THERMAL HYDRAULIC BENCHMARKING EXERCISES TO SUPPORT FLUORIDE-SALT-COOLED, HIGH-TEMPERATURE REACTOR (FHR) LICENSING

N. Haneklaus, J. Kendrick, L. Huddar, N. Zweibaum, P. F. Peterson
University of California at Berkeley, Department of Nuclear Engineering,
4118 Etcheverry Hall, MC 1730, Berkeley, CA 94720-1730, USA
n.haneklaus@berkeley.edu; jckendrick@berkeley.edu; lakshana.huddar@berkeley.edu;
nicolas.zweibaum@bekeley.edu; peterson@nuc.berkeley.edu

J. Hughes, E. Blandford
University of New Mexico, Department of Nuclear Engineering,
Farris Engineering Center 209, MSC01 1120 1,
University of New Mexico Albuquerque, NM 87131-0001, USA
jhughes7@unm.edu; edb@unm.edu

Q. Lv, X. Sun
The Ohio State University, Department of Mechanical and Aerospace Engineering,
201 W. 19th Avenue, Columbus, OH 43210, USA
lv.11@buckeyemail.osu.edu; sun.200@osu.edu

G. Yoder
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37831, USA
yodergljr@ornl.gov

ABSTRACT

The U.S. Department of Energy is supporting two Integrated Research Projects (IRPs) to study fluoride-salt-cooled, high-temperature reactors (FHRs). A major element of the work of these two IRPs involves performing a series of benchmarking exercises to support design and licensing of future FHRs. This paper presents the initial strategy for thermal hydraulic benchmarking exercises for FHRs as they are currently studied at the University of California, Berkeley (UCB); the Massachusetts Institute of Technology; the University of Wisconsin, Madison; the University of New Mexico; the Georgia Institute of Technology; the Ohio State University; and Texas A&M University. The benchmarking exercises are to verify and validate key thermal hydraulics codes for future use in safety analysis and licensing of FHRs. Code-to-code comparisons as well as code validation exercises using experimental facilities such as the Compact Integral Effects Test facility at UCB are foreseen as part of these efforts. A brief overview of the relevant thermal hydraulic experimental facilities within the two FHR IRPs as well as first benchmarking exercise considerations for thermal hydraulic benchmarking are provided here and may encourage participation in the ongoing FHR development from institutions and experts other than the listed universities. First results for the example problem sets are not provided at this early stage of the project but will be part of future meetings and workshops within the IRPs and with other FHR benchmarking participants.

KEYWORDS

Thermal hydraulic benchmarking; Integrated research project; Fluoride-salt-cooled, high-temperature reactors; Code-to-code comparison; Code validation.

1. INTRODUCTION

Since the original concept of fluoride-salt-cooled, high-temperature reactors (FHRs) was first proposed in 2003 [1], substantial progress has been made in understanding the neutronics, thermal hydraulics, and materials challenges posed by this innovative technology. Past studies have found that FHRs have desirable safety features due to the high coolant volumetric heat capacity and low vapor pressure of salt coolants, and the relatively large thermal margins (more than 700°C) to fuel damage during transients and accident scenarios. Given these attributes, significant effort has been made to develop the scientific and technical basis to design and license FHRs in the United States. Figure 1 provides a brief overview of the first pre-conceptual FHR designs developed at Oak Ridge National Laboratory (ORNL) [2, 3] and the University of California at Berkeley (UCB) from 2008 to 2014 [4].

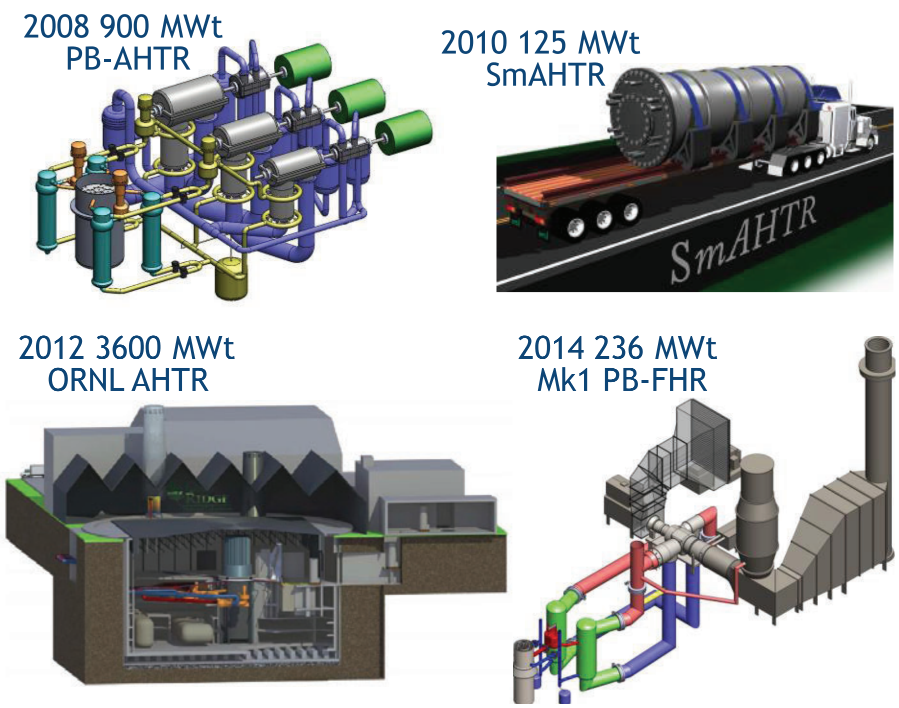

Figure 1. First pre-conceptual FHR designs from ORNL and UCB.

