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Evaluation of Power Fluidic Pumping Technology for Molten Salt Reactor Applications

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Reactor and Nuclear Systems Division

EVALUATION OF POWER FLUIDIC PUMPING TECHNOLOGY FOR MOLTEN SALT REACTOR APPLICATIONS

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June 2020

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ACRONYMS, INITIALISMS, AND ABBREVIATIONS

AC	alternating current
AHTR	Advanced High Temperature Reactor
ARE	Aircraft Reactor Experiment
ATR	Advanced Test Reactor
CFR	Code of Federal Regulations
CSP	concentrating solar power
DFR	Dual Fluid Reactor
DOE	US Department of Energy
DRACS	Direct Reactor Auxiliary Cooling System
EERE	Office of Energy Efficiency and Renewable Energy
EPRI	Electric Power Research Institute
ESBWR	Economic Simplified Boiling Water Reactor
FHR	Fluoride Salt Cooled High Temperature Reactor
FHR-DR	Fluoride Salt Cooled High Temperature Reactor Demonstration Reactor
HFIR	High Flux Isotope Reactor
IAEA	International Atomic Energy Agency
ID	inner diameter
IMSR	Integral Molten Salt Reactor
KP	Kairos Power
LFTR	Liquid Fluoride Thorium Reactor
LWR	light-water reactor
MCFR	Molten Chloride Fast Reactor
MSDR	Molten Salt Demonstration Reactor
MSR	molten salt reactor
MSRE	Molten Salt Reactor Experiment
NPP	nuclear power plant
NVE	NuVision Engineering
O&M	operations and maintenance
ORNL	Oak Ridge National Laboratory
NRC	US Nuclear Regulatory Commission
PB	pebble bed
PF	Power Fluidics™
SmAHTR	Small Modular AHTR
SMSR	Space Molten Salt Reactor
SSR	Stable Salt Reactor
TAMU	Texas A&M University
TAP	Transatomic Power
UC	University of California
UM	University of Michigan
UW	University of Wisconsin
VT	Virginia Tech

ABSTRACT

Power Fluidics™ (PF) is a NuVision Engineering proprietary technology which uses gases to control the flow of other fluids in industrial applications. This unique technology has several advantages over traditional centrifugal pumps. Molten salt nuclear reactors and associated systems have unique fluid handling demands. This report explores the applicability of PF to molten salt systems. Several potential applications are identified, necessary modifications of existing PF technology for salt service are discussed, and a path for development and demonstration is proposed.

1. OVERVIEW OF POWER FLUIDICS™

1.1 TECHNOLOGY DESCRIPTION AND KEY ADVANTAGES/CHARACTERISTICS

Power Fluidics™ (PF) is a NuVision Engineering (NVE) proprietary technology which uses fluids, usually air, to control the flow of other fluids in industrial applications [1]. It is especially suited for pumping and mixing of liquids in hazardous or safety-related applications (e.g., in nuclear process plants or waste tanks) due to its lack of energized components and moving parts. NVE has developed and deployed different configurations of the PF technology in the form of pulse jet mixers (PJMs), pumps, and single point fluid samplers.

Common to the different PF configurations, there are no moving parts like impellers, valves, or bearings that come in contact with the fluid. Furthermore, there are no electrically powered systems or electronics near the process fluid. The gas supply and control system driving the process can be located far away from the process fluid of interest. PF technology is characterized by inherent safety, robustness, low maintenance, high reliability, and long operating life.

A PJM can be used to mix the contents of a tank that may contain solids or liquids of varying viscosities and/or densities. The basic operating process of a PJM is illustrated in Figure 1. Away from the process fluid of interest, a control system supplies pressurized air or another fluid to a pair of jet pumps. The jet pumps are formed by specially engineered nozzles and contain no moving parts. Depending on the location from which air is supplied to the jet pumps, fluid can either be suctioned into or forced out of the pulse tube. During the suction phase, the pressurized air creates suction in the pulse tube through the Venturi effect. The suction draws fluid from the tank into the pulse tube. During the drive phase, the pressurized air forces the contents out of the pulse tube and back into the tank to mix its contents. Finally, during the vent phase, the pressure in the pulse tube is equalized with the vent line. Note that by locating the double jet pumps inside the tank, no vapors or fluids are drawn outside of the tank.

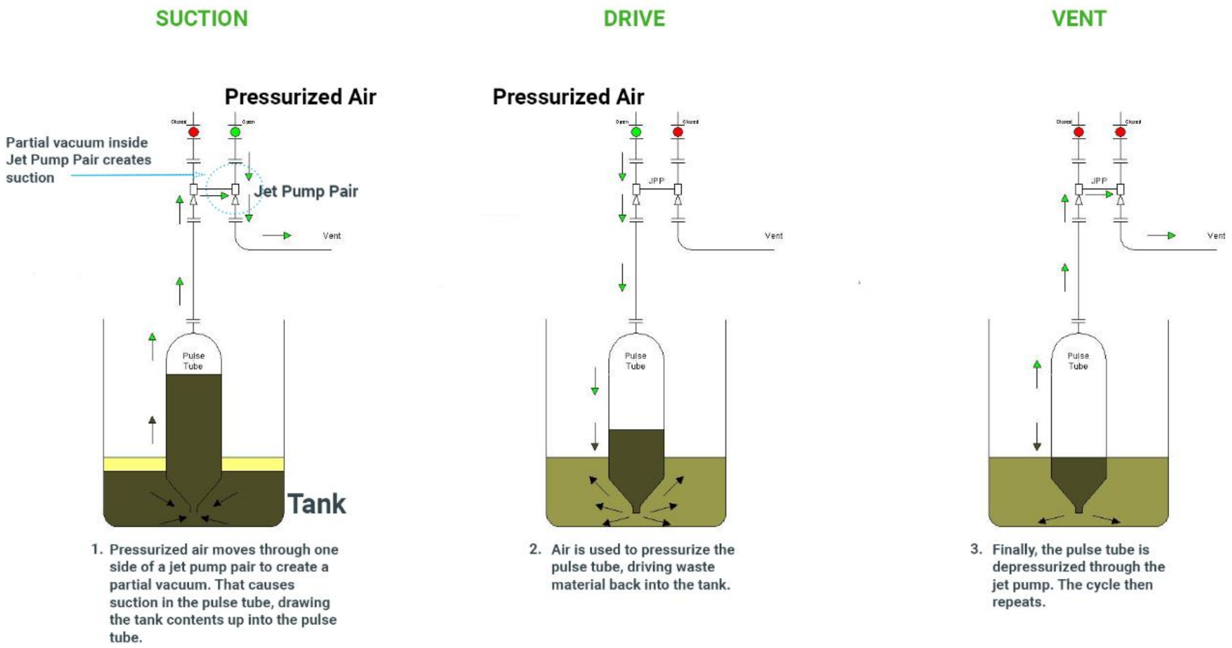

Figure 1. Example arrangement and operation of PF mixer.

Two different PF configurations have been developed for pumping fluids. The diode pump uses two vortex diodes connected to a charge vessel. A vortex diode is formed by a cylindrical vessel with a tangential nozzle and an axial nozzle, as shown in Figure 2. The pressure drop of fluid entering and leaving through the two nozzles differs depending on the direction of flow. If fluid enters the tangential nozzle, then a swirling flow or vortex is formed in the cylindrical section, which causes pressure losses. If fluid enters through the axial nozzle, then a vortex is not formed, and the fluid experiences less pressure loss.

Figure 2. Illustration of a vortex diode and the different flow paths depending on flow direction [2].

The diode pump uses two vortex diodes, a charge vessel, and a gas supply system, as illustrated in Figure 3. The two vortex diodes form what is effectively a leaky check valve. During the suction phase, the process fluid is drawn into the charge vessel, preferentially through the bottom “fill” vortex diode, as it is oriented to have a lower resistance to flow than the other vortex diode. During the drive phase, the charge vessel is pressurized, and its contents are discharged. The discharged flow preferentially passes through the other vortex diode, as the fill diode is oriented to have a higher flow resistance. The suction–drive cycle can then be repeated.

