Design, Fabrication and Startup Testing in the Compact Integral Effects Test (CIET 1.0) Facility in Support of Fluoride-Salt-Cooled, High-Temperature Reactor Technology

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Executive Summary

To develop the scientific and technical basis to design and license fluoride-salt-cooled, high-temperature reactors (FHRs), the University of California, Berkeley (UCB) has conducted an experimental test program to validate simulation codes for application to FHRs. These experiments are novel, because they use organic simulants to provide the ability to reliably predict salt cooling behavior in FHRs. The capability to validate integral transient response models is a key issue for licensing new reactor designs. UCB designed and constructed the first integral effects test (IET) facility to study FHRs, called the Compact Integral Effects Test (CIET 1.0) facility, which reproduces the integral transient thermal hydraulic response of FHRs under forced and natural circulation operation. CIET 1.0 provides data to validate simulation codes for direct reactor auxiliary cooling systems, used for natural-circulation-driven decay heat removal in FHRs. CIET 1.0, shown in Fig. ES-1, is designed to replicate FHR transient response for a wide range of licensing basis events (LBEs).

Figure ES-1. The UCB CIET 1.0 facility.

The CIET 1.0 facility uses Dowtherm A oil as a simulant fluid for fluoride salts, because at relatively low temperatures (50-120°C), Dowtherm A can match 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 was scaled based on the earlier design of a 900-MWth channel-type pebble bed advanced high-temperature reactor (Bardet et al., 2008). After the scaling and design of CIET 1.0 were finalized, UCB developed a new, pre-conceptual design of a 236-MWth Mark 1 pebble bed FHR (Mk1 PB-FHR) (Andreades et al., 2014). Figure ES-2 provides an isometric view of the Mk1 primary and power conversion systems. The scaled elevations of the main heat sources and sinks in CIET 1.0 and the Mk1 PB-FHR design have reasonable agreement.

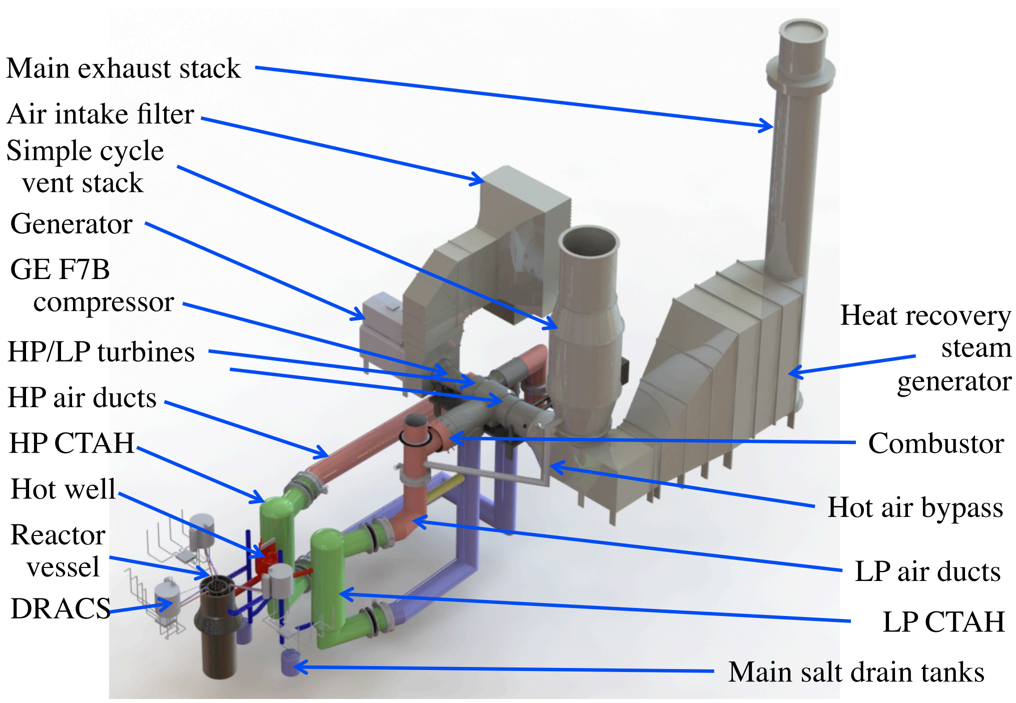

Figure ES-2. Mk1 PB-FHR primary and power conversion systems.

To develop experience prior to designing and constructing CIET 1.0, a simplified natural circulation loop was operated on the CIET Test Bay at UCB. Key components (e.g., resistive heating element and instrumentation) were tested in the CIET Test Bay before being adapted to the CIET 1.0 facility. Test loops for CIET were fabricated from stainless steel tubing and welded fittings, allowing rapid construction and design modifications. The simplicity of the construction, compared to the complexity and safety requirements for tests with the prototypical salt and other prototypical reactor coolants, was a key element in enabling the proposed experiments to be performed at much lower cost than previous IETs for other types of reactors.

Over the course of a three-year, U.S. Department of Energy funded Integrated Research Project, the CIET 1.0 facility was designed, fabricated, filled with Dowtherm A oil and operated. Isothermal pressure drop tests were completed, with extensive pressure data collection to develop validated models for flow losses in the system. CIET-specific friction loss correlations were compared with handbook values used in the initial design of the facility, and empirically measured values were implemented in the system codes that are to be validated by CIET data.

Significant insights were gained about the accuracy of different friction and form loss correlations provided by handbooks and by vendor literature for specific CIET components such as flowmeters and static mixers. The project then entered a phase of heated tests, from parasitic heat loss tests to more complex feedback control tests and natural circulation experiments, which will continue on the same facility with no major modifications in the near future. In parallel, UCB has been developing thermal hydraulic simulation models to predict FHR steady-state characteristics and transient response for a set of reference LBEs. The general FHR strategy, recommended by an expert workshop (Cisneros et al., 2013), 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 and FHR natural circulation modeling, whose results will be compared with RELAP5 and validated by data from CIET 1.0.

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Acronyms and Abbreviations

ANSI – American National Standards Institute
APEX – Oregon State University advanced plant experiment
ASME – American Society of Mechanical Engineers
AWS – American Welding Society
CIET – Compact Integral Effects Test facility
CTAH – Coiled-tube air heater
DAQ – Data acquisition
DHX – DRACS heat exchanger
DOE – U.S. Department of Energy
DOE-NE – U.S. Department of Energy's Office of Nuclear Energy
DRACS – Direct reactor auxiliary cooling system
FANCY – FHR advanced natural circulation analysis code
FHR – Fluoride-salt-cooled, high-temperature reactor
IET – Integral effects test
IRP – Integrated Research Project
LBE – Licensing basis event
LOFC – Loss of forced circulation
LOHS – Loss of heat sink
Mk1 PB-FHR – Mark 1 pebble-bed, fluoride-salt-cooled, high-temperature reactor
NEUP – Nuclear Energy University Programs
NQA-1 – Quality assurance requirements for nuclear facility applications
NRC – U.S. Nuclear Regulatory Commission
OSU – Oregon State University
PB-AHTR – Pebble bed advanced high-temperature reactor
PWR – Pressurized water reactor
QA – Quality assurance
QAP – Quality assurance plan
RTD – Resistance temperature detector
SET – Separate effects test
TC – Thermocouple
TCHX – Thermosyphon-cooled heat exchanger
UCB – University of California, Berkeley
VFD – Variable frequency drive
V&V – Verification and validation

1 Introduction and Background Information

The capability to validate integral thermal hydraulic transient response simulation codes is a key issue for designing and licensing new reactor designs, particularly those using passive safety (Cisneros, et al. 2013). The models for heat transfer, pressure drop, and other phenomena used in these codes can be validated using separate effects test (SET) experiments, where boundary and initial conditions are normally generated externally and may be varied over wide ranges. The concern exists, however, that 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, the validation of thermal hydraulic transient response simulation codes also requires comparisons with data generated in integral effects test (IET) facilities.

Fluoride salts have a number of positive attributes for use as coolants for high-temperature reactors. Due to their very high boiling temperatures (above 1400°C) and chemical stability, fluoride-salt-cooled, high-temperature reactors (FHRs) can operate with intrinsically low pressure. The salts are compatible with high-temperature structural alloys such as Alloy N and 316 stainless steel, as well as with graphite and high-temperature, coated particle fuels. Generally, peak temperatures reached in FHRs during accidents are far below damage thresholds for FHR fuel. However, it is important for design and licensing to predict peak temperatures reached by metallic structures, and for overcooling transients, to verify that freezing does not occur due to the high melting temperatures of fluoride salts (commonly around 460°C). Until the work reported here was completed, no IETs have been built to validate simulation codes for such FHR transients.

Normally, the construction and operation of a 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), would occur late in the development of a new reactor technology, due to the substantial cost of conventional IET facilities. Because the compact size and short height of fluoride-salt-cooled, high-temperature reactors 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 originally developed for use on sodium-cooled fast reactors. A system with multiple DRACS modules, as well as an independent normal shutdown cooling system, provides diverse and redundant means to remove decay heat, even in the event that the normal shutdown cooling system does not function. The baseline FHR DRACS considered here, 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 heat sink for decay heat (Andreades, et al. 2014). An isometric view of one of the three DRACS modules used in the Mk1 PB-FHR is shown in Figure

1-1. 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 is flibe (Li_2BeF_4), and the baseline DRACS coolant for the Mk1 PB-FHR is also flibe. 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 bypass 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 1-2 and Figure 1-3 show the primary coolant flow paths under normal power and shutdown cooling operation, and under natural-circulation-driven decay heat removal mode, respectively (Andreades, et al. 2014). Thicker lines in these schematics indicate main flow paths. Bypass flows are not shown for simplicity, although these will need to be quantified as they can have a significant effect on the behavior of the primary coolant loop and structural materials, particularly under forced circulation. These flow paths, as well as bypass flows, are replicated in the CIET experiment constructed at UCB, using two coupled loops, as described in further detail in this report.

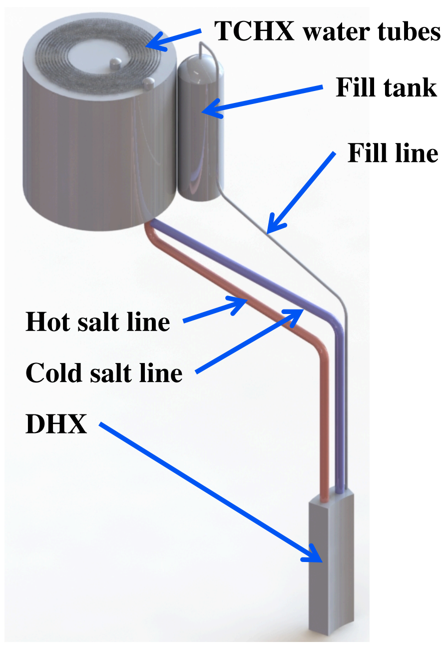


Figure 1-1. One of three DRACS modules used in the Mk1 PB-FHR.

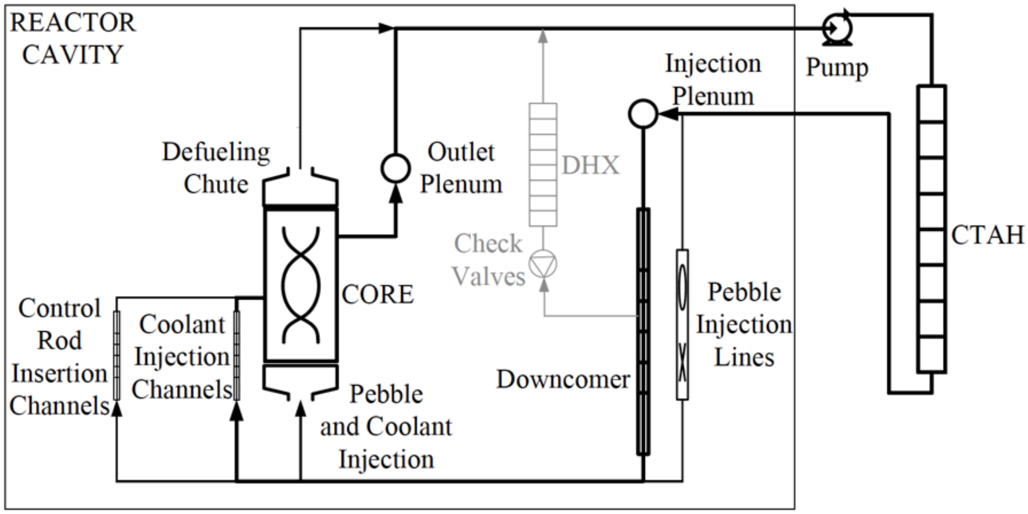


Figure 1-2. Primary coolant flow paths under normal power and shutdown cooling operation.

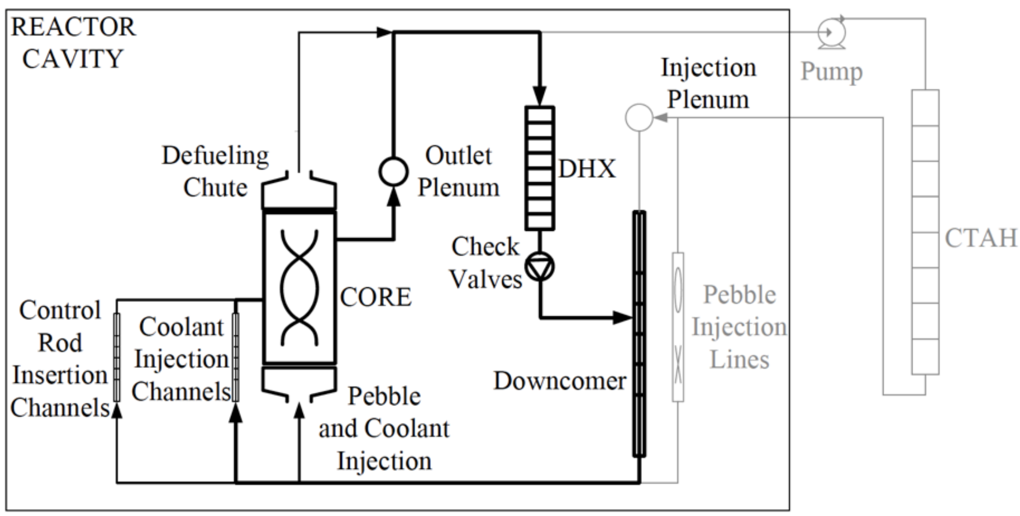


Figure 1-3. Primary coolant flow paths under natural-circulation-driven decay heat removal.

This report describes efforts to design, fabricate, and perform startup testing in the first configuration of the CIET facility at UCB, named CIET 1.0. Dowtherm A oil is used as the simulant fluid for the fluoride salt flibe in this experiment. Moreover, test loops for CIET 1.0 have been fabricated from stainless steel tubing and welded fittings. The simplicity of the 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 (Table **1**-**1**) were large facilities that provided data to validate integral thermal hydraulics 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, as detailed later in this report, the use of reduced height, area and power scaling, combined with the use of simulant fluids in CIET 1.0, allowed the construction of the entire third-generation facility with a budget under $1 million.

Table 1-1. Comparison of the third-generation CIET 1.0 IET, with the first-generation Semiscale, BETHSY and ROSA-IV IET facilities.

Facility	CIET	Semiscale	BETHSY	ROSA- IV
Plant type	AHTR/FHR	PWR	PWR	PWR
Effective power (MW)	6.3	2.0	3.0	10
Actual power (MW)	0.01	2.0	3.0	10
Fraction of scaled full power	10%	100%	10%	14%
Effective flow area scaling	1:190	1:1705	1:100	1:48
Actual height scaling	1:2	1:1	1:1	1:1
Time scaling	1:1.4	1:1	1:1	1:1

The reference system that was used for initial scaling of CIET 1.0 was a 900 MWth modular pebble-bed, advanced high-temperature reactor (PB-AHTR) using a core composed of pebble channel assemblies (Bardet, Blandford, et al. 2008) with higher core pressure drop than the annular pebble core design selected for the Mk1 PB-FHR (Andreades, et al. 2014). 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 reactor. 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. When further detail is available for the specific FHR of interest, distortions and applicability of this data can be further evaluated.

Before CIET 1.0 was built, a CIET Test Bay was constructed and operated to develop experience and provide initial forced and natural circulation data. Detailed progress on the CIET Test Bay was described in a previous report to the U.S. Department of Energy (DOE) Nuclear Energy University Programs (NEUP) (Scarlat, Bickel, et al. 2012). Most of the major components of the CIET 1.0 facility, listed in this report, were tested on the 10-kW CIET Test Bay, including the instrumentation configuration, data acquisition (DAQ), and computer control systems. A simple natural circulation loop was also studied in the CIET Test Bay. The loop consisted of an annular resistance-heated channel at the lower elevation of the loop, and a water-cooled heat exchanger module at the top. The single natural circulation loop provided an initial simple validation case for RELAP5-3D modeling of natural circulation decay heat removal in FHRs, and it helped identify improvements needed in the design and choice of instrumentation for the CIET 1.0 facility. For example, experience with venting gas bubbles in the Test Bay resulted in careful efforts in designing the piping orientation of the CIET 1.0 facility. In particular, horizontal pipes in the CIET 1.0 experiment always included a slight slope and a vent point in local maximum elevation locations to allow bubbles and entrained gasses to vent more easily.

In 2011, the NEUP office put out a call for an Integrated Research Project (IRP) to investigate advanced thermal reactor concepts. DOE's Office of Nuclear Energy (DOE-NE) requested programs “utilizing both in-reactor and non-reactor testing” and teams to “utilize a cadre of experimental facilities to demonstrate critical technologies” (U.S. Department of Energy’s Office of Nuclear Energy 2011). Under Task 4 (“Thermal Hydraulics, Safety, Licensing, and Related Tools”) of the original technical proposal submitted by the IRP (Forsberg, et al. 2011), UCB had the primary responsibility for developing thermal hydraulic and neutronic modeling tools to predict FHR steady-state and transient response characteristics for a variety of LBEs. UCB proposed an experimental test program to validate simulations of reactor thermal hydraulic conditions, using organic simulants to provide the ability to reliably predict salt cooling behavior in FHRs. This task included experimental validation of computational tools used for thermal hydraulic analysis of FHRs. This report is one of the deliverables for the IRP.

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. Specific information about instrumentation and data acquisition is provided in Section 4. The CIET project follows a stringent quality assurance (QA) program presented in Section 5. In Section 6, key tasks for the CIET 1.0 research plan are listed, and initial experimental results are provided. Section 7 explains the methodology developed for thermal hydraulic modeling of the facility and validation efforts pursued using CIET 1.0 data. A cost table and a timeline for the three-year project are provided in Section 8. Finally, the current status of the program and future work with CIET 1.0 are reviewed in Section 9.

2 Scaling and Simulant Fluids

Thermal hydraulic transient phenomena associated with FHR response to LBEs evolve over relatively short time periods. Time scales can range from the order of minutes to days. Therefore, the major constraint on thermal hydraulic experiments in support of FHR technology 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 geometric and power scaling was recognized early in the pre-conceptual design of the FHR (Blandford and Peterson 2009), and scaling methodologies were developed and applied to the design of the CIET 1.0 facility.

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 remarkably 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 (Bardet and Peterson 2008). Prandtl number dictates the selection of the simulant liquid and its average operating temperature for scaled thermofluid 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 reproduce flow transitions from laminar to turbulent and wall shear stresses. If Pr is also matched, along with the scaled flow-channel geometry, when mass, momentum, and energy conservation equations are nondimensionalized, the solutions become identical. Therefore, the Nusselt number (Nu) for forced convection heat transfer is matched. These observations explain the well-known form of the Dittus-Boelter correlation for $\mathrm{Re} > 10000$:

$$\mathrm{Nu} = 0.024 \cdot \mathrm{Re}^{0.8} \mathrm{Pr}^{0.33}$$

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. Because the Froude number (Fr) can be expressed as a ratio of Re and Gr (Fr = Re^2/Gr), Fr is also matched.

Simplified correlations for flibe's temperature-dependent density (ρ), dynamic viscosity (μ), heat capacity (c_p) and thermal conductivity (k), based on data in the 600 to 800°C range, are as follows, with the temperature T in ºC (Williams, Toth and Clarno 2006) (Sohal, et al. 2013):

$$\rho = 2279.92 - 0.488 \cdot T \ (\mathrm{kg/m^3})$$

$$\mu = \frac{(4.638)10^5}{T^{2.79}} \ (\mathrm{kg/m \cdot s})$$

$$c_p = 2415.78 \ (\mathrm{J/kg°C})$$

$$k = 0.7662 + 0.0005 \cdot T \text{ (W/m°C)}$$

Dowtherm A is a eutectic mixture of two thermally stable compounds, biphenyl ($C_{12}H_{10}$) and diphenyl oxide ($C_{12}H_{10}O$). The manufacturer, Dow Chemical, recommends using this fluid in the temperature range between 15°C and 400°C. Combined with its remarkable thermophysical properties to simulate heat transfer in fluoride salt systems, its high stability makes Dowtherm A an ideal candidate for scaled IETs such as CIET 1.0. Dowtherm A's temperature-dependent thermo-physical properties, based on data in the 20 to 180°C range, are as follows, with the temperature T in °C (The Dow Chemical Company 1997):

$$\rho = 1078 - 0.85 \cdot T \text{ (kg/m}^3\text{)}$$
$$\mu = \frac{0.130}{T^{1.072}} \text{ (kg/m} \cdot \text{s)}$$
$$c_p = 1518 + 2.82 \cdot T \text{ (J/kg°C)}$$
$$k = 0.142 - 0.00016 \cdot T \text{ (W/m°C)}$$

Table **2-1** shows scaled parameters between flibe and Dowtherm A 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 the CIET 1.0 facility. Table **2-2** 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 (which are based on scaling parameters in Table **2-1**). 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. This is graphically represented in Figure **2-1**.

Table 2-1. 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 2-2. 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

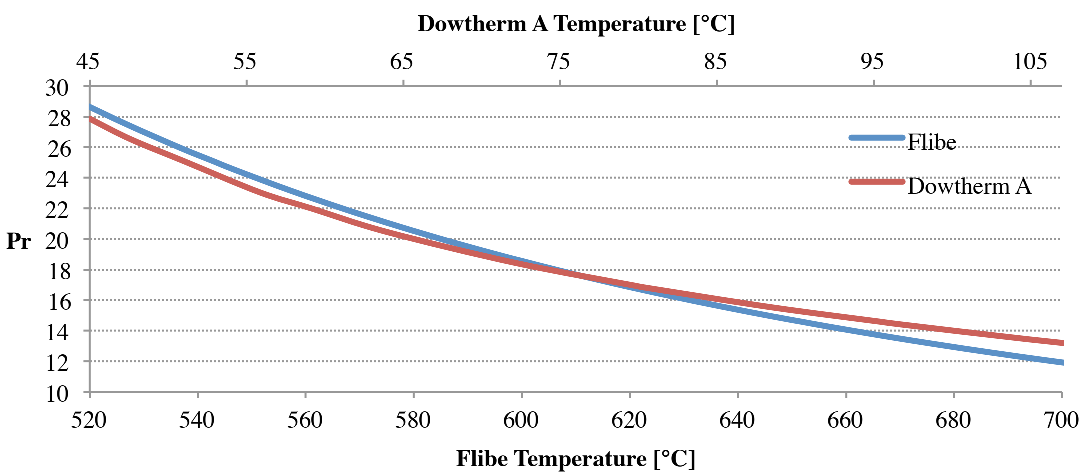


Figure 2-1. Impact of temperature on Pr in the prototypical and model systems.

Because scaled experiments inherently involve some distortions of phenomena, IET designs often include the capability to vary parameters such as power, temperature, flow velocity, or geometric configuration. The response of the system to such parametric variations can often identify the relative roles of different phenomena and increase the confidence in the capability of models to predict the integral system performance. In the case of CIET 1.0, as described in this report, power can be varied in the range from 0 to 10 kW, temperatures are controlled through heat addition and 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. Finally, while the geometric configuration of CIET 1.0 is fixed, the design has extensive modularity to allow future modifications. This last item is important because at the time of the initial design and construction of the CIET 1.0 facility, several parameters in the Mk-1 PB-FHR design had not yet been developed.

2.2 Preliminary Component Testing on the CIET Test Bay

Prior to design and construction of CIET 1.0, a simplified natural circulation loop was operated on the CIET Test Bay at UCB. As previously mentioned, details of the CIET Test Bay project can be found in an earlier report submitted to NEUP (Scarlat, Bickel, et al. 2012). Components tested on the CIET Test Bay before being adopted for use in the CIET 1.0 facility are described here.

2.2.1 Heater Element Simulating the PB-FHR Core

The heater, which simulated the heat input of the PB-FHR core, was an annular flow pipe, electrically heated with DC current, and instrumented with in-line and surface thermocouples (TCs). A test heater element of reduced length was first assembled and leak tested. A full-length annular heater element was subsequently installed on the CIET Test Bay and used for data collection in the Test Bay. Figure **2-2** shows assembled end-sections for the annular heater element tested on the CIET Test Bay, and Figure **2-3** shows the detailed design of an annular heater initially intended for use on the CIET facility. Design of the heater was subsequently simplified for CIET 1.0, as described later in this report.

Figure 2-2. Assembled end-sections for the annular heater element tested on the CIET Test Bay. For complete assembly of the annular heater element, two concentric tubes slide into the end sections.