In the first FHR Integrated Research Project (IRP-1) conducted by UCB, the Massachusetts Institute of Technology (MIT), and the University of Wisconsin (UW) between 2012 and 2014, key areas for design and licensing of FHRs were determined [5, 6]. To ultimately prove to a licensing agency that FHRs fulfill necessary safety requirements, data from validated codes and experiments is paramount [7]. As a result, a major element of the upcoming FHR IRP (summarized here as IRP-2) will consist in benchmarking exercises to support future FHR licensing and the understanding of FHR specific phenomena. These exercises are divided between three key areas: neutronics, thermal hydraulics, and materials corrosion and mass transport, as defined during the first IRP-2 workshop held in March 2015 in Berkeley, California.

This paper presents the proposed thermal hydraulics benchmarking strategy for FHRs within IRP-2 through the review of relevant thermal hydraulic experimental facilities at the IRP institutions and their partners in Section 2. Resulting benchmarking exercise considerations are presented in Section 3.

2. RELEVANT THERMAL HYDRAULIC EXPERIMENTAL FACILITIES WITHIN IRP-2

The set of experimental facilities and data for FHR thermal hydraulics is diverse and growing. Currently, the primary IRP-2 experimental facilities under consideration for FHR thermal hydraulics benchmarking are located at UCB, the University of New Mexico (UNM), and the Ohio State University (OSU). Scaled loops that intend to simulate parts of the primary and/or secondary coolant flow paths in FHRs are presently the dominant thermal hydraulic facilities of interest. Experimental work with heated flibe (Li_2BeF_4), the baseline primary coolant in FHRs, is challenging due to the chemical toxicity of beryllium [8] and the relatively high coolant temperatures under prototypical conditions (600 to 700°C). As a result, most of the constructed or planned loops use less hazardous simulant fluids such as heat transfer oils that show characteristics very similar to high temperature flibe at relatively low temperatures [9]. The main source of data obtained from experimental salt loops that will be utilized for FHR benchmarking will come from experiments conducted at ORNL in the United States and the Shanghai Institute of Applied Physics (SINAP) in China using the less hazardous salt flinak (LiF-NaF-KF). The following is a summary of experimental capabilities to collect experimental data relevant for thermal hydraulic benchmarking exercises within IRP-2.

2.1. University of California, Berkeley

For safety and licensing purposes in pebble-bed FHRs (PB-FHRs), it is important to accurately model the heat transfer coefficient between fuel pebbles and the flibe coolant so that the fuel temperature in the FHR core can be predicted accurately. UCB has been performing scaled pebble-bed heat transfer experiments using simulant oils that match key non-dimensional parameters of flibe and using its Pebble Scaled High Temperature Heat Transfer (PS-HT^2) facility [9]. Using measured temperatures throughout a scaled pebble-bed test section along with other experimental parameters, the interfacial heat transfer coefficient can be extracted as a function of time and position within the bed. The scaled pebble-bed test section used for past tests at UCB is shown in Fig. 2 (left). Correlations for interfacial heat transfer coefficients are available in the literature, but the experimental interfacial heat transfer data that was used to develop these correlations for typical PB-FHR Reynolds (Re) and Prandtl (Pr) number ranges. There is significant disagreement between established correlations and experimental data collected in PS-HT^2, proving the value of performing tests and developing new correlations in the appropriate Reynolds (Re) and Prandtl (Pr) numbers range [10].

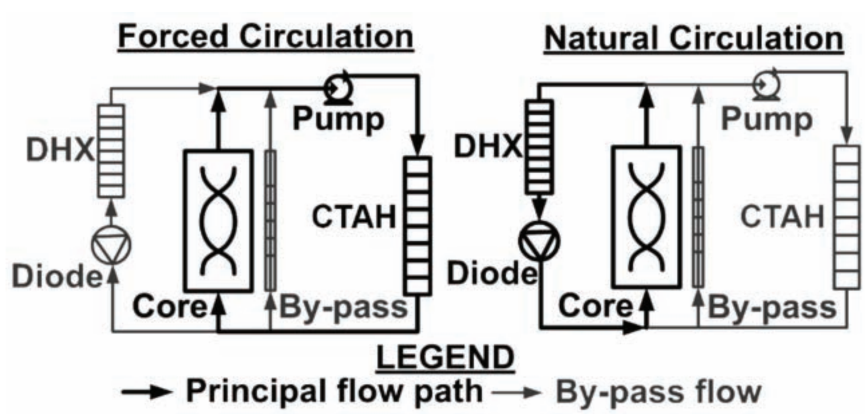

Figure 2. Pebble-bed test section for heat transfer coefficient measurement experiments (left), FHR primary coolant flow paths for forced and natural circulation operation (right).

