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HAMILTON SUNDSTRAND, A UNITED TECHNOLOGY COMPANY

Concentrating Solar Power – Molten Salt Pump Development

Final Technical Report (Phase 1)

Contract No. DE-FC36-08GO18031

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1. Project Objectives

The purpose of this project is to develop a long shafted pump to operate at high temperatures for the purpose of producing energy with renewable resources. In Phase I of this three phase project we developed molten salt pump requirements, evaluated existing hardware designs for necessary modifications, developed a preliminary design of the pump concept, and developed refined cost estimates for Phase II and Phase III of the project. The decision has been made not to continue the project into Phases II and III.

There is an ever increasing world-wide demand for sources of energy. With only a limited supply of fossil fuels, and with the costs to obtain and produce those fuels increasing, sources of renewable energy must be found. Currently, capturing the sun's energy is expensive compared to heritage fossil fuel energy production. However, there are government requirements on Industry to increase the amount of energy generated from renewable resources. The objective of this project is to design, build and test a long-shafted, molten salt pump. This is the type of pump necessary for a molten salt thermal storage system in a commercial-scale solar trough plant. This project is under the Department of Energy (DOE) Solar Energy Technologies Program, managed by the Office of Energy Efficiency and Renewable Energy.

To reduce the levelized cost of energy (LCOE), and to meet the requirements of "tomorrows" demand, technical innovations are needed. The DOE is committed to reducing the LCOE to 7-10¢/kWh by 2015, and to 5-7¢/kWh by 2020. To accomplish these goals, the performance envelope for commercial use of long-shafted molten salt pumps must be expanded. The intent of this project is to verify acceptable operation of pump components in the type of molten salt (thermal storage medium) used in commercial power plants today. Field testing will be necessary to verify the integrity of the pump design, and thus reduce the risk to industry.

While the primary goal is to design a pump for a trough solar power plant system, the intent is for the design to be extensible to a solar power tower application. This can be accomplished by adding pumping stages to increase the discharge pressure to the levels necessary for a solar power tower application.

This report incorporates all available conceptual design information completed for this project in Phase I.

2. Project Scope

This project specifically addresses "Integration of Advanced Low-Cost Thermal Storage for Parabolic Trough Systems". The work was divided into 3 phases, each concluding with a critical milestone. Information generated during each specific phase would be submitted to the DOE, along with all required deliverables, so that a "Go/No-Go Decision" could be made by the DOE in respect to project continuation to the next phase. The decision has been made not to continue the project into Phases II and III.

Phase 1 developed the parameters on which to base the pump conceptual design. Starting with existing solar pump technologies, areas needing improvement were evaluated, and changes incorporated into this project's pump design. The current state of the art solar power plants were examined, and projected future needs considered. From this, a conceptual design for a full-scale solar power plant evolved. The final activities in Phase I of the project included development and refinement of cost estimates for the design, build and testing activities to take place in Phase II and Phase III of the project.

Phase II builds on the conceptual design work performed during Phase I. In this phase, the detailed design shall be presented in both a preliminary design review (PDR) and a critical design review (CDR). After completion of the CDR, drawings shall be finalized and used for the fabrication of pump hardware, assembly and support equipment. During the fabrication and assembly operations, opportunities for improved manufacturing and lower production cost will be identified.

Once the cost of the prototype pump is known, estimates of production pump costs can be made for various production rates, and a refined LCOE determined. Detailed maintenance and assembly procedures to support pump operations shall also be created. Prior to completion of Phase II, detailed plans shall be made for testing of the prototype in molten salt as required in Phase III.

Phase III is the actual testing of the full scale prototype pump in molten salt (as used in commercial applications). Testing is planned to take place at the National Solar Thermal Test Facility (NSTTF). Molten salt temperatures are to range from 550°F to 1050°F, as outlined in the test plan created in Phase II. Support activities shall include reviewing all data collected, as well as providing a summary report of the testing and results. Opportunities to reduce costs shall be considered (making components easier to manufacture, lower-cost components/subsystems), however these should not significantly reduce overall system performance or cost effectiveness.

3. Phase 1 – Conceptual Design

Phase I of this project is the evaluation of molten salt pump parameters for a solar power plant, conceptual design of the pump itself, and cost projections for Phase II and Phase III. Section 3 of this report discusses these topics in detail.

Molten salt is considered “cold” at a temperature of 550°F, and “hot” at a temperature of 1050°F, and these terms will be used throughout the report. The 60/40 Nitrate Salt remains a liquid at temperatures above ~ 460°F, but begins to chemically break down at temperatures above 1050°F. Both extremes are undesired, therefore the plant system design shall maintain a salt temperature between 550°F and 1050°F at all times.

3.1 Task 1: Develop molten salt pump requirements for indirect and direct systems

Phase 1 includes defining the molten salt pump requirements for indirect and direct thermal storage systems, generating the top-level specifications for pump operation and to generate the general pump configuration. In order to set the top level operational parameters for a pump design, it was necessary to understand the system that the pump is intended to be used in. Below is an example of a trough two tank system, with direct thermal collection of molten salt in the field.

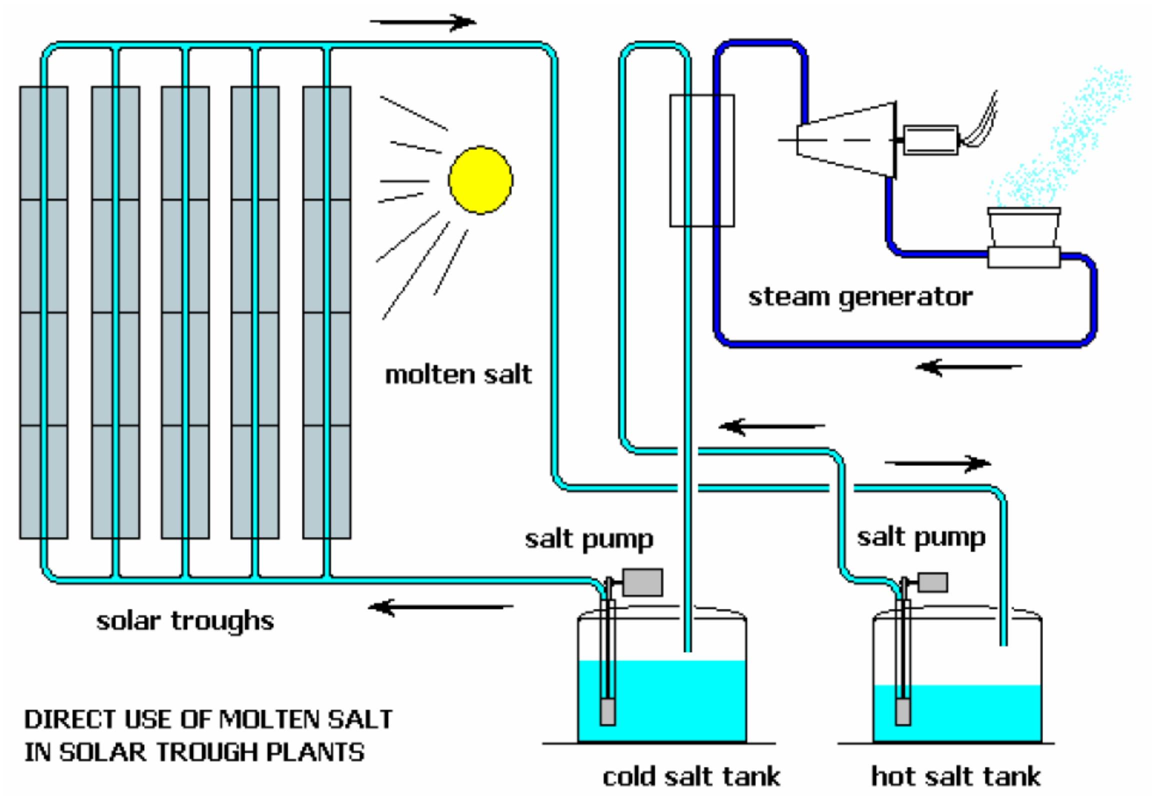


Figure 1: Trough, Direct Molten Salt System

3.1.1 Historical Lessons Learned

Historically, solar projects in the 1990's (such as Solar II) used a sump pump type design. Lessons learned from Solar II established the basis for thermal energy systems in the solar market today. Today, the desire for larger plants favors the use of long shafted vertical pumps. Associated valve and piping needs are reduced with this design, and (due to large storage capacity) the need for heat tracing is reduced. These changes have improved the efficiency of the thermal storage systems. In addition, there are cost savings from the elimination of aforementioned equipment, and a reduction in failure modes, resulting in reduced risk factors. Maintenance costs are also lower. Overall operational costs decrease, reducing the LCOE of the plant. This project, therefore, focused on vertical shafted pumps.

It was desired to develop a "generic" design for the hot side of the plant system, which would be applicable throughout the solar power industry. Both trough and power tower systems were evaluated. Pumps that met the elevated temperature and high pressure (for the power tower systems) requirements were not commercial available at the inception of this project. Solar II was a 10MWe system, designed for 3 hours of thermal storage. The industry standard today is a 100MWe system, designed for 4 hours of thermal storage. In addition, it uses two tanks (60/40 nitrate salt), with multiple top-entry pumps, and shell and tube heat exchangers. Comparisons between the two systems provided insight into potential cost saving measures.

3.1.2 Comparison of Indirect vs. Direct Trough Thermal Storage

There are two methods for transferring collected sun thermal energy to a heat exchanger, where water is ultimately converted into a high pressure vapor used in the production of electrical energy. The two methods are defined as indirect and direct.

Indirect systems use a high temperature fluid (HTF) such as Therminol in the solar collection field. This fluid is heated in the field, then pumped though a heat exchanger to another medium (such as molten salt), which is then accumulated in a storage facility (tank). With this type of system, either one or two storage tanks can be used. The one tank system uses a thermocline to separate the cold salt from the hot salt, whereas the two tank system has a dedicated cold tank and dedicated hot tank. Currently, both systems are considered to be experimental. One advantage of the single tank system is that cheaper fillers can be used in place of the more costly salt.

Direct systems are so named because only a single HTF (such as molten salt) is used for both solar collection and thermal storage. This reduces the number of components, such as heat exchanger, required. Today, direct systems are used in both trough and power tower designs, and use dedicated cold and hot tanks for the storage of thermal fluids.

Although experience with these systems is limited, its is clear that the two storage systems need to operate at the same top level conditions, and therefore solutions for reducing costs of energy production apply to both. Simplifying the system (reducing the number of pumps, valves, piping, fittings, heat traces, etc.) reduces potential failure modes, as well as overall operation and maintenance costs. As previously mentioned, a long shafted pump mounted above the thermal storage tanks eliminates valving, piping and heat trace associated with a sump pump type design. Since trough and tower systems can use the same type of thermal storage tanks, the same pump design (with minor modifications) can also be used on both.

