstration project.

The specific SOPO tasks and milestones are summarized in this section, along with broader objectives incorporate during the project. These objectives were met during Phase 2.

2. Objectives

During Phase II, the team's objectives were to advance the SandShifter technology into an integrated, working Prototype, while examining various design options, quantifying performance and cost potentials, advancing the related fundamental science (largely a new area), and improving the Preferred Design Approach for the SandShifter technology. Pursuit of these objectives advances the maturity of this new-to-the-world technology and provides a platform for Phase III of the Award, construction a nominally 1 MW scale demonstration project, which will feature further investigation of certain aspects while demonstrating the technology at larger scale. The Prototype will allow examination of the core heat exchanger and sand conveyance system, demonstrating simultaneously implementation of key aspects of the SandShifter concept.

Generally, the team sought to learn as much as possible on as many avenues as possible, given the resources and formal objectives. The following are the official Tasks and Milestones are excerpted from the "SOPO" for the project, shown below in Table 2.1.

In addition, the team sought to expand its knowledge and further validate in each of the perceived "Fatal Flaw" areas, topics that were potential issues for which to examine, quantify and/or qualify performance, and include in the total system model. See Table 2.2.

3. Summary

All issues were investigated, SOPO milestones met, and results included in the this report, as well as in the performance modeling, cost analysis, and learning set for future investigation or addressing in future design evolutions.

Task/ Milestone	Item	Description	Status
Task 2.0	**Design Prototype**	Develop a design for a lab-scale prototype of the technology, including definition of the required tests, instrumentation to perform tests, and a	Done. See Section 5 "Prototype"
Milestone 2.0	**PROTOTYPE DESIGN FINAL**	Prototype Design Finalized	Done. See Section 5 "Prototype"
Task 2.1	**Construct Prototype**	Implement the prototype, as designed, adapting along the way for lessons learned and new observations. Test instrumentation. Test sub-prototype system components.	Done. See Section 5 "Prototype"
Milestone 2.1	**PROTOTYPE OPERATIONAL**	Prototype Fully Operational	Done.
Task 2.2	**Operate Prototype & Perform Tests**	a) Commence operation of the prototype, performing the tests designed and b) seeking to maximize lessons learned in support of the	Done: a) Section 5 "Prototype"; b) Section 17 "Lessons Learned"; c) Section 5 and Appendix 5-[1]
Task 2.3	**Final Detailed Cost Estimate**	Update cost estimates based upon design modifications resulting from prototype experiments.	Done. See Section 14 "Cost Estimate" and Appendices
Milestone 2.2	**COST ESTIMATE COMPLETE**	Cost Estimate Complete	Done, per above.
Task 2.4	**Analyze Scaling Issues**	Analyze the ability of the project to successfully scale to 1 MW and 50 MW formats in terms of 1) Technical Issues; 2) Required design modifications as indicated by prototype effort findings and their cost implications.	Done. See Section 14 "Cost Estimate" and Section 19 "Phase 3 Proposal", as well as cumulative results of Phase 2, summarized in Section 18 "Conclusions".
Task 2.5	**Develop Test Plan Outline for Demo Project**	Use operation of the prototype to outline the operational plan and tests required for the Demonstration Phase. Seek support in these tasks from the national laboratories.	Done. See Appendix [X] "Demo Project Test Plan Outline".
Task 2.6	**Project Management & Reporting**	Reports and other deliverables will be provided in accordance with the Federal Assistance Reporting Checklist following the instructions	Done.
CRITICAL MILESTONE	**GO/NO-GO DECISION**	In order for either/each TES technology to proceed to Phase 3, it must (including design modifications during this phase):	USSTS team recommends Phase 3:
		1) Have shown successful functionality in a way that leads the project team to believe it will function successfully over a multi-year term at the 1 MW and 50 MW scale.	Yes; prototype quantative and qualitative results, with related learnings support likely viability at 1 MW and 50+ MW scales. See results throughout report.
		2) Still meet cost-effectiveness objectives at the 50+ MW scale or have promise to do so.	Yes, see Section 14 "Cost Estimate" and 15 "Cost Analysis".
		3) Still meet budgetary provisions for the 1 MW demonstration phase.	Yes

Table 2.1 – Project SOPO Overview & Status

In meeting the SOPO objectives, the team also applied a constructive cross-lens to inform its efforts, focusing R&D efforts on the most critical areas for the technology to develop. Thus, the addressing following "Limiting Flaws" or "Fatal Flaws" were key research objectives, and the results addressing each area form the structure of this report, as shown in Table 2.2.

Potential Issue	**Description of Issue**	**Comments/Status**	**Applicable Report Section**
Excess Parasitic Power (O&M)	Confirm the parasitic and auxiliary levels. Model these into total performance model. Confirm not fatal or exceedingly burdensome to technology.	Auxiliary and parasitics have been calculated and included in the technology performance model. Total modeled parasitics of roughly 7% are acceptable and likely reduceable with alternative MHE design.	Section 10 – Auxiliary & Parasitics
Sand-to-Metal Heat Transfer	Quantification of maximum and field achievable Sand-to-Metal heat transfer needed as basis for SandShifter thermodynamic model. Key driver in SS sizing and therefore SS cost.	Lab and field experiments (including operational Prototype) confirm achievability of 450 W/m2-K with commercial grade sand. Likely 600 W/m2-K will be approachable with design improvement. Included in SS thermodynamic model.	Section 7 – Heat Transfer
Sand Distribution over/in Tube Bundle	Good distribution of sand over tube bundle required for good heat transfer performance. Drives SS cost as a contributor to heat transfer performance. Two components, 1) Sand over top of tube bundle; 2) Sand within tube bundle.	Prototype demonstrated that this is achievable and heat transfer results confirm success. Several lessons were learned however and will guide future design.	Section 5 – Prototype; Section 12 – Sand Kinematics; Appendix 5-5 – Lessons Learned
Tube Bundle Structural Strength	Tube bundle must be long enough to span the drum but needs to be largely self supporting.	Initial indications are that this will be achievable. Zig-zag design is relatively self supporting. Truss perhaps needed; included in cost estimate.	Section 8 – Heat Exchanger Design
Tube Bundle overload by sand	If excessive sand accumulates in bundle, structural or functional failure possible.	Not considered a material issue. Essentially a function of plate spacing, managed with design.	Section 8 – Heat Exchanger Design
Heat Losses to Surrounding Soil	Need to quantify heat losses for in-ground storage vessels. Confirm acceptable levels. Include in system model.	Model was developed. Knowledge developed on transient and static losses, convergence rates. Levels are acceptable, converging to 50kW-th/pit in 50 days, and included in model.	Section 11 – Heat Loss
Excessive Wear / Erosive Sand Effects	Erosive effects of sand may erode tubes or grind away mechanical parts	Internal wear (tube bundle) minor issue (if at all); wear in MHE managed through design/cost; manage at interface points (lesser) to refine.	Section 13 – O&M Section 9 – Sand Erosion
Technology Cost	Price needs to be competitive with alternative technologies	Technology very promising, likely/potential superiority to prevailing TES technologies.	Section 14 – Cost Analysis

Table 2.2 – Fatal Flaws to Analyze

Section 3
Methodology

1. Executive Summary

The SandShifter is a new-to-the-world technology being developed in a multi-phase R&D project. The technology is largely mechanical in nature and oriented towards achieving a lowest cost outcome through improvement in heat transfer performance, minimizing of thermal and auxiliary losses, and minimizing capital expenditure. The final technology needs to deployable through project finance in multi-hundred million dollar CST power plants. During Phase 2 of the project, *the goals were to further advance supporting science and validate the SandShifter working concept through fabrication and testing of a 100 KW prototype (the "Prototype").*

As a result, an interdisciplinary approach was adopted which, in Phase 2 particularly, employed an iterative, trial-and-error approach to develop optimal outcomes, particularly in development of the design and ultimate fabrication techniques for the Prototype.

2. Objectives of Methodology

To state and discuss the methodology utilized by the USSTS team to develop the SandShifter technology during Phase 2 and the project as a whole. The methodology adopted needed to:

a) Accommodate a continuous expansion of knowledge based on experimental work, new knowledge, trial-and-error; and iterative advancements, and,

b) Breakdown the proposed system into its primary issues areas, in terms of sub-systems, components, technical areas, and potential fatal flaws.

c) Achieve the Project Objectives

3. Literature Review

N/A

4. Methodology

The methodology pursued on the SandShifter project incorporated the following principles and values:

- Highly-observant and adaptive learning modality
- Adjust strategies and tactics based on real-time knowledge development during the project.
- Multi-disciplinary team which incorporates several key perspectives, including power engineering experts, financial analysts, steel fabricators, general contractors, civil contractor specialist, materials handling equipment experts, a utility, and power project developers, among others – a range including academia, construction, and end-customers.
- Creative
- Iterative
- Investigation and demonstration of subsystems and supporting phenomena to develop qualitative and quantitative understanding of key behaviors for the combined system.
- Literature investigation

- Seek specialist help from expert vendors where possible
- Manage costs effectively to realize the optimal “bang for buck”
- Focused on key issue areas and potential fatal flaws:

    - System Design
    - Prototype
    - Thermodynamic Modeling
    - Heat Transfer
    - Heat Exchanger Design
    - Sand Erosion
    - Auxiliary/Parasitics
    - Heat Loss
    - Sand Kinematics
    - Operations & Maintenance
    - Cost Estimate
    - Cost Curve Potential

During Phase 2, the goal was to advance the design and performance of the core heat exchanger and better quantify certain fatal flaw area behaviors (such as heat loss to ground) while working toward an integrated, proof-of-concept validation in the form of the Prototype.

5. Analysis

This methodology was highly successful. The adaptive mentality enabled the team to maintain a measured approach when design alternatives and improvement opportunities were encountered. Lessons learned were documented to capture all the hands-on experience and operational “know-how” gained during Phase 2 activities, This ultimately allowed for lessons to be learned less expensively by optimizing the prototype system in every step of development. While this did increase the time in the process, it also helped the team avoid fabricating an entire Prototype system with a potentially expensive flaw to correct. Furthermore, the documented lessons learned from the prototype phase directly translate into system performance benefits moving forward towards the goal of commercialization.

.

Section 4 - Design Overview

1. Executive Summary

The US Solar Thermal Storage ("USSTS") team has continued advancement of the SandShifter ("SS") Thermal Energy Storage ("TES") technology with certain further advances in design at the system level, sub-system level, and component level. The larger system proposed under this project remains essentially the same. Key developments were primarily at the subsystem level, including further development of an alternate interior design for the heat exchanger, "Zig-Zig Plates". This approach, instead of finned tubing more than doubled the MW capacity of a given length of heat exchanger, with a significant downward shifting of the technology cost curve, as the heat exchanger represents a major portion of the system costs. The Rotating Drum SandShifter system as currently envisioned is described in this section of the report, using 50 MW, conventional VP-1 system with four (4) hours of storage. This "Reference Plant" is utilized as the basis reference point for the cost estimate performed, for performance analysis, and for scaling and cost analysis contained in Section 14 of this report. That analysis also contemplates the cost curve impacts for application of the SandShifter to alternative CST configurations, such as high temperature environments with salt or steam as the HTF.

2. Objectives

The objective of this section is to describe the Rotating Drum SandShifter TES technology as currently envisioned and to document the Reference Plant attributes utilized as the basis of the performance and cost analyses contained in this report.

3. Literature Review

The pertinent literature for consideration as relates sand TES system design is somewhat limited, as the use of sand for TES is a relatively new field. Two primary systems have been proposed previously, as follows:

Babcock and Wilcox, "Selection and Conceptual Design of an Advanced Thermal Energy Storage Subsystem for Commercial Scale (100 MWe) Solar Central Receiver Power Plant", 1981.

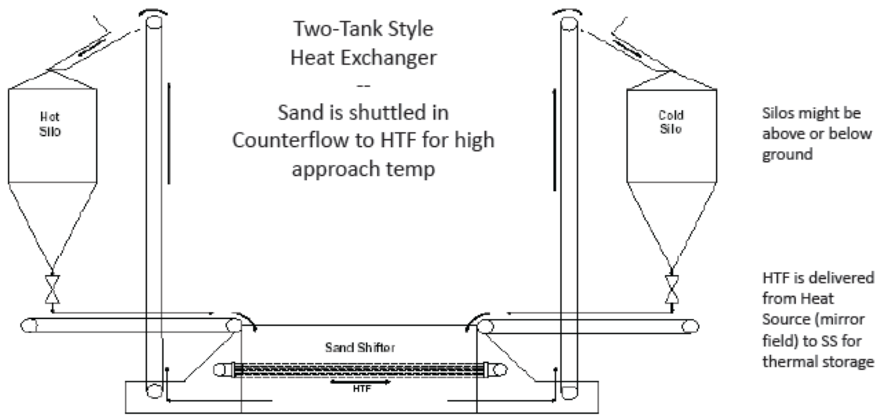
Warerkar, et al, published a paper titled "Air-Sand Heat Exchanger for High Temperature Storage".

4. Rotating Drum SandShifter - System Design Overview

The Rotating Drum SandShifter TES system remains similar to the design presented in the end of the Phase 1 Report. Design advances have continued, in particular with the redesign of the heat exchanger's interior tube bundle from a finned-tubing concept to a "Zig Zag" plates design. The Zig Zig plates concept (with a diameter change) increases the reference 100' rotating drum from a 6.25 MW reference capacity in Phase 1 to a 16.7 MW. In relation to this and other factors, the pit dimensions have expanded, in view of the potential for cost reductions.

<u>System Overview (Macro Level)</u>: The goal of the SandShifter technology is to use sand or other cheap particulate as the storage medium. The SandShifter is a new enabling technology which is a combined sand conveyor and heat exchanger. This unit moves the sand and oil in general counterflow as heat is exchanged, as shown in Figure 4.1. The configuration is similar in style to

other two-tank TES technologies, however seeks to leverage the 10-25X cost superiority of sand versus molten salt per unit of energy stored via creation of a cost effective heat exchanger.



The "SandShifter" is *combined* Conveyor & Heat Exchange Device

Figure 4.1: SS Process Flow System Overview Diagram

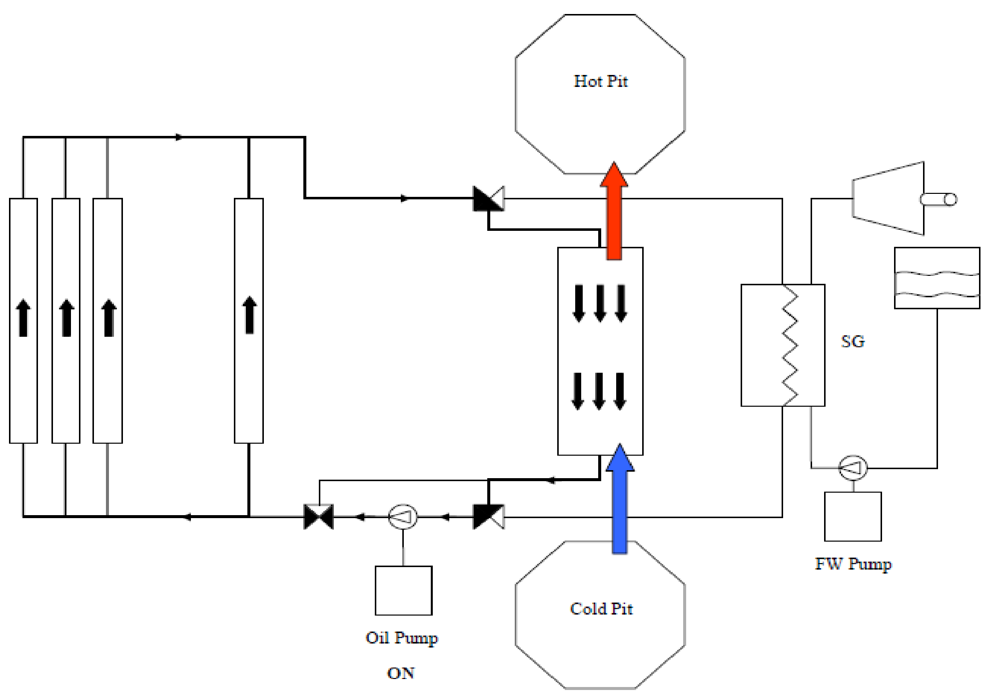


Figure 4.2: System Diagram (Charging TES) – Overhead View

<u>Component Systems:</u>

The Rotating Drum SandShifter is comprised of the following major subsystems.

- **SandShifter Heat Exchanger** (SSp) – a combined heat exchanger & conveyance device ("SandShifter proper")
- **Rotating Drum:** Device for conveyance of sand from Vessel to Vessel and Heat Txfr. Contains tube bundle.

- **Sand Storage Vessels:** Tanks, pits, bins, silos – for the sand to be stored in, taken from.
- **Tube bundle:** The actual heat exchanger. Construct through which sand falls and HTF flow (separated).
- **Materials Handling Equipment (MHE):** Deliver the sand to/from the Vessels and SSp.

Each of these component systems are explained further in this report as section. Detailed examination of their respective behaviors, as well as their combined behaviors, have been examined more closely in the experimental work conducted in Phase 1 and 2, and are discussed in the various applicable sections of this report.

Each SSp unit (including its respective subsystems) would be able to operate independently, providing varying storage capacities which could adapt to CST plant operating conditions. The capacity of each SSp depends on the scale and effective heat transfer achieved. The number of hours of storage for a SSp's capacity level is dictated by the amount of sand made available to the unit. Operations and controls are further discussed in "Section 13 – O&M".

<u>SandShifter Heat Exchanger Design</u>:
The Rotating Drum SandShifter is an innovative alteration of the classical Archimedes screw, which uses the traditional internal helical vane to move sand axially and an added longitudinal vane or scoop to lift sand and rain it over the stationary tube bundle. The SSp's rotating drum is situated on a chassis on which it rotates longitudinally. As illustrated in Figure 4.3, sand is shuttled between hot and warm reservoirs using an Archimedes screw. As the sand is conveyed, it is also continuously lifted via scoops and rained over piping carrying the heat transfer fluid (HTF) for heat transfer. Direction of sand flow is reversible by reversing the rotation direction drum.

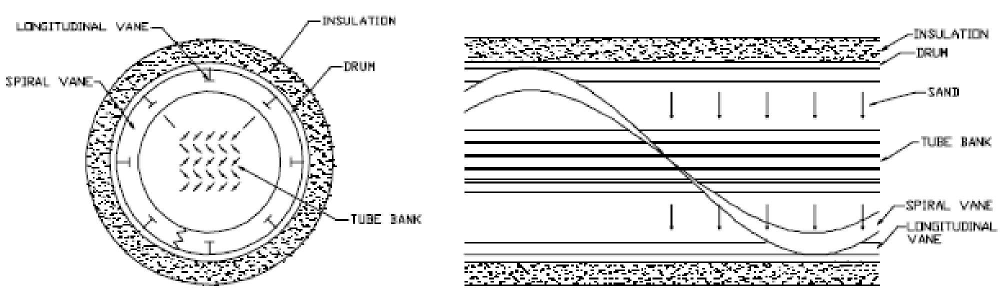


Figure 4.3: Cross Section and Profile Views of Detains the Conveyor and Heat Exchange Drum in the Sand-Shifter TES System

Figure 4.4: Images of Design Employed in 50 KW Prototype

Note that the Archimedes screw has no close sliding fits and no sliding metal to metal contact at all (which is in contrast to an auger or screw conveyor), minimizing the issue of abrasive contact of sand. Indeed, sand falls gently on the tube bundle. (Our sand erosion experimental work and related analysis is discussed in Section 9 of this report.)

