Track B: Components for Molten Chloride Systems

PUMPS

Gen3 CSP summit 2021

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Assume Ternary Chloride Salt

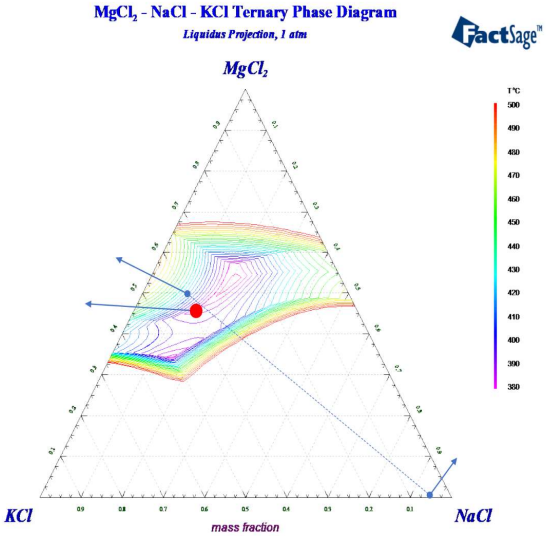


Fig 1. NaCl-KCl-MgCl2 phase diagram calculated by FactStage showing the composition of the purified baseline salt, AC, and SPK halite. Source [1].

The liquidous temperature of the ICL AC salt is around 450°C, the main objectives of adding SPK halite are:

1. Lower liquidous temperature of ICL AC and provide an extra safety margin for CSP loop operations in the temperature range of 500°C to 720°C.
2. Reduce Overall cost of salt inventory (SPK halite is significantly cheaper)

The **"baseline salt"** made of ICL AC + SPK Halite has an approximate melting point of 430°C and follows:

- 2.5 g of Mg for every 1 kg of AC salt.
- 65 g of SPK halite (NaCl) from Albemarle for every 1 kg of AC salt.

	$MgCl_2$	KCl	NaCl
Composition	wt.%		
Average	45.31	38.70	15.99
Stdev	1.40	1.46	1.27
Composition	mol.%		
Average	37.51	40.92	21.57
Stdev	1.16	1.54	1.72

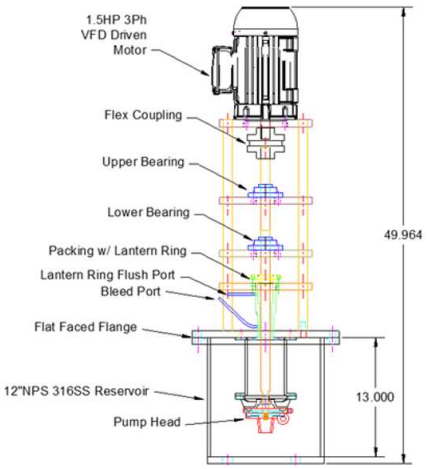
Table 1. Average Composition and Standard Deviation (Stdev) of Purified AC + Halite Based on ICP-AES Measurements of 10 Samples from 7 purification batches. Source [1].

Fluid	Tmelt	Tboil	Density	Energy Density(ρ·Cp)	k	μ	Pr	Cp	volume expansion
	[°C]	[°C]	[kg/m³]	[MJ/m³-K]	[W/m-K]	[cp]	[-]	[J/kg-K]	
Chloride salt (650C) (45%MgCl3, 39% KCL and 16%NaCL by weight)	430	1200	1590	1.59	0.421	2.597	6.156	998	30%

[1] Zhao Youyang,"**Molten Chloride Thermophysical Properties, Chemical Optimization, and Purification**" NREL/TP- 5500-78047, Nov 2020.

Experimental Scale Molten Salt Pumps

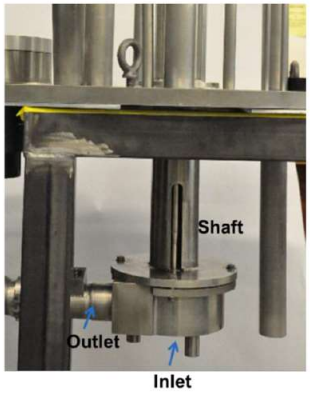
Generation 1 Pump



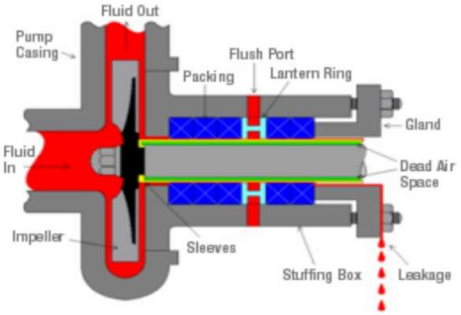
UW small scale lab pump with lantern ring packing seal

