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High Temperature Ternary Chloride Molten Salt Pump

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ABSTRACT

This work investigates the design criteria considering thermal, structural, and material selection of a ternary chloride ($MgCl_2$-NaCl-KCl) molten salt pump that is capable of running at temperatures above 720 °C. In this work, preliminary testing of salt-wetted hydrodynamic bearings was done to investigate different material pairings including Colmonoy grades, Stellite grades, and a novel NiWC-based alloy (i.e., Hybrimet^{TM} NiWC3b) used as a High Velocity Oxygen Fuel (HVOF) coating. The coating has shown to withstand the corrosive nature of the salt and is additionally used to protect a 316L stainless steel pump reservoir. The pump wetted components are made of Inconel 625 and features a carbon ring seal (CIRPAC Seal) flooded with a N_2 gas flow on the overhead to keep salt vapors from interacting with the external ambient air. A comprehensive pump test program has been completed. Over 90 hours run time pumping hot chloride salts at temperatures up to 720 °C in which enough data was captured to produce performance curves at 3 different operating speeds. This research showcases a promising design for use in the Concentrated Solar Power (CSP) Gen 3 liquid-pathway and sets the ground for further development and use of the Hybrimet^{TM} NiWC3b as a competitive alternative to available superalloys.

INTRODUCTION

Currently deployed Nitrate Salt CSP systems necessitate high temperature molten salt pumps that are capable of withstanding corrosion and temperatures up to 600 °C [1]. These systems rely on long-shafted sump pump technologies, which incorporate salt-lubricated bearings compatible with nitrate salts at 565 °C [2]. To meet the CSP Gen3 technical goals [3], Sulzer developed a multistage vertical type long-shafted pump that features a floating ring seal, salt-wetted hydrodynamic bearings, and a high temperature corrosion resistant ceramic-metal composite (i.e. Hybrimet^{TM} NiWC3b), which can be used as a coating and for molded pump components. It can pump a ternary chloride salt mixture ($MgCl_2$-NaCl-KCl) investigated by NREL [4] at temperatures above 720 °C. An instrumented molten salt test loop was built to further test and investigate the prototype pump, which we will call “Validation Pump”. The work presented in this study includes the following: 1. Pump thermal management during pre-heat and operation. 2. Hybrimet^{TM} NiWC3b HVOF coated 316L stainless steel pump reservoir integrity. 3. Molten salt pump loop. 4. Pump characteristics (e.g. pump curves) in both water and high temp chloride molten. The testing of this validation pump proves it can withstand the high-temperature ternary chloride salt environment as well as meet performance requirements with a cost-effective solution.

TRIBOLOGY TEST DEVELOPMENT

Prior to this project, laboratory fixtures that can test materials and pump components in 720 °C chloride salt were nonexistent. The 720 °C Pin-On-Disk (POD) wear Test apparatus designed and built under Powdermet’s SBIR Phase I program is the first instrument to be able to test material wear rates in this environment. This is a basic tribology test and is used to rank materials by their wear performance. While most tribologists attempt to accelerate these tests to predict component life by increasing load, speed and temperature or decreasing lubrication. For these experiments testing in a 720 °C molten salt environment, was limited to increased load. Speed is usually related to a surface temperature rise; in our application the salt temperature over-rides any frictional temperature increase.

A second test apparatus, the Tribology Test Bed (TTB) was constructed to evaluate materials as wear components, plain bearings, shaft sleeves and vanes in a laboratory setting. The TTB can test multiple specimens simultaneously in extended tests to maximize the data output. Results are obtained by measuring changes in weight, dimensions, and surface finish. A 500-hour test completed on 3 bearings and 5 pins to obtain preliminary wear and erosion rates showed no significant wear or erosion.

The pressure-velocity (PV) factor for the tests run on the TTB was about the same as the validation pump. The pin-on-disk PV was substantially higher to accelerate the test and estimate the material limits (Figure 1). A 96-hour pin-on-disk test indicates that we have a useful bearing at PV equal to Validation Pump. The measured wear rate for NiWC3b is 1.41 x 10-5 mm^3/N-m which is 20% of Haynes 230 (control sample). For NiWC3b, there is evidence that suggests the formation of a lubricating layer being formed in between the disk and pin throughout the test. The measured data indicates that the pump will operate in a low wear PV regime.

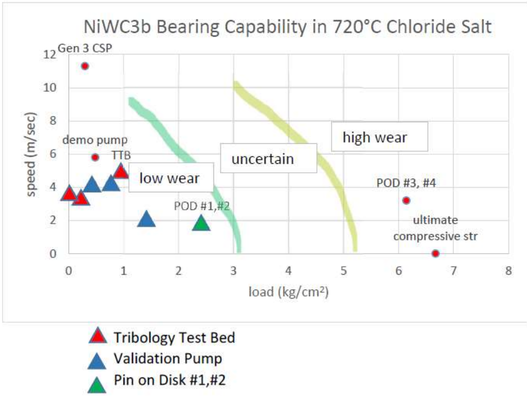

Figure 1: *NiWC3b Bearing Capability in 720 °C Chloride salt*

Pin-on-Disk Fixture

The Pin-on-Disk testing instrument features a design that is rated to operate at 725 °C. This vessel is made mostly of stainless steel 316 coupled to a water jacket which cools the shaft thermally isolating the motor and the torque sensor. Figure 2 shows the details of the components. The load, applied by a weight in the salt vessel, and rotation speed can be controlled for each material combination. The fixture enables measurements of average torque before pin is applied, average torque with pin on disk, average torque after pin is removed from disk, coefficient of friction, pin relative travel velocity, and total travel distance. Surface analysis conducted on the pins and disks after test provides a wear amount. The test vessel is sufficiently filled with the chloride salt so that both the pin and disk are fully submerged.

The torque sensor is an Omega TQ513-022 with a 200 in-oz max range and 1.5x allowable torque overload. The motor used is a National Instruments ST34-7 DC stepper motor. This motor was chosen due to its high torque at low speeds. The motor and torque sensor are connected using flex couplers.

To operate at 725 °C, the device was heat traced and insulated. It is important to note that proper ventilation of the exposed leads of the serpentine must be well exposed and ventilated, given that at high temperatures, oxide can form on the outer surface of the copper sleeves compromising the electrical contact. The system is entirely controlled by NI-DAQ system-based control schemes.