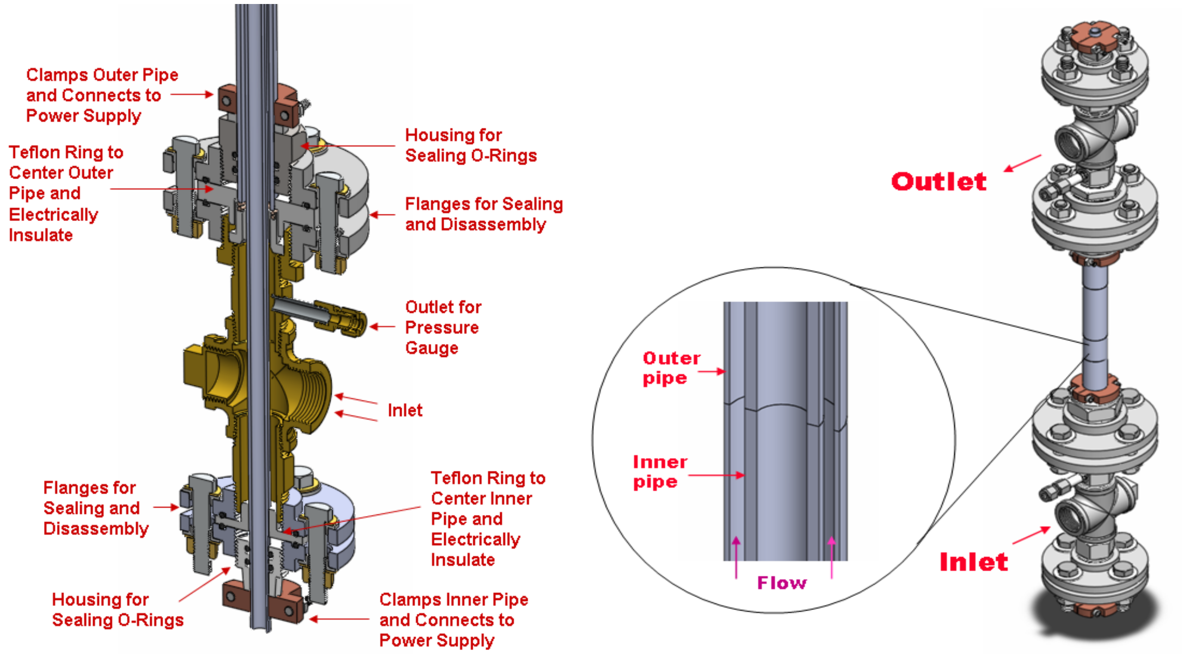


Figure 2-3. Detailed design of the annular heater element for the CIET Test Bay.

2.2.2 DRACS Heat Exchanger

The oil cooler on the CIET Test Bay, which reproduced the thermal load of a DHX, was assembled from silver-brazed copper tubing and connectors, and a limited number of threaded NPT connections. It was a simple tube-in-tube heat exchanger with Dowtherm A oil flowing through four parallel legs. The shell side of the heat exchanger carried tap water, and the tube side carried Dowtherm A. The oil cooler was instrumented with TCs on the outside of the tube-side wall. Moreover, manometers at the inlet and outlet were used for direct measurement of the coolant head, to calculate pressure drop across the cooler. As the oil cooler's tube-in-tube heat exchanger was a system of four parallel legs, one, or all flow paths could be used. This flexibility was needed during operation of the CIET Test Bay as no detailed design for a DHX in the Mk1 PB-FHR had yet been developed. Moreover, the water cooling of the oil cooler could be adjusted easily, which allowed variance in heat removal during natural circulation experiments while power input was varied over the range from 1 kW to 10 kW.

Because CIET 1.0 is a coupled-loop natural circulation experiment (as opposed to the single natural circulation loop operated on the CIET Test Bay), one major difference between the two facilities was the design of the CIET 1.0 DHX, which couples to a scaled DRACS loop. As detailed later in this report, a more prototypical shell-and-tube heat exchanger is used for the CIET 1.0 DHX, with Dowtherm A oil flowing on both sides.

2.2.3 Instrumentation

A Siemens Coriolis flowmeter was used on the CIET Test Bay. The flowmeter transmitter was configured for integration with the LabVIEW DAQ system, through a National Instruments DAQ bus that was also used subsequently on CIET 1.0. The National Instruments DAQ bus measures voltage in its default configuration. Current reading from the flowmeter transmitter was achieved by installing high precision resistors to the terminals that measure current. The same flowmeter vendor and hardware-software integration method is used on CIET 1.0.

For direct pressure measurements, 1/4" semi-transparent Teflon tubing manometer lines were used and subsequently replicated in CIET 1.0. This tubing is designed to work with compression fittings, allowing for easy connection to the metal fittings on the isolation valves for the loop pressure taps. Construction and sloping of the manometer tubes was designed to ensure that gas bubbles were not trapped in the lines, and thus distorting measured values.

In-line, type-T sheathed TCs were installed and tested on the CIET Test Bay. Several measurements were taken in series along the same flow leg to ensure that the in-line TCs accurately reflected bulk fluid temperatures. To do this, flow loop piping included tees and other ports that allowed for the insertion of the sheathed TCs directly into the fluid. Custom teflon TC guides were designed and fabricated (Figure 2-4) to ensure that TCs could be inserted into the flow and remain at a given, desired location, and that the temperature reading was taken at the center of the piping, and not against the surface of the piping or other solid components. The same teflon TC guides were used on CIET 1.0.

At the outlet of the CIET Test Bay heater and heat exchanger, static mixers (Figure 2-5) were added before the in-line TCs. This ensured that measured temperature was representative of the bulk temperature of the fluid. These Test Bay static mixers were designed and custom-built out of copper sheet. As these Test Bay mixers proved effective, commercially-available low pressure-drop static mixers were eventually identified and selected for installation in CIET 1.0, as discussed later in this report.

Ultimately, the experience building a smaller natural circulation loop in the CIET Test Bay proved invaluable in designing the CIET 1.0 experimental facility. Many improvements were incorporated into the CIET 1.0 facility that would have otherwise been overlooked, had the CIET Test Bay not been built.

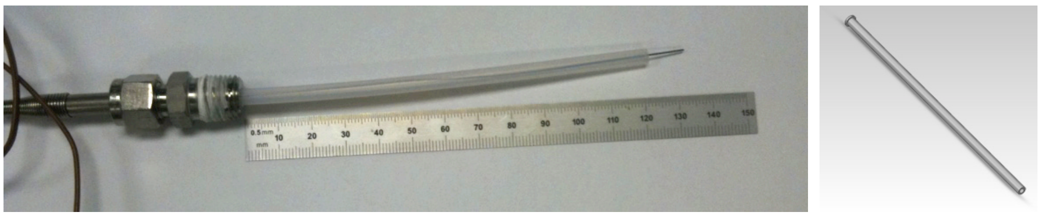


Figure 2-4. In-line TC assembly, with Teflon guide-tube (left), and 3D SolidWorks model of Teflon guide-tube (right).

Figure 2-5. 2.5-cm-diameter, 4.3-cm-long flow mixer prototype.

2.3 Scaling Methodology for CIET 1.0

2.3.1 General Scaling Criteria

Initial scaling of CIET 1.0 was based on an early design of a 900-MWth channel-type PB-AHTR design developed by UCB (Bardet, Blandford, et al. 2008). A diagram of this design is shown in Figure **2-6** with key dimensions listed. Absolute heights of the primary loop heat source and heat sink (reactor core and DHX), as well as relative distances between elevations of the main heat sources and sinks for natural circulation (reactor core, DHX, and TCHX) are scaled to ~50% of prototypical elevations in the CIET 1.0 facility. The prototype and model key dimensions are listed in Table **2-3**.

Abbreb.	Length (m)
L_{AC}	2.2
L_{CHI}	20.0*
L_{CL}	5.5
L_{CLIL}	0.5
L_{D}	9.118
L_{DD}	2.912
L_{DHX}	2.6
L_{DIL}	0.5
L_{FDL}	5.05
L_{HLD}	0.5
L_{HLII}	1.0
L_{HLN}	1.0
L_{HLP}	4.5
L_{IHX}	7.33
L_{IL}	0.5
L_{ILD}	1.0
L_{ISD}	0.5
L_{LR}	1.85
L_{NDHX}	3.5*
L_{P}	1.0
L_{LP}	4.0
L_{LPH}	0.7
L_{R}	4.0
L_{RH}	1.5
L_{TPH}	0.7
L_{UP}	4.0
L_{UPH}	0.1
L_{UR}	1.068
L_{URH}	0.618
L_{VLL}	8.0*

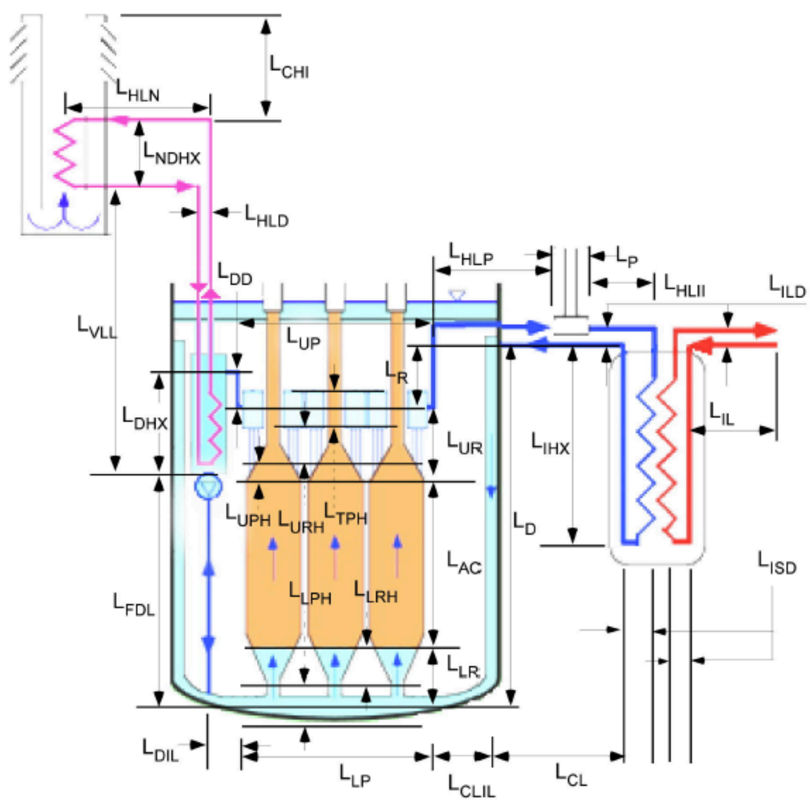


Figure 2-6. Diagram of the 900-MWth channel-type PB-AHTR design (Bardet, Blandford, et al. 2008) used for scaling of CIET 1.0.

Table 2-3. Absolute heights and relative distances between elevations of main heat sources and sinks in 900 MWth PB-AHTR and CIET 1.0.

Absolute Heights		
	Prototype	Model
Core and upper reflector/Heater	3.27m	1.62m
DHX	2.60m	1.30m
Relative Distances Between Elevations		
	Prototype	Model
Core-to-DHX/Heater-to-DHX	2.90m	1.57m
DHX-to-TCHX	8.45m	4.23m

The pre-conceptual design of a 236-MWth Mk1 PB-FHR was developed after scaling and design of CIET 1.0 were finalized (Andreades, et al. 2014). Elevations of the main heat sources and sinks in CIET 1.0 and the Mk1 PB-FHR design are shown on Figure **2-7** and reveal a reasonable agreement between the scaled model and prototype.

One take-away from Table **2-1** is that 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 (Table 1-1) and is comparable to nominal powers of planned test FHRs such as the solid fuel version of the Thorium Molten Salt Reactor (TMSR-SF1) experimental facility designed by the Shanghai Institute of Applied Physics in China. Future plans for the CIET facility include modifications to the resistive heating element to more closely match scaling of coolant residence time in the Mk1 PB-FHR.

Temperature scaling in CIET 1.0 is based on average temperature and temperature difference scaling factors listed in Table **2-1**. Prototypical temperature values for the primary coolant loop are based on the Mk1 PB-FHR design (Andreades, et al. 2014), while values for the DRACS loop under natural circulation, and under forced circulation assuming 2% parasitic heat losses, are derived from preliminary transient analyses of the 236-MWth modular PB-AHTR using RELAP5 (Galvez 2011). Prototypical temperatures and corresponding CIET 1.0 temperatures are listed in Table **2-4**.

Table 2-4. Prototypical and CIET 1.0 temperatures.

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

Mass flow rates $\dot{m}$ in various branches of the CIET 1.0 loop depend on power input Q, average fluid temperatures (which determine fluid heat capacity, c_p) and temperature differences (ΔT) through the energy conservation equation:

$$Q = \dot{m} c_p \Delta T$$

Under forced circulation in the primary loop (normal operation), the heater power is 10 kW, ΔT across the heater is 31°C, and c_p(95°C) = 1786 J/kg°C. Therefore, the mass flow rate in the primary loop is $\dot{m}$ = 0.18 kg/s.

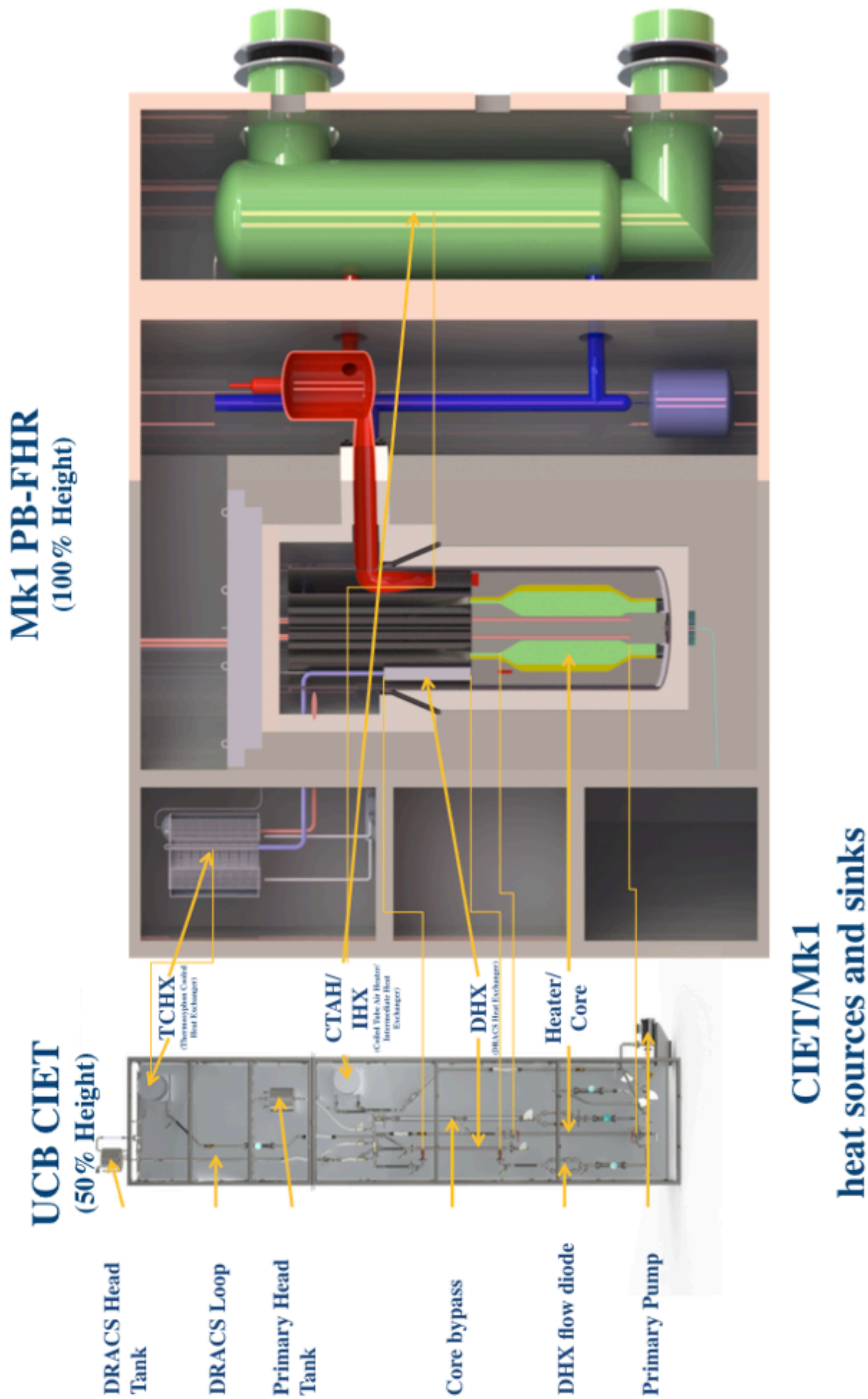


Figure 2-7. Scaling between heat sources and sinks of CIET 1.0 and the Mk1 PB-FHR.

In natural circulation operation, the heater power is 2 kW, ΔT across the heater and DHX is 31°C, and ΔT across the TCHX is 26°C. c_p(95°C) = 1786 J/kg°C and c_p(59°C) = 1684 J/kg°C. Therefore, the target flow rate in the heater/DHX loop is $\dot{m}$ = 0.036 kg/s and the target flow rate in the DRACS loop is $\dot{m}$ = 0.046 kg/s. Because under natural circulation, flow rates depend upon the balance between buoyancy driving forces and flow losses in the loop, the actual flow is likely to be different from this. However, design calculations have shown that flow losses can be adjusted through needle valves on all branches of CIET 1.0 to achieve the target flow rates in both the heater/DHX loop and the DRACS loop.

2.3.2 Resistive Heater Scaling

For IETs, 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 provided by a pebble bed core. In this heater configuration, the outer tube is heated resistively. Scaled loss coefficients can be matched between the model and prototype by throttling the orifice in the needle valve. This approach is simpler than attempting to construct a reduced scale pebble bed: heating pebbles electrically is difficult, pressure drops may be too high in a reduced scale pebble bed, wall effects become significant and can cause significant distortion, and thermal inertia may be difficult to scale. Because pebble beds have higher friction pressure losses than straight channels, it is possible to use an annular channel in conjunction with a needle valve to replicate the pressure losses of a pebble bed. The annulus gap can be adjusted to match the coolant residence time. The annular channel can be designed with low thermal inertia by using thin-walled tubing, and thermal inertia of the pebble bed can be replicated in the experimental model using a computer-controlled power input into the heater.

This annular-heater-and-needle-valve approach was used in the CIET 1.0 facility. As stated, 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, similar to the design tested in the CIET Test Bay (see Section 2.2). The natural circulation decay heat removal flow rates in the Mk1 PB-FHR correspond to the pebble bed flow regime in which both the Reynolds-dependent and the Reynolds-independent terms of the friction coefficient are significant (Scarlat 2012). To model the dynamic behavior of the natural circulation loop, the friction coefficient of the pebble bed must be replicated over the entire range of flow rates. The pebble bed friction factor, f_{PB}, is given by:

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

where various values for f_1 and f_2 are found in the literature, depending on pore velocity and bed porosity.

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 must be sized to ensure that flow remains in the laminar regime. The dimensions of the CIET 1.0 resistive heater are listed in Table **2-5**.

Table 2-5. CIET 1.0 resistive heater dimensions.

Annulus inner diameter [m]	3.18 x 10^{-2}
Annulus outer diameter [m]	3.81 x 10^{-2}
Channel length [m]	1.62
Hydraulic diameter [m]	6.4 x 10^{-3}
Cross-sectional area [m^2]	3.48 x 10^{-4}

The natural circulation mass flow rate in the heater is 0.036 kg/s and the average dynamic viscosity is μ(95°C) = 9.86 x 10^{-4} Pa-s. Therefore, Re = 666 and we can conclude that flow is 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 use because once installed, its pressure drop can be tuned to ensure that scaling is appropriately achieved in the as-built experiment. The needle valves used on CIET 1.0 have Reynolds-independent loss coefficient. Pressure drop through the valve, Δp_{valve}, depends on fluid mass flow rate, $\dot{m}$, fluid density, ρ, and valve coefficient, C_v, through:

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

Valve curves provided by the manufacturer give the value of C_v as a function of the percent opening of the valve. One important effort as part of the CIET 1.0 experimental campaign will be to validate these curves based on collected flow rate and pressure drop data.

2.3.3 Heat Exchangers 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. For lack of detailed heat exchanger designs when scaling was performed and design decisions were made for CIET 1.0, the three heat exchangers 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, as detailed in Section 2.3.1. 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.

Oil flow exiting these heat exchangers passes through static mixers, to improve the accuracy of the measurement of the oil bulk temperature. Further details on the design of the heat exchangers are provided in Section 3.1.2 and Section **Error! Reference source not found.**.

2.3.4 Pump Scaling

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 in terms of pump head and resulting flow rates in the system.

To obtain the flow rate through the CIET 1.0 primary loop, a pump performance curve can be used. Knowing the motor speed and pump head, flow rates can be determined using this curve. Multiple curves can be used to show the pump performance for varying motor speeds. Pump performance curves for motor speeds 90-1725 rpm were analytically derived during the design phase of this project using similarity laws and a pump curve provided by the vendor for a motor speed of 1725 rpm. This range is obtained on CIET 1.0 by controlling the pump motor speed with a variable frequency drive (VFD) and knowing the pump motor turndown to be 20:1.

The flow coefficient, a dimensionless parameter, is defined as:

$$C_Q = \frac{Q}{ND^3}$$

where Q is the volumetric flow rate, N is the pump motor speed, and D is the pump's characteristic diameter (impeller diameter). If two pumps are similar, they have the same flow coefficient, such that:

$$C_Q = \left(\frac{Q}{ND^3}\right)_1 = \left(\frac{Q}{ND^3}\right)_2$$

When using a fixed impeller diameter, $D_1 = D_2$, the volumetric flow rate becomes proportional to motor speed (similarity law):

$$\left(\frac{Q}{N}\right)_1 = \left(\frac{Q}{N}\right)_2$$

The pump performance curve for a motor speed of 1725 rpm, obtained from the vendor, is shown in Figure **2-8** as the green curve, along with a system curve (in blue). The system curve can be created using an energy equation:

$$h_a = \sum h_l$$

where h_a is the head added to the system by the pump and h_l is the head loss along the loop.

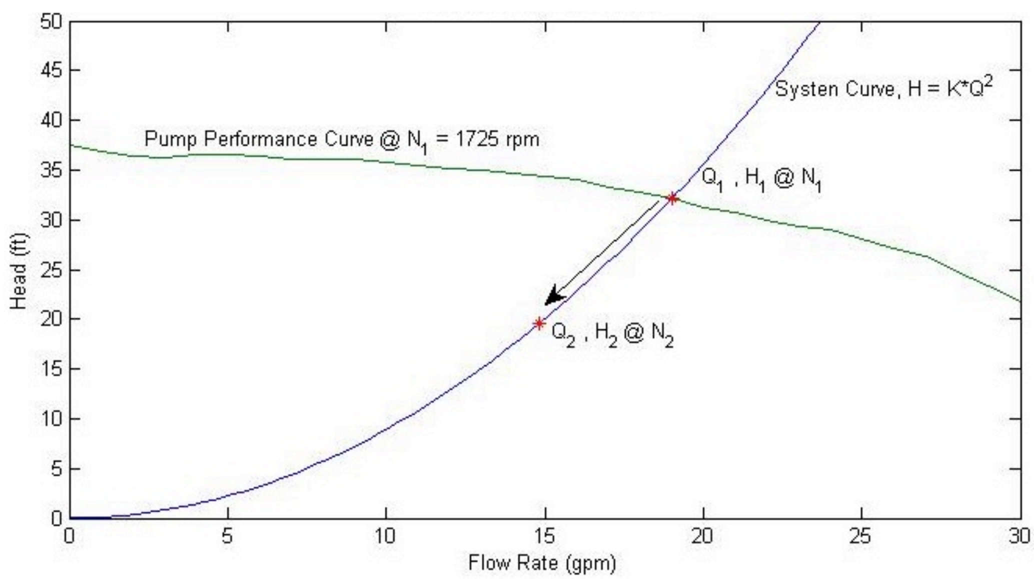


Figure 2-8. CIET 1.0 pump performance curve at 1725 rpm.

Since h_l is proportional to Q^2, the system curve is described by:

$$h_a = KQ^2$$

The intersection point of the system and pump performance curves is labeled as state 1, such that the volumetric flow rate is Q_1 and the operating head is H_1. To find Q_2 and H_2 at a new motor speed N_2, the similarity law discussed above is used. Solving the similarity law for Q_2:

$$Q_2 = \frac{N_2}{N_1} \cdot Q_1$$

The coefficient K of the system curve is determined by the following equation:

$$K = \frac{H_1}{{Q_1}^2}$$

Therefore, H_2 is:

$$H_2 = H_1 \cdot \frac{{Q_2}^2}{{Q_1}^2}$$

Resulting pump curves for a wide range of pump speeds are shown in Section 3.2. Using a variable speed motor allows to vary flow rates and study the system for a large range of Reynolds numbers.

3 Design and Fabrication of CIET 1.0

As previously mentioned in this report, CIET 1.0 has two coupled flow circuits: the primary coolant flow circuit and the DRACS circuit. The two flow circuits exchange heat through the DHX. An annular electrically powered heater heats the working fluid (in this case, Dowtherm A oil) in the primary flow circuit. A pump, located at the bottom of the primary circuit, is used to force flow around this loop. Air-cooled heat exchangers (the CTAH and TCHX) were installed on both the primary coolant flow circuit and the secondary flow circuit. The CTAH is on the primary loop and the TCHX is on the DRACS loop. Both of these oil-to-air heat exchangers exhaust heat to ambient air outside of the CIET experiment, which serves as the ultimate heat sink. In addition to the three heat exchangers, CIET 1.0 is instrumented with several flowmeters, TCs, and manometer lines in order to measure flow rates, temperatures, and pressure drops along the loops. This section details the design and fabrication phases of the CIET 1.0 experiment.

3.1 Design of CIET 1.0

The detailed design of the CIET 1.0 facility builds upon experience with the CIET Test Bay, as further explained in Section 2.2. 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 illustrated in Figure 1-2 and Figure 1-3. The resulting piping and instrumentation diagram is shown in Figure **3-1**. 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 bypass branch, which simulates bypass 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 Figure **3-2** with the main components labeled. Practical design aspects for some of these components are detailed herein. It is important to note that, while all information listed here was key in supporting the design phase of CIET 1.0 by providing predicted data for critical aspects of operation of the facility, all design values have subsequently been validated and, if necessary, updated based on experimental data collected on the loop. This effort will continue as more experience is gained running the fluid loop in various conditions.