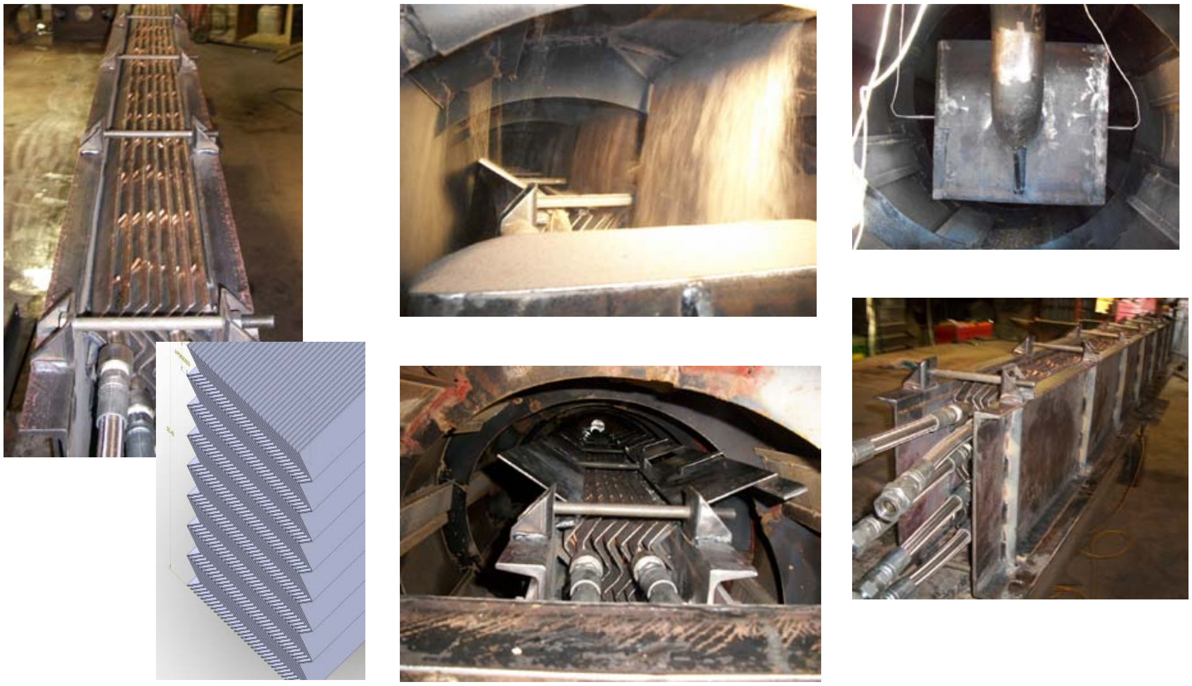
As the oil passes through the conduits in the drum (shown above as pipes, for the sake of illustration), the sand rains across the surfaces of the HTF-filled conduits, causing heat transfer through two successive heat transfer processes:

1) *Sand-to-metal heat transfer*, a relatively new technology area (see Section 7); and
2) *Metal-to-HTF heat transfer*, a well understood area of science and technology

Depending on flow directions, the process is either charging the HTF with heat from hot sand or, conversely, charging the sand with heat from the hot HTF. The conduits were initially contemplated as pipes equipped with fins (longitudinal fins are shown in the figure above); the preferred design is currently a Zig Zag plate based design (shown in Figure(s) 4.3 – 4.5).

The Zig Zag design is relatively self-supporting and provides two key features resulting in superior heat transfer: 1) Good oil side convection coefficient; and 2) Good sand coverage on the metal surfaces. As a result, heat transfer coefficient assumed in our thermodynamic model increased from 300 W/m2-K for the former Phase 1 design to 450 W/m2-K for the Zig Zag design (substantiated in experiments discussed in Section 7, Heat Transfer). As high as 600 W/m2-K may be achievable with commensurate reductions in the resulting SS cost curve.

Heat exchanger design options and the evolution thereof are discussed more fully in Section 8.



Zig Zig Tube bundle Design Concept and as Fabricated for 50 kW unit

Zig Zag Tube bundle installed in 50 kW Prototype

Manifold and connectors for 50 kW Prototype

Figure 4.5: Zig-Zag tube bundle design; employed in 50 KW Prototype

<u>SS Plant Layout & Storage Vessels</u>

The SandShifter is currently contemplated with in-ground storage vessels, as shown below in Figure 4.6 and 4.7. This is due to a perceived cost advantage of in-ground pits (over above-ground tanks or silos) in the expected project areas, such as the Desert Southwest, realizable through a construction technique which allows for large earth movers to excavate in a cost effective manner (show below in Figure 4.8). The in-ground design minimizes auxiliary materials handling equipment since the Sand Shifter drum can deliver sand to the pits and only a vertical conveyor is needed to remove the sand.

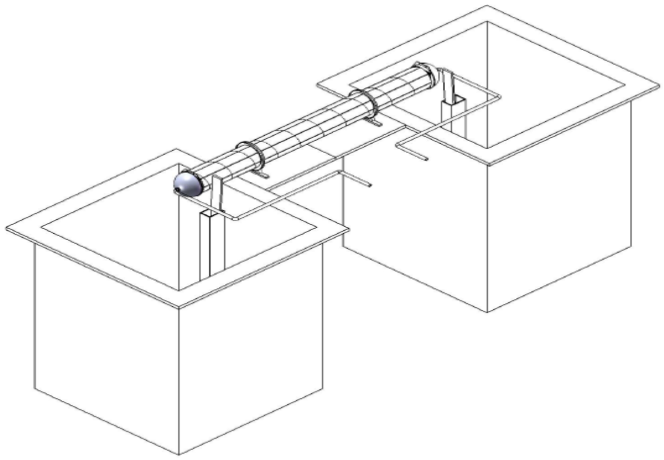


Figure 4.6 : Single SandShifter Unit with Sand Storage Vessels ("Pits")

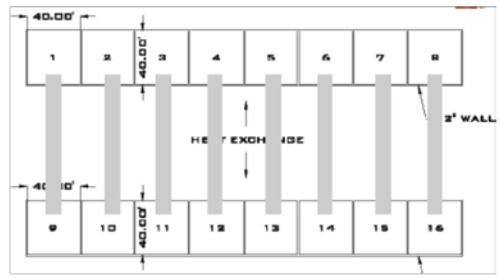


Figure 4.7: Example System Layout – Overhead View

Pit utilization is assumed at 70%, which requires the used of a low cost, yet to be designed, gravity-driven distribution ramp system. 78% is perhaps achievable, relative to a likely theoretical limit of 83% for a rectangular volume. (Going from 70% to 78% is worth around $0.25/kWh-th on average among the cases, around 50-cents for the Reference Plant case.) Appendix 4-2 discussis this further.

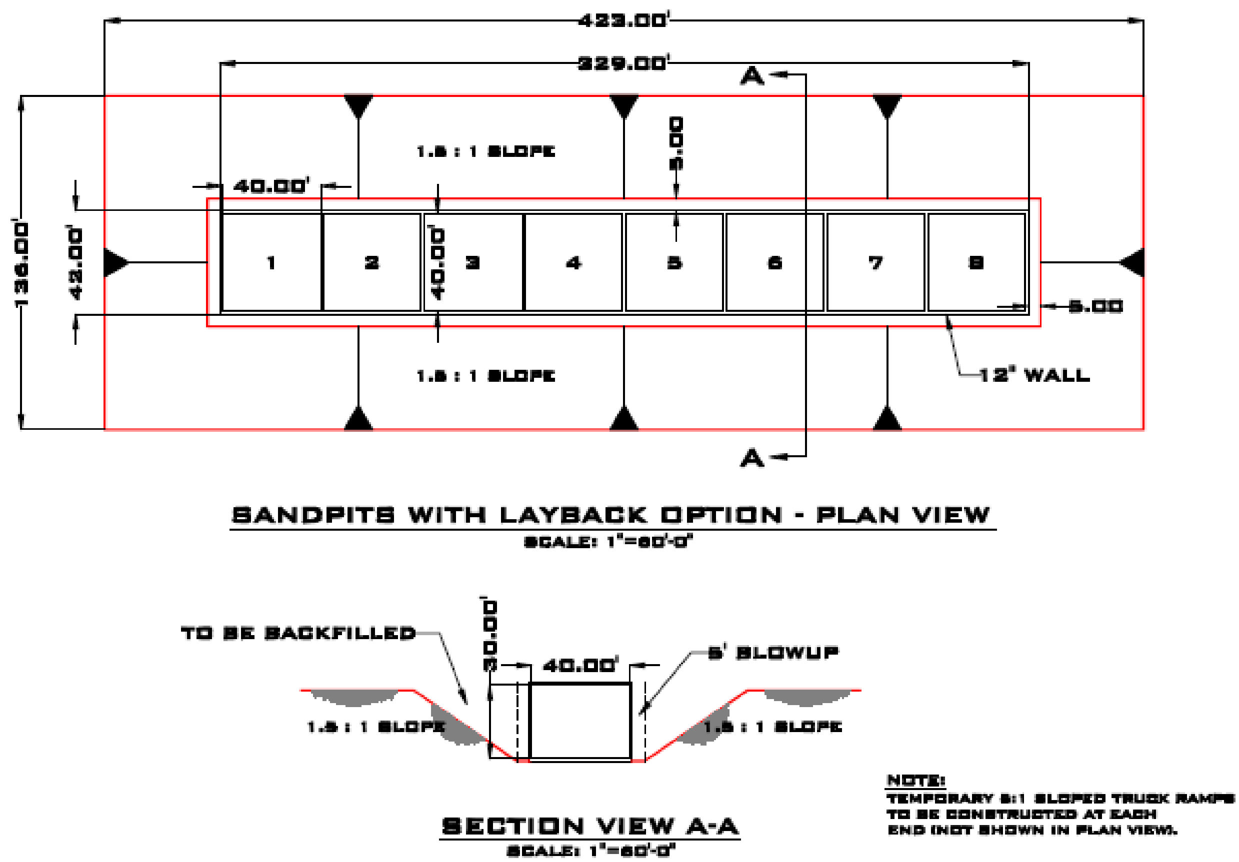


Figure 4.8: Example System Layout for Row of Pits
Showing Construction Technique
(not actual dimensions for Reference Plant)

Alternate in-ground designs have also been considered, as shown below in Figures 4.9 and 4.10 which are labeled, respectively, Trough #1 (flattened V bottom) and Trough #2 (inverted pyramind with flat bottom). The goal of these options was to evaluate the potential for cheaper storage vessel costs on a per unit basis.

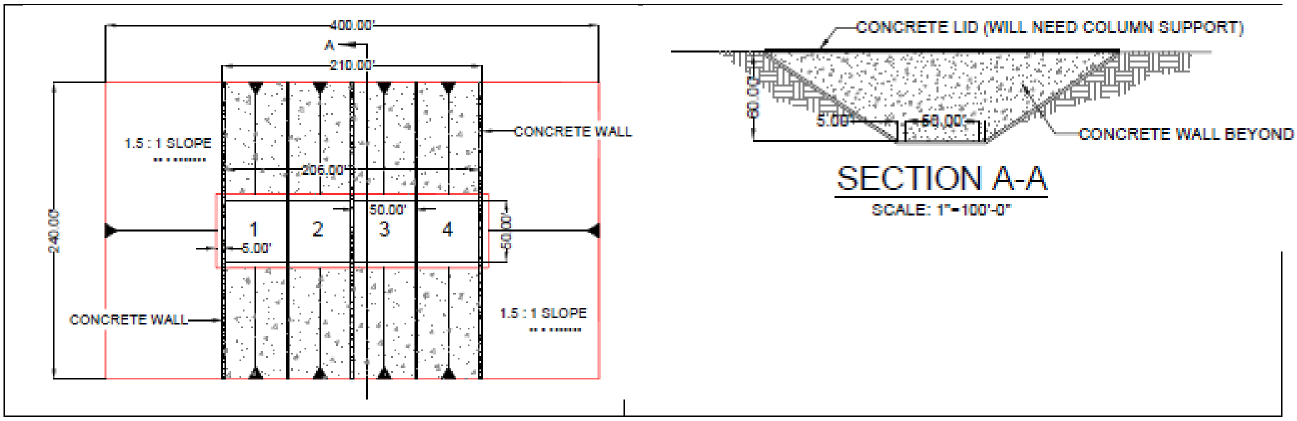


Figure 4.9: Trough #1 Design Option
(not base design for Reference Plant)

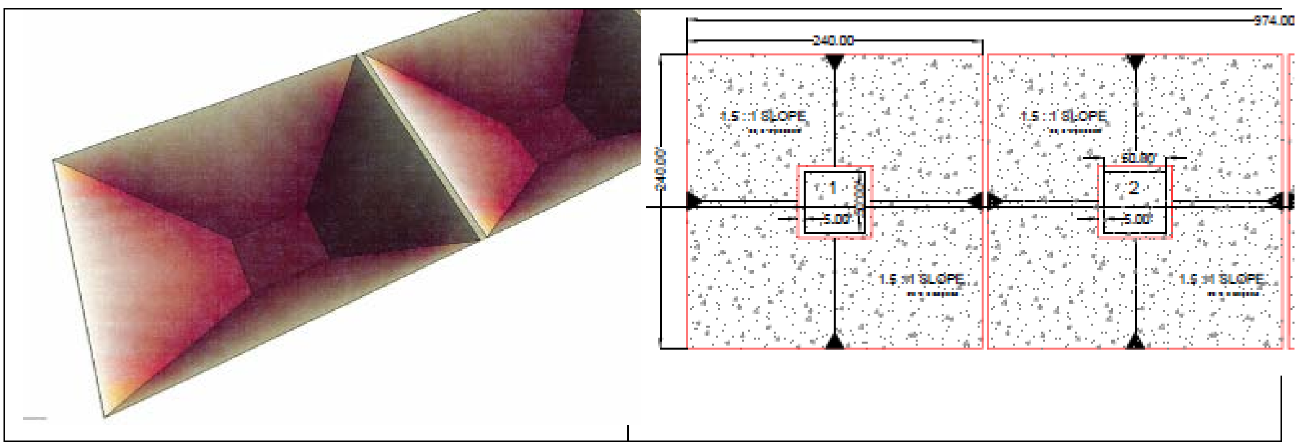


Figure 4.10: Trough #2 Design Option – Inverted Pyramid
(not base design for Reference Plant)

Complete design documents used for these in-ground cost estimates are shown in the Appendices for this section and discussed more fully in Section 14 – Cost Estimate.

Reference Plant Characteristics

For the sake of having a primary design as the basis for discussion and certain investigations (i.e., performing a cost estimate), the following "Reference Plant" was defined and examined. The Reference Plant is a design to achieve four (4) hours of thermal energy storage for a 50 MW plant using the operating conditions (temperatures) of a traditional Therminol VP-1 based

Parabolic Trough as the base CST plant configuration. (The technology could also be applied to other CST plant configurations and operating temperatures, discussed further below in this section and examined more closely in Section 6.)

A 100’ length rotating drum was the base SSp unit from which the remaining system was sized. This size derived from expectations of improved economies of scale at a larger unit size for each SandShifter Proper (rotating drum assembly), which minimizes the number of MHE assemblies, a key cost driver; thus, the team focused on the largest scale which seemed comfortably achievable. Assuming Sand-to-Metal heat transfer rates of 450 W/m2-K (the lower end of lab levels), each SSp unit then shows a nominal 16.7 MWe capacity for storage. Actual hours of storage derives from the volume of sand available. Final preferred scale of the SSp subsystem (and performance at a given scale) would depend on a more detailed cost analysis of the impacts of different scaling variations.

Total plan scale is flexible and due to the modularity of the SSp units. In the Reference Plant, three 16.7 MW units are combined to create a peak storage capacity (pre-parasitics) of 50 MWe. Doubling the number of units, for example, would provide for a 100 MW system. Application scale could be adapted per specifications for as many units as desired and supportable by the larger CST plant and its site conditions.

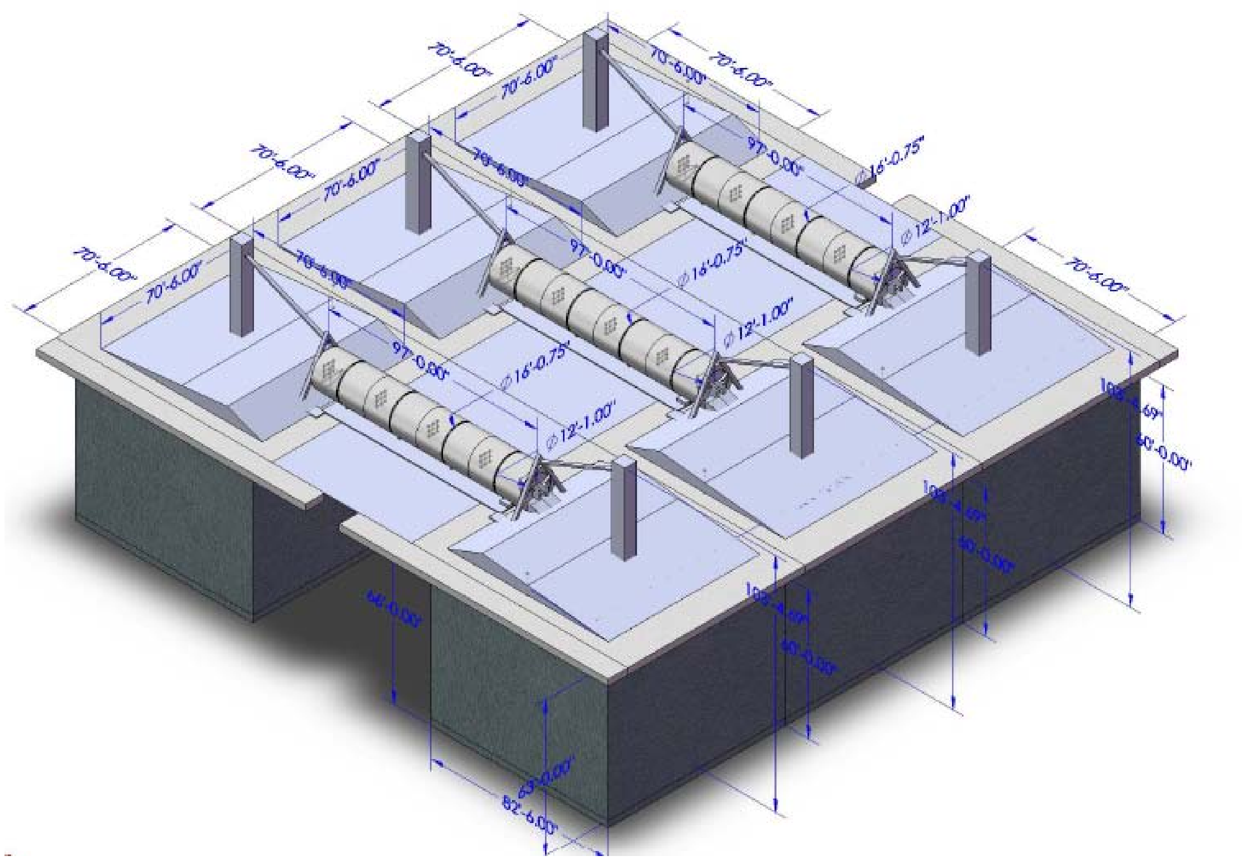


Figure 4.11: Reference Plant Design

Full design specifications for the Reference Plant are provide in Appendix 4-1. Additional drawings are found in Appendix 4-3 – Reference Plant Design Drawings. Dimensions would vary with various CST configurations.

Materials Handling Equipment

Initially, the critical significance of the auxiliary materials handling equipment was not fully appreciated. Nevertheless, as the design has been further developed and analyzed, this sub-system has emerged as a major cost driver. This subsystem bears the bulk of the impacts from the abrasive nature of sand and for the high temperature operating environment. Equipment is thus designed and specified to deal with these issues, each of which is separately familiar to the MHE industry, however the combined effect of the two is a key reason for the high cost of the related equipment in the estimates contained herein. Currently we are considering conventional conveyors, such as the bucket elevator (costed herein). Low cost alternatives such as a clamshell/dragline pits (merits discussed further in Section 10), could reduce capital costs and parasitic loads. In addition, we are continuously trying to conceive of simpler transformative ideas. Support has been provided by Screw Conveyor Corporation in this area, including design options and cost estimation. Implementation will require closer examination of design details and their cost and performance consequences, to be considered more fully in Phase 3. A more extensive investigation into design alternatives and optimization of this subsystem is recommended. It is a key area for cost reduction, both in terms of initial capital expense and long-term O&M costs.

Sand

Various sands are available commercially with size and cost varying somewhat. Sand is generally a cheap commodity and plentifully available, particularly in CST project locations. As heat transfer improves with a decrease in particle size, finer, perhaps manufactured sands are preferred, as discussed in Section 7.

U.S. spot market pricing for sand ranges from $30 to $70 per short ton, driven in the U.S. by the oil and gas industry, which utilizes the currently preferred 100-mesh sand for hydraulic fracturing extraction techniques ("fracking"). However, sand purchased via a negotiated contract is expected to be safely at the lower end of this range, if not lower. Given CST project development cycles, such contracts could be comfortably negotiated and planned for by producers. Shipping costs are very location specific and depend on rail costs. The model assumes $30/ton in shipping costs, which would be consistent with regional shipping via truck. Rail is around half; some sources could be closer or farther. $25/ton corresponding to $1-3/kWh-th, depending on the CST configuration. Use of on-site materials, perhaps from the excavation of the pits merits further investigation, as does cost versus particle size optimization.