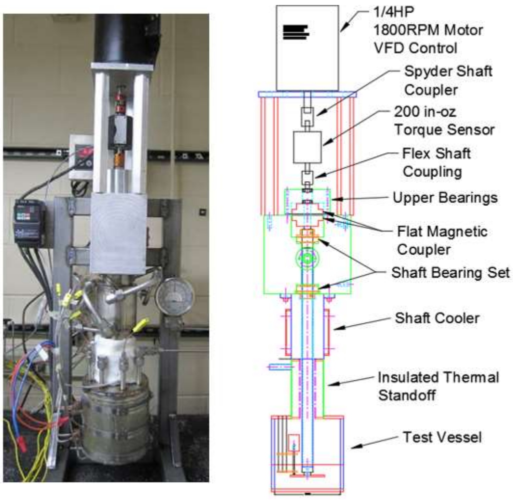

Figure 3: *Pin-on-disk fixture*

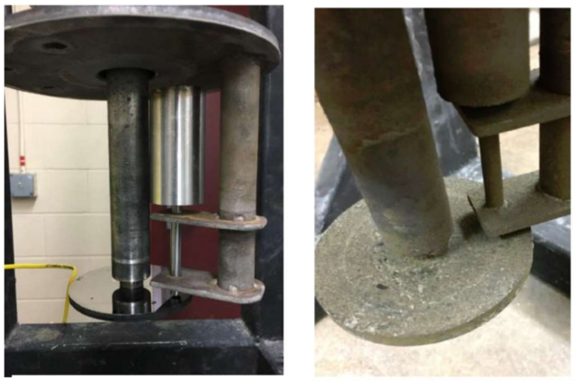

Figure 2: *H230 disk, NiWC3b pin before and after test (left); H230 disk, NiWC3b pin after test (right)*

Pin-on-Disk Tests
The goal of the Pin-On-Disk fixture (Figure 2) is to provide a laboratory test to quickly evaluate and rank materials for use as pump bearings in salt. During this project, the fixture was used to better understand the ternary chloride salts ($MgCl_2$-KCl-NaCl) lubricative properties and to make a comparison of the bearing limits in 725 °C molten salt for Haynes 230 (H230) and nickel tungsten carbide cermet (NiWC3b).

Four tests were run. The testing procedure loosely followed Standard ASTM G99-17 and used a profilometer to measure the wear. The first two tests were run at a load of 1.544 N and speed of 550 RPM (2.43 kg/cm^2; 6588 meters/hour) for 96 hours. Run #3 and #4 were conducted at substantially more severe conditions (4.14 N and 960 RPM (6.14 kg/cm^2; 11500 meters/hour)).

In Run #1 and #2, The torque was erratic for the first few minutes and then smoothed out for the duration of the test. Both H230 and NiWC3b were run at the same parameters. At these speeds and loads, both disks (NiWC3b & H230) and pin (NiWC3b) exhibit measurable but limited wear. The measured wear rate of NiWC3b was 20% of the wear rate of H230. The measured coefficient of friction of both materials was about the same at 0.6.

During run #3 and #4, run at the higher speed and load, there was excessive galling on both the NiWC3b and H230 specimens, clearly exceeding the capability of either material. In our attempt to accelerate the wear rate in the 96 hour test, it appears that we have exceeded the capability of the materials at the higher loading and speed. We expect the demonstration pump to run at a load x speed factor (PV) of about 2.8 kg/cm^2 x mm/sec. POD run #1 and #2 were run at a PV of 4.4 and POD run #3 and #4 at 19.6. POD #1 and #2 demonstrated low wear rates and ranked the materials well. POD #3 and #4 still ranked the HybriMet NiWC3b better than the H230 but the material transfer and galling, on both materials makes it impossible to measure wear rate. The first important conclusion is that the PV limit for NiWC3b is higher than 4.4 and lower than 19.6. A second important conclusion from this early data is that the onset of galling of NiWC3b in 750 ºC salt is at loads well above any expected in the pumps. The NiWC3b bearing will run well in the validation pump, the demonstration pump, and full-size Gen 3 CSP pump.

Tribology Test Bed Fixture
The goal of the Tribology Test Bed (Figure 4) is to obtain wear and erosion rates in 720 ºC salt to be used in the design of pump components, specifically bearings and impellers. The tribology test bed features a test system (tribology system), purification vessel, salt loop, and salt transfer line. By spinning pins and vanes in the molten salt, this test equipment provides initial measurement of erosion caused by flowing salt. Additionally, the bearings that support the spinning hub provide journal bearing wear data to compliment the pin on disk data. This test bed is designed to evaluate bushing materials in direct contact with the mating surfaces as will be seen in startup, shut down, and unstable situations. The bushing specimens had no flutes, wear was measured on the bearings, erosion was measured on pins. The test bed is capable of testing specimens in particulate loaded salt, but the evaluations included in this series of tests used filtered salt.

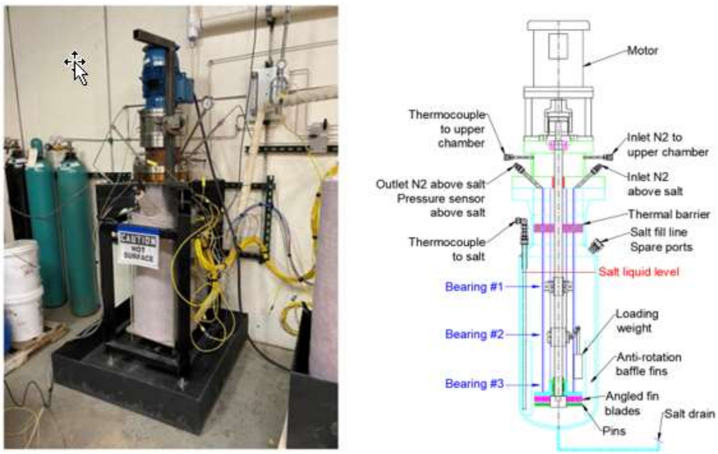

Figure 4: *Tribology Test Bed*

The test bed is designed using a mag-drive to ensure no oxygen will reach the molten chloride salts. The upper section of the test rig has two N_2 gas purge sections, a control bushing and a heat shield to help cool the shaft and upper magnetic drive coupling. The upper N_2 chamber has a higher gas pressure than the lower chamber to ensure that salt vapors do not enter it. There is a thermal barrier to minimize the radiant heat to the mounting flange of the inner column. The tribology test bed is composed of a SS316 vessel and inner column assembly (Figure 5). The inner column assembly consists of a SS316 structure, shaft, three journal bearing housings, and a hub for holding pin samples. The test rig has three bushing carriers to measure bearing wear lubricated only with salt, and a hub to hold five flat vane specimens and five pins to measure erosion versus speed and impingement angle.

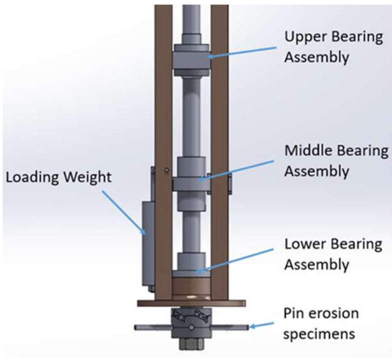

Figure 5: *Inner column assembly*

At 720 ˚C approximately 70 kg of salt is needed to submerge all pin and bearing samples while keeping the salt liquid level below ports of the vessel. The 4.275 lb. loading weight applies a force to the middle bearing, which ensures contact between the three NiWC3b bearings and three NiWC3b-coated SS316 shaft sleeves. All shaft sleeves, bushings, hub fins and pins can be replaced with new test components for subsequent test runs. To reach the operating temperature of 720˚C the tribology vessel was heat traced and insulated (Figure 6). The neck region of the vessel was insulated with ¼" of Kaowool and ½" of Pyrogel. From the vessel flange and above, the tribology test bed is not insulated to keep motor and coupling components cool. The leads of the serpentine heaters are exposed for cooling because at high temperatures formation of oxides on the surface of the leads can compromise the electrical contact. The heating is controlled by NI-DAQ PID control.

