INL/CON-14-32433
PREPRINT

A Multi-Purpose Thermal Hydraulic Test Facility For Support of Advanced Reactor Technologies

2014 ANS Winter Meeting and Nuclear Technology Expo

James E. O'Brien*, Piyush Sabharwall and SuJong Yoon

November 2014

A Multi-Purpose Thermal Hydraulic Test Facility
For Support of Advanced Reactor Technologies

James E. O'Brien*, Piyush Sabharwall and SuJong Yoon
Idaho National Laboratory, Idaho Falls, ID *83402,*
James.Obrien@inl.gov

INTRODUCTION

Effective and robust high temperature heat transfer systems are fundamental to the successful deployment of advanced nuclear reactors for both power generation and non-electric applications. Plant designs often include an intermediate heat transfer loop (IHTL) with heat exchangers at either end to deliver thermal energy to the application while providing isolation of the primary reactor coolant system. In order to address technical feasibility concerns and challenges associated with the IHTL, a new high-temperature multi-fluid, multi-loop test facility called the Advanced Reactor Technology Integral System Test (ARTIST) facility is under development at the Idaho National Laboratory (INL). The facility will include three flow loops: high-temperature helium, molten salt, and steam/water. The three loops will be thermally coupled through an intermediate heat exchanger (IHX) and a secondary heat exchanger (SHX). Research topics to be addressed with this facility include the characterization and performance evaluation of candidate compact heat exchangers such as printed circuit heat exchangers (PCHEs) at prototypical operating conditions, flow and heat transfer issues related to core thermal hydraulics in helium-cooled and salt-cooled reactors, and evaluation of corrosion behavior of new cladding materials and accident-tolerant fuels for LWRs at prototypical conditions.

The loop will utilize advanced high-temperature compact PCHEs operating at prototypical IHX conditions. The initial configuration will include a high-temperature (750°C), high-pressure (7 MPa) helium loop thermally integrated with a molten fluoride salt flow loop operating at low pressure (0.2 MPa) at a temperature of ~450°C. Liquid salts have been identified as excellent candidate heat transport fluids for intermediate loops, supporting several types of advanced high temperature reactors [1 - 4]. Fluoride salt coolants are eutectic binary or tertiary mixtures of fluoride salts with melting points in the range of 320 to 500°C. The experimental database will guide development of appropriate predictive methods and be available for code verification and validation (V&V) related to these systems.

ARTIST FACILITY RESEARCH APPLICATIONS

In addition to the heat exchangers, each flow loop will include high temperature test sections operating at prototypical conditions which can be customized to address specific research issues associated with each working fluid. Possible research topics for the high temperature helium test section include flow distribution, bypass flow, and heat transfer in prototypical prismatic core configurations under forced and natural circulation conditions [5], parallel flow instability during pressurized cool-down [6], and turbulent heat transfer deterioration [7, 8]. Oxidation effects associated with water or air ingress could also be examined [9].

The high temperature test section in the liquid salt loop can be used for examination of materials issues, thermal stresses, and heat transfer. Metallic materials have been studied extensively in liquid salt environments [1 - 3], but additional research is needed to evaluate the performance of ceramic and composite materials such as SiC/SiC in liquid salt environments [10]. Fundamental heat transfer issues for liquid salts are related to the fact that these are high Prandtl number fluids with high viscosities and specific heats, and relatively low thermal conductivities. Accordingly, prototypical Reynolds numbers are low (in the laminar or transitional flow regimes) and heat transfer enhancement strategies (e.g., extended surfaces) may have to be employed in the core and other components. The high Prandtl number reduces the potential for thermal shock (compared to low-Prandtl-number liquid metal coolants), but the possibility of large thermal stresses still exists [10]. Bypass flow can also be an issue for prismatic reactor core configurations with liquid salt coolants. The liquid salt loop will include a thermal energy storage (TES) system for support of thermal integration studies.

The high temperature test section in the steam/water loop will be used primarily for prototypic evaluation of new cladding materials and accident-tolerant fuels. It will be designed to characterize the thermal, chemical, and structural properties of candidate advanced fuel cladding materials and designs under a variety of simulated flow and internal heating conditions to mimic operational reactor conditions prior to in-reactor testing The capability for out-of-pile mock-up testing of candidate (surrogate) fuel-clad systems is essential for reactor readiness, in particular when innovative fuel cladding will be in direct contact with the test reactor primary coolant system without secondary containment. Careful control of water chemistry will be essential for these studies; a water chemistry control section is included in the design of the loop.