3.1.3 Requirements of a pump in a Trough System

At the time this project was originally proposed, trough systems were the most common design for molten salt power plants, therefore the pump design was conceptualized for this application. The vendor examined its existing pump designs. Having significant involvement with molten salt applications in both the USA and Europe, the review covered 300 molten salt pump applications, with single and multi-stage wet ends, 20 impeller sizes, 5 bearing pedestal sizes, and 7 materials used for columns, wet end and pump discharge. All pumps operating in the same temperature range (~550°F to 1050°F) required today. Shaft lengths were shorter than required today (20 feet long compared to 50 feet), however. The pumps operated with motors up to 800 HP.

While there were obviously design differences between the pumps, common features were identified as necessary to ensure successful operation. These include: a vertical submerged bearing design, variable speed capability, self draining, capable of running at dead heat (shut-off), replaceable thrust bearing with the pump installed (maintenance issue), vibration and temperature monitoring system, reverse rotation protection, non-contacting labyrinth seal, grease lubricated thrust bearings, heat-dissipation fans, axial adjustment capability, balanced heat in column and discharge piping, and salt lubricated radial bearings.

3.1.4 Top level pump operating parameters for the new pump concept

The parameters used to envelope the pump design were based on commercial-sized power plants, with solar condition and energy needs similar to the conditions found in Southern California. Southern California has a high percentage of “sun” days for the production of thermal energy, and due to the population density there is also a large consumption of electrical power.

In both the near and long term future, world-wide energy consumption is expected to increase. Today, the largest molten salt power trough plant has a maximum power generation capability of 50MWe In the near future, power plants could require outputs of as much as 150MWe or more. For this project, the basis for the pump design was assumed to be a trough plant producing 100MWe, and with 4 hours of thermal storage. While double the size of existing trough plants, this is considered to be a reasonable step to take.

The pump volumetric flow requirements were determined assuming 4 hours of thermal storage, the specific heat of the salt (a 60% Sodium Nitrate ($NaNO3$) + 40% Potassium Nitrate ($KNO3$) by weight mixture) and other salt properties, heat transfer rates, and the steam generation system efficiency. This calculation determined that ~19 million lbs of salt are required, equivalent to a flowrate of ~5500 GPM. Redundancy favors multiple pumps rather than a single pump for operating the hot side of the system. Once the number of pumps for the final system configuration is determined, the volumetric flow rate, speed, and horse power requirements will be adjusted accordingly.

To simplify the system, the pump will be designed for a two tank plant. Focus will be on the hot tank design, with a vertical pump orientation and top entry to eliminate associated valving, piping, fitting and heat trace. The pump shall operate at a rotational speed of ~1800 rpm, but will have the variable speed capability. A total of 750 HP (which is well within both motor supplier and vendor experience) will be required, with actual motor HP requires dependant on the number of pumps chosen.

The salt has a melting point of ~490°F, and the system must be designed to prevent a phase change from liquid to solid. For this reason, and leaving some margin, the operating fluid shall be maintained at a minimum of 550°F. The salt thermal properties break down at temperatures above 1050°F, thus creating the maximum allowable fluid temperature. This operating range will be used to determine the most appropriate stainless and non-stainless steels for this application.

Based on vendor experience, the bearing system incorporates a single thrust bearing, and is capable of being removed for replacement and scheduled maintenance without requiring removal of the pump from the tank. The radial bearings shall be submerged in the tank and are a hydrodynamic configuration, utilizing the salt as coolant.

The pump shall generate a delta discharge pressure of ~100 psi. This value is based on other existing trough plant designs, taking into consideration piping friction, fittings, heat exchangers, bypass flow for bearing coolant, etc. It should be noted that the discharge pressure can be impacted rather significantly by component changes, and therefore will need to be re-evaluated in the next phase. Additionally, should this pump be needed for a tower application, the discharge pressure requirements would increase several times. This challenge can be overcome by the addition of multiple wet end stages. If this change was required, other parameters (such as bearing loading) would also need to be re-evaluated.

3.2 Task 2: Evaluation of exiting hardware designs for necessary modifications

The vendor evaluated its existing line of pumps, based on current RFP requirements for Solar Trough Plants with Thermal Energy Systems (TES) utilizing molten salt pumps. For reference 68% of the time a pump with a 10 inch discharge, 16.5 inch impeller diameter, and an operating speed of less than 1800 RPM met the customer requirements. The size of pump selected for this application would be used in parallel with 2 or 3 other pumps of the same size, to provide redundancy within the TES system, to control equipment costs, and to reduce the risk of a complete system shut down during scheduled maintenance periods.

All vertical pumps can be of single stage or multi-stage wet end designs. Applications requiring higher head use a multi-staged wet end. Multi-staged wet end designs are custom manufactured for molten salt applications. The three types of vertical pumps (cantilever, non-submerged bearing and submerged bearing) offer different advantages and disadvantages.

Vertical cantilever pumps allow multiple mounting arrangements (including both in-tank and outside of tank), giving system designers greater flexibility. They have no bearings below the main mounting plate, and are therefore easier to disassemble, but as a result can only offer single volute designs.

Vertical pumps (non-submerged) have a lower radial bearing. They also allow several mounting arrangements, both in-tank and outside of the tank. Vertical pumps (non-submerged) can offer multi-stage volutes as an option. They have longer settings than the cantilever pumps, but are more difficult to disassemble.

Vertical submerged bearing pumps are the longest design offered. They can only be mounted in the tank. Vertical submerged bearing pumps can offer multi-staged volutes, but are the most difficult to disassemble.

Given the length requirements of this application, choices are limited to either a vertical submerged bearing pump with a separate discharge line, or a vertical (non-submerged) turbine design pump with a central discharge column. Below is an evaluation of these two designs, taking into consideration twenty-two key design features. Six technical barriers were identified that require further assessment, as a result of increased pump shaft length (up to ~50 feet), and variable speed operation.

3.2.1 Technical Barriers

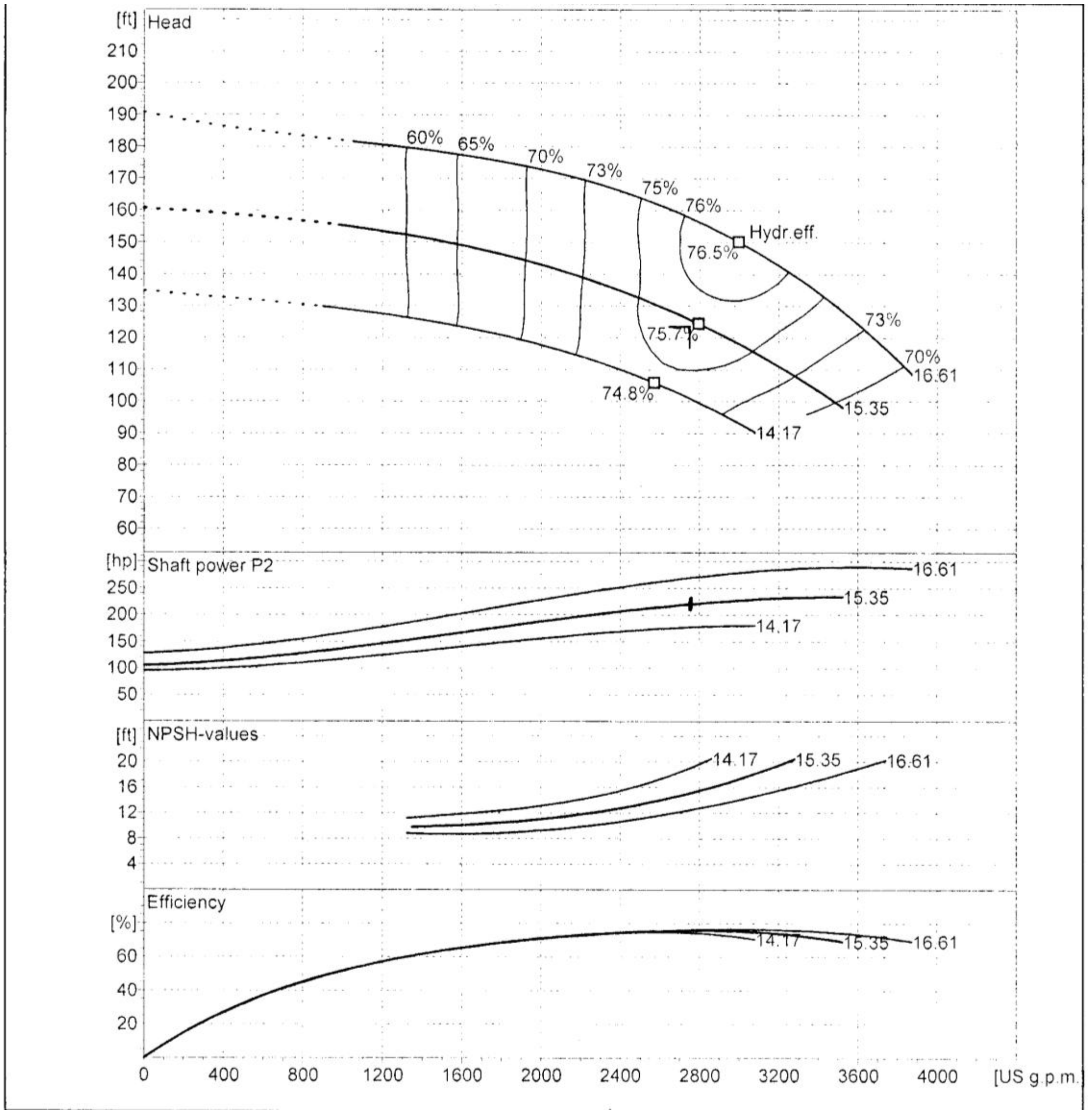
The primary technical barriers have been identified:

1. Shaft Harmonic
2. Column Harmonics
3. Column assembly mounting to main mounting plate
4. Radial bearing lubrication
5. Effects of tank liquid level on pump harmonics
6. Minimum submergence and vortexing

