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High Temperature Ternary Chloride Molten Salt Pump

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Abstract. A ternary chloride ($MgCl_2$-NaCl-KCl) molten salt pump has been developed to operate up to 720°C. The design is the result of a thermal, structural and material study of critical components. The vertical overhung pump incorporates first of a kind salt-wetted hydrodynamic bearings. Several bearing material pairings were tested which include: colmonoy grades, stellite grades, and a novel NiWC-based alloy (i.e. Hybrimet™ NiWC3b) used as a High Velocity Oxygen Fuel (HVOF) coating. The coating withstands the corrosion effects of the molten salt, and is also used to protect a 316L stainless steel pump reservoir. The pump bowl assembly components are made of Inconel 625. A Nitrogen flushed carbon ring seal is used to keep salt vapors from interacting with external ambient air. Preliminary testing shows a promising pump design for use in the Concentrating Solar Power Gen 3 systems and sets the ground for further development of the Hybrimet™ NiWC3b as a competitive alternative to available superalloys.

Keywords: Molten salt, Ternary chloride salt, Molten salt pump, Hydrodynamic bearings, Hydrodynamic bearing, Carbon ring seal, Superalloys, Stellite, Colmonoy, NiWC, Inconel 625, 316L stainless steel, High velocity oxygen fuel coating, High temperature, 720 °C.

1. Introduction

Commercially available Nitrate Salt Concentrating Solar Power (CSP) systems require molten salt pumps that are capable of withstanding corrosive salt environments up to 600°C [1]. Pump technologies used in these systems are vertical long-shafted sump pumps, which can utilize salt-lubricated bearings developed for temperatures up to 565°C [2]. The CSP Gen 3 goals necessitate pump designs that can handle temperatures beyond 700°C [3], for which a multistage vertical type long-shafted pump design has been innovated by Sulzer. Its design features a floating carbon ring seal, high temperature salt-wetted hydrodynamic bearings, and a high temperature corrosion resistant ceramic-metal composite (i.e. Hybrimet™ NiWC3b). The composite, or cermet, can be used as a coating or as molded pump components. The pump and cermet are compatible with a ternary chloride salt mixture ($MgCl_2$-NaCl-KCl) investigated by NREL [4] at temperatures above 720 °C. A molten salt test loop was developed and instrumented to monitor temperature, pressure, flowrate and vibration to investigate the pump prototype performance. This work presents the following: 1. Molten salt test loop. 2. Pump thermal management during pre-heat and operation. 3. Hybrimet™ NiWC3b HVOF coated 316L stainless steel pump reservoir performance. 4. Preliminary pump test results in water and salt. The pump prototype can withstand the high temperature ternary chloride salt environment while incorporating a cost-effective corrosion resistant coating. Preliminary testing in molten salt suggests that the pump is capable of meeting the CPS Gen 3 system pump requirements.

2. Sulzer High Temperature Chloride Validation Pump

The molten salt pump developed for the project follows the Sulzer Ensival Moret VNY 40-13-2s [5]. It is a 2-stage pump vertically suspended overhung pump which for a rated speed of 1450 rpm, and flow of 8 m^3/h (~35 GPM) produces a head of 10 m at an efficiency of ~54.5%. The wetted end is designed to withstand operation at 720 °C considering a ternary chloride salt mixture with a baseline composition of 45.31 wt.% $MgCl_2$, 38.70 wt.% KCl and 15.99 wt.% NaCl, as reported by NREL [4]. The pump includes in its design a throttle bushing and two bowl bushings. The impeller diameter lies around ~139 mm, and the pump is rated to a maximum speed of 2000 RPM. The salt-wetted and hydraulic components of the pump are made of Inconel 625, which follows relatively good resistance and chemistry balance in molten salt [4,6]. Following the characterization of select candidate materials to determine their tribocorossion associated to the candidate ternary chloride salt, Colmonoy grades, Stellite grades and NiWC3b were determined suitable to use in the pump. The specific grades of Colmonoy & Stellite are propiertary to Sulzer, but all details to the preliminary tribocorrosion tests and materials in consideration is found in [5].