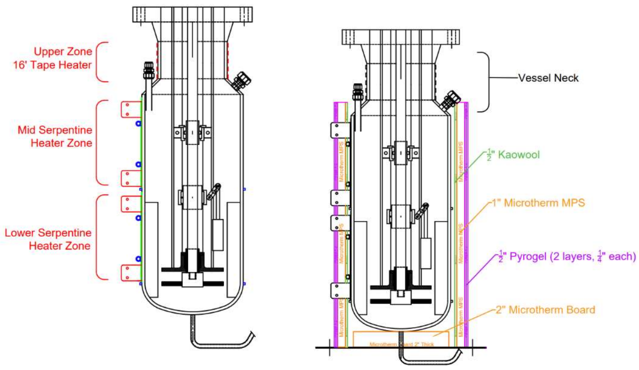

Figure 6: *Tribology Test Bed (TTB) Insulation design.*

Because of the long time required for each test and the time required to prepare, load, and seal the test fixture for each run we set a goal of putting as many specimens in the fixture at one time as possible. The fixture was designed to hold three bearings and five pins and five vanes. The motor did not have sufficient torque to turn all the pins and vanes, so load was reduced to three bearings and five pins.

It has been decided to size the bearing test specimens and test bed to simulate the pressure-velocity factor (PV) expected on the demonstration and production pumps. The bearings will be journal bushings and not have any hydrodynamic lubrication grooves. The data generated is expected to be a sufficient number of wear versus PV points to extrapolate to the large pumps. The bearings will be of three different diameters providing three different surface speeds for one rate of rotation. The bearings will also be of three different lengths providing three bearing pressures for one side load on the center bearing.

An important aspect of the design of this test bed is to keep the load on the bearing bushings constant over the test run, despite the thermal expansion of the fixture and the potential wear on the bearings. The center bushing assembly has a radial load applied by a mechanical counter weight that can be changed to increase or decrease the load. The surface contact area of this bushing can be changed to evaluate the length of bushings needed for the intermediate bushings between bowl assemblies and the upper column bushings. The center bushing will have the largest OD to study surface speed effect on wear. In place of actual impellers, erosion data was generated on test specimens shaped as pins and vanes mounted radially on a hub. Stator fins were employed to prevent the salt rotating with the pins. Erosion was measured radially around the pin and along the length of the pin. This provides erosion versus angle of impingement and versus speed. Because there is flow turbulence, we expect that this provides a more aggressive environment than a well-designed impeller. To properly size the tribology test bed, Sulzer Pumps Equipment provided the estimated operation parameters for the validation pump that was used to qualify the materials, the design and the production methods to be used for the different critical parts of the pumps, as well as the demonstration pump that will be quoted for the demonstration Gen3 CSP plant and the production pump that will be used in the full size plant. In order to establish the critical material design data, the relative speeds between the pump components and the fluid and the material loads, or stresses were established for the different critical components of the pump: bushings, shaft, impeller outlet and diffuser inlet.

The test bearings were run against NiWC3b coated stainless steel sleeves assembled to the shaft. The bearings are plain bearings with no lubrication grooves. The chosen diametrical running clearance hot is 0.010”. We believe that there will be solids in the ICL salt, mandating lubrication grooves (fluting). The groove design will be selected based upon previous experience and not evaluated in this tribology test bed in this series of tests. Future work in this test bed could include evaluations with particulate filled salt.

Finish Bushing Sizes (inches)		
OD +.0/-.001	ID +.002/-.0	Length +.010/-.000
2.062	1.581	0.375
2.750	2.273	0.118
2.046	1.645	1.397
Sleeve (inches)		
OD +.0/-.001	ID +.001/-.0	Length +.010/-.000
1.562	1.252	3.000
2.25	1.252	3.000
1.625	1.252	3.000

Table 1: Tribology Test Bed Bearing Specimen Sizes

Commissioning Runs and Design Modifications

During commissioning the Tribology Test Bed was run while filled with water. Both H230 and NiWC3b pins and vanes were installed. The different material densities and placement in the hub caused excessive vibration. The full complement of pins and vanes caused sufficient resistance that the TTB was able to reach only 1500 RPM because of insufficient motor horsepower. For commissioning run#2, the applied load weight was doubled. The pins and vane were reduced to three each (rather than the designed capacity of five each). One each pin and vane of the three materials to be tested were installed in the best possible balance. The test was terminated at 1700 RPM because of noise and vibration without reaching the goal of 2100 RPM.

We decided to proceed to the hot salt run installing only 5 pins of one material (NiWC3b) and no vane specimens (rather than the designed 5 pins and 5 vanes) to reduce the horsepower required and maintain balance. We also revised the test plan to raise the speed slowly over a few minutes and to back off as necessary to control vibration. The tribology test bed was heated to a salt temperature of 720℃ and motor speeds of 700, 900, 1200, 1300, and 1400 RPM were tested for system vibration, motor amperage, and viscous heating to select the motor speed to be used for testing. The system was chosen to run at 1100 RPM for the 500-hour molten salt test.

VALIDATION PUMP

The validation of the materials, technologies and design parameters developed by running laboratory material and component tests and modelling can only be achieved by building and running a pump. Therefore, we built a small, 35 gpm vertically suspended, 2-stage, submerged wet end pump (VS1 Construction). The Validation Pump (Figure 7) is utilizing a standard hydraulic from the pump manufactures existing product line but has been highly modified in order that it can operation in 720 °C chloride salt, including but not limited to materials of construction, shaft sealing and thermal management.

Figure 7: *Validation Pump*

Design

The basic design of the validation pump is an evolution of a vertically suspended pump from the manufacturers standard molten salt pump product range. This one is designed for a salt temperature of 720 °C and the expected nominal salt composition is 40/40/20 mol% for KCl/MgCl2/NaCl. The validation pump was tested in a dedicated loop erected at the University of Wisconsin – Madison to qualify the materials, the design, and the production methods used for the critical parts of the pump, with a special focus on the wetted components.

The lessons learned from the pin-on-disk wear tests and the operation of the tribology test bed at the University of Wisconsin - Madison were applied to the validation pump and confirm that a commercial pump will operate under these very difficult conditions. The validation pump that was designed is a smaller version of the commercial design intended be used in full size CSP plants.

In order to establish the critical material design data, the relative speeds between the solid parts and the fluid, the material loads or stresses were established for the different critical components (bearing bushings, shaft, impeller outlet and diffuser inlet) within the validation pump. This data was used to establish the Hybrimet^{TM} NiWC3b materials test campaign, and the design of the test loop used to evaluate the validation pump. Drawings and 3D models of the critical pump components have been used to establish the manufacturing techniques that used for their production.