Additionally, UCB has designed the first iteration of the Compact Integral Effects Test (CIET 1.0) facility to reproduce the integral transient thermal hydraulic response of FHRs under forced and natural circulation operation [11]. CIET 1.0 provides validation data to confirm the predicted performance of the direct reactor auxiliary cooling system (DRACS) in FHRs. The facility has two coupled flow circuits: the primary coolant flow circuit, which replicates the main and bypass flow paths shown in Fig. 2 (right), and the DRACS circuit. The two flow circuits exchange heat through the DRACS heat exchanger (DHX). The facility uses Dowtherm A as a simulant fluid for flibe, at reduced geometric and power scales. Test loops for CIET 1.0 were fabricated from thin-walled (schedule 10) 304 stainless steel (SS) pipe and butt-welded fittings to minimize the mass and thermal inertia of the system. The favorable power scaling with oil (10 kW into oil being equivalent to 625 kW into flibe [11]), along with the simplicity of the construction for low-temperature operation compared to the complexity and safety requirements for tests with the prototypical salt and other prototypical reactor coolants, were key elements in enabling the CIET 1.0 facility to be constructed and operated at much lower cost than previous integral effects tests (IETs) for similar reactors.

As the designs of FHR commercial prototypes evolve, inherent distortions will exist between CIET 1.0 and future FHRs. For transient response, such distortions may arise from non-matched relative coolant residence times between future FHRs and CIET 1.0 sub-systems, as well as the use of reduced flow area SS piping with non-scaled thermal inertia in CIET 1.0. However, while CIET 1.0 was scaled based on the earlier design of a 900-MWth channel-type pebble-bed advanced high-temperature reactor (PB-AHTR), and the pre-conceptual design of a UCB 236-MWth “Mark 1” PB-FHR (Mk1 PB-FHR) [4] was completed after the scaling and design of CIET 1.0 was already finalized. Elevations of the main heat sources and sinks in CIET 1.0 and the Mk1 PB-FHR design reveal a reasonable agreement between the scaled model and the Mk1 PB-FHR prototype. Therefore, CIET 1.0 will provide useful validation data for integral transient behavior of a generic set of FHRs, and given the low cost of the CIET facility, final code validation for a future commercial prototype plant would likely include construction of a new CIET-type loop scaled to even more closely match the prototypical design.

For lack of detailed heat exchanger designs when scaling was performed and design decisions were made for CIET 1.0, the heat exchangers in the system are not scaled to any prototypical heat exchanger. Instead, their designs are based on functional requirements in terms of heat transfer performance, and only relative elevations of the heat sources and sinks are scaled to the 900-MWth modular PB-AHTR. However, the ability to control fan speeds on the two oil-to-air heat exchangers using variable frequency drives (VFDs), as well as to interchange the current DHX with another scaled heat exchanger design, leaves great flexibility in heat removal options for future modifications and upgrades to the CIET facility. Similar to the heat exchangers, the primary pump on CIET 1.0 is not scaled to any prototypical pump. Instead, its design is based on functional requirements in terms of pump head and resulting flow rates in the system. All instrumentation, as well as the computer-controlled power supply and VFDs are integrated using the LabVIEW software and are manually or automatically controlled from a central computer station. Figure 3 shows the computer-aided design rendering of the CIET 1.0 loop with the main components labeled.

Between 2011 and 2014, CIET 1.0 was designed, fabricated, filled with Dowtherm A oil and operated. Isothermal pressure drop tests were completed, with extensive pressure data collected to determine friction losses in the system. CIET-specific friction loss correlations were compared with handbook values, and empirically measured values were implemented in the system codes that are to be validated against additional CIET data. The project then entered a phase of heated tests, from parasitic heat loss tests to more complex feedback control tests and natural circulation experiments. In parallel, UCB has been developing thermal hydraulic models to predict FHR steady-state characteristics and transient response for a set of reference license based events (LBEs). The general strategy is to rely on existing general-purpose thermal hydraulic codes with a significant verification and validation basis for design and licensing by the U.S. Nuclear Regulatory Commission, such as RELAP5. However, UCB has also been developing a one-dimensional FHR advanced natural circulation analysis (FANCY) code for CIET 1.0 and FHR natural circulation modeling. FANCY results will be compared to results obtained using RELAP5 and validated against data from CIET 1.0. Validation data will include steady-state forced and coupled natural circulation data in the primary loop and the DRACS loop [10], and thermal transients data (e.g., startup, shutdown, loss of forced circulation with scram and loss of heat sink with scram) [11].