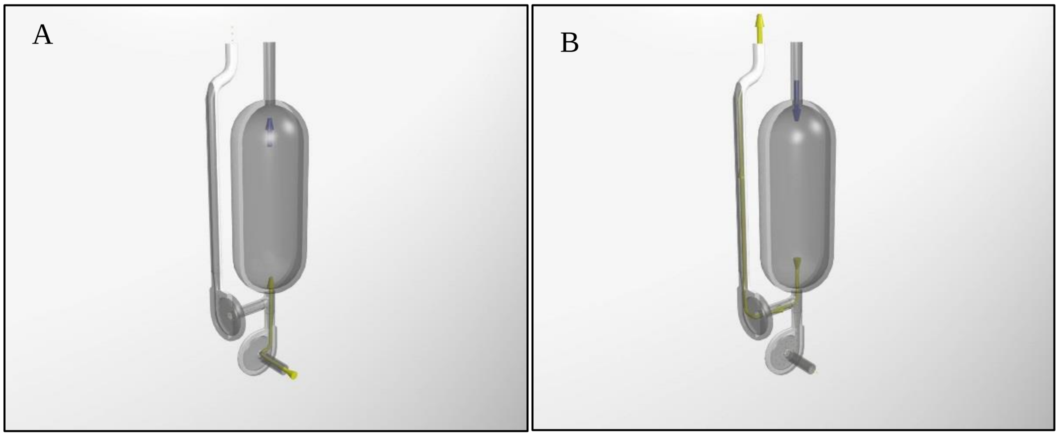

Figure 3. Diode pump during suction phase (A) and drive phase (B) [3].

A reverse flow diverter (RFD) pump includes a charge vessel and an eductor, as illustrated in Figure 4. During the suction phase, fluid is drawn into the charge vessel through the fill line that is either connected to or immersed into the process fluid (see the pipe illustrated in the bottom left of the figure). During the drive phase, the charge vessel is pressurized, and its contents are discharged. During discharge, the specially designed eductor results in high velocity flow across the fill line. Through the Venturi effect, the high velocity flow entrains additional fluid into the discharge line. The suction–drive cycle can then be repeated.

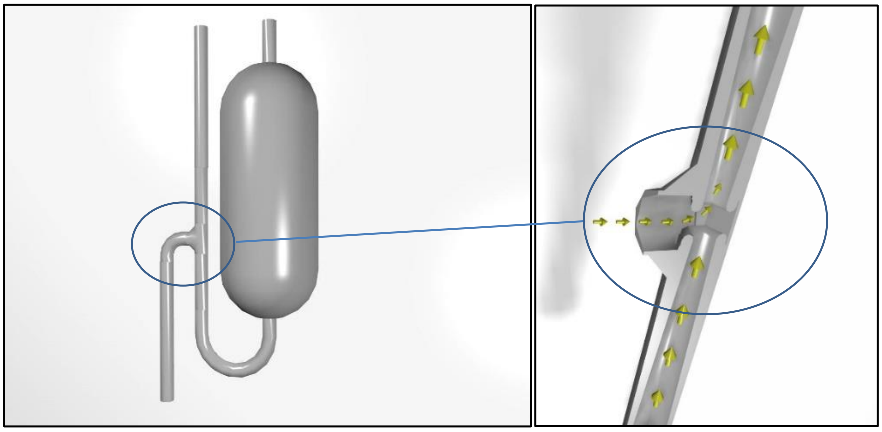

Figure 4. RFD pump and eductor [4].

For both the diode pump and the RFD pump, a single operating unit can provide a pulsating flow. However, two or more units can be grouped together in a staggered configuration to provide a near-continuous flow that is similar to the way three-phase alternate current (AC) power provides a voltage with a relatively small ripple.

A fluidic single point sampler can be incorporated into the described PF technology. Through the pressure differentials developed during the suction and drive cycles, a sample of the process fluid can be passively drawn into a separate reservoir.

1.2 CURRENT APPLICATIONS

Starting in 1996, an early application of the PF technology was used at the Oak Ridge Bethel Valley Evaporator Storage Tanks location to mix waste in large tanks. Over the following years, NuVision continued to successfully design, build, deploy, and operate PF systems for projects in the United States and worldwide. PF technology is used in US nuclear industries such as Hanford, in the United Kingdom at Sellafield, and also in Japan and China. PF systems have been widely adopted for use in waste tanks containing high viscosity or high solids wastes, as well as with aggressive chemical environments and high radiation fields.

2. MOLTEN SALT REACTOR APPLICATIONS OF POWER FLUIDICS™

2.1 MOLTEN SALT REACTOR BACKGROUND

Molten salt reactors (MSRs) are nuclear reactors that use molten halide salts in their primary systems. There are two subsets of MSRs: concepts which use a solid fuel with a molten salt coolant, and liquid-fueled concepts in which the fissile material forms part of the molten salt. MSR designs include secondary salt circuit(s) to transport the heat generated in the reactor to a power cycle or another tertiary system. There are many potential configurations, including reactors that use chloride- or fluoride-based salts and reactors that operate under fast, thermal, or epithermal spectra.

Historically, MSRs were developed and demonstrated at Oak Ridge National Laboratory (ORNL) during the 1950s through the mid-1970s. Today, several MSR developers are advancing their unique MSR designs towards commercialization. Section 2.1.1 summarizes some of these reactor concepts. Other MSR concepts are under early phase development. The International Atomic Energy Agency (IAEA) maintains a database of MSR concepts that is anticipated to be updated in 2020 [1]. While pumps are included in the primary and secondary systems, several other systems, processes, and diagnostics involve moving salts from one location to another. Section 2.3 summarizes several of these other MSR-related fluid handling needs.

2.1.1 Overview of MSR Concepts Under Commercial Development

This section provides a brief summary of some of the MSR concepts under commercial development to illustrate the diverse range of concepts being pursued. It is important to note that this list is not exhaustive, and ORNL does not endorse any one concept over another. Finally, as these concepts are under development, their designs may alter from that described herein.

The Kairos Power (KP) Fluoride Salt Cooled High Temperature Reactor (FHR) is being developed by Kairos Power, LLC [20]. It will have a power level of approximately 320 MWth using solid ceramic fuel pebbles cooled by $2LiF\text{-}BeF_2$ (FliBe) salt. The primary system is described as consisting of two pumps which transfer heat through heat exchangers to an intermediate loop which utilizes nitrate salt. The pumped intermediate loop transfers heat to a steam power conversion system.

Three fast-spectrum reactors using chloride salts are under development. The Molten Chloride Fast Reactor (MCFR) is being developed by TerraPower, LLC [6]. The Molten Chloride Salt Fast Reactor (MCSFR) is being developed by Elysium Industries Ltd. / Elysium Industries USA [8]. Their reactor is described as having a flexible thermal capacity of 110–2,700 MWth and producing 50–1,200 Mwe. Based on a 2018 report, different systems configurations using 1–6 primary pumps, are used to accommodate the range of power options. For the commercial design, the core inlet temperature is 600°C, and the core outlet temperature is 750°C, and $NaCl\text{-}XCl_2\text{-}UCl_{3/4}\text{-}PuCl_3\text{-}FPCl_y$ salt is used on the primary side [9]. In recent renderings, their primary system may also include 8 pumps, with a total of 4 pumps on the secondary side. The Dual Fluid Reactor (DFR) is under development by IFK Berlin. The core consists of a fueled chloride salt and a separate lead heat transfer loop [10].

Moltex Energy has two unique MSR designs for which the molten salt fuel is static inside fuel tubes (i.e., not pumped through a circuit), and a separate non-fueled molten salt is used as a coolant. The Stable Salt Reactor from Wasteburner (SSR-W) is a fast reactor that uses a fluoride salt coolant and is sized at 750 MWth. The SSR – Thermal Spectrum reactor (SSR-U/Th) uses fluoride salt in primary and secondary loop(s) and solar salt (i.e. a nitrate based salt) in a tertiary loop [9]. Other tube type reactors include designs by (1) Seaborg Technologies, which employ an NaOH moderator, (2) Copenhagen Atomics, which employs a heavy water moderator tank, and (3) the fast-spectrum dual-fluid reactor by the German Institute for Solid State Physics, which employs fuel salt in tubes cooled by liquid lead. While the reactor physics of these systems appear favorable in some respects, substantial materials science and chemistry hurdles remain to be addressed.

A few fluoride salt–fueled reactors are also under development. Seaborg Technologies is developing the Compact Molten Salt Reactor (CMSR) [40]. The Integral Molten Salt Reactor (IMSR) is being developed by Terrestrial Energy and commercialized in the United States by Terrestrial Energy USA. Based on a 2018 summary, the fluoride salt–fueled reactor is sized to produce approximately 400 MWth of energy [9]. Six pumps circulate the fueled salt in the primary system. The heat is transferred to a fluoride salt secondary system and then to a tertiary solar salt system. The ThorCon MSR, developed by ThorCon US Inc., is a fluoride salt–fueled reactor that is to produce 557 MWth. The primary loop (fueled fluoride salt), secondary loop (fluoride salt), and tertiary loop (solar salt) each contain one pump. Detailed information on their system is provided on their website [11]. The Liquid Fluoride Thorium Reactor (LFTR) being developed by FliBe Energy, Inc. is described in a 2015 Electric Power Research Institute (EPRI) report. [7] The reactor generates 600 MWth and uses a fuel diluted into $LiF\text{-}BeF_2$ salt. A secondary loop contains non-fueled FLiBe and transfers heat to a power cycle. The primary and secondary loops use one pump each. Finally, Copenhagen Atomics recently announced development of a heavy water–moderated MSR which uses a $LiF\text{-}ThF_4$ fuel salt [12].