Material Selection and Design Considerations

The characteristics of materials suspected of having the mechanical properties needed for these pumps but having a coefficient of thermal expansion compatible with a coating with the Hybrimet^{TM} materials were reviewed. It was decided to perform design calculations on Inconel 617, Haynes HR120 and Alloy 909 PH. Haynes HR120 and Alloy 909 PH would rely completely on the Hybrimet^{TM} coating for corrosion resistance; Inconel 617 as a HVOF substrate was tested for static corrosion. Haynes HR120 was tested for HVOF coating compatibility. Inconel 617 was initially selected as the base material for this pump. Contacts were established with foundries to supply the parts of the pumps in Inconel 617. Due to the difficulties in finding suitable supply chain for the piping parts of the validation pump with IN617 as a base material, it was decided to change this base material to IN625.

The method for production of the coated parts, mainly bearing bushings and hydraulic components, required validation as the thermal expansion difference of the selected base material (IN625) with the Hybrimet^{TM} material was a challenge. The acceptance of adhesion was validated through thermal cycling of coated IN625 specimens. Transient thermal analysis was completed to finalize component design. Thermal expansion coefficient difference between cermet bushing and the IN625 housing could not be managed without a major redesign of the bearing interference fit retention concept.

The Validation Pump was used as a test bed for materials and design attributes.
Rotating shaft sleeves and stationary bearing bushing materials were selected to be able to build a hard facing material ranking.

- The stage 1 incorporated a Colmonoy 6 sleeve vs a solid Stellite 6 bushing.
- The 2nd stage has a Stellite 21 sleeve vs a massive Stellite 6 bushing.
- The throttle bushing has a Hybrimet^{TM} NiWC3b sleeve vs a Stellite 6 bushing.

N_2 injection was calculated to be 6 Nm3/h for a Delta P of 10 mbar. A reduction of the requirements for N_2 injection was needed for the validation pump tested because of the limited N_2 storage capacity available on site. Hard face floating rings to reduce the consumption of N_2 were chosen. These could be also introduced for the CSP Gen 3 Liquid Pathway pumps.

Thermal and Structural Analysis

The main goals of the thermal analysis were to define; 1) The temperature level in steady state condition at both the bearing location an the pump to tank flange. 2) Evaluation of the thermal loads in the static structural model by performing both a static and fatigue assessment of the critical seam welds.

Different operation conditions were envisioned but only the two following cases were fully analyzed from a thermal and structural point of view; Case 1: Pump stopped; tank filled with molten salt at 740°C at the maximum salt level 800 mm above intake; No forced injection of N2; with and without tracing. Case 2: Pump running at 1450 rpm pumping 8 m3/h molten salt (40% Mg 20% NaCl 40% KCl); tank filled with molten salt at 740°C at the maximum salt level 800 mm above intake; Force N2 injection of 8 m3/h

Figure 8 shows the different elements and materials of construction of the validation pump as well as the boundary conditions used in the thermal and structural analysis.

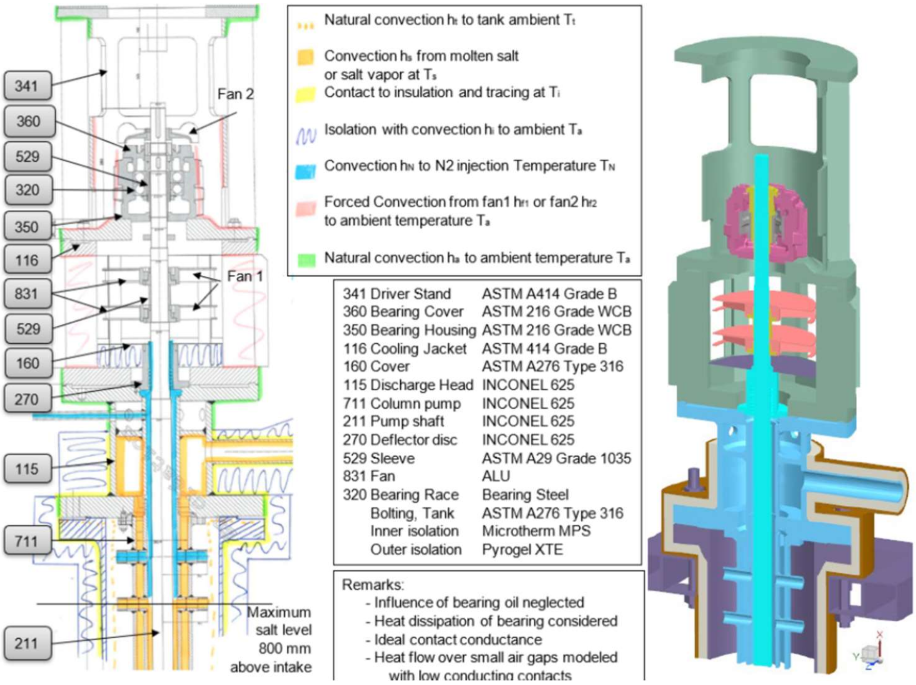

Figure 8: *Validation pump with the different elements and material of construction used in thermal analysis.*

Summary of the Results

Some conclusions that were drawn from the Thermal analysis; The heat tracing does not heat everywhere, especially corners to temperatures about 444 °C (melt point of salt) which means a potential of salt freeze in those areas. Additionally, the high temperatures in the studs with different coefficient of thermal expansion from bolted connections poses some challenges in keeping bolts preloaded. On a positive note, the analysis has shown that the maximum thrust bearing temperature in all cases is lower than 70 °C which is withing the design temperature limits.

Results of the Structural analysis uncovered a few items. There are large differences in radial flange expansion and this is posing a risk for the fasteners and the main head to tank seal. The weld assessment has significant uncertainty due to the unknows about the material characteristics in such high temperatures. The analysis uncovered that welds A and D (Figure 9) are highly loaded by thermal gradient in Case 2. Both static and fatigue assessment are within acceptable limits. Static thermal load of the weld is found to be more critical than fatigue.

To help mitigate the risks we implemented two additional features into the discharge head. Isolations were included on discharge head everywhere possible. Additionally, we reduced the bending stiffness in in the area between weld A and the top flange of the discharge head.

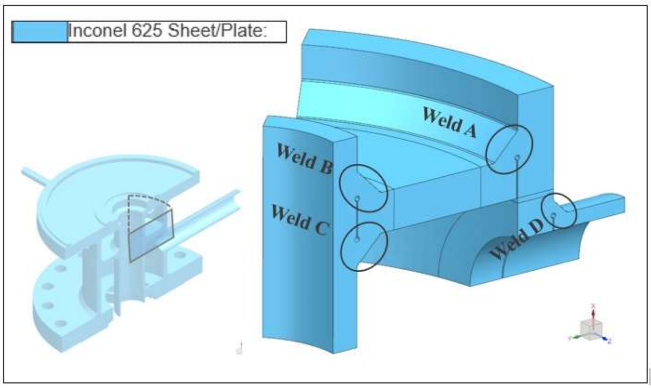

Figure 9: *Weld Locations in Discharge Head*

We introduced the necessary modifications in the original pump design to reduce the possible impact of strong temperature gradients observed from the thermal analysis. The special features included in the pump (cooling chamber with double fan and others features) show a very good decrease in temperature from the operating temperature area to the rolling bearing area.