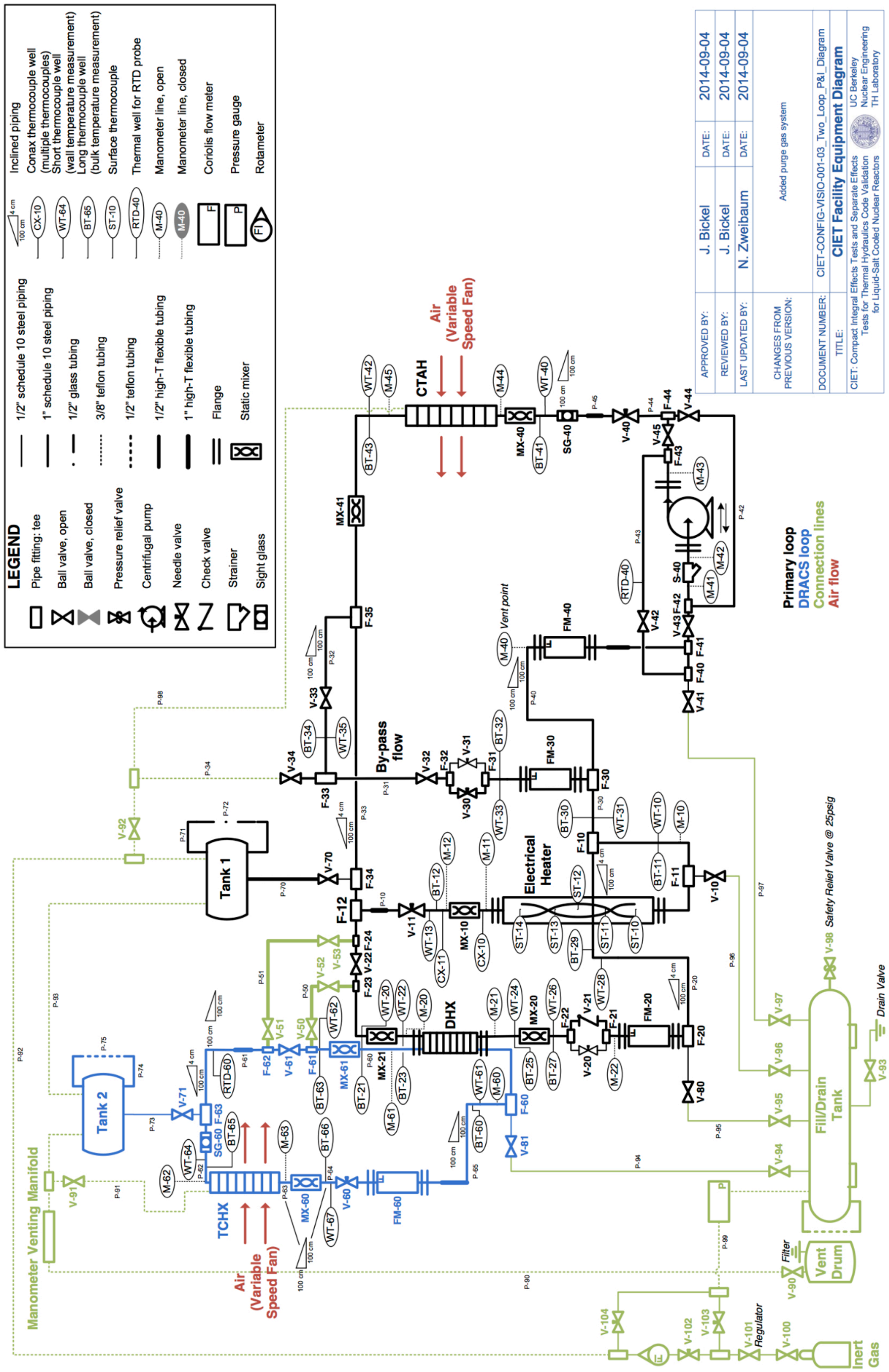


Figure 3-1. CIET 1.0 piping and instrumentation diagram.

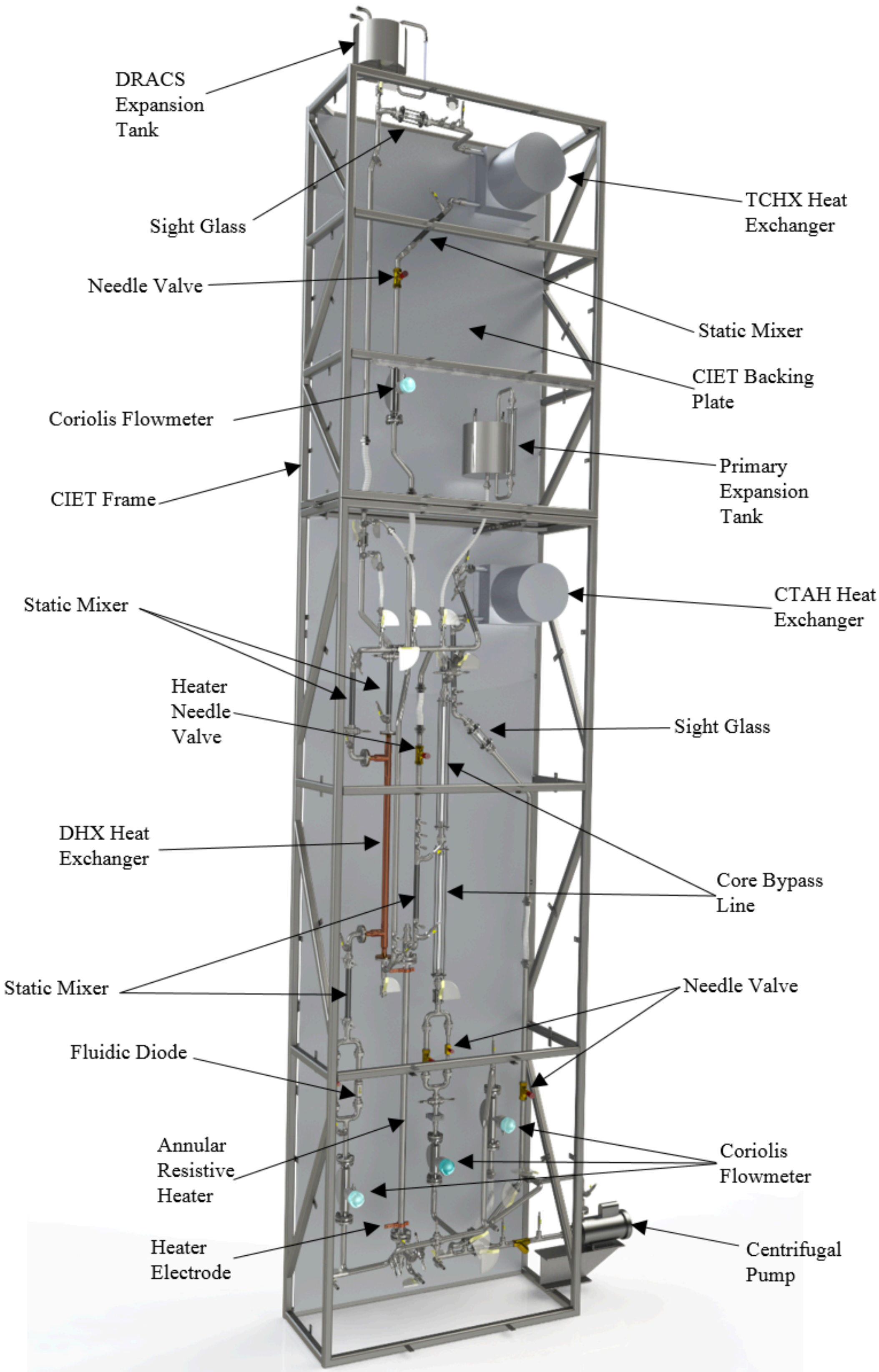


Figure 3-2. 3-dimensional rendering of CIET 1.0 with main components.

3.1.1 Electrical Heater

An resistance-heated annular electric heater simulates heat generation in the core. The computer-controlled power supply is currently designed to supply up to 10 kW of input heat. Additionally, the controller can provide time-dependent power profiles to the heater to simulate reactor scram and decay heat generation in the FHR core.

Dimensions of the CIET 1.0 heater based on scaling methodology are listed in Table **2-5**. In addition, the dimensions of the outer tube of the annular heater, which inputs heat into the fluid, were selected for manufacturability, safety factors, and the ability to deliver 10 kW or more from two 10-V, 1000-Amp TDK-Lambda GENESYS power supplies installed in series. The final dimensions of the CIET 1.0 heater outer tube are an inner diameter of 1.500" (3.81 cm) and an outer diameter of 1.575" (4.0 cm) achieved through tube honing and grinding, respectively. The tube is made of 304L stainless steel. The temperature-dependent electrical resistivity of 304 stainless steel, ρ, is given by:

$$\rho = 0.0612 \cdot T + 73.109$$

where ρ is in μΩ-cm and T is in °C. Therefore, the resistance of the heater varies between 0.0103 Ω at 20°C and 0.0123 Ω at 250°C, which is the maximum expected heater surface temperature for material integrity of Viton seals used on the heater inner tube. The resulting maximum resistive power input, using two 10-V, 1000-Amp power supplies in series, is 12.3 kW, above the 10 kW design threshold. The power input is limited by the maximum current of 1000 Amp supplied by the two power supplies in series. A maximum power input of 32.6 kW could be achieved if the same two power supplies were placed in parallel. However, the number of cables connecting the power supplies to the heater electrodes would be doubled in such a configuration and would be limited by resistive heating of the cables themselves. This situation was deemed impractical in the initial configuration of CIET 1.0, however the design could evolve in the future of the project.

Differences between the heater surface temperature and bulk oil temperature are listed in Table **3-1** under natural circulation operation (2 kW power input) and forced circulation operation (10 kW power input). The Nusselt number, Nu, is calculated from correlations based on data from the CIET Test Bay:

$$\mathrm{Nu} = 8 \text{ if } \mathrm{Re} < 2000 \text{ (laminar flow)}$$
$$\mathrm{Nu} = 5.44 + 0.034 \cdot \mathrm{Re}^{0.82} \text{ if } \mathrm{Re} > 2000$$

Table 3-1. Differences between the heater surface temperature and bulk oil temperature in CIET 1.0.

	2 kW	10 kW
Heater inlet fluid temperature	80°C	
Re	554	2768
Nu	8	28
Heater surface to bulk oil temperature difference [°C]	116	166
Margin to maximum surface temperature [°C]	54	4
Heater outlet fluid temperature	111°C	
Re	786	3932
Nu	8	36
Heater surface to bulk oil temperature difference [°C]	121	134
Margin to maximum surface temperature [°C]	18	5

With the given dimensions, the CIET 1.0 heater is sized to deliver up to 10 kW of power to the fluid while not exceeding a surface temperature of 250°C in all operating modes of the facility. During startup testing, one activity will involve further characterization of the CIET 1.0 heater, and development of improved models for its behavior and performance. The heater is currently equipped with five surface TCs and several other in-line TCs at the inlet and outlet of the heater.

3.1.2 CTAH and TCHX

Commercial air-cooled heat exchangers (Xylem Standard Exchange Model 15L F700 FanEx) simulate heat extraction from two locations on the CIET 1.0 experiment. The first location is the power conversion system through the CTAH in the primary loop; the second is 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.

For simplification purposes, the two heat exchangers are identical, though in a prototypical FHR such as the Mk1 PB-FHR, this would not be the case. The assumed room air inlet temperature used for sizing of the heat exchangers is 18°C. From scaling calculations based on the modular 900-MWth PB-AHTR design, on the tube side (oil side), the fluid inlet/outlet temperatures are 72/46°C with a mass flow rate of 0.046 kg/s in natural circulation mode (TCHX). Similarly, the inlet/outlet temperatures would be expected to be 111/80°C with a mass flow rate of 0.18 kg/s in forced circulation mode (CTAH). Both sets of values are listed in Table **2-4**. The vendor selected the appropriate heat exchanger based on these functional requirements. Detailed design performance parameters provided by the vendor are listed in Table **3-2**. During startup testing of the CIET 1.0 loop, one activity will involve further characterization of the heat exchangers and development of improved models for their behavior and performance. Inlet and outlet temperatures and fan motor speeds will be recorded continuously through the CIET 1.0 DAQ system.

Table 3-2. CIET 1.0 fan-cooled heat exchangers design performance parameters.

	2 kW	10 kW
Air side		
Inlet temperature [°C]	18	18
Outlet temperature [°C]	23	41
Oil side		
Mass flow rate [kg/s]	0.046	0.18
Inlet temperature [°C]	72	111
Outlet temperature [°C]	46	80
Heat exchanger		
Log mean temperature difference [°C]	36	62

3.1.3 DRACS Heat Exchanger

The DHX is designed to transfer heat 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. Tubes are organized in a regular triangular array, the bundle of which can be thought of as a hexagon inside a circle. Figure 3-3 shows a picture of the DHX tube bundle during fabrication. The main dimensions and predicted performance of the initial CIET 1.0 DHX to extract 2 kW under natural circulation operation are listed in Table **3-3**.

Figure 3-3. DHX tube sheet configuration

Table 3-3. Main dimensions and predicted performance of the initial CIET 1.0 DHX for 2 kW heat transfer.

Tube side (DRACS loop)	
Number of tubes	19
Hydraulic diameter [m]	6.35×10^{-3}
Average fluid temperature [°C]	59
Heat exchanger length [m]	1.30
Nu	4.36
Tube surface to bulk oil temperature difference [°C]	45
Shell side (primary loop)	
Tubes outer diameter [m]	7.94×10^{-3}
Shell inner diameter [m]	5.08×10^{-2}
Hydraulic diameter [m]	9.17×10^{-3}
Average fluid temperature [°C]	95.5
Nu	5.5
Tube surface to bulk oil temperature difference [°C]	43
Heat exchanger	
Tube side to shell side bulk oil temperature difference [°C]	88

In this preliminary configuration of the experiment, the predicted temperature difference between the tube side and the shell side of the DHX is 88°C, higher than the required 36°C for 2 kW heat transfer between the primary loop and the DRACS loop under natural circulation operation. Unless the DHX performance is significantly better than predicted, this points to the need to move to enhanced heat transfer surfaces (knurled, finned, or some other method), or using a new heat exchanger design. One proposed design for this application is a twisted tube heat exchanger. If these new types of heat exchangers are used at a later date, variances in pressure drops and impacts on natural circulation performance will be analyzed and compensated for by adjusting throttling valves located elsewhere in the loops.

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 flow resistance for natural circulation in the downward flow direction. Flow diode options include check valves, flapper valves, and fluidic diodes. The flow diode in the CIET DHX branch is simulated using two valves in parallel. For flow control, a needle valve is used in one branch to ensure the desired amount of bypass 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 for natural circulation.

Initial testing of the CIET 1.0 check valve revealed that the high density of the stainless steel disc that serves as the stopper-element prevents the check valve from closing at the desired low flow rates in the upwards direction; the mass of the stopper element is too high and the stopper is far from being nearly neutrally buoyant. Moreover, a water hammer effect occurs when the valve shuts at higher flow rates.

To remedy this problem, a new stopper for the check valve will need to be fabricated. During the Winter 2014 quarter of the project, a separate effects testing program was initiated on a similar check valve in a simplified water loop to investigate various low density plastic materials that could replace the initial stainless steel disc while maintaining compatibility with Dowtherm A at high temperatures (up to 120°C). Future work will characterize the modified check valve, including the forced circulation flow rate required to close it.

3.1.5 Shutdown Rod Channel and Core Bypass Line

A bypass flow line in the flow loop runs parallel to the resistive heater branch and can be viewed in Figure 3-1. This flow path simulates core bypass flow, and therefore has a needle valve to allow the flow resistance and bypass 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 prototyipical FHRs, and observed through the glass tubing. This work will continue research investigating buoyancy-driven passive safety shutdown rod insertion started at UCB in 2008 (Blandford and Peterson 2008).

3.1.6 Centrifugal Pump

A single pump is needed and was included on the primary coolant loop of CIET 1.0. Bypass connections and valves between the primary loop and the DRACS loop permit forced circulation through the DRACS loop for isothermal pressure drop measurements in this loop, as discussed in Section 6.1. 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 as well as for 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. More details on pump scaling and fabrication are provided in Section 2.3.4 and Section 3.2, respectively.

3.2 Fabrication of CIET 1.0

CIET 1.0 uses modular construction, with various piping subassembly sections installed inside a steel frame approximately 7.6 m (25’) in height and 1.8 m (6’) in width. The CIET 1.0 experiment can be thought of as a simple plumbing system, instrumentation, and a set of polycarbonate windows housed inside a metal truss structure. The experimental loop consists of approximately 30 m (100 linear feet) of 3.34-cm-outside-diameter (1.315” OD, 1” nominal) Schedule 10 (0.28-cm-wall-thickness-) 304L stainless steel piping. The piping is attached to the steel frame by pipe supports, brackets, unions, and other similar couplings.

As the size of this experiment is rather large, the experiment was split into upper and lower structural modules that could be mated together during final assembly. This final assembly can be envisioned similar to the configuration of many common household refrigerators. The upper frame assembly – or “freezer” section – measures ~2.6x1.8x0.9 m (~8.5’x~6’x~3’ – see Figure 3-4). The lower frame – or “refrigerator” portion – measures ~5.0x1.8x0.9m (~16.5’x~6’x~3’ – see Figure 3-5). Both frame components were constructed of 2”x2”x1/4” thick hollow square steel tubing. Tube stock was specified to be American Society for Testing and Materials 8500 (A500) alloy steel.

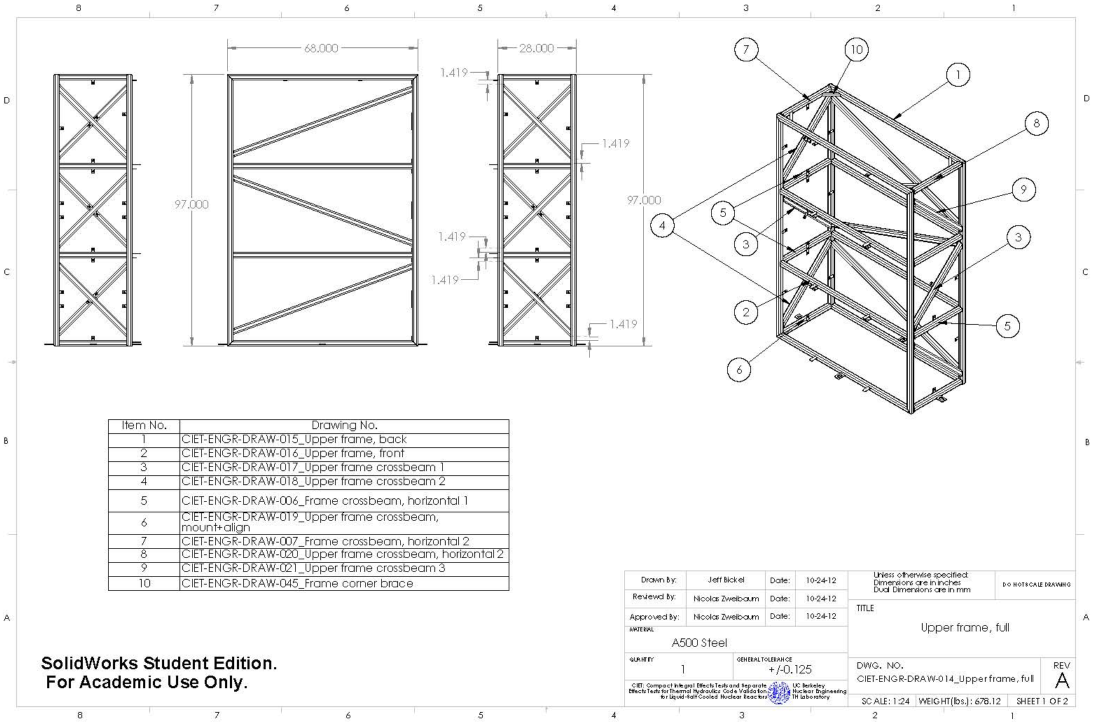


Figure 3-4. Engineering drawing of the CIET 1.0 upper frame.

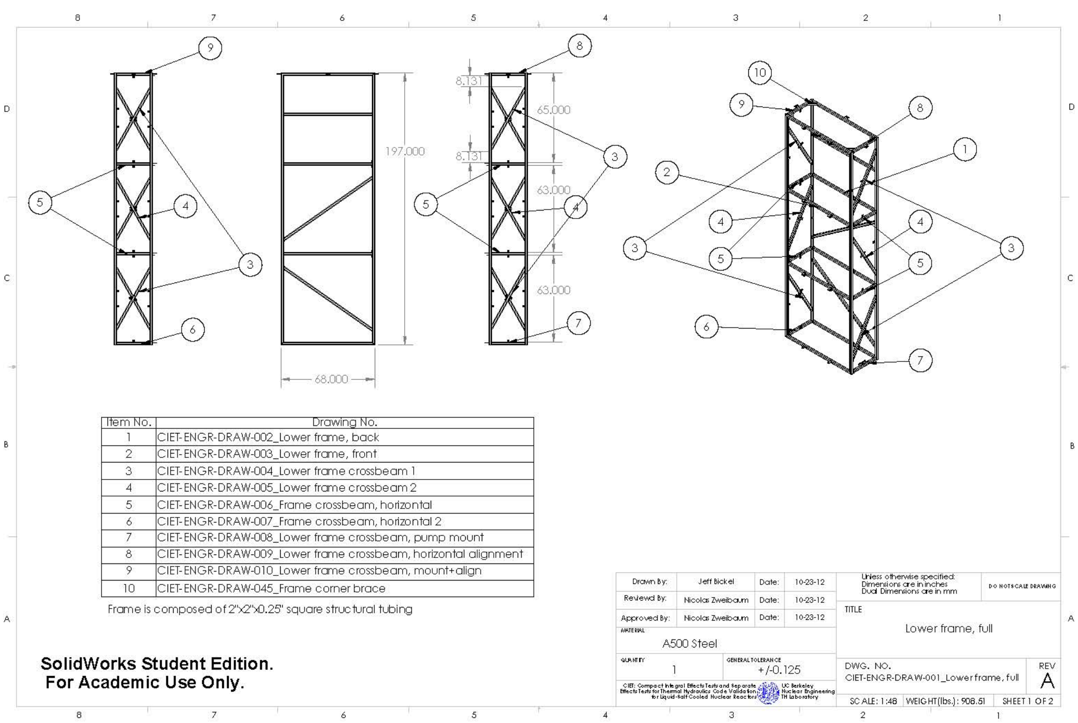


Figure 3-5. Engineering drawing of the CIET 1.0 lower frame.

While preliminary design and scaling work was done at UCB, the majority of fabrication was outsourced to a local pressure vessel and commercial process piping fabricator. Staff members of the *UCB Mechanical Engineering Student Machine Shop* suggested several nearby fabrication companies. The cost of fabrication for the experiment was bid by three different contractors, and ultimately Johansing Iron Works, Inc., based in Oakland, California, was chosen.

Johansing Iron Works was selected for several reasons. Firstly, they are an American Society of Mechanical Engineers (ASME) certified pressure vessel and process piping fabricator that routinely handles similar large-scale fabrication jobs. Secondly, they were quickly and easily able to point to the ASME and American Welding Society (AWS) quality control standards that they abide by. Documenting the fabrication and quality control of the CIET 1.0 experiment was of high importance to UCB. Thirdly, they were conveniently located in close proximity to UCB, simplifying the frequent visits needed for QA controls during construction, and were highly responsive and communicative during the design process.

Engineering drawings were completed by UCB and submitted to Johansing Iron Works in December 2012. Construction began in the first quarter of 2013. In addition to the design drawings, UCB also supplied Johansing Iron Works with an initial set of responsibilities for each party. The set of responsibilities supplied to Johansing Iron Works are listed below:

1. Fabricator was responsible for purchasing all necessary stock material required for the fabrication of the frame, the pipe fittings and piping, expansion tanks, and heater, based on design drawings provided by UCB.
2. Fabricator was responsible for fabricating all custom parts and components that were to be installed on the CIET 1.0 flow loop. The bill of materials for this project was provided by UCB to Johansing Iron Works, specifying parts to be purchased by the fabricator and parts to be provided by UCB.
3. Fabricator was responsible for fabricating and painting the experimental frame and backing plate.
4. Fabricator was responsible for welding and assembling the CIET 1.0 flow loop piping. When assembling parts such as the strainers, valves, manometer and TC ports, the fabricator was to ensure that directional parts were installed correctly.
5. Fabricator was responsible for leak testing the loop and tanks to 20 psi.
6. Fabricator was responsible for installing the pipe loop and components (fans, flowmeters, etc.) to the backing plate via supports, Unistrut, or as fabricator saw fit. One important goal for UCB was to have piping mounted in a way that minimized thermal conduction losses between the pipe loop and the experiment frame.
7. Fabricator was responsible for documenting deviations from the initial design, if any.
8. Fabricator was responsible for providing on-site access to UCB students/employees. This was to allow UCB to take mass and property measurements, as well as tag components with identification numbers.
9. Fabricator was responsible for documenting all welding, fabrication, and testing standards that were performed during construction.
10. Fabricator was responsible for standing upright both of the two frame structures at the end of fabrication. The purpose of this was to ensure that both frame structures could, in fact, be stood upright as well as transported by crane.
11. Fabricator was responsible for delivering the CIET 1.0 experiment to UCB.

In addition to the list of responsibilities that was specified to Johansing Iron Works, UCB's responsibilities included:

1. UCB was responsible for providing a full set of engineering drawings to the fabricator for the apparatus.
2. UCB was responsible for purchasing and providing all pre-fabricated components of the flow loop (flowmeters, static mixers, pump, heat exchangers, etc.).
3. UCB was responsible for connecting both of the frames together on-site in Etcheverry Hall.
4. UCB was responsible for providing all instrumentation for the flow loop. This included, but was not limited to, TCs, manometers, other temperature sensors and flowmeters.
5. UCB was responsible for purchasing and supplying all valves (needle and ball type) for the apparatus.
6. UCB was responsible for purchasing and supplying thermal insulation to be installed onto the CIET 1.0 experiment. This included both insulation onto the backing plate of the frame and insulation surrounding the piping of the loop itself.
7. UCB was responsible for providing any other component which was not explicitly stated.
8. UCB was responsible for identifying each flow loop component prior to assembly, on fabrication site, with a unique number, using a vibrating marker, for traceability purposes.
9. UCB was responsible for weighing each flow loop component after identification and prior to assembly, on fabrication site. It was critical for UCB to have an accurate understanding of the individual and total mass of the piping/fittings/components for heat transfer calculations.
10. UCB was responsible for taking digital photos, with time stamps, of each loop component.
11. UCB was responsible for providing technical support, necessary fabrication information, and onsite counseling during the fabrication process.
12. UCB was responsible for payment to the fabricator. An initial deposit to begin work, and the remainder of the balance upon completion.

