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DEVELOPMENT OF A HIGH-TEMPERATURE, LONG-SHAFTED, MOLTEN-SALT PUMP FOR POWER TOWER APPLICATIONS

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ABSTRACT

A new hot-salt pump has been developed for molten-salt solar power tower applications that will reduce the capital cost of the plant, eliminate many of the piping, valve and sump problems associated with the handling of molten salt and improve the reliability of a critical part of the operating system of the plant. Previous systems required that the pumps in these plants be housed in shallow sumps that were gravity fed by the storage tanks. This new pump arrangement will eliminate the sump-level control valves and the potential for overflowing the pump sump vessels. Until now only cantilever pumps were qualified for hot molten-salt service because no suitable bearing materials had been tested. This paper describes the successful qualification of a long-shafted pump with salt-lubricated bearings tested for over 5000 hours with nitrate salt at 565 °C.

BACKGROUND

In a molten salt power tower, two-axis tracking mirrors (heliostats) redirect sunlight to the top of a tower where a heat exchanger (receiver) is located. “Cold” molten salt at 290 ºC is pumped from a sump - gravity fed from a cold-salt storage tank located at the bottom of the tower - to the receiver where the salt is heated by concentrated sunlight from 290 ºC to 565 ºC. The hot salt returns to grade level and flows into a hot tank. To generate electric power, hot salt is pumped from a sump – gravity fed from the hot storage tank - through a steam generator to produce high-pressure superheated steam to power a turbine-generator set. Molten-salt power towers have cost-effective thermal storage systems that allow electricity to be produced (dispatched) when it is needed (in cloudy weather, at night, even 24 hours a day), decoupling it from solar collection. A prototype molten-salt power plant was demonstrated at the Solar Two facility in Daggett, CA as part of a cost-shared project between U.S. utilities and industry and the U.S. Department of Energy. This project completed its test and evaluations operation in April 1999 (Pacheco and Gilbert, 1999). A photograph of this facility is shown in Fig. 1.

The Solar Two project demonstrated that the key systems (receiver, steam generator, Rankine turbine, heliostat field) performed at or near their design and the plant was able to dispatch power around-the-clock. Simplifying the molten salt system can greatly improve the reliability and reduce the maintenance and capital costs of the plant.

The Solar Two plant used pump sumps to house the hot and cold salt pumps. Control valves maintained the level of molten salt in the sump. Salt was gravity fed into the sumps from the tanks. Fig. 2 shows a photograph of the pump sumps used at Solar Two. The cold salt pumps were

Figure 1. Photograph of the Solar Two molten-salt power tower.

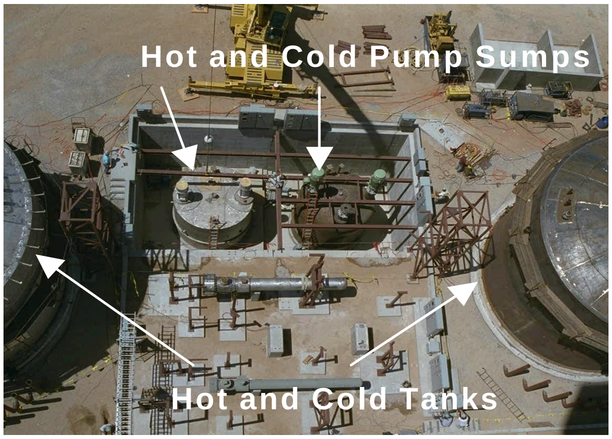

Figure 2. Photograph of the molten-salt pump sumps used at Solar Two.

multistage, vertical turbine pumps, fabricated from carbon steel with salt-lubricated bearings. The hot pumps were centrifugal, cantilever pumps made of stainless steel, which were supported from above and hung in the hot sump. The hot pumps did not have any bearings in the salt. These pumps were chosen based on the favorable experience testing large, molten-salt pumps of the same design at Sandia National Laboratories (Smith, D. C., et. al, 1992, De Laquil, et. al., 1992).

