DESIGN, FABRICATION AND STARTUP TESTING IN THE COMPACT INTEGRAL EFFECTS TEST FACILITY IN SUPPORT OF FLUORIDE-SALT-COOLED, HIGH-TEMPERATURE REACTOR TECHNOLOGY

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ABSTRACT

The capability to validate integral transient response models is a key issue for licensing new reactor designs. The Compact Integral Effects Test (CIET 1.0) facility reproduces the thermal hydraulic response of fluoride-salt-cooled, high-temperature reactors (FHRs) under forced and natural circulation operation. CIET 1.0 provides validating data to confirm the predicted performance of the direct reactor auxiliary cooling system, used for natural-circulation-driven decay heat removal in FHRs, under a set of reference licensing basis events. CIET 1.0 uses a simulant fluid, Dowtherm A oil, which, at relatively low temperatures (50-120°C), matches the Prandtl, Reynolds and Grashof numbers of the major liquid salts simultaneously, at approximately 50% geometric scale and heater power under 2% of prototypical conditions. CIET 1.0 has been designed, fabricated, filled with Dowtherm A oil and operated. Isothermal pressure drop tests were completed, with extensive pressure data collection to determine friction losses in the system. The project then entered a phase of heated tests, from parasitic heat loss tests to more complex feedback control tests and natural circulation experiments. This paper presents the scaling strategy, design and fabrication aspects, and startup testing results from CIET 1.0.

KEYWORDS
Fluoride-salt-cooled, high-temperature reactor; Integral effects test; Single phase natural circulation; Scaling.

1. INTRODUCTION

The need to validate integral thermal hydraulic codes is a key issue for developing and licensing new reactor designs, particularly those using passive safety [1]. The models for heat transfer, pressure drop, and other phenomena used in these codes can be validated using separate effects tests (SETs), where boundary and initial conditions are generated externally and may be varied over wide ranges. However, the actual boundary and initial conditions that occur in an integrated system, due to the coupling between spatial regions and the transitions from early to later phases of transients, may differ from the more idealized conditions that exist in SETs. Therefore, validation of thermal hydraulic codes for reactor safety also requires comparisons with data generated in scaled integral effects test (IET) facilities.

The construction and operation of a conventional, scaled IET facility, like the Idaho National Laboratory Semiscale facility, the Oregon State University (OSU) advanced plant experiment (APEX), or the Purdue University multi-dimensional integral test assembly (PUMA), usually occur late in the development of a new reactor technology, due to substantial costs. Because the compact size and short height of fluoride-salt-cooled, high-temperature reactors (FHRs) depends upon the predicted excellent natural-circulation, single-phase decay heat transfer capability of the coolant, validating data from the University of California, Berkeley (UCB) compact integral effects test (CIET) facility, designed to reproduce the integral transient thermal hydraulic response of FHRs under forced and natural circulation operation, plays an important role in confirming the predicted performance of the direct reactor auxiliary cooling system (DRACS) used in FHRs under a set of reference licensing basis events (LBEs).

The DRACS is a natural-circulation-driven decay heat removal system. A system with multiple DRACS modules, as well as an independent normal shutdown cooling system, provides diverse and redundant means to remove decay heat. The baseline FHR DRACS, based upon the Mark 1 pebble-bed FHR (Mk1 PB-FHR) design, transfers heat to a thermosyphon-cooled heat exchanger (TCHX) that rejects heat to ambient air, which serves as the ultimate decay heat sink [2]. The DRACS coolant loop uses natural circulation to transfer heat from the DRACS heat exchanger (DHX) to the TCHX. The baseline primary coolant in FHRs and the DRACS coolant for the Mk1 PB-FHR are flibe (Li_2BeF_4). For emergency decay heat removal through the DRACS, natural circulation is established in the primary system, with flow upwards through the core, then downwards through the DHX and downcomer. During normal operation, the primary coolant flows in forced circulation upwards through the core, and a small amount of coolant by-passes the core upwards through the DHX and other core by-pass paths. A fluidic diode (or an equivalent system using a check or flapper valve) provides high flow resistance for upwards flow through the DHX during forced convection, but low flow resistance for downwards flow through the DHX during natural circulation. Figure 1 shows the coolant flow paths and by-pass flows during forced circulation and natural circulation operation. These flow paths are replicated in the CIET experiment constructed at UCB, using two coupled loops.

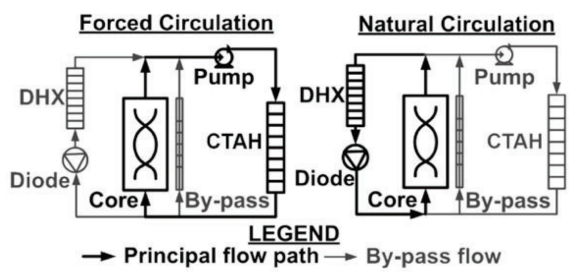

Figure 1. FHR primary coolant flow paths for forced circulation (left) and natural circulation (right) operational modes [3].

In this paper, we describe efforts to design, fabricate, and perform startup testing in the first configuration of the CIET facility (CIET 1.0) at UCB. The simplicity of construction (particularly compared to the complexity and safety requirements for high-temperature tests with the prototypical salt and other prototypical reactor coolants) was a key element in enabling the proposed experiments to be constructed and performed at much lower cost than previous IETs for other types of reactors. Early first-generation IET facilities like Semiscale, ROSA and BETHSY were large facilities that provided data to validate integral thermal hydraulic codes for pressurized water reactors (PWRs). These first-generation facilities required total budgets of several tens of millions of dollars and decade-long schedules. Improvement occurred with the advent of reduced height scaling (e.g., second-generation IET facilities like APEX at OSU and PUMA at Purdue University), but test program costs still remained in the range of $10 million. In comparison, the use of reduced height, area and power scaling, and the use of simulant fluids in CIET 1.0, allowed the construction of this third-generation facility with a budget under $1 million.