Ultimately, Johansing Iron Works fabricated the following components of the CIET 1.0 experiment:

- The frame that surrounds the flow loop
  - The top frame (Figure 3-6) – roughly 38.3 m (~1508 linear inches) of A500 5.1x5.1x0.64 cm (2"x2"x0.25") square tubing (~125' in length). Each of the tube stock intersections was welded per AWS D1.1. The top frame has 28 intersections where the tube stock needed to be welded.

Figure 3-6. CIET 1.0 upper frame, March 14th, 2013 (left is top).

- The bottom frame (Figure 3-7) – roughly 51.1 m (~2011 linear inches) of A500 5.1x5.1x0.64 cm (2"x2"x0.25") square tubing (~168' length). Intersections of square tubing were welded to AWS D1.1. The bottom frame for the CIET 1.0 experiment had 34 intersections to be welded.

Figure 3-7. CIET 1.0 lower frame, March 14th, 2013 (right is top).

- Backing plates (visible in Figure 3-6 and Figure 3-7) – Backing plates were specified to be 0.25"- (0.64-cm-) thick A36 plate steel. These plates were welded onto the truss frame of both the upper and lower section of the experiment. Plates were welded to the frame approximately every 12" (30.5 cm) and meet AWS D1.1 standards. Backing plates are visible in the two photos taken of the CIET 1.0 frame during construction on March 14th, 2013.

- Expansion tanks – The two expansion tanks allow for fluid overflow in both flow circuits in the loop. The total capacity of each tank is ~10 gallons (37.9 L). The engineering drawing of the DRACS loop expansion tank is shown in Figure 3-8.

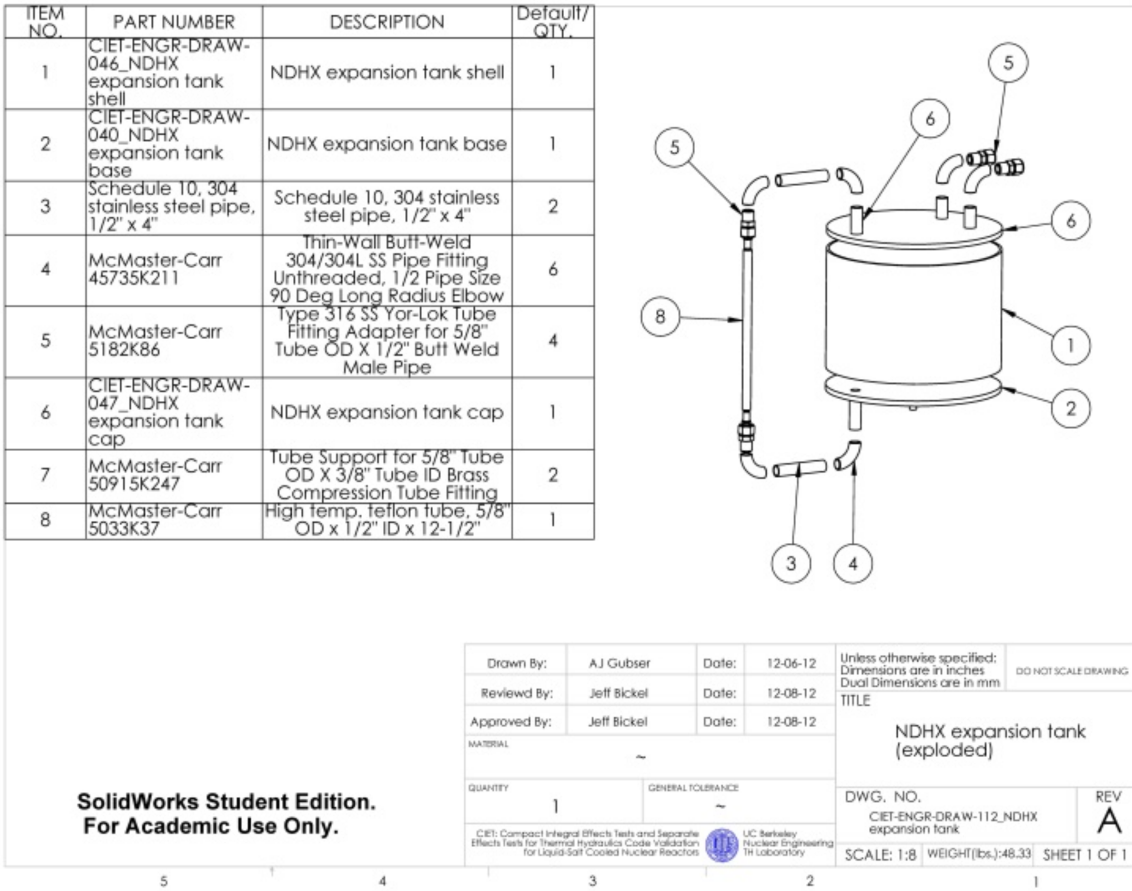


Figure 3-8. Engineering drawing of the upper fluid expansion tank (DRACS loop).

- Loop piping – In addition to the frame that supports the flow loop, Johansing Iron Works was also responsible for fabricating the piping. As previously stated, the loop consists of approximately 30 m (98 ft) of 1” nominal diameter 304L stainless steel piping. A photograph of the piping assembly in progress is shown in Figure 3-9.

Figure 3-9. Piping assembly in progress, September 27th, 2013.

- Fill/drain tank – The final fully-fabricated component from Johansing Iron Works was a stand-alone tank on casters used to fill and drain the fluid loop. The total fluid inventory of the CIET 1.0 flow loop is approximately 15 gallons (~57 L). The fill/drain tank was designed with a capacity of ~30 gallons (115 L) to allow for flexibility in fluid inventory. Several valves and ports were welded to the tank in order to attach plumbing components needed to fill and drain the loop. Furthermore, a safety relief valve was installed to prevent over-pressurization of the tank. Filling the loop involves connecting a cylinder of pressurized gas to the tank. The tank pressure is used as the driving force to fill the loop. Gas is throttled through a regulator and a flowmeter equipped with a needle valve. The fill/drain tank is illustrated in Figure 3-10.

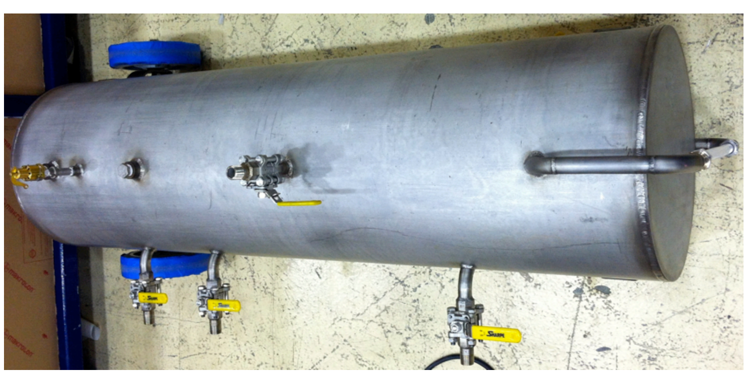


Figure 3-10. CIET 1.0 fluid inventory fill/drain tank.

In addition to the items that Johansing Iron Works welded and assembled, several key components were procured from vendors. Most notably, these included the pump, the oil-to-air heat exchangers, the flowmeters, fluid static mixers, and power supplies needed to supply current to the resistive heater.

- Pump – The pump procured for CIET 1.0 is a Price Pump Company centrifugal pump (catalog #JM3458) driven by a 1/3 HP (250 W) Baldor Reliance Industrial motor. The operational limits of the pump are specified to be a maximum service pressure of 150 psi (1.03 MPa), a maximum operating fluid temperature of 300°F (149°C), and a maximum rotational speed of 1725 rpm. The discharge diameter of the pump is 0.75" (1.9 cm) and the impeller diameter is 5.375" (13.7 cm). Both the suction and discharge sides of the pump are connected to the CIET 1.0 flow loop with stainless steel flanges. Pump speed is varied through a VFD and operated through the LabVIEW DAQ system on the computer control station. Pump curves, calculated using the similarity laws detailed in Section 2.3.4, are listed for both low and high motor speeds in Figure 3-11 and Figure 3-12. Future work will verify these pump curves using pressure drop and flow data measured in the loop, and will develop pump efficiency estimates so that the loop energy balance can be corrected for pump work, both for losses that occur in the pump, and for energy dissipation due to flow around the loop.

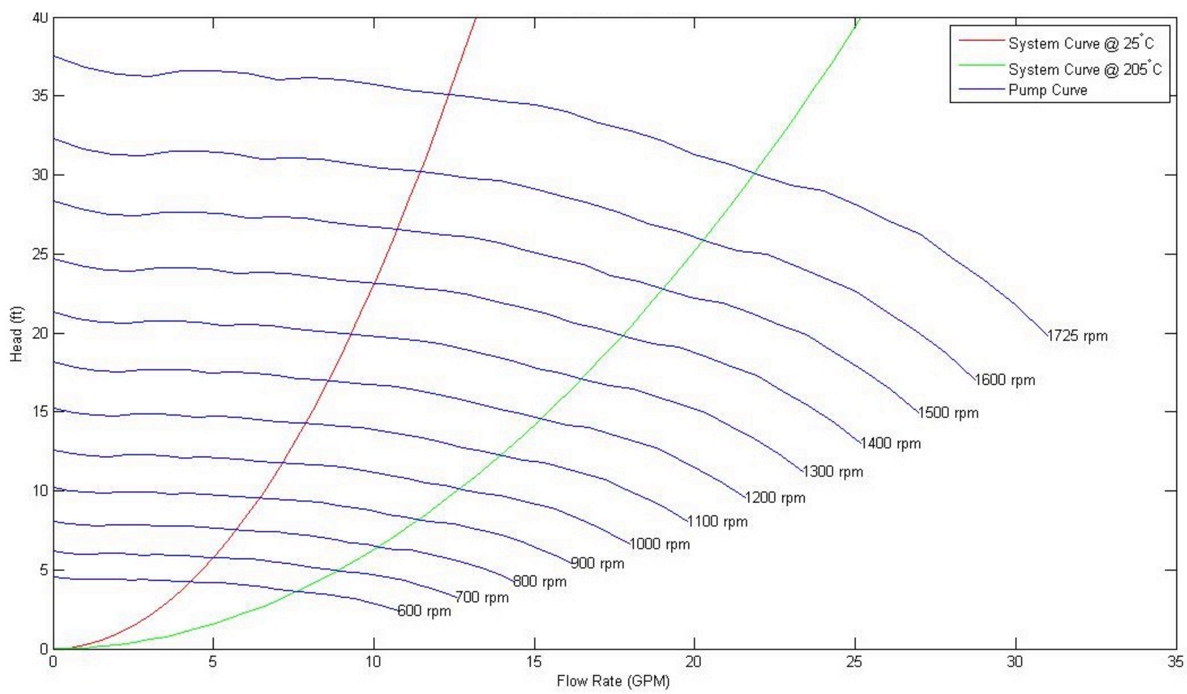


Figure 3-11. Calculated CIET 1.0 pump curves for high motor speeds.

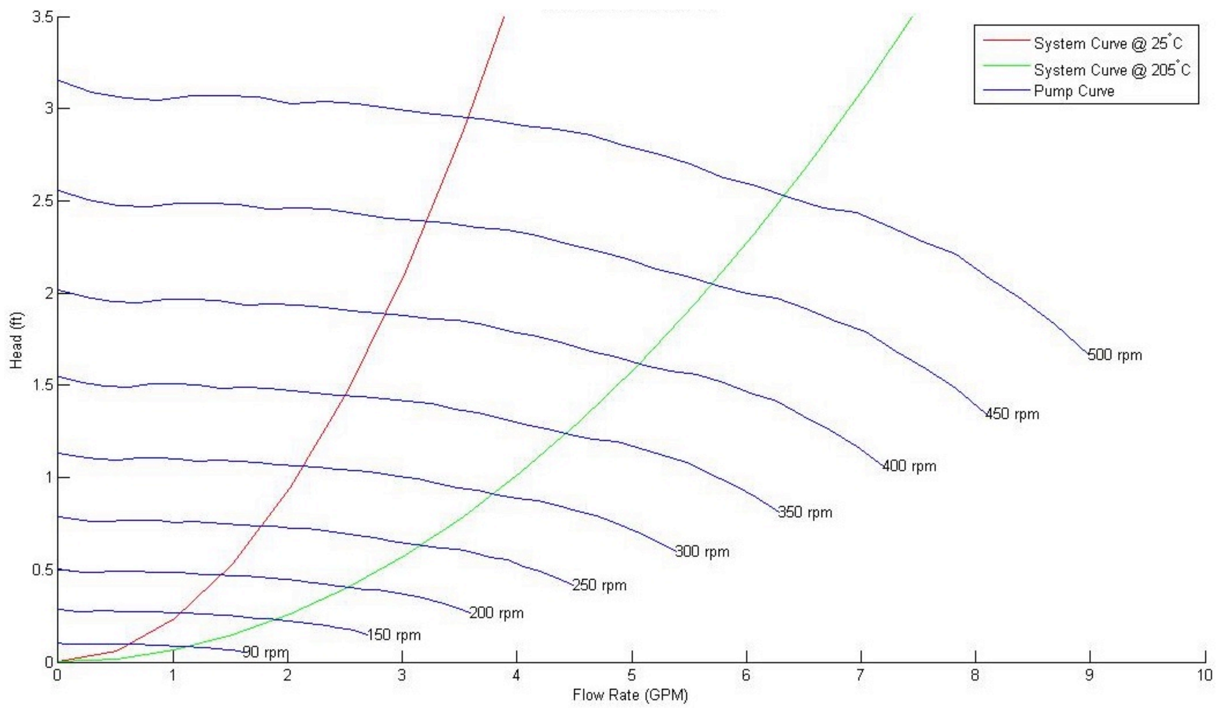


Figure 3-12. Calculated CIET 1.0 pump curves for high motor speeds.

- Oil-to-air fan heat exchangers – Two FanEx oil-to-air heat exchangers were selected and purchased to replicate the thermal loads generated by the CTAH and TCHX/IHX of FHRs. One of these heat exchangers is shown on Figure 3-13. They were sized to extract 10 kW of heat under forced circulation conditions, and 2 kW of heat under natural circulation conditions. Scaling calculations based on the former 900-MWth modular PB-AHTR design, detailed in Section 2.3.1, show the tube side (oil side) of the TCHX to have inlet and outlet temperatures of 72°C and 46°C, respectively, under natural circulation, at a mass flow rate of 0.046 kg/s. Similarly, the CTAH/IHX inlet and outlet temperatures under forced circulation operation were calculated to be 111°C and 80°C, respectively, at a mass flow rate of 0.18 kg/s.

  One substantial modification was made to the two oil-to-air heat exchangers. The inlet of the tube side manifold was located below the top of the tube sheet. Therefore, approximately 2-3 tubes were located above the inlet connection to the manifold. As part of the list of corrective actions performed on CIET 1.0, further detailed in Section 5.5, small vent holes were drilled, and valves installed, into the highest points of the manifolds to allow for venting of air trapped in both heat exchangers. Had this not been done, it is likely that air bubbles would have collected in these local maximum elevation locations, perturbing pressure drop and heat transfer measurements.

Figure 3-13. FanEx oil-to-air heat exchanger.

- Fluid static mixers – Eight in-line static mixers from the Koflo Corporation are used in the CIET facility to provide mixing for bulk temperature measurements in locations where imperfectly mixed flow is expected to occur (as in laminar flow, and if the working fluid were thermally stratified, in exiting a heater or cooler). The static mixers are made of nominal 1” diameter, schedule 40, 304L stainless steel piping containing six fixed mixing elements. Because they are made of 304L stainless steel, the static mixers can withstand the same high temperatures and same pressure as the rest of the CIET 1.0 piping. Figure 3-14 and Figure 3-15 illustrate the static mixers used on CIET 1.0.

Figure 3-14. Labeled Koflo static mixer used on CIET 1.0.

Figure 3-15. Fixed mixing element inside Koflo static mixer.

The vendor work to fabricate the CIET 1.0 flow loop was completed in December 2013 and the upper and lower modules were delivered to UCB on December 13th, 2013. The experimental apparatus was received, but not immediately stood up. First, the piping and frame backing plates were insulated, using fiberglass, foam, aluminum sheeting, and high-temperature mastic. Polycarbonate panels were installed on the sides of the frame to provide thermal insulation while allowing for visual access to the inside of the structure. Insulation installation continued for approximately four months. Various stages of the insulation process are shown in Figure 3-16.

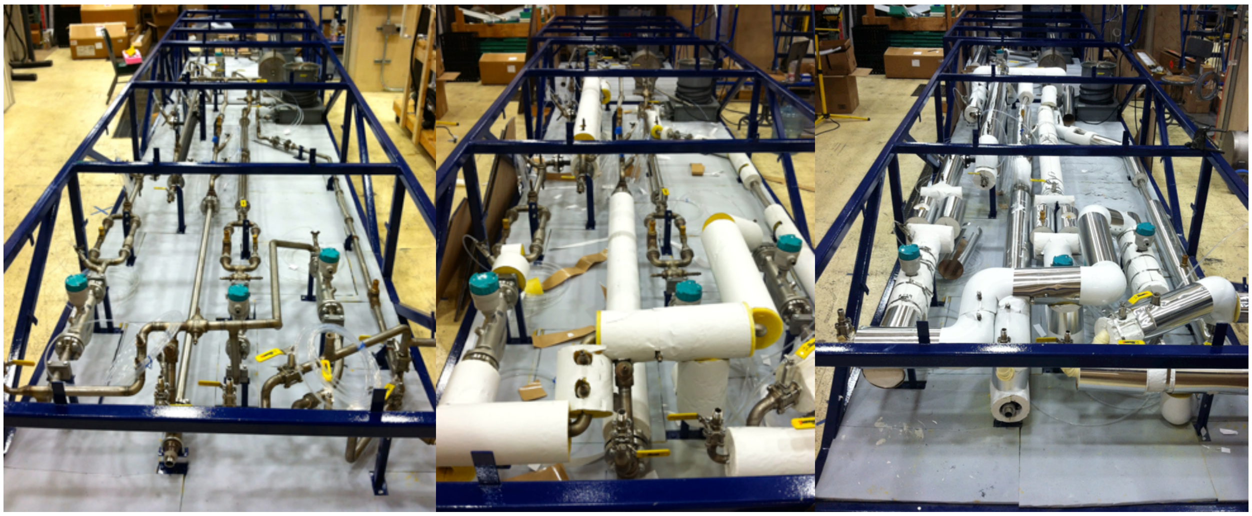


Figure 3-16. CIET 1.0 piping insulation in progress, February 2014 (left), March 2014 (center) and April 2014 (right).

During that time, other work was performed in parallel. Instrumentation was calibrated, as detailed in Section 4.1, electrical infrastructure was installed in the basement of Etcheverry Hall, a welded secondary-containment drip tray to contain spills was built, illustrated on Figure 3-17, and a system of braces to support the erected experimental apparatus was designed. The experiment was stood upright in June 2014.

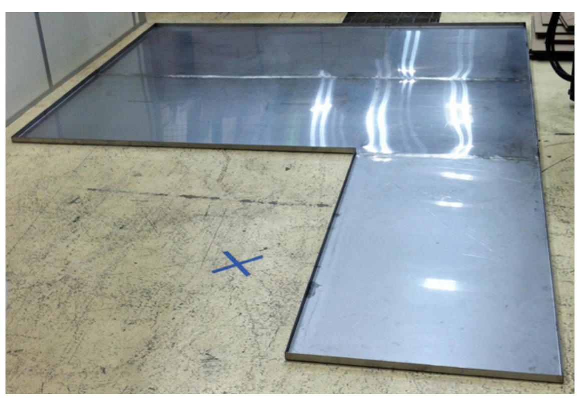


Figure 3-17. The CIET 1.0 drip tray is designed to contain twice the inventory of Dowtherm A oil in the flow loop in case of a major leak. It uses fully welded construction because Dowtherm A can dissolve conventional caulking materials.

Figure 3-18 shows the lower frame assembly and piping being placed in its final location using a five-ton bridge crane. The total weight of the lower portion of the CIET 1.0 apparatus is approximately 2000 lbs (910 kg). Once the lower frame assembly was properly placed, the upper frame was lifted and mated to the top of the bottom frame. Piping was connected between the two sub-assemblies using flexible stainless-steel-sheathed, high-temperature rubber hoses with unions, and the seismic bracing that encircles the flow loop, the scaffolding, and the adjacent structural building columns was assembled around both parts of the facility, as shown in Figure 3-18.

Figure 3-18. CIET 1.0 lower frame assembly (left) and upper frame assembly (right) being set in place, June 2014.

Leak testing of the entire loop began in late June 2014. All open ports (e.g., manometer and TC ports) were capped with Yorlok fittings (an equivalent type of fitting to Swagelok compression fittings, only supplied by McMaster-Carr, Inc.). The loop was pressurized with helium at 25 psi (172 kPa) and a handheld helium leak detector was used to detect leaks. The detector used was an Agilent G3388A detector and measured variances in thermal conductivity. Its precision is listed as measuring 0.01 mL/min of helium in atmospheric conditions[1]. Over the course of two months of leak testing, several leaks were discovered in the piping. Ultimately, welds performed by Johansing Iron Works were sound, but NPT threaded fittings and poorly-seated ball unions had a tendency to not seal properly. Leaks were sealed with additional thread

[1] Agilent G3388A Leak Detector – Operation Manual. Agilent Technologies. 2007

sealant, gaskets, or where appropriate, metal epoxy. Once no further leaks were detected and the flow loop would hold pressure indefinitely, the TCs were inserted and the process repeated. In early September 2014, the CIET flow loop was deemed "leak tight" and subsequently filled with Dowtherm A.

3.3 Good Practice in the Design of CIET 1.0

In addition to the design and construction features previously mentioned, several noteworthy elements were included into the design of the CIET 1.0 experiment. These features help with modularity and interchangeability of components, and extend the service life of the CIET 1.0 facility by allowing for future research.

3.3.1 Sight Glasses and Gas Entrainment

Gas entrainment in the oil loop must be avoided to prevent distortions in pressure drop and heat transfer. Furthermore, removing residual gas after filling fluid loops can often be problematic. In order to monitor for entrained gas during forced circulation operation, glass tubing was installed to create sight glasses in two locations on the CIET 1.0 flow loop: one sight glass 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 global high points of each loop. These ~8" (20 cm) in length 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 throughout 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.

3.3.2 Thermal Insulation and Guard Heating

It is also desirable to minimize heat losses from the loop piping to the ambient surrounding. Although the flow loop 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 significant parasitic heat losses, an infrared camera is used to identify hot surfaces that require additional insulation, and subsequently guard heating will be used on the CIET 1.0 experiment to further reduce parasitic heat loss. Installed on the sides of the CIET frame are two sets of polycarbonte panels. Each panel is 0.25" (0.635 cm) thick. Using a set of two panels on the CIET 1.0 experiment is analogous to double-paned windows installed on many houses, with the air layer between the two panels providing effective thermal insulation. Rubber gasket material seals the interstitial space between each panel and the steel CIET frame. In addition to the polycarbonate side panels, the front of the CIET enclosure is 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. Lastly, inside the CIET enclosure, a commercial space heater circulates heated air. The heater is designed to keep the ambient temperature inside the enclosure at ~80°C, while the side panels and front rolling-shutters limit heat losses to the outside ambient air.

3.3.3 Modularity

The DHX and the resistive heater on the flow loop were designed such that they can be removed from the loop piping. As the CIET 1.0 design was frozen before a final design was established for the Mk1 PB-FHR, some scaling parameters were still unspecified. Therefore, the DHX was constructed with only four specific functional requirements: 1) that it be able to remove at least 2 kW of heat, 2) that it occupy enough volume that a potentially larger, more robust heat exchanger could be interchanged with the current DHX, 3) that it be able to mate with the flow loop via four standard American National Standards Institute (ANSI) flanges, and 4) that it be located at the correct scaled relative elevation with respect to the other heat sources and sinks of the CIET 1.0 flow loop. All of these design criteria points are met with the current DHX, though it is anticipated that, as the point design for the Mk1 PB-FHR develops further, a new DHX design will be required.

As previously stated, the current CIET 1.0 heater design scales coolant residence time and core pressure drop by using a resistively heated annular flow channel in series with a needle valve. Similar to the DHX, if it is determined at a later point in time that this setup does not adequately represents the desired physics of a true PB-FHR pebble bed, an updated heater design can be interchanged.

3.4 Initial Fill-Up

The CIET loop was first filled up with Dowtherm A on September 15th, 2014, following a pre-established reviewed and approved fill-up procedure as per the CIET QA program detailed in Section 5. The procedure was divided in five phases:

1. Transfer of Dowtherm A oil from primary drum to CIET fill/drain tank (for initial fill-up)
2. Fill-up of the primary and part of the DRACS loop
3. Fill-up of the rest of the DRACS loop
4. DRACS isolation
5. Cleanup.

The fill/drain tank is a cylindrical, horizontal vessel with several ports and valves, equipped with a level sight glass on one end. It is used to fill up the loop since it can be pressurized to 15 psig (before a safety relief valve relieves excess pressure), while the maximum required head to fill up the entire CIET 1.0 loop is 13 psig.

A hand pump was used to transfer Dowtherm A from the 55-gallon storage drum to the fill tank. Throughout the fill-up process, the fill/drain tank was securely mounted on top of a platform weighing scale to continuously measure fluid weight as Dowtherm A oil was added to/removed from the tank. The total expected weight of oil in the loop was predicted to be ~53 kg. This did not include inventory in the manometer lines. Moreover, there would be leftover oil in the fill/drain tank once the loop was filled. Therefore, 70 kg of oil were pumped from the storage drum into the fill/drain tank. The oil level in the fill tank was continuously monitored using the tank level indicator to confirm that the fill tank was not being overfilled.