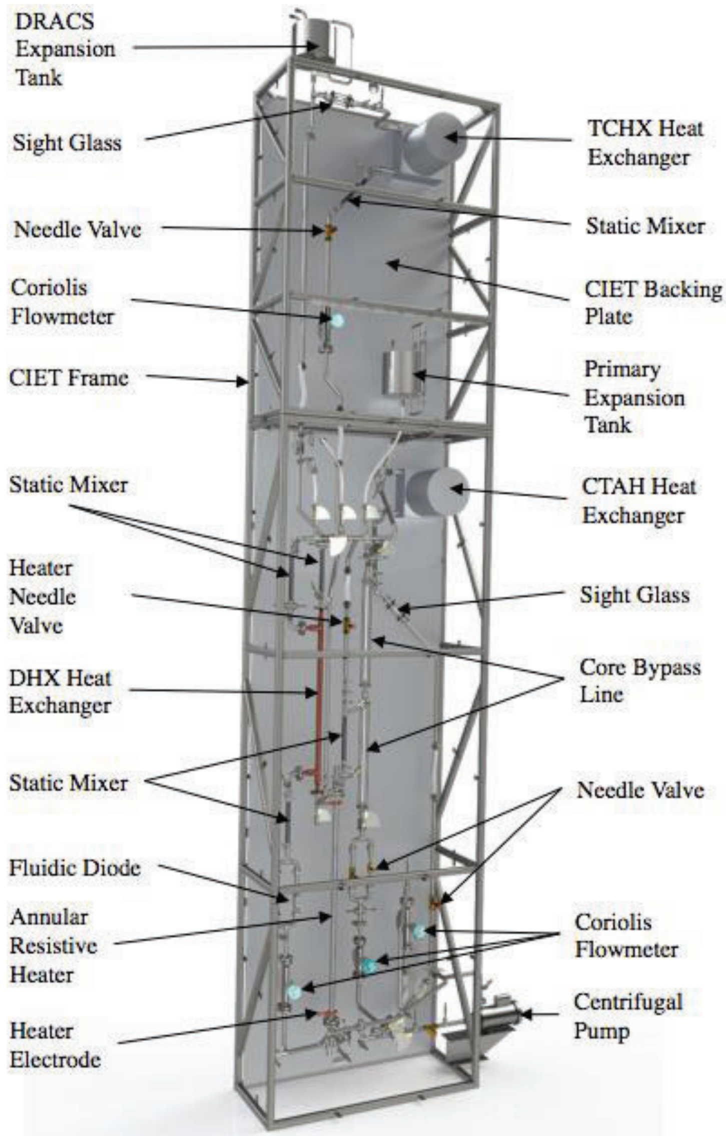

Figure 3. Three dimensional rendering of the CIET 1.0 facility at UCB.

2.2. University of New Mexico

Due to the high volumetric heat capacity of fluoride salts, FHR heat exchangers commonly operate in the transition and laminar flow regimes where heat transfer coefficients can depend strongly on Re and potentially on Grashof number (Gr). Several reduced-scale experiments investigating heat exchanger phenomenology for FHRs are currently underway at UNM. A multi-flow regime heat transfer loop, shown in Fig. 4, has been constructed for use with Dowtherm A to collect data and validate current heat transfer correlations (or develop new correlations, if necessary) for several promising heat exchanger concepts. In parallel, a simple water loop investigating hydrodynamics was constructed and has been testing directional heat exchanger concepts for the DHX, which have the potential to help minimize parasitic heat losses during normal operation of the plant and enhance heat extraction during accidents. The loop will be able to match shell-side Re and Pr for the DHX, as well as have the capability to test a range of Gr, and by extension, Rayleigh (Ra) and Richardson (Ri) numbers owing to the flexibility of the temperature conditions.

Figure 4. Heat transfer loop at UNM.

Moreover, the heat transfer loop is being used to perform a number of separate effects tests (SETs) on heat exchanger concepts. It was initially designed to test bayonet-style heat exchangers, which are inserted into the FHR coolant pool from the top and feature both the secondary (tube-side) feeder and outlet tubes attached to the top of the heat exchanger. Validation data will be collected for two conventional bayonet-style configurations: plain tubes and twisted tubes (shown in Fig. 5). Twisted tubes are a particularly promising technology for the development of FHRs due to their enhanced heat transfer as well as their self-supporting design, which eliminates the need for baffles and reduces hot spots and tube vibration.

Figure 5. Twisted heat exchanger tubes at UNM [12].

The same plain and twisted tube bayonet heat exchangers will also be tested in a novel directionally-enhanced shell concept. Since the DRACS is passive and always operating, heat is perpetually being removed from the primary coolant through the DHX. These parasitic heat losses lower the effective reactor outlet temperature during normal operation, reducing the efficiency of the FHR. The hydrodynamics of a directional DHX has been empirically investigated using a simple water loop and has shown promising initial results. The design will be further optimized in conjunction with computational fluid dynamics (CFD) and the resulting shell design will be implemented in the heat transfer loop and tested with the plain and twisted tube bundles.

Finally, the loop will be configured to test and provide data for a double-wall twisted-tube heat exchanger. Due to the relatively large quantity of tritium generated in FHRs relative to other reactor concepts and the high operating temperature, which encourages the transport of tritium through and out of the system, the use of double-wall heat exchangers utilizing an intermediate fluid such as lithium to capture the tritium is under consideration. By using a twisted outer tube, it is possible to take advantage of the higher shell-side heat transfer coefficients and more uniform shell-side flow while also enhancing heat transfer to the intermediate fluid flowing in the annulus. Two configurations will be tested at UNM: a double-wall exchanger with inner plain tube/outer plain tube and a double-wall exchanger with inner plain tube/outer twisted tube to determine the heat transfer enhancement possible with the twisted-tube version [11].