The reference system that was used for initial scaling of CIET 1.0 was a 900 MWth pebble-bed, advanced high-temperature reactor (PB-AHTR) [4]. Because the design of the FHR commercial prototype reactor has been constantly evolving, there will be inherent distortions between the CIET 1.0 facility and a scaled version of the final FHR commercial prototype. For transient response, such distortions may arise from non-matched relative coolant residence times between the Mk1 PB-FHR and CIET 1.0 sub-systems, as well as the use of reduced flow area stainless steel piping with non-scaled thermal inertia in CIET 1.0. However, CIET 1.0 will provide useful validation data for integral transient behavior of a generic set of FHRs. Moreover, all key components of CIET 1.0 are modular, enabling easy modifications to the loop as prototypical FHR designs evolve and require new scaled parameters.

In Section 2, the scaling methodology developed to design CIET 1.0 is introduced. Section 3 details key design and fabrication aspects of the CIET 1.0 facility. In Section 4, key tasks for the CIET 1.0 research plan are listed, and initial experimental results are provided.

2. SCALING AND SIMULANT FLUIDS

Thermal hydraulic phenomena associated with FHR response to LBEs evolve over short time periods of minutes to days. Therefore, the major constraint on FHR thermal hydraulic experiments is not duration, but rather power and physical scale, because of the impracticality of performing IETs at the full-power level of a commercial reactor. The importance of scaling was recognized early in the pre-conceptual design of the FHR [5], and scaling methodologies were developed and applied to the design of CIET 1.0.

2.1. Use of Dowtherm A Oil as a Simulant Fluid for Flibe

Liquid salts are unique candidate reactor coolants because simulant fluids can replicate salt fluid mechanics and heat transfer phenomena at reduced length scale, temperature, and heater and pumping power, with low distortion. UCB had identified a class of heat transfer oils that, at relatively low temperatures (50-120°C), match the Prandtl (Pr), Reynolds (Re) and Grashof (Gr) numbers of the major liquid salts simultaneously, at approximately 50% geometric scale and heater power under 2% of prototypical conditions [6]. Prandtl number dictates the selection of the simulant liquid and its average operating temperature for scaled experiments where single-phase heat transfer phenomena are important. For forced convection, Re represents the balance between inertial and viscous forces, and thus, matching Re allows geometrically scaled experiments to cover flow regimes of interest. If both Pr and Re are matched, the Nusselt number (Nu) for forced convection heat transfer is matched. For the case of buoyancy-driven flows, the scaling procedure is similar, except that the velocity scale emerges from the energy equation, where convective and diffusive transport must balance each other. When this velocity scale is inserted into the momentum equation, Gr emerges. Adjustment to the temperature difference scaling ratio allows Gr to be matched, and thus for a scaled oil system, Pr, Re, and Gr of a prototypical salt system can be matched.

Table I shows scaled parameters between flibe and Dowtherm A oil at characteristic coolant temperatures in FHRs. The subscripts m and p are used for model and prototypical parameters, respectively. These scaling parameters and the use of Dowtherm A as a simulant fluid serve as the design basis for CIET 1.0. Table II shows the impact of temperature on the range of nondimensional parameter values in the prototypical and model primary loops, using characteristic length scales and velocities in the FHR core and CIET 1.0 heater under natural circulation operation. With a 104°C temperature difference across the FHR core, matching the average Pr through average fluid temperature and Gr through temperature difference in the scaled system leads to moderate distortions for Pr at both ends of the temperature space, as shown in Fig. 2.

IETs include the capability to vary parameters such as power, temperature, flow velocity, or geometric configuration to meet different scaling requirements. The response of the system to parametric variations can identify the relative roles of different phenomena and increase the confidence in the capability of models to predict the integral system performance. In CIET 1.0, power can be varied from 0 to 10 kW, temperatures are controlled through heat addition/rejection to/from the system through an electrical resistive heater and variable speed fan-cooled heat exchangers, and flow velocity is varied using a variable speed motor on the primary loop's centrifugal pump. The CIET 1.0 design has extensive modularity to allow future modifications.

Table I. Scaling parameters to match average Pr, Re and Gr for flibe and Dowtherm A.

		DRACS loop		Primary coolant loop
		Normal operation mode	Natural circulation mode	
Flibe average temperature [°C]		543	567	652
Dowtherm A average temperature [°C]		51	59	95
Length scale	L_m/L_p [a]	0.49	0.48	0.45
Velocity scale	U_m/U_p [b]	0.70	0.69	0.67
ΔT scale	$\Delta T_m/\Delta T_p$ [c]	0.31	0.31	0.30
Transient time scale	τ_m/τ_p [d]	0.70	0.69	0.67
Pumping power	$P_{p,m}/P_{p,p}$ [e]			3.1%
Heating power	$P_{q,m}/P_{q,p}$ [f]			1.6%

[a] L: length; [b] U: velocity; [c] ΔT: temperature difference; [d] τ: transient time; [e] P_p: pumping power; [f] P_q: heating power

Table II. Impact of temperature variations on nondimensional parameter values in the FHR core and CIET 1.0 heater under natural circulation operation.

	Flibe (600 – 704°C)	Dowtherm A (80 – 111°C)
Pr	11.7 – 18.6	12.8 – 16.9
Re	139 – 215 [a]	146 – 206 [b]
Gr	$3.65 \times 10^5 – 8.89 \times 10^5$ [a]	$3.97 \times 10^5 – 8.34 \times 10^5$ [b]

[a] $L_p = 0.03$ m, $U_p = 0.02$ m/s; [b] $L_m = 0.013$ m, $U_m = 0.013$ m/s

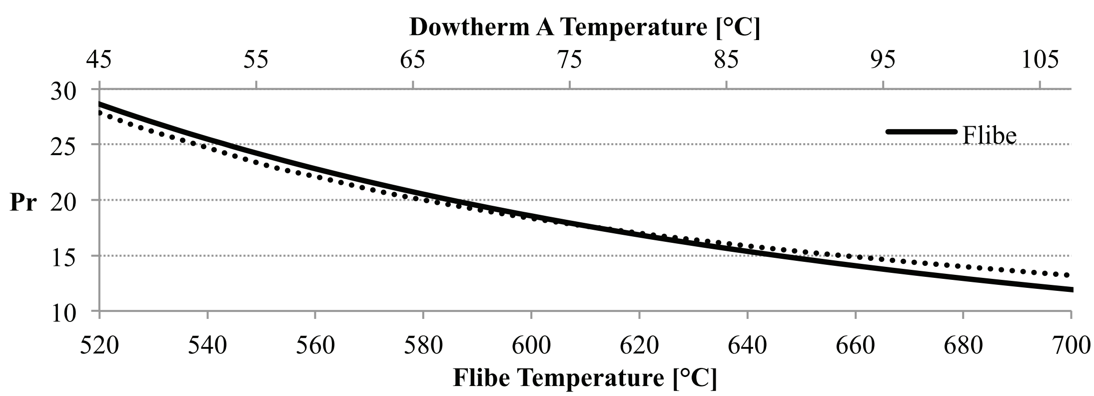

Figure 2. Impact of temperature on Pr in the prototypical and model systems.