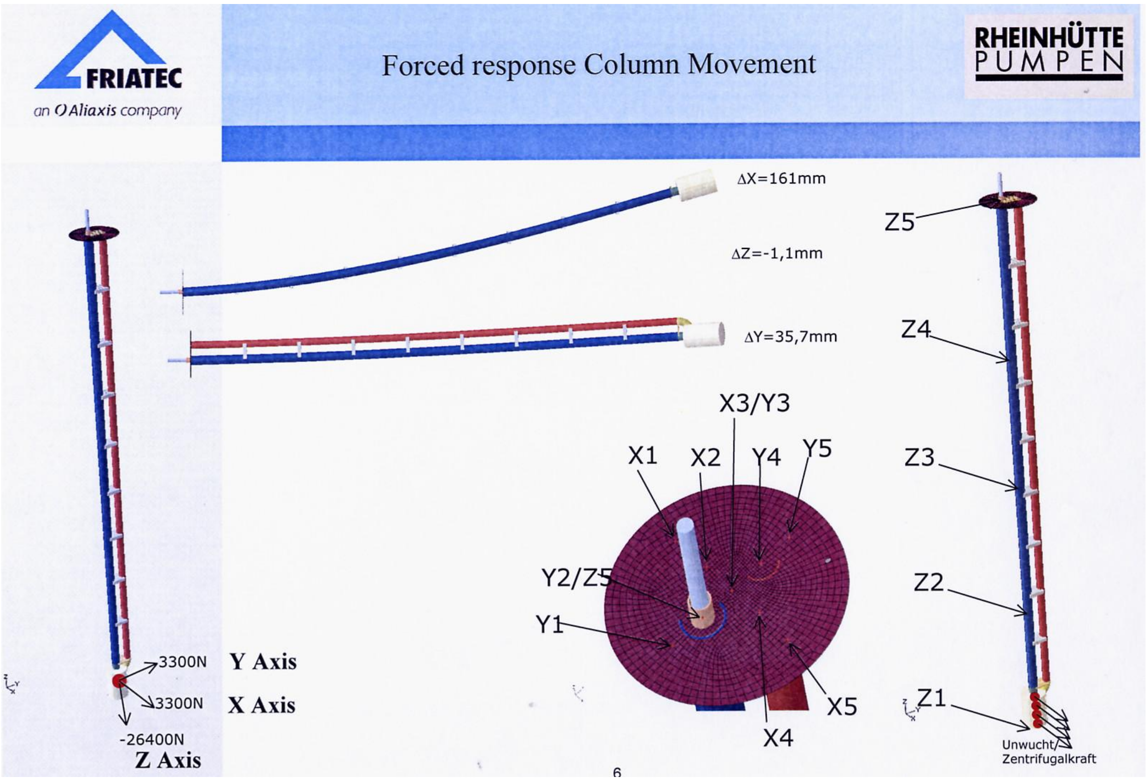
It was has determined that the pump required for the DOE program is a 250/355 pump (10 inch discharge, 16.6 inch diameter impeller, ~1500 rpm, 250 hp, single stage wet end). Finite Element Analysis (FEA) and Computation Fluid Dynamic (CFD) analysis on a similarly sized 200/400 pump has already been performed (8 inch discharge, 18.3 inch diameter impeller, 1800 rpm, 2300 hp, 4 stage wet end).

The pump design concepts developed under Phase I are similar to one of Friatec’s existing vertical pumps. The attached curve is representative of the flow and head requirements for such a pump. This curve is specifically for a pump with a 16.6” diameter impeller, operating at 1450 rpm, at a flow rate of

2750 gpm, a TDH of 130 ft., with a 10” discharge, and of a single volute design. The operating conditions required for this program are similar to previous commercial designs by Friatec, but requiring a longer pump shaft length. The program would require two of these units to operate in parallel.



While the generalized design concepts were anchored to prior CFD and FEA analysis, a refined CFD and FEA analysis would be required for the actual detailed design. FEA, for example, shows that column movement can cause very high forces on assembled joints of a long shafted pump. 3-D models based on actual pump components must be developed and evaluated. As part of the normal design iteration process, weaknesses in the shaft or column harmonics, or mounting plate weaknesses are often uncovered. Also, a significant amount of detailed work needs to be done to ensure pump reliability. Until the final design is completed (in Phase II), however, it is not practical to provide additional design information.



Forced response Column Movement

Figure 2: FEA analysis of column movement

Because molten salt test facilities, for large pumps, are not currently available, the pump design will depend on FEA and CFD analysis. Some studies have been done which correlate molten salt and water test data (see below), however additional water testing may be required.

Both the column assembly and mounting plate must be evaluated for harmonics at a range of operating speeds. The mounting plate acts as the foundation of these long pumps.

The following pages are representative of the type pump selected for the DOE study. Phase II would require a more refined study be conducted. The analysis shown below is for the shaft column, but a similar analysis has also been performed on the mounting plate.

