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Original Article

# TRANSFER CHARACTERISTICS OF A LITHIUM CHLORIDE–POTASSIUM CHLORIDE MOLTEN SALT

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ABSTRACT

Pyroprocessing is an alternative method of reprocessing spent fuel, usually involving the dissolving spent fuel in a molten salt media. The National Nuclear Laboratory designed, built, and commissioned a molten salt dynamics rig to investigate the transfer characteristics of molten lithium chloride–potassium chloride eutectic salt. The efficacy and flow characteristics of a high-temperature centrifugal pump and argon gas lift were obtained for pumping the molten salt at temperatures up to 500°C. The rig design proved suitable on an industrial scale and transfer methods appropriate for use in future molten salt systems. Corrosion within the rig was managed, and melting techniques were optimized to reduce stresses on the rig. The results obtained improve the understanding of molten salt transport dynamics, materials, and engineering design issues and support the industrialization of molten salts pyroprocessing.



## 1. Introduction

Electrometallurgical processing ("pyroprocessing") is a dry, high-temperature alternative method of reprocessing spent fuel, which does not require the use of solvent extraction and its associated chemicals. Pyroprocessing typically involves the dissolution of spent fuel into a molten salt media, for example, lithium chloride–potassium chloride eutectic (LKE) salt [1]. Uranium is electrochemically separated using a solid cathode (typically steel or graphite), and plutonium and transuranics are separated using a liquid cadmium cathode. Advantages of molten salt reprocessing compared to that of aqueous reprocessing include lower quantities of waste produced, inherent actinide partitioning, good nonproliferation characteristics, and better criticality margin (no water phase) [2]. In addition, the metal products of pyroprocessing could be utilized to close the nuclear fuel cycle, e.g., the metal fuel is produced from pyroprocessing of spent oxide fuel, and metal-fueled fast reactors burn this metal fuel and then the metal fuel undergoes pyroprocessing again, creating the closed cycle.

Molten salts have a variety of uses other than pyroprocessing, including molten salt reactors and molten salt solar power towers. Most molten salt applications still rely on pumps with significant moving parts, e.g., high-temperature centrifugal pumps [3], as these technologies are well developed and well understood. However, while handling radioactive fluids, two key issues are maintaining containment and preventing dose exposure for workers. Centrifugal pumps have significant disadvantages in this area, namely maintenance of moving parts, lubrication leaks and maintaining seals to prevent the spread of contamination, and back diffusion of radioactive gases [3]. In addition, when working with molten salts, maintaining cooling and managing thermal expansion must be addressed.

One solution commonly used in aqueous reprocessing is use of no-moving-part fluidic devices, e.g., reverse flow diverters (RFDs), vacuum lifts, air lifts, double diode pumps, and steam/air/water ejectors [4–6]. These pump devices address many issues around containment and maintenance but often at a sacrifice of efficiency.

Examples of no-moving-parts pumping technologies that have been tested in molten salt applications include vacuum pumps [7], suction pumps, [8,9] and vibrating pipe pumps [10].

Other no-moving-parts pumping technologies worth mentioning are electromagnetic (EM) or magneto-hydrodynamic pumps. These work through application of a strong magnetic field and electrical current to a conducting fluid in a channel, giving rise to an EM force in the fluid, causing it to move through the

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channel. EM pumps were used in nonnuclear applications such as pumping seawater, liquid metal reactors, and suggested for use in molten salt high-temperature reactors. The advantages of EM pumps include their simplicity and high power density but disadvantages include the need for good thermal insulation or cooling to protect permanent magnets [11].

## 2. Materials and methods

The National Nuclear Laboratory (NNL), at that time a part of British Nuclear Fuels Ltd, designed, built, and commissioned a molten salt dynamics rig (MSDR) during 2001–2004 to investigate technologies for pumping molten LKE salt. The approach taken for the MSDR was to select pumping technologies that were well understood and used by the nuclear industry and to investigate their suitability for molten salts. Therefore, the pumps selected were a high-temperature centrifugal pump (standard off-the-shelf design, high flow rate), gas lift (no moving parts, low flow but reliable), and a reverse flow diverter (no moving parts, good flow rates and off-the-shelf design possible).

The MSDR was made up of two main vessels: pumping vessel V2002 and receipt vessel V2003, each with a capacity of 182 L. The LKE salt was pumped from V2002 to V2003 using one of the three pumping technologies, with the LKE then returning to V2002 via a gravity drain pipeline (see Figs. 1 and 2).

The vessels were constructed using 316 stainless steel with a vessel thickness of 6 mm. Electric heaters were placed on the outside vessel wall. These were encased by a layer of steel cladding, Rockwool mineral wool insulation, and finally an outer steel cladding. All piping was constructed using 316 stainless steel, wrapped with an electrical heating tape, and surrounded by layers of Rockwool mineral wool insulation.

As described previously, three pumping technologies were selected for testing.