2.2. Scaling Methodology for CIET 1.0

In this section, we detail the scaling methodology used in the design of CIET 1.0, including specific components such as the resistive heater, the heat exchangers and the primary pump.

2.2.1. General scaling criteria

Absolute heights of the primary loop heat source and sink (reactor core and DHX), and relative distances between elevations of the main heat sources and sinks for natural circulation (reactor core, DHX, and TCHX) in CIET 1.0 are scaled to ~50% of prototypical elevations in the 900-MWth channel-type PB-AHTR. Although the pre-conceptual design of a 236-MWth Mk1 PB-FHR was developed after scaling and design of CIET 1.0 were finalized [2], elevations of the main heat sources and sinks in CIET 1.0 and the Mk1 PB-FHR, on Fig. 3, reveal a reasonable agreement between the scaled model and prototype.

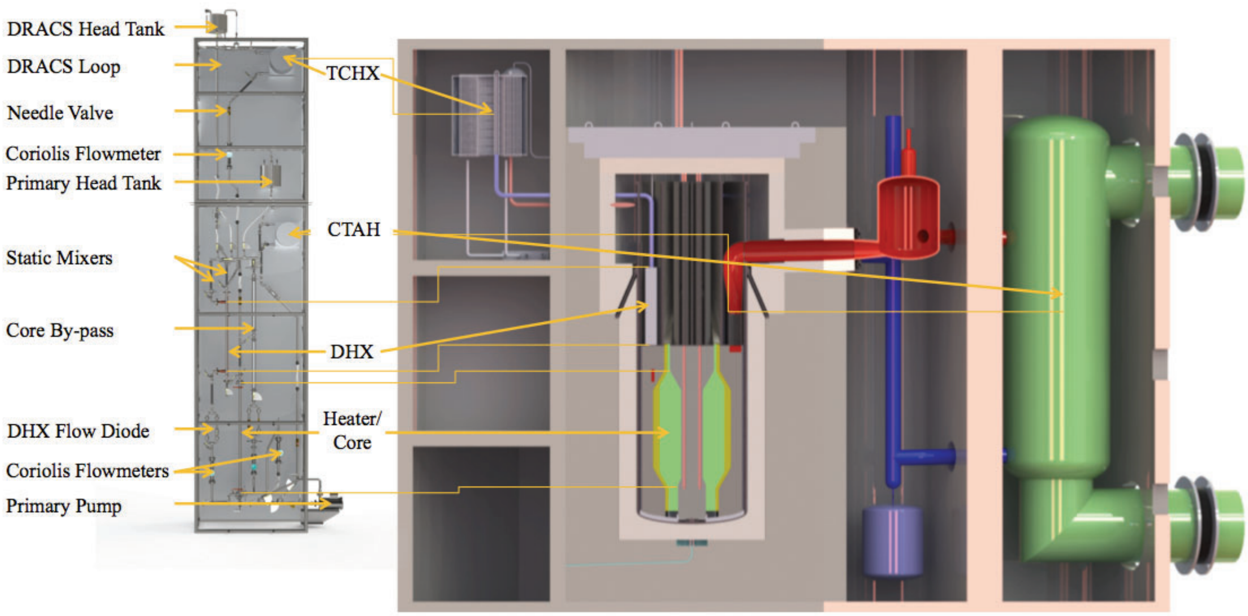

Figure 3. CIET 1.0 (left) 50% height scaling reasonably matches the Mk1 PB-FHR (right) design.

As seen in Table I, the heating power in a scaled IET facility using Dowtherm A oil is only 1.6% of the prototypical heat input into a salt system. Moreover, the CIET 1.0 heater is scaled to a prototype operating at 10% of full power. As a result, the 10-kW resistive heater installed on CIET 1.0 simulates a prototypical IET with a nominal power of 6.3 MWth. This is lower than the 236-MWth Mk1 PB-FHR, but is high compared to earlier PWR IETs and is comparable to nominal powers of planned test FHRs such as the 10-MWth solid fuel version of the Thorium Molten Salt Reactor (TMSR-SF1) experimental facility designed by the Shanghai Institute of Applied Physics in China.

Temperature scaling in CIET 1.0 is based on average temperature and temperature difference scaling factors listed in Table I. Prototypical temperatures and corresponding CIET 1.0 temperatures are listed in Table III. Temperatures for the primary loop are based on the Mk1 PB-FHR design [2], while values for the DRACS loop under natural circulation, and under forced circulation assuming 2% parasitic heat losses, are derived from preliminary analyses of the 900-MWth modular PB-AHTR using RELAP5 [7].

2.2.2. Resistive heater scaling

For CIET 1.0, it is more practical to use an annular tube geometry and a needle valve located in series with the heater to replicate the heat addition and pressure losses provided by a pebble bed core. In this heater configuration, the outer tube is heated resistively. The Mk1 PB-FHR core is simulated using a straight, annular channel resistive heater element in series with a needle valve with Reynolds-independent friction factor. The natural circulation decay heat removal flow rates in the Mk1 PB-FHR correspond to

Table III. Prototypical and CIET 1.0 temperatures.