Molten Salt Test Loop

The third test facility is a Molten Pump Test Loop (MPTL) into which a validation pump was installed to evaluate its design and the bearing bushing materials. The test loop (Figure 10) for the Validation Pump was designed and built at University of Wisconsin – Madison to test the pump up to 720 °C across flowrates of 0-17 m3/h (~75 GPM) and pump speeds between 1300-2000 RPM. The test loop layout and design were evaluated for different conditions to identify stresses at salt temperatures across the components of the loop. The loop can operate at 550 °C and 750 °C and features 2'' Sch 40 SS316 piping with a control valve and venturi to control and measure flow throughout the system during operation. It is instrumented with over 40 K-Type thermocouples, pressure transducers, and heat traced in multiple stages with AC serpentine & tape heaters controlled via a National Instruments C-Rio chassis coupled with LabView software. It is insulated with a layering of Kaowool, microtherm MPS, and Pyrogel that enable an adequate temperature distribution during pre-heat and steady operation up to 720 °C.

The pipe support structure accounts in its design for the thermal expansion that is expected throughout the test.

The loop features a separate salt tank storage reservoir coated with NiWC3b to protect the vessel from salt corrosion. to which salt can be exhausted from the pump reservoir when not in use. This facilitates disassembly and prevents additional strains on the pump during cool down to standard ambient conditions.

The test loop features in its majority stainless steel components with a pneumaticactuating valve to control the flow across the loop. A novel NiWC3b cermet coated reservoir is used in the system to protect the vessel from salt corrosion.

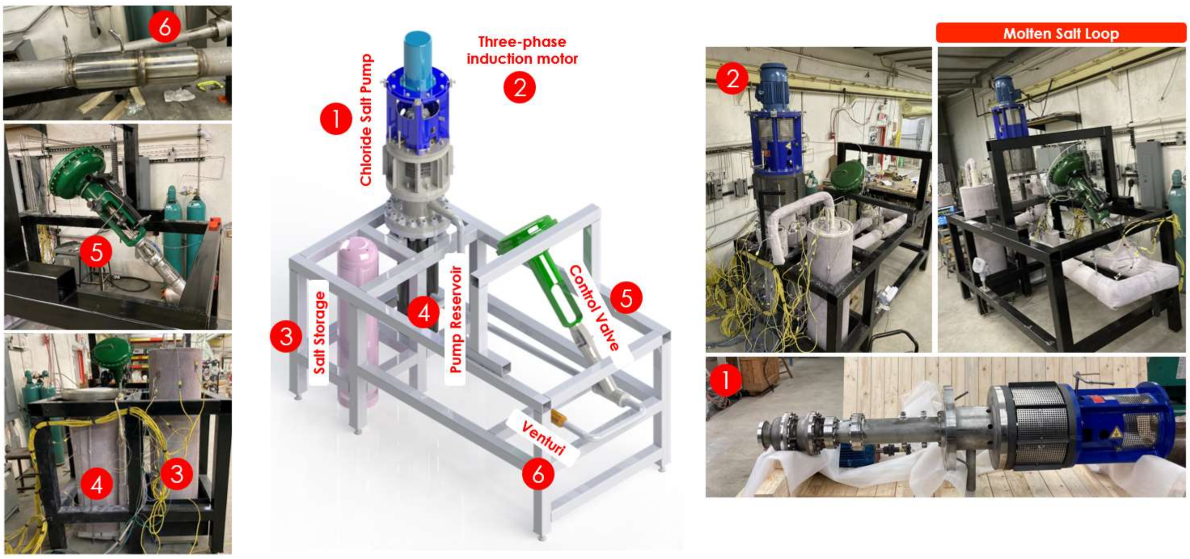

Figure 10: *Molten Salt Loop Components and facility layout at UW-Madison*

The system is fully instrumented to log temperature, flow, pressure, N_2 overhead gas pressure and vibrational data on the pump. System temperature control and data logging done by via LabView. The system is very modular and contained in a structure which Promotes accessibility for maintenance and trouble shooting. Some of the system specifications are listed in Table 2 below.

Component	Use
Frequency Inverter	A Hitachi frequency inverter was used to modulate the motor speed up to 2000 RPM. The inverter drives a W22 WEG three phase motor (Spec. 7.5 Hp @ 460 V, 1765 RPM).
Scale	The salt storage vessel sits on a high precision scale to monitor the amount of salt available and to control salt-exhaust sequences.
Valve	A Conval Double bellows seal valve size 657 with a 3582i pneumatic positioner is used to throttle across any of the pre-determined flowrates.
Validation salt pump	Vertical style pump Validation Pump rated to nominally run at 1450 rpm, flowing 8 m^3/h (~35 GPM) and produce a head of 10 m.
Venturi	Provides a measure for the differential and absolute pressure. Custom made in 316L Stainless Steel coupled to a NaK filled EJA110E Differential Pressure HARP Transmitter (Yokogawa), which has a DP Accuracy of +/-0.055% of Span, Static Pressure Accuracy of +/-0.5% of Span, and Stability of +/-0.55% of Span.
Salt storage tank	316L stainless steel 12'' NPS Sch 40 vessel with two end caps with capacity of storing up to 170 kg of salt.
Pump reservoir	316L stainless steel 12'' NPS Sch 40 vessel coated with a HVOF NiWC3b Cermet rated to withstand corrosiveness of molten salt up to 750 °C.
Pump gasket & flange	304 stainless steel spiral wound custom gasket in between raised face type flanges, bolted down with spring washers to ensure pump tightness within range of operating temperatures.

Table 2: Molten Salt Loop Component Details

Pump Run

Test Plan

The test plan was designed to acquire pump performance data at two temperatures (550 ºC and 720 ºC) and three pump speeds (1300 RPM, 1450 RPM and 2000 RPM). At each temperature / speed setting the flow control valve was throttled from fully open to almost closed to generate pump curves at flow rates from zero to 18 m3/h (80 gpm), over twice the design flow rate of 8 m^3/h (35 gpm). The valve was adjusted only after the system became stable for 15 or 20 seconds. At each point mass flow and pressure measurements were recorded. The valve was never fully closed so there was no risk to deadhead the pump.