Because the hot pump was a cantilever design, its shaft length was limited to about 3 m since longer shafts would have unacceptable vibration. Since no bearing materials had yet been demonstrated to work in hot (565 ºC) salt, there was too much risk for the Solar Two project to implement a supported, vertical hot pump. If suitable bearing materials could be found, then hot pumps of much greater lengths could be made and fitted directly into the molten salt storage tanks. The molten salt system could be greatly simplified by eliminating the pump sumps, control and shutoff valves, associated piping, heat trace, sump heaters, level controller and insulation. Furthermore, the efficiency of the thermal storage system would increase because the associated heat loss from the deleted components would be eliminated as well.

As part of DOE's Concentrating Solar Power program, Sandia National Laboratories teamed with Nagle Pumps, Inc. to develop a long-shafted molten-salt hot pump for power-tower applications.

DESCRIPTION OF THE TEST PUMP AND EXPERIMENTAL SETUP

In order to evaluate this new pump concept, we needed to design a pump (Fig. 3) with the ability to test several different bearing and sleeve materials and a pump long enough to reasonably prove its viability to operate in the hot salt storage tank, under the severe conditions of high-temperature molten salt.

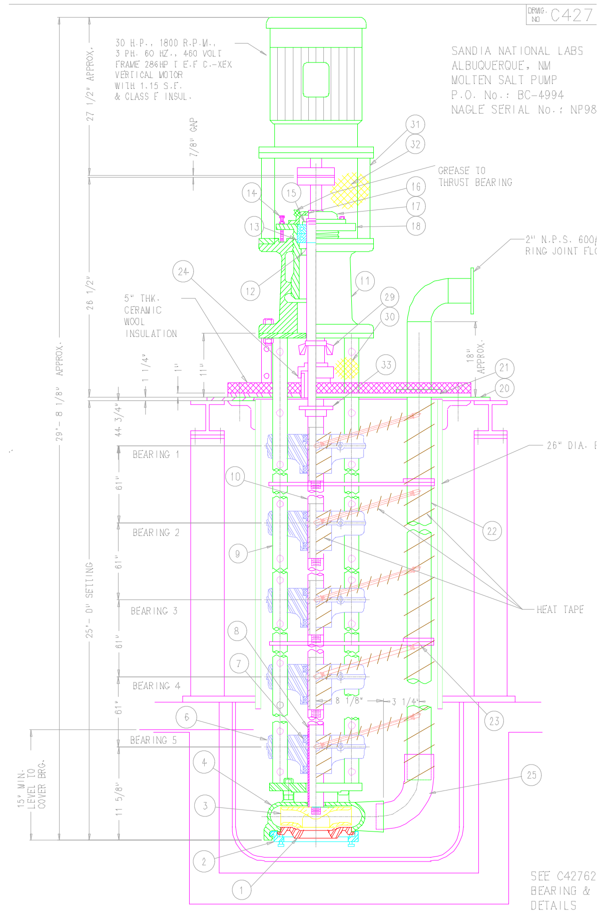

Figure 3. Drawing of salt lubricated pump.

The long-shafted pump selected for the test was a modified Nagle YWS design (Fig. 4) with special journal sleeves – the rotating component that contacts the bearings mounted to the pump shaft - and modified yoke assemblies (Fig. 5) designed for high-temperature molten salt. The pump was built with five yoke assemblies so that up to ten different bearing materials - two bearings in each yoke assembly - and five different sleeve materials could be tested with this design, however, some of the materials were repeated. The bearings are the non-rotating wear components mounted to the yoke. The bearings and sleeves were lubricated with hot salt from the discharge of the pump. Due to this type of lubrication and the low liquid levels in the morning startup of the pumps, the bearings and sleeves needed to be capable of running dry for a short time. The top and bottom yokes were used to test a full-length bearing (instead of separate upper and lower bearings) to determine the effects of both lubrication and wear caused by this type of operation. The total length of the pump from impeller cover to the flanged mounting plate was 7.6 m - long enough for use in the Solar Two molten-salt storage

Figure 4. Nagle YWSR salt pump with salt lubricated bearing tested at Sandia National Laboratories.