Application to Alternate CST Plant Configurations

A key merit of the SandShifter technology is its adaptability to alternative CST plant configurations, including Power Tower and applications using Molten Salt or Steam as HTF. Sand is not temperature limited (workable to over 1500 C), so 1000C applications are feasible. It can also take advantage of broader "delta T" designs capturing the ability to store more heat per unit of volume, as sought in molten salt power tower applications. These applications are not expressly examined in the Phase 2 work, however performance for such application was analyzed in “Section 6 – Thermodynamic Modeling” and economic outcomes are discussed in “Section 14 – Cost Analysis”.

5. Analysis

A viable initial design for the SandShifter technology has been advanced as a platform for further analysis of the system’s development and economic potential. Analysis of the attributes of the subsystems and potential fatal flaw issues is provided in several sections of this report. Generally speaking, experimental work has validated the overall functionality of the proposed system, and provided insight as to future design direction. The preferred design will continue to mature through the Phase 3 efforts which will provide further insights into the cost potential for the technology.

6. Lessons Learned

Several key lessons learned, pertaining to the SandShifter design:

- Improvements in heat transfer performance have a significant impact on total cost curve for the technology as they achieve proportional reduction in the cost of the heat exchanger system – including the actual number of units required, and therefore also the number of MHE units is reduced.
- The importance of the iterative prototyping efforts yields significant benefits in learning what design details should be modified and how to best fabricate system components. These lessons will ultimately yield significant dividends in the reduction of total system costs (and thus the DOE’s funding of tiered development process is well justified).
- Analysis of the preferred MHE design approach is critical and will drive future modifications in design.
- More resources are needed to investigate subsystems and fully optimize them.

7. Looking Forward

Topics for further investigation in system design are several. Several areas are likely to yield non-incremental reductions in critical areas, due to the very new area of system technology and the potential for innovative application of existing technologies and/or invention of new approaches. At a high level, these investigational areas correspond to the primary subsystems of the SandShifter technology. A particular emphasis is merited for:

a) Materials Handling Equipment, due to the high capital costs of this equipment; and
b) Heat Exchanger, where two fronts will bear direct impact to the SandShifter’s cost curve:
  i) Heat Transfer Performance (increases MW capacity per SS unit); and
  ii) Fabrication Technique (reduce cost per unit).

Improvements for each of these subsystems, due to their prominent cost positions, likely reduces total system costs by a half to a third of that same amount. During Phase 3, several of these areas will be investigated more fully. A focused effort is recommended to more systematically develop alternatives and preferred designs in each of the critical areas. “Looking Forward” recommendations are more fully discussed in Section 16.

8. Summary

The USSTS team has developed a system design for the Rotating Drum SandShifter and a Reference Plant configuration. This platform provides an important reference point upon which analysis (particularly cost estimation) in the report is centered.

Design work for the SandShifter matured significantly in Phase 2, with particular focus place on the Heat Exchanger with material gains in expected performance (and consequent cost reductions to the system).

9. Relevant Appendices

Appendix 4-1 – Reference Plant Design Specifications
Appendix 4-2 – Volumetric Efficiency of Pits
Appendix 4-3 – Reference Plant Design Drawings

Section 5 - Prototype

1. Executive Summary

The main objective in Phase 2 was to design, fabricate, and test the SandShifter concept in a fully integrated prototype system as well as demonstrating the performance of isolated sub-components. Our team approached this objective by advancing the design and performance of the core heat exchanger design and quantifying fatal flaw area behaviors while simultaneously working toward a fully integrated, proof-of-concept validation of the SandShifter system in the form of the 50-kW-th prototype. Experimental results support various sections of this report.

The experimental approach was driven by the following key values:

- *Fatal Flaws Viewpoint*: Emphasis was placed on addressing the technology's critical issues (i.e. sand kinematics, heat transfer). Sub-components were isolated and investigated to develop qualitative and quantitative understanding of key behaviors and determine optimal solutions.
- *Iterative Advancements*: Strategies and tactics were adjusted based on real-time knowledge development. Improvements and lessons learned were captured at every stage.

2. Lab Scale Experiments

Lab scale testing isolated and tested specific components of the SandShifter design. Lab tests examined system issues in a real-time, controlled environment in order to drive design and construction decisions for the 50 kW-th unit.

Experimental Setup: A complete list of experiments is shown in Appendix 5-5 (Table 1), including a brief description of each test and resultant conclusions.

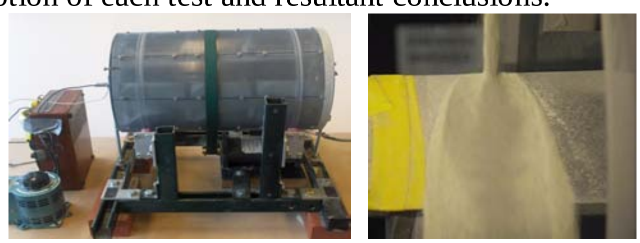


Figure 5-1 – Drum Heat Exchanger (right) and Sand Flow Velocity (right) Experiments

3. 50 kW-th Prototype

A fully integrated prototype system was constructed and operated, complete with rotating drum, heat exchanger, screw auger MHE, and heat transfer fluid loop. Sub-components of the system were iteratively fabricated, tested, and analyzed on an individual basis to address fatal flaw issues and move towards a complete and integrated system. For a complete view of how the prototype effort progressed throughout Phase 2, please reference Appendix 5-1 - Visual History of 50kW Prototype (*recommended).

Objectives: To investigate fatal flaw issues and arrive at preferred design solutions based upon qualitative and quantitative investigation. Construction and operation of a fully integrated prototype as a proof-of-concept demonstration of SandShifter technology.

Design: The integrated prototype went through multiple iterations of design and construction, driven by preferred design options, lab scale findings, and sub-component testing and analysis.

Experimental Setup: The 50 kW-th prototype was designed to be flexible and adapt to lessons learned during component testing. Experiments were conducted upon the construction of each critical component or sub-system. For example, once the prototype SandShifter drum conveyor was fabricated, sand flow experiments were conducted to validate sand kinematics. A full list of the experimental program is shown in Appendix 5-5 (Table 5-2). Please also reference Appendices 5-2, 5-3, and 5-4 for a complete list of protocols for prototype construction, commissioning, and testing.

Figure 5-2 – SandShifter 50kW-th Prototype System

Figure 5-3 – Sub-System and Component Testing for SandShifter Prototype System

4. Lessons Learned

The iterative approach of the prototype experimental program resulted in numerous lessons learned regarding the physical processes and procedures of the SandShifter system. Please reference other sections of the report for a more detailed discussion of specific components, as well as "Appendix 5-5 - Lessons Learned". Overall, the prototype process was a huge success, wherein each component was rigorously tested, all physical processes were demonstrated on an individual and integrated basis, protocols were developed for construction, operation, and testing, and instrumentation and measurement strategies were refined.

The fully integrated prototype itself was operated frequently for extended periods of time. The entire system was operated on multiple testing runs of 3-6 hours of continuous operation to collect performance data. Additionally, multiple commissioning runs were conducted at every level of construction and system iteration to ensure proper system operation and function.

Results from the Prototype and laboratory experiments are described in the respective report sections applicable to the type of data produced.

5. Relevant Appendices

Appendix 5-1 – Visual History of 50kW Prototype
Appendix 5-2 – SS Construction Key Items Checklist
Appendix 5-3 – SS Commissioning Protocol
Appendix 5-4 – SS Research Testing Protocol
Appendix 5-5 – List of Experiments Conducted
Appendix 5-6 – Prototype Fabrication – Lessons Learned

Section 6
Thermodynamic Modeling

1. Executive Summary

A thermodynamic performance model is required to analyze the SandShifter's capabilities. The Phase 1 model was updated in Phase 2 given current design parameters and Phase 2 learnings, preserving the 100' drum length, and calculating out the corresponding performance capacity of a given SSp unit. With updated assumptions, the SSp reference unit case found to have peak storage capacity of 16.7 MW, assuming 450 W/m2-K sand-side heat transfer. Three such units combined to provide the 50 MW target plant storage capacity.

Using this same thermodynamic model, the SandShifter TES technology was examined for various CST plant configurations to determine SSp (heat exchanger) size required to preserve the same MW performance. Varied inputs included thermodynamic cycle type and efficiency, inlet/outlet temperatures, collection media (and assumed heat transfer attributes), and approach temperature. The SSp size output and surrounding attributes served as an inputs to the cost performance analysis for each CST case. This chapter summarizes results of these thermodynamic modeling cases.

For discussion on the resultant implications on the technology cost, refer to S14 – Cost Estimate.

2. Modeling Cases

Table 6-1provides a summary of each modeling case as well as their respective system performance outputs (required heat exchanger sizing and sand mass). The chosen cases represented a range of system configurations (Troughs, Towers, Linear Receivers, Particle Heating Receiver), heat transfer fluid media (VP1, molten salt), and temperatures. All except Case 9 assume a steam cycle.

<u>Cases 0.1 – 0.3: "Reference Plant". Parabolic Trough with VP1 HTF as collection media</u>.

> Here sand is heated via VP1 HTF from the solar field and steam is generated in the SandShifter. Three sub-cases were modeled where the approach temperature was varied from the standard 20° to higher approach temperatures of 40° and 60°, enabling compaction of the heat exchanger.

<u>Case 0.1 ENH: Trough with VP1 HTF and an enhanced heat transfer performance</u>.

> The enhanced case was modeled with a heat transfer coefficient of 600 W/m^2K (shown here), resulting in 16.6% and 19.9% reductions in the length of the drum and plates, respectively. The results of this case were also projected out on a proportional basis, in the S14 – Cost Analysis (not shown here).

<u>Case 1: Central Receiver Power Tower (CRPT) with Particle Heating Receiver (PHR)</u>

> Here sand is heated directly for storage in the PHR and steam is generated in the Shifter. Steam is on tube side. Efficiency is taken equal to representative coal-fired steam plant. Very high sand maximum temperature and approach temperature are feasible.

Cases 2, 3, and 4: Steam as HTF and collection media. This case presupposes a hypothetical system design in which steam is used as the HTF and heated to supercritical temperatures in the tower and SandShifter however used at subcritical temperature in the steam turbine for generation. This is done to accommodate the challenging temperature duty diagram of steam. Further development of the design concept is necessary (and proposed). This is currently a thermal design; mechanical design considerations have not been fully developed (ie., SS).

Case 2: CRPT similar to Brightsource with steam generated in receiver.

Case 3: Compact Linear Fresnel Reflector (CLFR). Hypothetical higher temperature case with steam generated in linear receiver tubes and sand is used in Shifter as storage medium.

Case 4: CLFR similar to Areva with moderate steam conditions with direct steam generation.

Cases 5, 6, 7, and 8: Molten as HTF and collection media: In these cases, molten salt is used as the working heat transfer fluid in the system and various temperature ranges were examined.

Case 5 – Salt LT: 290 to 390 C. Low temp salt case, eg, salt in parabolic trough

Case 6 – Salt BL: 290 to 450 C.

Cases 7.1 – 7.3: 290 to 500 C, examining various approach temperatures (20, 40, 60 C).

Cases 8.1 – 8.3: 290 to 500 C, examining various approach temperatures (20, 40, 60 C). Similar to the Solar Reserve Power Tower.

Case 9: Central Receiver Power Tower (CRPT) with Particle Heating Receiver (PHR) and gas cycle.

Here sand is heated directly for storage in the PHR and later transfer in the Shifter. Air in a gas turbine cycle is on the plate side. Efficiency is taken equal to representative advanced gas turbine with intercooling and possible recuperation. GE LMS-100 efficiency data is used specifically. Very high sand maximum temperature and very high approach temperature, which allows small plate bundle even with air on plate side, are feasible. Larger number of Sand Shifter HXer-Conveyors likely needed to limit pressure drop (6 SS drums used in this scenario as opposed to 3 unit). This is provided as a reference case.

3. Relevant Appendices

N/A

Case Number	Brief Description	Collection; TES Media; Conversion Cycle Type	Temperature of Approach	Steam Low Temp	Steam High Temp	Steam Cycle Efficiency	Delta-T	Length of Drum	Length of Plates	Energy to Store	Sand Mass	Sand Volume
			C degrees	C	C	(%)	C	(m)	(m)	kJ	kg (10^3)	1000s m3
0.1	*Trough, VP1*	*VP1 Collection; Sand TES; Steam Cycle*	*20*	*310*	*395*	*29.2*	85	*32.6*	*29.20*	2,465,753	28,440	18
0.2	*Trough, VP1 - 2X*	*"*	*40*	*310*	*395*	*26.8*	85	*20*	*15.6*	2,686,567	30,987	19
0.3	*Trough, VP1 - 3X*	*"*	*60*	*310*	*395*	*24*	85	*16.5*	*11.4*	3,000,000	34,602	22
0.1-ENH	*Trough, VP1 - ENH*	*VP1 Collection; Sand TES; Steam Cycle - 600*	*20*	*310*	*395*	*29.2*	85	*27.2*	*23.4*	2,465,753	28,440	18
1	CRPT, PHR	Sand Collection; Sand TES; Steam Cycle	250	240	550	43.7	310	31.6	26.9	1,647,597	5,211	3
2	CRPT, steam	Steam Collection; Sand TES; Steam Cycle	See Details	150	600	33	450	46.4	42	2,181,818	4,753	3
3	CLFR, steam	"	See Details	150	500	32.2	350	46.4	42	2,236,025	6,263	4
4	CLFR, steam	"	See Details	150	450	31.5	300	46.4	42	2,285,714	7,470	5
5	Salt LT	Salt Collection; Sand TES; Steam Cycle	20	290	390	28.5	100	43.7	41.9	2,526,316	24,768	15
6	Salt BL	"	20	290	450	30.1	160	42.5	39.7	2,392,027	14,657	9
7.1	Salt HT 500	"	20	290	500	31.3	210	40.8	38.2	2,300,319	10,739	7
7.2	Salt HT 500 - 2X	"	40	290	500	29.1	210	23.6	20.5	2,474,227	11,551	7
7.3	Salt HT 500 - 3X	"	60	290	500	26.6	210	18.3	15	2,706,767	12,637	8
8.1	Salt HT 550	"	60	290	550	32.4	260	39.4	37	2,222,222	8,379	5
8.2	Salt HT 550 - 2X	"	60	290	550	29.9	260	22.5	19.3	2,408,027	9,080	6
8.3	Salt HT 550 - 3X	"	60	290	550	27.5	260	17	13.8	2,618,182	9,872	6
9	CRPT, PHR	Sand Collection; Sand TES; Gas Conversion Cycle	250	600	800	44	200	14.6	14.6	1,636,364	8,021	5

Table 6-1 –Modeling Cases for 50 MW SandShifter TES Technology Configurations

Section 7
Heat Transfer

1. Executive Summary

Quantification of potential Sand-to-Metal heat transfer and demonstration of achievability of such results is essential to both validating the SandShifter concept and understanding the potential performance of such a device. Sand-to-Metal heat transfer, particularly in thin sheet flow, is a little studied area of science. The team successfully developed and advanced knowledge and related examination techniques for this area of science. Original experimental devices were constructed and tested, both in the laboratory and the field. A representative range of sand types and particle sizes were examined.

The resulting data and analysis show heat transfer coefficients showed results ranging from around 300 to nearly 600 W/m^2-K for coarser to finer grained silica sand and as high as 670 W/m^2-K for fine grained Olivine sand. Smaller particle sizes showed higher results and the smallest silica particles somewhat approached the values for the more exotic Olivine sand.

Results from the 50 kW SandShifter Prototype confirm the achievability of such results from the proposed technology in the field, even without optimal sand coverage in the experiment. Results of [400-450] W/m^2-K were demonstrated in the Prototype, which validates the 450 W/m^2-K assumed in the thermodynamic model. The team is confident it will likely eventually achieve field results higher than currently observed in the Prototype.

The team expects that sand particles will have some degradation over the lifespan of a SandShifter unit. Phase 2 testing was conducted with the preferred sand materials (100 mesh silica fracking sand) and showed indirect evidence of heat transfer performance improvement with degradation. These observations were consistent with Phase 1 heat transfer testing which showed a negative correlation between sand particle size and heat transfer.

Further experiments are recommended and intended to isolate the heat exchanger from the full system kinematics to optimize the tube bundle design and demonstrate maximum achievable sand-to-metal heat transfer rate achievable in the lab.

2. Objectives

In regards to heat transfer performance, the objectives of Phase 2 were to:

- To understand Sand-to-Metal heat transfer, a critical performance driver for SandShifter technology, including maximum achievable values, sensitivity to various sands, and expected variation in certain applications
- To develop supporting science, including examination techniques, analysis, and supporting data
- To validate the achievability of laboratory results in the field, using the Prototype
- To validate and support heat transfer assumptions made in the SandShifter thermodynamic model.

3. Literature Review

Pertinent literature is discussed in Chapter 3 of Appendix 7-1, the full heat transfer report. Some, but not extensive, literature was available, including Patton, et al, Denlove, et al, Hyde, and the Babcock and Wilcox report. The work of the first three authors show consistency with the results achieved in our laboratory experiments. The latter report suggested much higher heat transfer coefficients than seen in our experimental result.

4. Experiment

Lab Scale Testing

The data relies on a rotating drum apparatus which achieves a nearly constant flow of a thin layer of sand over a heated plate. Details of the apparatus and procedure and details of the error propagation analysis are presented in Appendix 7-1.

This apparatus, seen in Figure 7.1, as well as adjusted methodology was an improved means to allow continuous heat transfer operation over a larger range of temperatures with more realistic test articles.

Figure 7.1 Drum Heat Exchange Measurement Apparatus

Here, a rotating drum with an array of internal scoops continuously lifted the sand from the bottom of the drum and poured it over an axially fitted test article.

Experimental runs with no sand, using only air for cooling, yielded a heat transfer coefficient of around 10 W/m²-K. This result fell within the documented range of buoyant gas convection and was confirmed using the well-known formulas from McAdams for heated plates. The experiment was then repeated with sand, the upper side thermocouples reading surface temperature contacted by the sand and the lower side thermocouple measuring the temperature of the slat surface exposed to air.

Experimental runs were conducted employing different types of particulates. Employing these particles, heat transfer coefficient was determined for each type of particles. For the particle types, the following were used (experimentally measured particle size; standard deviation):

(1) Fine grained olivine sand (mean diameter of 80 µm; standard deviation 30 µm);
(2) A slightly larger fine sifted silica (140 µm, 50 µm);
(3) Another sifted silica sand (290 µm; 100 µm);
(4) A coarser locally purchased construction silica sand (550 µm; 320 µm);
(5) Finally spherical alumina particles (760 µm; 120 µm).

Examination was done using film and bead thermocouples, to see if the experimental results remained fairly consistent between different means of measurement.

50 kW SandShifter Prototype Testing

In addition to lab scale testing of sand-to-metal heat transfer performance, a primary Phase 2 goal was to demonstrate similar performance in a medium-scale, representative SandShifter system. Thus the team designed and constructed a fully integrated 50 kW prototype system complete with a heat transfer fluid loop, rotating SS drum conveyor, screw conveyor materials handling equipment, and the ability to insert different heat exchanger designs. Experimental runs were conducted using preferred sand material (100 mesh silica sand) and designed to analyze the achievable sand-to-metal heat transfer coefficient (HTC) in the prototype system.