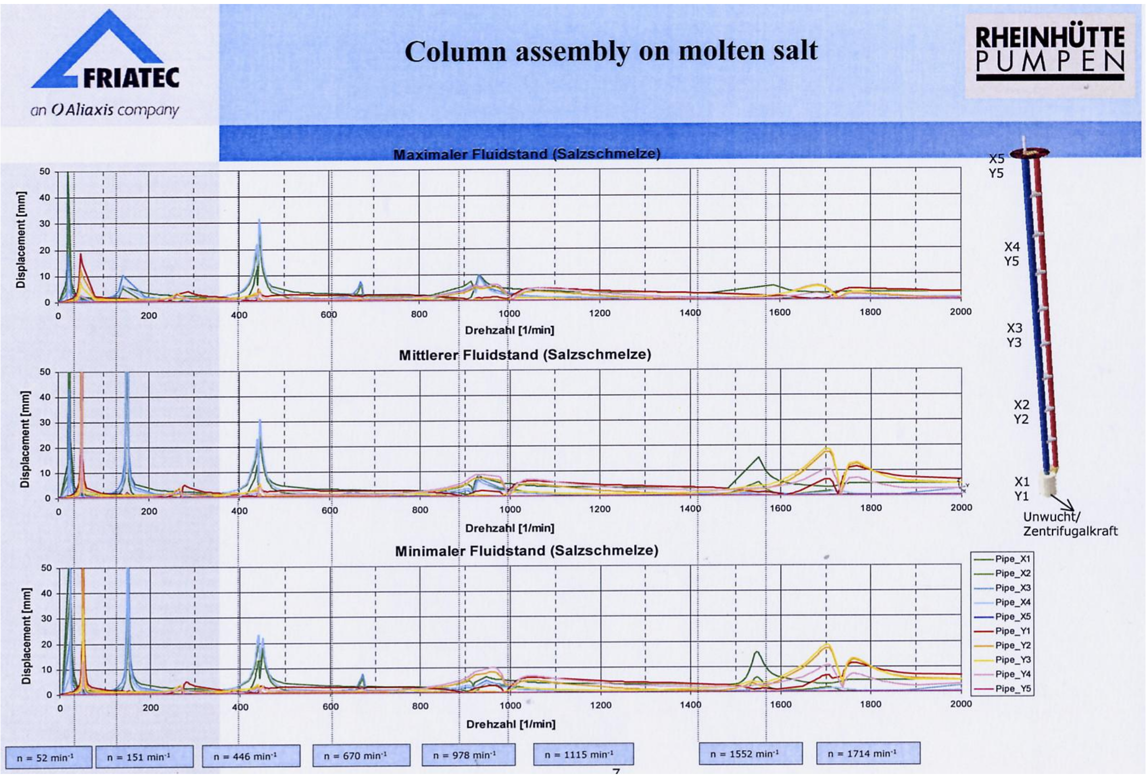


Figure 3a: Column Dynamic response vs. operational speed in Molten Salt

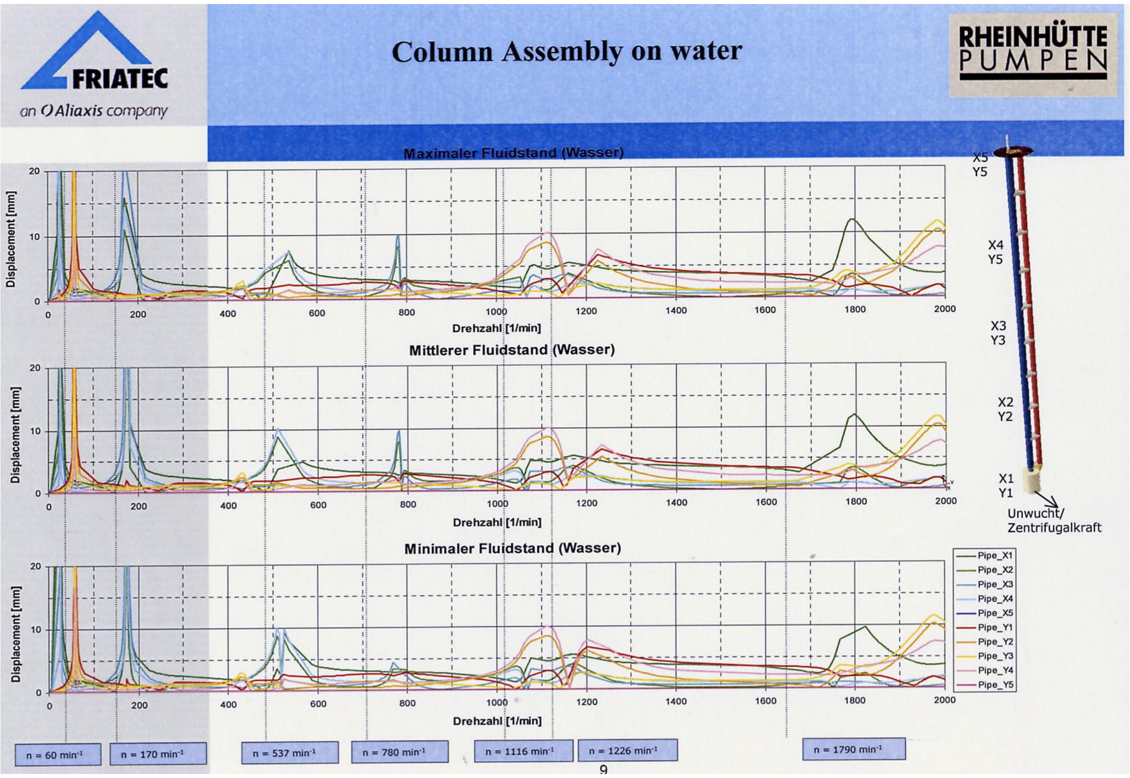


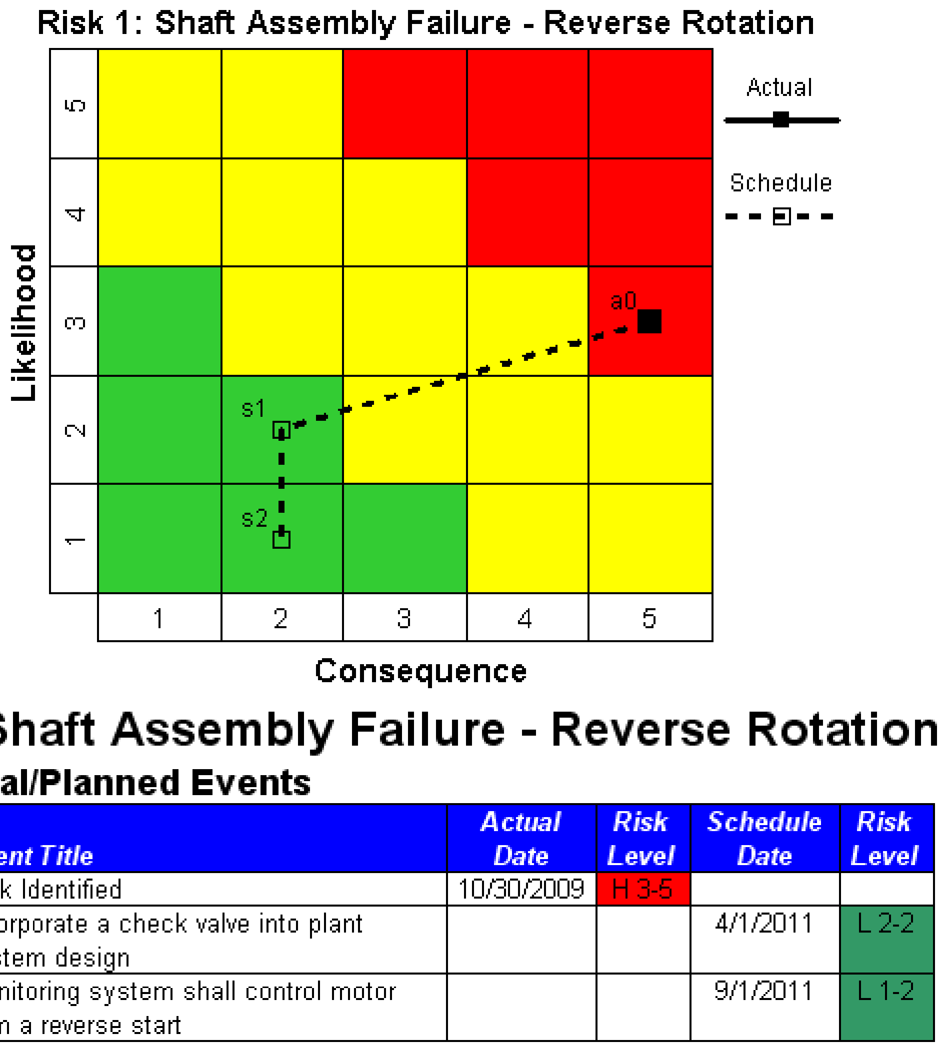
Figure 3b: Column Dynamic response vs. operational speed in Water

The specific technical barriers identified for a vertical, submerged radial bearing design pump are as follows:

1) Shaft Assembly Failure due to Reverse Rotation

The shaft can break at coupling locations if a pump is started while in reverse rotation. Shaft failure at the keyways was cited as just one of the examples of the detailed work that would need to be done to ensure pump reliability. Torque loads are higher with molten salt than with other applications. Standard manufacturing practice is to use square cut keyways in pump shafts, however most shafts are not designed for an "across the line" restart at full RPM when the pump is in reverse rotation. Machining a radius corner in the bottom of the keyway is standard practice for steel mill rolls, and is a feature that would be incorporated in this application.

Figure 3: Shaft Failure examples



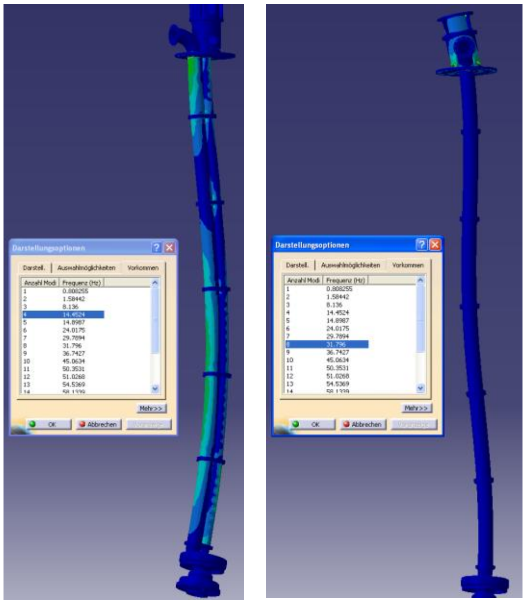
1) Shaft Assembly Failure - Reverse Rotation

Actual/Planned Events

#	Event Title	Actual Date	Risk Level	Schedule Date	Risk Level
0	Risk Identified	10/30/2009	H 3-5		
1	Incorporate a check valve into plant system design			4/1/2011	L 2-2
2	Monitoring system shall control motor from a reverse start			9/1/2011	L 1-2

2) Shaft Assembly Failure – Harmonics

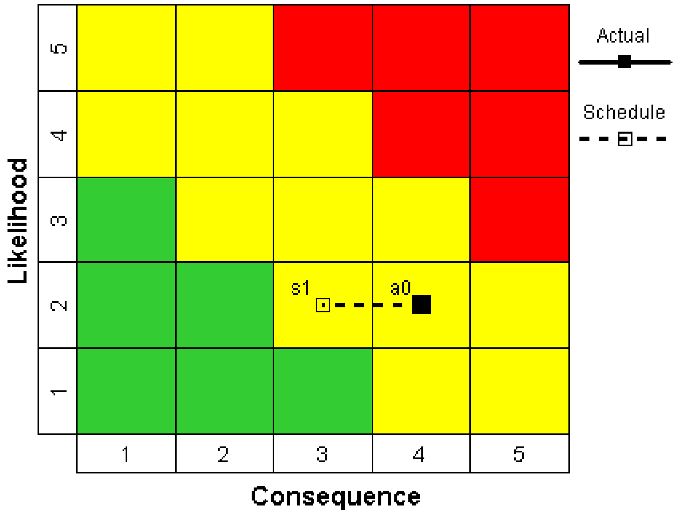
Excitement of a natural frequency can cause failure of the shaft.

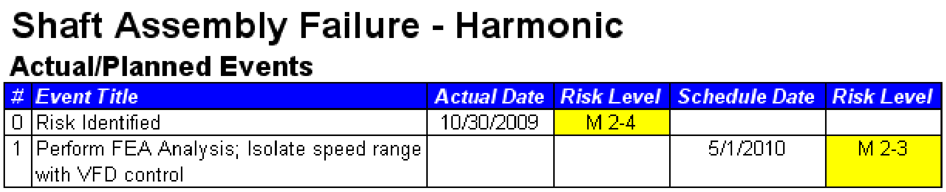


Anzahl Modi	Frequenz (Hz)
1	0.808255
2	1.58442
3	8.136
4	14.4524
5	14.8987
6	24.0175
7	29.7894
8	31.796
9	36.7427
10	45.0634
11	50.3531
12	51.0268
13	54.5369
14	58.1339

Figure 4: Shaft FEA Strain

Risk 2: Shaft Assembly Failure - Harmonic





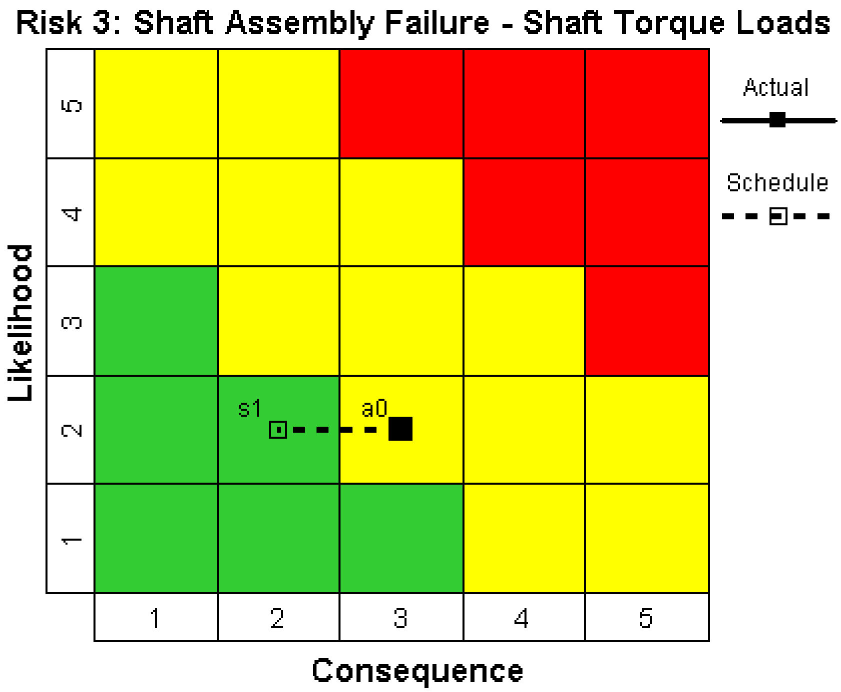
Shaft Assembly Failure - Harmonic

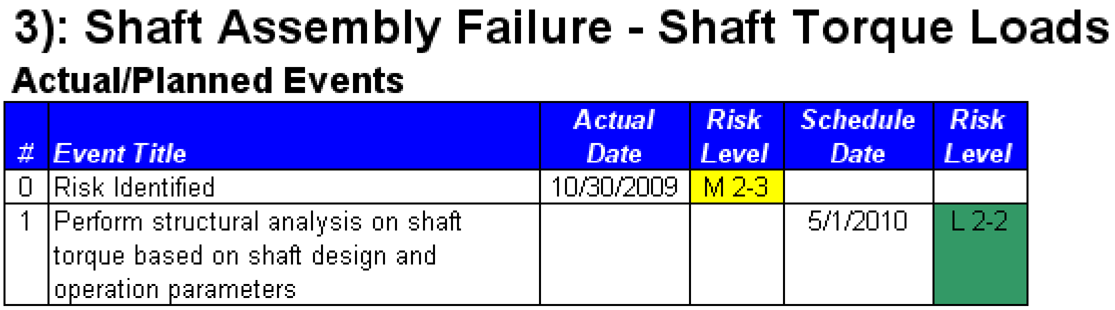
Actual/Planned Events

#	Event Title	Actual Date	Risk Level	Schedule Date	Risk Level
0	Risk Identified	10/30/2009	M 2-4		
1	Perform FEA Analysis; Isolate speed range with VFD control			5/1/2010	M 2-3

3) Shaft Assembly Failure – Shaft Torque Loads

Increasing the length of the shaft adds coupling points, through which torque loads are transmitted. Fluids with high specific gravity, such as molten salt, increase the torque loads which must be accounted for. Operational parameters (such as direct across the line starting verses slow roll starting) are major factors in torque loads.





3): Shaft Assembly Failure - Shaft Torque Loads

Actual/Planned Events

#	Event Title	Actual Date	Risk Level	Schedule Date	Risk Level
0	Risk Identified	10/30/2009	M 2-3		
1	Perform structural analysis on shaft torque based on shaft design and operation parameters			5/1/2010	L 2-2

4) Column Assembly Failure – Mounting Plate Attachment

Structural failures are typically at fasteners or welded joints.