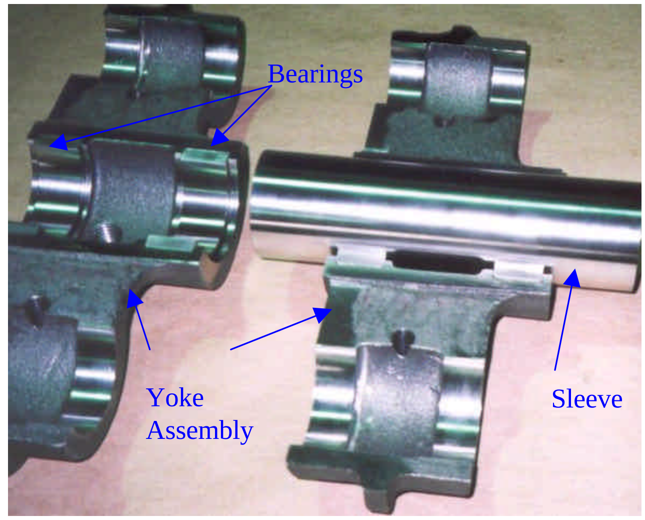

Figure 5. Yoke / split bearings / journal sleeve.

tanks.

Nagle Pumps evaluated several other critical aspects of the design of a longer pump (15 m) that would be mounted on top of the hot-salt tanks for larger (30-50 MWe) commercial plants. In the design and through testing, we evaluated the pump for its structural integrity, thermal expansion of major pump components, vibration limits, the ability of the bearings to run dry for a short period of time at startup, the ability of the yoke assemblies to be self draining to prevent freeze up of the bearings during long idle periods, and the estimated life cycle between rebuilds.

The mechanical design of a pump fifteen meters long needs to minimize the number of replacement parts, provide easy accessibility to these parts and simplify the mechanical assembly in order to insure a cost-effective maintenance program when the pump needs to be rebuilt. Accessibility to these parts is critical for the disassembly and replacement of wear parts that have been exposed to molten salt for long periods of operation.

Initial screening of bearing materials in the pump using water at the Nagle Pumps test facility revealed that the following materials galled and were unsuitable as bearing-sleeve combinations: Stellite 6B (sleeve) on Stellite 6 (bearing), Tribaloy T-900 (sleeve) on the following bearing materials: Inconel 625, Nitronic 50, 17-4 stainless steel, and Stellite 6B.

After consulting with metallurgists from the bearing suppliers, a list of candidate bearing-sleeve combinations that should not gall was proposed for the pump in the molten-salt flow tests. These candidate bearing-sleeve combinations are listed in Table 1. The pump efficiency was not part of this test since the main objective was to evaluate bearing materials. The test pump was designed with extra clearance between the impeller, suction plate and housing to help alleviate thermal growth and to ensure its highest reliability. Also, the pump discharge line had a slip joint (to eliminate thermal expansion issues), which allowed salt to bypass. Because of the extra clearances and the slip joint, its efficiency was not very high. However, with tighter clearances and a different type of slip joint, the efficiency is expected to be higher. Each yoke assembly was fitted with two thermocouples to measure the temperature of each bearing for local heating and to indicate if the bearings were above 290°C at pump startup.

The pump was installed in a molten salt flow loop at Sandia National Laboratories in Albuquerque, NM. The test system consisted of a sump where the impeller sat submerged in the salt, a standpipe encasing the pump shaft and support structure, a flow loop containing a flow control valve, flow meter, and pressure transducer, and a frame to support the pump and flow loop. A photograph of the pump next to the test setup is shown in Fig. 6.

TEST PLAN

Three major tests were conducted in the molten salt flow loop to characterize the pump, to simulate various operating modes, and to operate the pump for an extended time period. The first test was designed to characterize the pump outlet head and motor current as a function of flow

TABLE 1. CANDIDATE JOURNAL SLEEVE AND BEARING MATERIALS USED IN NAGLE TEST PUMP

Yoke Number	Journal Sleeve Material (Mounted to Shaft)	Bearing Material (Mounted to Yoke Assembly)
1 (Top)	NPI 420 Stainless	60-45-10 Ductile Iron (Full Length)
2	Stellite 6B	Ni-Resist Type 1 (Upper) 60-45-10 Ductile Iron (Lower)
3	NPI 420 Stainless	Gray Cast Iron Grade 40 (Upper) Gray Cast Iron Grade 40 (Lower)
4	Tribaloy T-900	Ni-Resist Type 1 (Upper) Ni-Resist Type 1 (Lower)
5 (Bottom)	Stellite 6B	Gray Cast Iron Grade 40 (Full Length)

Figure 6. Photograph of long-shafted hot pump suspended to the side of the flow loop and support structure.