For the following phases, the fill tank was connected to the CIET loop fill ports using flexible high-temperature rubber hoses with stainless steel wire jackets. The valve line-up for loop fill-up, included in the procedure, was performed and verified, then the fill tank was slowly pressurized with nitrogen, using a regulator and a control valve, to push the fluid from the fill tank into the CIET loop. As an example, the valve line-up table for all valves located on the ground floor of the CIET facility is reproduced in Table **3-4**. Valve labels refer to the piping and instrumentation diagram shown in Figure **3-1**. Phase 1 corresponds to fill-up of the primary loop and part of the DRACS loop, while Phase 2 corresponds to fill-up of the remainder of the DRACS loop. Throughout the process, all transparent lines (i.e. manometer lines and sight glasses) were carefully monitored to verify the absence of entrained gas bubbles, as shown in Figure 3-19, and fluid inventory in the loop, measured by the weight of oil removed from the fill tank, was recorded. Once the primary loop expansion tank was 1/3 full, as expected during normal operation of the facility, the primary loop expansion tank and manometer lines were isolated, and the fill-up process continued to fill up the DRACS loop. Finally, once the DRACS loop expansion tank was 1/3 full, the fill-up process ended, the DRACS loop was isolated from the primary loop, the fill tank was isolated from the loop and the area was cleaned up according to procedure. In total, 51.4 kg of Dowtherm A oil were loaded into the CIET 1.0 loop.

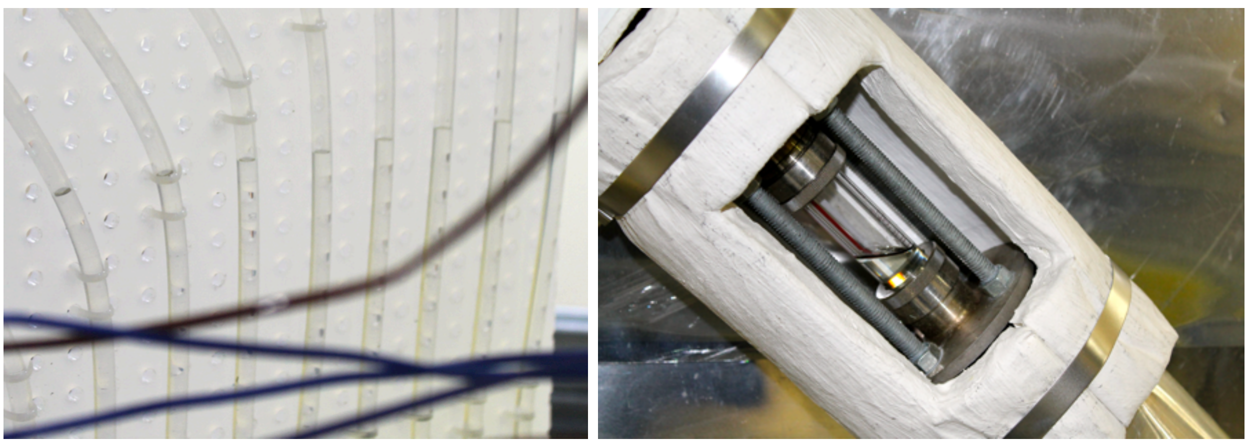


Figure 3-19. CIET 1.0 transparent sections monitored during fill-up to verify absence of gas bubbles.

Table 3-4. Valve line-up for fill-up of the CIET 1.0 loop (ground level valves only).

Valve Location	Valve Label	Phase 1	√	Phase 2	√	DRACS Isolation	√
Flow Routing Valves							
Bottom of heater	V-10	OPEN		OPEN		CLOSED	
Bottom of DHX	V-20	OPEN		OPEN		CLOSED	
Bottom of bypass line	V-30	OPEN		OPEN		CLOSED	
Bottom of bypass line	V-31	OPEN		OPEN		CLOSED	
Bottom of bypass line	V-32	OPEN		OPEN		CLOSED	
CTAH line	V-40	OPEN		OPEN		CLOSED	
Pump manifold area	V-41	OPEN		OPEN		CLOSED	
Pump manifold area	V-42	OPEN		OPEN		CLOSED	
Pump manifold area	V-43	OPEN		OPEN		CLOSED	
Pump manifold area	V-44	OPEN		OPEN		CLOSED	
Pump manifold area	V-45	OPEN		OPEN		CLOSED	
Bottom of DHX branch	V-80	OPEN		OPEN		CLOSED	
Bottom of DRACS	V-81	OPEN		OPEN		CLOSED	
Vent drum	V-90	OPEN		OPEN		OPEN	
Fill/drain tank drain valve	V-93	CLOSED		CLOSED		CLOSED	
Fill/drain tank	V-94	OPEN		OPEN		CLOSED	
Fill/drain tank	V-95	OPEN		OPEN		CLOSED	
Fill/drain tank	V-96	OPEN		OPEN		CLOSED	
Fill/drain tank	V-97	OPEN		OPEN		CLOSED	
Manometer Valves							
Valve Location	**Valve Label**	**Phase 1**	**√**	**Phase 2**	**√**	**DRACS Isolation**	**√**
Bottom of heater	M-10	OPEN		CLOSED		OPEN	
Bottom of DHX	M-22	OPEN		CLOSED		OPEN	
Pump manifold area	M-40	OPEN		CLOSED		OPEN	
Pump manifold area	M-41	OPEN		CLOSED		OPEN	
Pump manifold area	M-42	OPEN		CLOSED		OPEN	
Pump manifold area	M-43	OPEN		CLOSED		OPEN	

4 Instrumentation and Data Acquisition

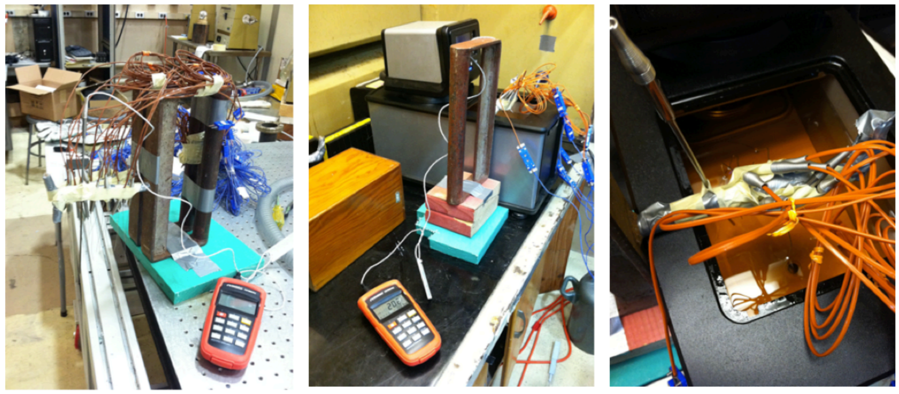
4.1 TCs, RTD Probes, and Temperature Measurements

The CIET 1.0 project uses Omega Engineering, Inc. type-T sheathed TCs (model TMTSS-020U). Type-T TCs are used because they are best suited for measurements in the -200 to +250°C range. Moreover, they give more accurate temperature measurements under 50°C compared to other TC types. The smaller the sheath diameter, the faster the response time, and the more accurate the results because of limited thermal conduction along the probe, which is why the smallest available sheath diameter for the Omega type-T TCs (0.02”) was chosen. All TC junctions are ungrounded to provide a less noisy signal. TC wires are Teflon-coated (and therefore compatible with Dowtherm should they come in contact with the fluid) and are compatible with ambient operating conditions up to 260°C.

In total, 47 TCs are positioned at various locations around the CIET 1.0 fluid 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 in horizontal sections). Static mixers are installed upstream of in-line TCs to ensure an accurate measurement of bulk fluid temperature. Because they add pressure drop to the flow line, mixers are only used at the outlets of the heater and heat exchangers, where the flow may not be well mixed. Surface TCs measure external surface temperature of the heater at five different axial locations, and ambient condition temperatures inside the CIET frame.

Calibration of all TCs was performed at UCB. TCs were manually calibrated to a known, reference temperature using a calibrated resistance temperature detector (RTD) probe acquired from Omega Engineering, Inc. TCs were calibrated at 25°C intervals from ~0°C to ~175°C to create a calibration profile over the temperature range of interest for the CIET 1.0 experiments. For ambient temperature to 175°C calibration points, a heated oil bath was used. The circulator bath was a Polyscience, Inc. model AD07H200 with a capacity of 7 L and temperature control of ±0.1°C. For calibration at ~0°C, an ice bath and stir bar were used. Figure **4-1** illustrates the calibration setup used for temperatures above ambient conditions. TCs must be calibrated yearly against an RTD measurement system. While calibration was initially done off the loop before the TCs were installed in the CIET 1.0 loop, 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.

During operation of the CIET 1.0 facility, temperatures are recorded by measuring the voltage across the TC probe junction. This signal is sent into a DAQ system controlled with the National Instruments LabVIEW software.



Thermocouple stand **Calibration apparatus** **Calibration bath**

Figure 4-1. Calibration of CIET 1.0 TCs.

In order to minimize heat losses between the fluid, the piping, and the ambient exterior, all components of the flow loop are insulated with 2” (5.1 cm) of fiberglass insulation. Components that are anticipated to potentially leak or to be removed (e.g., modular components or flexible tubing) were insulated with removable insulation. Permanent piping, however, was insulated with rigid melamine surrounded by aluminum sheeting and mastic. In addition to the immediate insulation surrounding the piping, guard heating is also employed to minimize heat losses. As previously mentioned, the CIET 1.0 enclosure is sealed with two sets of polycarbonate panels along the sides, an insulated backing plate, and an insulated rolling-shutter door system on the front. An 8.1 kW space heater is to be installed inside the enclosure to heat the ambient temperature to approximately 80°C.

4.2 Pressure Measurements

All pressure measurements taken from the CIET 1.0 flow loop are direct head measurements read through 16 manometers. No pressure transducers are used. 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 are 1/4” (0.635 cm) outer diameter, 3/16” (0.476 cm) inner diameter transparent teflon tubing. This tubing is routed from various Yorlok compression fitting isolation valves connecting manometer ports on the fluid loop up to a vertical manometer board. The manometer board is backed with a reference grid so that free surface elevations can be read easily. Furthermore, the grid has been installed at a known height above a reference datum (the centerline of the pump inlet; a global minimum elevation in the loop), measured with a NIST-standard-calibrated laser ruler. All fluid free surface elevations inside the manometer lines can therefore be measured as absolute as well as relative heights.

The manometer board extends well above the free surface of the fluid loop to a height of ~35’ (10.7 m) above ground. Figure **4-2** shows a portion of the manometer board with fluid in the manometer lines, and the board seen from the ground. Because it would be time consuming to manually record visual readings of fluid free surface elevations inside the manometer lines, two digital cameras are used to record the 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. Parallax is taken into account in determining oil levels, and the resulting values of absolute pressures and pressure differences can be generated through an automated process, as further detailed in Section 6.1.

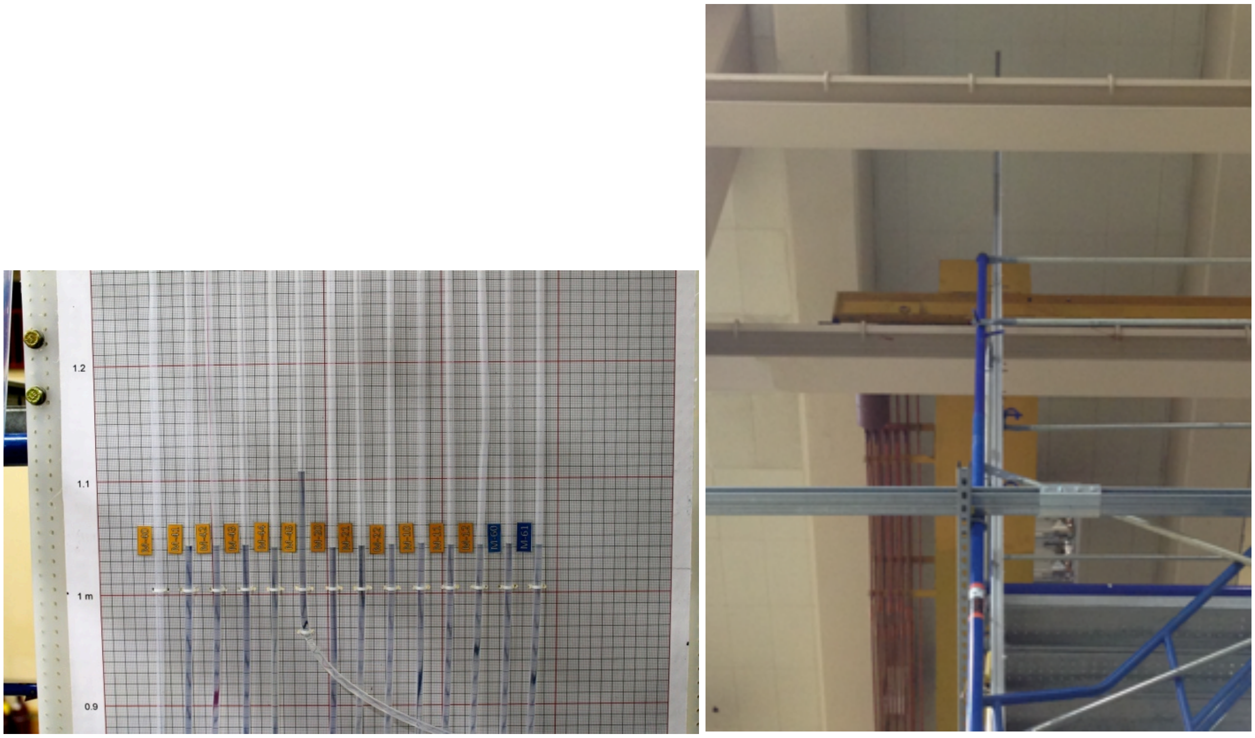


Figure 4-2. Manometers (left) and manometer board seen from the ground (right).

4.3 Flow Rates Measurements

Coriolis flowmeters provide a direct, dynamic mass flow rate measurement in each branch of the CIET 1.0 loop. Four Coriolis flowmeters were procured from Siemens Industry, Inc. for CIET 1.0. All four are model FC430 with three of the four having the same DN25 sensor, located on the CTAH branch, DHX branch and DRACS loop. The remaining has a DN15 sensor for higher sensitivity at low flow rates and is located on the bypass branch. These flowmeters take direct measurements of mass flow rates. They were sized to provide accurate measurements within ±2% uncertainty of the mass flow over the expected flow range of the test loop.

The maximum operational limits for this style of flowmeter are listed to be 145 psi (1 MPa) at 392°F (200°C), a temperature range of -58°F (-50°C) to 392°F (200°C), and maximum flow rates between 0-32,000 kg/h (8.86 kg/s) for the DN15 sensor and 0-88,400 kg/h (24.6 kg/s) for the DN25 sensor. Flowmeters are bidirectional and can measure both temperature and mass flow rate in any flow direction. It was, however, advantageous to mount them in a vertical orientation to allow for venting of gas bubbles.

The flowmeters mate with the CIET 1.0 flow loop with ANSI B16.5 stainless steel compression flanges. It was important, however, to ensure that vibrations in the loop were minimized. This was achieved through the installation of bellows, pipe clamps, or flexible tubing in the immediate adjacent area to each of the flowmeters.

Three of the four Coriolis flowmeters can be seen before their insulation was applied, in Figure **4-3**. One of the flowmeter transmitters, which converts signals from the sensor to a current output read by the CIET DAQ system, can also be seen in Figure **4-3**.

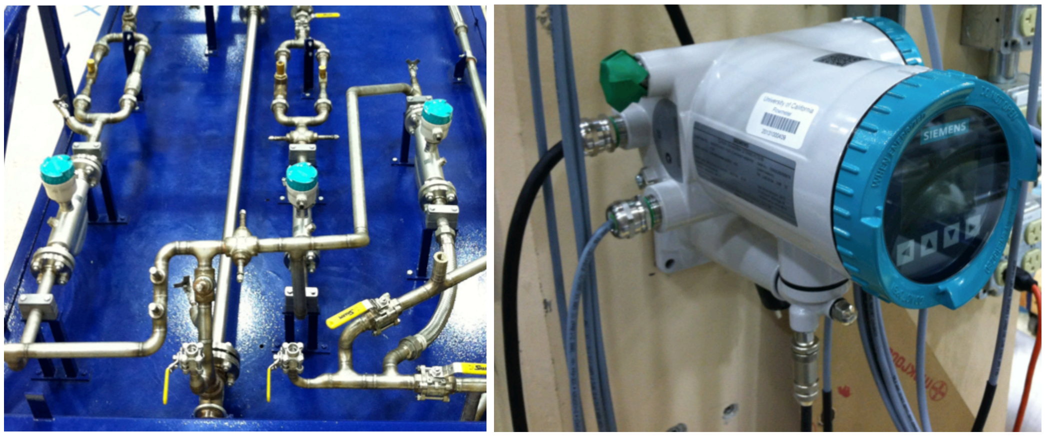


Figure 4-3. Three uncovered flowmeters installed on the primary loop before insulation (left) and flowmeter transmitter mounted on a wall (right).

By appropriate alignment of bypass lines, the CIET 1.0 facility 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.

4.4 Viscosity Measurements

UCB has also developed the capability to perform viscosity measurements on simulant oils at temperatures ranging from ambient conditions (~20°C) up to 200°C. Glass capillary viscometers manufactured by Cannon Instrument Company are used for these measurements. The viscometers currently used by UCB, shown in Figure **4-4**, are models #25 and #75. Kinematic viscosity measurements of fluids can be taken using glass capillary viscometers by measuring the time it takes for a fluid to drop between two established reference points. Two Cannon-Fenske viscometers are required for these measurements as the valid viscosity range for each viscometer is limited. The two viscometers also allow viscosity data to be collected for a wide range of temperatures. Initial calibration of the viscometers was performed by Cannon Instrument Company as per the American Society for Testing and Materials D 2162 standards and ensures accuracy within ±0.16%.

Figure 4-4. Cannon-Fenske glass capillary viscometers used for measuring oil kinematic viscosity.

4.5 DAQ System and Interface with LabVIEW Software

CIET 1.0 is equipped with a National Instruments DAQ system. The DAQ system consists of two TC signal reader terminal blocks (SCXI-1303) connected to two TC signal reader modules (SCXI-1102B) that are housed in a chassis (SCXI-1000), which sends the data to the CIET control computer via a USB connection module (SCXI-1600). With a total of 64 input channels, the CIET 1.0 DAQ system can accommodate the 47 TCs and 4 Coriolis 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. The CIET 1.0 DAQ system is shown in Figure 4-5. The blue wires shown in the photo are TC extension wires connecting individual TCs to the DAQ TC signal reader.

Figure 4-5. CIET 1.0 DAQ located at the operator workstation.

The SCXI-1102B and SCXI-1303 modules can be used for signal conditioning of TCs and signal acquisition from 4 to 20 mA current sources, in particular. They have 32 differential analog input channels and one cold-junction sensor channel used to scale temperature readings from TCs. For CIET 1.0, over the two modules, 47 channels are used to acquire TC signals, and 4 channels acquire 4-20 mA current outputs from flowmeter transmitters. Output from the SITRANS FC430 Coriolis flowmeters is 4-20 mA current while SCXI-1102B modules with SCXI-1303 terminator blocks read voltage from TCs in their default configuration. To accommodate the signal from the flowmeter transmitters, resistors have been installed on the channels of the SCXI-1102B module where the flowmeters are connected. The SCXI Process Current Resistor Kit is a pack of four precision resistors for measurements of 0-20 mA and 4-20 mA current inputs. The kit includes four high-precision 249 Ohm, 0.1%, 5 ppm/°C, 0.25 W resistors that have been installed in silkscreened component locations in the CIET 1.0 SCXI-1102B modules.

The CIET 1.0 DAQ system can interface with any 32-bit computer (64-bit computers are not compatible with the SCXI-1600 USB module). On the CIET 1.0 computer 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. The DAQ Assistant can both acquire and generate signals. However, for CIET purposes, signals are only acquired, from analog inputs. Each input from a physical channel is associated with a local, virtual channel, which can be configured for types of measurement (TC vs. current output from flowmeter transmitters), measurement units, data acquisition range, etc.

- As mentioned before, three VFDs are used to control the pump motor and the CTAH and TCHX fan speeds. LabView communicates with the three Automation Direct GS1 VFDs via the Modbus serial communication protocol. To bridge this communication, a USB-485M cable supplied by Automation Direct is used. Once appropriate controls have been set through the LabVIEW VI's main block diagram, the front panel of the VI can offer experimenters many options to control the VFDs. As an example, Figure 4-6 shows the controls used for the CIET 1.0 pump feedback control test. The *RUN/STOP* button is used to remotely start and stop the pump. Then, the user can either manually control pump speed by varying the value under "*Pump Frequency*" (left), or set proportional, integral and derivative control parameters K_p, K_i, and K_d for automatic feedback based on a desired mass flow rate ("*Pump Set-Point*," right). By integrating VFD control and data acquisition from flowmeter transmitters in particular, the LabVIEW software is a powerful tool to test control strategies on CIET 1.0. A similar type of feedback is implemented for control of fan-cooled heat exchanger fan speeds based on measured bulk fluid temperatures.

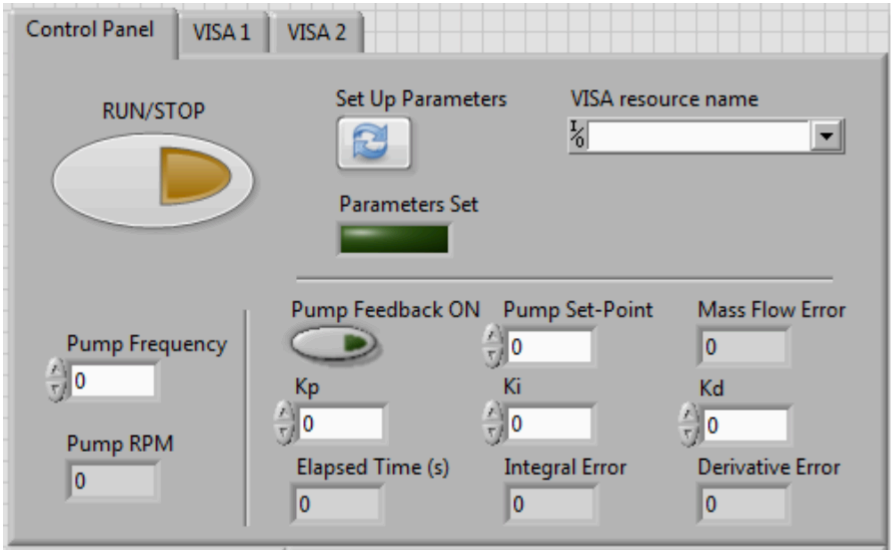


Figure 4-6. User controls for the CIET 1.0 pump feedback control test in LabVIEW.

- In addition to LabVIEW, a second DAQ software program, Origin, is used. Origin is a spreadsheet program used to record and analyze data from CIET. Origin comes with pre-built LabVIEW VIs that allow the user to activate and manipulate Origin from LabVIEW. Therefore, for each test performed on CIET 1.0, all data collected by the DAQ system, as well as pump and fans motor speeds, and the power input to the resistive heater, are automatically recorded and stored in an easy-to-use format for subsequent data extraction and post-processing.

Figure 4-7 is a full view of the front panel of a generic CIET 1.0 LabVIEW VI. To the upper left are controls for the three VFDs connected to the CTAH, TCHX and pump. To the bottom left are key temperature values and flow rates recorded from the DAQ system. A simplified diagram of the CIET 1.0 loop, adapted from the full piping and instrumentation diagram (Figure 3-1), shows the main flow paths and temperature measurements at their approximate locations. All values are continuously updated when the VI and the DAQ system are both running.

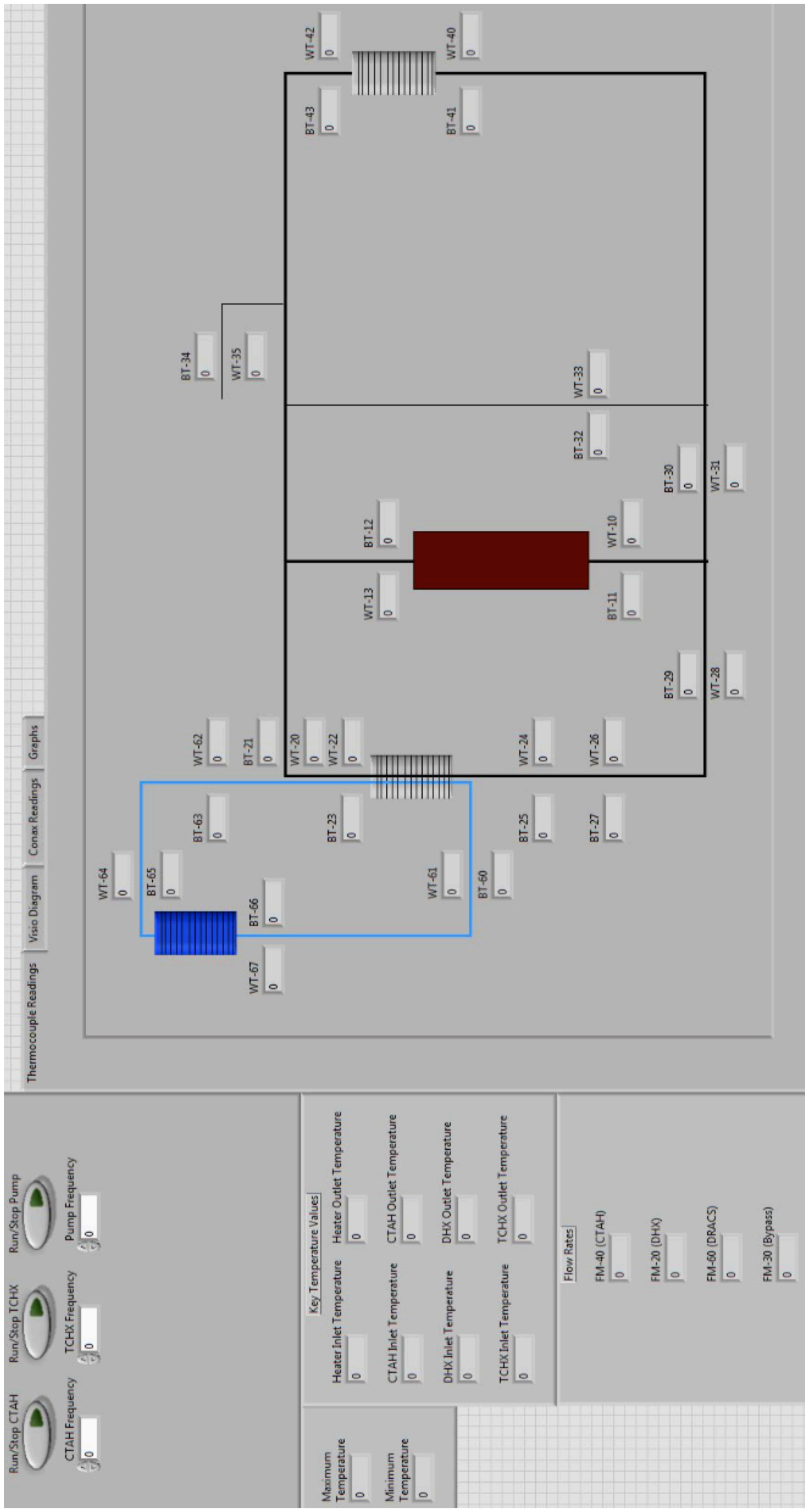


Figure 4-7. Front panel of a generic CIET 1.0 LabVIEW interface.