Table 1. Materials of construction chosen for evaluation as the shaft sleeves & bearings [5].

Subcomponent	Sleeve	Bush
Stage 1	Inconel 625 + Colmonoy	Stellite
Stage 2	Inconel 625 + Stellite	Stellite
Throttle bushing	Inconel 625 + NiWC3b cermet	Stellite

Figure 1. Validation pump developed by Sulzer following the water test.

2.1 Pump thermal & structural study, design and management

Thermal & structural analysis via Finite Element Analysis (FEM) were employed during the design stage to evaluate the temperature distribution keeping critical system components under temperature limits (e.g. tank flange, upper bearing housing, drive). This evaluation also helped in determining the static and fatigue assessment of critical weld seams of the pump. The model accounted for: 1. Natural convection between pump rotor & pump reservoir internal ambient temperature, 2. Convection from the molten salt liquid & vapor, 3. Contact resistance between pump and insulation, 4. Conduction across insulation & heat tracing materials, 5. Convection associated to a continuous flow of overhead N_2, 6. Forced convection associated to upper fans, 7. Natural convection from exposed pump structure to ambient air. Four case-studies were developed, but two particular cases were explored and considered:

Case 3: Pump stopped, tank filled with molten salt at 740 °C at the maximum sat level 800 mm above the intake; no forced injection of N_2, with and without tracing.

Case 4: 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 N_2 injection of 8 m^3/h.

Table 2. Summary of the results from the thermal & structural analysis alongside mitigation solutions

Thermal analysis	Structural analysis	Mitigation
Tracing does not heat every corner T > 444°C (risk of salt freeze) Maximum bearing temperature is in all cases lower than 70°C High temperatures in studs (different thermal expansion coefficient.)	Large differences in radial flange expansion (Risk for fastener and seal) Weld assessment has significant uncertainty because of uncertainty of material characteristics in such high temperatures Thermal loads from case 4 highly affect some welds. Both static and fatigue assessment are within acceptable limits. Static thermal load of the weld is found to be more critical than fatigue.	Use isolations on discharge head as high as possible Reduce bending stiffness in section between weld and top flange

Table 2 presents a summary of key results that were found. One of the main concerns was to keep the tank flange temperature within limits as thermal expansion is key in loosening the seal and exposing the system to leaks, and the upper bearing housing under 110 °C at all times. Fig 1. shows real-time temperature readings using a FLIR infrared camera to validate the thermal model estimates, and monitor the temperature on the critical components in case a over-temperature shut down were required. The thermocouple measurements on the pump during service also helped project a temperature distribution profile along the shaft, this helped verify that there were no potential salt freeze points of concern below the flange during the test.