Flow-induced vibration of fuel rod bundles has been identified as an important issue for sodium-cooled reactors [11]. The high-temperature test section of the hot water loop can also potentially be used to study flow-induced vibration of simulated sodium-cooled reactor fuel rod bundles. Hot water at 200°C and 1.38 MPa matches the density of sodium. This condition is well within the operational range of the proposed loop.

PRELIMINARY DESIGN OF THE ARTIST FACILITY

A process flow diagram for the ARTIST facility is shown in Fig. 1. The facility includes three thermally interacting flow loops: helium, molten salt, and steam/water. Selection of the overall scale of this facility in terms of flow rates, pump requirements, heater power, heat exchanger duty, piping size, etc. is based on a compromise between capability and cost. A survey of existing liquid salt flow research facilities was performed to provide guidance on sizing of the INL salt loop. Results of the survey are presented in Table 1. As expected, the university facilities are relatively small, with salt flow rates much less than 1.0 kg/s. The ORNL facility and the TNT loop in Japan have flow rates on the order of 1.0 kg/s. By far the largest facility listed is the MSTL at Sandia National Laboratory, with a salt flow rate of up to 50 kg/s. Based on the expected funding available for the INL facility and the desire to develop a facility of relevant scale for PCHE characterization and other research objectives, the INL facility has been designed to support a liquid salt flow rate of 1 kg/s with a temperature rise across the IHX of 50°C. Once this selection is made, the IHX heat duty is fixed. Flow rates of the remaining fluids in the multi-fluid loop can subsequently be calculated based on appropriate values of temperature change across the IHX and/or the SHX. Operating conditions, heat exchanger duties and flow rates for KF-ZrF_4, He, H_2O liquid, supercritical CO_2, and Na are listed in Table 2, corresponding to a KF-ZrF_4 flow rate of 1 kg/s and a delta-T across the IHX of 50°C, which yields a heat exchanger duty of 52.6 kW.

Helium Loop

The helium loop will be initially charged from pressurized gas storage cylinders to the loop operating pressure of 7 MPa. Helium flow through the loop will be driven by a water-cooled centrifugal gas circulator rated for high-pressure service, with a design flow rate up to 525 LPM at 7 MPa (11,300 SLPM) and a loop pressure drop of 100 kPa. The helium circulator will be designed to operate with a maximum helium temperature of 100°C. It is therefore located in the low-temperature section of the helium flow loop. The gas is preheated to intermediate temperature by flowing through a helium-to-helium