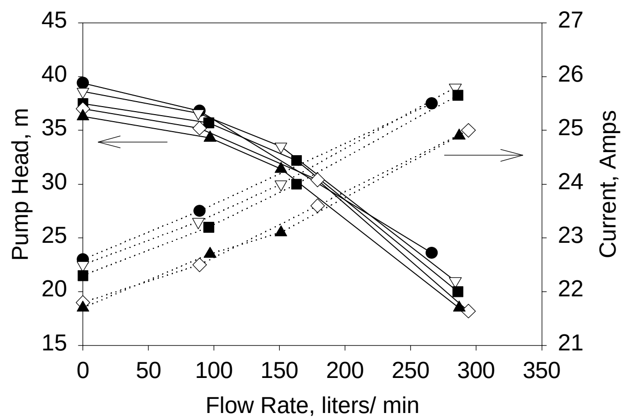

Figure 7. Pump outlet head and motor current draw as a function of salt flow rate and salt temperature. The symbols correspond to tests conducted at different salt temperatures: ● = 345 °C salt, Ñ **=** 400 °C salt**,** ■ = 455 °C salt**,** **=** 510 °C salt, and **=** 566 °C salt**.**

rate by varying the flow control-valve position between 0 and 50% opened. This test was conducted at salt temperatures of 345 ºC, 400 ºC, 455 ºC, 510 ºC, and 565 ºC. The second test simulated the typical nightly shutdown, drain, and dry daily startup with a salt temperature of approximately 565 ºC and the valve opened approximately 19%. This test qualified the bearings' ability to start dry after a full drain. The third test's objective was to put the pump through an endurance test where the pump was run unattended in an automated sequence: 7 hours on, 1 hour off, continuously around the clock at full flow with the salt temperature at approximately 565 ºC. The test allowed the pump to experience as many hours of operation as possible, while still providing some cycling.

TEST RESULTS AND DISCUSSION

Figure 7 shows the pump outlet head pressure and motor current draw as a function of salt flow rate for the first test. The head and motor current were measured to be about what were expected based on calculations done by Nagle Pumps.

For the second test, the pump was operated for 7 hours on and 17 hours off until the pump had accumulated 105 hours of total operation (only counting the time the pump was actually on). Also, an initial vibration measurement

TABLE 2. INITIAL AND FINAL (AFTER 5069 HOURS) JOURNAL SLEEVE MEASUREMENTS

Yoke Number	Material	Initial Outer Diameter Measurement, mm	Final Outer Diameter Measurement, mm	Difference, mm	Comments
1 – Top	NPI 420 Stainless Steel	71.425	71.45 to 71.501	0.025 to 0.076	Good material. Bearing surfaces smooth. Minimal pitting.
2	Stellite 6B	71.412	71.349 to 71.374	-0.063 to -0.038	Best material. Bearing surfaces very smooth. No scale. Very expensive.
3	NPI 420 Stainless Steel	71.425	71.425 to 71.399	0.000 to -0.026	Good material. Bearing surfaces smooth. Minimal pitting.
4	Tribaloy T-900	71.417	71.399 to 71.374	-0.018 to -0.043	Worst material. Heavy pitting between bearing surfaces.
5	Stellite 6B	71.425	71.399 to 71.349	-0.026 to -0.076	Best material. Bearing surfaces very smooth. No scale. Very expensive.