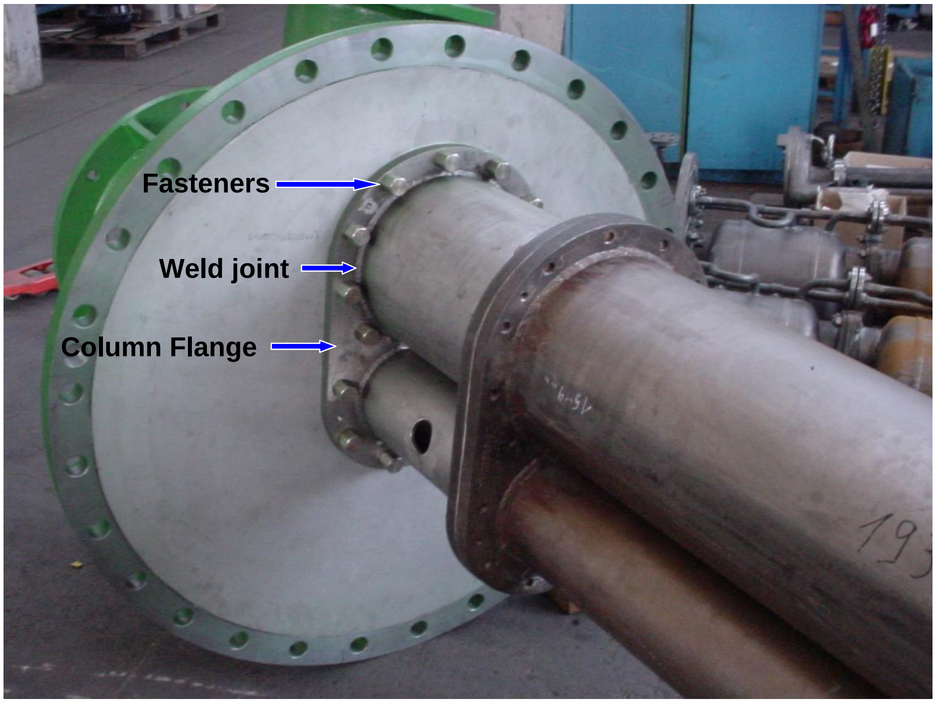
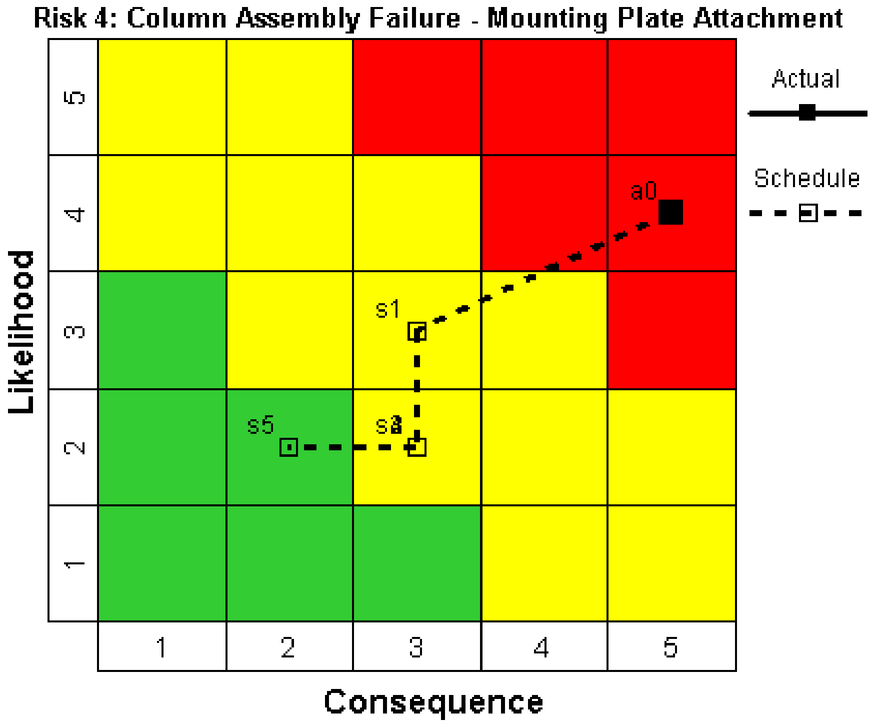
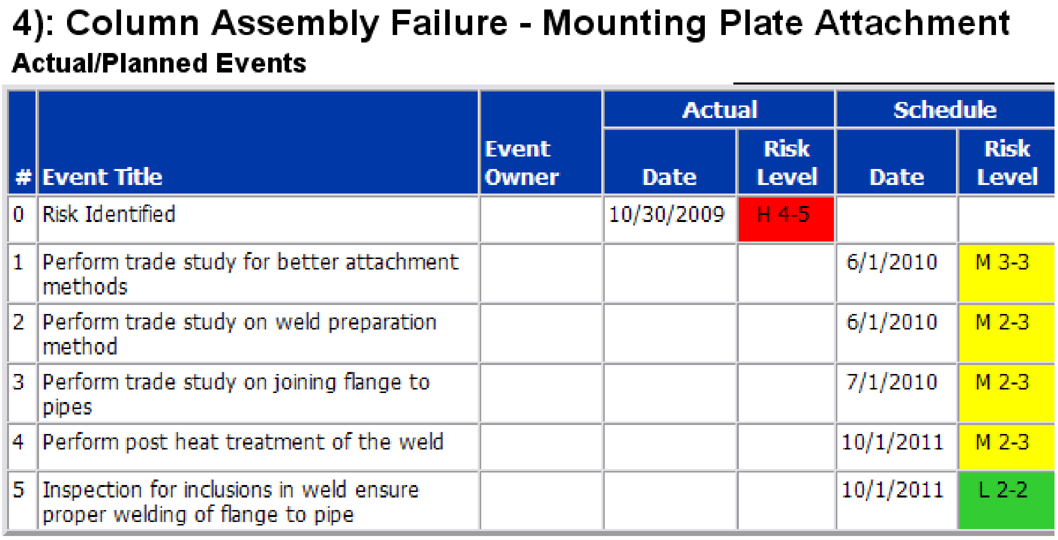


Figure 5: Mounting Plate





4): Column Assembly Failure - Mounting Plate Attachment

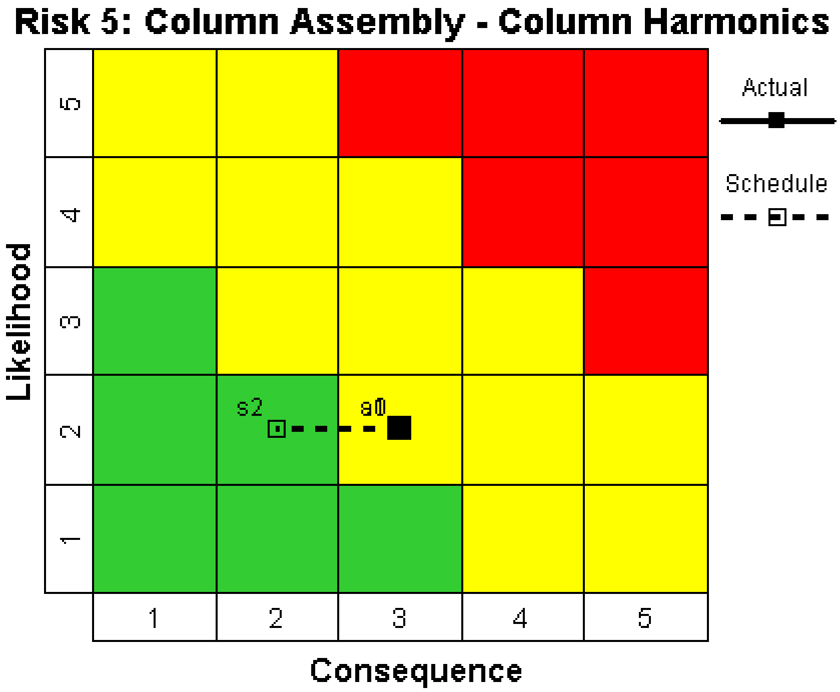
Actual/Planned Events

			Actual		Schedule	
#	Event Title	Event Owner	Date	Risk Level	Date	Risk Level
0	Risk Identified		10/30/2009	H 4-5		
1	Perform trade study for better attachment methods				6/1/2010	M 3-3
2	Perform trade study on weld preparation method				6/1/2010	M 2-3
3	Perform trade study on joining flange to pipes				7/1/2010	M 2-3
4	Perform post heat treatment of the weld				10/1/2011	M 2-3
5	Inspection for inclusions in weld ensure proper welding of flange to pipe				10/1/2011	L 2-2

5) Column Assembly Failure – Column Harmonics

Column harmonics can be very destructive to structural components, causing leaks, broken welds and eventually pump failure.

Figure 6: Column Failure due to Harmonic vibration



5): Column Assembly - Column Harmonics

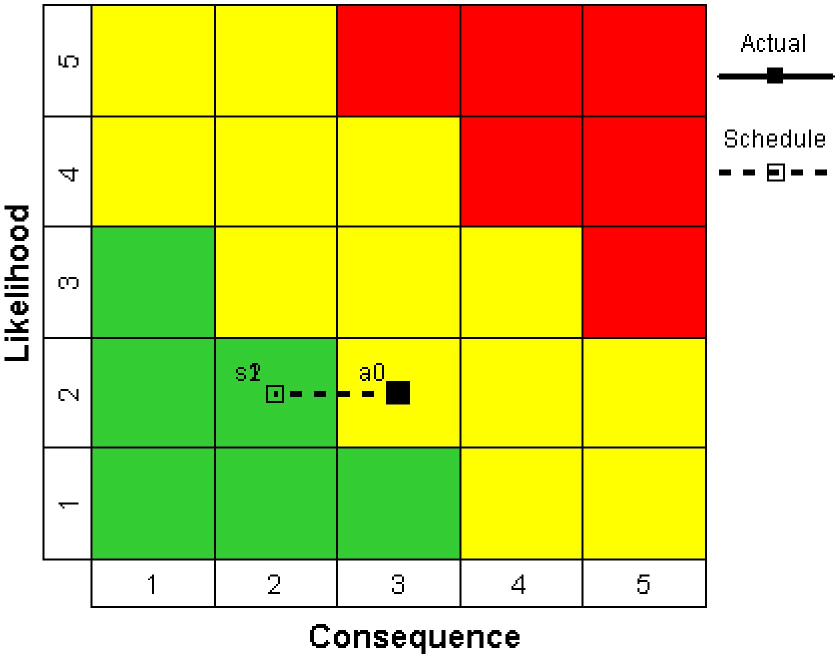
Actual/Planned Events

#	Event Title	Actual Date	Risk Level	Schedule Date	Risk Level
0	Risk Identified	10/30/2009	M 2-3		
1	Perform FEA Analysis			6/1/2010	M 2-3
2	Post molten salt test - Isolate speed range on VFD			8/1/2010	L 2-2

6) Column Assembly Failure – Strength, Flexibility, Stability

The bending forces which can loosen studs or crack welds on the column must be evaluated closely to prevent a pump failure. Many factors, such as salt temperature pump speed and liquid levels in the tank, can affect the structural stability of the pump assembly. FEA analysis and specialized software can identify most of the problem areas, but full scale hot testing is required for 100% validation.