5 Quality Assurance Plan

As part of the original grant awarded to fund the CIET project, the NEUP program stipulated that “applicants should have sound quality assurance plans for all aspects of the proposed IRP programs” (U.S. Department of Energy’s Office of Nuclear Energy 2011). As a result, the project’s goal is to meet QA standards established by ASME, and in particular, the 2008 revision of the QA requirements for nuclear facility applications (NQA-1-2008) with the NQA-1a-2009 addenda. These QA standards outline procedures and guidelines for fabrication, operation, and design of nuclear-related equipment. This very rigorous set of standards was adopted in this instance to ensure that data acquired from the CIET project is not only reproducible, but that design methodology and fabrication of the experiment are fully traceable and documented.

All program activities related to the CIET project comply with the applicable requirements from Parts I and II of NQA-1-2008 with the NQA-1a-2009 addenda through a graded approach. Furthermore, NQA-1-2008 Part IV Subpart 4.2 provides guidance for application of QA requirements to research activities. This was done by tailoring the CIET QA program to a level proportional with the staffing and resources invested in the project. This tailored approach is the recommended approach under NQA-1-2008 Part IV Subpart 4.2 and allows progression of research when resources are limited.

The full ASME QA standards are broken down into many specific categories. The eighteen requirements outlined by the NQA-1-2008 standards are listed below:

1. Organization
2. Quality Assurance Program
3. Design Control
4. Procurement Document Control
5. Instructions, Procedures, and Drawings
6. Document Control
7. Control of Purchased Material, Equipment, and Services
8. Identification and Control of Materials, Parts, and Services
9. Control of Special Processes
10. Inspection
11. Test Control
12. Control of Measuring and Test Equipment
13. Handling, Storage, and Shipping
14. Inspection, Test, and Operating Status
15. Nonconforming Items
16. Corrective Actions
17. Quality Assurance Records
18. Audits

As previously mentioned, the QA program developed as part of the CIET project uses a tailored approach to these eighteen requirements. Tailoring of the QA program was based on prudent management, planning, cost, and personnel devoted to the project. Rather than establish procedures and criteria for all eighteen points, the UCB CIET QA program uses only twelve sections:

1. Quality Assurance Plan
2. Configuration Management
3. Design Control
4. Instructions, Procedures, and Drawings
5. Material, Equipment, and Services
6. Measuring and Test Equipment
7. Test Control and Collected Data
8. Software and Modeling
9. Training Program Plan
10. Corrective Actions
11. Audits and Surveillance
12. Records

The first component of establishing a QA program for the CIET project was to draft an overarching *Quality Assurance Plan* (QAP). This document[2] outlines the scope of oversight, establishes a structure for generating procedures, and delegates roles to personnel working on the CIET project. It also cites several ASME, DOE, and U.S. Nuclear Regulatory Commission (NRC) documents in establishing these guidelines[3]. A system of checks and balances and review processes were established. Moreover, the QAP outlines the scope of the twelve topics listed above. Each topic includes specific written procedures for handling everything from the design of heat exchangers to particular training requirements. In addition, the QAP outlines how an online repository was established to maintain all relevant documents used for the CIET project. A copy of the QAP is included in the Appendix for further reference.

While the CIET QAP only lists twelve sections, those twelve include at least minimal discussion of all eighteen elements required by NQA-1-2008. This was done to avoid devoting entire sections to areas that are not fully relevant to the CIET project. For example, *NQA-1-2008*

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[2] CIET-PLAN-QAP-001-04_Quality_Assurance_Plan

[3] ASME NQA-1-2008 with the NQA-1a-2009 addenda, Part I and applicable requirements of Part II: "Quality Assurance Requirements for Nuclear Facility Applications." American Society of Mechanical Engineers. (2009)

ASME NQA-1-2008 with the NQA-1a-2009 addenda, Part IV, Subpart 4.2: "Guidance on Graded Application of Quality Assurance for Nuclear-Related Research and Development." American Society of Mechanical Engineers. (2009)

DOE Order 414.1D: "Quality Assurance." Department of Energy. (2011)

NRC Title 10 CFR 50 Appendix B: "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants."

NRC Title 10 CFR 830, Subpart A: "Quality Assurance Requirements for Nuclear Safety Management."

Section 4, Section 5 and Section 13 are all addressed by CIET QAP Section 5 – *Material, Equipment, and Services*.

5.1 Organization and Responsibilities

The CIET program adopted an organizational hierarchy established by the NQA-1 2008. The major roles are outlined in Figure **5-1** with associated program responsibilities listed in Table **5-1**. As the project adopted a graded approach to implementing a QAP, there were instances where it was not appropriate, or not feasible, to assign responsibilities. For example, the *Configuration Manager*, *Equipment Manager*, and *Instrumentation and Control Manager* roles were left unassigned. Similarly, there are instances where one person serves in multiple roles. For example, Nicolas Zweibaum currently serves as the *Design Coordinator*, *Operations Coordinator*, as well as the *System Modeling Coordinator*. Similarly, Jeff Bickel serves as the *Quality Assurance Support,* the *Facility Manager*, and the *Safety Manager*.

Including the Principal Investigator, six people populate all eleven roles used in the CIET project. Since in some instances, the same person serves in both the supervisory and subordinate role, any calculation, document, or procedure generated is required to be reviewed by the next supervisory role. For instance, the responsibilities of the *Facility Manager* are reviewed by the *Operations Coordinator*. If those people happen to be the same person, documents generated by the *Facility Manager* are reviewed and approved by the *Quality Assurance Support* (or the *Program Manager*). This system of oversight provides the ability to review and approve all documents generated for the project while only having a limited number of fully-devoted research staff.

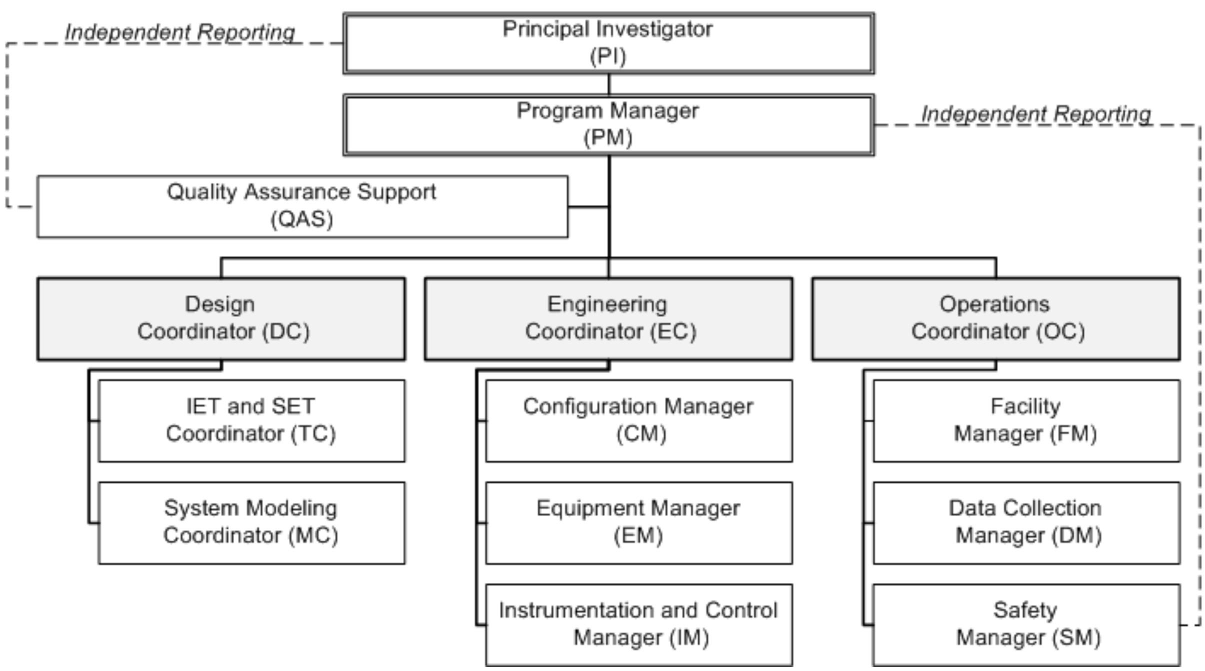

Figure 5-1. QA program organizational chart.

Table 5-1. CIET project organizational roles and responsibilities.

Role	Responsibility and Authority
Principal Investigator (PI)	Provides program requirements to the Program Manager, and interfaces with the Sponsoring Organization(s). Adjudicates unresolved quality concerns. Has overall responsibility for executing program requirements and for ensuring that quality related activities are in compliance with the QAP.
Program Manager (PM)	Maintains Program Research Plan. Takes direction from the PI to implement the QAP. Designates and/or certifies all project personnel. Ensures that performers of the work assess and monitor their activities. Adjudicates unresolved safety concerns.
Quality Assurance Support (QAS)	Develops and maintains QA documents consisting of the QAP and all derived documents, per quality requirements provided by the PM. Maintains QAP and all derived documents. Provides QA support for the program. Coordinates document control and records. Performs an oversight function.
Design Coordinator (DC)	Ensures that experiment design goals align with system modeling goals, and is ultimately responsible for code validation analysis. Prepares baseline design and approves design changes. Identifies appropriate specifications and critical items. Critical items shall be procured from a qualified manufacturer.
Engineering Coordinator (EC)	Responsible for detailed engineering design, construction, startup testing, maintenance and repair of the test facility and each of its components (hardware and instrumentation), instrument calibration, and maintaining configuration records.
Operations Coordinator (OC)	Has overall responsibility to ensure effective and safe operation of the test facility and compliance with design and engineering requirements, QA requirements, and all other applicable requirements.
IET and SET (Test) Coordinator (TC)	Responsible for experimental design, test planning and supervision of test execution. Has overall responsibility for preparation and execution of tests including test procedures and test reports.
System Modeling Coordinator (MC)	Responsible for system modeling, and meeting the corresponding QA requirements, including code verification and documentation of results. Has overall responsibility for development of validation plan.
Configuration Manager (CM)	Responsible for developing and managing design of overall configuration of facility, including hardware and instrumentation.

Role	Responsibility and Authority
	Manages and approves all changes to facility configuration. Responsible for facility construction, startup testing, and turn-over to Facility Manager.
Equipment Manager (EM)	Responsible for the detailed design, procurement, manufacturing, assembly, maintenance and storage of experimental components and equipment. Responsible for startup testing of each component or piece of equipment, and turn-over to Facility Manager. Responsible for selecting technically acceptable and responsible suppliers including distributors authorized by the manufacturer.
Instrumentation and Control Manager (IM)	Responsible for design, procurement, assembly, configuration and maintenance of data acquisition and automatic controls, including electronic hardware and software and related equipment. Reviews and approves sensor selection proposed by CM or EM. Responsible for all instrument calibration, and quantification and documentation of sensor uncertainty. Responsible for startup testing of the DAQ and control system, sensors and other related instrumentation, and turn-over to Data Collection Manager or Facility Manager, as appropriate.
Facility Manager (FM)	Responsible for operation, maintenance and repair of the facility, including spare parts, procurement, and vendor services. Has overall responsibility for development of facility operation and maintenance procedures and best practices, and for training the corresponding operating and maintenance personnel.
Data Collection Manager (DM)	Responsible for collection, verification, appropriate pre-processing and conditioning, and archiving of test data. Responsible for application to collected data of data analysis algorithms provided by DC or EC, and archiving of analysis outputs. Responsible for the design, procurement, configuration, and management of the computer systems and software, necessary to meet the data collection requirements.
Safety Manager (SM)	Responsible for safety of all operations related to the CIET facility. Responsible for coordinating with UCB Campus Environmental Health and Safety staff, Nuclear Engineering Department Safety Coordinator, and Building Manager, to ensure that the appropriate safety requirements are met.

5.2 Document Control

One critical part of implementing the QAP is document control. As several hundreds of documents (training procedures, design methodologies, engineering drawings, loop diagrams, etc.) were (and are still being) developed during the CIET project, a coherent system of organization is required. Furthermore, it is critical to avoid instances where multiple people add or subtract material from the same version of a particular document. In addition to version control, accessibility is another critical component for the CIET project. It is important that all personnel involved with this research project be able to access files easily and from any location, while at the same time ensuring that the correct version of a particular document is available.

All of these requirements are well met by the online file repository company, Dropbox Inc. Using Dropbox, all personnel involved in the CIET project can access up-to-date files related to the project from any computer with an Internet connection. Moreover, permissions for each student involved with the project are easily set to appropriate levels. All students involved in the project are granted access to read files. Access to edit, delete and move files, however, is reserved to personnel listed in the hierarchy shown in Figure **5-1**. Ultimately, all files generated through the course of the CIET project are named, reviewed, approved, uploaded to Dropbox, and filed according to a strict set of guidelines.

In addition to where and how documents are stored, the cataloguing of documents is assisted by an established naming convention. All files take a name that gives the reader information about how they are filed and where they can be located inside the Dropbox repository. Figure **5-2** illustrates how a typical file might be named.

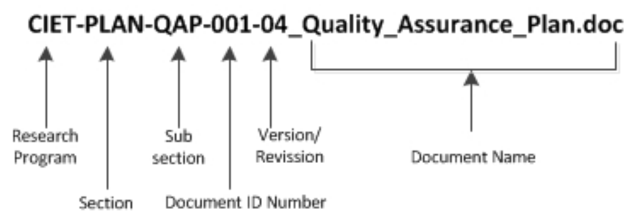

Figure 5-2. CIET file naming convention.

The first part of the file name indicates the research program that the file is part of. In this instance, it is the CIET research project, though the CIET QAP has been adopted by other research projects within the Thermal Hydraulics group at UCB. The second portion of the file name gives the section. This is one of the twelve sections adopted by the QAP as mentioned above. The third item lists the sub-section (if any). A new document identification number is given for each new document that is generated as part of the research project. Similarly, any revision number is referenced by the following identifier. Lastly, the document name is representative of the contents of the document.

In addition to current versions of all documents, historical drafts and revisions are kept in *Repository* folders on Dropbox. This allows one to not only review how the research project has developed over time, but also how corrective actions have changed procedures or other documents. Figure 5-3 illustrates an example of how the QA folder hierarchy is setup.

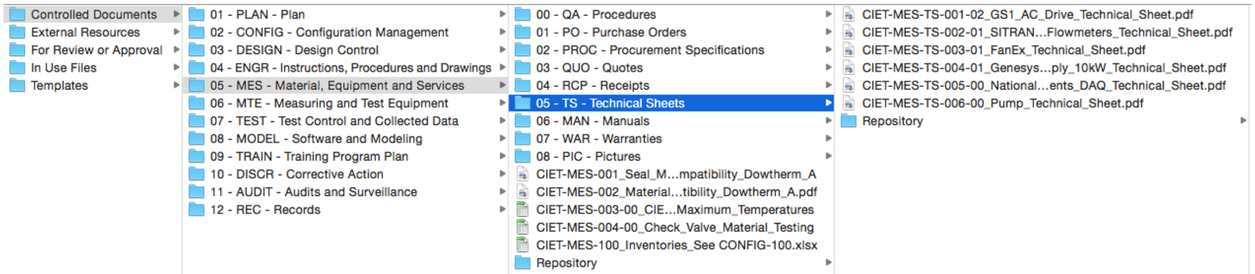

Figure 5-3. Folder organization on the CIET Dropbox repository.

5.3 Audits

One component of NQA-1-2008 is the requirement of regular audits. The frequency of audits is dictated by the particular research project. The CIET project requires that an independent, third-party auditor be brought in yearly to review all material relevant to the test program. Audits shall be performed using written checklists developed as part of the QAP for the CIET project. The Program Manager (or designee) is responsible for management assessment of the audit.

Two external audits of the CIET research program have already been conducted. The first audit was conducted on January 15th-16th, 2013. The main conclusions of the audit were that:

- "The CIET Project [had] made considerable progress in establishing a QAP to meet early Project phase QA requirements,"
- "The QAP and implementing procedures did not address all requirements of DOE Order 414.1, NQA-1 and 10 CFR 50 Appendix B (as applicable),"
- "As the CIET Project moves forward, the QA Program must be able to demonstrate meeting all applicable requirements and demonstrating implementation of those requirements through use of implementing procedures, instructions, etc."

Through 2013 and early 2014, significant efforts were made to develop a complete set of implementing procedures. A second external audit was conducted on April 29th-30th, 2014. The main conclusions of the audit were that:

- "The CIET Program personnel were very professional and knowledgeable of the CIET QA Program requirements. The level of effort put into the development of the CIET QA Program [was] noteworthy,"
- "The CIET QA Program documentation would be given a higher rating if it was only performing basic or applied research not intended for an NRC license. However, the CIET Program research and development activities and support activities are intended for NRC licensing in the future and therefore the audit [was] rated as Marginally Effective/Meets Some Requirements."

Following the second audit, major efforts were developed to correct the existing QAP and implementation procedures in response to all audit findings and judgments of need. Both audits were conducted by Darren Jensen, an ASME NQA-1 Certified Auditor and former QA Lead

Auditor for NEUP. In addition to the external audits, an internal audit was conducted on March 21st, 2013. Findings from all three of these audits were communicated in writing to members of the Thermal Hydraulics group as well as archived on the CIET Dropbox repository.

5.4 Component Tracking, Mass Measurements, Photos, and Documentation

One beneficial corollary from the thorough documentation of the CIET QAP was the cataloguing of all items used to fabricate the CIET 1.0 flow loop. All pipes, valves, tees, elbows, unions, and other components were weighed, measured and permanently tagged before and after assembly. Photos of each component were uploaded to the CIET Dropbox repository. An example is shown in Figure 5-4. The purpose of this exercise was to establish a high-fidelity model of the as-built flow loop. Material properties and mass measurements of all the components were used in constructing system heat transfer models to be validated with CIET 1.0 experimental data, as detailed in Section 7, to determine thermal inertia and heat losses for each part of the flow loop.

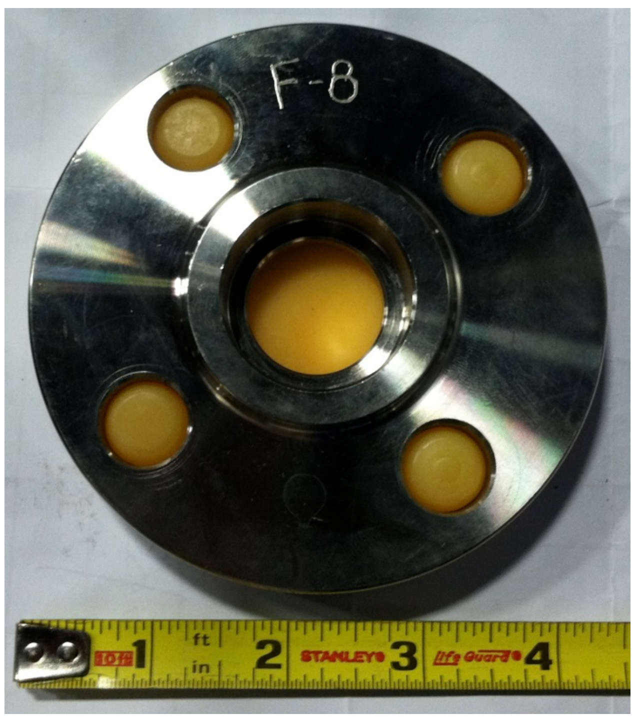

Figure 5-4. Cataloguing of flange #8.

Mass measurements and component tracking will also allow for a detailed characterization of the thermal capacity and thermal inertia of major segments of the flow loop. Future work will include a series of transient experiments to further validate thermal hydraulic models.

5.5 Corrective Actions

Section 10 of the CIET QAP is devoted towards corrective actions. This component of the QA program has been key in identifying, documenting, and correcting problems that have arisen during various aspects of the project. The *Corrective Action Procedure* developed as part of the

CIET QA program outlines how concerns are to be documented and investigated. It is the responsibility of all CIET researchers to be actively looking for problems and report adverse conditions. A log of reported issues, major or minor, is kept on the Dropbox repository.

Table **5-2** lists several examples of corrective actions that have been reported and catalogued over the course of the CIET project.

Table 5-2. Examples of CIET 1.0 initiated corrective actions, in chronological order.

Number (Date)	Initiating Event	Solution
CIET-DISCR-CR-001-A (December 2013)	A leak on the shell side of the DHX was detected by Johansing Iron Works during final leak testing of the loop. It was observed that there was a ~5 mm hole on one of the braze joints in a 2” copper tee.	The hole was filled with braze material and both the shell and tube sides of the DHX were further leak tested by UCB. Leak testing was performed by capping off both of the flanges for a respective side of the DHX. A female quick-connect air fitting was installed on one of the flanges and then connected to pressurized air. A pressure gauge was installed on the other flange. The heat exchanger was pressurized to ~35 psi and left to sit for ~48 hours. After 48 hours, if pressure was maintained, the HX was deemed to be “leak tight”. Corrective action report closed on January 14th, 2014.
CIET-DISCR-CR-002-A (May 13th, 2014)	Using a multimeter, Nicolas Zweibaum identified that the inner and outer heater tubes were in electrical contact. If the heater were to be electrified under these conditions, current would propagate to the entire piping rather than being confined to the sole resistive heater, which would pose a health and safety risk.	New Teflon gaskets and washers were ordered. All flange bolts connecting the heater heads were wrapped with nonconductive electrical tape. Flanges were re-aligned with clamps while bolts could be reinserted. Electrical conductivity between the inner and outer heater tubes was then checked with a multimeter. Once all bolts were tightened, clamps were removed and electrical conductivity was checked again.  Corrective action report closed on July 9th, 2014.
CIET-DISCR-CR-003-A (June 19th, 2014)	Jeff Bickel noticed that the bridge crane in 1140 Etcheverry Hall interfered with the vent pipes of the upper	At ~27’ above ground, the only solution for this item was to remove the expansion tank, cut the three protruding vent pipes, remove ~1.5” of material, and re-weld the pipes back together. This work was performed by the UCB *Mechanical Engineering Professional Machine*

Number (Date)	Initiating Event	Solution
	expansion tank. These pipes represent the global high-point in the loop.	*Shop* staff. New welds were leak-tested to 30 psi and the tank was reinstalled. The tank no longer interferes with the bridge crane. Corrective action report closed on July 7th, 2014.
CIET-DISCR-CR-004-A (July 15th, 2014)	Per Peterson initiated a corrective action report regarding foreign material exclusion in the flow loop. During the insulation stage of the project, several tubes, flanges, unions, TC and manometer ports, and other orifices exposed the interior of the plumbing to the exterior surroundings. Dirt, debris, insulation wool, and other items could potentially fall inside the plumbing loop.	The PI suggested that painter's tape (or equivalent) be placed over all openings in the flow loop that remained uncovered. Even when removing a TC for a temporary calibration check, the exposed port should be covered. This would help minimize inadvertent inclusion of foreign materials into the flow loop. If a problem were to be discovered whereby we expect that foreign material has been entrained into the flow loop, it may be necessary to purge the piping system with high-velocity inert gas. If this approach were not to work, a boroscope may need to be purchased to further investigate the interior of the piping system. All open ports were immediately covered with painters tape. No foreign objects (or symptoms of their entrainment) have been observed as of December 2014.
CIET-DISCR-CR-005-A (July 25th, 2014)	During leak testing, it was noticed that gas was escaping through the sheathing of TCs. Not through the Swagelok fittings, but up through the internal chamber of the TCs. It was determined that Omega Engineering, Inc. had not adequately sealed the electrical TC wire to the compression fitting housing.	Although leaks were only noticed on several TCs, all TCs were removed from the flow loop and the junctions in question were soldered. Two different solders were used. TCs installed on the DRACS loop (and therefore exposed to lower bulk-fluid temperatures) were soldered using lead-free tin solder (melting temperature was rated at 221°C, or 430°F). TCs on the primary loop were soldered using 97.5Pb-1.5Ag-1Sb solder purchased from McMaster-Carr, with a rated melting temp of 304°C (580°F). All TCs were re-calibrated, then reinserted into the flow loop and tested for hermeticity.

Number (Date)	Initiating Event	Solution
		 Corrective action report closed on August 28th, 2014.
CIET-DISCR-CR-006-A (August 12th, 2014)	It was discovered by Zhangpeng Guo that the electrical tape used to cover the heater head bolts was not rated for high temperature and would fail above ~95°C (200°F). The design temperature for the heater surface under normal operation is up to ~260°C (500°F).	Preliminary analysis shows that for a Nu=4.36, the heater outer tube temperature, under forced circulation, with 10 kW of input power and 0.1 kg/s of flow, will yield a peak tube temperature of 264°C. The heater was again disassembled. All bolts were removed. Electrical tape used to wrap the bolts was discarded. New tensilized PTFE Tape rated to 260°C (500°F) was purchased from *www.findtape.com* (product #PTFE-5/136). New PTFE tape was wrapped around the heater head bolts and bolts were reinstalled. Teflon washers were replaced during disassembly to avoid wear. Heater tubes were re-aligned in a similar manner as previously described and the heater was reassembled. Electrical conductivity was tested between the inner and outer tubes. No electrical conductivity was observed between the two tubes. Corrective action report closed on August 28th, 2014.