Figure 7.2 – 50 kW Integrated Prototype System (testing of corrugated plate heat exchanger shown on right)

5. Analysis

Lab Scale Analysis

The results of the lab-scale experiment are as follows:

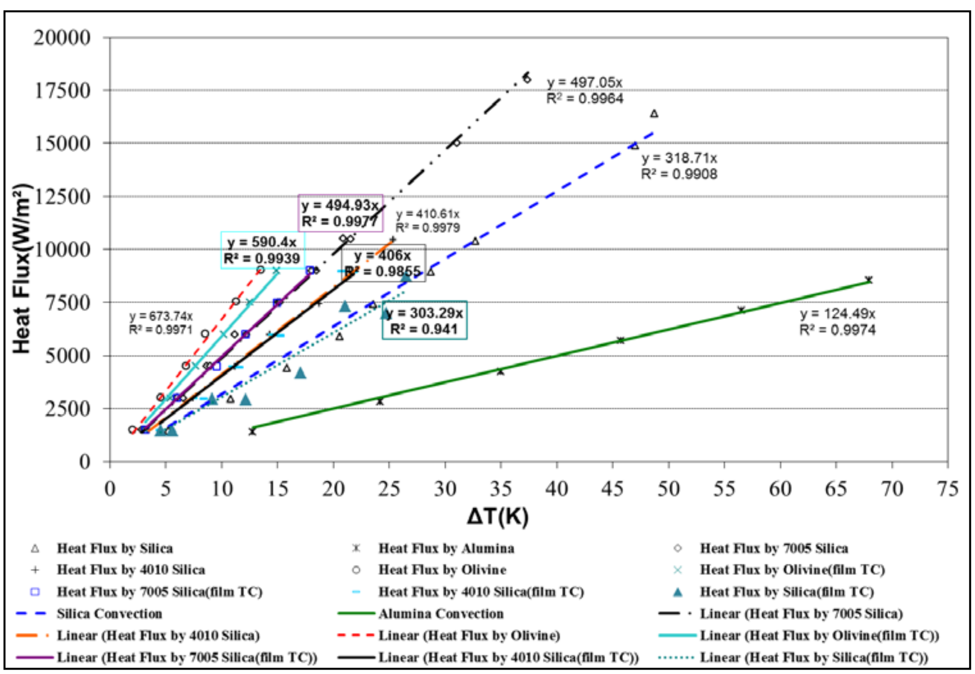


Figure 7.3 – Flowing Particle Heat Transfer Data: Film Thermocouples

The regression line slopes in Figure 2.2 indicate a somewhat lower average convection coefficient from the particles for film versus bead type thermocouples. This was expected as the bead type thermocouples were more protruded into the flow from the surface and therefore experience somewhat greater cooling than the surface. The thin film thermocouples, due to close surface profile, return a more true surface temperature when submerged in the sand flow. There was the same consistent trend in temperature difference as the power input was varied. The calculated convection results for both experiments are summarized in Table 7.1. Examination of the data confirms that showed that the particle size plays the leading role in convective performance with smaller grain sizes achieving better flowing surface contact and better overall performance.

Sand Type	Average Grain Size (μm)	Film Heat Transfer Coefficient (W/m²-K)	Bead Heat Transfer Coefficient (W/m²-K)
Olivine Foundry Sand	80	590	670
Fine Sifted Silica (7005)	140	490	500
Sifted Silica (4010)	290	410	410
Construction Silica	550	300	320
Alumina Beads	760		125

Table 7.1 Heat Transfer Coefficients by Sand Type: Film Thermocouples

<u>50 kW SandShifter Prototype Testing</u>

Research testing results from the 50 kW prototype are summarized as follows:

Test #	Heat Exchanger	Test Setup / Iteration Comments	HTC ($W/m^{2-}K$)
1	Bare Tube Bundle	Baseline prototype test run	300 – 315
2	Corrugated Plate	Piping insulation & Slow drum rotation	320 – 420
3	Corrugated Plate	Drum insulation & Improved sand coverage	400 +
4	Corrugated Plate	Augmented sand temperature measurements	500 +
5	Corrugated Plate	Increased temperature and sustained operation	400 – 450

Table 7.2 – Heat Transfer Coefficients in 100kW Prototype System

The bare tube heat exchanger design was initially used to commission the prototype system and primarily served as a baseline measurement of heat transfer performance. The potential to increase HTC results for this design can easily be accomplished by adjusting sand coverage and incorporating the various fin designs explored in Phase 1.

The main focus of prototype testing, however, centered on the corrugated plate heat exchanger. The corrugated plate design was identified as the preferred heat exchanger solution due to both heat transfer and structural performance considerations (reference Section 8 – Heat Exchanger Design). Initial prototype testing results (tests #2 and #3) showed ~425 W/m^2-K sand-to-metal heat transfer, confirming lab results.

Further refinement of the system (improved sand coverage, insulation, and temperature measurements) resulted in consistent demonstration of heat transfer coefficients in the range of 400-450 W/m^2-K, which validates the 450 W/m^2-K assumed in the thermodynamic model. Prototype results for 500+ W/m^2-K were often observed, and the team anticipates future designs to push beyond 450 W/m^2-K toward the theoretical limit with commensurate reductions in technology cost curve.

Figure 7.4 – Corrugated Plate Heat Exchanger installed with RTDs

6. Lessons Learned

Prototype operation and testing resulted in many lessons learned not only in terms of heat transfer performance, but also in regard to how to configure, operate, observe, and measure the heat transfer performance of the SandShifter system. In summary:

- Longitudinal vanes within the SS drum were improved to minimize parasitic power losses and must be properly angled to ensure even distribution of sand falls atop the heat exchanger.
- The preferred sand for commercial scale operations was identified (100 mesh silica).
- Accurate sand temperature measurements are difficult to achieve in a live system. An innovative design was used to ensure sand flow over temperature-sensing devices.
- Temperature sensors (RTD’s, thermocouples) must be in specific locations to measure the temperature change of sand across the heat exchanger. Specifically, locations directly above and below the ends of the heat exchanger are recommended.
- Meticulous labeling of temperature sensors and linking them all to a central data acquisition system is required.
- Design and construction of SS systems must be conscious of providing accessible view points within the drum (typically windows in the drum endcaps).
- Secure sand storage is required to protect from moisture and other contaminants.

7. Looking Forward

Further laboratory experiments are recommended and intended to isolate the heat exchanger from the full system kinematics to optimize the tube bundle design and demonstrate maximum achievable sand-to-metal heat transfer rate achievable in the lab. The primary experiment contemplated would isolate a small section of the tube bundle for continuous circulation of HTF and sand, emphasizing achieving full coverage of sand on the heat exchanger surface. Such a setup could be achieved with minimal cost and would allow various test articles to be examined. This would better quantify the full potential of the technology as per given heat exchanger designs. The designs could then be deployed in a larger device to confirm achievability of results in the field, to develop optimal fabrication approaches, and to demonstrate construction and operation thereof.

8. Summary

The team sought to understand the potential maximum achievable values for Sand-to-Metal heat transfer. This information is critical to evaluating the achievable performance of a sand based heat exchanger, its design, and its resulting cost curve. Laboratory experiments to examine the heat transfer coefficients showed results ranging from around 300 to nearly 600 W/m^2-K for coarser to finer grained silica sand and as high as 670 W/m^2-K for fine grained Olivine sand. The team developed and tested a 50 kW Prototype to confirm the achievability of such results from the proposed technology. Results of 400-450 W/m^2-K were demonstrated in the Prototype, using 100 mesh silica fracking sand and while only achieving 'somewhat good' though not excellent surface coverage (in terms of uniformity, percentage of sand delivered, and thinness of flow). This validates the 450 W/m^2-K assumed in the thermodynamic model. Further, the team is confident it will likely eventually achieve results higher than currently observed in the prototype. Further laboratory experiments are recommended and intended to isolate the heat exchanger from the full system kinematics to optimize the tube bundle design and demonstrate maximum achievable sand-to-metal heat transfer rate achievable in the lab.

We believe that something near 600 w/ is likely achievable in future design. The cost impacts of this are discussed in section 14 with sensitivities (maximum performance capabilities of the technology)

9. Relevant Appendices

Appendix 7-1 – Heat Transfer Coefficient Measurements for Sand-to-Metal (Lab)
Appendix 7-2 – Heat Transfer Coefficient Measurements for Sand-to-Metal (Prototype)

Section 8
Heat Exchanger Design

1. Executive Summary

The SandShifter technology is at its essence a heat exchanger for the working mediums of sand (TES media) and a Heat Transfer Fluid (HTF). All of the surrounding work is ultimately in order to achieve cost effective and reliable heat transfer, including the delivery and storage of materials. This section addresses the Heat Exchanger itself, its design evolution, supporting experimental work, the current preferred design, and our understanding of the potential for the technology.

Experimental work included 1) laboratory examination of component behaviors; 2) development of an integrated 50 kW prototype (the “Prototype”). The team successfully constructed and tested the Prototype, a significant achievement demonstrating successful deployment of the SS’s heat exchanger concept in an integrated, field environment, and providing a first-of-its-kind experimental apparatus to serve for further investigation. The Prototype results validated heat transfer rates in the Prototype assumed in the SandShifter thermodynamic model.

Work from this section is supported by examination of sand kinematics, sand-to-metal heat transfer, materials performance, fabrication technique, development of sub-prototypes, thermodynamic modeling, and trial-and-error. It is informed by extensive heat exchanger knowledge and history of our lead investigator and inventor, Dr. Jeter, as well the interdisciplinary team, including our fabricators. Extensive learning resulted from this work which are pertinent to the advancement of the SS technology, from heat transfer to sand kinematics to fabrication techniques.

The core of the SandShifter heat exchanger is the tube bundle. Evolution of the preferred approach for the tube bundle evolved from the finned tubing design proposed in Phase 1 to the current preferred design, a Zig Zag plate system, a very compact and relatively self-supporting structure which maintains good sand side heat transfer and provides materially superior oil side and overall heat transfer. Indeed the Zig Zag design yields a drum about 1/3 the length of the corresponding finned tube design.

Development and validation of this design approach, including its heat transfer rates, constructability, and demonstration in the field Prototype, offers a material improvement in the SandShifter technology cost curve. In Phase 1, our 100’ x 10’ working unit had a 6.25 MW working capacity. Following Phase 2, our reference design (100’ x 12’) has a capacity of 16.7 MW. Comparative analysis of the tube bundle design options showed a reduction on the order of 70% for a parallel plate design versus a finned tubing design.

Detailed histories of the evolutions of the Prototype and the Heat Exchanger design are provided in this section’s appendices.

2. Objectives

- To develop and successfully demonstrate a sand-to-metal heat exchanger, which (is):
    - Provides effective heat transfer
    - Constructible
    - Cost effective

- To develop understanding of related phenomena to support further technology development
- To improve the performance of all of these attributes

3. Literature Review

A summary of the literature review and list of references is provided in Appendix 8-2.

4. Experimental / Design

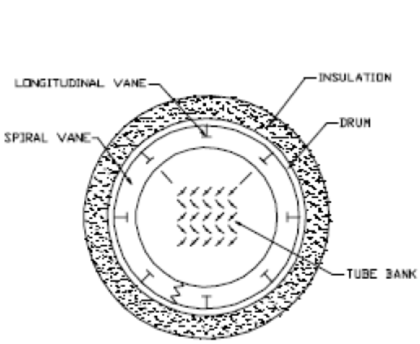
During Phase 2, the SandShifter team continued evolution of the tube bundle design building on the work in Phase 1. Understanding of the cost and heat transfer performance of the Phase 1 finned tubing based design, as well as further understanding of the requirements to achieve cost effective sand-to-metal heat transfer stimulated a creative effort to develop a new design that would achieve these goals whilst still being cost effective and achieving satisfactory heat transfer on the metal-to-HTF side. Ultimately a tube bundle of the preferred Zig Zag design was successfully installed, operated, and performance tested in the Prototype.

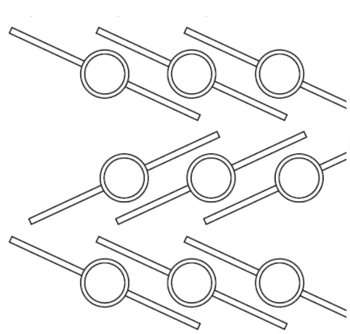
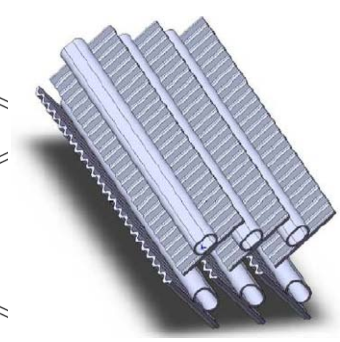
Several design approaches were considered in succession by the SandShifter team, including longitudinal and transverse finned tubing approaches (and variations thereon) evolving toward plate heat exchanger design concepts. The team systematically examined key attributes associated with these options and the evaluated the expected performance qualitatively and/or quantitatively, as applicable, including the following:

- Constructability
- Heat transfer performance
- Kinematic behavior
- Commercial availability of materials or methods
- Structural Integrity
- Likely cost outcomes

Generally speaking, *improved heat transfer performance was viewed as a proxy for the reduction in the expected cost curve* for a design, assuming a design approach appeared technically feasible and cost effective. (Better heat transfer implies less required materials and therefore less cost of such material and less labor to assemble a smaller structure.)

Examined designs included: Longitudinal fin designs; transverse fin designs; zigzag plate design; corrugated plate designs.



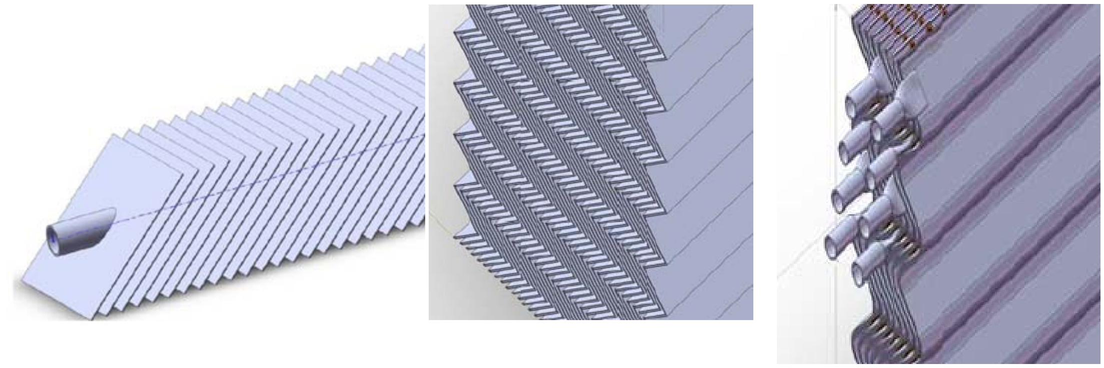


Figure 8.1 – Alternate tube bundle design approaches

A parallel plate-based heat exchanger was ultimately preferred. Such a design would have successive sandwiches with HTF on the interior and sand falling through in between – an alternation of sand, HTF, sand, HTF, etc. Costs and attributes summarized below.

An iterative discussion and fabrication was engaged between the design and lab team at Georgia Tech and the fabrication team at IronCo. Test articles were developed as well as knowledge on the fabrication, testing, system integration, commissioning, and operation of various design options, focused on the parallel plate concepts. Trial-and-error informed the process and often dictated the pace (as did availability of resources at our fabricator).

A corrugated plate design was contemplated, seeking to take advantage of readily available materials which could readily sandwich together, and which would achieve the desire thin flow and long period contact of sand with metal. This design may have future merits, however commercial materials had aluminum coatings which caused welding challenges at the prototype level. The team developed a cost-effective approach to fabrication of a Zig Zag design which was then successfully employed.

Development and tests of the heat exchanger test article in the Prototype yield the following successful outcomes:

- Fabrication technique knowledge
- Test methodologies for components and the integrated system and its subsystems
- Confirmation of heat exchanger's successful application in an integrated SandShifter application at a meaningful scale
- Performance data

System context for the heat exchanger is provided in Section 4 – System Design. Lessons learned are discussed below in the Lessons Learned Section.

Prototype

The mutually reinforcing Zig Zag tube bundle was successfully employed in the Prototype. Metal braking, stamping, and beading processes were employed to create the zig-zag shape. The Prototype successfully ran and performed heat exchange. Heat transfer rates of 400-450 were observed in the device. Results are likely to improve in future designs with the realization of improved sand coverage and a improvement in fabrication and reductions in spacing. See the following images.

Figure 8.1: Zig-Zag Design Employed in 50 KW Prototype

5. Analysis

Analysis of heat exchanger design evaluation results are shown below in two parts: 1) Tube bundle design options, comparative analysis; 2) Prototype results.

<u>1) Tube bundle design options</u>

The following table shows the relative specifications and resulting cost implications for each of the primary design options considered for the SandShifter Heat Exchanger. Each design shown is for an independent 6.25 MWe SS heat exchanger unit. The team examined the surface area and mass requirement shifts to support the MW-capacity goal in order to estimate associated costs. Better performance equates to less surface area being required and a corresponding reduction in the mass of steel and also fabrication costs.

Based on this indicative level cost estimate, the Parallel Plate / Zig Zag design[s] could result in a 70% reduction in the cost of the SandShifter heat exchanger assembly for a given MW-capacity sized unit. The original Zig-Zag concept was modified to a Dimpled Plate version of the same concept. This change provided an alternate means of supporting the plates against each other . Indeed it is an earlier self-supporting design based on a zig-zag dimpled plate spot welded to a matching flat plate. Questions about the reliability of the numerous spot-welds needed to mutually reinforce the matching plates lead to the later design in which so-called beads transmit stress from one sandwich to the other and finally to an exterior load-adsorbing support.

The dimpled plate may have special advantages with low vapor pressure salt, if as expected the numerous dimples help enhance the limited salt-side heat transfer.

Parameters (Estimated)	**Longitudinal Fin**	**Transverse Oblique Fin**	**Zigzag Plate***	**Corrugated Plate**
Total Sand Side HXer Area (m^2) for 50 MWe	7,559	12,940**	3818 (half actual plate area)	3818 (half actual plate area)
Relative Area	100	171	51***	51***
Total HXer Mass (kg) for 50 MWe	168,000	69,000****	75,200	75,200
Relative Mass	100%	41	45	45
Rough Estimate of HXer Cost (excluding drum)	$741,000	$ 517,500	$234,000	$234,000
Relative Cost	**100%**	**70%**	**31%**	**31%**
Pressure Integrity	Excellent	Excellent	Acceptable (Demonstrated)	Acceptable
Structural Stiffness	Needs Augmentation	Needs Augmentation	Excellent	Excellent
Oil Side Convection Coeff. (W/ m^2-K)	1426	1434	1632	1632
Sand Convection Coeff. (W/ m^2-K)	450	450	450	450
Average HXfer Coefficient rel. sand to side	177	102	351	351

* Performance quite similar to Corrugated Plate Design. Earlier Zig-Zag design was modified to include dimpling which provide interpolate support.
** Most sand side surface is fin surface with relatively low fin efficiency.
*** All primary surface in these designs so no surface inefficiency.
**** Design never developed to effectively contact both fin sides with sand.
***** Perhaps less challenging in a low pressure (molten salt) environment.

Preferred Design: The Zig-Zag design likely reduces the SandShifter's "internal heat exchanger" costs by approximately 70% relative to the initial design. It is now therefore considered the preferred design. Impacts of current design are analyzed in Section 14 – Cost Analysis.

2) Prototype

Heat transfer rates of 400-450 were observed in the Prototype. Results are likely to improve in future designs with the realization of improved sand coverage and very likely improvement in fabrication and reductions in spacing. A maximum of 600 W/m2-K is likely achievable. More detail is discussed in “Section 7 – Heat Transfer”.

6. Lessons Learned

The successful mutually reinforcing plate bundle design and lab and prototype testing has demonstrated both the excellent heat transfer design and feasibility of fabrication. By flow visualization in a transparent model, we have demonstrated the effectiveness of our simple internal manifold design for insuring uniform oil distribution inside the plate sandwiches. We have also demonstrated an effective and non-intrusive means of venting air from cavilites in the sandwiches. Basically while improvements are possible and expected, we have demonstrated a fully functional design. Plate spacing, air vent, fabrication, fluid flow distribution, and other issues were learned about. Additional Lessons Learn are discussed in “Section 5 – Prototype” and its appendices.

7. Looking Forward

Additional investigation to more fully develop the heat exchanger design is merited. In particular, development of designs for alternate HTFs is of particular interest.

8. Summary

Alternative tube bundle designs were further examined and developed in Phase 2 showing the preference of a parallel plate based design. A Zig Zag plates design was designed, fabricated, and constructible. The Zig Zag design’s advantage include a relatively self-supporting structural nature (reducing external structural support) and two key features resulting in superior heat transfer: 1) Good oil side convection coefficient; and 2) Good sand coverage on the metal surfaces. These yield a corresponding heat transfer improvement over the Phase 1 assumed finned tubing design and a cost improvement of perhaps 70% for the SSp.