Risk 6: Column Assembly - Strength, Flexibility and Stability



6): Column Assembly - Strength, Flexibility and Stability

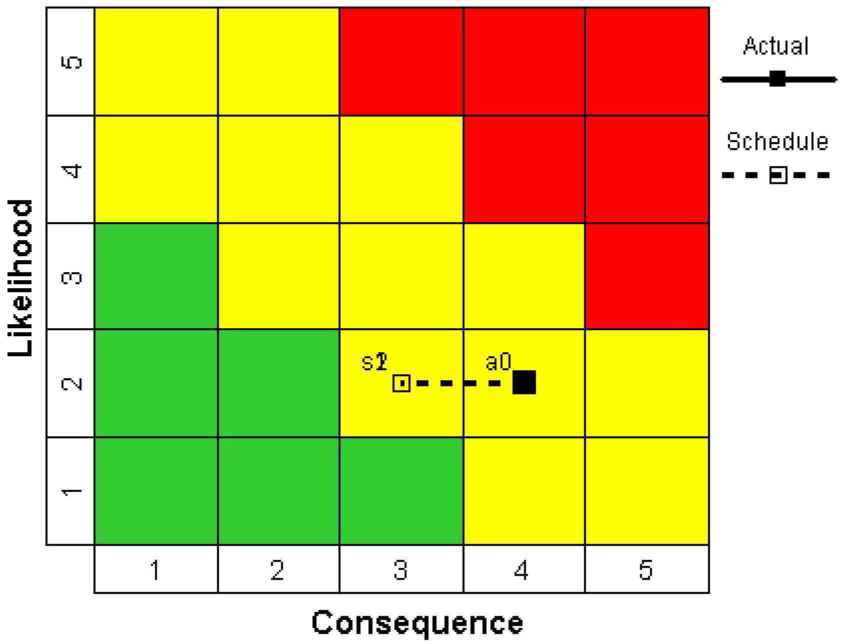
Actual/Planned Events

#	Event Title	Actual Date	Risk Level	Schedule Date	Risk Level
0	Risk Identified	10/30/2009	M 2-3		
1	Perform stud shear load evaluation for various tank levels and speeds (FEA)			6/1/2010	L 2-2
2	Perform structural analysis of welded connection of flange and pipes			8/1/2010	L 2-2

7) Thrust Bearing Failure – Axial Loads

The thrust bearings are the primary failure mode for this pump. Increased shaft length will greatly increase the bearing thrust loads as a result of the added weight of the shafts and thrust loads from the multi-staged wet end. Thrust bearing failure can cause damage to other components, which could result in having to remove the entire pump.

Risk 7: Thrust Bearing - Axial Loads



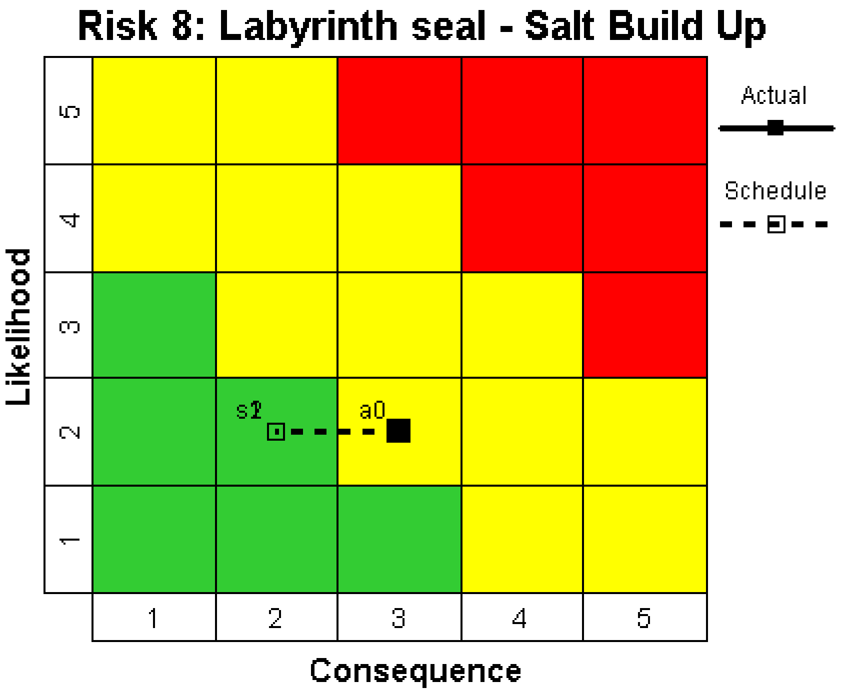
7): Thrust Bearing - Axial Loads

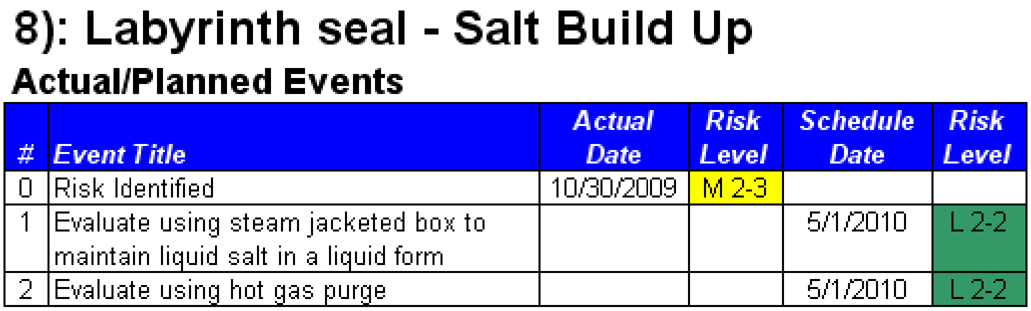
Actual/Planned Events

#	Event Title	Actual Date	Risk Level	Schedule Date	Risk Level
0	Risk Identified	10/30/2009	M 2-4		
1	Perform analysis of thrust bearing loads			5/1/2010	M 2-3
2	Perform analysis of impeller thrust loads			5/1/2010	M 2-3

8) Labyrinth Seal Failure – Salt Build Up, Shaft Binding

Salt buildup from vapors or splashing could cause the shaft to freeze up during times of ideal operating conditions. Starting a pump with a frozen shaft can break the shaft or damage the motor. The temperature of the labyrinth seal area of the pump must be kept above the solidification temperature of the salt.


Risk 8: Labyrinth seal - Salt Build Up


8): Labyrinth seal - Salt Build Up

Actual/Planned Events

#	Event Title	Actual Date	Risk Level	Schedule Date	Risk Level
0	Risk Identified	10/30/2009	M 2-3		
1	Evaluate using steam jacketed box to maintain liquid salt in a liquid form			5/1/2010	L 2-2
2	Evaluate using hot gas purge			5/1/2010	L 2-2

In addition to the technical barriers identified above, there are other factors which need to be considered in the design of any molten salt pump. Some of the more significant factors are listed below:

Salt freeze up:

WARNING: This is a major problem. This type of pump has a very high risk of freezing up, due to the design of the hydro seal area. Several things will/can affect this, including (1) the specific labyrinth seal design and effectiveness of the nitrogen purge, (2) effectiveness at controlling leakage of salt into the tube from the bearing and threaded joint area, (3) consideration of the operational sequence of the pumps, (4) ensuring the seal can handle pump operation at shut off.

Salt leakage at discharge flange due to poor mounting plate design:

Molten salt is very difficult to handle. The slightest separation can cause it to leak through the ring joint flanges. Mounting plate design is critical.

Grease lubricated thrust bearings:

A grease lubricated thrust bearing is a preference. Oil lubrication can be a problem if leakage occurs.

Load carrying of thrust bearings:

WARNING: This is a major problem. The design of the thrust bearing carrier, and how the assembly is mounted, are very critical. This is the first point of failure for this equipment. Monitoring these bearings is critical. The bearings must be mounted and lubricated properly. This assembly needs one true thrust bearing and at least one radial bearing.

Sealing of thrust bearings:

Since oil lubrication is being used in a vertical arrangement, sealing is very difficult. This design has a very high risk of being overfilled, which can cause a fire. This type of lubrication system requires high maintenance.

Heat dissipation to the thrust bearings:

A thermal analysis must be performed to determine the heat dissipation through several of the major components of the pump, including the shaft, sump cover and pedestal. An accurate model of the thermal environment of the thrust bearings is critical in determining thrust bearing life. The bearing will see higher wear due to the long distance between the thrust bearing and the pump itself. In addition, high shaft runout will cause higher wear of the bearing, allowing additional molten salt to go into the tube (with its associated problems).

Hydro seal bearing clearance:

The bearing will see higher wear due to the long distance between the thrust bearing and pump itself. In addition, high shaft runout will cause higher wear of the bearing, allowing additional molten salt to go into the tube (with its associated problems).

Hydro seal vents

Several different types of problems can occur depending on how much pressure and volumetric flow that the two vents see.

Axial adjustment

CAUTION: Limited axial adjustment can be a major problem during the charging of the system with hot salt, and when replacing a rebuilt pump into a hot tank. Well defined procedures must be followed to prevent pump damage.

Structural design of the upper column flange

WARNING: This is a major problem area. Due to the length of these pumps and the high temperature environment, design of the attachment point of the lower sections of the pump is critical. These pumps will see forces which will include sway, orbital, torsional and directional movement from currents inside the tanks caused by agitators, re-circulation systems and return lines.

Vibration due to long center between thrust bearing and first radial bearing

The distance between the thrust bearing and the first radial bearing is very critical. Major problems from vibration can cause pump damage, requiring the removal of the pump and a major rebuild.

Leakage in threads joining hydro seal tubes:

Molten salt will wick through the threads joining the hydro tubes. The pressure of the discharge, as well as the joint location and the amount of salt wicking past the threads can allow salt to climb the shaft.

Shaft coupling design considerations:

WARNING: The intermediate shafts must be locked together to prevent them from unscrewing when a back flow occurs in the system. If not locked, catastrophic damage can occur.

Maintenance of pumps:

All rotating equipment will require maintenance. Equipment that has been in molten salt can be very difficult to disassemble. Designs that account for this, and allow for easy replacement of radial bearings, impeller, etc. will reduce overall costs for the customer more than would the purchase of less expensive pumps without this consideration.