	Mk1 PB-FHR [°C]	CIET 1.0 [°C]
Primary loop		
Minimum/average/maximum temperatures	600/652/704	80/95/111
DRACS loop (normal operation)		
Minimum/average/maximum temperatures	521/543/565	44/51/58
DRACS loop (natural circulation)		
Minimum/average/maximum temperatures	526/567/607	46/59/72

the pebble bed flow regime in which both Reynolds-dependent and Reynolds-independent terms of the friction coefficient are significant [8]. To model the dynamic behavior of the natural circulation loop, the friction coefficient of the pebble bed must be replicated over the entire flow regime. The pebble bed friction factor, f_{PB}, is given by:

$$f_{PB} = \frac{f_1}{Re_{PB}} + f_2 \tag{1}$$

where Re_{PB} is the Reynolds number in the pebble bed and various values for parameters f_1 and f_2 are found in the literature. To match the Reynolds-dependent part of the pebble bed friction factor, the annular channel friction factor must have an inverse reciprocal dependence on Reynolds. Laminar flow through a pipe has the required 1/Re functional form, so the channel is sized to ensure that flow remains in the laminar regime. To match the Reynolds-independent part of the pebble bed friction factor, a needle valve in series with the heater is convenient to adjust pressure drop. The needle valves used in CIET 1.0 have Reynolds-independent loss coefficients. Pressure drop through the valve, Δp_{valve}, depends on fluid mass flow rate, $\dot{m}$, fluid density, ρ, and valve coefficient, C_v, through:

$$\Delta p_{valve} = \frac{\dot{m}^2}{\rho {C_v}^2} \tag{2}$$

Valve curves provided by the manufacturer give the value of C_v as a function of the percent opening of the valve, and have been validated through isothermal pressure drop tests.

2.2.3. Other key components scaling

CIET 1.0 is equipped with three heat exchangers that were modeled after the three heat exchangers in a prototype reactor design: a coiled-tube air heater (CTAH), a DHX and a TCHX. In CIET 1.0, the DHX is a copper single-pass straight shell-and-tube heat exchanger, and the CTAH and TCHX are identical oil-to-air fan-cooled heat exchangers. Their designs are based on functional requirements for heat transfer performance, and only relative elevations of the heat sources and sinks are scaled to the 900-MWth modular PB-AHTR. It is important to note, however, that the ability to tune fan speeds on both oil-to-air heat exchangers, as well as interchange the current DHX with another heat exchanger design, leaves great flexibility in heat removal options for the CIET 1.0 system.

Similar to the heat exchangers, due to the lack of a detailed pump design for a prototypical PB-FHR, the primary pump on CIET 1.0 is not scaled to any prototypical pump. Instead, its design is based on functional requirements for pump head and resulting flow rates in the system. Knowing the motor speed and pump head, flow rates can be determined using a pump performance curve. The desired range of flow rates is obtained by controlling the pump motor speed with a variable frequency drive (VFD).

3. DESIGN AND FABRICATION OF CIET 1.0

This section details the design and fabrication phases of the CIET 1.0 experiment. This includes good practice in the design of CIET 1.0 that is applicable to future iterations of CIET and other IETs.

3.1. Design of CIET 1.0

Flow paths in the CIET 1.0 fluid loop, controlled through valve alignments, replicate the primary and DRACS flow paths of the Mk1 PB-FHR. A simplified version of the CIET 1.0 piping and instrumentation diagram is shown in Fig. 4. The primary flow loop consists of the pump manifold, electrical heater branch and CTAH branch. The DHX branch of the primary circuit, similar to the prototypical DHX branch in the Mk1 PB-FHR, has high flow resistance for upwards flow through the DHX during forced convection, therefore limiting parasitic heat losses to the DRACS loop under normal operation. Similarly, this leg has low flow resistance for downwards flow through the DHX, and would simulate natural circulation decay heat removal if the reactor core cooling pump were to fail in a prototypical reactor. The primary circuit is also equipped with a by-pass branch, which simulates by-pass paths in the Mk1 PB-FHR. Relative flow resistances between all branches are regulated with needle valves, which provide Reynolds-independent flow losses. The computer aided design rendering of the CIET 1.0 loop is shown in Fig. 3 (left) with the main components labeled. Practical design aspects for some of these components are detailed herein. While vendor-provided information was key in supporting the design phase of CIET 1.0, all design values have subsequently been experimentally validated and, if necessary, updated.

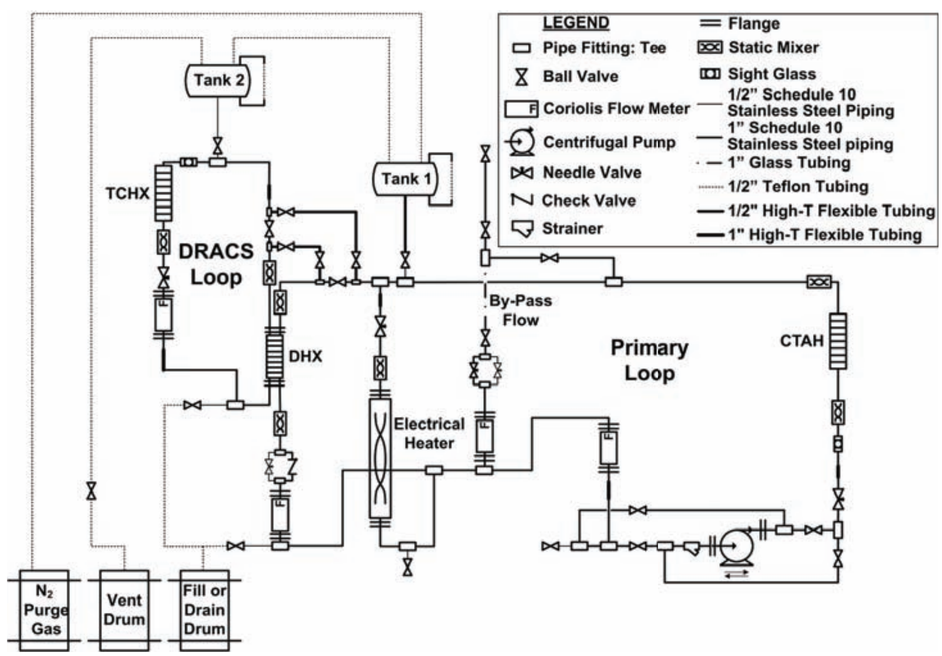

Figure 4. Simplified CIET 1.0 piping and instrumentation diagram [9].

3.1.1. Electrical heater

A resistance-heated annular electric heater simulates heat generation in the core. The scaling methodology for the CIET 1.0 heater is detailed in Section 2.2.2. The computer-controlled power supply is designed to supply up to 10 kW of input heat to the fluid while not exceeding a surface temperature of 250°C in all operating modes of the facility. Additionally, the controller can provide time-dependent power profiles to the heater to simulate reactor scram and decay heat generation in the FHR core. The heater is equipped with five surface thermocouples (TCs) and several other in-line TCs at the fluid inlet and outlet for further characterization of heat transfer performance.