Experimental task sequence:

1. Preheat system to 550 °C without salt
2. Confirm pump is free to spin at each 100 °C increment3. Transfer salt and stabilize temperature
4. Start pump at 1450 RPM and flowrate 10 m3/h (44.03 gpm)
5. Pump Test R1
    a. 550 °C & 1450 RPM
    b. 550 °C & 1300 RPM
    c. 550 °C & 2000 RPM
6. Set flowrate to 10 m3/h
7. Heat up to 720 °C. (< 2°C/min)
8. Pump Test R2
    a. 720 °C & 1450 RPM
    b. 720 °C & 1300 RPM
    c. 720 °C & 2000 RPM
9. Pump Test R3: Shutdown & Start-up
    a. Shut down & Restart at 750 ºC from 1450 RPM
    b. Shut down & Restart at 550 ºC from 1450 RPM
10. Cool down to 550 °C
11. Exhaust salt to storage tank at 550 °C

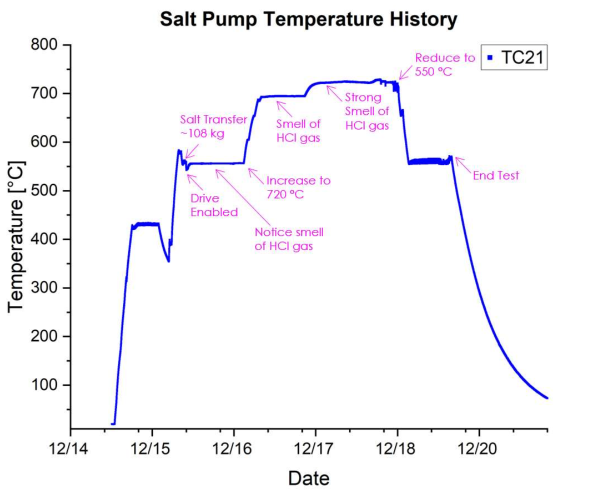

Figure 11: *Salt temperature history for Validation Pump Run as measured by TC21, the Salt Temperature in the reservoir*

Test Observations

The pump ran successfully for 91.1 hours. Five shutdown and re-start cycles were completed from 1450 RPM, three at 720 ºC and two at 550 ºC in addition to the initial startup and final shut down. These cycles were completed successfully including a long shut down of 22 minutes.

Temperatures, flow rates and salt pressure were recorded throughout the campaign and results show good correlation with model predictions and the factory quality confirmation water test.

Occasional rattling noises (probably caused by cavitation) were observed, most noticeably at the valve open position.

At 720 ºC, salt degradation gases escaped the shaft seal. Attempts to eliminate the leakage by increasing the N2 blanket flow rate were not successful. The gas concentration in the laboratory limited the 720ºC data points to fewer than planned.

18 kg of Salt are unaccounted for after salt exhaust into storage tank. We expect that it is entrained in the system and will confirm when the system is disassembled.

System Temperature Measurement

The entire salt loop was heated with thermal blankets and connected with multiple thermocouples to monitor and control the system temperature (Figure 12 and Figure 13). Heaters are only able to bring the discharge section of the pump (TC13) up to about 360 ºC. This area therefore relies on salt flow to stay above melting temperature. The temperature of the salt in the pump reservoir is measured by TC21 and is the primary control temperature for our tests.

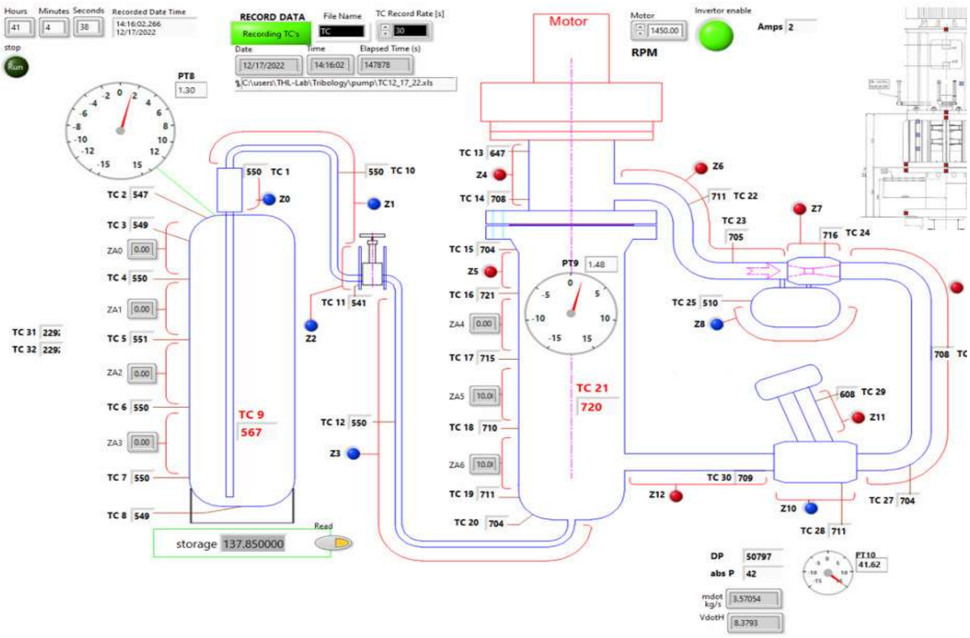

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Figure 12: *System Thermocouple and Heat Element Locations*

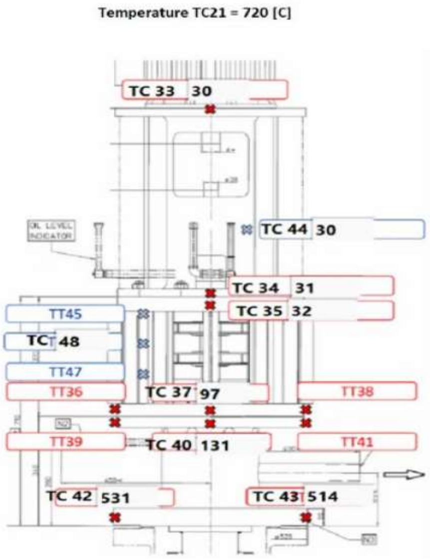

Figure 13: *Thermocouple locations in pump above grade area.*

During startup the system was preheated to 550 ºC. Figure 14 below show the timeline for system temperature during preheat and start-up. The pump reservoir was filled with salt from the storage vessel in about 20 minutes. The amount of salt (108kg) was measured using a scale under the storage reservoir and thermocouple level sensors in the reservoir. The drive was started about 40 minutes after the reservoir was full and the temperature in the reservoir (TC21) was stable. TC16 drops about one hour after the salt is fully loaded. This thermocouple is in the reservoir at the salt level and drops as it becomes exposed to the N_2 blanket

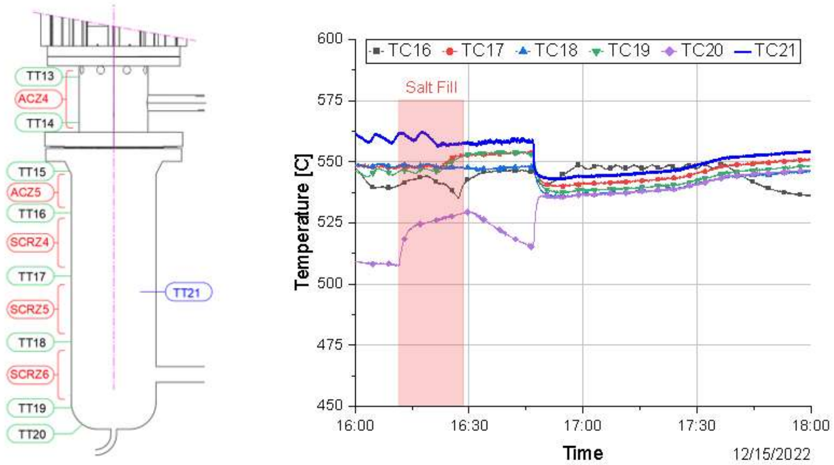

Figure 14: *System temperature distribution during preheat, loading the salt into the test loop and pump start up.*

Thermal Model Predictions Confirmed

While running at 720 ºC the temperatures above the reservoir in the discharge area and above remained at acceptable levels and confirm the design model predictions. The thermocouple readings were periodically confirmed using an infrared thermometer and a Fluke portable temperature probe, see Figure 15.