2.1.2 Other MSR Concepts

Numerous MSR concepts have been developed to various degrees by national laboratories, universities, or other research and development entities. While these concepts are not being pursued for commercial deployment, open publications provide insight into some general characteristics and the pumping requirements of potential commercial MSRs. The following section briefly summarizes the designs and pumping requirements.

A few FHR concepts have been developed at ORNL in recent years, including the Advanced High Temperature Reactor (AHTR) [13], the Small Modular AHTR (SmAHTR) [14], and the FHR Demonstration Reactor (FHR-DR) [15]. The AHTR is a large 3,400 MWth salt-cooled reactor concept, while SmAHTR is a small 125 MWth modular concept. The 100 MWth FHR Demonstration Reactor preconceptual design was developed for consideration as a demonstration plant to provide irradiation testing capabilities and to advance MSR technology. Another FHR concept, the Mark 1 Pebble Bed FHR (Mk1 PB-FHR), was developed by University of California (UC) Berkley [16]. The 236 MWth reactor is fueled by solid pebbles and is cooled by FLiBe salt.

The Molten Salt Reactor Experiment (MSRE) was a 7.3 MWth MSR operated at ORNL from 1965–69 [17]. The reactor employed a $^7LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4$ (65.0-29.1-5.0-0.9 mole%) fuel salt and a $^7LiF\text{-}BeF_2$ (66-34 mole%) coolant salt. Both the fuel salt loop and the coolant salt loop used a cantilever style vertical shaft centrifugal pump. The primary pump operated at a speed of 1,160 rpm to deliver 75 l/s (1,200 gpm) at a discharge head of 14.9 m (49 ft). The coolant salt pump operated at 1,750 rpm to produce a flow of 53.6 l/s (850 gpm) at a head of 22.9 m (75 ft) [18].

The Molten Salt Demonstration Reactor (MSDR) concept was intended to be one of the successor reactors to the MSRE, scaling up the technology towards large commercial size (750 MWth/350 MWe) while incorporating lessons learned [19]. The MSDR was designed to employ a mixed fuel salt containing lithium, beryllium, thorium, and uranium fluoride, as well as a lithium beryllium fluoride coolant salt, and a eutectic mixture of nitrite and nitrate tertiary coolant salt ($KNO_3\text{-}NaNO_2\text{-}NaNO_3$) to transfer the thermal energy to a steam cycle. The primary purpose for the third salt was to capture the tritium generated in the fuel salt and diffused through the heat exchanger tubing. The design featured three fuel salt loops each with a 511 l/s (8,100 gpm) pump which would develop a 45.7 m (150 ft) head.

The Transatomic Power MSR (TAP MSR) was developed by the Transatomic Power Corporation with the goal of commercialization. However, development efforts have been suspended. The reactor was designed to use fuel diluted into a LiF salt with a core outlet temperature of 650°C. The secondary side was to use FLiNaK to transport heat to a steam power cycle. The reactor was designed for grid-scale power production, sized at 1,250 MWth and 500 MWe. Details of the primary and secondary flow paths and pumping requirements are not covered in the most recent design white paper [22].

As an example of a chloride salt MSR, the Fused Salt Fast Breeder reactor concept was developed by a student team from the Oak Ridge School of Reactor Technology in 1956 [23]. The 700 MWth reactor would be fueled by plutonium with a mixture of sodium and magnesium chloride as a fuel diluent. The primary side would use a single large pump, with a fluid temperature of 1,050°F at the pump. The breeder blanket and secondary sides would both consist of liquid sodium metal. The secondary sodium loop transports heat to a steam power cycle.

2.1.3 Summary of MSR Concept Fuel/Coolant Circuit Pumping Needs

The estimated pump requirements for the commercial and noncommercial concepts discussed in Sections 2.1.1 and 2.1.2 are summarized in Table 1 and Table 2. It should be stressed that these tables only include public information, and many of the reactor designs are under continual refinement. The tables are to provide insight into the potential range of pumping needs for MSRs. Also, note that hydraulic pump power does not account for efficiency or design margin.

Table 1. Summary of pumping needs for MSR concepts pursued commercially

Reactor type	Reactor concept	Power (MWth/MWe)	Circuit	Fluid	Number of pumps	Flow rate (per pump)		Head (m)	Temp. fluid at pump (°C)	Hydraulic pump power (kW)
						kg/s	m^3/s			
Salt cooled	KP-FHR	320/140	Primary	LiF-BeF$_2$	2	600–700	0.33	ND	650	ND
			Secondary	Solar nitrate salt	ND	ND	ND	ND	ND	ND
Salt fueled	ThorCon	557/258	Primary	NaF-BeF$_2$-ThF$_4$-UF$_4$	1	2,955	1.34	46	704	1,324
			Secondary	NaF-BeF$_2$	1	1,534	0.77	132	454	1,979
			Tertiary	Solar salt	1	1,633	0.97	65	570	1,037
	LFTR	600/270	Primary	LiF-BeF$_2$+U	1	1,700	0.871	49	653	823
			Secondary	LiF-BeF$_2$	1	1,629	0.842	55	633	876
	IMSR	400/194–202	Primary	Fluoride fuel salt	6	900	0.27	ND	670–700	ND
			Secondary	Fluoride coolant salt	ND	ND	ND	ND	ND	ND
			Tertiary	Solar salt	ND	ND	ND	ND	ND	ND

ND: Not determined or not disclosed
1 m^3/s = 15,852 US gpm
**Reactor concepts by Moltex, Terrapower, Elysium, Copenhagen Atomics, Seaborg Technologies, and IFK Berlin were not included in the table due to the limited identified public information on their pumping requirements.*

Table 2. Summary of pumping needs for other MSR concepts.

Reactor type	Reactor concept	Power (MWth/MWe)	Circuit	Fluid	Number of pumps	Flow rate (per pump)		Head (m)	Temp. fluid at pump (°C)	Hydraulic pump power (kW)
						kg/s	m^3/s			
Salt cooled	FHR-DR	100/NA	Primary	LiF-BeF$_2$	2	500	0.26	25	660	120
			Secondary	LiF-NaF-KF	2	500	ND	ND	ND	ND
	SmAHTR	125/50	Primary	LiF-BeF$_2$	3	350	0.18	2	700	5
			Secondary	LiF-NaF-KF	3	247	0.12	3	600	8
	Mk1 PB-FHR	236/100	Primary	LiF-BeF$_2$	2	488	0.27	15	700	80
	AHTR	3400/1530	Primary (opt. 1)	LiF-BeF$_2$	3	9,500	4.84	5	650	437
			Secondary (opt. 1)	KF-ZrF$_4$ or LiF-NaF-KF	3	14,400	6.88	62	600	8,706
			Primary (opt. 2)	LiF-BeF$_2$	3	9,500	4.84	50	650	4,653
			Secondary (opt. 2)	KF-ZrF$_4$ or LiF-NaF-KF	3	14,400	6.88	3	600	482
Salt fueled	MSRE	7.5/NA	Primary	LiF-BeF$_2$+ZrF$_4$+UF$_4$	1	170	0.079	23	662	39
			Secondary	LiF-BeF$_2$	1	105	0.054	24	650	25
	MSDR	750/350	Primary	LiF-BeF$_2$-ThF$_4$-UF$_4$	3	1,663	0.50	46	677	745
			Secondary	LiF-BeF$_2$	3	932	0.47	69	593	629
			Tertiary	KNO$_3$-NaNO$_2$-NaNO$_3$	3	958	0.57	77	538	727
	TAP MSR	1250/550	Primary	LiF-(actinide)F$_4$	ND, 4*[1]	ND	ND	ND	<625	ND
			Secondary	LiF-NaF-KF	ND, 2*[1]	ND	ND	ND	<625	ND
	Fused Salt Fast Breeder	700/260	Primary	NaCl-MgCl$_2$-PuCl$_3$-UCl$_3$	1	4,338	1.74	43	566	1,815
			Blanket	Na	1	983	1.18	44	482	424
			Secondary	Na	4	1,498	1.80	20	482	291

ND: Not determined or not disclosed; NA: Not applicable
*1: based on image in report
1 m^3/s = 15,852 US gpm

2.2 GENERIC ADVANTAGES OF POWER FLUIDICS FOR MOLTEN SALT REACTORS

Before discussing potential MSR applications, it is instructive to highlight several advantages of PF:

1. There are no electrical equipment or electronics (e.g., pump motor, solenoids, instrumentation) required near a high-temperature and potentially high-radiation environment. The removal of these electrical components enhances reliability (e.g., no breakdown of insulating materials), avoids the potential for sparking or ignition in combustible environments, reduces the need for rad-hardened electronics, and ultimately reduces operations and maintenance (O&M) costs.
2. There are no salt-wetted moving parts like impellers, bearings, or valves. This reduces O&M and enhances reliability.
3. By design, the PF system includes intrinsic metering of fluid flow. This provides a redundant (or perhaps the only necessary) measurement of flow rates and assists in mass accountancy.