3.1.2. CTAH and TCHX

Commercial air-cooled heat exchangers simulate heat extraction from two locations on CIET 1.0: the power conversion system through the CTAH in the primary loop, and the TCHX in the DRACS loop. They are designed to extract up to 10 kW under forced circulation and 2 kW under natural circulation, or 10% and 2% of scaled reactor full power, respectively. Computer-controlled VFDs connected to the fan-cooled heat exchangers allow for automated control strategies for various LBEs, where fan speed is varied to match the predicted heat load in the prototypical CTAH and TCHX. Appropriate heat exchangers were selected based on the temperature requirements listed in Table III. Inlet and outlet temperatures and fan motor speeds are recorded continuously through the CIET 1.0 data acquisition (DAQ) system.

3.1.3. DHX

The DHX is designed to transfer up to 2 kW with minimal thermal resistance between the primary loop and the DRACS loop. The modular design of CIET 1.0 can accommodate testing of several DHX designs. The initial (CIET 1.0) configuration of the DHX includes a baffled tube-in-shell heat exchanger.

3.1.4. Flow diode

The DRACS in FHRs require flow diodes to restrict upward primary coolant flow through the DHX under forced circulation, but to provide low downward flow resistance for natural circulation. Flow diode options include check valves, flapper valves, and fluidic diodes. The flow diode in the CIET 1.0 DHX branch is simulated using two valves in parallel. For flow control, a needle valve is used to ensure the desired amount of by-pass flow in the upwards direction during forced circulation. On a parallel branch, a check valve is used to block flow in the upwards direction and allow free flow in the other direction.

3.2. Good Practice in the Design of CIET 1.0

Several noteworthy elements were included into the design of CIET 1.0, which help with modularity and interchangeability of components, and extend the service life of the facility, allowing for future research.

3.2.1. Sight glasses and gas entrainment

Gas entrainment in the oil loop must be avoided to prevent distortions in pressure drop and heat transfer. In order to monitor for entrained gas during forced circulation operation, sight glasses were installed in two locations on the CIET 1.0 flow loop: one on the primary loop, and one on the DRACS loop. Gas entrainment can be visually monitored through these sight glasses, which are located near the high points of each loop. These 20-cm-long glass sections connect to the piping with Viton double-o-ring seals. In addition to monitoring entrained gas, the ability to vent gas bubbles from the loop is critical. Vent points, using manometer ports or vent valves, are located at every local high point in the loop. Moreover, every horizontal length of piping is slightly sloped to enable entrained gas to rise to a local high point (and vent location). All vent valves are connected to the manometer manifold purge system, to contain any overflow and to control the release of Dowtherm A vapor. The use of sloped lines is also key in enabling complete draining of the loop for maintenance and repairs.

3.2.2. Thermal insulation and guard heating

It is desirable to minimize heat losses from the loop to the ambient surroundings. Although the piping has been fully insulated, there remain some non-negligible parasitic heat losses from protruding metal parts such as uninsulated manometer ports and valve handles. To limit heat losses, an infrared camera has been used to identify hot spots that require additional insulation, and subsequently guard heating will be used to further reduce parasitic heat losses. Two sets of transparent polycarbonate panels are installed on the sides of the CIET frame. Each panel is 0.635 cm thick and the air layer between the two panels provides effective thermal insulation. Rubber gasket material seals the interstitial space between each panel and the steel CIET frame. The front of the CIET enclosure is also sealed by an insulated rolling-shutter door system. Extruded aluminum panels with foam cores can be raised to adjust valves or provide sight access to components inside the frame. Inside the CIET enclosure, a space heater circulates heated air.

3.2.3. Modularity

The DHX and the resistive heater on the flow loop were designed so that they can easily be removed from the loop piping. As the point design for a commercial FHR develops further, new DHX designs (e.g., twisted tube heat exchangers) can be investigated. Similarly, the resistive heater design can easily be modified to better match relative residence times in key subsystems.

3.2.4. Shutdown rod channel and core by-pass line

A by-pass flow line in the CIET 1.0 loop runs parallel to the resistive heater branch. This flow path simulates core by-pass flow, and therefore has a needle valve to allow the flow resistance and by-pass flow rate to be adjusted. Furthermore, it is instrumented with a Coriolis flowmeter to measure mass flow rate. In the initial configuration of CIET 1.0, this leg of the flow loop was constructed of the same stainless steel piping used for the rest of the loop. However, in subsequent iterations of the CIET experiment, this branch will be replaced with glass tubing so that the flow line will be transparent. A neutrally-buoyant element will be inserted in this channel, simulating a shutdown rod in prototypical FHRs, observed through the glass tubing. This work will continue research started at UCB in 2008 investigating buoyancy-driven passive safety shutdown rod insertion [10].

3.2.5. Centrifugal pump

A single pump is needed and was included on the primary coolant loop of CIET 1.0. By-pass connections and valves between the primary loop and the DRACS loop permit forced circulation through the DRACS for isothermal pressure drop measurements. The pump speed is computer-controlled through a VFD, so that feedback control can be done on the primary coolant flow rate for steady-state operation and various simulated LBEs. A pump manifold is included in the design, to run the primary loop flow in both directions for pressure measurements across the DHX.

3.3. Instrumentation and Data Acquisition

In this section, we describe instrumentation and the DAQ system used to collect data from CIET 1.0.

3.3.1. TCs, RTD probes, and temperature measurements

CIET 1.0 uses type-T sheathed TCs, which are best suited for measurements in the -200 to +250°C range, with a ±0.5°C accuracy. Small-sheath-diameter (0.02") TCs were chosen for their fast response time. All TC junctions are ungrounded to minimize signal noise. In total, 47 TCs are positioned at various locations around the CIET 1.0 loop. In-line TCs are used to measure bulk fluid temperatures. At each measurement point, two TCs are installed at different radial locations in the flow, to indicate any temperature non-homogeneity (e.g., thermally stratified flow). Static mixers are installed upstream of in-line TCs to ensure an accurate measurement of bulk fluid temperature. Surface TCs measure external surface temperature of the heater at five different axial locations, and ambient condition temperatures inside the CIET frame.