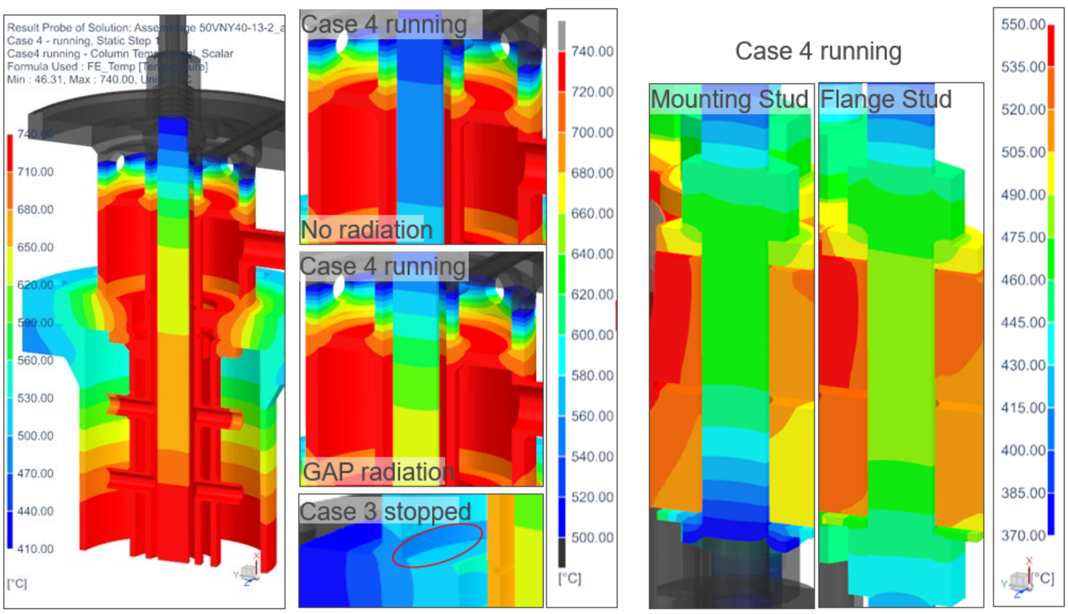

Figure 2. Sulzer validation pump thermal study pump cross-section. Select detail results on steady-state thermal & structural FEM results for case 3 and 4.

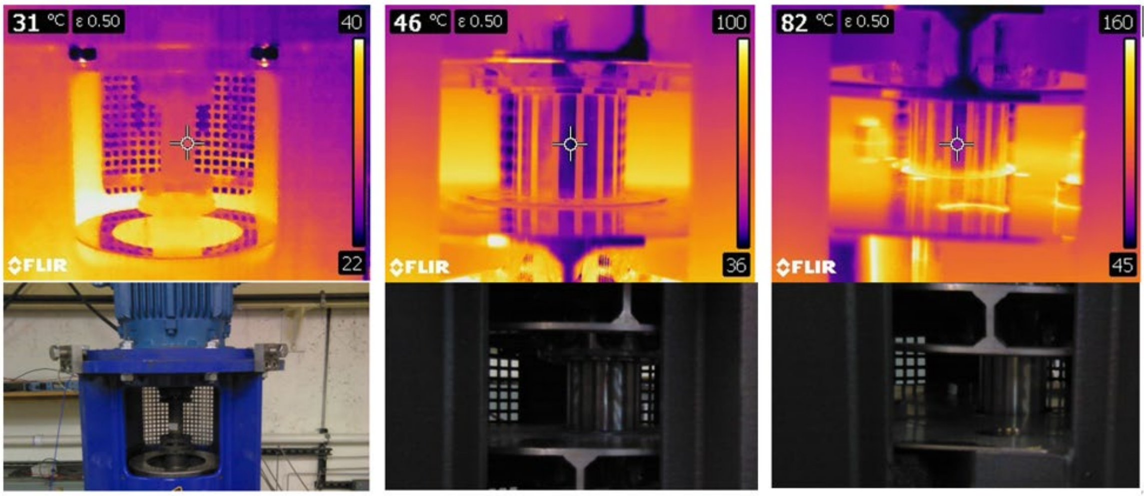

Figure 3. FLIR infrared readings of select pump component.

2.2 Hybrimet^{TM} NiWC3b Coated Pump Reservoir

During the corrosion testing campaign, the NiWC cermet was evaluated under different compositions and as a coating in molten salt conditions at 750 °C. The NiWC3b configuration which includes the properties found in table 3 performed well as a coating in 250-hour static corrosion tests (See fig 4). The University of Wisconsin-Madison salt loop features a 12” diameter Hybrimet^{TM} NiWC3b coated 316L stainless steel vessel for which materials & manufacturing was ~34% cheaper than the market price of Inconel 625, which had a 6-week lead time and would have cost $21,082 for the material alone. This vessel was heated to 650 °C and lightly thermally cycled between 25 – 650 °C. Upon opening the pump reservoir to extract the pump, the interior Hybrimet^{TM} HVOF coated vessel was visually inspected. Figure 4 shows how the vessel was intact and well protected from corrosion. There was no chloride salt ($MgCl_2$-KCl-NaCl) level line or indication on the interior walls of the vessel, nor discoloration of the exposed faces as is normally observed with bare 316L or other alloys that have been exposed to salt corrosion.