2.3. University of Wisconsin, Madison

UW was primarily involved in investigating materials phenomena in the FHR class in IRP-1. However, as part of IRP-2, a portion of their research and study will be developing thermal hydraulic loops for the investigation of thermal hydraulic phenomena present in FHRs as well as continuing their investigations of molten salt chemistry and corrosion. Fluid loops will be used for both SETs and IETs.

2.4. The Ohio State University

A high-temperature DRACS test facility (HTDF) under construction at OSU is shown in Fig. 6 (in red), along with the low-temperature DRACS test facility (LTDF) under current operation (Fig. 6, in gray) [14]. Both the HTDF and LTDF are scaled down from a 200-kW prototypical DRACS design for a PB-FHR, following a rigorous scaling analysis [15]. The HTDF employs flinak and KF-ZrF_4 as the primary and secondary coolants, respectively. With the HTDF, the capability of the DRACS to remove decay heat under prototypical reactor conditions can be evaluated. 1-1/2” (OD: 48.26 mm; ID: 40.89mm) and 1-1/4” (OD: 42.16 mm; ID: 35.05 mm) Schedule 40 pipes are used for the primary and secondary loops, respectively. The HTDF core is simulated with 7 electric cartridge heaters with a total nominal power of 10 kW. The DHX employs a shell-and-tube heat exchanger design containing 80 5/8” (15.88 mm) BWG-18 tubes with a length of 0.325 m. Due to the large temperature difference between the secondary salt and ambient air, plain tubes are used for the natural draft heat exchanger (NDHX). A total of 36 1/2” (12.7 mm) BWG-16 tubes are adopted in a staggered array in two rows. A vortex diode design that will exhibit desired pressure drop characteristics for both the forward and reverse flow directions has been obtained via a parametric CFD study [14, 16]. The diode design employs converging/diverging nozzles and a disk-shape chamber with a diameter of 6.6 cm and thickness of 1.56 cm [14]. In addition, a cantilever sump pump for high-temperature applications has also been employed in the HTDF. The nominal design conditions for steady-state operation of the HTDF are summarized in Table I.

Table I. Nominal design conditions of the HTDF.

	Primary Salt (FLiNaK)	Secondary Salt (KF-ZrF_4)	Air
T_{hot} (°C)	722.1	665.3	110.0
T_{cold} (°C)	677.9	589.7	40.0
ΔT (°C)	44.2	75.6	70.0
$\dot{m}$ (kg/s)	0.120	0.127	0.142

The HTDF will be fully instrumented with gauge pressure transmitters to monitor the cover gas pressure in all the salt tanks, capacitance level sensors to monitor the tank salt levels, and thermocouples (N-type) to measure/monitor the salt temperatures along the loop, as well as in the tanks. High-temperature clamp-on ultrasonic flow meters from Flexim will be employed to measure the flow rates. The same flow meters have been used by ORNL for a similar application with temperature up to 700°C. For the differential pressure measurement, in-house designs utilizing commercial differential pressure transmitters have been developed, which will require accurate control of the salt-Ar interface in the pressure sensing lines.

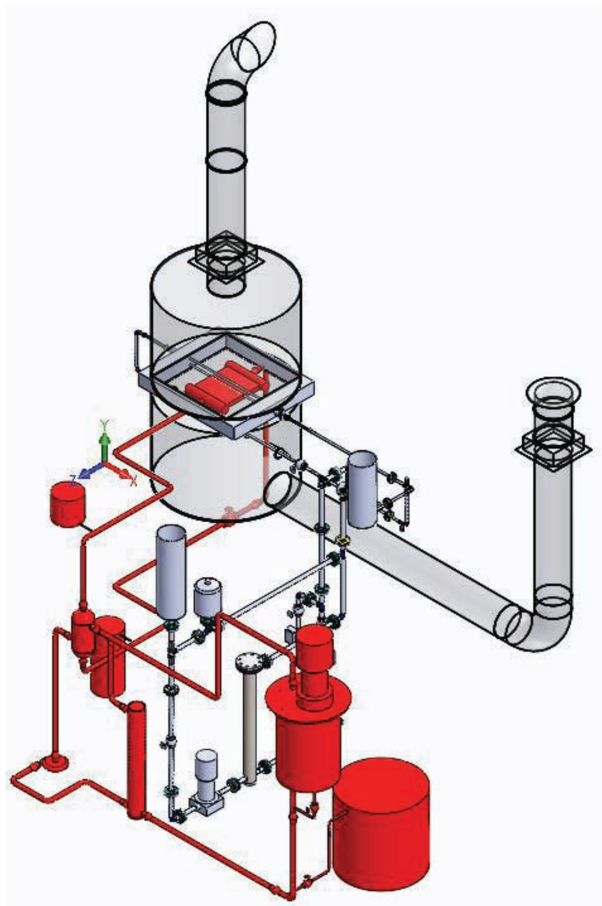

Figure 6. DRACS test facilities at OSU.