TCs must be calibrated yearly against a resistance temperature detector (RTD) measurement system. While calibration was initially done off the loop before the TCs were installed on CIET 1.0, after installation, calibration can be redone in-situ against two RTD probes installed in two thermowells on the loop, located in the pump manifold and in the DRACS loop (low and high elevations). This option allows for frequent recalibration by running the loop with isothermal conditions. The on-loop RTDs are designed to be easily removable from their thermowells and sent to the vendor for recalibration.

3.3.2. Pressure measurements

All pressure measurements taken from the CIET 1.0 flow loop are direct head measurements read through 16 transparent manometers. All manometer lines connect to the same tubing diameter. Therefore, at the connection point on the loop, the flow cross-sectional area is the same for all manometer lines, and for pressure drop measurements, the dynamic pressure term of the Bernoulli equation can be disregarded. Manometers from both the primary and DRACS loop use transparent Teflon tubing, routed to a vertical manometer board. Two digital cameras are used to record oil levels in the primary and DRACS loop manometers. These cameras are remotely operated from the computer control station. Pictures are taken and digitally transmitted to the CIET computer, and fluid levels are converted to relative pressure measurements with an automated script.

3.3.3. Flow rates measurements

Four Coriolis flowmeters provide direct, dynamic, bidirectional mass flow rate measurements in each branch of CIET 1.0. They were sized to provide accurate measurements within ±2% uncertainty of the mass flow over the expected flow range of the loop. By appropriate valve alignment, CIET 1.0 allows forced circulation flow to be induced through multiple flowmeters in series. Comparison of the measured flow rates can confirm that individual flowmeter calibrations are not drifting.

3.3.4. DAQ system and interface with LabVIEW software

CIET 1.0 is equipped with a National Instruments DAQ system, which sends data to the CIET control computer. With a total of 64 input channels, the DAQ system can accommodate the 47 TCs and 4 flowmeters used for temperature and fluid mass flow rate measurements. The DAQ system takes the signals generated from the TCs and flowmeter transmitters, and writes the data to individual files. On the CIET 1.0 control station, the National Instruments LabVIEW 2013 software has been installed for optimal integration with the DAQ system. LabVIEW has a series of key virtual instruments (VIs) for control and data acquisition from CIET 1.0:

- The “DAQ Assistant” VI is used to calibrate and coordinate instrumentation, and properly process TC and flowmeter transmitter signals through LabVIEW.
- Three VFDs, used to control the pump motor and the CTAH and TCHX fan speeds, are controlled, manually or through automatic feedback, through LabVIEW. By integrating VFD control and data acquisition, LabVIEW is a powerful tool to test control strategies on CIET 1.0.

3.4. Fabrication of CIET 1.0

CIET 1.0 uses modular construction, with piping subassembly sections installed inside a steel frame 7.6 m in height and 1.8 m in width. The experimental loop uses 3.34-cm-outside-diameter (1.315” OD, 1” nominal) Schedule 10 (0.28-cm-wall-thickness) 304L stainless steel piping. Due to the large size of the experiment, it was split into upper and lower modules that were mated together during final assembly. Figure 6 shows the timeline of the CIET project. In particular, Fig. 7 shows various stages of the insulation process, and Fig. 8 shows the lower and upper frame assemblies and piping being placed in their final location.

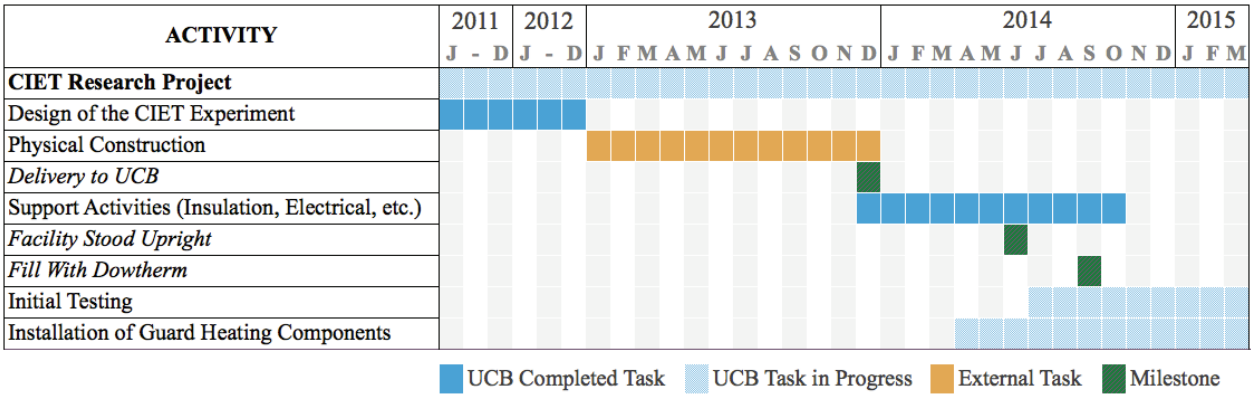

Figure 6. CIET project timeline.

Figure 7. CIET 1.0 piping insulation in progress, February 2014 (left), March 2014 (center) and April 2014 (right).

Figure 8. CIET 1.0 lower (left) and upper (right) frame assemblies being set in place, June 2014.

3.5. Initial Fill-up

The CIET loop was first filled up with Dowtherm A on September 15th, 2014. A fill tank was slowly pressurized with nitrogen, using a regulator and a control valve, to push the fluid into the CIET loop. Throughout the process, all transparent lines (i.e. manometer lines and sight glasses) were monitored to verify the absence of entrained gas bubbles, as shown in Fig. 9, and fluid inventory in the loop, measured by the weight of oil removed from the fill tank, was recorded. In total, 51.4 kg of Dowtherm A oil, or a total volume of 48.4 L, were loaded into the CIET 1.0 loop.

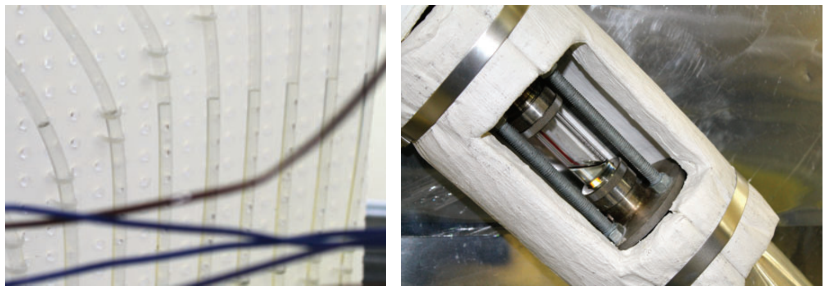

Figure 9. CIET 1.0 transparent sections monitored during fill-up to verify absence of gas bubbles.