A gas lift uses gas injected into a rising pipe to transport fluid against gravity, resulting in two-phase flow up the pipe. Different flow regimes (bubbles, slugs, churn, annular flow, etc.) occur at different gas and liquid flow rates. In the MSDR, argon gas was used to pump molten salt from V2002 to receipt vessel V2003, up a vertical pipeline with an inner diameter of 26.7 mm and length of approximately 4.2 m. Pressurized argon was introduced just above an elbow bend such that there was a 2.2 m head of molten salt above it. The argon line ran counter currently along the molten salt

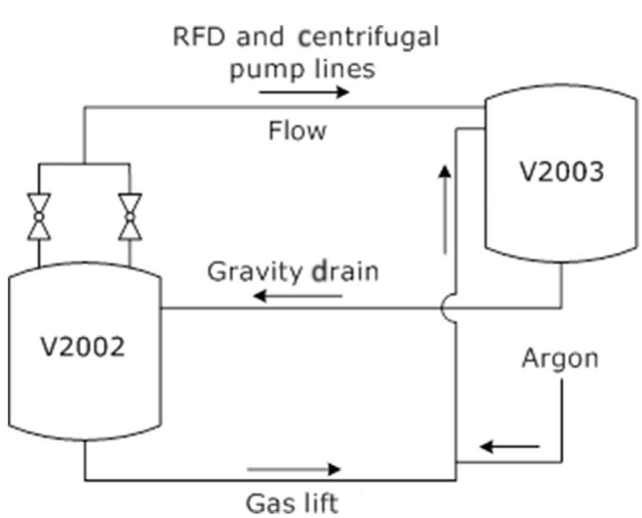


**Fig. 1.** Simplified schematic representation of the MSDR. MSDR, molten salt dynamics rig; RFD, reverse flow diverter.

transfer line to preheat the gas, and there was no sign of the argon cooling the salt during gas lift operation. Under normal operation conditions it was expected that the gas would pneumatically transport the melt in the slug flow regime of two-phase flow.

A vertical centrifugal pump (Rheinhütte GVSN 40/200A) with a 415 V three-phased Siemens motor was installed in V2002 to pump molten salt along a 4.2 m long pipe with six 90° bends to V2003. The rotor speed of the pump was controlled by a variable speed drive (Siemens Micromaster 440 Inverter Drive 0.37 kW, http://uk.rs-online.com/web/p/products/4660268/?grossPrice=Y), and the shaft was sealed with graphite gland packing. Nominal duty of the pump was 4.5 $m^3$/h with a 10 m head.

The RFD in the MSDR was submerged in V2002 along with a 10 L charge vessel and used argon gas. Molten salt was delivered to V2003. An RFD controller (Accentus Fluidtec Fluidic Pump Controller) controlled the argon supply to the suction and jet pumps, allowing drive time, drive pressure, and suction pressure to be set. Suction time was automatically controlled by the RFD software as a function of suction pressure to prevent fluid being sucked through the charge vessel up toward the jet pumps.

The rig was first commissioned with water in 2004, after which full molten salt trials ran from 2004 to 2006. Owing to organizational changes, the rig was put into a state of care and maintenance at the end of 2006 and was recommissioned in 2013 as part of the NNL's contribution to the REFINE project (a consortium of universities investigating molten salt reprocessing). After recommissioning, testing resumed, but a significant leak was discovered in 2015 during a gas lift pumping trial and operations halted. Investigations into the cause of the leak were carried out and the rig is now being decommissioned.

LKE was used as the salt medium as it has been identified for use in pyroprocessing flowsheets. The LKE supplied had a melting point of 357°C [12], a solid density of 2200 kg/$m^3$, and a liquid melt density of around 1620 kg/$m^3$ at 500°C [13]. The substantial decrease in the salt density on melting required careful designing and testing of the rig heating process. Salt melting started and progressed from free surfaces only (i.e., top down) to prevent the failure of components from thermal expansion of salt and subsequent pressurization.

The LKE salt was supplied in the form of solid, cylindrical slugs weighing approximately 1.3 kg each, at a purity of 99.99% anhydrous LiCl/KCl eutectic (LiCl 44 %w/w). The total salt inventory of the system was 115.6 kg or 69.2 L at 415°C.

LKE salt is hygroscopic in nature and readily deliquesces (absorbs moisture from the air and dissolves in it). This concentrated chloride salt solution is highly corrosive to stainless steel and carbon in the presence of oxygen and/or water. Therefore, controlling oxygen and water content was critical during all phases of rig operation. An argon-inerting and -purging blanket was used to prevent air and moisture ingress (resulting in an internal conditions of less than 500 ppm oxygen and 150 ppm water), controlled through a panel of control valves, regulators, relief values, and instrumentation connected to the rig.

Precautions also were taken while adding salt to the rig to maintain an inert atmosphere. Salt slugs were fed into a rig charging vessel V2001 via a sealed carrousel mechanism, designed to drop slug one at a time into the vessel minimizing the moisture entrainment. A total of 84 salt slugs were introduced into V2001 and melted over three batches of approximately 36 kg each. Initially, the vessel temperature was increased in a gradual stepwise manner until enough was known about the behavior of the system; subsequently, larger temperature increments were used to decrease the melting time. After each batch had been melted in the charging vessel, it was allowed to drain under gravity to the main pumping vessel V2002.

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