2.3 POTENTIAL USES OF FLUIDIC TECHNOLOGY

2.3.1 Primary and Secondary Side

While technically feasible, the use of PF for the MSR’s primary or secondary circuits requires further study to determine its practical implementation and tradeoffs compared to traditional pumps. The following section discusses some of the factors to be considered.

As summarized in Section 2.1, the MSR concepts being pursued cover a range of potential salt pumping requirements. These are generally large capacity (i.e., 4,000–22,000 gpm with 1,100–2,700 hp hydraulic power). At these sizes, pumping power demands and efficiency are important factors. Using large quantities of compressed gases and the lower intrinsic hydraulic efficiency of PF, the reduced efficiency and higher power demands of a PF-driven system must be assessed against more traditional pump options.

As explained in Section 4, inert gases are required for molten salt applications. The large flows of salt in the primary or secondary side would require significant volumes of compressed gases that would likely need to be recycled—recaptured and compressed. An overall advantage of MSRs is that they are low-pressure systems. Implementation of PF may require features for off-normal events to isolate the compressed gas from systems designed for low pressures.

In contrast to a pulsating flow from one PF system, multiple PF systems could be combined to provide a steady flow. Like a pump trip occurrence, the impact of losing one or more of the PF systems would require evaluation. The potential for time-varying flow and its impact on MSR design-specific dynamics would require investigation.

As noted in Section 2.2, a PF system has several advantages. The intrinsic metering of the flow may negate the need for another flowmeter, or it may provide a redundant measurement. With no moving parts in a high-radiation field and high-temperature salt, a PF system could have higher reliability, longer service life, and significantly easier maintenance compared to a traditional pump.

2.3.2 On-line Fuel Salt Sampling

MSRs will need to allow for taking fuel salt samples for multiple purposes:

1. to ensure that the salt’s chemical and physical properties remain within acceptance limits,
2. to validate and allow for planning future fuel and chemistry adjustment additions,
3. to provide confirmatory information for fissile material accountability, and

4. to assess the extent of salt-wetted structural material corrosion as expressed through changes in salt chromium content.

Fuel salt sampling at MSRs has substantial technical challenges. The reactor environment is both extremely radioactive and thermally hot. Moreover, during operation, the fuel salt will be flowing rapidly, requiring mechanically robust components. Conventional hydraulic components such as valves and flanges are not available for fuel salt. While the MSRE sampler–enricher's operation was adequate [26], some samples appear to have been contaminated in the handling operations, perhaps from deposits on the transfer tube. Use of a bypass line would likely provide more representative samples.

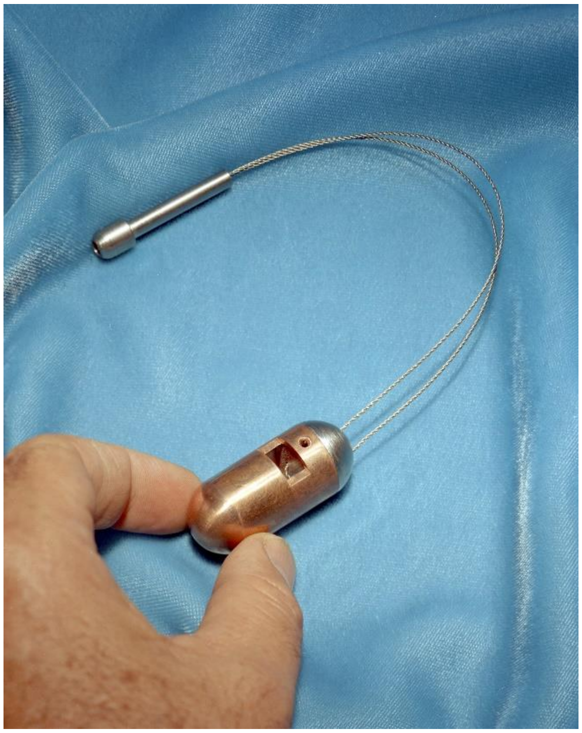

Figure 5. MSRE sampler capsule [27].

The MSRE fuel salt sampler design was based on a capsule with holes near its top at the distal end of a cable (see Figure 5) [28]. The MSRE's fuel salt sampling system obtained samples that were ~10 g each. The sample size was in large part dictated by the diameter of the sampler-enricher tubing. Smaller samples would likely be preferred in future reactors to minimize shielding requirements and waste generation. The MSRE sampler-enricher cable was required to penetrate through shielding and sealing boundaries, which proved to be problematic. Developing improved salt sampling devices and approaches was highlighted in the MSRE critique performed by its staff shortly after final shutdown [29].

> *In a manner of speaking the sampler-enricher was more difficult to operate than the reactor. The reactor itself was very forgiving of mistakes and would accept an operator error with no adverse effects. The sampler, however, was very unforgiving. Many times it would respond adversely even with the best of attention and care. The sampler-enricher was, by necessity, a complex combination of mechanisms.*
>
> *Problems associated with the operation of the sampler-enricher caused more delay in the MSRE test program than did any other component. Considering the basic difficulty of its task, it performed rather well, but its operation was always rather ticklish. This was to*

> *some extent unavoidable, but every effort should be made to develop reactor equipment that is robust and if not "foolproof" is as simple to learn to operate as possible.*

Another fuel salt sampling approach was demonstrated earlier in the molten-salt breeder reactor (MSBR) program [30]. The earlier design was based on a small side tube that was welded onto a fuel salt loop with a port at the sampling tube's proximal end. The system relied upon inserting a sample chamber into the side tube through the sample port. The sample chamber was itself a smaller tube with a metal frit at its distal end. The system functioned by drawing fuel salt through the metal frit into the sample chamber, withdrawing the sample chamber through the port, and relying on the salt's surface tension and viscosity to prevent leaking from the bottom of the sample chamber before freezing. The frit type design prevents assessment of the particulate build-up in the salt, is vulnerable to fouling, and requires relatively complex mechanical manipulation in the high radiation environment.

2.3.3 Fuel Salt Additions or Removal

MSRs need the capability to allow the addition of fuel salt to the reactor to compensate for burn-up. For reactors with conversion ratios above 1, bred fuel salt would instead be removed and replaced by fertile salt as needed. Fuel may be added to the reactor as a concentrate to minimize dilution of salt already in the reactor. The carrier salt is not consumed during the fission process, so it does not need to be replenished. At MSRE, the uranium tetrafluoride concentration in the fuel salt was nominally 0.9 mole%, whereas the fuel concentrate contained 27 mole% uranium tetrafluoride [52]. While the melting point of the MSRE fuel salt concentrate was slightly less than 500°C and could have been added as a liquid, it was instead added as a solid that was placed into a capsule and mechanically lowered into the pump bowl, where it was dissolved into the remainder of the fuel salt.

Fluidic technology could be used as a high reliability metering pump to add or remove precise amounts of fuel to operating MSRs as needed to compensate for burnup or power level shifts. In the Aircraft Reactor Experiment (ARE), the fuel salt ^{235}U concentration was increased 8.8% over the course of operations—from 0.383 g/cc to 0.416 g/cc—as operational power was increased [53], demonstrating the potential to alter fuel loading to provide power level shifts.

The ability to provide precise amounts of additional fissile material on demand distinguishes fluidic pumping technology from alternate methods. Pressure-driven fluid transfer is imprecise, whereas solid fuel additions must be batched to the required size, and they also require a mechanical structure to be placed in the salt to hold the new fuel as it dissolves. Precise addition of liquid fuel salt allows the material to be added to any part of the circuit.

The amount of fuel salt required depends on the reactor power. The new salt must balance the amount of fissile material consumed or produced in the reactor. A large commercial plant (2,500 MWth) would consume ~2.7 kg of fissile material per day of operation, or a few liters of salt. In contrast, a small test reactor would only require a few cubic centimeters of fuel salt each day of operation.