4. RESEARCH PLAN AND INITIAL RESULTS

The formal research program for CIET was planned as follows, with specific objectives associated to each step. Completed stages of the research plan, as of March 2015, are italicized.

1. *Isothermal, forced circulation flow around the loop, with pressure data collection to determine friction losses in the system: CIET-specific friction loss correlations have been compared with handbook values, and empirically measured values have been implemented in the system codes that are to be validated by data from CIET 1.0.*
2. *Steady-state forced and coupled natural circulation in the primary loop and the DRACS loop: collected data has been compared to predicted performance and forms the validation basis for best estimate steady-state models.*
3. Thermal transients, including startup, shutdown, loss of forced circulation (LOFC) with scram and loss of heat sink (LOHS) with scram: the set of collected data will serve the double purpose of confirming strategies for operation of FHRs, and validating best estimate transient models.

4.1. Isothermal Pressure Drop Tests

In this series of tests, pressure drop was measured at various flow rates in each branch of the CIET 1.0 loop at room temperature, and CIET-specific pressure loss correlations were implemented in CIET system modeling codes. Flow rates in the loop were controlled through pump speed and, secondarily, by throttling flow through needle valves. Flow paths were controlled through valve line-up. Pressure drop in the loop was measured directly through fluid level differences in manometer lines. Ambient air and fluid temperatures were continuously measured with TCs. The flow rate ranges selected for this series of tests covered expected Reynolds numbers in each branch during forced and natural circulation operation of CIET 1.0. Pump speeds were circulated up and down to verify reproducibility of the results and absence of hysteresis. As an example, fluid levels in the CTAH and heater branch manometer lines at various flow rates are shown in Fig. 10.

The goal of this series of tests was to generate CIET-specific component-scale friction number correlations in the following non-dimensional form, which can subsequently be implemented in system modeling codes such as RELAP5:

$$K + f\frac{L}{D} = A + B\mathrm{Re}^{-C} \quad (3)$$

where f is the friction factor, L the component length, D the component hydraulic diameter, K the sum of form losses, and A, B and C empirically-derived coefficients.

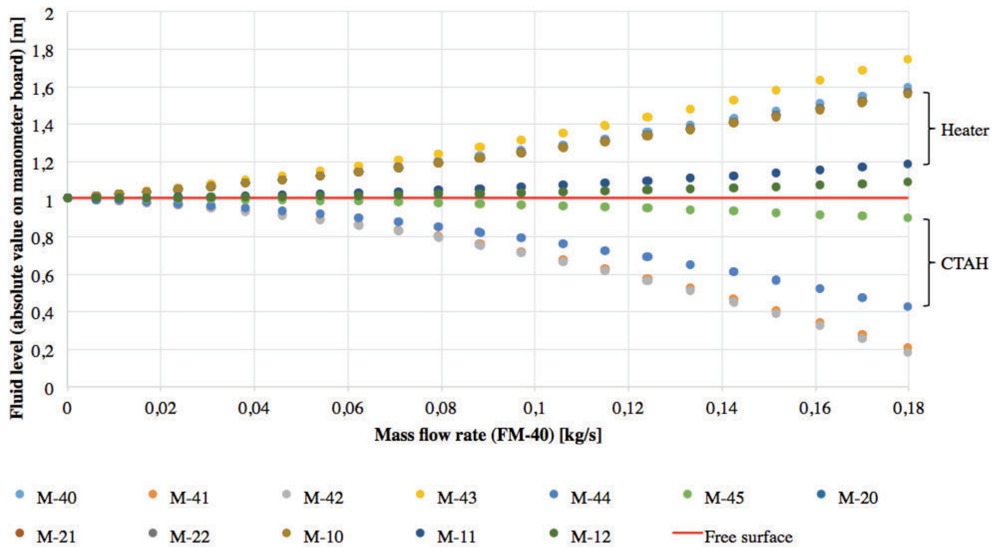

Figure 10. Fluid levels in the CTAH and heater branches at various flow rates.

The following equations were used to calculate friction and Reynolds numbers for each set of data, based on measured fluid levels, mass flow rates $\dot{m}$ and temperatures (dynamic viscosity μ and density ρ are temperature-dependent):

$$\Delta p = \frac{\rho u^2}{2}\left(f\frac{L}{D} + K\right) \Rightarrow f\frac{L}{D} + K = \frac{2\Delta \mathrm{p}}{\rho u^2} = \frac{2\rho A^2 \Delta p}{\dot{m}^2} \quad (4)$$

$$\mathrm{Re} = \frac{\rho u D}{\mu} = \frac{\dot{m} D}{A\mu} \quad (5)$$

where Δp is pressure drop, u fluid velocity and A flow cross-sectional area.

This series of tests also validated the analytical correlation for laminar flow friction factor in straight, cylindrical pipes ($f = 64/\mathrm{Re}$) and its applicability to the CIET 1.0 annular heater, with an agreement within 10% between experimental data and the analytical correlation, as shown in Fig. 11.

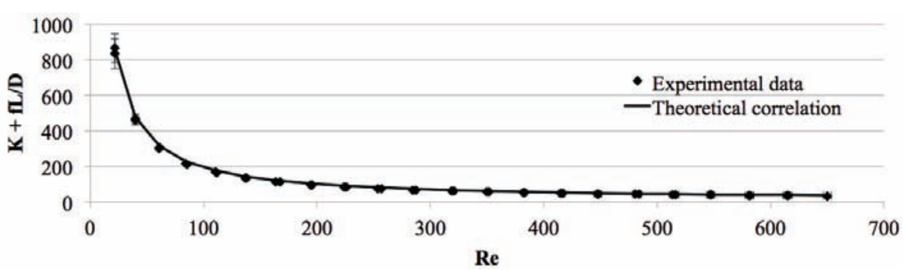

Figure 11. Friction number correlation for the CIET 1.0 annular heater.