The LTDF uses water as both the primary and secondary coolants. The LTDF is intended to examine the couplings among the natural circulation/convection loops and may provide experience to OSU before building the HTDF. 1-1/4” (OD: 42.16 mm; ID: 35.05 mm) and 3/4” (OD: 26.67 mm; ID: 20.93 mm) Schedule 40 pipes are used for the primary and secondary loops, respectively. The LTDF core is simulated with 3 electric cartridge heaters with a total nominal power of 2 kW. The DHX employs a shell-and-tube heat exchanger design containing 80 3/8” (9.53 mm) BWG-18 tubes with a length of 0.356 m. For the NDHX, to enhance the air-side heat transfer, 52 5/8” (15.88 mm) BWG-20 finned tubes with a length of 0.99 m have been employed in a staggered array in two rows. In the LTDF, a fluidic diode simulator consisting of two parallel branches is used to simulate the forward and reverse flow directions. In each branch, a globe valve provides the desired flow resistance while an automated ball valve opens or closes in the corresponding branch based on flow direction. In addition, a vertical inline recirculation pump has been employed in the loop that simulates the intermediate heat transfer loop, enabling the study of the pump trip process experimentally. The nominal design conditions for steady-state operation of the LTDF are summarized in Table II.

Table II. Nominal design conditions of the LTDF.

	Primary Water (1.0 MPa)	Secondary Water (0.1 MPa)	Air
T_{hot} (°C)	76.5	65.2	40
T_{cold} (°C)	63.7	34.8	20
ΔT (°C)	12.8	30.4	20
$\dot{m}$ (kg/s)	0.038	0.016	0.102

The LTDF is fully instrumented. T-type thermocouples are used to measure temperatures at the inlets and outlets of all heat transfer components (core, DHX and NDHX), and differential pressure transmitters from Honeywell are employed to measure the pressure drops over the fluidic diode simulator and the throttling valve in the secondary loop. A gauge pressure transmitter is also utilized to monitor the pressure of the primary loop as it is pressurized. Clamp-on ultrasonic flow meters from Flexim are installed for flow rate measurement. The flow meters have been demonstrated to function well in the LTDF. The LTDF is currently in operation and data is being acquired, which will be used to benchmark a computer code that has been developed for the DRACS design and thermal performance evaluation [16].

2.5. Oak Ridge National Laboratory

The liquid salt test loop facility at ORNL has been constructed to support the development of the FHR concept. It is capable of operating at up to 700°C and incorporates a centrifugal pump to circulate flinak salt through a removable test section. A unique inductive heating technique is used to apply heat to the test section, allowing heat transfer testing to be performed. An air-cooled heat exchanger removes the added heat. Supporting loop infrastructure includes a pressure control system, a trace heating system, and a complement of instrumentation to measure salt flow, temperatures, and pressures around the loop. The facility properties are given in Table III.

Table III. ONRL Liquid Salt Test Loop system parameters.

Parameter	Description
Salt	Flinak (LiF-NaF-KF)
Operating Temperature	700°C
Flow Rate	≤ 4.5 kg/s ≈ 3.5 m/s (1 in. pipe ID)
Operating Pressure	Near Atmospheric
Material of Construction	Inconel 600
Operating Run Time Life	2+ years
Primary Piping ID	2.667 cm (1.05 in)
Loop Volume	0.072 m^3
Trace Heating	≈ 20 kW
Thermocouples	47 (8 in bed)
Pressure Gauges	1 in salt 2 in gas spaces
Flow Rate Measurement	Ultrasonic Flow Meter
Salt Level	1 radar – sump tank 2 H-T/C – sump and surge tanks (1 each)

The goals of this facility (shown in Fig. 7) include providing infrastructure (operational knowledge and equipment) to test high temperature salt systems, developing a nonintrusive inductive heating technique that can be used for thermal/fluid experimentation, measuring heat transfer characteristics in a molten salt-cooled pebble bed, and demonstrating the use of silicon carbide as a structural material for use in molten salt systems [17].

Figure 7. ORNL liquid salt test loop.

ORNL was also the location of the molten salt reactor experiment project, and can provide legacy data that can be used for verification of experimental data and validation of computer models.

2.6. Shanghai Institute of Applied Physics

In parallel to several oil and salt loops under current operation, SINAP plans to build an FHR test reactor. The solid fuel version of the Thorium Molten Salt Reactor (TMSR-SF1) is an experimental test reactor designed to enable the development of the Chinese Academy of Sciences' TMSR solid fuel molten salt reactor (or FHR). The purpose of this test reactor is to verify the feasibility and safety of the solid fuel molten salt reactor concept, and to enable subsequent design and licensing of a demonstration commercial reactor design by providing a comprehensive experimental platform. The TMSR-SF1 adopts a conservative design approach, where reactor safety is the primary consideration in the design, taking into account the basic research capabilities.