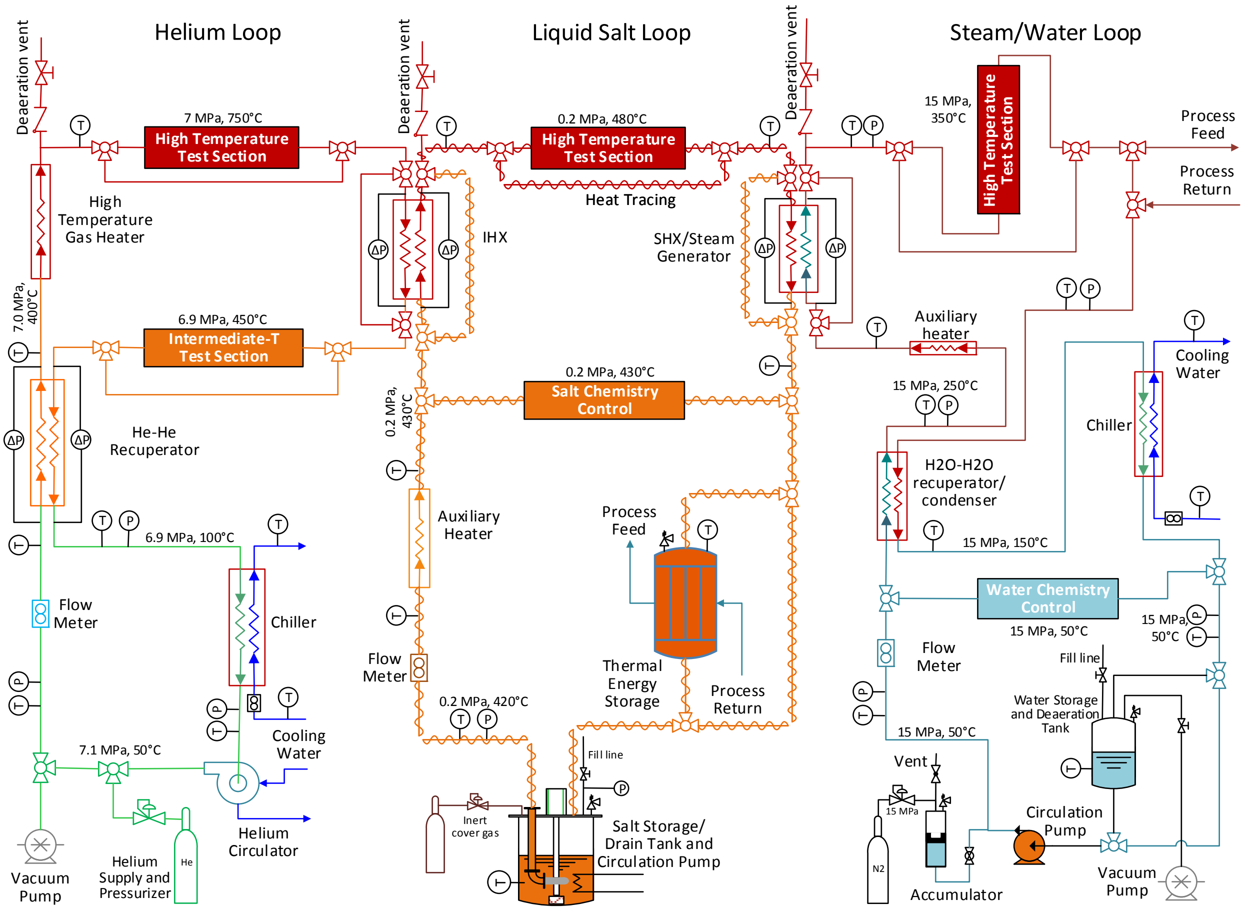

Figure 1. Process flow diagram of the ARTIST multi-loop multi-fluid test facility.

Table 1. Liquid salt flow research facility characteristics.

Institution	salt	T (°C)	P (kPa)	Flow rate (kg/s)	Application
ORNL [12]	FLiNaK	700	atmospheric	4.5	Nuclear/PB-AHTR
Sandia MSTL [13]	$60NaNO_3$-$40KNO_3$	300 - 585	580	44 - 50	solar
Korea [14]	FliNaK			.003	nuclear
U Wisconsin [15]	FLiNaK, KCl-$MgCl_2$,	600		8.3×10^{-4}	nuclear
U Wisconsin [15]	KNO_3-$NaNO_3$, 60:40	~200	200		nuclear
NIFS-Japan, [16]	KNO_3-$NaNO_2$-$NaNO_3$ 53:40:7 (HT salt)	~200		0.645	Fusion
Ohio State U [17]	FLiNaK, KF-ZrF4	600 - 700	atmospheric	0.12	nuclear

Table 2. Flow rates based on KF-Zr4 flow of 1 kg/s, with 50°C IHX delta-T.

Fluid	P (MPa)	T_{mean} (°C)	HX ΔT (°C)	HX Duty (kW)	Mass flow rate (kg/s)	Volume flow rate LPM (actual)	Volume flow rate (SLPM)	Volume flow rate (gpm)
KF-ZrF_4	0.2	~450	50	52.6	1	19.9	n/a	5.25
He	7	600	300	52.6	.0337	524	11330	n/a
H_2O liq	10	300	100	52.6	.096	7.94	n/a	2.10

recuperator which transfers heat from the higher temperature helium return flow. The high temperature portion of the flow loop is designed to handle helium temperatures up to 800°C. This temperature will be achieved using a high temperature electrical in-line gas heater (60 kW). The helium loop will include a high temperature test section for heat transfer and materials studies. Downstream of the test section, the helium gas flows through a heat exchanger where heat will be transferred to the adjacent molten salt loop using a scaled version of an intermediate heat exchanger. This heat exchanger will be a high efficiency compact microchannel PCHE. Downstream of the IHX, the helium flows through an intermediate-temperature test section and the recuperator to transfer heat back to the inlet stream.