Our thermodynamic model assumed a heat transfer coefficient of 300 W/m2-K for the former Phase 1 design. We now assume 450 W/m2-K for the Zig Zag design (substantiated in experiments discussed in Section 7, Heat Transfer). As high as 600 W/m2-K may be achievable with commensurate reductions in the resulting SS cost curve.

9. Relevant Appendices

Appendix 8-1– Heat Exchanger Design – Literature Review
Appendix 7-1 – Heat Transfer Analysis – Full Report

Section 7 – Heat Transfer
Section 5 – Prototype

Section 9
Sand Erosion

1. Executive Summary

This section describes the experimental investigation and analysis done by our team to understand the degree of materiality for one of the potential fatal flaw areas (and an obvious concern) identified for the SandShifter: Sand causing erosion of the system's equipment due to abrasive contact. Extensive experiments were run simulating the expected behavior of sand in the system to quantify the abrasion potential which are summarized in this section; the full report is provided in Appendix 9-1.

Our team was satisfied that this issue was negligible in the tube bundle and manageable in other areas. Due to the fact that the interior of the system entirely avoids abrasive contact, almost zero erosion is expected in the tube bundle. Tests showed 0.0001% per day losses for sand pouring continuously on steel in a 100+-day experiment. Abrasive contact is a concern for metal on metal interactions. However these are limited to two primary locations in the system, each of which we consider sufficiently managed at this point and will receive further investigation in practice in Phase 3:

Materials Handling Equipment: Abrasion would occur in the chain and gear assemblies of the bucket elevator. For this concern, we yield to the experience of the manufacturers of MHE, experience in dealing with abrasive materials, who included sufficient design life in their equipment. As such, this is primarily a price question. And future MHE design innovations will consider overhead dragline MHE which will eliminate much of the erosive contact opportunity. This will be more fully examined in operation in the Phase 3 with complete MHE systems incorporated.

The plenum/cap interface with the end of the rotating drum. This interface could have a certain amount of risk of abrasive contact. However, we anticipate designing sufficient tolerance to avoid any contact, which should be achievable. Sacrificial metal could be used as well.

2. Objectives

To address and quantify potential erosion of SandShifter's mechanical equipment due to abrasive contact, a potential fatal flaw issue

3. Literature Review

Little material literature was found on soft contact sand erosion. As regards erosion in the MHE, for the purposes of Phase 2, the team took vendor comments that equipment could manage the erosion at face value. Additional learning will occur on this in Phase 3 with equipment is put into service.

4. Experiment

The purpose of the sand erosion trials was to examine the wear effect of different types of sand on the primary interface portion of the heat exchange tubing. The experiment evaluated the wear of the sand on the heat exchange tubing through mass loss. This was done by employing a rotating tumbler drum with internal scoops angled to pour the sand over the tubing thus subjecting it to nearly continuous exposure. Through periodic measurements of the tube and fin assembly mass, a loss rate associated with the sand wear on the heat exchange tubing could be estimated. Experimental runs were conducted employing different particulates.

The following four (4) particulates have been investigated: (1) Fine grained olivine foundry sand [1], experimentally observed to have a mean diameter of 80 µm with a standard deviation 30 µm, (2) A coarser locally (Atlanta, Ga) purchased construction silica sand, which was measured to have a mean diameter of 550 µm with a standard deviation of 320 µm, and (3) Commercially prepared spherical alumina "propant" particles observed to have a mean diameter of 760 µm with a standard deviation of 120 µm. (4) Additionally, a fine grained commercially available fracking sand available in Phoenix was tested. The average grain size of the 100 mesh fracking sand was 153 µm.

The experiment featured over 100 days of continuous gravity-fed sand exposure to individual test articles.

Table 9.1 Sand Erosion Data – Steel Fins with Silica sand

Silica Sand Erosion Trial			Continuous sand exposure	
	Steel Finned Steel Tube		0.0004	% mass loss a day
		Scale 1 +/- 0.001g		
Date	(Days)	mass(g)		Rate(g/day)
9/23/2009	0	152.005		
10/5/2009	12	151.992		0.00108
10/6/2009	13	151.985		0.00154
10/16/2009	23	151.981		0.00104
11/5/2009	43	151.978		0.00063

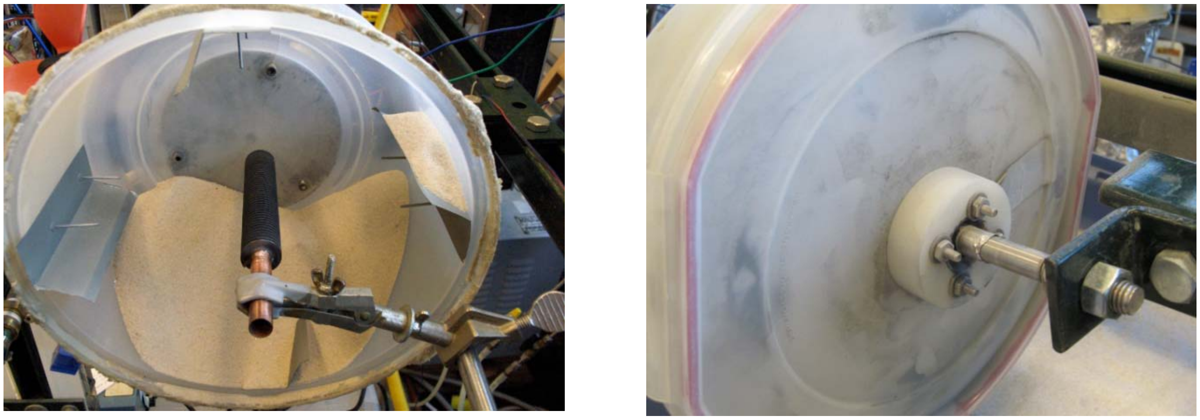


Figure 9.1 Sand Erosion Assembly

5. Analysis

Summary: Experiments were conducted to simulate the interior of the SS wherein sand falls softly with the force of gravity. *No appreciable wear was noticed for any of the sand particles flowing over steel sample coupons*, while appreciable wear was observed with the alumina beads.

Aluminum: Even with a conservative rate of 0.04% loss per day. The aluminum finned tubing would lose 1% of its total mass after less than a month of continuous exposure. Visible wear was observed with aluminum material.

Copper: The copper tube steel finned had a far lower loss rate as seen in Table 1.2. At 0.0037% mass loss a day it would take about 9 months of continuous exposure to lose 1% of its total mass. Visible wear was observed with copper material.

Steel: With silica sand, the steel tube steel fin wear rate at 0.0004% mass a day was an order of magnitude less than the copper tube steel fin assembly. It would take about 7 years of continuous exposure for it to lose 1% of its total mass. Inspection of the piece showed no appreciable wear.

Cromgard Steel: After nearly 100 days of constant exposure, there was little change in the Cromgard sample mass (< 0.0001%). Inspection showed some slight surface build up and discoloration.

6. Lessons Learned

Steel articles are definitely favored over aluminum. Steel showed negligible wear. Abrasive contact definitely needs to be managed; however, our design largely avoids that issue.

7. Looking Forward

Phase 3's larger system will include a full, operating SS system. This will allow observation of sand erosion issues throughout the system, particularly in the MHE system, where it will provide a learning platform for the supporting vendors.

8. Summary

Extensive experimental examination of the potential for sand abrasion in the SS system showed little cause for concern in the interior tube bundle if using the intended steel material. Abrasive contact in the interface sections (drum end caps) and MHE needs to be managed through design.

9. Relevant Appendices

Appendix 9-1 – Sand Erosion Experimental Report

Section 10
Auxiliary/Parasitics

1. Executive Summary

One of the critical questions for the evaluation of the SandShifter's ultimate performance pertains to the matter of parasitic loads. This section of the report addresses our team investigation and quantification of the expected auxiliary (or parasitic) loads for the SandShifter technology, using our Reference Plant as a basis for analysis. The Reference Plant's key parasitic loads are for 1) the rotating drum equipment and 2) the materials handling equipment, A paper study analysis was performed (see Appendix 10-1) of the performance of equipment comprising the total system.

Investigation showed electrical parasitic of approximately 3% and 4% of energy stored for the rotating drum and the Materials Handling Equipment (MHE) respectively, for a total of approximately 7% losses to parasitic electric loads. The theoretical minimum of these losses (keeping bucket elevator and drum) is roughly 4.5% (depends somewhat on heights and spatial configuration of equipment and routing of sand), and practical design variations such as implementation of a clamshell/dragline concept might perhaps achieve a reduction to about 50% of the MHE parasitic loss. Round trip efficiency for the current Reference Plant SandShifter system is calculated at roughly 93%.

2. Objectives

- To quantify auxiliary loads in the Rotating Drum SandShifter system due to mechanical equipment and HTF pumping.
- To understand the expected parasitics are not a fatal flaw for the SandShifter technology.
- To provide an input to the model for the technology so that the net cost-performance impact can be accounted for.

3. Literature Review

a. Ref: Equipment specs
b. Ref: Commonly known/accepted physics and efficiencies
c. Ref: Use of similar equipment for other tasks (commercial uses)

Suitable efficiency data was not found in the technical literature for either the Rotating Drum or the bucket elevator devices *as systems*. *Therefore*, quantitative estimates of the attainable efficiency utilizing sound empirical data for the respective sub-systems, supported by available literature for the component equipment and supported by consultation with subject matter experts.

4. Experimental

The parasitic load analysis was conducted primarily as a paper analysis. This is due primarily to the fact that the Prototype behaviors would not be representative of performance at a large scale for the technology. Experimental examination of auxiliaries is recommended and intended for Phase 3.

5. Analysis

Parasitic loads totaling approximately 7% are estimated for complete charge and discharge, using the 16,666 kWe rated power served by each of the 3 assumed TES units. *This is not a negligible amount of energy but is within the range of parasitic power losses in conventional energy plants.*

Sub-System	**Efficiency of Sub-system**	**Total Parasitic Losses**
Bucket Elevator	0.79-0.82	3% of stored energy
Rotating Drum	0.60	4% of storage energy
		7%

Table 10.1 – Summary of Parasitic Losses

The theoretical minimum of these losses (keeping bucket elevator and drum) is roughly 4.5% (depends somewhat on heights and spatial configuration of equipment and routing of sand), and practical design variations such as implementation of a clamshell/dragline concept might perhaps achieve a reduction to about 50% of the MHE parasitic loss. Round trip efficiency for the current Reference Plant SandShifter system is calculated at roughly 93%.

6. Lessons Learned

The parasitic losses are a material but acceptable burden to system performance. Further optimization is possible and merits further investigation. Attention to the design of the final system should pay attention to the auxiliary consequences to spatial movement of TES media and equipment selection.

7. Looking Forward

There are opportunities for innovation to reduce the parasitic loads associated with the equipment, however subject to a physical limit based on the work required to lift the sand some distance. Potential innovations for future investigation are:

1) Optimize Pit Dimensions: MHE height is a key cost driver for SS. A larger optimization of pit costs, MHE, and thermal losses is needed to determine the optimal design strategy.

2) MHE Alternative: An alternative to vertical bucket elevators is a clamshell or dragline system to excavate sand from the top a pit. Such a system is not commercially available today. Our vendor partner suggested that such a system could be uniquely designed and would likely reduce capital costs (by as much as 70%) for the MHE and also reduce parasitic losses (~50% less).

8. Relevant Appendices

10-1 - SS Auxiliary Loads Analysis – Full Report
10-2 - SS Round-trip Efficiency calculation

Section 11
Heat Loss Analysis

1. Executive Summary

One of the critical analysis areas for the SandShifter technology is heat loss to the environment, particularly from sand storage vessels, the primary focus of this analysis. Losses must be quantified as a part of the total system performance model, in order to both predict performance and vet this as a fatal flaw issue.

An extensive modeling and related analysis was conducted for the storage vessels, focused on in ground pits, using an ANSYS model based. The dimensions for the initial analysis were 14.7m by 14.7m by 18.3, similar to the Reference Plant (final Reference Plant sizing had not occurred at the time of this analysis.

The anticipated steady-state heat leak is low (15.4 kW), and the enhancement caused by transient start-up, although not negligible, is also not overwhelming. The losses drop off quickly, reaching 40 kW in less than 50 days, then decreasing to 20 kW over a few years. After 10 years, the heat loss of the system (in Watts) has come to within 12% of the steady-state heat loss. These results were incorporated in the SandShifter thermodynamic model. A comparison was done to an an above ground design which had much higher losses. Hot temperature on the nearby surfaced was not deemed a material issues. Drum and HTF piping losses were deemed minor and not a primary focus.

Future analysis would look at optimization of the whole system given pricing of pits versus heat losses for given pit dimensions, as well as site specific soil conditions. Reductions in losses assumed may occur in multi-pit scenarios and pursuant to certain configurations.

2. Objectives

To quantify system heat losses for the SandShifter for incorporation in to the system performance model and to vet that heat loss is not a fatal flaw issue.

3. Literature Review

See Appendix 11-1, full report.

4. Experimental

Approach: A finite element ANSYS model was created to investigate heat loss from a hot-sand storage pit in the SandShifter Project. Both steady-state and transient models were solved and compared against simplified analytic models with exact solutions. The analytic methods included shape factors and solving analogous 1-dimensional problems.

The team also examined the effects on heat loss rates from varying pit size, varying insulation amounts, and above-ground vessels.

Assumptions: Boundary conditions were specified as follows: the inside of the pit was set to a constant temperature of 380^{o}C, the far-field temperature and the surface of the Earth were set to 25^{o}C, and the roof of the pit was made adiabatic. The material properties used in the simulation are given in Table 11.1.

The roof of the pit is assumed to be a continuous thermal barrier (ample insulation to prevent any heat leak through the top of the pit). Constant and uniform properties will be assumed for all materials. For now, time variation of the driving temperature (i.e. filling and depleting of the pit) is ignored, and a constant temperature boundary condition will be applied to the inside walls of the pit. Finally, seasonal variation of the ambient temperature is assumed to have a negligible effect, and a constant ambient temperature is specified. The surface temperature of the Earth is set equal to the ambient temperature, since it is assumed that convection will keep the surface close to the temperature of the ambient air.

The pit was modeled as 0.4m-thick perlite concrete that is 14.7m by 14.7m by 18.3 m on the inside. The material properties for the perlite concrete and earth used in this simulation are tabulated below.

Property\ Material	Perlite Concrete	Earth/Soil
Thermal Conductivity (W/mK)	0.053	0.27
Density (kg/m^3)	105	1515
Specific Heat (kJ/kg-K)	387	800

Table 11.1. Material Properties

The Earth was simply modeled as a large block. A constant-temperature boundary condition of 380^{o}C was applied to the four inside walls of the pit, as well as its floor. The top of the perlite walls was given an adiabatic boundary condition. Earth exposed faces of the block were given a constant-temperature boundary condition of 25^{o}C.

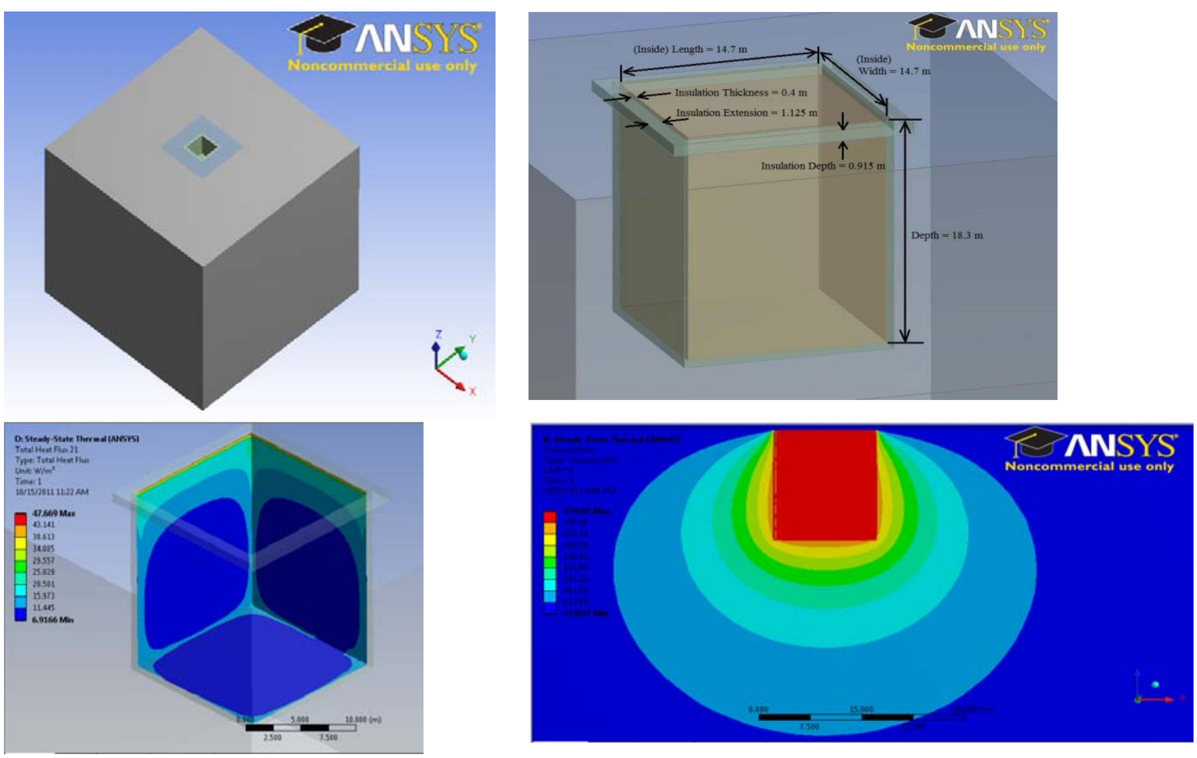


Figure 11.1. Geometry and Temperature Contours of the ANSYS simulation

Steady-state results were found to be in good agreement with a prediction using shape factors, and a transient simulation was validated by comparison with exact solutions to simpler, 1-dimensional analytic models. Convergence of the model was checked by refining the mesh and by increasing the size of a large block meant to represent the semi-infinite Earth.

5. Analysis

The anticipated steady-state heat leak is low (15.4 kW), and the enhancement caused by transient start-up, although not negligible, is also not overwhelming. After 10 years, the heat loss of the system (in Watts) comes to within 12% of the steady-state heat loss. Also after 10 years, transient effects will have increased the *cumulative* thermal energy loss of the system (in Joules) by 34% (see figure 30).

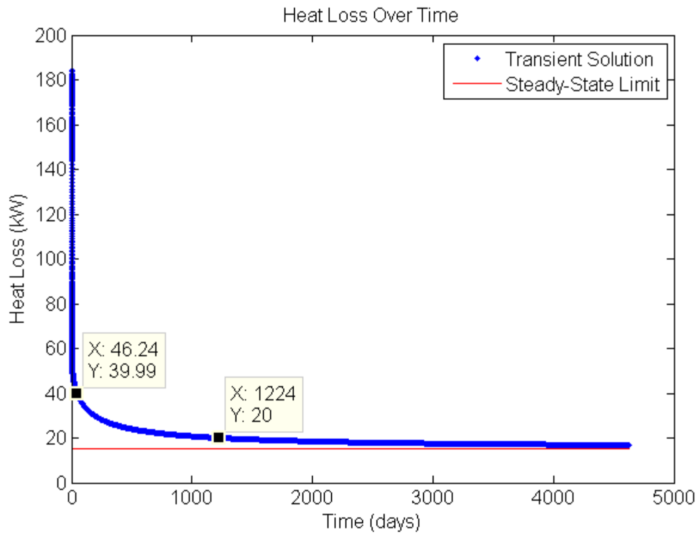


Figure 11.2. Transient Heat Loss from the Pit

The transient solution eventually approaches the steady-state prediction as expected, but transient effects are present even after a long period of time. While the steady-state heat loss predicted by ANSYS was only 15.35 kW, the transient solution indicates that actual heat losses will be higher (20 to 60 kW) when considering a timeframe of 500 days. The losses drop quickly to a manageable level though, reaching 40 kW in under 50 days. These heat losses are still very small in comparison with the capacity of the plant (~133MW_{th}).

Over the lifetime of the power plant, transient effects will have a modest impact on the average heat loss. After twelve years, the transient solution will come within 10% of the steady-state heat loss, and the cumulative energy leak will be 7500 GJ (see figure 14). This implies an average heat loss of 19.8 kW – a 30% increase over steady state. The transient effect on average heat loss is less pronounced for a smaller pit and with thicker insulation.