SINAP has designed and built several test loops to support their development process. The three principal loops SINAP has constructed are a HTS test loop, a flinak test loop, and a flibe test loop. The purpose of these loops includes basic instruction on the experimental method, design, and construction of molten salt loops; thermal hydraulics of molten salts; development of equipment to operate and measure salt loop properties; and exploration of chemistry concerns for molten salts that include fluoride and beryllium.

The TMSR-SF0 is an electrically-heated thermal hydraulics simulator for solid fuel molten salt reactors. As a comprehensive experimental platform, its primary function is to provide data and experience to support TMSR-SF1 licensing, and practical experience for SF1 design, startup, operation and maintenance, including verification of TMSR-SF1 thermal hydraulic design and safety programs and other key engineering and technical solutions; testing of SF1 key equipment; simulation and experimentation of SF1 startup, operation and accident conditions; and maintenance. TMSR-SF0 will also provide experimental evidence for verification and validation of solid fuel molten salt reactor thermal hydraulics and safety analysis codes.

Based on the above considerations, the TMSR-SF0 is designed as a full-scale simulator for the TMSR-SF1. The key materials, technologies and equipment used in the SF0 have the same design as the SF1, and the plant layout is also identical. The main differences between the SF0 and SF1 are that SF0 graphite fuel pebbles are not loaded with nuclear fuel. Instead, the coolant is heated by electrical heating elements with a total power greater than 1MW. The electrical heating is currently expected to use heating rods installed in channels in the graphite reflector. In addition, flinak is used as the primary salt instead of flibe to simplify the safety issues involved with using beryllium. Taking into account the needs of thermal hydraulic experiments and the low radiation levels, the SF0 core and loop have more instrumentation than expected for the SF1. In addition, the loop has a flow control valve and shut-off valves to facilitate experiments. For longer-term development considerations, the SF0 will include pebble fuel recirculation test equipment.

3. EXAMPLE BENCHMARKING EXERCISES

Key thermal hydraulic phenomena that have been identified in previous FHR workshops that are important to address in benchmarking exercises include: (1) natural circulation, including passive decay heat removal; (2) heat transfer in high Pr coolants, including enhanced heat transfer surfaces such as pebble beds and twisted tubes; (3) heat/flow distributions in critical components such as bypass flow in the reactor; (4) heat exchanger performance; (5) conduction in the fuel and the reactor structures; and (6) radiation heat transfer in molten salts [5, 7]. The benchmarking exercises that are foreseen to be conducted over the course of the project will be down-selected according to the identified key thermal hydraulic phenomena of interest listed above based on the importance of the phenomena, the quality of the available data, current knowledge gaps, and licensing concerns.

The down selection will be conducted using proven systematic methods such as phenomena identification and ranking tables (PIRTs) that are recommended by the U.S. Nuclear Regulatory Commission [18]. During the development of the practical set of benchmarking exercises, it may be necessary to supplement the PIRT process with a more limiting evaluation method that takes into account existing validation datasets, operating experimental facilities, and the resources of the IRPs.

Benchmarking best practices suggest gradually enhancing the complexity of the exercises. Candidate exercise one (CE1) will most likely explore steady-state natural circulation flow in a loop. The purpose of this very basic exercise is to validate the relevant performance models against experimental data for validation. This is regarded as a critical first step before more advanced models/scenarios can be explored. Since the exercise is relatively simple, it may be performed on various experimental facilities, including CIET 1.0, the UNM Heat Transfer Loop, thermal hydraulic loops developed at UW, the OSU DRACS test loops, the Liquid Salt Test Loop at ORNL, and the thermal hydraulic loops at SINAP. The ability to perform CE1 on several test facilities and validate different codes should lead to very accurate and comprehensive natural circulation models.

Candidate exercise two (CE2) is meant to represent a mature benchmarking exercise that should be performed towards the end of the project after more fundamental areas are fully explored and essential knowledge gaps have been filled. CE2 is a time-at-temperature study for loss-of-forced-cooling (LOFC) transients, both with and without scram. The purpose is to determine the time the system remains above a certain temperature threshold during a LOFC transient in the FHR, both with and without a full scram occurring. The experimental facility used in this exercise is the CIET facility at UCB. The figures of merit include (1) the peak bulk coolant outlet temperature, (2) the time at temperature for metallic and ceramic structures, (3) the temperature difference across the DRACS, and (4) the time to establish natural circulation.

SETs are an important part of benchmarking as they directly support IETs by exploring individual phenomena in isolation. This allows IETs to test how different thermal hydraulic phenomena interact in a larger system. Examples of SETs would be tests to provide pressure drop correlations and heat transfer coefficients for integral test facilities. An example of SET is the exploration of bi-directional shell-side heat transfer in the DHX with buoyancy effects using both plain and twisted tube geometries. The purpose of this exercise is to address the lack of data for buoyant flows in twisted tubes. Bi-directional flow data is of interest to model flow reversal in the DHX. Data can be provided for a range of Re and Pr, which will give heat transfer correlations for several candidate salts over a range of operating conditions. CE1 will use the DHX heat transfer loop at UNM, and the figures of merit are heat transfer enhancement due to twisted-tubes and the effect on heat transfer due to local buoyancy forces for up- and down-flow (degrading/enhancing).