Nagle molten salt pump

Nagle molten salt pump installed in UW flow loop



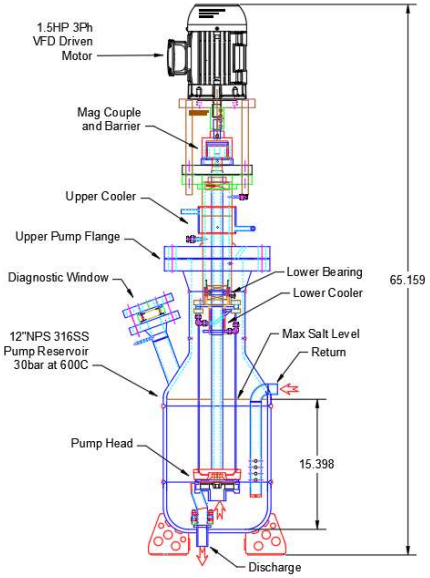
ORNL LSTL pump
John Crane 2800 rotating shaft seal. ORNL/TM-2016/199



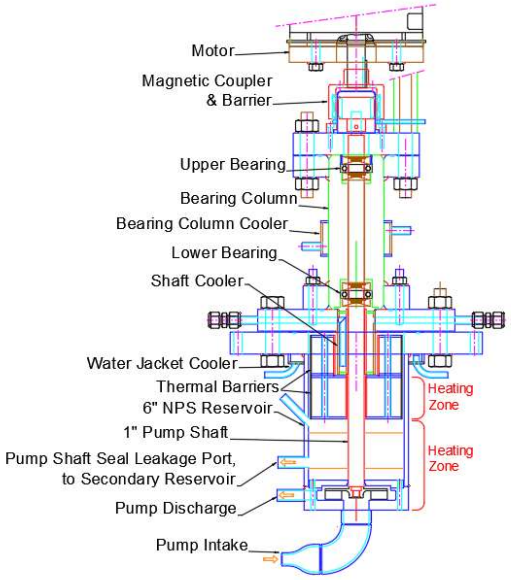
Lantern ring and packing installed in clear stuffing box. (Sepco.com)

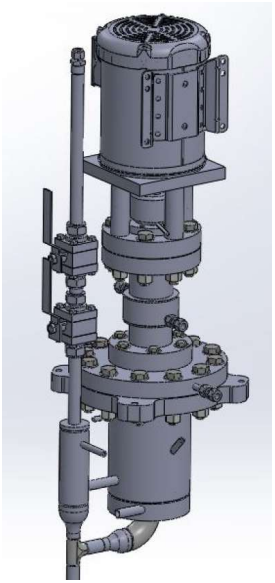
- Cantilever type
- Limits of 650C, 36 m^3/h (160 GPM), 35' (10m) Head, Lantern Ring Shaft Seal
- Work well for oxidizing salts Nitrates/Carbonates control gas release fairly well with lantern ring.
- Temperature limited by upper bearings
- Can go to higher temperatures and be used for Chlorides/Fluorides
- Concerns with gas partial pressure and release of gas vapor and/or consumption of purity of inert gas cover.