The temperature in the driver stand area was monitored via:

- FLIR (Thermal Imaging Camera)
- FLUKE (Infrared Temperature Gun)
- K-Type Thermocouples & NI LabVIEW

While the test selection was at 720 °C, temperatures in the driver stand and above remained at acceptable low levels.

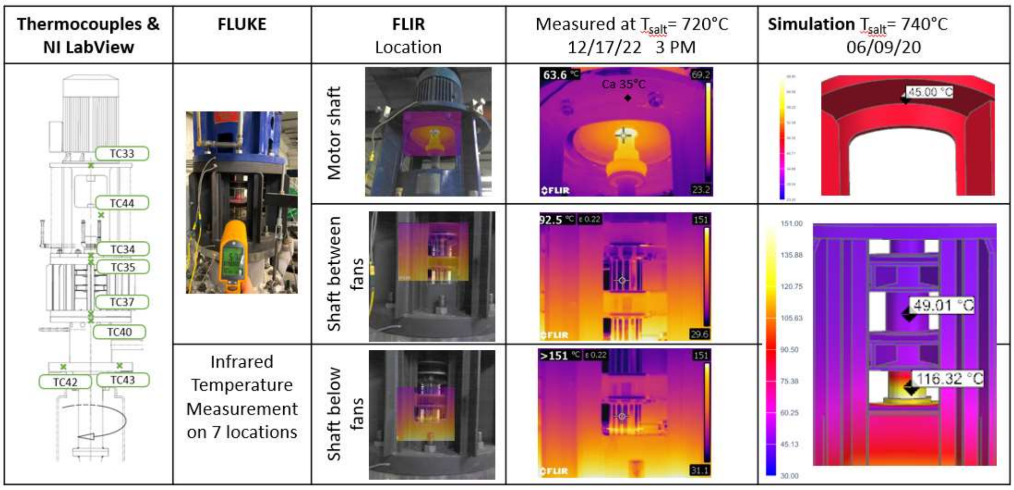

Figure 15: *Validation Pump Above Grade Temperature Comparison.*

Shutdown and Restart

During shutdown and restart cycling the temperature in the discharge area remained high enough to prevent the salt from solidifying. Figure 16 below clearly shows the inflection points in the reservoir salt temperature (TC21) when the pump was shut off and when it was restarted. Temperature in the discharge area (TC35, TC37 and TC46) increased about 15 ºC while the fans in on the shaft were not spinning during the 22-minute shutdown at 720 ºC.

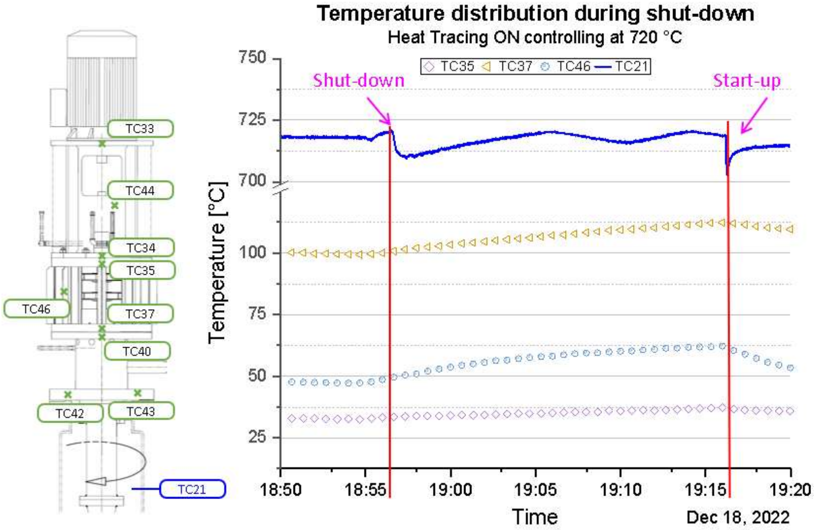

Figure 16: *Pump Temperature Distribution During Shutdow.*

Coast Down

Five shutdown and re-start cycles were completed from 1450 RPM, three at 720 ºC and two at 550 ºC in addition to the initial startup and final shut down, See Table 3 for details. These cycles were completed successfully including a long shut down of 22 minutes. No salt freezing or system difficulties occurred during these shutdown cycles.

	Temperature (ºC)	Duration (min)
1	720	2
2	720	13
3	720	22
4	586	1
5	557	2

Table 3: Shutdown, Re-start cycles

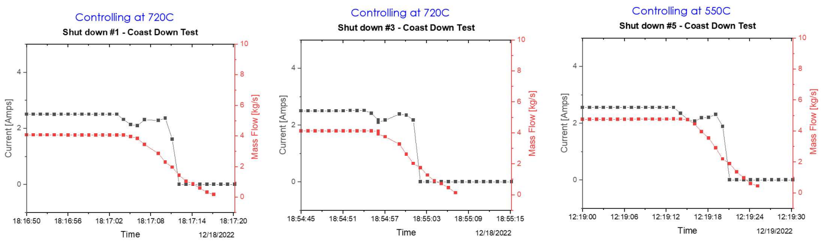

Figure 17: Motor and Pump Performance (current and flow rate) during Coast Down

Data Acquisition and Pump Curves
When the system was stable at the designated salt temperature (550 ºC or 720 ºC) and pump speed (1300 RPM, 1450 RPM or 2000 RPM) the flow control valve was adjusted from closed to 80 gpm. The valve was adjusted after the system was stable for 15 to 20 seconds. Volumetric flow, pressure and temperature were recorded at a rate of one data point per second.

The data recorded at 550 ºC and 1450 RPM including all the transients caused by the change of the valve setting and settling of the salt flow. The data shows a reliable and responsive system.

The data was reduced to pump performance curves displaying the head (m) and versus the volumetric flow rate (m3/h), See Figure 18. Error bars were calculated as two standard deviations of the rms value of the last 30 measurements (30 seconds) prior to changing the valve position.