4. CONCLUSIONS

This paper specifically addresses the thermal hydraulic benchmarking efforts currently performed and planned at UCB, MIT, UW, UNM, GT, OSU, and TAMU as part of two U.S. Department of Energy-supported IRPs that aim to develop strategies for near-term FHR licensing. Relevant thermal hydraulic experimental facilities as they exist or are planned within the two FHR IRPs, as well as first benchmarking exercise considerations for thermal hydraulics, are introduced in this work and may encourage participation in the ongoing FHR development from institutions/experts other than the listed universities.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to all experts and students participating in the first workshop within IRP-2 on FHR code benchmarking in Berkeley in March 2015. The participants' comments and discussions provided direct support for the structure and input for this paper.

This research is performed using funding received from the U.S. Department of Energy Office of Nuclear Energy's Nuclear Energy University Programs.

REFERENCES

1. C. W. Forsberg, "Molten-salt-cooled advanced high-temperature reactor for production of hydrogen and electricity," *Nucl. Technol.*, **144**, pp. 289-302 (2003).
2. Greene, S.R., et al., "Pre-Conceptual Design of a fluoride Salt-Cooled Small Modular Advanced High-Temperature Reactor (SmAHTR)", ORNL/TM-2010/199. Dec. (2010).
3. V. K. Varma, et al., AHTR Mechanical, Structural, and Neutronic Preconceptual Design, ORNL/TM-2012/320, Oak Ridge, TN, September (2012).
4. C. Andreades et al., "Technical Description of the 'Mark 1' Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (PB-FHR) Power Plant," Department of Nuclear Engineering, University of California, Berkeley, UCBTH-14-002 (2014).

5. N. Zweibaum et al., "Phenomenology, methods and experimental program for fluoride-salt-cooled, high-temperature reactors (FHRs)," Prog. *Nucl. Energy*, **77**, pp. 390-405 (2014).
6. R. O. Scarlat et al., "Design and licensing strategies for the fluoride-salt-cooled, high-temperature reactor (FHR) technology," *Prog. Nucl. Energy*, **77**, pp. 406-420 (2014).
7. Idaho National Laboratory, "Guidance for Developing Principal Design Criteria for Advanced (Non-Light Water) Reactors", INLIEXT-14-31179, Idaho Falls (2014).
8. F. Lantelme and H. Groult, *Molten Salts Chemistry: from Lab to Applications*, pp. 471-496, Elsevier Inc. (2013).
9. L. Huddar, R. Scarlat, Z. Guo, P. F. Peterson, "Experimental Strategy For the Determination of Heat Transfer Coefficients In Pebble Beds Cooled by Fluoride Salts," *International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16)*, Chicago, IL, August 30-September 4, 2015 (submitted).
10. N. Zweibaum, Z. Guo, L. R. Huddar, and P. F. Peterson, "Validation of Best Estimate Models for Fluoride-Salt-Cooled, High-Temperature Reactors Using Data from the Compact Integral Effects Test (CIET 1.0) Facility," *International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16)*, Chicago, IL, August 30-September 4, 2015 (submitted).
11. N. Zweibaum, L. Huddar, J. T. Hughes, M. R. Laufer, E. D. Blandford, R. O. Scarlat, and P. F. Peterson, "Role and Status of Scaled Experiments in the Development of Fluoride-Salt-Cooled, High-Temperature Reactors," *Proc. Int. Congress on Advances in Nuclear Power Plants (ICAPP '15)*, Nice, France, May 3-6, 2015, American Nuclear Society (2015).
12. Twisted tube heat exchanger, http/www.oxide.co.il/en/twisted-tube.html, accessed 24th of March, 2015.
13. N. Zweibaum, J. E. Bickel, Z. Guo, J. C. Kendrick, and P. F. Peterson, "Design, Fabrication and Startup Testing in the Compact Integral Effects Test Facility in Support of Fluoride-Salt-Cooled, High-Temperature Reactor Technology," *International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16)*, Chicago, Illinois, August 30-September 4, 2015 (submitted).
14. Q. Lv et al., "DRACS Thermal Performance Evaluation for FHR," *Ann. Nucl. Energy*, **77**, pp. 115-128 (2015).
15. Q. Lv et al., "Scaling Analysis for the Direct Reactor Auxiliary Cooling System for FHRs," *Nucl. Eng. Des.*, **285**, pp. 197-206 (2015).
16. Q. Lv et al. "Design of Fluidic Diode for a High-Temperature DRACS Test Facility," *Proc. 21st Interntional Conference on Nuclear Engineering (ICONE21)*, Chengdu, China, July 29-August 2, 2013, American Society for Mechanical Engineers (2013).
17. G. Yoder, et. al., "An experimental test facility to support development of the fluoride-salt-cooled high-temperature reactor," Annals of Nuclear Energy, **64**, pp 511-517 (2014).
18. U.S. Nuclear Regulatory Commission, "Regulatory Guide 1.203: Transient and Accident Analysis Methods," (2005).