Gen 2 and 3 mag coupled hermetically sealed pumps



Gen 2 – mag coupled hermetically sealed

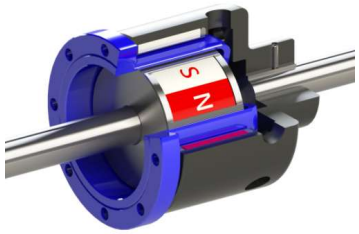


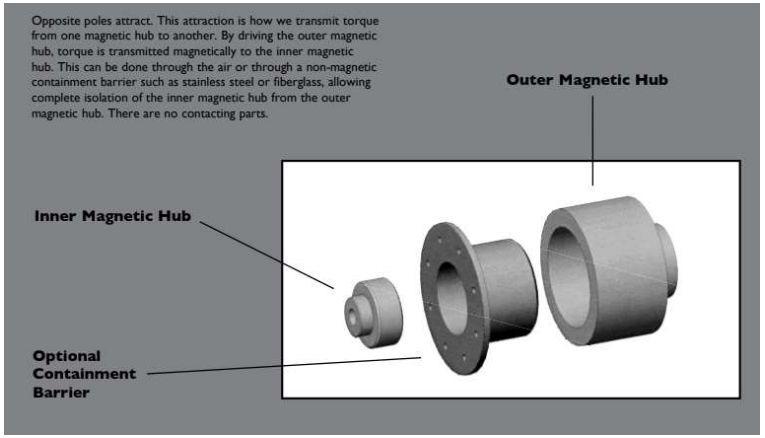


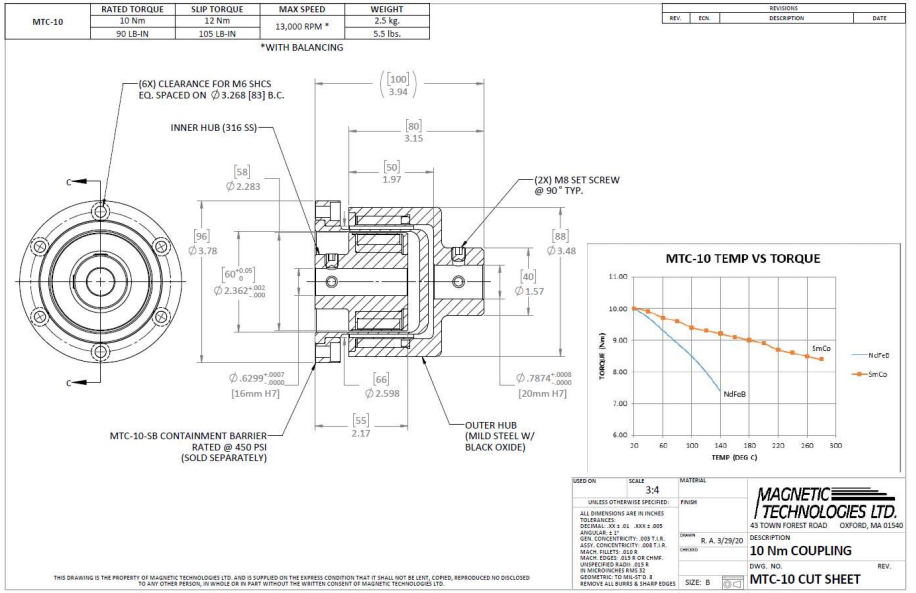
Gen 3 – improved cooling / thermal insulation. Shorter shaft
Custom volutes, improved alloys.

- Mag coupler allows hermetic seal no leakage of corrosive gases
- Eliminates issues with gas purge and easies control/contamination of salts
- Adds active cooling to keep upper bearings cool – still cantilever type
- Scales ok but may hit torque limits for commercial size systems.

Magnetic Couplings (Magnetic Technologies LTD, Oxford MA)





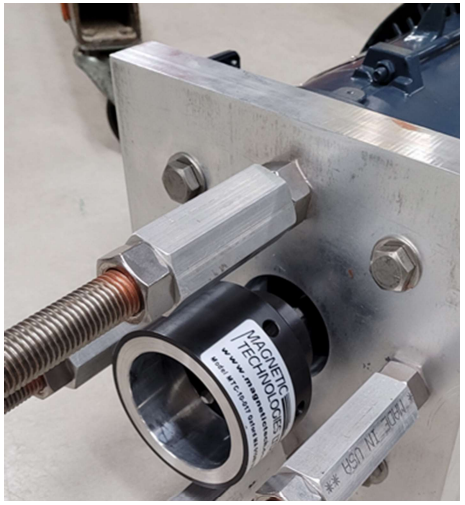


- Standard configurations available to 208 ft-lb (280Nm) nominal torque. Lead times on large barriers (ceramic), are significant
- Scale ok but may hit torque limits for commercial size systems.

Typical Installation

Barrier sealed over inner hub

Barrier off inner hub



Outer hub mounted to motor

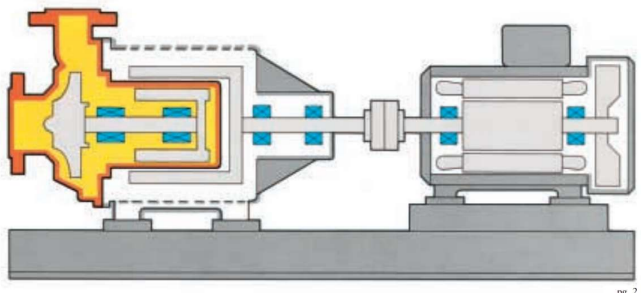
Assembly

Magnetic coupled hermetically sealed Forced Flow FLiBe pump operated over 1000 hours at 2GPM, +700°C