2.3.4 Fuel Salt Separations

MSRs will accumulate fission products in their fuel salt as power is produced. Fission products have primarily thermal neutron absorption cross sections. Consequently, MSRs that rely upon a thermal-spectrum thorium-uranium breeding cycle will require that fission products be separated from the fuel salt to minimize parasitic neutron absorption. To achieve a net breeding gain, thermal spectrum Th-U molten-salt breeder reactors also need to separate out ^{233}Pa to allow it to decay in a low neutron flux environment [45].

The need to separate ^{233}Pa has the potential to result in a proliferation vulnerability for this fuel cycle. The issue was summarized by MSBR design team members in 1978 as follows [46]:

> *… little or no thought has been given to alternative uses of nuclear fuels such as proliferation of nuclear explosives. As a consequence, the conceptual designs that evolved (e.g., the ORNL reference design MSBR) all favored enriched ^{233}U as fuel with an on-site chemical processing facility from which portions of that fuel could be diverted fairly easily*.

The technology planned for removing protactinium, fission product, and corrosion product at the MSBR was reductive extraction. This would be accomplished through contacting a side stream of the fuel salt with lithium-spiked liquid bismuth [47]. The fuel processing system would be an integral part of the system and would be operated continuously. A flow diagram of the fluorination–reductive extraction–metal transfer process is shown in Figure 6.

The MSBR salt treatment system [48] concept consisted of two parts: (1) removal of uranium and protactinium from salt, leaving the reactor and reintroduction of uranium into salt returning to the reactor, and (2) removal of the lanthanide fission products from the salt. A ~3.3 l/min side stream of fuel salt was planned to be extracted from the reactor and would be allowed to decay for 30 minutes. Following this, ~95% of the uranium would be stripped from the salt via fluorination. The salt would then be contacted with liquid bismuth containing lithium reductant to remove the ^{233}Pa and residual uranium. Then the remaining lanthanide containing salt would be contacted again with bismuth-lithium, transferring most of the rare earths to the bismuth. The lanthanide-loaded bismuth would then be stripped of the contaminants through contact with lithium chloride. Finally, the lanthanides would be stripped from the lithium chloride through contact it with bismuth containing high concentrations of lithium.

Technology development for the liquid-liquid contacting processes continued throughout the MSBR program [49]. The preferred contactor technology at the conclusion of the program was mechanically rotating, non-dispersing contactors [50]. Non-dispersing contactors are important for the fuel salt–to–bismuth transfer process because nickel is soluble in bismuth. Carryover of the bismuth phase back to the fuel salt could thus substantially corrode the fuel salt circuit’s structural material. Most of the salt and bismuth transfers in the separation system were envisioned to be performed by pressure-driven flows. However, having an effective pumping technology available would significantly simplify the system’s implementation.

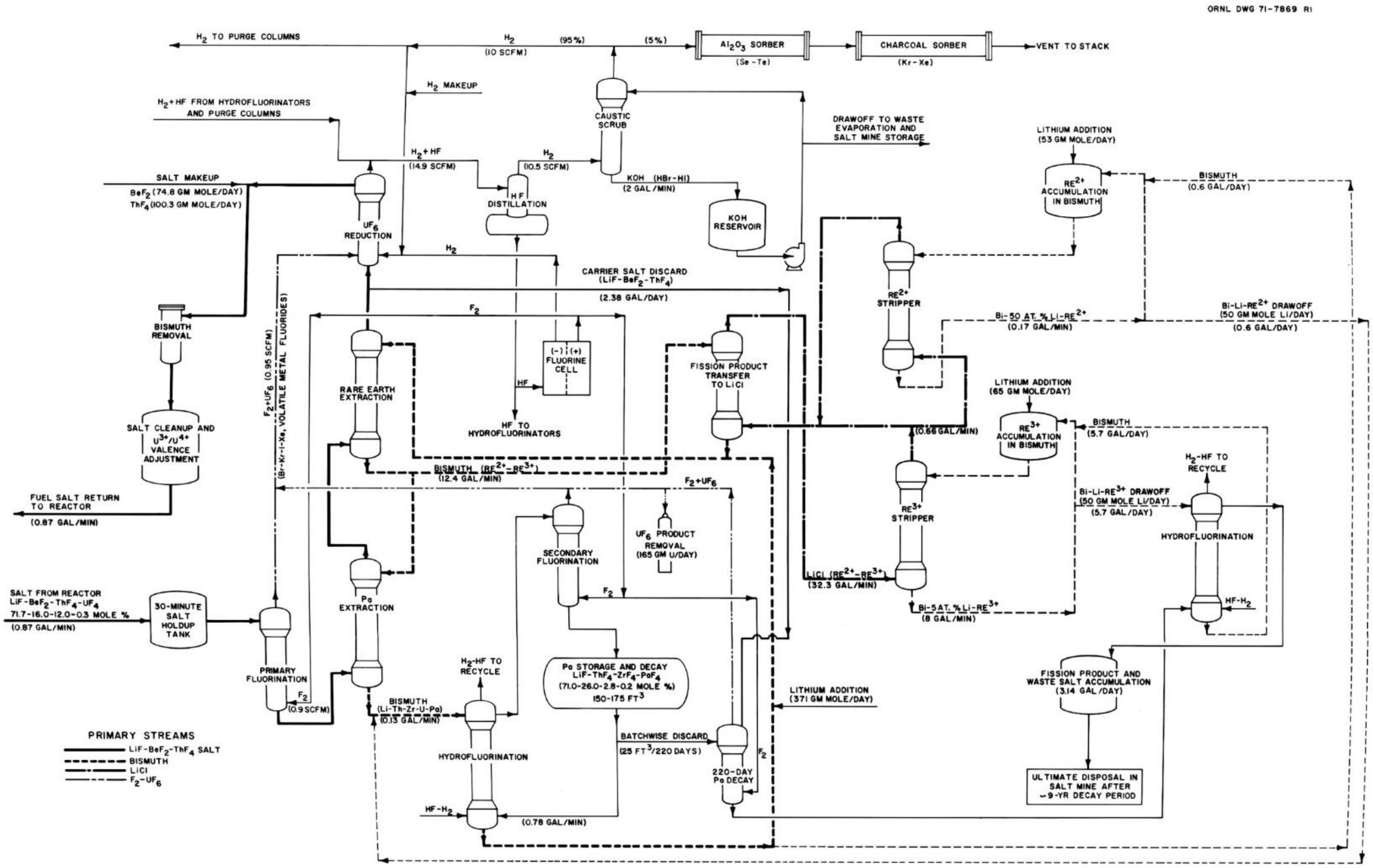

Figure 6. Continuous salt processing system flowsheet for single-fluid MSBR by fluorination, reductive extraction, and metal transfer [51].

Few materials are compatible with both liquid bismuth and halide salts at high temperatures. Consequently, corrosion of the fuel salt processing system was an ongoing concern. Refractory alloys and graphite were the only materials identified as adequately compatible. Fluidic pulse-jet mixers fabricated from a refractory alloy could be the preferred technology for the liquid-liquid contactors, as they eliminate the moving parts and allow precise control of the contacting process, minimizing the potential for bismuth carryover into the returning fuel salt. High-temperature liquid bismuth would rapidly dissolve any nickel-based structural alloy.

Diversion of fissile materials would require reconfiguring the fuel salt flow path, which would require mechanical access to the salt stream. Increasing the reliability of the components within the fuel salt processing system decreases the frequency of the need for maintenance access and thus the opportunities to install a diversion capability. Fluidic technology, with its lack of moving parts and high reliability, offers the possibility of maintenance-free, plant lifetime components. Some fuel and nuclear waste processing cells are already designed as not maintainable or repairable. Cells within Japan's Rokkasho-mura nuclear fuel processing plant and parts of the Hanford vitrification facility are intended to be abandoned and grouted in if their interior components fail. Fluidic technology could be a key element of the necessary technology suite for Th/U fuel cycle MSRs to follow a similar strategy, thereby improving safeguardability and proliferation resistance.

Fuel salt processing could be contained within a sealed, steel/reinforced concrete structure located near the reactor vessel. A sealed, reinforced concrete barrier would substantially increase the time needed, the difficulty, and probability of detecting any attempted diversion of fissile material. The fuel salt processing envisioned for the MSBR involved fluorination, hydrofluorination, and reductive extraction. All of these processes would need to be performed within a permanently inaccessible cell to avoid the potential for creating a separated stream of fissile material. Only reactor-grade fissile material mixed into the fuel salt would enter or leave the cell. The fissile content of the mixed fuel salt would be analogous to used solid light-water reactor (LWR) fuel containing reactor-grade plutonium mixed into the remainder of the highly radioactive fuel. If full plant lifetime components cannot be developed, then it may be possible to replace the entire inaccessible fuel processing block structure as a major maintenance activity.