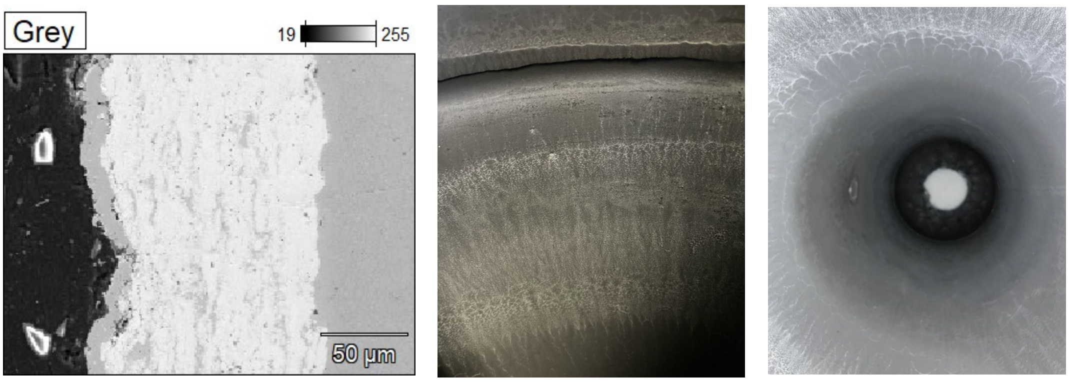

Figure 4. (left) SEM of NiWC3b HVOF after 250-hour corrosion test in $MgCl_2$-KCl-NaCl at 750 °C [5]. (center, right) NiWC3b HVOF coated 316L pump reservoir after preliminary pump testing in molten salt within 550-650 °C.

Table 3. HybriMet^{TM} Metal Matrix Composite typical properties as given by Powdermet.

Typical Properties				
				Typical Value
Property	**Method**	**Conditions**	**Units**	**NiWC3b**
Density	ASTM C134	RT	g/cc	12.8

Hardness	ASTM E18	RT	GPa	17.1
Tensile Strength	ASTM E8	RT, Ultimate	Mpa	1019
	ASTM 21-17	750°C, Ultimate	Mpa	463
		750°C, 0.2% yield	Mpa	413
Tensile Elongation	ASTM E8	RT	%	0.25
Elastic Modulus	ASTM E8	RT	GPa	425
	ASTM C1161/1341	RT	GPa	
	ASTM 21-17	750°C	GPa	214
Flex Strength	ASTM C1161	RT	Mpa	1182
	ASTM C583	720°C; 1 hr soak	Mpa	1110
Flex Str retention	ASTM 1161	salt 750°C, 250 hrs	%	98%
Compressive Strength	ASTM E9-09	RT, ultimate	Mpa	3230
		RT, 0.2% yield	Mpa	2644
Compressive Modulus	ASTM E9-09	RT	Gpa	379
Bulk Fracture Toughness	ASTM C1421	RT	Mpa*m^1/2	19.9
Thermal Conductivity	ASTM E1461	0 to 500°C	W/m-°C	38
Specific Heat Capacity	ASTM 1461	0 to 500°C	J/g-°C	0.35
Thermal Diffusivity	ASTM 1461	0 to 500°C	cm^2/sec	0.08
Electrical Conductivity				high
Thermal Expansion	ASTM E228	0 to 750°C	ppm/°C	8.96
Corrosion Resistance	Uwisc	ICL salt 750°C	% wt loss	0.28

3. Molten Salt Loop

The molten salt loop at UW-Madison was built to test the pump up to 720 °C across flowrates of 0-17 m3/h (~75 GPM) and pump speeds between 1300-2000 rev/min. The piping holding structure accounts in its design for the thermal expansion that is expected throughout the test. It is instrumented with over 40 k-Type Omega 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 preheat and steady operation up to 720 °C. The loop features a separate salt tank storage to which salt can be exhausted from the pump reservoir when not in use; this facilitates disassembly and prevents additional strains on the pump shaft during cool down to standard atmospheric conditions. Table 4 presents the main salt loop components and specialty instrumentation found. Preliminary testing in molten salt reviewing start-up and shut-down sequences has been done, including several bearing materials to be evaluated (see Table 1). Based on learnings and results of the preliminary test, Hybrimet™ NiWC3b will be further used for the sleeves with appropriate bush materials and will be further tested in 2022 to evaluate steady state operation at different speeds. Post-exposure material evaluation will be performed to assess the tribocorrosion and functionality of the bearings at an operating temperature range of 550-720 °C.