Heat losses even over a relatively short period of time at startup are small. After 50 days, cumulative heat loss from the pit is 200 GJ – equivalent to about 25 minutes of plant operation at 50 MWe ~= 133 MW_{th}.

Looking at heat losses when sand is stored over a long period of time: After the transient heat loss has decreased to a roughly steady 20 kW, if the sand is stored over a period of 50 days, the total thermal energy leak is 86 GJ, or about 18% of its initial energy.

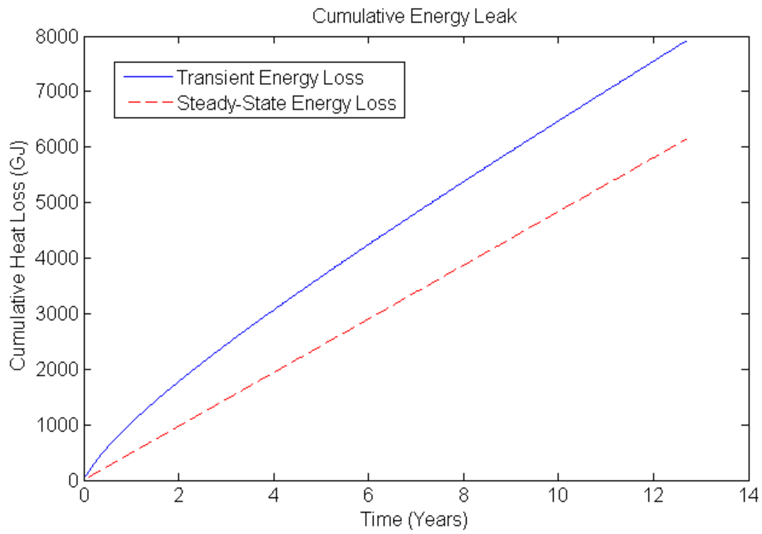


Figure 11.3. Cumulative Energy Loss over 12 Years.

Ground temperature implications were also examined for in-ground. The surface of the ground will never become dangerously hot. The maximum heat flux out the ground near the pit (according to ANSYS) is 46 W/m^2; the maximum surface temperature comes to 34.2^{o}C. The full report also looks at implications of varying insulation thickness, depth, and lip size.

Above Ground Storage Vessels

The analysis also considered above ground vessels. The transient heat loss is plotted as a function of time in Figure [11.x], and approaches a steady-state limit of 51.77 kW. The above-ground bin approaches its steady-state configuration more rapidly than the in-ground pit, but has greater heat loss overall.

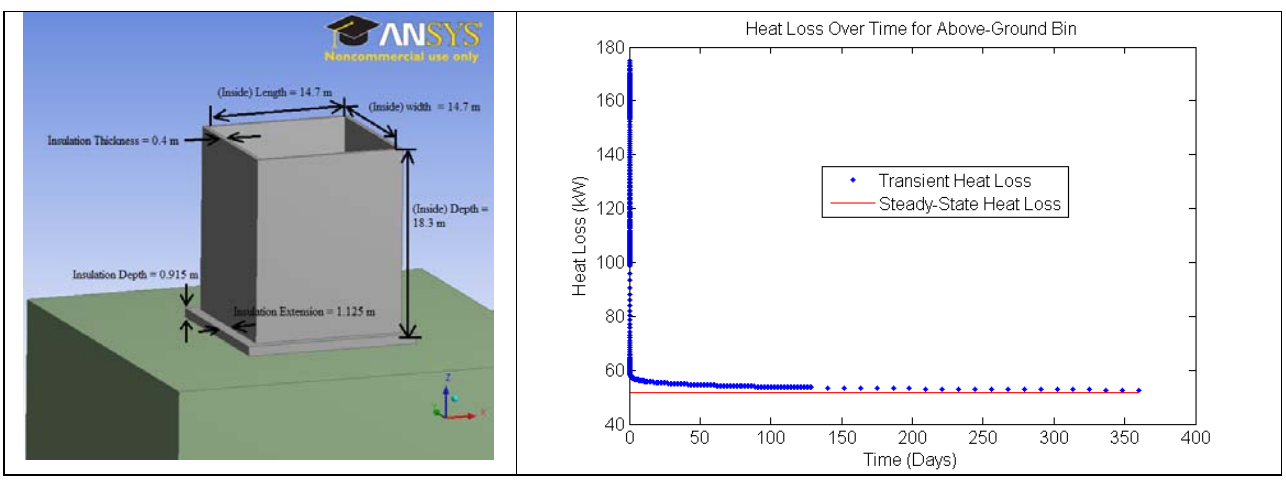


Figure 11.4. Alternative Storage Method: Above-Ground Bin.

6. Lessons Learned

Below Ground Storage Vessels

- Transient effects of heat loss are larger than anticipated, however manageable

- Steady state heat losses around 15 kW
- Transient heat losses drop below 60 kW within several *weeks* and within 10% of steady state losses within 500 days
- Total average heat loss around 20 kW
- Ground temperature will not exceed 34.7 C
- Heat loss is greatest at the very top of the pit, where there is a “short-circuit” between the hot interior of the pit and the cold surface of the Earth. A large temperature gradient in the area is unavoidable, so heat loss is best reduced by placing material with a low conductivity along the rim of the pit.
- Since the heat capacity of the Earth is large, the transient response of the system is slow, making the average heat loss significantly greater even over a period of a year.
- Heat Loss per unit area decreases as the thickness of the insulation around the pit increases and also as the dimensions of the pit become larger.
- The steady-state R-value of the system is well-represented by a simple, linear function of the insulation and soil R-values.
- Heat loss per unit area is higher for an above-ground bin than for an in-ground pit.

<u>Above Ground Storage Vessels</u>

- Higher heat losses than in-ground
- Nearly 2X the losses per unit surface area
- Steady state heat losses around 52 kW
- Transient heat losses drop below 60 kW within several *days* however remain higher

7. Looking Forward

There are several simplifications made in this analysis which may deserve closer scrutiny in a future analysis. The following should be examined more closely:

- Multiple Pits in proximity (possibly even sharing walls), which would reduce the average heat loss per pit.
- The “cold” pits might also be located close enough to the hot pits to reduce average heat loss even further.
- Average heat loss may be increased by the fact that the pits are not always filled with sand; earth surrounding the pits will have a chance to periodically cool down.
- Location-specific properties of soil
- The effect of rain

8. Summary

Heat loss was analyzed and found within acceptable ranges. See Lessons Learned above for an outline of key findings.

9. Relevant Appendices

Appendix 11-1 – Heat Loss Analysis – Full Report

Section 12
Sand Kinematics

1. Executive Summary

The task of moving material through the SandShifter is three-fold. First, sand must be conveyed along the axis of the heat exchanger with the use of an Archimedes screw. Second, sand must be lifted in the circumferential direction so that a steady flow of material can be poured over the heat exchanger bundle in an even distribution. This is accomplished with the use of longitudinal scoops which are positioned in segments between the Archimedes screw threads. Third, sand flow within the heat exchanger tube bundle is critical to heat transfer performance, which must be sufficient in volume and uniform and thin in flow. (Reference “Section13 – O&M” for discussion of materials handling equipment solutions to connect sand flow between the SS drum and storage areas.)

Bench and lab scale models were built to verify mechanical concepts. Sand flow distribution, flow rate, and flow through the heat exchanger were all successfully demonstrated on the lab scale as well as within the integrated prototype. The following groups of experiments were conducted: bench and lab scale experiments to verify mechanical concepts, sand distribution experiments, and sand flow experiments through the heat exchanger tube bundle.

2. Objectives

Phase 2 objectives were to understand and demonstrate the kinematic behaviors of sand as pertains to the rotating drum SandShifter technology which required examination of performance in the following areas:

- System-level sand flow kinematics
- Sand flow rate through the SS drum
- Sand distribution over the heat exchanger tube bundle
- Sand distribution and flow rate within the heat exchanger tube bundle

Phase 2 sought to examine these component behaviors separately and to successfully demonstrate them in combination in a working integrated Prototype.

3. Experimental

1. *Bench scale mockup of SS drum:*

   Early kinematic tests focused on validating the sand flow behavior as a whole within the system. A bench scale mockup with a transparent SS drum was built to visualize sand behavior. Testing this bench scale model verified the mechanical concept of the technology by showing the transport and distribution of sand.

2. *Lab scale working model:*

   A larger, lab scale mockup of the SS drum was built at Georgia Tech with a 1 ft diameter by 10 ft length. This drum was built as a full working model complete with a demo drum conveyor (transparent), demo auxiliary MHE, and vertical conveyor. Model results successfully demonstrated the velocity and volumetric flow of sand (as representative of the rates required in a commercial system).

Figure 12-1 – Lab Scale Working Model (1 ft by 10 ft)

3. Sand Distribution Experiments:

Lab scale sand distribution experiments were built to demonstrate the ability of longitudinal scoop designs to deliver sand over the tube bundle (Figure 12-2). Results lead the team to design a double-sided sand scoop of the appropriate angle to pick up and distribute sand over the tube bundle in either direction of SS drum rotation. The double-sided sand scoop was fabricated, tested, refined, and ultimately deemed successful in the Prototype (Figure 12-3).

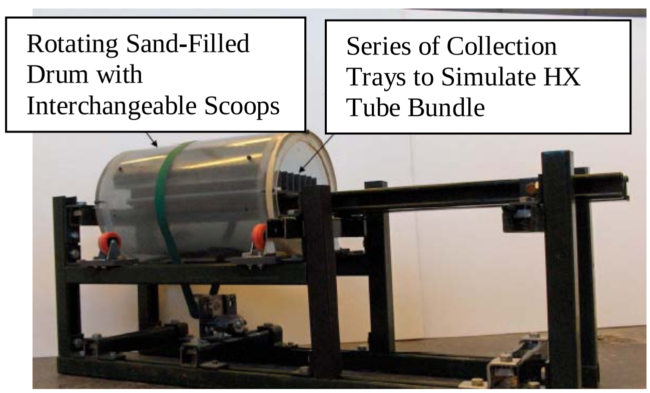


Figure 12-2 – Sand Distribution Experiment

Figure 12-3 – 50 kW Prototype Sand Distribution

4. Sand Flow Rate Experiments:

Bench and lab scales models demonstrated desired sand flow rated through the SS drum conveyor. Larger scale tests were conducted in the Prototype. Initial results lead to the installation of a 2nd spiral vane within the Prototype, which subsequently improved sand flow rate performance. Sand flow rate results were measured and scaled up to the needs of a commercial plant. Results showed that the current spiral vanes in the Prototype supported flow rates that were adequate, yet were on the low end of the desired operating rate. Opportunities for improvement have been identified, such as increasing the depth of the spiral vanes or increasing drum rotation speed.

Figure 12-4: 50 kW Prototype Sand Flow Rate Experiments

5. *Sand Flow Through Heat Exchanger Experiments:*
   A prototype tube bundle was fabricated for the Corrugated Plate Heat Exchanger (the preferred design). Sand flow through the corrugated plate heat exchanger was tested to determine the maximum flow rate supported, which was an important parameter to demonstrate that sand flow would not become clogged within the heat exchanger during operation (and the heat exchanger could still achieve the required flow rate for heat transfer). Experimental results successfully exceeded the design goal for maximum sand flow rate through the corrugated plate heat exchanger. Refer to Appendix 12-1 details.

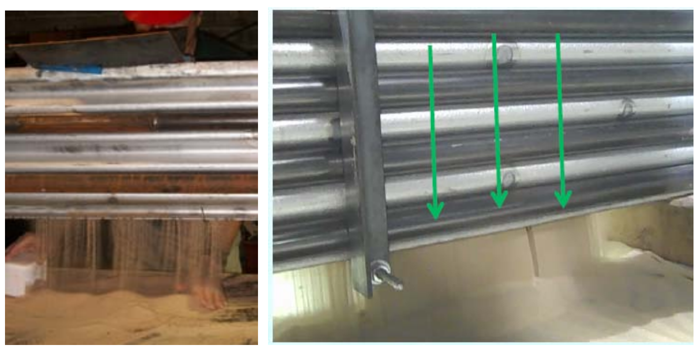


Figure 12-5: Sand Flow Through the Corrugated Plate Heat Exchanger

4. Looking Forward

Although adequate sand distribution and sand flow rates were achieved in the lab and in the operation of the integrated Prototype, there is an opportunity for further improvement. The proposal for Phase 3 is to commence testing with sand flow and distribution on the 1MW scale prior to installing the heat exchanger tube bundle. This will enable the spiral and longitudinal vanes to be tested and refined. Potential augmentations have already been identified from Phase 2: to improve the sand flow rate, the drum speed may be increased, additional spiral vanes can be added, and the vanes can be made to be deeper.

5. Relevant Appendices

Appendix 12-1 – Sand Flow within Corrugated Plate Heat Exchanger

Section 13
O&M

1. Executive Summary

This Section overviews Phase 2 observations on the expected O&M approach as well as learning applicable to Phase 3 activities and future commercial deployment. Generally, the SandShifter will be integrated into a CST plant like other Two Tank TES systems. Operationally, the multiple SandShifter units will be run individually, through remote control, based on the desired peak storage capacity needed in real time, using as many units as necessary. Special maintenance considerations apply to the equipment, due to the rotating drum and MHE and high temperature applications. These issues are partially overviewed, not exhaustively addressed here. More detailed development of O&M understanding, strategies, details, and costs will be developed during the Phase 3 demo project, per the project plan, and thereafter. The Phase 3 inclusion of representative MHE and the planned equipment cycling will create a good platform for this important future investigation.

2. Objectives

During Phase 2, the O&M related objectives were to learn from the Prototype development and testing about O&M issues where possible, so as to inform SandShifter implementation and development in Phase 3 and beyond. (It is assumed that HTF delivery from/to the CST plant and related integration are essentially 'obvious' and not addressed in the Phase 2 scope.)

3. Literature Review

Two primary categories of literature might apply to the SandShifter O&M issues set. One is literature for operation of Two-Tank TES systems. Generally, the highest level comparisons apply here, in terms of operational configuration, essentially at the flow-diagram and concept implementation level, and the physical integration, which is basic (HTF piping, valve control). Literature in the two tank molten salt is otherwise generally more specific than bears referencing here. The second category is for MHE. In this area, we generally relied on consultant/vendor information that such equipment could be acquired and applied in the required setting. Detailed development of design and implementation strategy in the MHE arena is necessarily the subject of dedicated future efforts to fully investigate, analyze, understand, and design the MHE systems, and the resulting O&M issues.

4. Discussion

<u>Operation</u> of the SandShifter in the charge direction, given delivery of charged HTF, involves, per SS unit: 1) MHE running, delivering TES media (sand) to SandShifter proper (SSp); 2) Operation of the SSp, whose rotating drum causes heat transfer and delivery of TES media to exit-MHE; 3) Entrance and distribution of TES media into Storage Vessel. In the discharge direction, this activity set is the same but reversed, drawing TES media from the opposite storage vessel to add heat to (instead of take heat from) the HTF.

The number of SandShifter units run will determined the peak capacity storage rate for the plant. Units can be run one-at-a-time, or in any number of quantities or combinations, depending on plant operational requirements and/or maintenance activities/status. The required amount of HTF would be directed to the units per this operational intent at any given time.

System Controls: The strategy for addressing control systems has two major areas:

(1) *Observational*: Observational instrumentation used for monitoring the performance of systems and subsystems, particularly in reference to heat transfer performance, sand flow and distribution, and power usage. This instrumentation mainly consists of temperature monitoring sensors, data acquisition systems, flow meters, and power meters.

(2) *Mechanical*: Mechanical instruments used to control active behaviors for system operation. Mechanical instrumentation includes HTF pumps and control valves, a motor system for drum rotation, and heat sourcing for HTF circulation.

Maintenance: Maintenance of the SandShifter system will occur at a subsystem level. Each subsystem will have its particular requirements, in terms of inspection actions, maintenance expected, and associated staffing requirements and replacement parts/equipment costs.

Several miscellaneous O&M related observations follow:

- SS components will be designed to have a service life commensurate with the CST plant
- MHE is the largest wear area expected. The bucket elevator could have annual maintenance cost of as high as $100,000 per year. Development of a clamshell/dragline system would have substantially lower maintenance costs.
- Staffing-wise, it is currently unclear as to whether the plant would add a small specialized team to manage the SandShifter system or expand the training of the existing staff. It is likely a mix. This would need fuller development as the technology advances and would be very interactive with the future development of detailed MHE designs.

5. Analysis: See “Discussion” and “Lessons Learned”

6. Lessons Learned

Controls & Instrumentation:

(1) *Refinement of observational instrumentation:* Via iterations of research testing, the location and exact placement of temperature-sensing instrumentation was refined to achieve maximum accuracy. This was particularly important to collect accurate sand temperature measurements (specific location and setup is shown in S17). (Please refer to S17 – Lessons Learned for full details regarding refinement of SandShifter controls and instrumentation):

(2) *Confirmation of mechanical instruments:* Mechanical systems were successfully demonstrated and shown to be functional in system operations.

(3) *See Appendix 13-1* for Notes on Controls for Phase 3 work.

Design:

(4) *Sand flow angles:* MHE feeders and ancillary equipment must be monitored carefully, design-wise, to ensure flow angles are sufficient to achieve sand flow.

(5) *Vibration assisted flow*: Use of vibrators to facilitate sand flow can be helpful, a tool.

(6) *Drum Rotation Speed, Chassis/Rollers*: As our prototype didn't intend to run for long operational periods, only for short term intervals to prove the concept, collect thermal data, and learn, the team realized that when the system ran at higher speeds, it was more sensitive to imperfections in the rollers (which were not made to tight tolerances).

7. Looking Forward

An O&M plan will develop as more a working knowledge of the operational requirements and consequences develops through Phase 3 and successive implementation projects. Phase 3 work includes actual, and iterative, operation of a complete system, which resultant learning expected.

Critically, the actual operation of the MHE in an operating environment (as well as the design and implementation of actual equipment for the Phase 3 Demo Project) will very much aid the MHE vendors in working out the design and O&M issues for the SandShifter. The cycling and operation of this equipment in Phase 3 is an important opportunity.

8. Summary

Phase 2 Prototype work contributed meaningfully to the SandShifter O&M knowledge set. Contributions were primarily a combination of general and miscellaneous learnings, of varying degrees of value, as well as helpful specific understanding in the placement of instrumentation for controls and data collection in future systems. Phase 3 will accelerate the O&M learning curve with implementation of a complete system.

9. Relevant Appendices

Appendix 13-1 – Notes on Phase 3 Controls

Section 14
Cost Estimate & Cost Analysis

1. Summary

In order to understand the commercial opportunity potential for the SandShifter, it is necessary to understand its cost structure and the potential costs for the various CST plant configurations which might employ the SandShifter. This section discusses the Phase 2 SandShifter cost estimate update. The analysis focuses first on the "Reference Plant" case – a conventional 50 MW VP-1 based parabolic trough plant. The Phase 1 SandShifter cost estimate was updated for Phase 2 utilizing a) Phase 2 heat exchanger design improvements, and b) using the knowledge developed from fabrication of the 50 kW Prototype. Cost outcomes were scaled from 2 to 12 hours of storage.

Various cost reduction opportunities are considered, including innovations in MHE, fabrication learning curves, and increasing the approach temperature in the SS heat exchanger. The analysis then extends to address higher temperature, alternate HTF configurations. Finally, the analysis considers achievement of peak heat sand-to-metal heat transfer (600 W/m2-K), as the base analysis here uses a more conservative number (450 W/m2-K) which has been essentially already achieved in the first Prototype.

Cost per unit of energy storage for the Reference Plant 50 MW VP-1 plant, "As Estimated", scaled from $63 to $41 per kWh-th in the 4 to 12 hour TES range, confirming the non-linear SandShifter cost curve found in Phase 1. Cost per unit of energy stored decreases as hours of storage increase, because the relative cheapness of sand and its storage vessels dilutes the cost of the SS heat exchanger and MHE as hours increase at a given peak MW capacity.

Reasonable innovations and learning curves in design, fabrication, and construction ("Reduced Case 1") suggest further reductions of 20-30% below this for the Reference Plant case, suggesting cost potential of $38-$33 per kWh-th for 6 to 8 hours of storage TES in a conventional trough application – and $31/kWh-th for 12 hours.

Tripling the approach temperature, with those innovations shifts the VP-1 curve to range from $33 to $30/kWh-th (8 to 6 hours TES).