2.3.5 Waste Form Preparation

MSRs have several potential possible fuel salts and cycles. Many of the details of the fuel salt waste stream depend on the specific design elements. Liquid halide salts do not accumulate radiation damage in use, so fuel salt does not have a burn-up limit. The lifetime limit of the salt derives instead from the accumulation of undesirable materials (corrosion products, contaminants, and fission products). For fast-spectrum fluoride salt designs, one key lifetime limit would be the gradual buildup of lanthanide fission products, which compete for solubility with the actinide fuel. Unless the lanthanides are stripped from the fuel salt, it will become waste once insufficient amounts of fissionable materials can be dissolved. Limited actinide solubility can be less of a concern for thermal spectrum reactors because their fissile material requirements are nearly an order of magnitude lower than that of other reactors. However, thermal spectrum reactors can also be designed to operate with smaller amounts of more concentrated fuel salt, the fuel salt of which would also be lifetime limited according to the actinide solubility. Chloride salts can also reach the end of their useful life if they accumulate a dissolved material burden that approaches a chemical phase separation and their salt melting point increases beyond acceptable limits, or if their salt viscosity rises beyond the point at which natural circulation passive decay heat removal would provide adequate heat removal under accident conditions.

Fluidic pumping and mixing would be a useful means for transferring the used fuel into and within the used fuel processing facility due, as there are no moving parts, and there is no requirement to pressurize the used fuel salt source container. Systems with moving parts are inevitably more complex and tend to be less reliable. While it is possible that pressurizing the fuel salt container to transfer the salt would result in a rupture, the threat to radionuclide containment would remain small: a containment rupture would be a significant accident. A pinhole type leak in the heat exchanger tubing would be more likely to occur and would also result in the spread of contamination. Consequently, a fuel salt transfer mechanism that avoids pressurization-related accident potential is preferred.

2.3.6 Passive DRACS Augmentation with Stored Pressure

MSRs will rely upon natural circulation cooling to provide decay heat rejection during events in which forced cooling has failed. MSRs have a number of potential natural circulation design options. A significant fraction of the proposed designs employs natural circulation of a clean salt loop to transfer the decay heat to the environment. Initial enhancement of natural circulation flow would be significantly useful. One option for enhancing the natural circulation cooling flow during loss of power events would be to use stored energy to temporarily drive a pump on the cooling loop. Pumping would reduce the required size of the cooling system compared to other designs. Using stored energy to drive pumping would minimize the potential for overcooling the fuel salt if the amount of stored energy is size to be exhausted as decay heat production declines. Also, some natural circulation decay heat removal system designs may be nearly stagnant during normal operations and would consequently require some time to start up. Decay heat production is at its maximum immediately following shutdown, so the peak fuel salt temperature excursion can be minimized by providing enhanced decay heat rejection at the beginning of the loss of forced flow event. The ability to provide rapid-start decay heat rejection that declines over time would be particularly useful for high power density MSRs for which a time lag in starting decay heat rejection could result in a larger thermal excursion.

Fluidic pumps are well suited to augment natural circulation flow due to their reduced flow obstruction when not operating. A key design challenge in natural circulation augmentation is to minimize the potential for an increase in pressure drop along the loop, such as would be produced by a mechanical pump failure caused by a stuck impeller. Using stored pressure to provide motive energy for nuclear power plant safety systems is an established practice; for example, nitrogen accumulators are used to drive in shutdown rods in GE-Hitachi's Economic Simplified Boiling Water Reactor (ESBWR) [31].

2.3.7 Spill Cleanup Vacuuming – Post-Accident Cleanup

A key technology necessary for effective MSR operations is the capability to clean up both large- and small-scale fuel salt spills. Confining the fuel salt radionuclides behind multiple barriers is an essential safety requirement for MSRs. Spilling fuel salt would decrease the number of barriers to environmental release, with severity ranging from a technical specification violation to a design basis accident. Large fuel salt leaks would remain liquid for a substantial period of time due to their substantial decay heat production. Smaller leaks would rapidly solidify due to thermal contact with structures such as the floor. Solidified halide salts tend to be mechanically robust and can adhere to structures, making it more difficult to mechanically remove the solid salt. Any leaked or spilled fuel salt would require clean-up before the plant could be restarted.

Very small spills would likely be cleaned up by a combination of scraping and vacuuming. Spills on irregular surfaces and/or spills that are mechanically adherent would be more challenging to scrape off. Re-melting the salt and vacuuming up the liquid would be a useful technique to clean up these spills. Traditional vacuum systems require electric motors and fan blades in the flow path, and fluidic based pumping systems have the advantage of not requiring motors or moving parts that are extremely hardened to radiation. Maintaining support systems in an MSR containment would be difficult and expensive, so there is incentive to use components that are as robust as possible. A fluidic pumping system would need to be integrated with a local heating system to remove solidified materials.

2.3.8 Pumps for Molten Salt Irradiation Test Loops

In the near term, fluidic pumping could be used in support of MSRs in small pumps for in-pile forced convection fuel salt test loops. Fluidic pumps could also support out-of-pile test loops (see Section 3.1). However, the robust nature of fluidic technology makes it particularly useful for in-pile systems, and technology developed to support in-pile loops would also be applicable ex-pile. In-pile fuel salt test loops have multiple purposes, including instrumentation demonstration, radionuclide release and deposition demonstration, structural materials testing, salt handling component and technology demonstration, and salt property evolution demonstration.

The United States has operated a number of in-pile forced convection fluoride fuel salt test loops during the 1950s and 1960s [54, 55, 56] and an example is shown in Figure 7. Equivalent loops for chloride fuel salt have never been built or deployed, and prospective reactor vendors have indicated that they are currently developing chloride salt fast-spectrum MSRs. It is technically advantageous for fuel salt pumps in test loops to be as close as possible to the reactor core (1) to minimize the *dilution ratio* (ratio of fuel not undergoing irradiation to fuel in the core), (2) to decrease the total amount of expensive fuel salt required and high-level waste produced, and (3) to avoid the difficulty of cumbersome, long, heat-traced salt lines in a reactor pool.