TABLE 3. INITIAL AND FINAL BEARING MEASUREMENTS

Yoke Num.	Material	Initial Inner Diameter Measurement, mm	Final Inner Diameter Measurement, mm	Difference, mm	Comments
1 – Top	60-45-10 Ductile Iron	71.780	71.806 to 71.857	0.026 to 0.077	Worst material tested. Heavy scale. Unsuitable.
2	Ni-Resist Type I	71.806	71.882 to 71.958	0.076 to 0.152	Possible material. Dark color. Minimal build up.
2	60-45-10 Ductile Iron	71.819	71.628 to 71.704	-0.191 to -0.115	Worst material tested. Heavy scale. Unsuitable.
3	Gray Cast Iron Gr. 40	71.780	71.730 to 71.780	-0.050 to 0.000	Best material. Light build up on ID. Low cost.
3	Gray Cast Iron Gr. 40	71.806	71.704 to 71.73	-0.102 to -0.076	Best material. Light build up. Low cost.
4	Ni-Resist Type I	71.806	71.704 to 71.755	-0.102 to -0.051	Could be considered for bearing material. Light build up on ID.
4	Ni-Resist Type I	71.806	71.704 to 71.730	-0.102 to -0.076	Could be considered for bearing material. Light build up on ID.
5	Gray Cast Iron Gr. 40	71.806	71.882 to 71.907	0.076 to 0.101	Best material. Light build up. Low cost.

was made to compare to one made at the conclusion of all testing. The pump ran without any problems related to the pump itself, however, some salt that lubricated the top bearings wicked or shot up the shaft. During startup, this salt from the top bearing came in contact with the cold sleeve mounted to the pump mounting plate, froze, and accumulated a frozen annulus on the inside of the sleeve. The frozen annulus built up to the point that it caused the pump shaft to bind and trip out the motor on over-current. We eliminated the freezing by installing heat trace at the sleeve. A different design of a flinger mounted to the shaft below the mounting plate along with heat trace added to the mounting plate should resolve the problem.

For the last test, we operated the pump in the automated sequence, 7 hours on, 1 hour off, until a total of 5069 hours of pumping time had been accumulated (including the 105 hours from the second test).

After all three tests were completed, the pump was removed from the test stand and washed with hot water to dissolve the solidified salt. The pump was then disassembled at Sandia National Laboratories' maintenance shop. All shaft assemblies and bearing/yoke assemblies were disassembled without damage to any part. The bearings, journal sleeves, and yoke assemblies were shipped back to Nagle Pumps for measurements, inspection, and reconditioning. All shaft fits for journal sleeves and connecting fits were cleaned and inspected. All major components could be reused. All bearings and journal were reusable with only polishing the surfaces. Yoke assemblies were cleaned and refit with new thermocouples. All items were returned to Sandia National Laboratories and the pump was reassembled for use in another test.

Tables 2 and 3 show the journal sleeve and bearing measurements before and after all the testing was completed in addition to comments regarding the condition and suitability of the materials. Some of the final diametrical measurements increased with use. This was due to the fact that an oxide layer built up on the surface. The diametrical measurements were not the only criteria of the suitability of the material. How well the bearing surfaces faired in the molten salt based on a visual inspection, was also taken into consideration.

As noted in the tables, the combination that had the least wear and held up well to the corrosive molten-salt environment was a Stellite 6B journal sleeve with a gray cast-iron bearing. It should be noted that in place of the Stellite 6B, NPI 420 stainless could be used as well. The stainless material is lower cost. The Tribaloy T-900 and the ductile iron were unsuitable for this application. The Tribaloy showed heavy pitting on the bearing surface. The ductile iron had heavy scale build up and flaking. The Ni-Resist could be considered as a bearing material, but is more expensive that Gray Cast Iron.

CONCLUSIONS AND RECOMMENDATION FOR COMMERCIAL PLANTS

Pump lengths of fifteen meters can be commercially and economically manufactured for mounting on top of the hot salt tanks at a solar molten-salt tower plant with minimal risk based on the success of the bearing and sleeve materials demonstrated in this test. Both the cold and hot salt tanks will be able to use a pump similar to the one tested (such as the modified Nagle YWS pumps). In a commercial plant, the tanks could be over 12 m tall. The best journal sleeve/ bearing material combination is Stellite 6B with Gray Cast Iron Grade 40. NPI 420 stainless steel performed well and could be used a sleeve material. To improve the efficiency, the clearances on the impeller should be tightened and a better-designed slip joint should be incorporated. To reduce the likelihood of freezing up the shaft on startup, the area where the shaft penetrates the mounting plate should be heat traced and a better-designed flinger should be installed on the shaft just below the mounting plate.

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