With fully enhanced heat transfer at 600 W/m2-K, and "Reduced Case 2", analysis showed results of {$41 to $29} and {$35 to $29}, for 1X and 3X approach temperature ranges respectively, in a VP-1 application. Increasing approach temperature decreases heat exchanger size and therefore costs; ultimately a total plant optimization would need to occur, considering the net effects to LCOE for the plant.

Scaling this reference case for application of the SandShifter technology to alternate CST plant configurations, utilizing the thermodynamic cases shown in Section 6, we developed corresponding potential cost curve outcomes. Molten salt- and steam-as-HTF and/or leveraging broader steam cycle temperature profiles demonstrates the full potential of sand as TES media and the SandShifter as a TES technology. **Such analysis shows costs potential for molten salt application of $14 to $24 per kWh-th for 6 to 8 hours of storage TES in a high temperature (290-550C) application – and as low as $11/kWh-th for 12 hours.** This assumes most reasonable cost reductions and heat transfer of 600 W/m2-K on the sand side. Steam-as-HTF applications have potential of similar, overlapping cost curves. More design development work is needed in each case and further innovations beyond those here may allow additional cost reductions. Each application has special considerations in practice and is subject to more detailed design development and optimization of configuration for minimization of TES costs and total system LCOE.

Molten Salt Cases - Cost Curve Potential for Rotating Drum SS (w Proxy 550C)						
HTF / CST Configuration	**2**	**4**	**6**	**8**	**10**	**12**
Salt HT 500 (Case2) + ENH w 550C	60	33	24	20	17	15
Salt HT 500 - 2X (Case2) + ENH w 550C	46	26	19	16	14	12
Salt HT 500 - 3X (Case2) + ENH w 550C	40	23	17	14	13	11

Table 14.1 – Cost Curve Potential for High Temp Molten Salt HTF with SandShifter

2. Objectives

The objectives of this section are to describe the economic or 'cost curve' potential of the SandShifter as a TES technology, through the following:

1. **Describe Cost Estimation of the Reference Plant** (50 MW, conventional VP-1 trough, with 4 hours of TES), and show the results thereof;

2. **Show cost curve analysis results for Reference Plant scaled to various hours of storage** (2, 4, 6, 8, 10, and 12 hours)

3. **Show cost curve analysis results for application of the SandShifter in alternate CST configurations**, including considering commonly contemplated configurations or variations in CST plant for TES and LCOE cost optimization, such as:
    a. <u>Alternate HTFs</u>: i) Molten Salt; ii) Steam; iii) Sand
    b. <u>Alternate CST Plant Operating Profiles</u> (Temperature Configurations), varying key CST plant characteristics:
        i. Steam cycle target operating temperature
        ii. Approach temperature for HTF through heat exchanger
        iii. Delta T in storage media during charge/discharge
    c. <u>Realization of improvements in Sand-to-Metal heat transfer</u> (from 450 to 600 W/m2-K)

4. Literature Review

Comparison to available estimates of competing or prevailing TES technologies is appropriate. Such numbers are not entirely available to the public, so references are made using guidance from DOE and/or those presented by certain companies in their promotional materials and presentations. Our current understanding is that Two-Tank Molten Salt with a VP-1 interface is budgeted for $100-120 kWh-th; and, a tower with inline, two-tank molten salt storage might aspire to $35-$50/kWh-th. Rotating Drum SandShifter costs compare favorably.

5. Cost Estimate for 50 MW Reference Plant

Introduction: For Phase 2, the team updated the Phase 1 SandShifter cost estimate utilizing the same Reference Plant design case (50 MW, trough, 4 hours TES) as a baseline for estimate. This Reference Plant is described more fully in Section 4. Improvements in the heat exchanger design (going to zig-zag based design) materially increased the performance per SS unit favorably affected the costs, getting more "bang for the buck" from a single SandShifter device. Though, this favorable shift competed with increased costs for MHE which have to serve higher volume flow rates per SS unit. Optimal configuration requires additional analysis. (Development of alternate CST configurations cost curves is discussed in the next section.)

Methodology: Cost estimation mixed updated numbers from Phase 1 estimates (i.e. MHE) with new ground-up estimates for the key equipment wherein we had more learnings (i.e., the SandShifter heat exchanger) and major design changes. Where possible, the team supplemented prior information with additional data points (i.e. pit costs for various dimensions) to facilitate analysis of various configuration approaches and impacts from scaling on the resulting cost curves. More comments on the estimation approach are provided in Appendix 14-1.

- *The overall estimate* was prepared by a general contractor and steel fabrication expert with familiarity with the project for the past three years, with inputs from USSTS and various supporting specialists (particularly for the SS tube bundle, pits, and MHE).
- *SS drum and tube bundle*: The SS reference unit was resized due to improved heat transfer preserving Phase 1 comparison to the 100' rotating drum size unit. This increased the performance per SS unit from 6.25 MW to 16.75 MW for the given 100' length-per-SS unit. Knowledge developed from fabrication of the 50 kW Prototype informed the SS drum and tube bundle cost estimate.
- *MHE estimates* from Phase 1 were scaled and inflation-adjusted using vendor input.
- *Pits estimates* were performed for various depths and dimensions to develop guidance for pit costs. Depending on depth, cost per unit volume ranges from $4.00 to $6.50 per cubic foot. The Reference Plant assumes $4.50/c.f. A low cost metal lid with insulation is used.
- *Sand costs*, base case assumption of $40/ton, which is at the lower end of spot market pricing, however the vendor indicated this is reasonable with scheduled production. Shipping costs of $30/ton were added. A 25% reduction is used in the Reduced Case 1.
- *Engineering* costs are only assumed for project specific costs, assuming a known design has already been developed and largely perfected, and the technology is being applied to a site. R&D costs and further SS development are not included. 5% is consistent with the plug number from consulting engineers.

The Reference Plant case was then scaled to look at the cost consequences of 2, 4, 6, 8, 10, and 12 hours of TES – as well as outcomes for alternate CST configurations. These results are discussed in the analysis section below.

Results:

	50 MW VP-1 Ref Plant (4 hrs) - As Estimated vs. Realization of Cost Reduction Opportunities							
	Item	As Estimated ($)	%cost			% potential red	Reduced ($)	New%
1	Design and Engineering	$ 1,686,500	5%			0%	$ 1,686,500	5%
2	General Conditions	$ 1,177,360	3%			0%	$ 1,177,360	4%
3	Site Work (non-Storage Vessel)	$ 298,000	1%			0%	$ 298,000	1%
4	**Storage Vessels (Pits)**	**$ 8,656,410**	**24%**			**0%**	**$ 8,656,410**	**26%**
5	**Structure - Sand Shifter Drum**	**$ 1,902,650**	**5%**			**10%**	**$ 1,712,385**	**5%**
6	**MHE**	**$ 7,774,145**	**21%**			**60%**	**$ 3,109,658**	**9%**
7	**Heat Exchanger/Tube Bundle**	**$ 9,152,800**	**25%**			**20%**	**$ 7,322,240**	**22%**
8	Mechanical Systems	$ 1,250,000	3%			0%	$ 1,250,000	4%
9	Electrical &Instrumentation	$ 1,250,000	3%			0%	$ 1,250,000	4%
10	**TES MEDIA**	**$ 2,248,400**	**6%**			**25%**	**$ 1,686,300**	**5%**
11	Other	$ 481,552	1%			0%	$ 481,552	1%
12	Testing and Commissioning	$ 295,500	1%			0%	$ 295,500	1%
13	Freight	$ 44,000	0%			0%	$ 44,000	0%
	Sub-Total	$ 36,217,317	87%			20%	$ 28,969,905	87%
15%	Mark-up	$ 5,432,598	13%				$ 4,345,486	13%
	TOTAL	**$ 41,649,915**	100%			**20%**	**$ 33,315,391**	100%
		200						
		29.50%						
	50 MW VP-1 Ref Plant (4 hrs), As Estimated	$ 61	$/kWh-th			With Cost Reductions	$ 49	

Table 14.2 Reference Plant Cost Estimate & Cost Reduction Estimate

The above estimate shows the cost estimate for the 50 MW Reference Plant case (4 hrs TES), as estimated (left), for $41.6 MM total. With moderate assumptions about the degree of cost reduction potential (right), including development of a dragline-based MHE system, this number could reduce on the order of 20%, to $33.3 MM, or $49/kWh-th. Items in bold are those which would vary with either number of hours or change in plant configuration; these are the main cost movers in the scaling analysis provided below.

Scaling analysis examining 2 to 12 hours of TES shows cost per unit of energy storage. This was conducted holding all the costs constant except those varying with the hour of storage, which are just the volume of sand and the size of the TES storage vessels.

	50 MW VP-1 Ref Plant (4 hrs), As Estimated											
	Item	Amount	%	%	Hrs?	2	4	6	8	10	12	
1	Design and Engineering	$ 1,686,500	4%	5%	0	$ 1,686,500	$ 1,686,500	$ 1,686,500	$ 1,686,500	$ 1,686,500	$ 1,686,500	
2	General Conditions	$ 1,177,360	3%	3%	0	$ 1,177,360	$ 1,177,360	$ 1,177,360	$ 1,177,360	$ 1,177,360	$ 1,177,360	
3	Site Work (non-Storage Vessel)	$ 298,000	1%	1%	0	$ 298,000	$ 298,000	$ 298,000	$ 298,000	$ 298,000	$ 298,000	
4	**Storage Vessels (Pits or Silos)**	**$ 8,656,410**	**21%**	**24%**	**1**	**$ 4,396,965**	**$ 8,656,410**	**$ 14,036,762**	**$ 20,313,839**	**$ 27,487,642**	**$ 35,558,170**	
5	**Structure - Sand Shifter Drum**	**$ 1,902,650**	**5%**	**5%**	**0**	**$ 1,902,650**	**$ 1,902,650**	**$ 1,902,650**	**$ 1,902,650**	**$ 1,902,650**	**$ 1,902,650**	
6	**MHE**	**$ 7,774,145**	**19%**	**21%**	**0**	**$ 6,182,722**	**$ 7,774,145**	**$ 9,110,776**	**$ 9,847,025**	**$ 10,468,759**	**$ 11,572,787**	
7	**Heat Exchanger/Tube Bundle**	**$ 9,152,800**	**22%**	**25%**	**0**	**$ 9,152,800**	**$ 9,152,800**	**$ 9,152,800**	**$ 9,152,800**	**$ 9,152,800**	**$ 9,152,800**	
8	Mechanical Systems	$ 1,250,000	3%	3%	0	$ 1,250,000	$ 1,250,000	$ 1,250,000	$ 1,250,000	$ 1,250,000	$ 1,250,000	
9	Electrical &Instrumentation	$ 1,250,000	3%	3%	0	$ 1,250,000	$ 1,250,000	$ 1,250,000	$ 1,250,000	$ 1,250,000	$ 1,250,000	
10	**TES MEDIA**	**$ 2,248,400**	**5%**	**6%**	**1**	**$ 1,124,200**	**$ 2,248,400**	**$ 3,372,600**	**$ 4,496,800**	**$ 5,621,000**	**$ 6,745,200**	
11	Other	$ 481,552	1%	1%	0	$ 481,552	$ 481,552	$ 481,552	$ 481,552	$ 481,552	$ 481,552	
12	Testing and Commissioning	$ 295,500	1%	1%	0	$ 295,500	$ 295,500	$ 295,500	$ 295,500	$ 295,500	$ 295,500	
13	Freight	$ 44,000	0%	0%	0	$ 44,000	$ 44,000	$ 44,000	$ 44,000	$ 44,000	$ 44,000	
	Sub-Total	$ 36,217,317	87%		0	$ 29,242,249	$ 36,217,317	$ 44,058,500	$ 52,196,026	$ 61,115,763	$ 71,414,519	
15%	Mark-up	$ 5,432,598	13%		0	$ 4,386,337	$ 5,432,598	$ 6,608,775	$ 7,829,404	$ 9,167,364	$ 10,712,178	
	TOTAL	**$ 41,649,915**	100%			**$ 33,628,586**	**$ 41,649,915**	**$ 50,667,275**	**$ 60,025,430**	**$ 70,283,127**	**$ 82,126,697**	
		200			1	100	200	300	400	500	600	MWH-e
		29.50%				339	678	1,017	1,356	1,695	2,034	MWH-th
	50 MW VP-1 Ref Plant (4 hrs), As Estimated	$ 61	$/kWh-th			$ 99	$ 61	$ 50	$ 44	$ 41	$ 40	$/kWh-th

Table 14.2 – VP-1 Reference Plant Cost Estimate – Scaling Hours of Storage

As you can see, the cost dilution of the heat exchanger equipment results in a decreasing cost per unit of energy storage as the hours of storage increase. This is shown graphically in the following chart (Figure 14.1), showing the cost stack for the cases.

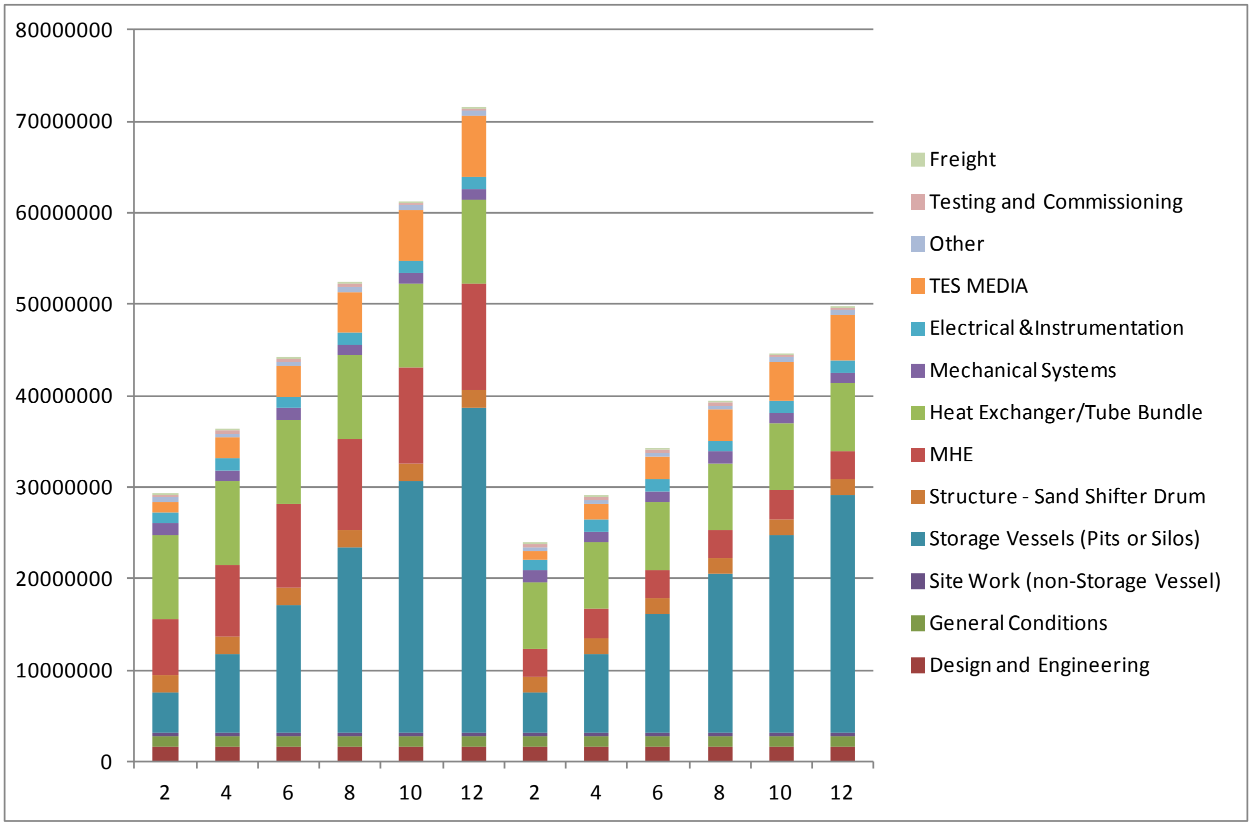


Figure 14.1 – Reference Plant Cost Stack – Scaling Hours of Storage
(*Left*: As Estimated. *Right*: Case 1 Reduction)

Cost Reduction Potential: The key limitations of the cost estimate completed include inherent vendor conservatism for costs provided without detailed design, as well as a compounding lack of ability to project the reductions from learning curve in actually fabricating these units, much less in successive projects. Also not included are the benefits of potential innovation. Development of the prototype demonstrated the reality of a new-to-the-world technology and how much learning and innovation is ahead as one further develops the technology.

Not all of these factors are quantifiable at this time. Therefore, a Reduced Cost cost estimate was developed making reasonable assumptions about key cost drivers that could experience cost reduction, using vendor guidance and judgment calls reflecting the percentage of the item cost from labor versus raw materials. Excepting the MHE, the other reductions don't reflect further reductions from more fundamental system innovations or improvements in heat transfer, which would further reduce the cost outcome. More comments on the reductions follow:

Case 1 Reductions:

- *SS drum and tube bundle* (Items 4 and 5) – 15-20% reductions from reasonable automation of certain fabrication and use of commercially available machine equipment to save on labor, as well as some learning curve in fabrication methodology.

- *TES Media* reduction for negotiating at 25% reduction outside of the spot market.
- *MHE-Dragline Alternative:* reduction potential of 60% is based on guidance from our expert consultant on the potential if the bucket elevator were completely replaced with a dragline based MHE system, subject to development of a new-to-industry configuration of existing technologies.

Case 2 Reductions:

- *MHE Conservatism* Reduction of 15% for just tightening up the estimate
- *Pits fabrication* reduction of 5%
- *Core Innovation* of 15% of technological improvements

Heat Transfer Enhancement ("+ENH"): Increasing the 450 W/m2-K to 600 W/m2-K

Cost Opportunity for SandShifter TES - Average of Cases per HTF							
Reduct	**HTF / CST Configuration**	**2**	**4**	**6**	**8**	**10**	**12**
0	Trough, VP1	$ 86	$ 55	$ 46	$ 41	$ 39	$ 39
1	Trough, VP1 (MHE+FabLearn)	$ 63	$ 41	$ 34	$ 31	$ 30	$ 30
2+	Trough, VP1 w Full Reduction Potential	$ 58	$ 38	$ 32	$ 30	$ 29	$ 29

Table 14.2 – VP-1 Reference Plant Cost Estimate – Scaling Hours of Storage

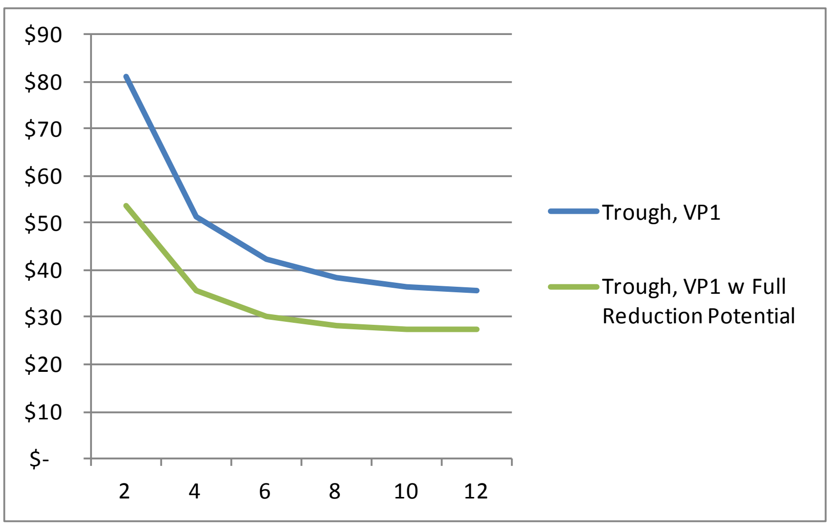


Figure 14.3 – VP-1 Reference Plant Cost Reductions

6. Analysis of Alternate CST Configuration Cost Curves

Using the Reference Plant estimate as a starting point, supplemented by scaling information from vendors on key cost estimates, the team looked at scaling costs for increased hours of storage, as well as application to alternate CST plant configurations.