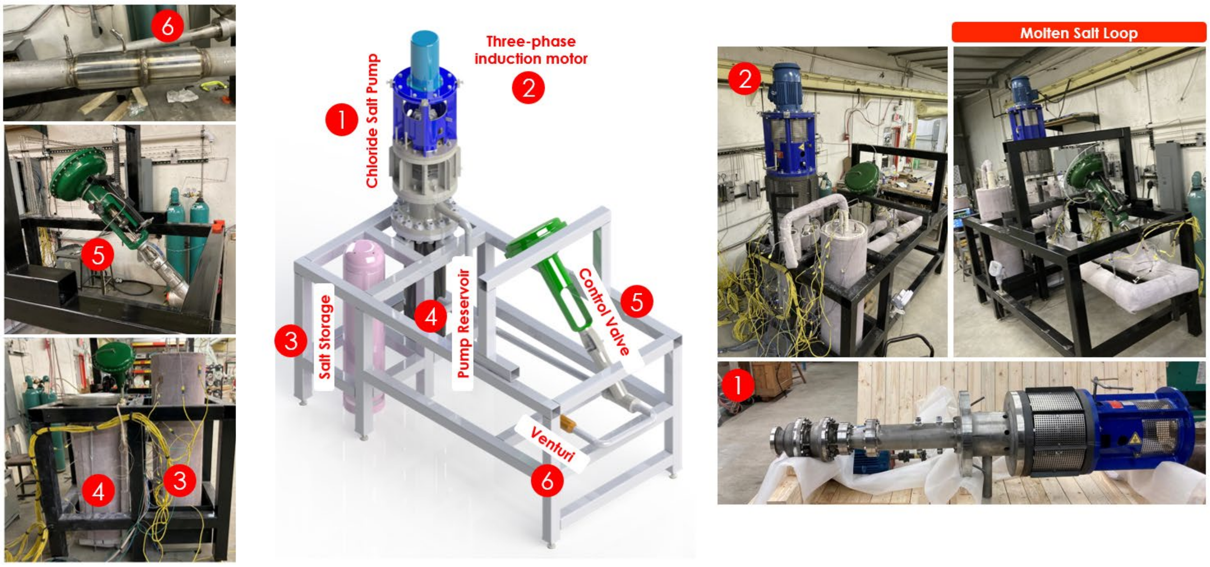

Figure 5. Molten Salt Loop Components and facility layout at UW-Madison.

Table 4. Molten Salt Loop Components detail.

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 predetermined flowrates.
Validation salt pump	Vertical style pump following Sulzer Ensival Moret VNY 40-13-2s 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.

4. Preliminary Testing & Future work

The pump testing plan comprises start-up, shut-down, operation at low end temperature (550 °C) and high end temperature (720 °C) representative of stages found in the operational sequences of the Gen 3 Concentrate Solar Power liquid pathway design found in [3]. Prior to the shipping and testing in molten salt conditions, water tests were performed to validate the hydraulic performance of the pump according to design parameters. Preliminary salt-testing at 550 °C was performed to revise start-up sequences.

4.1 Water Test

Prior to the salt test, a test in water was performed for different shaft speeds (1300, 1450, 2000 rev/min). Vibrations where evaluated following API610 11th, which included measurements of overall vibration & Fast Fourier Transform Spectrum (FFT Spectrum) at the rated speeds of operations, best efficiency point (BEP), maximum flow, and coast down. Measurements were taken at the bearing housing and driver mounting surface, and it was found that overall vibration lied around 1 mm/s RMS. During coast down, natural frequencies were found around 800 and 1000 rev/min at the bearing housing plate, and no resonance was found at speeds over 1300 rev/min. Similarly, natural frequencies of around 750 and 1000 rev/min were found at the motor stand, with no resonance above 1300 re/min. The test performed well overall, and pictures of the sleeves after strip down are found in Figure 6. After this test the stellite throttle sleeve was replaced by a NiWC3b cermet coated Inconel 625 sleeve.