Monitoring of radial bearings:

Monitoring of bearing health is critical. Monitoring will help to prevent catastrophic failures. In addition, it will allow accurate maintenance schedules to be developed, which will reduce lost time and increase profits.

Testing of long design in molten salt (or other molten fluids):

In-field testing, or laboratory testing with molten salt (or other molten fluids) is necessary to ensure satisfactory operation of these critical pumps. The long length of these pumps adds a new risk that must be evaluated.

Allowing pump to operate at shut off:

WARNING: Need to ensure the pump can be shut down for short periods of time without salt freeze up occurring. If internal salt freeze up were to occur, significant damage may occur to the pump during system restart

Shaft/column sealing:

This is a critical area. The seal design must not be affected by the pump discharge pressure, otherwise salt may leak or spray out.

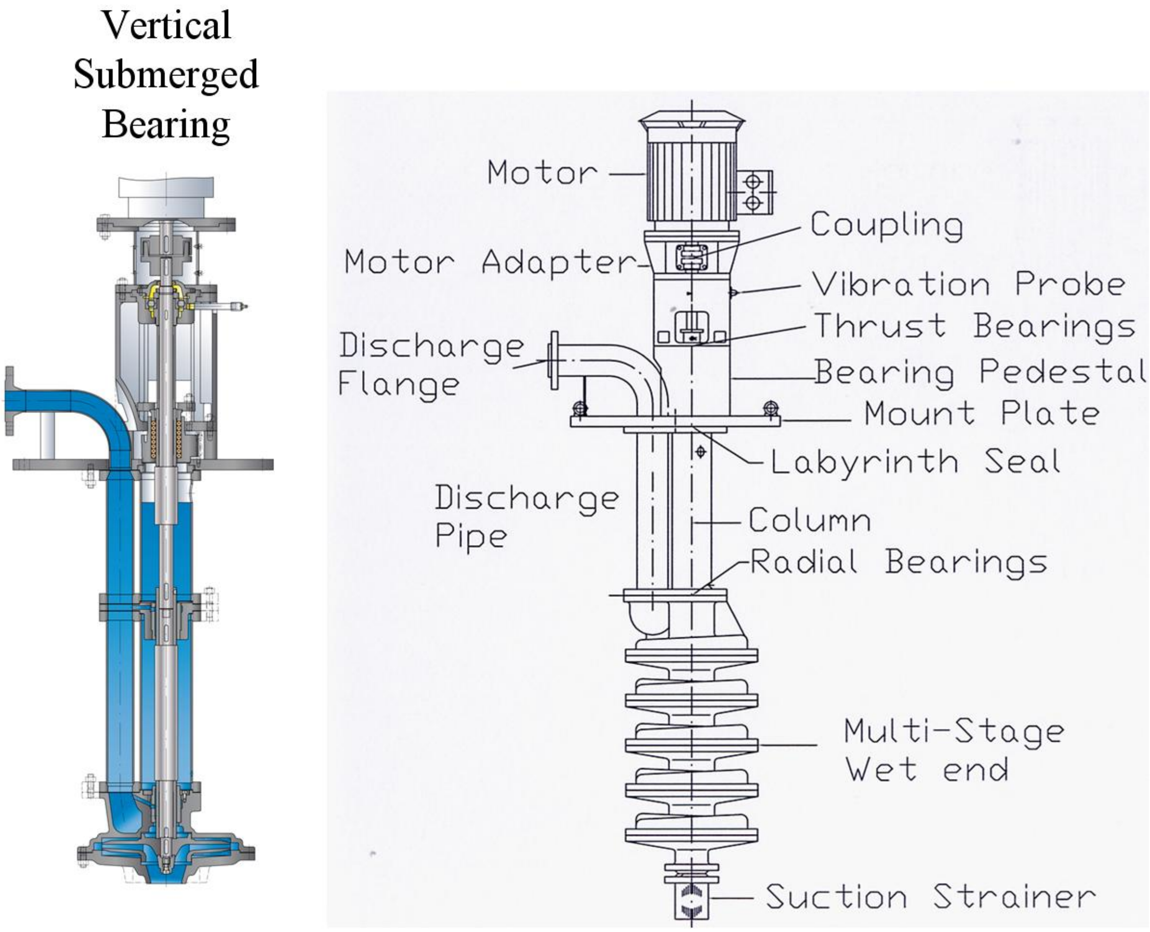
Lubrication of radial bearing:

It is critical that the design provide complete film lubrication for the bearings. Bearings that experience high pressure and direct discharge flow will wear faster.

Based on our findings, a commercial pump could be used for this application. This is providing that additional studies and testing of a full-scale pump have been completed, to ensure that the design modifications made to address the technical barriers were successful.

3.3 Task 3: Preliminary Design of the Pump Concept

Friatec (pump vendor participating in this study) has determined that the pump size required for the DOE program is a GVSO 250/355 pump (10 inch discharge, 16.6 inch diameter impeller, ~1500 rpm, 250 hp, and single stage wet end). It is planned that two pumps would be used in parallel to meeting the system requirements. Below is a cross sectioning of the conceptual design, listing the key components.



Vertical Submerged Bearing

Figure 7: Pump Cross Section

3.3.1 Levelized Cost of Energy (LCOE)

The Solar II project estimated a 12% savings in the cost of the thermal storage system by going to a vertical, long-shafted pump design. While these pumps are more expensive than horizontal shafted pumps, the savings are realized by a reduction in subsystem hardware costs. A recent review found similar expected savings ($10.4M for the vertical shaft system versus $11.8M for the horizontal shaft system).

The assumed total capital cost of a large solar plant is $700M. The molten salt thermal storage system is approximately $64.5M, or 9.2% of the total. The 12% cost savings with a vertical shaft system times the thermal storage system capital costs yields a 1.09% savings in total capital costs, or $7.64M.

At the time of the original proposal, the calculated cost of energy was 22 cents per kW-hour, and the calculated LCOE reduction was 0.35 cents per kilowatt-hour. The current calculated cost of energy is now 15 cents per kW-hour. 90% of that cost, or 13.5 kW-hour, is considered to be hardware costs. The 1.09% savings in capital costs results in a hardware LCOE of 13.5 * 1.09% = 0.147cents per kW-hour. In the proposal the LCOE reduction did assume a reduction in O&M costs, but today that saving has been incorporated into the 15 cents per kW-hour number.

3.4 Task 4: Develop and Refinement of cost estimates

It is PWR’s recommendation that the DOE does not direct us to proceed into Phase II. There are two significant reasons why it is neither in our or the DOE's interest to proceed:

1) While the molten salt pump would be built in Phase II, it is highly unlikely that a test facility (funded by the DOE) would be provided to test the pump during Phase III. The project proposal set as an expectation that such a test facility would be available, at no cost to the users. Without such a test facility, there will be little benefit gained by completing the design and fabrication of the pump, since no confirmation of the design will be obtained. Other test options may be possible, but would result in much higher costs to the participants, and therefore be unaffordable.

2) Long shafted molten salt pumps have become commercially available from several vendors. At the time this project was proposed, no vendor could supply a long shafted pump suitable for a molten salt thermal storage application, and only one vendor appeared to have the ability to create that technology (with funding from this project).

In spite of the above recommendation, the development and refinement of the costs associated with Phase II and Phase III of the project was performed and they have not changed significantly

3.4.1 Budget Period 2 Plan

The budget for Phase II of the molten salt pump assembly is ~$3,037,489 ($2,429,991 / 80% funded by the DOE, and $607,498 / 20% funded by Pratt & Whitney Rocketdyne). A $50,000 increase from the proposal estimates is required to update the conceptual design review information, including a review meeting. The design review held in November 2009 uncovered several areas of improvements needed to justify the pump design selection. This will be addressed at the start of Phase II.

3.4.1.1 Objectives – Phase II

The objectives of Phase II include 1) the overall design, fabrication and assembly of the molten salt pump, 2) delivery of said pump to Sandia National Laboratory for testing, and 3) a detailed test plan to be implemented during Phase III of the project. Tasks details required to meet those objectives are listed below:

Task 1: Define a comprehensive pump design. The design will include component and assembly drawings for pump systems needed for a commercial solar power plant. The molten salt pump design will be for a solar trough plant, but will be extensible to a solar power tower plant. Friatec will perform all pump design activities including drawing generation, with Pratt & Whitney Rocketdyne providing analytical support.

Task 1A: Perform an update of the Conceptual Design Review (CoDR)

Task 2: Perform preliminary and critical design reviews (PDR, CDR). The final designs will be presented to the customer. This task will be performed jointly by Pratt & Whitney Rocketdyne and Friatec.

Task 3: Fabricate a trough pump design. This task will include all pump construction, as well as procurement of the motor and variable-feed drive system. Opportunities to improve manufacturability and lower production costs should be identified during this task. Teaming opportunities with companies or universities outside of the existing solar community will also be evaluated. Pump fabrication will be done by Friatec. Hardware will be made ready for shipment to Sandia National Laboratory for testing.

Task 4: Provide an estimate of the change in pump production costs, based on varying annual production quantities. An Analysis on the impact on total power plant system cost and LCOE will be provided.

Task 5: Develop detailed test planning for the molten salt testing to be performed in Phase III. Work performed in this phase of the project will allow test assumptions to be improved and adjusted as necessary. Pratt & Whitney Rocketdyne will perform this task, and generate the test request to be submitted to Sandia National Laboratory.

Task 6: Detailed maintenance and assembly procedures to support pump operations will be generated. This task will be performed by Friatec.

3.4.2 Budget – Phase III

The budget for Phase III of this project, test support and data evaluation of the molten salt pump, is ~$933,813 ($747,050 / 80% funded by the DOE, and ~$186,763 / 20% funded by Pratt & Whitney Rocketdyne). This estimate has not changed from the original proposal, but it will be re-evaluated in Phase II of the project.

3.4.2.1 Objectives – Phase III

The overall objective of Phase III is testing the full scale prototype pump in molten salt, and evaluating the data collected. Task details required to meet these objectives are listed below.

Task 1: Perform a test series on a trough pump in molten salt. Testing will be assumed to take place at The National Solar Thermal Test Facility (NSTTF) at Sandia National Lab. Pratt & Whitney Rocketdyne and Friatec will support molten salt test activities. Testing will be performed with molten salt at operating temperatures of 550 to 1050 °F. Testing is expected to take 6 to 12 months.

To ensure the reliability of long-shafted pumps, a comprehensive test program must be completed at an independent laboratory such as Sandia National Lab. Validation testing will allow the manufacturer to set the lowest possible sale price per unit. Otherwise, risk factors of 1.5 to 3 times the actual cost will have to be applied. The following tests will be most useful in proving the pump design:

Test 1 – Start-Up Test

In this test, the flow rate will be correlated with motor current and the pressure generated. These correlations will be useful during plant operation in the event of a flow meter failure.