A key advantage of sand as a TES media is its temperature flexibility for application at a very wide range of temperature parameters. Essentially, sand has no meaningful temperature limitations for currently contemplated CST plant, in temperature ranges or absolute values. As such, applications can be considered varying the following dimensions:

1) Alternate HTFs (VP-1, Molten Salt, Steam; Sand);
2) Plant Operating Temperatures;
3) Delta T in TES Media;
4) Approach Temperature in Heat Exchanger (1X=20C, 2X, 3X)

In Section 6, various CST configurations are presented, showing the assumptions for parameters for each of these dimensions, roughly mimicking commercially contemplated CST systems, along with wider approach temperature options. The following are their curves "As Estimated":

Total Plant Costs ($000s) (As Estimated)						
Plant Design Option Configuration	**2**	**4**	**6**	**8**	**10**	**12**
Trough, VP1	$ 97	$ 59	$ 48	$ 42	$ 39	$ 38
Trough, VP1 - 2X	$ 77	**$ 49**	$ 41	$ 37	$ 35	$ 35
Trough, VP1 - 3X	$ 70	**$ 45**	$ 39	$ 35	$ 34	$ 34
Trough, VP1 - ENH (1X)	$ 89	**$ 56**	$ 45	$ 40	$ 38	$ 37
CRPT, PHR	$ 97	**$ 51**	$ 36	$ 28	$ 23	$ 20
CRPT, steam	$ 87	**$ 45**	$ 31	$ 24	$ 20	$ 17
CLFR, steam	$ 86	**$ 45**	$ 32	$ 25	$ 21	$ 18
CLFR, steam	$ 85	**$ 45**	$ 32	$ 25	$ 21	$ 19
Salt LT	$ 105	**$ 61**	$ 46	$ 40	$ 37	$ 35
Salt BL	$ 94	**$ 52**	$ 38	$ 31	$ 27	$ 25
Salt HT	$ 90	**$ 49**	$ 35	$ 28	$ 24	$ 21
Salt HT - 2X	$ 63	**$ 35**	$ 26	$ 21	$ 19	$ 17
Salt HT - 3X	$ 53	**$ 30**	$ 23	$ 19	$ 17	$ 15
CRPT, PHR	$ 77	**$ 42**	$ 31	$ 25	$ 21	$ 19

Table 14.3 – Cost for Alt CST Configurations (As Estimated)

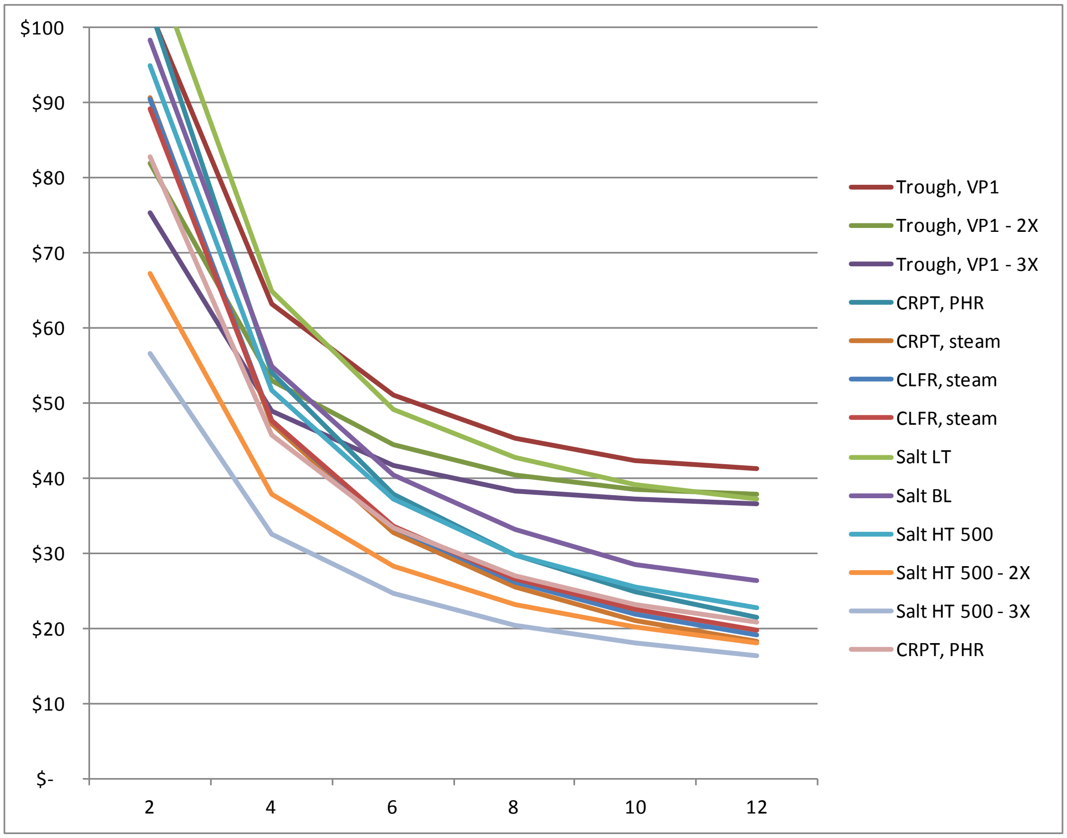


Figure 14.3 – Cost Curves for Alt CST Configurations (As Estimated) ($/kWh-th)

Notes:

- Higher approach temperatures were analyzed as a result of trying to find a way to decrease the cost of the heat exchanger. Doubling the approach temperature roughly halves the length of the SS drum, though with impacts to steam cycle efficiency (which are accounted for in TES costs, but total LCOE impact wasn't analyzed).
- The steam cases assume 1) an innovative design with super critical steam in the receiver and typical temperatures and pressures in the SandShifter for charge discharge; 2) 15% reduction in SS drum costs/length due to a less dense design. Each of these require extensive further examination and development, which is beyond the scope of this phase.

<u>Cost Opportunity Potential for SandShifter</u>

Extending the same cost reduction scenarios to each of the alternate CST configurations yields respective cost curves for each case. In order to temper the cases somewhat, and hedge against some of the steam cycle impact for increase approach temperature cases, the following table shows an average of the case set (approach temps and delta-Ts) for each HTF case, under the respective cost reduction scenarios. This provides a reasonable synthesis of the SandShifter's achievable potential as a technology, showing reductions, but not the most aggressive cases (though not also some newly identified cost reduction opportunities, much less future, unforeseen innovation).

Cost Opportunity for SandShifter TES - Average of Cases per HTF							
Reduct	**HTF / CST Configuration**	**2**	**4**	**6**	**8**	**10**	**12**
0	Trough, VP1	$ 86	$ 55	$ 46	$ 41	$ 39	$ 39
1	Trough, VP1 (MHE+FabLearn)	$ 63	$ 41	$ 34	$ 31	$ 30	$ 30
2+	Trough, VP1 w Full Reduction Potential	$ 58	$ 38	$ 32	$ 30	$ 29	$ 29
0	Steam	$ 90	$ 48	$ 33	$ 26	$ 22	$ 19
1	Steam (MHE+FabLearn)	$ 70	$ 37	$ 26	$ 20	$ 17	$ 15
2+	Steam (+ENH Ht Txfr)	$ 58	$ 31	$ 22	$ 17	$ 15	$ 13
0	Molten Salt	$ 85	$ 48	$ 36	$ 30	$ 26	$ 24
1	Molten Salt (MHE+FabLearn)	$ 66	$ 37	$ 28	$ 23	$ 21	$ 19
2+	Molten Salt (+ENH Ht Txfr w 550C)	$ 51	$ 29	$ 22	$ 19	$ 17	$ 15
0	Sand Particle Receiver	$ 93	$ 50	$ 36	$ 28	$ 24	$ 21
1	Sand Particle Receiver (MHE+FabLearn)	$ 79	$ 44	$ 32	$ 26	$ 23	$ 21
2+	Sand Particle Receiver (+ENH Ht Txfr)	$ 69	$ 39	$ 29	$ 24	$ 21	$ 19

Table 14.4 – Cost for Alt CST Configurations (Reduction Cases)

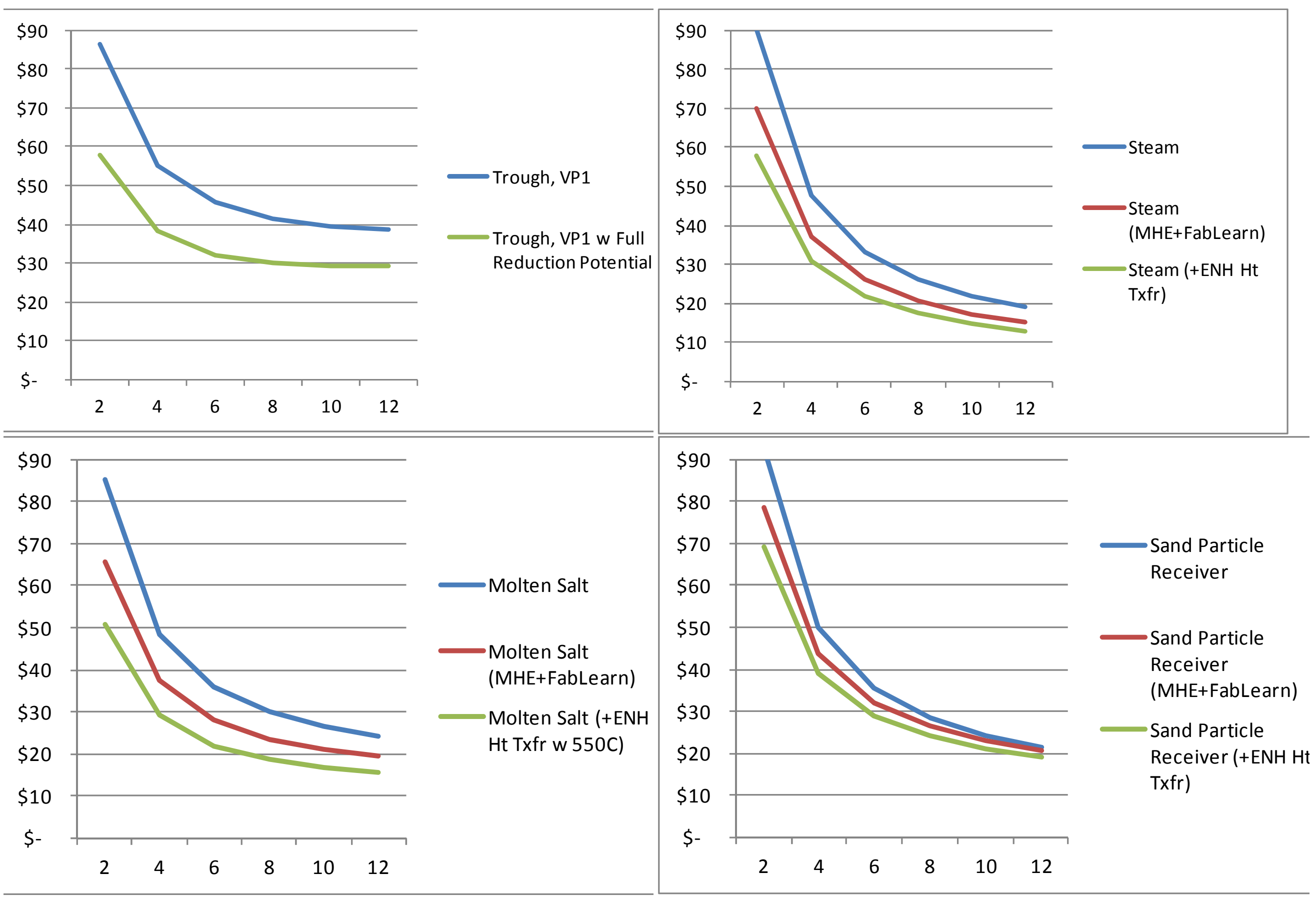


Figure 14.3 – Cost Curve Reduction Cases for Alt CST Configurations

Looking at the specific potential of molten salt, applied in a 290C to 550C application, the following Table 14.4 shows the SandShifter's full potential:

Molten Salt Cases - Cost Curve Potential for Rotating Drum SS (w Proxy 550C)						
HTF / CST Configuration	**2**	**4**	**6**	**8**	**10**	**12**
Salt HT (Case2) + ENH w 550C	51	28	20	16	14	13
Salt HT - 2X (Case2) + ENH w 550C	38	21	16	13	11	10
Salt HT - 3X (Case2) + ENH w 550C	33	19	14	12	10	9

Table 14.4 – Molten Salt Cost Curve Opportunity

Additional innovations not included may further improve the SandShifter cost curve potential.

7. Lessons Learned

Some lessons learned in the Cost Estimation and Analysis include:

- Profound impact of delta T in system cost, as it plays out through sand volume (the smallest impact) into the size of the pits (which get more expensive as they get deeper) and the MHE (non-linear cost increase with height, which follows depth)
- Opportunity for cost reduction in increasing approach temperature in heat exchanger
- Application to steam HTF due to steam phase change requires innovative solutions

8. Looking Forward

<u>Opportunities for Cost Reduction</u>

- Optimization of SS unit size vs. MHE and other primary cost drivers
- Cost refinement for low pressure environment
- Molten Salt to Metal Heat transfer enhancement opportunities
- Fundamental innovation in the system design
- Improvements in heat transfer
- Dragline based MHE technology development (Reduced CapEx & Aux)
- Large scale fabrication assembly; low cost component fabrication

9. Summary

A cost estimate was completed application of the SandShifter for the Reference Plant. Analysis was conducted of SandShifter's cost curve potential, showing the SandShifter is a potentially disruptive TES technology. In some cases, SandShifter has the potential to 60-80% cheaper than the prevailing technologies in comparable CST applications, leveraging sand's 10-25X cost per unit thermal storage capacity over molten salt. The technology has strong potential to achieve DOE's goals of TES technology with costs of below $15/kWh-th – and its wide temperature applications offer promise in a variety of CST applications. Further development of this technology is highly recommend, including funding of Phase 3, and expansion of Phase 3 to include special projects to advance specific aspects of the SandShifter technology.

10. Relevant Appendices

14-1 – Cost Estimation Methodology

Section 15
Summary, Conclusions, and Recommendations

1. Summary

During Phase 2, this subproject successfully demonstrated a small-scale prototype of the SandShifter system, having moved toward that result while simultaneously innovating new design approaches, advanced supporting science, and vetting or quantifying numerous critical issues. Most specifically, the promise of Sand as a high-temperature TES media has been initially validated for the first time in history. Most broadly, a new knowledge platform has been founded in sand-metal heat transfer and sand-HTF heat exchange which will inform the evolution of a promising technological area. The Phase 2 work will specifically inform the execution of Phase 3 of the project for a nominally 1 MW scale demonstration project, the next major milestone in further development of this technology, and related R&D and commercial advancement of the technology.

Noteworthy Phase 2 achievements include:

- **Vetting Potential Fatal Flaw Issues** for the SandShifter technology
- **Developing data to inform, support, and validate** technology development
- **Proof of Concept:** Fabrication, commissioning, and testing of the 50 kW-th Prototype demonstrates that the SandShifter technological concept can be successfully implemented.
- **General Lessons Learned:** Each investigational area, as represented by the sections of this report, resulted in material lessons learned. These ranged from fabrication techniques for the tube bundle to the effect of sand particle size to cost sensitivity to various design aspects.
- **Identification of Areas for Additional Investigation:** Almost every line of investigation pointed to new areas of investigation, whether as opportunities for innovation or to better quantify a specific performance aspect. The Looking Forward sections comment on many of these and the investigators recommend additional funding and effort on many of these.
- **Cost Analysis:** Updated cost estimation for the technology now informs the full potential of the technology in a variety of CST configurations. The potential of the SandShifter to achieve DOE cost targets and compete at a fraction of the price of the competing technologies is a major milestone.
- **Identification of Cost Curve Improvement Opportunities:** The Phase 2 process resulted in a broadening knowledge of various attributes of the SandShifter technology and thereby allowed the team to identify opportunities for additional cost reductions.
- **Publications:** Several publications and papers resulted from the work in Phase 2. Publications are listed in Appendix 16-2. Several papers are attached to this report as appendices to their applicable report sections.

The project also achieved all of its DOE SOPO objectives and milestone requirements:

Task/ Milestone	Item	Status
Task 2.0	Design Prototype	Done
Milestone 2.0	PROTOTYPE DESIGN FINAL	Done
Task 2.1	Construct Prototype	Done
Milestone 2.1	PROTOTYPE OPERATIONAL	Done
Task 2.2	Operate Prototype & Perform Tests	Done
Task 2.3	Final Detailed Cost Estimate	Done
Milestone 2.2	COST ESTIMATE COMPLETE	Done
Task 2.4	Analyze Scaling Issues	Done
Task 2.5	Develop Test Plan Outline for Demo Project	Done
Task 2.6	Project Management & Reporting	Done

2. Conclusions

In conclusion, during Phase 2, the SandShifter team achieved its desired objectives, most concisely, to:

1) Demonstrate the SandShifter's viability technologically and economically;

2) To advance related understanding, in terms of supporting science, design options, fabrication techniques, cost structures, and general know-how;

3) To evolve the Preferred Design Approach;

4) To provide a platform for Phase 3's 1 MW Demonstration of the SandShifter.

The promise of the SandShifter to perform in a variety of alternative CST applications, including high temperature environments, and to achieve cost levels as low as DOE cost targets of $15/kWh-th, is compelling. Further investment in this technology should continue to develop its full promise as a disruptive TES technology.

3. Recommendations

Looking Forward: Future work on the SandShifter technology must:

1. **Examine the system at larger scale, and with the full configuration** (including MHE and sand storage vessels), to learn from the experiences which will be derived in the areas of fabrication, O&M, and configuration for optimal future design. This is intended work for Phase 3, pursuing a 1 MW demonstration project.

2. **Examine application of the SandShifter for molten salt and steam as HTF options**, and the corresponding CST configurations.

a. Phase 3 work might be modified to focus on these applications.

b. Optimize the system design by more intensive investigation and development of design options, in terms of available technologies and development of new technologies and configurations, particularly in the context of alternative CST plant configurations.

This work must necessarily incorporate lessons learned and looking forward observations from Phase 2.

Recommendations:

1. **Approve and Fully Fund Phase 3** of the project, allowing adaptations for higher temperature and alt-HTF applications at the team's election, as manageable given the available Phase 3 budget. Please see Appendix 15-1 featuring partial plans for Phase 3.

2. **Expand the SandShifter R&D program** to more fully examine and demonstrate the potential of the SandShifter technology with alternate CST plant configurations, in order maximally cultivate and demonstrate the potential of sand as TES. This would ideally leverage additional engineering and analytical resources to systematically examine and cultivate the design options and their corresponding cost outcomes.

   Additional projects to add to Phase 3 work, and the respective budget increases are proposed as follows:

Special Project	Description	Incremental Cost
MHE Design Development	Special effort to develop a new MHE system for specific application for the SandShifter technology. Conversion of MHE to a clamshell/dragline system has potential to realize a 70% reduction in MHE costs, not including reduction 50% of applicable auxiliary loads. This requires a special design and engineering effort to develop a new-to-the-world MHE configuration using mostly exiting technology.	$475,000
Pits Design Advancement	This project would study conduct additional investigation of pits, studying heat loss and configurational impacts to find a preferred design approach and then to create a detailed design proposal.	$175,000 (assumes MHE project)
Alternate Geographies Analysis	This project would examine cost consequence for a) project deployment and b) component fabrication in alternate geographic environments. The SS project currently only analyzes cost for a AZ regional deployment and assumes 100% fabrication in the U.S. Likely, there are cost reductions achievable	$175,000

	from outsourced production. Additionally, different regions will have different labor and materials (sand) cost inputs.	
Alternate HTF System Development	Key promise of the SandShifter is its application to high temperature environments, best achieved by application of the technology with alternate HTFs such as molten salt, steam, and sand. This project would develop system designs for a given HTF application, develop supporting physical and computer modeling tools, and update expected cost estimates.	Molten Salt: $125,000 Steam: $100,000 Sand: $200,000
Molten Salt SS Heat Exchanger – Enhanced Salt-Side Heat Transfer Design	This project would work to develop and enhanced and optimal approach for a SandShifter heat exchanger application with molten salt as HTF.	$200,000
Steam SS Heat Exchanger – Develop Sand-Side Heat Exchanger Design	This project would work to develop and enhanced and optimal approach for a SandShifter heat exchanger application with steam as HTF, focusing on the sand side performance and achievement of a cost optimal, compact design.	$110,000
Sand Properties Analysis	This project would examine sand properties in detail, including economic and performance aspects in the system, to develop a preferred TES particle strategy.	$75,000

4. Relevant Appendices

Appendix 16-1 – Phase 3 Proposal

Appendix 16-2 - Publications