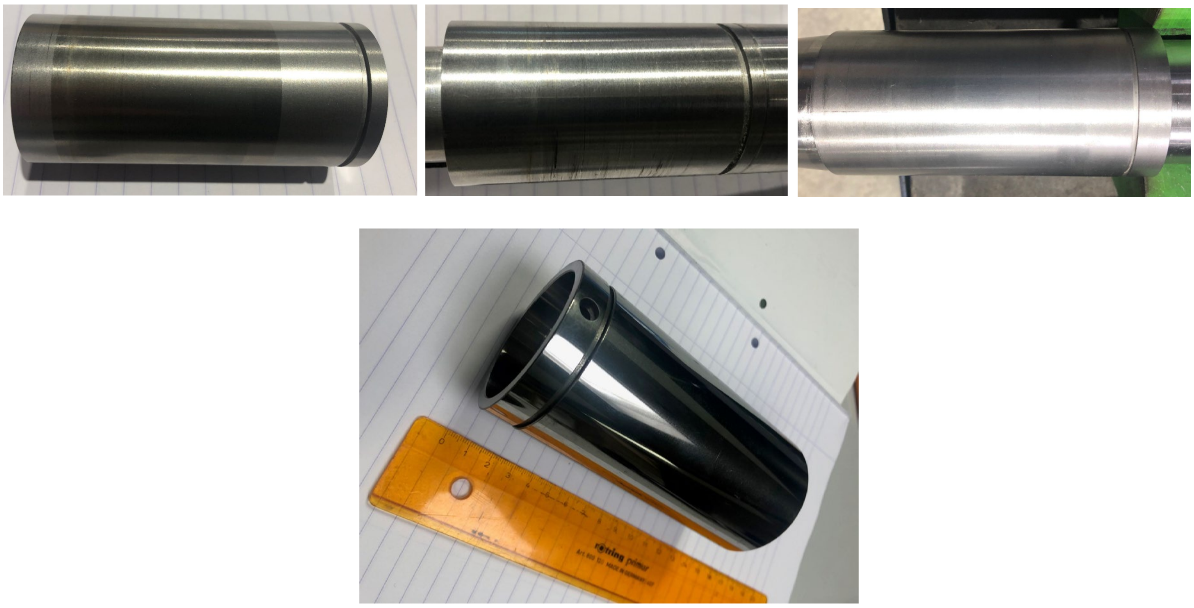

Figure 6. (Left) stage 1 colmonoy sleeve. (Center) stage 2 stellite grade sleeve. (Right) stellite sleeve. (Below) Inconel 625 + NiWC3b cermet coating throttle bushing

4.2 Salt Test

Preliminary testing in molten salt started at 2000 rev/min, a temperature of 530 °C and a flowrate of ~7 kg/s. The test halted for an issue which was later traced to the stage 2 bearing component which included two different grades of stellite. Stage 1 components and the throttle bushing displayed good integrity following the test. Figure 7 includes a comparison of the different components after the test, and after being sonicated in deionized water at 80 °C. Following the post-exposure analysis, the following corrective action was implemented: (1) Replace the stage 1 and stage 2 sleeves with NiWC3b coated Inconel 625, (2) Increase the bearing clearance by at ~3 mils (0.0762 mm), (3) Replace the stage 2 bushing for spare stellite (4) Reassemble the pump to gather hydraulic performance data at 1300, 1450, and 2000 rev/min.