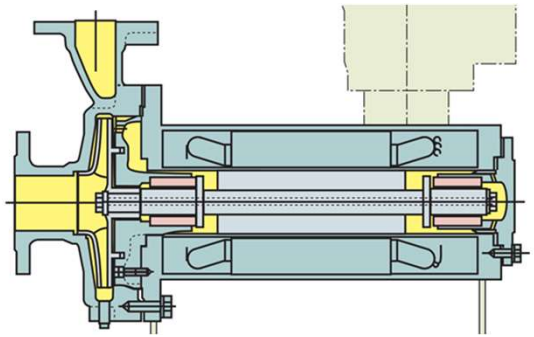
4TH ?? Generation advanced pump concepts

- High temperature Wetted bearing
- High temperature motor windings
  - Possibly canned motor pump designs

- Wetted high temperature bearings eases pump design (new materials – Powdermet may provide solutions)
- Higher temperature roller bearings
- Better Thermal management
- Magnetic Bearings
- High temperature motor wiring
- Improved high temperature pump diagnostics
- Coatings and materials for impeller shafts, volutes, bearings, etc – lower cost improve performance.



Mag coupled
With wetted or
magnetic bearings



High temperature
canned motor pump
with high temperature
magnet windings

https://www.texasprocess.com/wp-content/uploads/2019/02/Teikoku_brochure.pdf

Tribology and pump research

Research on wear rate & friction for wetted journal bearing

Pin-On-Disk salt friction coefficient

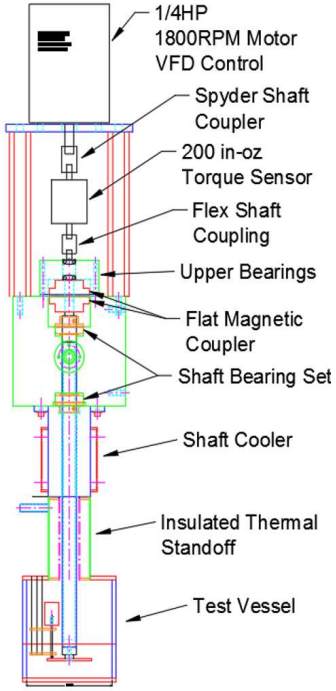
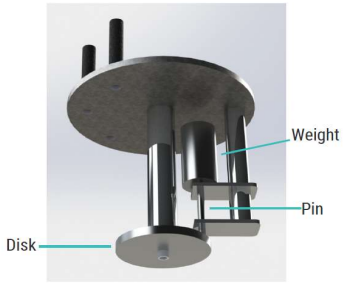
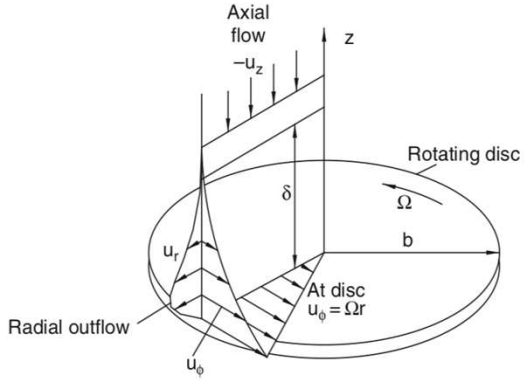


Fig 12. (Left) Pin-On-Disk instrumented facilities at UW-Madison & Device detail. (1) Upper assembly components. (2) Components ready for additional welding. (3) Upper bearing housing, shaft, bearing and coupler. (4) Upper bearing housing w/Mag coupler and flex coupler.



- The Pin-on-Disk testing instrument features a unique design that is rated to operate up to 800°C.
- Water jacket which cools down the shaft before the magnetic coupling with the motor and torque sensor. Capable of 1000 RPM,
- Weight on the pin can be switched to simulate different loads.
- used to investigate the effects of corrosion under high rotational speeds on bearing friction.



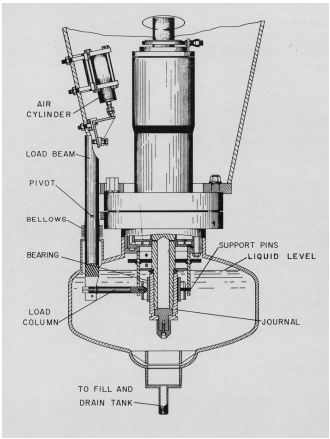
Larger scale bearing tribology test bed

- NiWC alloys, developed by Powdermet, have been found to display high corrosion and wear resistance in ternary salts during baseline material testing.