Conditions to be tested shall include:

- Salt temperature: 650 °F to 1050 °F, varied in 100 °F increments
- Salt flow rate: Valve open from 25% to 100%, varied in 25% increments
- System control: Manual stop/start, protection portion of controls in automatic mode
- Record and compare motor current, flow rate and pressure data.
- Check vibration of pump shaft at each valve position, with temperatures ranging from 650 °F and 1050 °F.

Test 2 – Simulated nightly shutdown, drain, and dry start-up

In this test, it will be determined if leaving the pump setting idle for durations ranging from several hours up to a few days, without salt flowing through the bearings, will cause excessive wear and/or damage of the bearings or sleeves upon start-up. This downtime will allow a majority of the salt to drip from the bearings, thus removing the lubrication from them. The following test conditions will be used:

- Salt temperature of 1050 °F
- Salt flow rate with valve open at 100%.
- System control: Manual stop/start, protection portion of controls in automatic mode
- Test duration of 1 month.
- Record and compare motor current, bearing temperatures (multiple locations) and flow rates as a function of time. Record data at 5 minute intervals.
- Set the heat trace on the tank to allow lower temperatures (down to 850 °F), and therefore create a temperature gradient along the shaft.
- After completing the above, perform a vibration test.

Test 3 – Bearing high-load test

This testing will determined if loading the bearing with the highest load in the pump set-up, with frequent starts and stops, will damage the bearings or sleeves. The following test conditions will be used:

- Salt temperature of 1050 °F.
- Operate pump near the maximum bearing load condition for 30-minute intervals.
- Salt flow rate with valve closed 100%.
- Pump start/stop cycle defined as pump on for 30 minutes, then pump off for 30 minutes.
- System control: automatic stop/start and protection portion of controls in automatic mode.
- Test duration of 1 week.
- Record and compare motor current, bearing temps (multiple locations) and flow rates as a function of time. Record data at 5 minute intervals.
- Check vibration of pump shaft at initial start-up, then periodically thereafter.

Test 4 – Long-term test

In this test, pump performance be observed over an extended period of time (approximately 1,000 hours). The following for the test conditions will be used:

- Salt temperature will be 1050 °F. Pump will be subject to nominal loading, and a nominal salt flow rate of 2,750 GPM.
- Pump start/stop cycle is defined as pump on for 7 hours, then pump off for 1 hour.
- System control: automatic stop/start and protection portion of controls in automatic mode.
- Test duration of at least 1,000 hours, or longer.
- Record and compare motor current, bearing temperatures (multiple locations) and pump flow rates as a function of time. Record this data at 10 minute intervals.
- Check vibration of pump shaft at the initial start-up, then periodically thereafter.

Test 5 - Tank liquid level tests

The purpose of this testing is to verify the results of the FEA studies for pump operation at different tank liquid levels and pump RPM ranges. This is a critical test. If vibration limits are exceeded, the pump must be shut down immediately.

- Tests will be performed with the tank at “low”, “medium” and “high” liquid levels.
- A complete eight point performance test will be performed at the rated speed for each tank liquid level
- A full 20-120% speed range test. This test will start at design conditions, then proceed from minimum to maximum speed at speed step changes of 10%. Strip charts are to be run at each point.

Test 6 – Instrumentation test

The purpose of instrumentation testing is to observe the reliability of the instrumentation to be used in the piping, over an extended period of time (approximately 5000 hours). This testing will be performed during all of the previously mentioned test steps, and will include the following:

- Test operation and reliability of vortex-shedding flow meter, or other flow rate sensing devices.
- Verify high temperature operation of two or three different pressure transducers.
- Data shall be logged whenever system is operated.

Test 7 – Bearing performance / measurements

In this testing, temperatures at the multiple bearing locations will be recorded and compared as a function of time. The pump will be pulled from the setup at predetermined intervals to inspect the bearings, and to measure and compare dimensions.

- Bearing and sleeve dimensions when new, and after completion of testing. These measurements are very critical, with the baseline measurements (when new) crucial.
- Bearing temperatures measured over time.
- Visual inspection of bearing and sleeve surfaces when new, and after completion of testing.

Test 8 – Minimal submergence and vortexing test

Both cavitation and vortexing can cause catastrophic damage to the pump and system. This testing will verify the results of the basic calculations and fluid system modeling that have been performed.

Low liquid levels must be maintained accurately to confirm the basic calculations for low-head operation of the pump. In addition, NPSH will be directly evaluated. Vortexing, which can occur at low liquid level operation, shall also be studied.

The following describes a list of possible test conditions:

- Salt temperatures of both 550 °F and 1,050 °F.
- Pump submergence levels of 1 foot, 2 feet, 3 feet and 4 feet.
- Pump intake elevations measured off the bottom of tank of 12 inches, 18 inches and 24 inches.
- Matrix of various speed ranges at different salt temperatures
- Compare different vortex breaker designs
- Compare different horizontal distances between the pump location and the sidewall of the tank.
- Monitor vibrations during testing.
- Monitor motor current during testing.

Test 9 – Line freeze and reverse-flow testing

This testing shall simulate upset conditions, which can occur during plant operation, and could cause catastrophic failures and damage to the equipment.

Test conditions in this series includes running the pump at shut-off conditions, and simulating the backward flow of high volumes of molten salt from the riser piping.

Test 10 – Removal and installation of a hot pump

The removal / insertion of a pump from / into the molten hot salt tank will require detailed and validated procedures. Maintenance of this type of equipment is critical, and as it will be very costly in both time and money if the pumps are not handled properly.

Tests shall be performed to study the removal of a hot pump at 1,050 °F from the molten salt tank. Tests shall be performed to verify and ensure the pump is 100% self-draining.

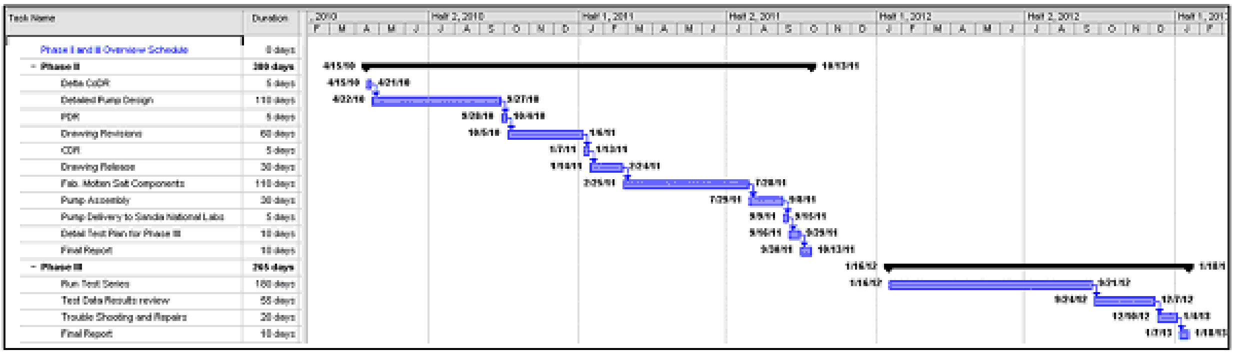
Procedural testing shall be performed to ensure proper disassembly practices for pumps in the vertical orientation.

Tests shall be conducted to study the preheating process for re-insertion of a pump into the hot molten salt tank at 1,050 °F.

Task 2: Pratt & Whitney Rocketdyne will review test results and generate a summary report.

3.4.3 Phases I and II Schedule

Though the decision has been made not to continue, the Phase II and Phase III schedules shown below reflect the general steps needed to complete the tasks listed above. Phase II has been extended beyond the proposal estimated duration by 6 months. This extension is consistent with the vendor’s re-evaluation of work involved in this phase, including the design, fabrication and assembly of the unit. The Phase III durations have not changed from that of the original proposal, but will be further evaluated for completeness during Phase II.



Task Name	Duration
Phase I and II Overview Schedule	0 days
− Phase II	389 days
Delta CoDR	5 days
Detailed Pump Design	110 days
PDR	5 days
Drawing Revisions	60 days
CDR	5 days
Drawing Release	30 days
Fab. Molten Salt Components	110 days
Pump Assembly	30 days
Pump Delivery to Sandia National Labs	5 days
Detail Test Plan for Phase III	10 days
Final Report	10 days
− Phase III	265 days
Run Test Series	180 days
Test Data Results review	55 days
Trouble Shooting and Repairs	20 days
Final Report	10 days

Figure 8: Phase II and Phase III Schedule

3.4.3 Benefits

This project supports the Concentrated Solar Power (CSP) market in two specific areas, and will be instrumental in allowing the DOE to meet its objectives. Designing a prototype molten salt pump, which will be tested in the wide range of conditions necessary for solar trough and solar power tower systems, will bridge technological gaps in current state of the art pump designs. In addition, field testing will demonstrate and qualify the design for commercial implementation. This field testing will provide the industry with the empirical data necessary to obtain financial backing from institutions willing to invest in this developing market.

There are many benefits in continuing this project. LCOE emphasizes that continued product innovation is necessary to lead to costs reductions in the price of energy per kWh. Until these innovations are proven to the market, additional cost reductions from increases in the economy of scale and larger production volumes will not occur. The benefits of proving these ideas with on-sun testing, at performance levels that simulate power tower conditions, are significant. The real data gathered will provide the measurable gains that the analysis predicts. Pratt & Whitney Rocketdyne feels very strongly that this testing is very important to the long term growth and success of power tower technology.

4. Unobligated Balance

An estimate of the unobligated balance for Phase I of this project is 11% of the $452,000 budget, or ~$50,000, as of December 2009. This under run is a result of unperformed analysis on the conceptual design. This detailed analysis was not performed, due to a lack of details that were to have been provided by the vendor.

5. Project Risk Moving Forward

Phase III of this project requires full scale pump testing in molten salt. The testing will validate pump operations, which is critical for fully understanding the impacts of the modifications to be made to the basic pump design. At the genesis of this project, the Sandia National Laboratories facilities were expected to be upgraded in support of this full scale pump testing in the third quarter of 2010. Due to DOE funding limitations, a facility of the required sized is not expected to exist at the time of scheduled pump delivery. Additionally, it is not clear whether there is a financial commitment to ever build the required facility.

6. Critical Milestone Summary

This is a three phase project to develop a new long shafted pump to operate at high temperatures for the purpose of producing energy with renewable resources. The four major tasks from Phase I are: 1) develop molten salt pump requirements for indirect and direct systems, 2) evaluate existing hardware designs for necessary modifications, 3) complete a preliminary design of the pump concept, and 4) develop and refine cost estimates. These four tasks were completed to support the critical milestones of holding a CoDR, and producing the deliverable of a Phase I final report. A conceptual design review was held at the Pratt & Whitney Rocketdyne, De Soto facilities, on November 4th, 2009. In conjunction with the CoDR presentation, and information submitted in this report, the critical milestones have been achieved.