6 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 December 2014, 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 will be 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 will be compared to pre-predicted performance and form 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.

6.1 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 (except the bypass branch, which will not be used in near term testing), at room temperature. CIET-specific pressure loss correlations shall later be implemented in CIET system modeling codes. These tests will also generate data to develop pump curves, as a function of pump speed, for the CIET pump, and to verify that loop Coriolis flowmeters aligned in series give consistent flow rate measurements. For these tests, flow rates in the loop were controlled through pump speed and, secondarily, by degree of closure of needle valves in some branches of the loop. 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 measured with TCs. All instrumentation was connected to the CIET computer control system through a DAQ device and controlled through the National Instruments LabVIEW software, allowing one to continuously collect data during the experiment.

Prior to the tests, experimenters ensured that the branches where pressure drops were measured were free of air bubbles, by circulating fluid at various speeds in these branches without collecting data and ensuring that no bubbles were visible in all transparent lines. The procedure was divided in three phases with each phase corresponding to a specific, pre-established valve line-up configuration:

1. Pressure drop measurements in CTAH and heater branches: collected data covered the whole range between 0 kg/s and 0.18 kg/s (read on flowmeter FM-40) in increments of 0.01 kg/s.
2. Pressure drop measurements in DHX branch (upwards flow direction): collected data covered the whole range between 0 kg/s and 0.12 kg/s (read on flowmeters FM-40 and FM-20 in series) in increments of 0.01 kg/s.

3. Pressure drop measurements in DRACS loop and DHX branch (downwards flow direction): collected data covered the whole range between 0 kg/s and 0.07 kg/s (read on flowmeters FM-40, FM-60 and FM-20 in series) in increments of 0.005 kg/s.

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.

Because CIET 1.0 is equipped with 16 manometer lines and isothermal pressure drop tests involved many combinations of valve alignments and flow rates, it would have been impractical to manually collect all pressure drop data. Instead, two cameras were installed facing the CIET manometer board, at the elevations of the free surfaces of the primary loop and the DRACS loop, and remotely controlled from the CIET computer station. An automatic process was developed to convert pictures of the manometer board to fluid levels, and eventually pressure levels using Adobe Photoshop CC and Matlab R2014a. This process was first calibrated during initial loop fill-up, to ensure pressure drop measurement accuracies of +/-10 Pa. The process is illustrated in Figure 6-1.

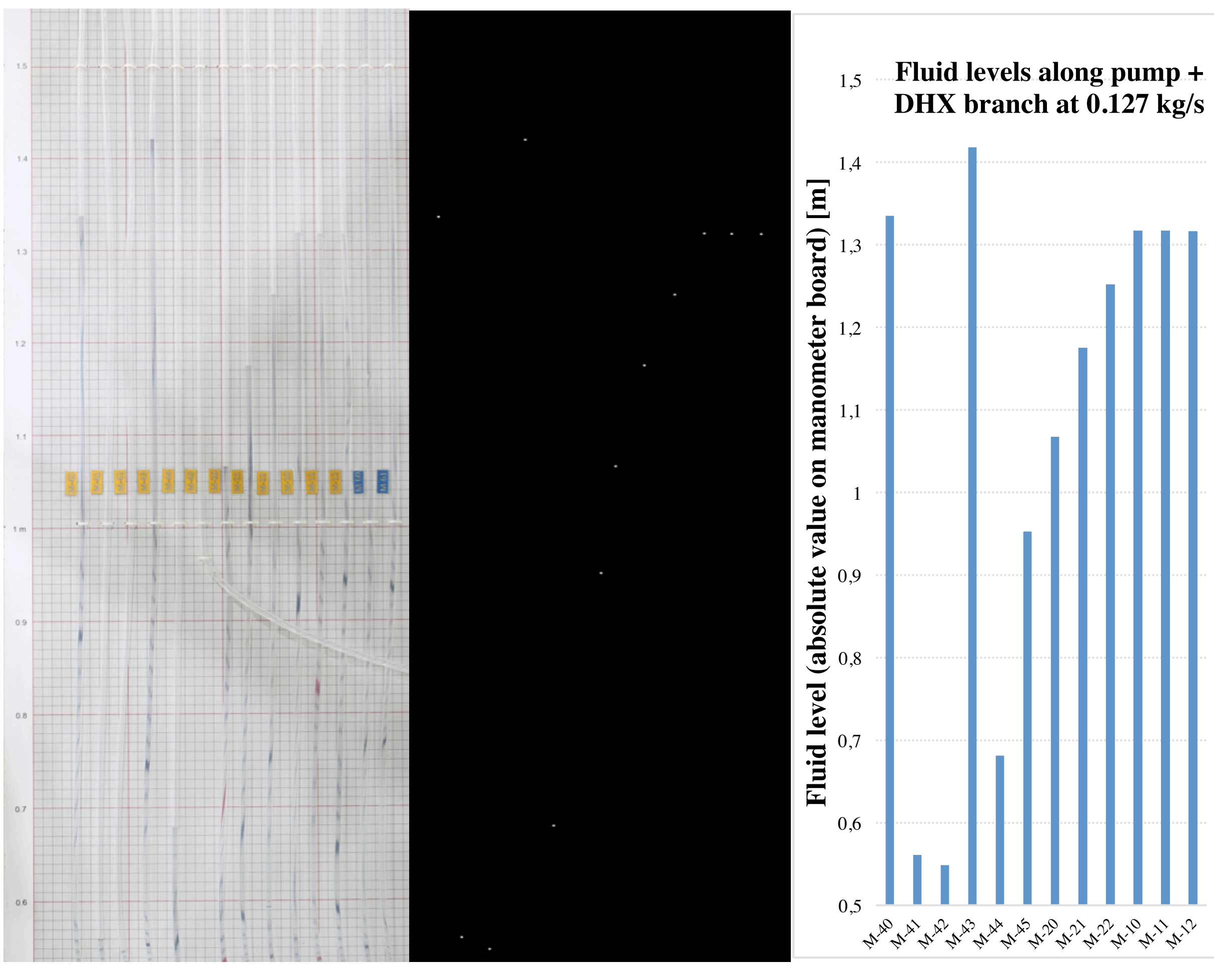

Figure 6-1. An automatic process converts manometer board pictures (left) to fluid level pictures (center), which are then converted to fluid level data (right).

Fluid levels in the CTAH and heater branch manometer lines at various flow rates are shown in Figure 6-2. Fluid levels in the CTAH and DHX branch manometer lines at various flow rates, with upwards flow through the DHX shell, are shown in Figure 6-3. Fluid levels in the DRACS loop and DHX branch manometer lines at various flow rates, with downwards flow through the DHX shell, are shown in Figure 6-4. On each figure, levels corresponding to the inlet and outlet of major components are specifically identified.

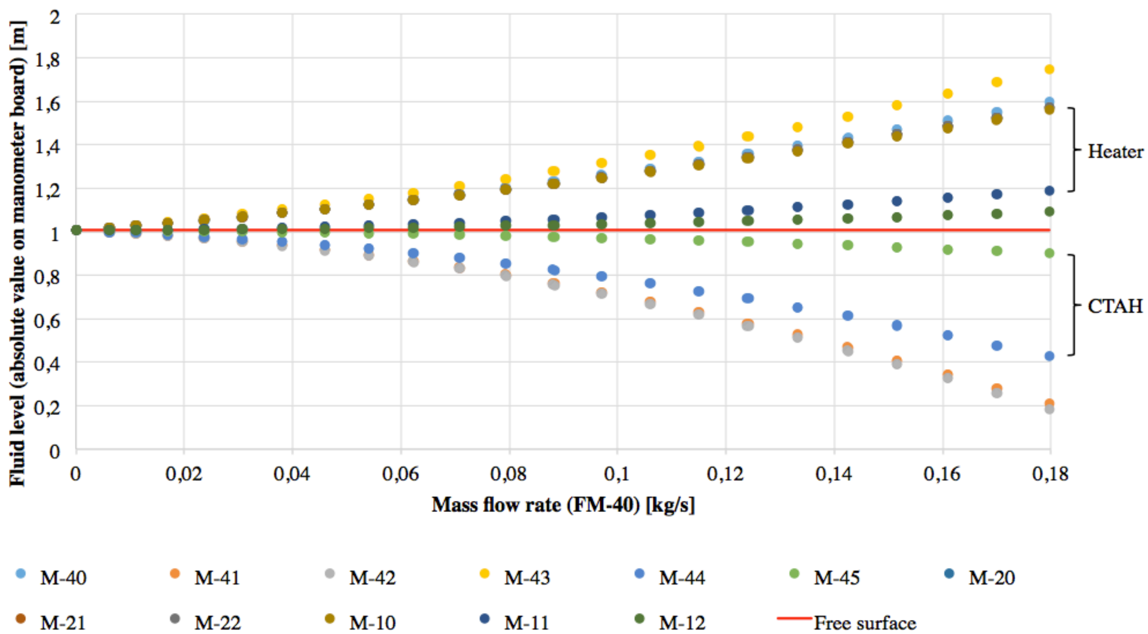

Figure 6-2. Fluid levels in the CTAH and heater branches at various flow rates.

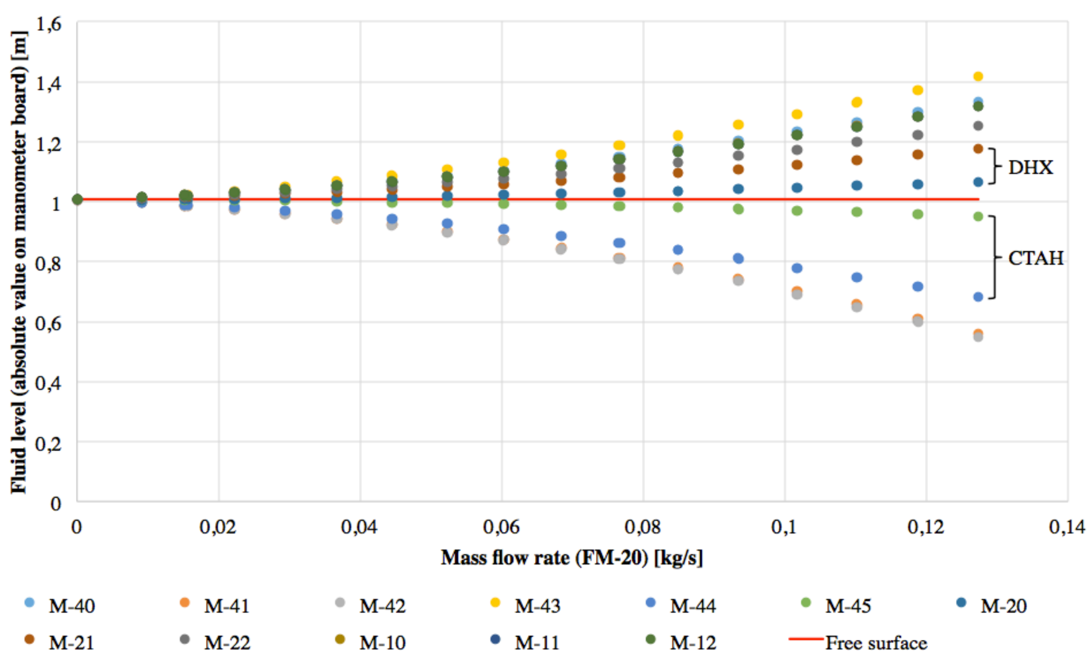

Figure 6-3. Fluid levels in the CTAH and DHX branches at various flow rates, with upwards flow through the DHX shell.

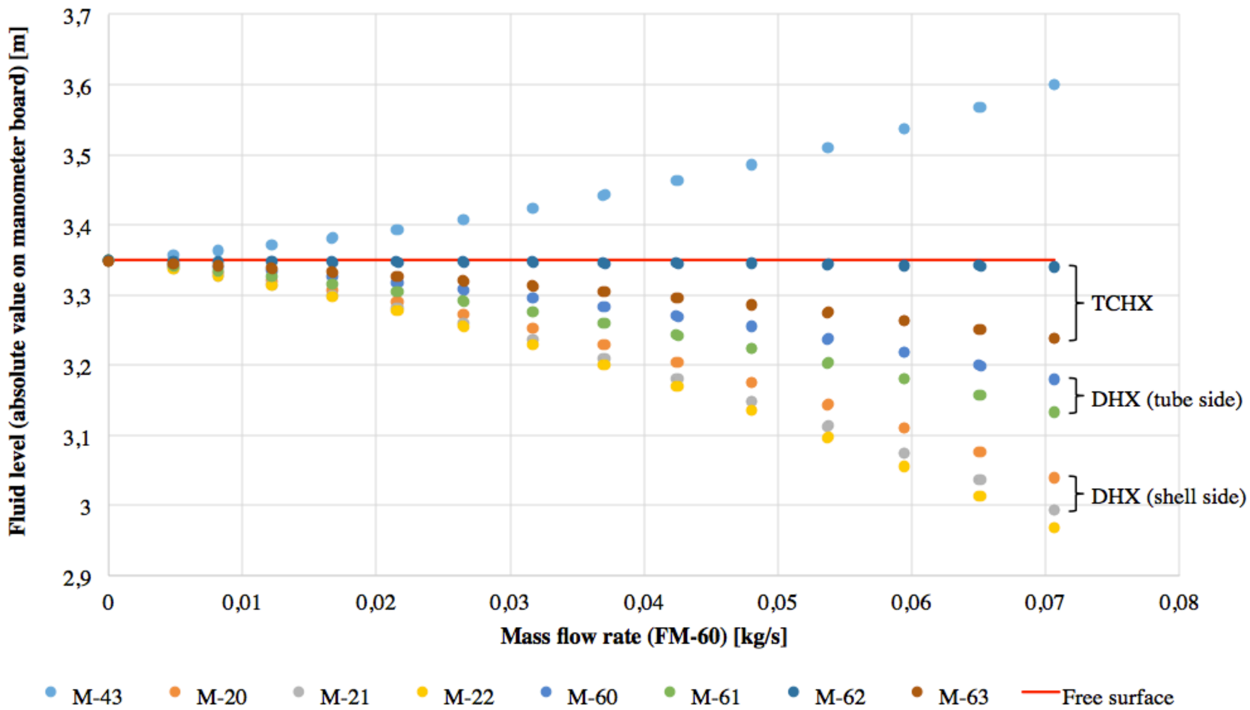

Figure 6-4. Fluid levels in the DRACS loop and DHX branch at various flow rates, with downwards flow through the DHX shell.

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:

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

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

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

$$\mathrm{Re} = \frac{\rho u D}{\mu} = \frac{\dot{m} D}{A\mu}$$

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

CIET-specific correlations for static mixers, Coriolis flowmeters and fan-cooled heat exchangers, derived from these tests, are listed in Table 6-1.

Table 6-1. CIET-specific friction number correlations for static mixers, Coriolis flowmeters and fan-cooled heat exchangers.

Component	Friction number correlation
Static mixer	$f\frac{L}{D}+K=21+\frac{4000}{\mathrm{Re}}$
Coriolis flowmeter	$f\frac{L}{D}+K=\frac{10340}{\mathrm{Re}^{-0.87}}$
Fan-cooled heat exchanger	$f\frac{L}{D}+K=\frac{8500}{\mathrm{Re}^{-0.67}}$

These correlations were based on optimal fits of calibration data collected from static mixer MX-10, flowmeter FM-40, and both fan-cooled heat exchangers. The corresponding fitting curves are shown in Figure 6-5, Figure 6-6 and Figure 6-7, respectively, and compared to vendor-provided values when available.

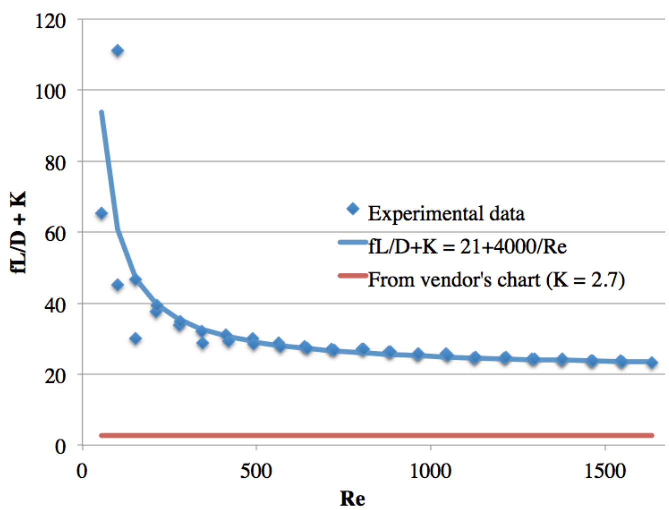

Figure 6-5. Friction number correlation for static mixer MX-10.

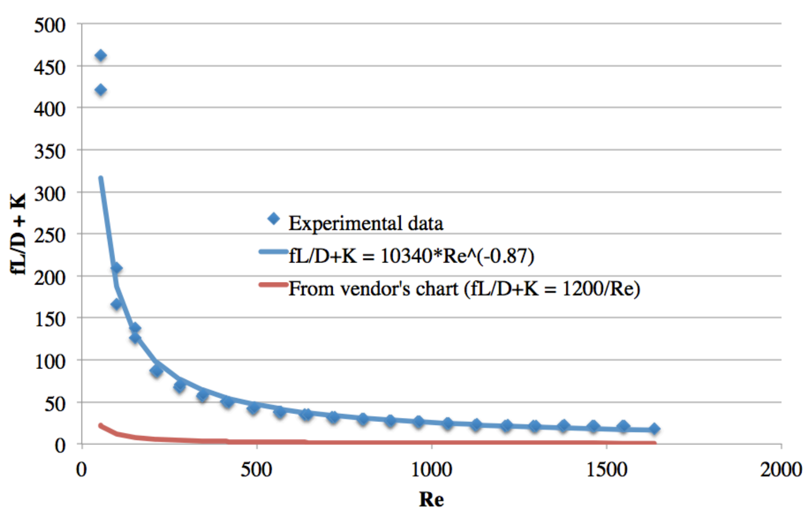

Figure 6-6. Friction number correlation for Coriolis flowmeter FM-40.

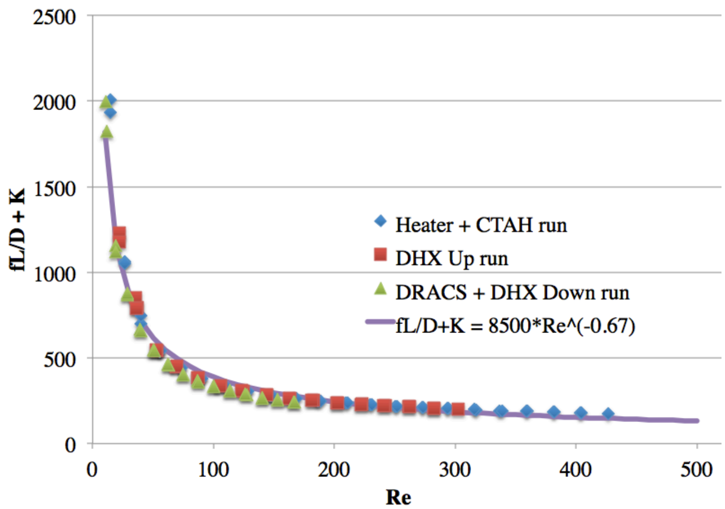

Figure 6-7. Friction number correlation for fan-cooled heat exchangers.

These correlations were further validated with data from other sections of the loop, as illustrated in Figure 6-8, which shows agreement within 10% between experimental data and CIET-specific empirical correlations for friction numbers in all sections of the loop containing static mixers, over the range of Reynolds numbers of interest in both forced and natural circulation operation.

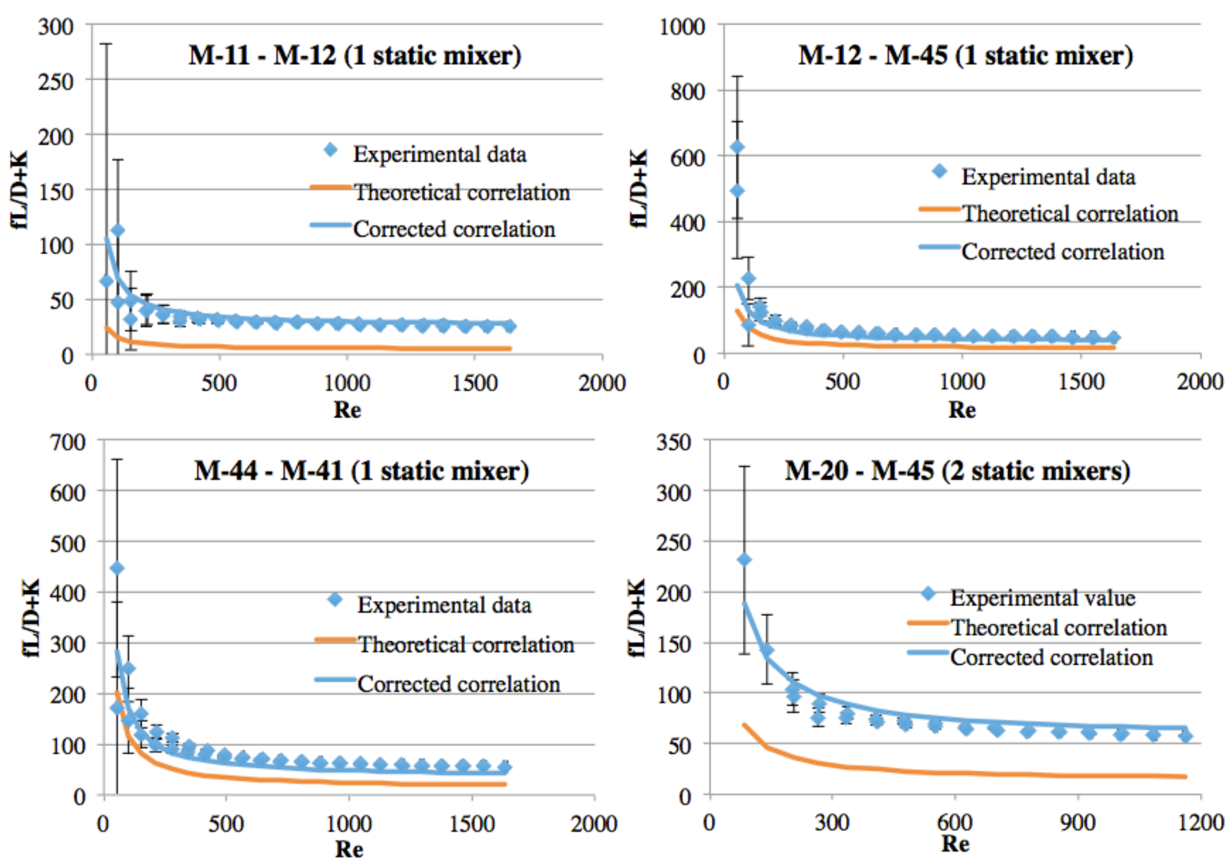

Figure 6-8. Friction number correlation for all sections of CIET 1.0 containing static mixers.

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 Figure 6-9.

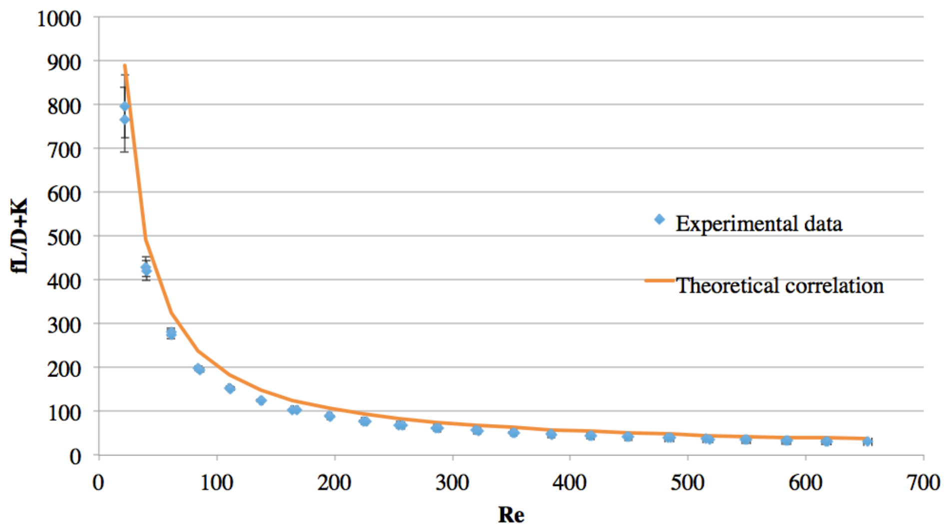

Figure 6-9. Friction number correlation for the CIET 1.0 annular heater.

These tests have confirmed that analytical correlations can be used for all regular piping sections of CIET 1.0, and component-scale correlation for some specific parts of the loop such as static mixers, Coriolis flowmeters and heat exchangers have been developed and match experimental data with an agreement within 10%. One key observation is that for components where vendor-provided correlations exist, such as static mixers and flowmeters, experimentally-measured pressure drop is higher than predicted from vendor charts, as shown in Figure 6-5 and Figure 6-6. Consequences on the integral behavior of the CIET 1.0 loop, especially flow losses balancing buoyancy driving forces for natural circulation, will have to be further assessed.

6.2 Initial Heated Tests

Before steady-state forced and natural circulation tests, 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.

6.2.1 Pump Control and Thermal Load

A first experiment, conducted on November 13th, 2014, had the double goal of testing a proportional feedback control system on the primary loop pump, based on fluid mass flow rate in this loop, and determining parasitic heat input from the pump at a nominal flow rate of 0.18 kg/s expected in the primary loop during forced circulation. If the heat input from the pump were to be non-negligible compared to the heat input from the electrical heater (up to 10 kW at full power), it would have to be taken into account in the integral energy balance for all CIET heated tests.

Throughout the test, the pump was run at nominal speed, resulting in the targeted 0.18 kg/s mass flow rate, with no additional heat injection or rejection to/from the system. The primary loop mass flow rate and average fluid temperature at the outlet of the pump were continuously recorded. This test confirmed that a proportional feedback controller on pump speed, based on mass flow rate in the primary loop, is appropriate to reach desired flow rates with minimal oscillations. At a fixed flow rate of 0.18 kg/s, the evolution of average pump outlet fluid temperature over time is shown in Figure **6-10**.