- To evaluate wear and erosion rates of NiWC pump components (i.e., bearings and impellers) in ternary chloride salt, a tribology test bed was designed with the capabilities of testing three journal bearings and five pin specimens, all submerged in molten salt.

Experimental conditions:
- Temperature: 720 C
- Time: 500 hours
- Motor speed: 1100 RPM
- Fluid: molten chloride salt
  - Approximate composition: 45.88% MgCl2, 38.91% KCl, and 15.11% NaCl by weight.
- Materials:
  - NiWC3b bushings and pins
  - NiWC3b-coated SS316 shaft sleeves
- Flushing gas: UHP N2

Fig. The Tribology Test Bed set up for testing with molten chloride salt. (joint venture between UW, High temperature Systems (Dan Barth) and Powdermet.



Salt-lubricated hydrodynamic journal bearing tests Nos 1 and 2. (ORNL 58-8-10, 1958, P.G. Smith) INOR 8 – vs- INOR 8

Tribology Test Bed

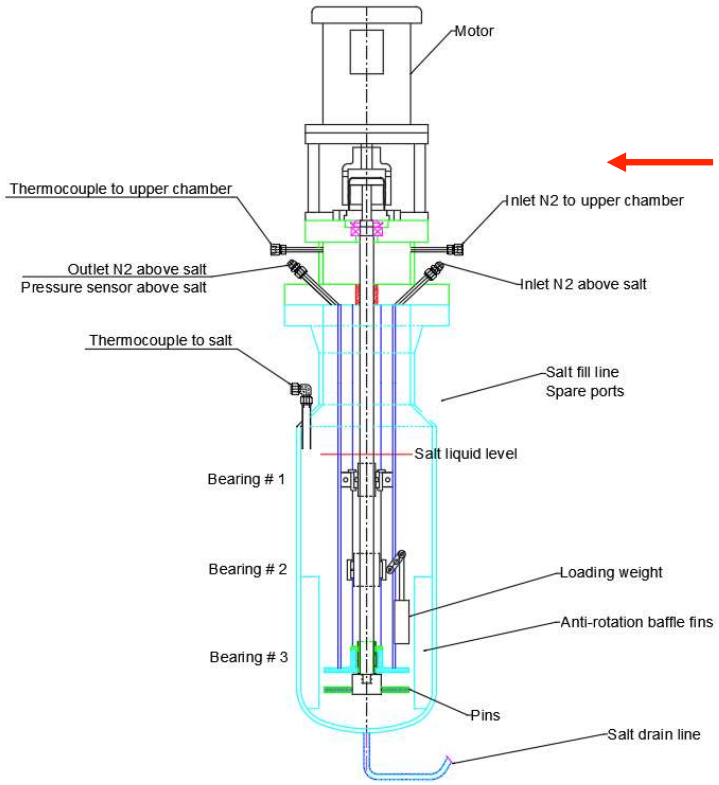


Fig. 16 A. AutoCAD drawing of the Tribology Test Bed structure.

- The Tribology Test Bed has SS316 structure made up of a salt vessel and inner column assembly magnetically coupled to the driving motor.
  - The salt vessel requires ~70 kg of purified and filtered chloride salt to submerge all test specimens.
- A loading weight forces contact between the bushings and their respective shaft sleeves to simulate wear conditions during startup and shutdown of a pump.
- The pin erosion specimens spin freely in the molten salt.

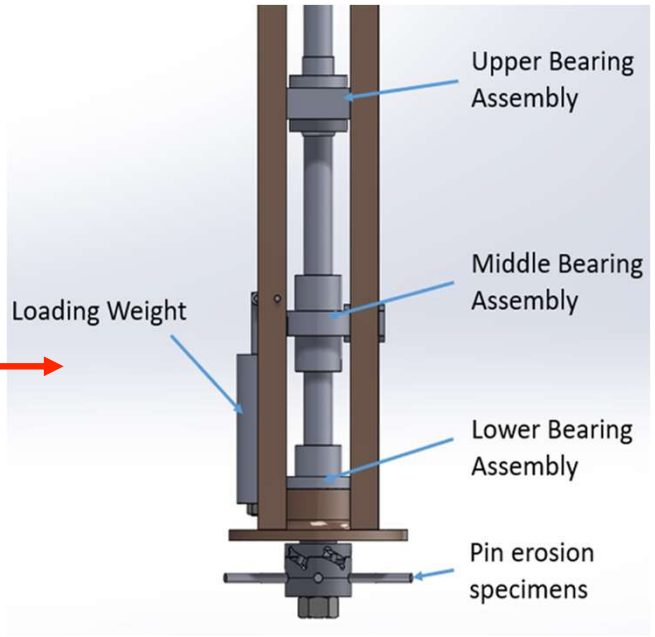


Fig. 16 B. The Tribology Test Bed inner column assembly features three bearing assemblies and a hub for pin specimens