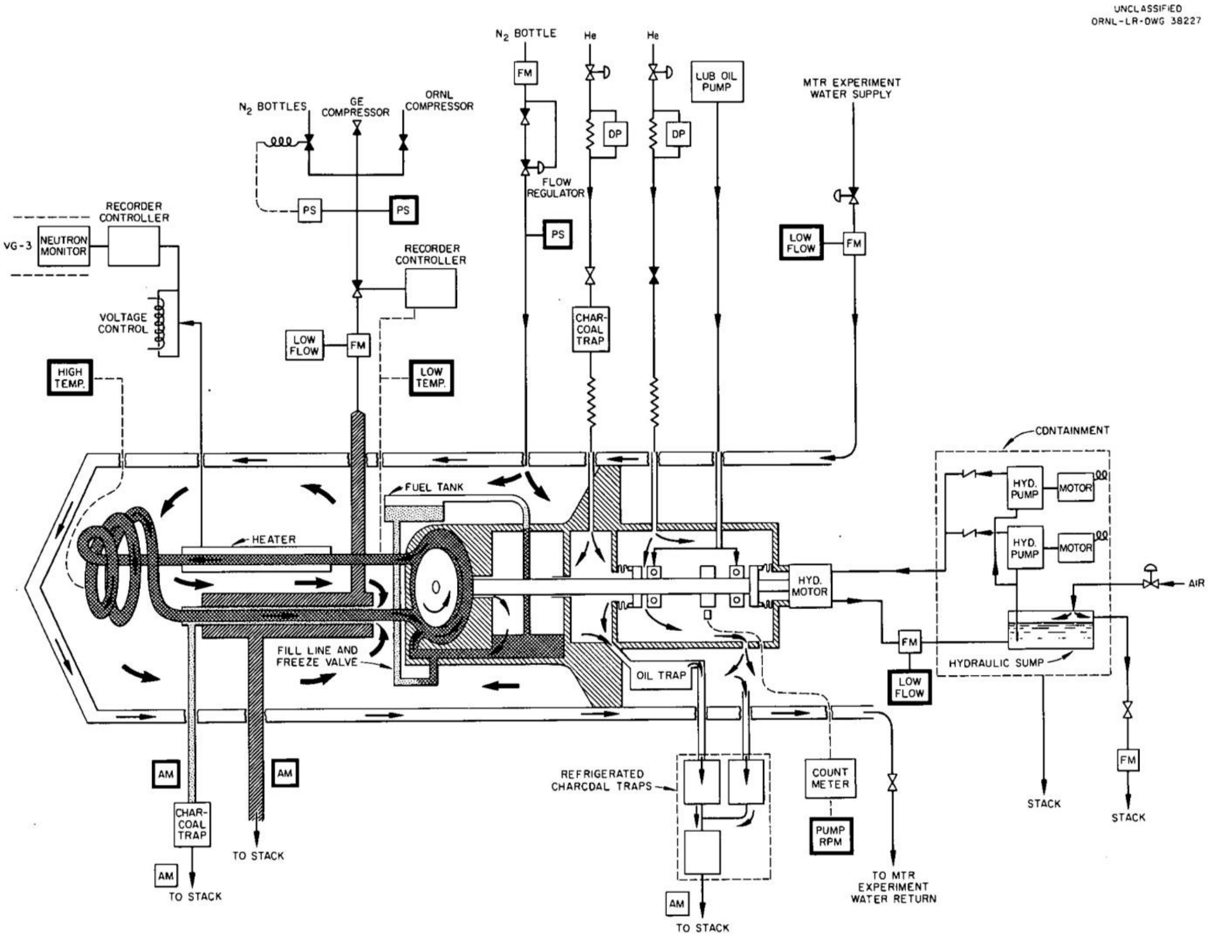

Figure 7. Flow diagram for ORNL-MTR-44 circulating fused salt fuel irradiation test loop (ORNL-3574, p. 70).

In-pile test loop pumps must be highly reliable as “thermal transients due to plugging of the loop, pump failure, etc. give rise to dangerous temperature levels within one second or less” [57].

Earlier in-pile test loops have used small diameter tubing (~5 mm inner diameter [ID] typically) with modest volumetric flow rates of ~5 l/m. Out-of-pile test loops would tend to require larger diameter piping of 25 mm ID and would require higher flow rates of 100 l/m typical. It would be advantageous for pumps supporting in-pile loops to be as small as possible, and ideally, they would fit within a small diameter cartridge. Most fuel salt loop testing purposes can be accomplished at lower flux university reactors. Pool-type university reactors tend to have a free face that provides space for loop components. However, US high-flux test reactors (e.g., the High Flux Isotope Reactor [HFIR] and the Advanced Test Reactor [ATR]) are geometrically constrained to limited diameter cylindrical insertions (i.e., cartridge experiments). Given the significant value of high-power test reactors and their multiple competing uses, systems in which a failure could result in having to trip the reactor would require demonstration of high reliability.

The primary concerns for reliability of fluidic pumps for in-pile fuel-salt test loops would be

1. plugging of the gas lines to the displacement vessels or build-up of solids within the displacement vessels due to production of volatile fission products and aerosols during use,
2. corrosion of the salt-wetted components due to the progressive increase in the oxidizing nature of the fuel salt during operation, and
3. dissimilar materials corrosion due to deposition of elements from other salt-wetted structural materials into the fluidic pumps.

The pulsating flow characteristic of a single fluidic pump does not appear to be significantly detrimental to test loop operation. A double-acting configuration would likely be preferred to provide some system redundancy.

2.3.9 Tank-to-Tank Transfer

Transferring salt from one tank to another, such as between the reactor and storage or processing vessels, can be performed using simple dip tubes and regulating pressure differentials between tanks. However, using power fluidics to pump salt between tanks negates the need to pressurize the vessels. While the elevation between tanks (i.e., static head required be overcome) is not significant, reducing the wall thickness and cost of large high-temperature tanks is advantageous.

2.3.10 Fuel Salt Synthesis from Used LWR Fuel

Multiple prospective reactor vendors have indicated that their preferred method for creating reactor fuel for their initial fuel salt loads is to incorporate the remaining fissile materials from used LWR fuel into a fuel salt. Used LWR fuel is highly radioactive, necessitating remote handling and providing strong incentive for highly reliable components.

Moltex Energy described a preferred route to convert used CANDU fuel to chloride salt fuel at a recent conference [32]. Terrestrial Energy Inc. has also discussed using pyrochemical processes to prepare fuel salt from used CANDU fuel [33, 34]. Elysium Industries has also referenced salt-based LWR fuel processing methods to prepare new fuel for their reactor design [35, 36]. Additionally both Muons Inc. (voucher title - *Conversion of Light Water Reactor Spent Nuclear fuel to Fluoride Salt Fuel*) [37] and Elysium Industries (voucher title - *Synthesis of Molten Chloride Salt Fast Reactor Fuel Salt from Spent Nuclear Fuel*) [38] have received GAIN vouchers from the US Department of Energy (DOE) to evaluate and/or demonstrate the technology to convert used LWR fuel to MSR fuel salt. Metatomic was recently formed to commercialize the conversion of used LWR fuel into MSR fuel salt [39].

While some of the envisioned processes begin with dry head end processes, all of the envisioned systems require pumping controlled amounts of highly radioactive, corrosive fluids for which fluidic pumps would be a preferred technology.

2.3.11 Tube Fuel Salt Type Reactors

Two MSR design variants have been proposed that transfer their heat to a cooling fluid in-core, not requiring high velocity fuel salt pumping. The Seaborg Technologies' design [40] uses a caustic soda moderator and coolant salt. The Dual Fluid Reactor from the German Institute for Solid State Physics [41] uses a lead coolant surrounding actinide chloride fuel salt tubes. In both designs, the fuel salt tubes have a common inlet and outlet manifold which allows for processing (refueling, fission product removal, fission gas escape, etc.) the fuel salt. Both designs are at a very early phase of development, with significant technological hurdles remaining to be resolved, notably including developing materials and corrosion control methods suitable for exposure to dissimilar fluids at elevated temperatures. However, the designs are conceptually similar to the original ARE, which used fuel salt tubes embedded in moderator blocks, which were cooled by sodium cooling loops. Caustic soda was extensively evaluated as a reactor coolant, moderator, and fuel carrier as early as the late 1940s [42], with efforts extending into the 1960s [43]. Lead-cooled reactors are another Generation IV reactor concept, with high-temperature corrosion being a primary issue that has yet to be fully resolved [44].

3. POTENTIAL PF APPLICATIONS BEYOND MSRS

3.1 MOLTEN SALT RESEARCH AND DEVELOPMENT FACILITIES

A range of R&D is required to support MSR commercialization [57, 58, 59]. During the 1950s–1970s, many forced-flow test loops were designed, built, and operated at ORNL in support of the culminating operation of ARE and MSRE. These efforts also informed future R&D and demonstration plans. To support these tests, ORNL developed approximately 12 pump designs, fabricated ≥84 units, and generated ≥96 years of combined total of testing [21]. These pumps ranged in size from 0.2–341 m^3/h at heads of 3–122 m.

With the recent resurgence in molten salt R&D, many entities either have forced-flow facilities in operation or under development. These facilities include ORNL, several universities (e.g., University of Wisconsin [UW], University of Michigan [UM], Texas A&M University [TAMU], and Virginia Tech [VT]), companies, as well as international efforts. Forced-flow loops are required for prototypic corrosion and chemistry control testing, component development and demonstration, and in-pile irradiation experiments. Based on recent experience sourcing molten salt pumps, insight from collaborators, and interactions with traditional pump manufacturers, the supply chain for high-temperature molten salt pumps is currently a challenge. PF technology may be able to fulfill some of the forced-flow testing required in support of MSR R&D.

3.2 CONCENTRATING SOLAR POWER

Concentrating solar power (CSP) thermal plants focus the sun’s energy to heat a working fluid and generate electricity. As of 2018, numerous CSP plants are in either in operation (98), under construction (18), or under development (24) worldwide [65]. Current state-of-the-art CSP plants use nitrate/nitrite-based salts as the heat transfer fluid and as a medium for thermal energy storage. In a solar power tower configuration, the salt is pumped from a large cold salt tank up a tower to a central receiver which heats the salt. The hot salt is then stored in a large hot salt tank. Hot salt can then be pumped back to the cold tank after passing through a heat exchanger to a steam power cycle. In practice, nitrate/nitrite salts are limited to peak temperatures of 565°C. The tower height can be on the order of 140–200 m (e.g., Gemasolar plant) yielding a required pump head of 30 bar to initially fill. The pumps used are typically of the multi-stage long-shafted design and are on the order of 7–15 m long [62]. Plants under development are in the 50–450 MWe range [64]. For a 100 MWe plant, the required nitrate salt flow rate is ~0.36 m^3/s (5,700 gpm).