The baseline design for the He-He recuperator will also be a PCHE. In addition to its heat recuperation role, this heat exchanger can simulate an IHX for the case in which He is used as an intermediate heat transfer fluid. Downstream of the recuperator, the helium flows through a water-cooled chiller to cool it back down to the gas circulator operating temperature.

Molten Salt Loop

The center part of Fig. 1 shows the molten salt portion of the multi-loop test facility. Selection of coolant salt properties in general and the particular salt to be used in this loop is discussed in reference [18]. While it is not necessarily the highest ranked salt in terms of heat transfer characterisitics, KF-ZrF_4 (58 mol% KF and 42 mol% ZrF_4) has been selected for the initial loop configuration primarily due to its low melting point (390°C), which mitigates some of the loop design challenges. The loop will be charged with salt from the salt storage tank. This tank will include both an immersion heater and wall heaters designed to heat the frozen salt to a temperature above its melting point. The head space in the molten salt storage tank will be filled with inert cover gas. The vertical cantilever salt pump will be designed to operate at 420°C at low pressure (~0.2 MPa). It will provide molten salt flow rates up to 20 LPM. The entire molten salt flow loop will be heat-traced to prevent salt from freezing and causing a flow blockage. A salt chemistry control section will be installed at the intermediate temperature location. Downstream of the pump, the salt flow rate will be measured using an ultrasonic flow meter. The salt temperature will be boosted as needed to the desired intermediate temperature using an in-line electrical auxiliary heater. Downstream of the high temperature test section, the molten salt flows through a secondary heat exchanger (SHX), transferring heat to the tertiary steam/water loop. An SHX bypass line is also provided for cases in which the molten salt loop will be operated independently of the steam/water loop. The salt can then flow directly back to the pump or it can flow through a thermal energy storage (TES) system for hybrid energy system (HES) process integration studies.

Steam/Water Loop

The right-hand side of Fig. 1 shows the steam/water tertiary loop. The SHX can serve as a steam generator or simply a single-phase heat exchanger, depending on the conditions to be simulated in the tertiary loop. For some tests, the conditions in the tertiary loop will be intended to simulate pressurized water reactor (PWR) conditions. PWR conditions will be needed for materials/corrosion studies of accident-tolerant fuels, new cladding materials, crud formation, etc. Alternately, at lower operating pressure, the tertiary loop can simulate the secondary side of a PWR system, with steam generation for HES process integration studies. The tertiary loop includes a condenser/chiller to cool the process stream back down to the pump operating temperature.

CONCLUSIONS

A new high-temperature multi-fluid, multi-loop test facility is under development at the Idaho National Laboratory. The facility will include three flow loops: high-temperature helium, molten salt, and steam/water. Details of some of the design aspects and challenges of this facility, which is currently in the conceptual design phase, have been presented. The loop will utilize advanced high-temperature compact printed-circuit heat exchangers operating at prototypic intermediate heat exchanger conditions. The initial configuration will include a high-temperature (750°C), high-pressure (7 MPa) helium loop thermally integrated with a molten fluoride salt (KF-ZrF_4) flow loop operating at low pressure (0.2 MPa) at a temperature of ~450°C. The facility will assist with component testing in the prototypical environment and experimental results obtained from this research will provide important data for code verification and validation (V&V) related to these systems.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy, Office of Nuclear Energy, Laboratory Directed Research and Development under DOE Operations Office Contract DE-AC07-051D14517.