Commercial size pumps

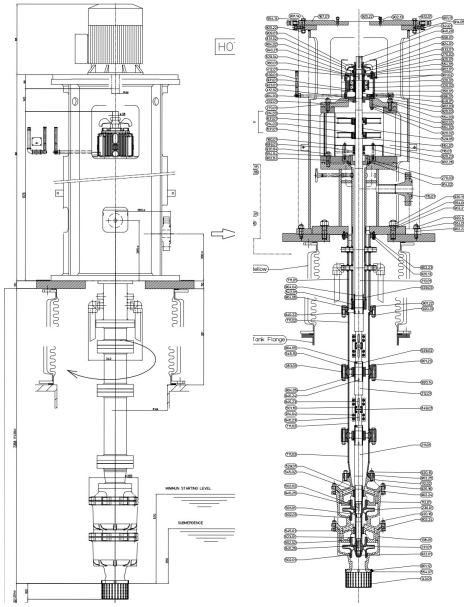
Demo scale pumps

Hot pump: 36 m^3/h (155gpm, 15.5 kg/s) and a head of 36 m (158 ft)

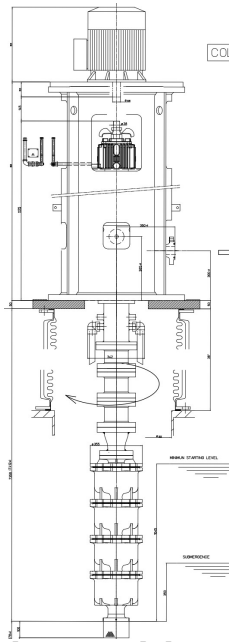
Cold pump: 25 m^3/h (110gpm, 11 kg/s) and a head of 90 m (295 ft)

Demo scale salt pumps (Sulzer and Flowserve)

- Vertical turbine pump design used for molten nitrate salts modified to use in chloride.
- Adds wetted salt journal bushing between each impeller/bowl assembly with a replaceable wear sleeve attached to the shaft.
- Multiple stages to achieve flow and head.



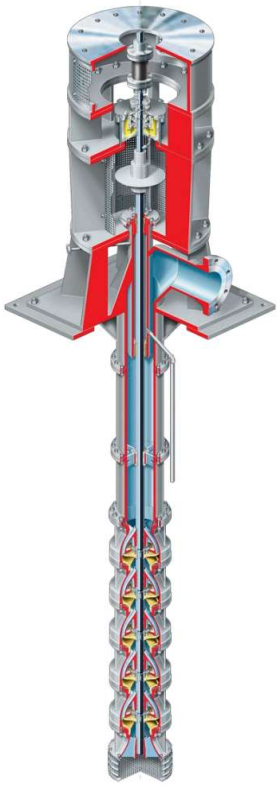
Sulzer hot pump



Sulzer cold pump

Flowserve cold pump

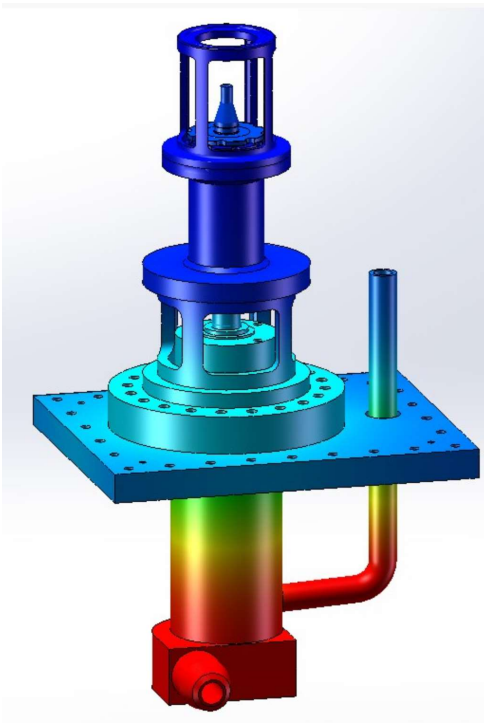
- Similar design as Sulzer
- API VS1 design vertical
- water-cooled thrust bearing housing
- Flowserve cold salt pump will require 12 stages (aka, bowls) and hot salt pump four bowls to achieve the desired head pressure
- Flowserve 08ELL-4 stage VTP
- Design temperature of 750°C [1364°F]
- Ambient temperature 35°C [96°F]
- Material Inconel H740