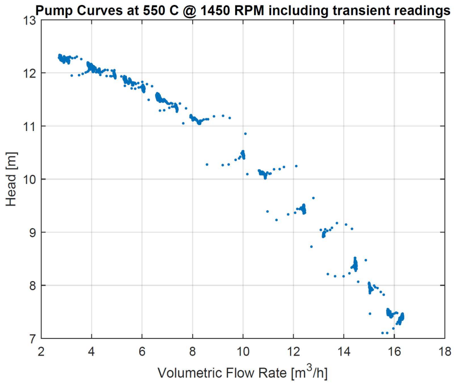

Figure 18: *Salt Volumetric flow and Head at 550 ºC and 1450RPM*

See Figure 19 which provides a pump performance summary and comparison of salt and water pump performance. The tests show higher Flow-Head performance in salt than in water. The results of the validation pump test did show good performance in both molten salt and water. It can be noted in the figure below that the tests did show higher head-flow performance in salt than it did in water. With the flow rates at each speed and temperature, the head measured was slightly higher in salt compared to water.
The droop in the 2000 RPM curve at the highest flow rates is probably caused by cavitation.

At 720 ºC we were able to obtain our full data set from zero to 80 gpm at 1450 RPM.

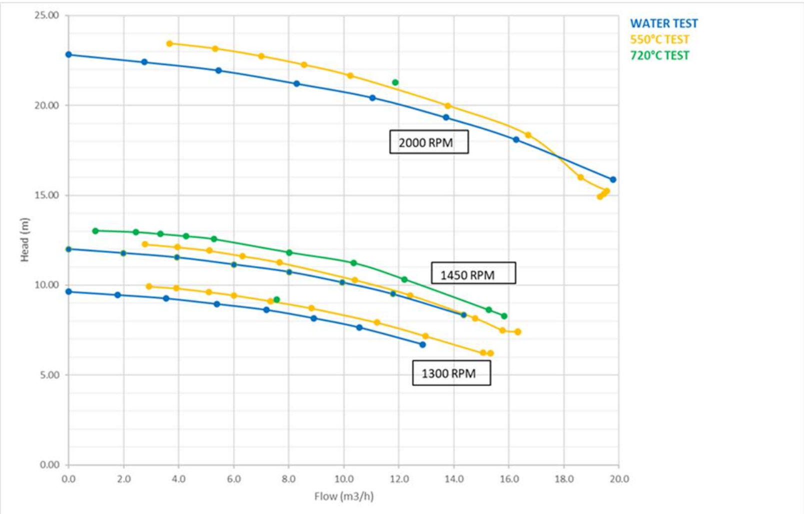

Figure 19: *Pump performance summary*

N_2 Overhead

At 720ºC, salt degradation gases escaped the shaft seal. Attempts to eliminate the leakage by increasing the N_2 blanket flow rate were not successful. The gas concentration in the laboratory limited the 720 ºC data points to fewer than planned. The pump is built with three N_2 ports, port 1 is inside the CIRPAC floating carbon ring seal (Figure 20) between the carbon rings, port 2 is below the seal and port 3 is intended for future use. In this test port 3 was not utilized, See Figure 21. The N_2 flow rates in port 1 and 2 were adjusted in attempts to eliminate the gas leakage.

Figure 20: *Floating Carbon Ring Labyrinth Seal*

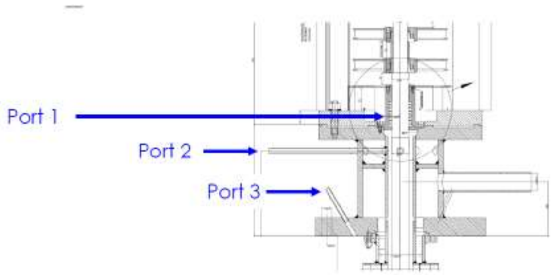

Figure 21: *N_2 Port locations in the pump Above Reservoir Area*

A Nitrogen flowrate of up to about 4.5 slpm (standard liters per minute) did not alleviate the problem. The CIRPAC seal was missing one graphite ring lost during disassembly and the N_2 blanket flow rate is well below recommendations. The vapor pressure of the hot salt is too high for the N_2 to prevent its escape.

CONCLUSIONS

The validation pump ran successfully and effectively in 720 °C chloride salts. During the validation test it ran in 720°C molten salt for over 90 hours and producing consistent performance curves. The tests showed good performance in both molten salt and water.

As with most high melting temperature salt hardware, separating close fitting salt wetted components at room temperature is extremely difficult. Salt residuals found after the salt has been transferred out of the pump reservoir seep into and through tight clearances, and solidify below the melting point, binding components together. Disassembly needs to be done above salt melting temperature (>430°C) to get the studs and nuts off, and to remove components with tight clearances. Consider alternate solutions to studs and nuts for assembly of the hydraulic cell.

The shaft gas seal labyrinth configuration needs to be revised to prevent salt degradation gas escape. At high temperatures, the vapor pressure of the salt causes leakage through sealing systems that don't hold pressure. Any slight exhaust of salt vapors into the atmosphere reacts with the ambient air producing HCl which is not only detrimental to the environment, but also exposes the pump parts above the seal to corrosion, compromising the structural integrity of the system. Modifying the system to include an alternate seal design is required. A project to investigate solutions is recommended.

Compared to Haynes 230, the baseline material, the flexural strength of NiWC3b is 37% higher at room temperature and 80% higher at 720ºC. NiWC3b hardness is 70% higher (very important for MgO2 wear resistance). NiWC3b corrosion rate is 73% lower than H230 in the ICL carnallite salt

More testing is needed to provide a better estimate for the wear rate and friction factor coefficient values. Overall, it can be concluded that the NiWC3b performs better than the H230 in molten salt conditions.

It is difficult to accurately characterize the corrosion rate of each material exposed to the molten salt. Because of the ionic nature of the salt, material transfer occurs in between specimens. Corrosion testing at the national laboratories has not reached a consensus on the corrosion rate of the H230 alloy used as a control. In some tests it gains weight and in others it loses weight. There is agreement that H230 and superalloys lose Cr along grain boundaries. The specimen geometry varied greatly. In the corrosion tests run in this program NiWC3b performed well in both weight gain and weight loss environments.

Using the measured corrosion rate for NiWC3b, in 30 years a pump component would suffer a loss of 4.9 mm of material off its surface or 16% off a wall 3 cm thick. This could be a viable pump design solution. The conclusions resulting from actual testing in molten chloride salts at 720°C of the NiWC3b offer a material option to all Pump OEMs for their bushing and sleeve materials that will de-risk this critical component within their designs.

The PV limit for NiWC3b is higher than 4.4 and lower than 19.6. The onset of galling of NiWC3b in 750ºC salt is at loads well above any expected in the pumps. The NiWC3b bearing will run well in the validation pump, the demonstration pump, and full-size commercial Gen 3 CSP pump.

The Tribology Test Bed with NiWC3b bushings and sleeves ran for 500 hours with no wear. NiWC3b pin specimens had no measurable erosion within the accuracy of the micrometer along the pin from the tip to the hub or around the pin from the leading edge to the trailing edge. NiWC3b bushings and NiWC3b-coated sleeves had no measurable wear within the accuracy of the micrometer. NiWC3b-coated sleeves had no measurable wear within the accuracy of the Zygo profilometer. It is believed that it could have continued to run for several thousand hours without a failure and minimal wear.

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