For the existing and upcoming nitrate salt-based CSP plants, the efforts to manufacture, maintenance, and structural support of the long-shafted pumps are not trivial. PF technology could potentially be employed in substitution of the traditional pumps. Note that for nitrate/nitrite salts, air can be used as a cover gas.

A new effort (Gen3 CSP) sponsored by DOE’s Office of Energy Efficiency and Renewable Energy (EERE) is focused on developing advanced CSP technology that can operate at higher temperatures with improved economics [61]. Chloride and carbonate molten salts are candidate options to be used for heat transfer fluids and thermal energy storage media. The hot sides of these systems will operate at temperatures exceeding 725°C. This enables the use of supercritical carbon dioxide power cycles boasting high thermal efficiencies.

For chloride salt–based Gen3 CSP, a key technology gap is high-temperature long-shafted pumps [61]. The pumping requirements are similar to the lower temperature existing nitrate salt CSP plants, but the engineering challenges are greater. Again, power fluidics may have application in these future Gen3 CSP plants.

3.3 3-D PRINTING REINFORCED CONCRETE

The civil works associated with NPPs continue to be the dominant cost. Any technology with the significant potential to decrease this cost is thus of very high interest to the nuclear industry. NPP concrete has both compressive and tensile strength specifications, and it also must have durability and the ability to withstand radiation damage, depending on intended usage. Fluidic pumping would be easier to integrate into automated manufacturing than more conventional pressure- and/or gravity-driven systems, as fluidic pumping has the potential for precise application of paste and aggregate mixtures, and it may also allow for pumping of reinforcing material into structural forms. The integration of the multiple forms of automated manufacturing incorporating reinforcement, cement, water, and aggregate into precise shapes, however, has not yet been entirely resolved. Automation of reinforced concrete manufacturing is currently a very active area of development. Given its rapid pace of development and its potential impact on the economics of advanced reactors, it should be closely monitored.

4. COMPARISON OF CURRENT TECHNOLOGY TO MSR REQUIREMENTS

PF has been used to pump and mix slurries, sludge, and mixtures in a variety of challenging environments and conditions. For MSRs, a few potentially unique technical requirements for a PF system stand out.

Halide salts can become highly corrosive if the proper chemistry control is not maintained. Generally, high-nickel low-chromium alloys are used for molten salt compatibility, while other more traditional metals may also be feasible if the appropriate chemistry control is applied. Given the relatively simple construction of the salt-wetted side of the PF system (i.e., pipes, tanks, standard machining and welds) fabrication of such a system using a different metal is not considered a technical impediment. However, the inclusion of a dissimilar metal into salt loops can itself enhance corrosion due to galvanic effects.

The halide salts of interest are very hygroscopic and readily react with oxygen, becoming much more corrosive. Therefore, the PF driver fluid needs to be a dry, inert gas. Molten salt test facilities have used argon or helium for cover gas. Air is typically used in current applications of PF. While incorporating an inert gas supply may impact the PF system’s operating cost, it is not viewed as a technical impediment.

Molten halide salts have relatively high melting points (e.g., >400°C). Thermal management (e.g., trace heating, insulation) is required to prevent freezing of salt in systems. Conversely, highly radioactive fuel salts can generate significant heat. Hold-up of heat-generating salt in piping or tanks must also be considered for system thermal management. While thermal management must be designed into a PF system, the same engineering challenge must be addressed by numerous other components of an MSR system.

Some fission product gases will be released from fuel salt (e.g., krypton, xenon) at free surfaces, and tritium can be liberated from non-fueled fluoride salt coolants. These potential source terms must be appropriately captured and stored. To handle these gases, most MSRs will include some type of off-gas system. As illustrated in Figure 1, the PF process requires a vent. The MSR off gas system or a separate system would be required to accommodate the flow of gas from the PF system.

The vapor pressure of halide salts is low; however, it is not zero. Some amount of salt species will volatilize out of the salt. Also, both beta decay recoils and fission reactions that occur near the surface of the salt will result in fuel salt aerosol particles (mists). These species would deposit in the downstream gas lines of a PF system. Depending on the species, they can deposit as liquids or as *soft* or *hard* solid deposits. The ARE incorporated *snow traps* to re-condense the ZrF_4 vapors that were released from the salt surface during operation [63]. During MSRE operation, inadvertent plugging of off-gas lines occurred frequently [66]. Depending on the application, the PF system would need to be designed to accommodate some type of scrapers, borers, or similar methods to clear lines out if they become blocked.

Nuclear reactor systems, structures, components, and operations are highly regulated. While current PF applications include nuclear waste tank applications, safety-related operations at an NPP require substantially higher levels of evaluation and quality assurance. Any system or component that supports achieving a safety objective will be required to be compliant with a 10 Code of Federal Regulations (CFR) 50 Appendix B quality assurance program. Also, PF will be required to be compliant with US Nuclear Regulatory Commission (NRC) Regulatory Guide 1.232, which includes Advanced Reactor Design Criteria 54 for *Piping systems penetrating containment*:

> *Piping systems penetrating the containment structure shall be provided with leak detection, isolation, and containment capabilities having redundancy, reliability, and performance capabilities that reflect the importance to safety of isolating these piping systems. Such piping*

> *systems shall be designed with the capability to verify, by testing, the operational readiness of any isolation valves and associated apparatus periodically and to confirm that valve leakage is within acceptable limits*.

Some example considerations:

- Isolation valves preventing backflow of radioactive material from the process to the PF system gas supply and controls
- Mitigation of failures of the pressurized gas supply
- Penetrations and pipe chase between the PF system gas supply and controls

5. TECHNOLOGY DEVELOPMENT ROADMAP

PF may be applicable to multiple aspects of MSRs, with some technical adjustments. Developing and validating these adjustments will be necessary for PF to enter the liquid salt market. Note that the technical adjustments are not conceptually central to the power fluidics themselves, so an extensive research program is not envisioned. The major steps of the envisioned development program include:

1. Developing an appropriate 10 CFR 50 Appendix B quality assurance program for the overall system and its components to allow it to be used in safety-related applications at NPPs
2. Providing fluid-wetted material options that are compatible with the fluids being pumped and/or mixed
    a. Fuel salt
    b. Coolant salt
    c. Processing fluids (e.g., liquid bismuth)
3. Developing technology to address material deposition in the gas supply tubes
4. Developing a high-purity, recirculating, inert gas–based control system (in lieu of air or a once-through system
5. Developing system temperature control and external heating for the gas and PF-wetted components

The PF gas lines represent a potential leakage path for radionuclides into the environment. Consequently, their design—including materials and component selection—will be subject to a nuclear safety grade quality assurance program.

Molten salt systems are vulnerable to dissimilar material corrosion, so it will be a design requirement to *not* introduce a significantly dissimilar alloy into the loop [67]. The salt-wetted materials in a PF system are likely to be constructed of the same materials as the remainder of the salt boundary: a high-nickel, corrosion-resistant alloy. Alternatively, the salt-wetted components may be fabricated from a refractory material such as molybdenum, which would also provide compatibility with liquid bismuth [68].

While the boiling points of molten salts are well above the operating temperature, the salts will generate some vapor pressure, and the fuel salts will also generate aerosols (mists) that will deposit in the gas lines [69]. However, the condensates will only be mechanically deposited onto the surfaces of the gas lines and will generally not be chemically bound. The scrapers/borers that are developed to remove these deposits will need to be demonstrated.

Molten halide salts would react with the oxygen in air, becoming much more corrosive. Consequently, the gas drive for the PF must employ high-purity inert gas. This would only be cost effective with recirculating use of the gas. Consequently, a compressor and temperature management system will be necessary. While gas handling technology is mature, the specific application has not been demonstrated in a nuclear reactor environment.

Demonstration of a working high-temperature liquid salt pumping system is recommended to provide confidence to customers that PF should be considered.

6. SUMMARY AND CONCLUSIONS

PF technology uses gases to initiate and control flow of liquids in industrial applications. This report has identified a number of potential PF applications in support of MSR operation and the molten salt fuel cycle. PF technology does not require any moving parts to contact the molten salt or nearby electronics, potentially resulting in highly reliable operation in harsh, high-radiation conditions. MSR-tailored PF technology would have wide applicability in plant and fuel cycle operations. However, the MSR customized version of the technology does not yet exist and would be necessary to address the specific technical issues for MSR deployment. Additionally, MSR developers are not generally aware of the capabilities of PF and are consequently not including PF in their designs. Developing and demonstrating a molten salt customized version of a PF-based pumping system is recommended to introduce the technology to potential customers and regulators.

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