Hayward Tyler

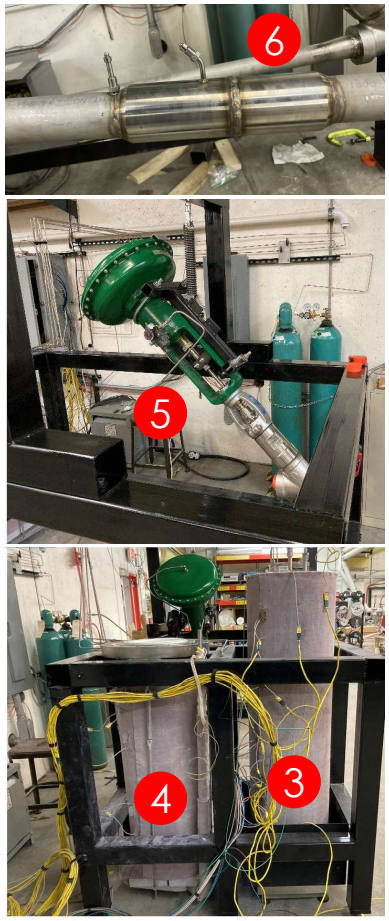
3rd vendor for molten salt pumps for demo
Did not submit details but they are working on pump designs

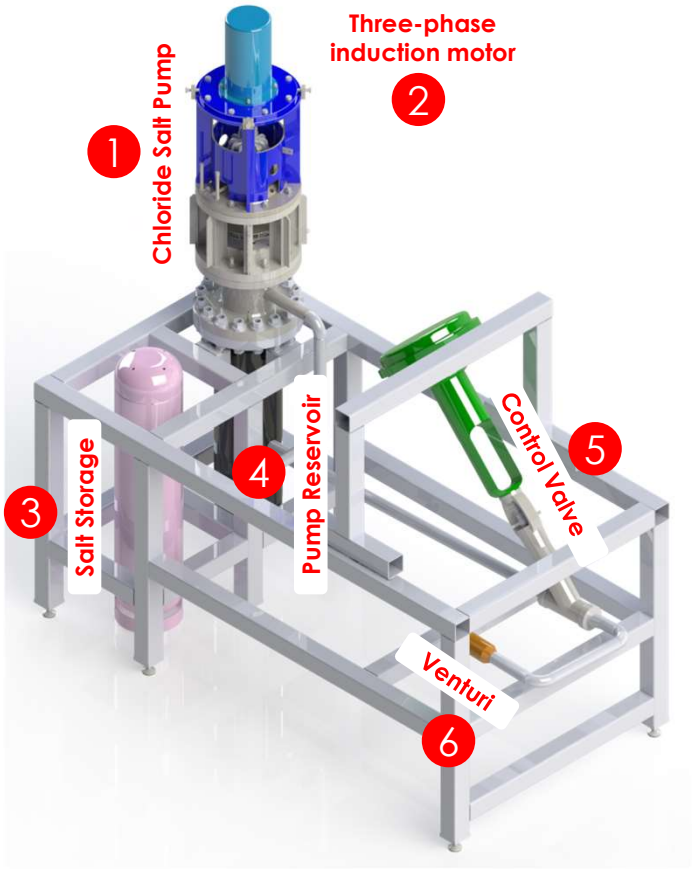
- Design temperature of 750C+ (1380F)
- Pump hydraulic design accounts for fluid corrosion rates
- Optimized for proper thermal management
- Validated thermal stress designs considering dissimilar materials and thermal growth rates
- Materials of construction include stainless steels and state of the art high nickel alloys, such as Inconel 625 and Hastelloy grades
- Design and build in accordance with ASME Section III, Div. 5 or ASME Section VIII, as needed
- Mag. Coupled hermetic seal



https://haywardtyler.com/products/high-temperature-pumps/

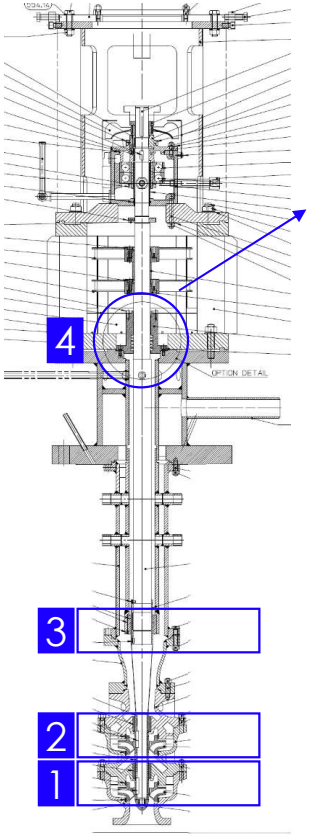
Chloride Salt Pump Loop testing (Sulzer pump/Powdermet – UW)