REFERENCES

1. Williams, D. F., Clarno, K. Y., and Toth, L. M., “Assessment of Candidate Liquid-Salt Coolants for the Advanced High-Temperature Reactor (AHTR),” ORNL/TM-2006/12, Oak Ridge National Laboratory, 2006.
2. Williams, D. F., and Clarno, K. T., “Evaluation of Salt Coolants for Reactor Applications,” Nuclear Technology, Vol. 163, pp. 330 – 343, 2008.
3. Sohal, M. S., Ebner, M. A., Sabharwall, P. and Sharpe, P., “Engineering Database of Liquid Salt Thermophysical and Thermochemical Properties,” INL/EXT-10-18297, March 2010.
4. Benes, O., Cabet, C., Delpech, S., Hosnedl, P., Ignatiev, V., Konings, R., Lecarpentier, D., Matal, O., Merle-Lucotte, E., Renault, C., and Uhlir, J., “Assessment of Liquid Salts for Innovative Applications,” ALISIA Deliverable (D-50), European Commission, Euratom Research and Training Programme on Nuclear Energy, Feb. 2009.
5. Schultz, R. S., et al., “Next Generation Nuclear Plant Methods Technical Program Plan,” INL/EXT-06-11804, January, 2007.
6. Reshotko, E., “Analysis of laminar instability problem in gas-cooled nuclear reactor passages,” *AIAA Journal*, Vol. 5, pp. 1606-1615, 1967.
7. McEligot, D. M., and Jackson, J. D., “Deterioration Criteria for Convective Heat Transfer in Gas Flow through Non-Circular Ducts,” *Nuc. Eng. and Design*, Vol. 232, pp. 327-333, 2004.
8. Lee, J. I., Hehzlar, P., Saha, P., and Kazimi, M. S., “Studies of the Deteriorated Turbulent Heat Transfer Regime for the Gas-Cooled Fast Reactor Decay Heat Removal System,” *Nuc. Eng. and Design*, Vol. 237, pp. 1033-1045, 2007.
9. Chapin, D., Kiffer, S., and Nestell, J., “The Very High Temperature Reactor: A Technical Summary,” MPR Associates, June 2004.
10. Zweibaum, N., Cao, G., Cisneros, A. T., Kelleher, B., Laufer, M. R., Scarlat, R. O., Seifried, J. E., Anderson, M. H., Forsberg, C. W., Greenspan, E., Hu, L. W., Peterson, P. F., Sridharan. K., “Phenomenology, Methods, and Experimental Program for Fluoride-Salt-Cooled High Temperature Reactors,” *Progress in Nuclear Energy*, in press, 2014.
11. Bojarsky, E., Deckers, H., Lehning, H., Reiser, P. H., and Schmidt, L., “THIBO Experiments – Thermohydraulically Induced Fuel Pin Oscillations in Na-Cooled Reactors,” *Nuclear Engineering and Design*, Vol. 130, pp. 21-26, 1991.
12. Yoder, G. L., Aaron, A., Cunningham, B., Fugate, D., Holcomb, D., Kisner, R., Peretz, F., Robb, K., Wilgen, J., and Wilson, D., “An Experimental Test Facility to Support Development of the Fluoride-Salt-Cooled High-Temperature Reactor, *Annals of Nuclear Energy*, Vol. 64, pp. 511-517, 2014.
13. Gill, D. D., Kolg, W. J., Briggs, R. J., and Pettit, K. P., “Customer Interface Document for the Molten Salt Test Loop (MSTL) System, Sandia Report SAND2012-1905, March, 2012.
14. Jeong, H-S., Hwang, I-S., and Bang, K-H>, “A Study on the Thermal-Hydraulic Characteristics of Molten Salt in Minichannels of an Intermediate Heat Exchanger for a Very High Temperature Reactor (VHTR), KSME-B.2010.34.12.1093, ISSN 1226-4881, pp. 1093-1099, 2010.
15. Sabharwall, P., Ebner, M., Sohal, M., Sharpe, P., Anderson, M., Sridharan, K., Ambrosek, J., Olson, L., and Brooks, P., “Molten Salts for High Temperature Reactors: University of Wisconsin Molten Salt Corrosion and Flow Loop Experiments – Issues Identified and Path Forward,” INL/EXT-10-18090, 2010.
16. Toda, S., Chiba, S. Yuki, K., Omae, M., and Sagara, A., “Experimental Research on Molten Salt Thermofluid Technology Using a High-Temperature Molten Salt Loop Applied for a Fusion Reactor Flibe Blanket,” Fusion Engineering and Design, Vol. 63-64, pp. 405-409, 2002.
17. Sun, Xiaodong, personal communication, 2014.
18. O’Brien, J. E., Sabharwall, P., and Yoon, S. J., “Development of a Multi-Loop Flow and Heat Transfer Facility for Advanced Nuclear Reactor Thermal Hydraulic and Hybrid Energy System Studies,” paper no. IMECE2014-39057, Proceedings, ASME 2014 International Mechanical Engineering Congress and Exposition, Montreal, CANADA, November 14-20, 2014