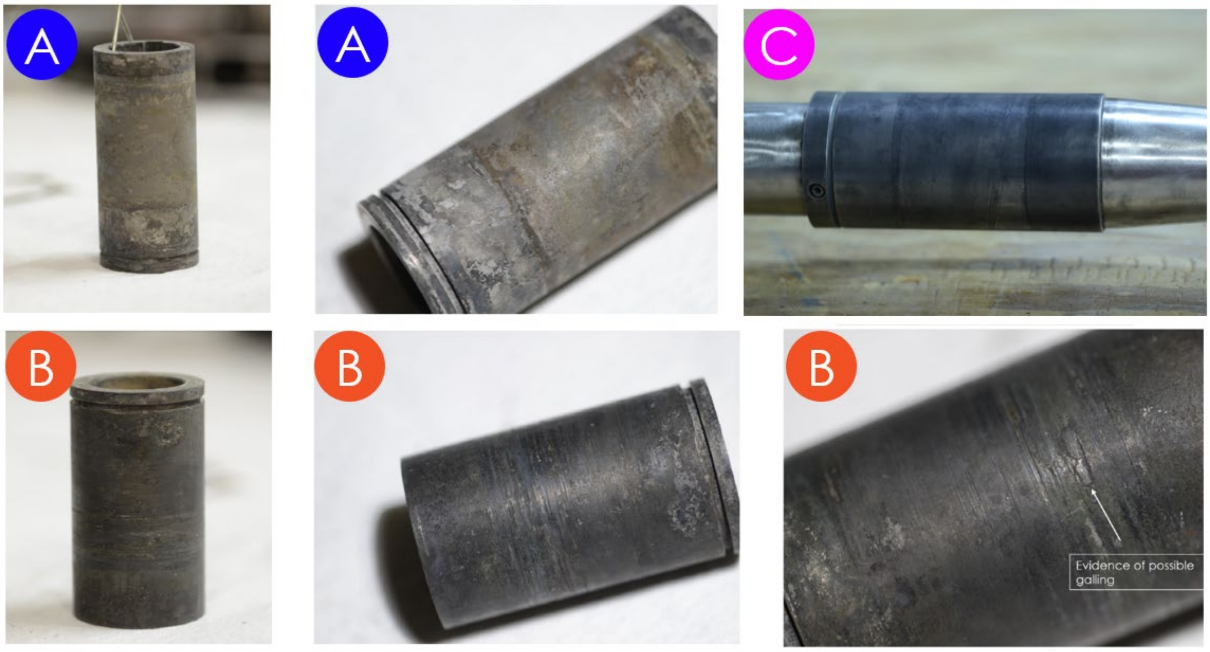

Figure 7. A. Stage 1 sleeve, Colmonoy post test & sonication. B. Stage 2 sleeve, Stellite post test & sonication. C. Throttle bushing sleeve, NiWC3b coating post tests & sonication.

5. Acknowledgement

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6. References

1. Angel G. Fernández, et al, "Mainstreaming commercial CSP systems: A technology review", Renewable Energy, Volume 140, 2019, Pages 152-176. https://doi.org/10.1016/j.renene.2019.03.049
2. Daniel L. Barth, et al, "Development of a High-Temperature, Long-Shafted, Molten-Salt Pump for Power Tower Applications", ASME. J. Sol. Energy Eng. May 2002, 124(2): 170-175. https://doi.org/10.1115/1.1464126
3. Mehos, et al, "Concentrating Solar Power Gen3 Demonstration Roadmap", 2017, United States. https://doi.org/10.2172/1338899
4. Zhao, Youyang, "Molten Chloride Thermophysical Properties, Chemical Optimization and Purification", 2020, United States. https://doi.org/10.2172/1734652
5. Turchi, C. S., Gage, S., Martinek, J., Jape, S., Armijo, K., Coventry, J., ... & Will, G. (2021). CSP Gen3: Liquid-Phase Pathway to SunShot (No. NREL/TP-5700-79323). National Renewable Energy Lab.(NREL), Golden, CO (United States); Sandia National Lab.(SNL-NM), Albuquerque, NM (United States); Australian National Univ., Canberra, ACT (Australia); Commonwealth Scientific and Industrial Research Organization (CSIRO), Newcastle, NSW (Australia); Queensland Univ. of Technology, Brisbane (Australia). https://doi.org/10.2172/1807668
6. Sun, H., Wang, J., Li, Z., Zhang, P., & Su, X. (2018). Corrosion behavior of 316SS and Ni-based alloys in a ternary NaCl-KCl-MgCl2 molten salt. Solar Energy, 171, 320-329. https://doi.org/10.1016/j.solener.2018.06.094