Molten Salt Loop

Salt tump testing details

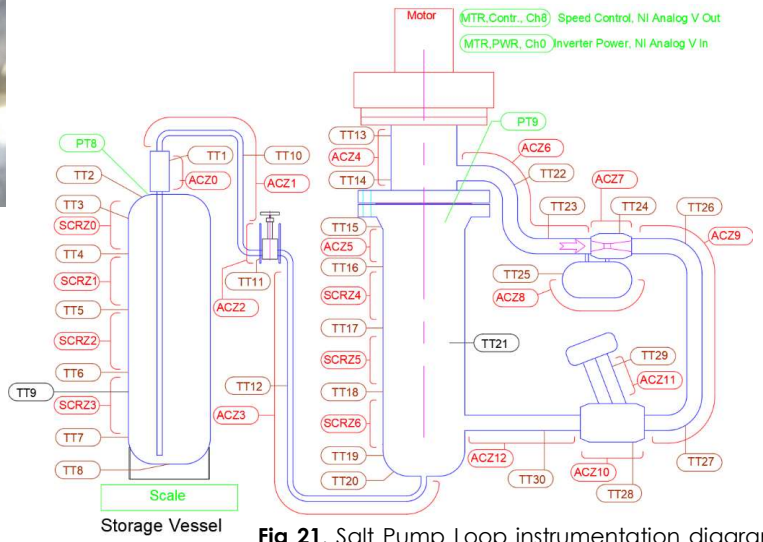


1 1st stage
2 2nd stage
3 Throttle bushing
4 Circpac MD

Fig 20. (Left) Sulzer VEY Pump design cross section. (Center) Chloride Validation Sulzer Pump cross section. (Right) Circpac MD Seal.

The validation pump developed by Sulzer follows the design of the VEY vertical mixed flow currently dispatched in CSP systems that employ nitrate salts. The main challenge with the testing campaign was to validate the pump design in molten chloride salt at 550°C and 720°C for a variety of flowrates ranging up to 75 GPM, and a variety of holding times, required simulate operation in CSP plants. Some of the unique features found in the validation pump include:

- Circpac MD flowserve seal.
- 1st stage → Inconel 625 + Colmonoy 6 sleeve riding on Stellite 6 bushing.
- 2nd stage → Inconel 625 + Stellite 21 sleeve riding on Stellite 6 bushing.
- Throttle bushing → Inconel 625 + CERMET (NiWC3b) sleeve riding on Stellite 6 bushing.
- Salt wetted parts manufactured mostly out of Inconel 625.



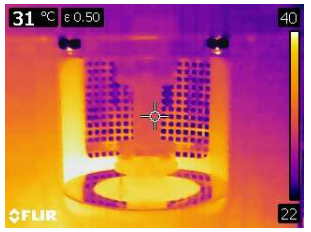


Fig 21. Salt Pump Loop instrumentation diagram with thermal imagery of motor coupling during pump operation at reservoir temperature of 550°C.

Summary comments

- Commercial pumps can be procured, however very little testing under high temperature operating conditions +700C. Further work is needed in this area
- Lead times and costs are high due to lack of commercial product, availability of materials and cost of high temperature materials.
- Current commercial platforms based on extension of lower temperature nitrate salt pumps where gas phase leakage and chemistry control isn't as problematic.
- Hermetically sealed magnetic coupled pumps are interesting if torques can be achieved, eliminates rotating seal and reduces cover gas flow rates.
- Need for work and testing on liquid salt pumps, room for improved designs
  - Wetted high temperature bearings eases pump design (new materials – Powdermet may provide solutions)
  - Higher temperature roller bearings
  - Better Thermal management (shorter shafts)
  - Magnetic Bearings
  - High temperature motor wiring (possible canned motors)
  - Improved high temperature pump diagnostics
  - Coatings and materials for impeller shafts, volutes, bearings, etc – lower cost improve performance.
- Need to understand maintenance issues (disassembly/repair after salt wetting)