These tests have confirmed that analytical correlations can be used for regular piping sections of CIET 1.0, and component-scale correlations for static mixers, Coriolis flowmeters and heat exchangers have been developed and match experimental data with an agreement within 10%.

4.2. Initial Heated Tests

Before steady-state forced and natural circulation, and eventually transient tests are performed on the CIET 1.0 facility, a series of initial heated tests were performed to confirm performance and the ability to control various key components of the experiment.

4.2.1. Heater control trials, parasitic heat losses

One series of experiments was aimed at testing the CIET 1.0 power supplies and heater functionality, and determining parasitic heat losses from the oil loop to ambient air through the piping thermal insulation without guard heating. This was done by varying power input from the heater and recording steady-state mass flow rates and bulk fluid temperatures in the loop with no active heat rejection. The energy conservation equation applied between consecutive temperature measurement points was used to calculate local heat losses from individual sections of the loop, and thermal insulation was enhanced in locations where high parasitic heat losses were observed. An infrared camera was used to identify specific locations where these losses occurred and to reduce them by adding thermal insulation.

4.2.2. CTAH control trials

For automated operation of the CIET 1.0 facility and optimized response to transients, feedback control must be implemented on the fan-cooled heat exchangers to vary fan motor speed based on heat exchanger average fluid outlet temperatures. An additional benefit from the development of this feedback control system involves the opportunity to collect extensive heat transfer data for these heat exchangers. This data can be used to improve models to better characterize heat rejection from the CIET 1.0 fan-cooled heat exchangers at various fan speeds, and oil and air temperatures. Throughout these tests, the heater power input was manually varied, and the CTAH feedback control system was used to control the CTAH steady-state outlet temperature. Several options were examined for feedback control of the CTAH, including proportional, proportional-integral and proportional-integral-derivative controllers.

Figure 12 shows results obtained using a simple proportional controller to vary CTAH fan speed based on CTAH outlet temperature set-points, with a fixed heat input of 1.06 kW through the resistive heater. The proportional controller, activated 4000 seconds into the test, was successful in reaching steady CTAH outlet temperatures of 40°C (step up), 38°C (step down) and 41.5°C (step up), successively.

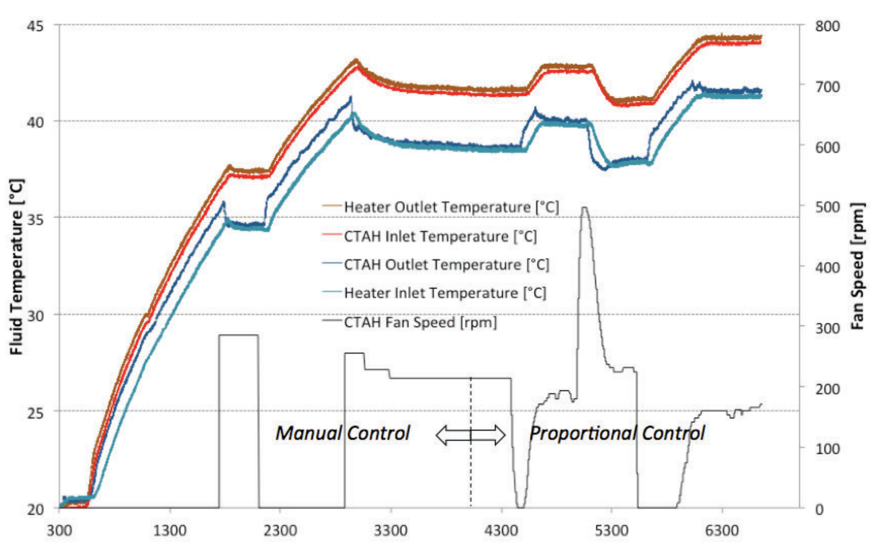

Figure 12. CTAH proportional feedback control test.

4.3. Single Loop and Coupled Loops Natural Circulation Tests

As part of the CIET research plan, single loop natural circulation in the DRACS loop and coupled natural circulation loops have been operated on CIET 1.0. For validation purposes, computational results from RELAP5 have been compared against experimental data. Experimental data and results from verification and validation (V&V) of RELAP5 models are detailed in a companion paper [11]. Reproducing such experimental setups in RELAP5 is key to better understanding thermal hydraulic phenomena specific to FHRs and how to best model them. Part of the V&V effort also includes code-to-code comparisons with the commercially available code Flownex, and the FHR advanced natural circulation analysis (FANCY) code specifically developed at UCB for CIET and FHR natural circulation modeling.

5. CONCLUSIONS AND FUTURE WORK

The CIET 1.0 facility was designed, fabricated, filled up with Dowtherm A oil, and is now fully operational, with extensive instrumentation and automated controls. Isothermal, forced circulation flow tests around the loop were completed, with pressure data collection 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 by data from CIET 1.0. Simple, initial heated tests were also completed, including parasitic heat loss tests at nominal flow rates and heat inputs from the resistive heater, and feedback control tests on the primary pump and fan-cooled heat exchangers. Further heated tests included steady-state natural circulation in the primary loop and the DRACS loop. Collected data was compared to predicted performance and forms the validation basis for best estimate steady-state models. Thermal transients (startup, shutdown, LOFC with scram and LOHS with scram) will also be run on CIET 1.0. The set of collected data will serve the double purpose of confirming strategies for operation of FHRs, and validating best estimate transient models. CIET 1.0 is equipped with all necessary instrumentation and controls to analyze control logic for prototypical FHRs. To this effect, a detailed control logic strategy has already been implemented for startup of the facility, and future tests will include load following and more complex transients.

With the detailed design of the 236-MWth Mk1 PB-FHR now available, modifications can be made to the CIET 1.0 facility to enhance scaling properties between the model and full scale prototype. Modifications will include testing of various DHX designs, including twisted tube heat exchangers, based on performance data collected from the current CIET 1.0 DHX. The resistive heater will also be modified to better match friction losses and relative residence time in the prototypical Mk1 PB-FHR core. Finally, the primary loop head tank will be integrated into the flow loop to replicate the location of the main salt pumps hot well on the hot leg of the Mk1 PB-FHR. All these modifications will be implemented during the second phase of a U.S.-Department-of-Energy-sponsored integrated research project (IRP), while data from CIET 1.0 is used for benchmarking of various thermal hydraulic codes used or developed by the members of the IRP and their partners.

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