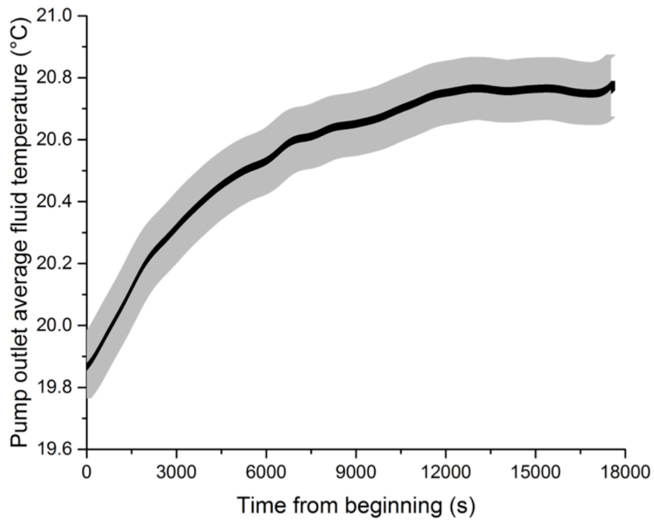

Figure 6-10. Pump outlet average fluid temperature over time at a mass flow rate of 0.18 kg/s.

Based on the maximum temperature increase rate at the beginning of the test (2.0×10^{-4} °C/s), the total mass of fluid in the primary loop (9.86 kg) and Dowtherm A heat capacity at 20°C (1576 J/kg°C), the heat input from the pump was estimated to be 3.11 W, which is negligible compared to the 10 kW heat input from the electrical heater during forced circulation operation.

6.2.2 Heater Control Trials, Parasitic Heat Losses

Another ongoing series of experiments is aimed at testing the CIET 1.0 power supplies and heater functioning, and determining parasitic heat losses from the oil loop to ambient air through the piping thermal insulation without guard heating. This is 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 can be used to calculate local heat losses from individual sections of the loop, and thermal insulation can be enhanced in locations where high parasitic heat losses are observed to minimize them.

To further reduce parasitic heat loss, an infrared camera is used to identify locations where these losses occur and to reduce them by adding thermal insulation. Eventually, remaining residual heat losses will be further reduced using a guard heating system to heat the CIET 1.0 enclosure to the average fluid temperatures in the loop.

6.2.3 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 (or other control parameters). An additional benefit from the development of this feedback control system involves the opportunity to collect extensive heat transfer data for these heat exchangers, that 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 a proportional controller, a proportional-integral controller, and a proportional-integral-derivative controller.

Preliminary results were obtained on December 8th, 2014, using a simple proportional controller to vary CTAH fan speed based on CTAH outlet temperature set-points. The test was run at a fixed mass flow rate of 0.18 kg/s, using proportional control of the primary pump speed based on primary loop mass flow rate, and fixed heat input of 1.06 kW through the resistive heater. Fluid temperatures were first ramped up by running the pump and power supplies without the CTAH fan on. In this first phase, there were non-negligible heat losses across the un-insulated CTAH. The temperature difference between the CTAH outlet and heater inlet at a given time was also due to minor heat losses, but more importantly to the time it takes for the fluid to travel from the CTAH to the heater (~30 s). CTAH fan speed was then manually set to arbitrary values to reach steady CTAH average fluid outlet temperatures at two different temperature levels. Based on the two values for fan speed at these two temperature levels, an appropriate proportional constant for control of CTAH fan speed, based on CTAH outlet temperature, was derived and tested after t = 4000 s. As seen on Figure **6-11**, the proportional controller was successful in reaching steady CTAH outlet temperatures of 40°C (step up), 38°C (step down) and 41.5°C (step up), successively.

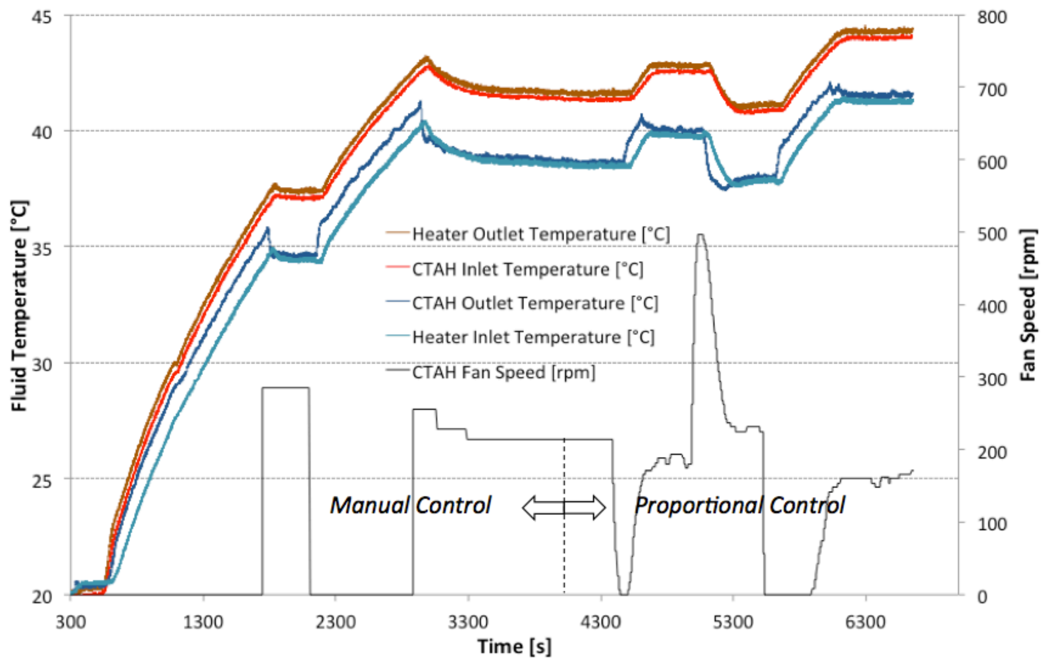

Figure 6-11. CTAH proportional feedback control test.

6.2.4 Load Following Trials

In this last series of initial heated tests, the goal will be to test basic load following capabilities using CIET 1.0 and more complicated control cases involving all three control parameters: pump speed, CTAH fan speed and resistive heater power input. For these tests, previously developed feedback controllers will be used to set bulk fluid temperatures at the heater outlet (hot leg) and CTAH outlet (cold leg) of the primary loop, and the CTAH heat rejection will be varied automatically to mimic "load following" conditions while the heater and pump respond using control systems.

7 Thermal Hydraulic Modeling

The thermal hydraulics of FHRs have many similarities with other reactor classes, but also key differences. UCB is developing thermal hydraulic simulation models to predict FHR steady-state characteristics and transient response for a set of reference LBEs. The general strategy is to rely on existing general-purpose thermal hydraulic codes with a significant verification and validation (V&V) basis for design and licensing by the NRC, such as RELAP5. The thermophysical properties of flibe have been implemented in RELAP5 (Davis 2005). For these reasons, RELAP5 is one of the preferred options for system modeling of FHRs. However, UCB has also been developing a single-phase simulation model, the one-dimensional FHR advanced natural circulation analysis (FANCY) code, to provide the capability to perform code-to-code comparisons and to verify that appropriate physical models are being used.

Since no FHR has been built to-date, additional V&V efforts for system codes used for FHR modeling involve identification of an existing experimental basis relevant to FHR phenomena, and the development of an FHR-specific experimental program where validation data is missing. CIET 1.0 experimental data is to be used as part of this validation basis, using the thermophysical properties of Dowtherm A implemented in RELAP5 (Moore 2010), as shown in Figure **7-1**.

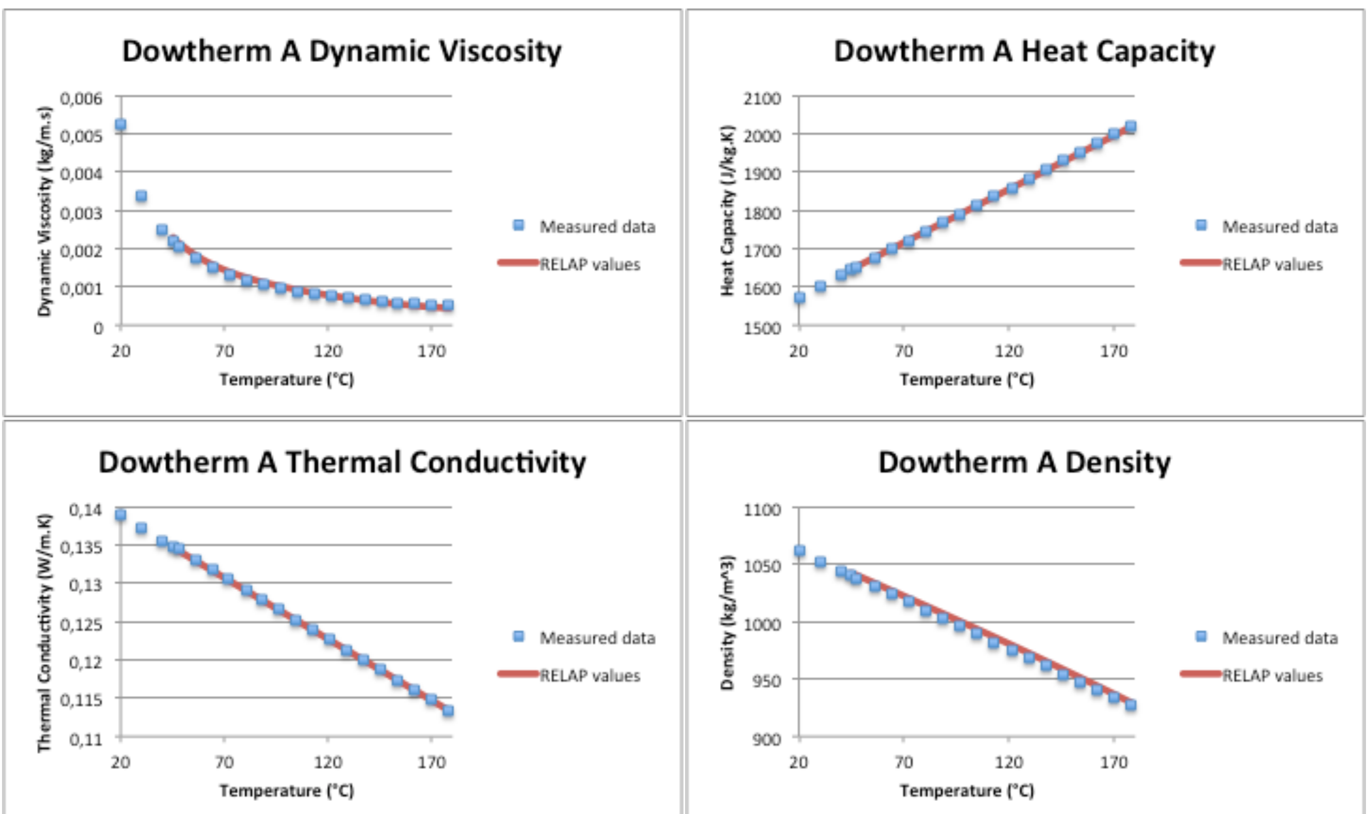

Figure 7-1. Thermophysical properties of Dowtherm A oil and implementation in RELAP5.

As an initial validation case, a single-phase forced/natural circulation loop was operated on the CIET Test Bay, models of the Test Bay were built in RELAP5, and computational results were compared against experimental data (Scarlat, Bickel, et al. 2012) (Zweibaum, Scarlat and Peterson 2013).

As part of the CIET research plan, coupled natural circulation loops will be operated on the CIET 1.0 facility. For validation purposes, computational results will be compared against experimental data. Reproducing such experimental setups in RELAP5 will be key to better understanding thermal hydraulic phenomena specific to FHRs and how to best model them. Part of the V&V effort will also include code-to-code comparisons with the commercially available code Flownex, and the FANCY code specifically developed at UCB for CIET and FHR natural circulation modeling. To this effect, common nodalization diagrams have been developed, as illustrated in Figure **7-2**. In addition to this diagram, a table has been developed with as-built properties of the CIET 1.0 loop to ensure that all models use the same assumptions. Listed properties include:

- Component lenghts
- Component elevation changes
- Component hydraulic diameters
- Component flow cross-sectional areas
- Form losses (e.g., tee junctions, elbows, etc.)
- Pipe wall material properties and thicknesses
- Thermal insulation properties thicknesses
- Number of hydrodynamic and heat structure control volumes.

Some gaps remain in the capabilities of RELAP5 and other existing general-purpose thermal hydraulic codes to properly model FHRs, for phenomena such as salt freezing (at 459°C for flibe at atmospheric pressure) and multidimensional porous media flow and heat transfer for pebble-bed FHRs. These limitations will have to be overcome for future modeling of FHRs.

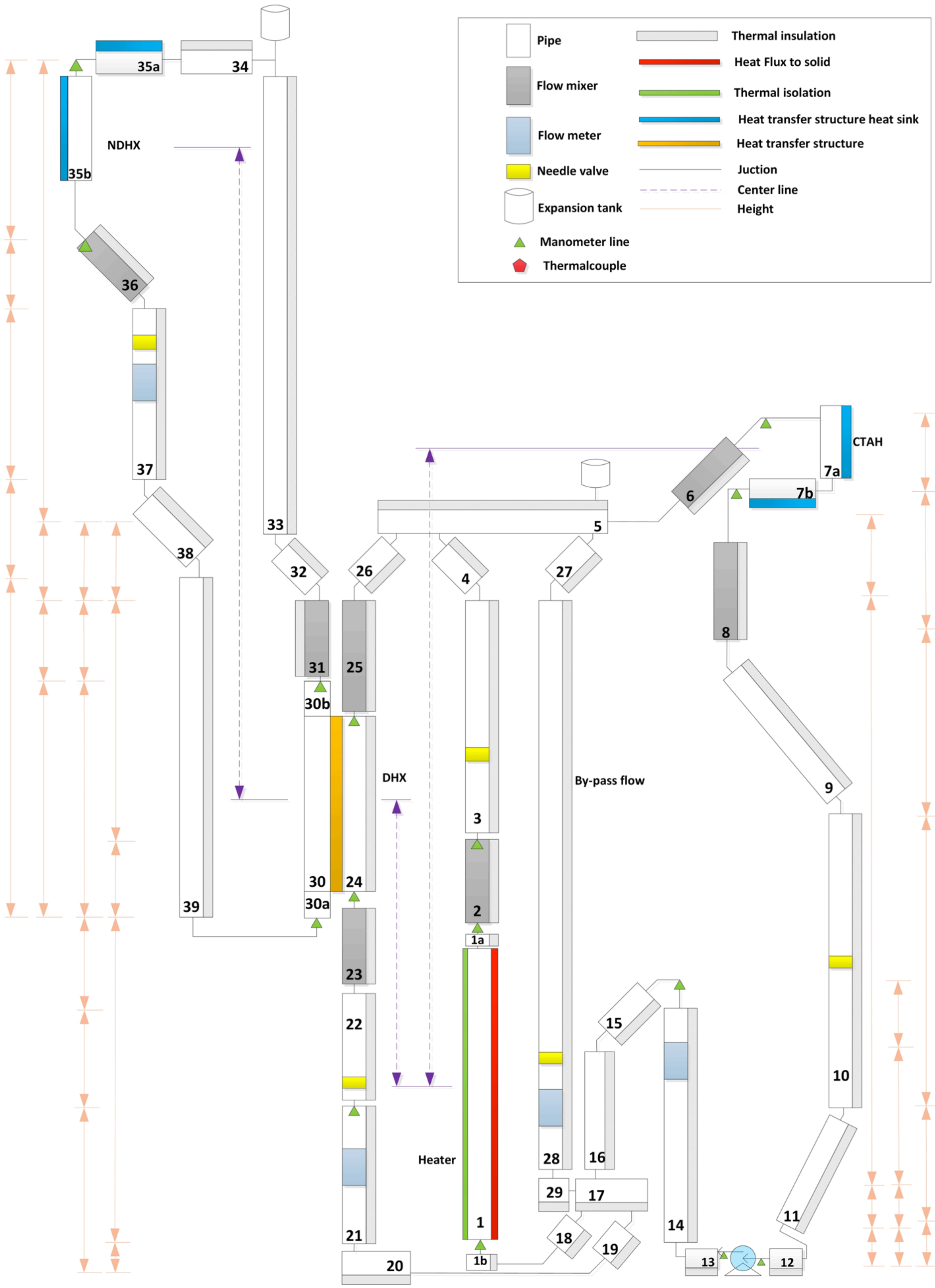

Figure 7-2. Common nodalization diagram used for CIET 1.0 modeling in RELAP5, Flownex and FANCY.

8 Project Cost and Timeline

While the total cost of the CIET project is significant, as previously stated, it is orders of magnitude smaller than previous first-generation and second-generation IETs. The DOE-NEUP grant was initially awarded in 2011. A categorical breakdown of costs for CIET 1.0 is listed in Table 8-1. Additionally, a full itemized cost table is available in the Appendix. It should be noted that the overhead cost of supporting students, staff, and post-doctoral researchers is not included in these dollar figures. An estimate on the time devoted thus far, however, is included.

Additionally, the timeline for the project is shown in Figure **8-1**. UCB tasks are labeled as those completed by personnel of the Thermal Hydraulics laboratory at UCB. External tasks were completed by fabricators, electricians, or other contractors who were not affiliated with the UCB Thermal Hydraulics group.

Table 8-1. CIET 1.0 cost list.

Equipment/Hardware	$65,069
Fabrication	$90,483
Instrumentation	$58,092
Services	$39,794
Total Construction Cost	$253,439
University Personnel	19,900 hours

CIET Research Project	12/1/2010	Present	1500+	80%
Design of the CIET Experiment	12/1/2010	10/31/2012	700	100%
CIET Component Test Bay Testing	12/1/2010	3/30/2012	486	100%
CIET Scaling Analysis	2/15/2012	6/30/2012	136	100%
Piping and Instrumentation Design	2/1/2012	7/31/2012	180	100%
CAD Design	2/1/2012	10/1/2012	243	100%
Production of Engineering Drawings	9/1/2012	12/20/2012	111	100%
Physical Construction	1/1/2013	12/11/2013	345	100%
Frame Construction	1/1/2013	3/14/2013	72	100%
Loop Construction	4/1/2013	12/11/2013	254	100%
Delivery to UCB (Milestone)	12/13/2013	12/13/2013	1	100%
Experimental Setup	12/2/2013	8/15/2014	254	100%
Thermal Insulation	2/25/2014	5/30/2014	93	100%
Electrical Installation	12/2/2013	12/16/2013	14	100%
Standing Upright/Positioning (Milestone)	6/6/2014	6/10/2014	4	100%
Leak Testing	5/12/2014	8/15/2014	95	100%
Instrumentation Setup	4/14/2014	10/10/2014	178	100%
Fill With Dowtherm (Milestone)	9/16/2014	9/16/2014	1	100%
Initial Testing	9/16/2014	Present	100+	60%
Isothermal Pressure Drop Tests and Analysis	10/31/2014	11/25/2014	25	100%
Pump Parasitic Heat Input Test and Analysis	11/13/2014	11/17/2014	4	100%
Initial Heated Tests	11/21/2014	Present	30+	30%
Installation of Guard Heating Components	7/24/2014	2/28/2015	~200	50%
Polycarbonate Side Panels Installation	4/1/2014	2/28/2015	250+	50%
Front Rolling Shutter Installation	12/5/2014	1/31/2015	30+	25%
Guard Heater Installation	2/1/2015	2/28/2015	28	0%

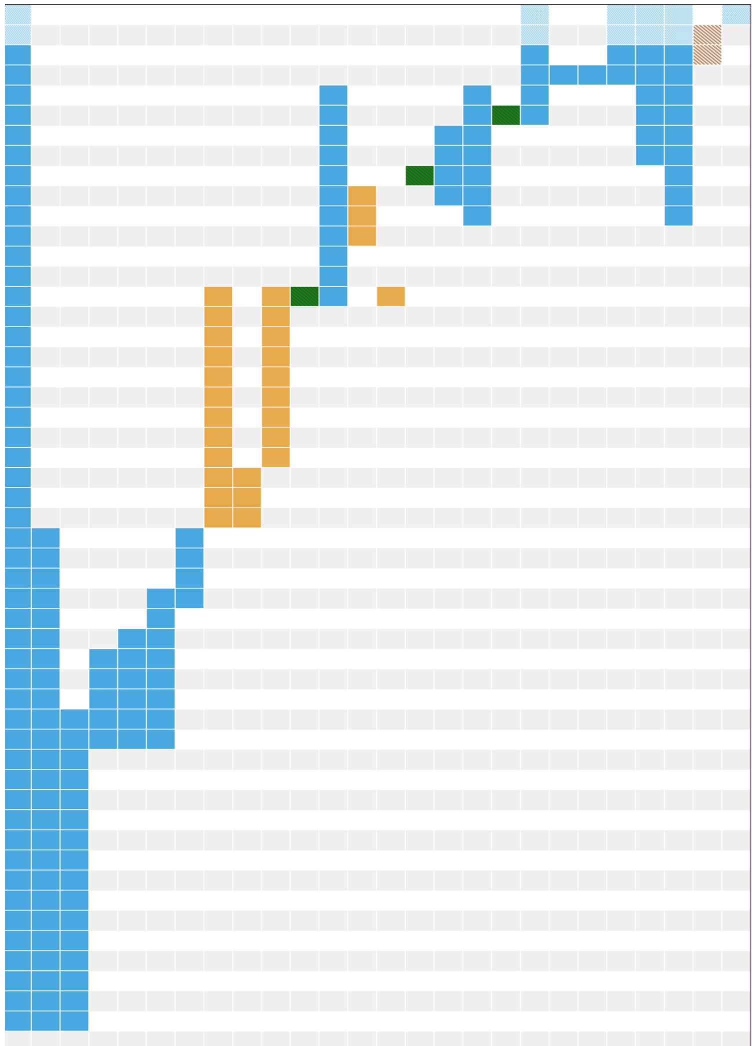

Figure 8-1. CIET project timeline.

9 Conclusions and Future Work

The CIET 1.0 facility was designed, fabricated, filled up with Dowtherm A oil, and as of December 2014 is fully operational, with extensive instrumentation and automated controls. All stages of the project, from early design to data collection, have followed a graded approach to QA based on NQA-1-2008 standards, therefore exceeding requirements by the DOE NEUP program.

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, intitial heated tests were also completed, including measurements of heat input from the primary pump, 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.

In the near future, further heated tests will include steady-state natural circulation in the primary loop and the DRACS loop. Collected data will be compared to predicted performance and form 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 the 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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Appendices

List of Personnel Involved with the CIET Project

Name	Start Date	End Date	Approximate Weeks	Hours/Week	Total Hours
AJ Albaaj	9/1/2014	Present	16	5	80
Jeff Bickel	1/1/2011	Present	192	25	4800
Jae Choi	11/1/2012	5/1/2013	20	6	120
Alex Chong	1/20/2014	3/20/2014	8	8	64
AJ Gubser	1/1/2011	1/1/2014	144	20	2880
Zhangpeng Guo	9/1/2013	Present	2	25	50
Lakshana Huddar	8/1/2010	5/1/2011	34	3	102
James Kendrick	7/14/2014	Present	20	5	100
Uday Mehta	1/20/2014	3/20/2014	8	8	64
Niv Moran	1/1/2010	8/1/2010	28	35	980
Aldrich Ong	6/1/2014	5/1/2014	42	12	504
Nicole Rahal	9/1/2013	4/1/2014	24	4	96
Raluca Scarlat	2/1/2010	12/1/2012	127	30	3810
Floren Rubio	6/1/2011	5/1/2011	48	15	720
Justin Tang	1/1/2010	8/1/2010	28	15	420
Rohit Upadhya	6/1/2012	Present	108	10	1080
Alan Yamanaka	1/28/2014	Present	44	13	572
Eric Yehl	3/1/2014	10/1/2014	30	8	240
Nicolas Zweibaum	2/1/2012	Present	127	25	3175

Total Man-Hours	19857
Total Man-Workdays	2482

Total Material Cost of the CIET 1.0 Project – 2010 to Present

Equipment/Hardware	$65,069.48
Fabrication	$90,483.91
Instrumentation	$58,092.54
Services	$39,794.02
Total Construction Cost	$253,439.95
Personnel	19857 Man-Hours

Itemized Cost of the CIET 1.0 Project

Equipment/Hardware	$65,069.48
Fabrication	$90,483.91
Instrumentation	$58,092.54
Services	$39,794.02

Vendor	Qty.	Unit	Part Number	Description	Est. Unit Cost	Total Cost
Tritek	2	EA	GEN 10-1000-3P208	Genesys 3U, 10kW 0-10VDC @ 0-1000A, Input 180-253 VAC, 3 Phase	7,055.00	14,110.00
Heat Technology Products	2	EA	F700	Oil-to-air heat exchanger (manufacturing order)	3,196.47	6,952.32
Scaffolding	1	EA	N/A	20' tall, non-mobile, with internal stairs	6,000.00	6,000.00
Fostoria Process Equipment	1	EA	HR-H1-8.1	Hot room heater, 240V, 1 phase, 8.1kW, 1/3hp, 36Amps	3,900.00	4,241.25
Koflo Corporation	8	EA	1-40-2-6.2-1	13" long, 1" diameter, schedule 40, 304 stainless steel static mixer	323.00	2,810.10
Polyscience	1	EA	AD07H200	7 Liter digital controlled heated circulator bath	2,115.90	2,301.04
Coker Pumps	1	EA	Price HP75SS-538-212	Flanged centrifugal pump with 3/4" connections, 1/3 hp, 1800 rpm	1,734.00	1,885.73
McMaster	4	EA	46425K16	Easy-Set Needle Valve Bronze, 1" NPTF (Dryseal) Female	288.94	1,256.89
Swagelok	4	EA	SS-8GUF16	Stainless steel needle valve, NPTF connection to 1" piping	268.42	1,167.63
Swagelok	8	EA	SS-16-UT-A-20	Stainless Steel Ultra-Torr Vacuum Fitting, Adapter, 1 in. Ultra-Torr Fitting x 1 1/4 in. Tube Stub	85.10	740.37
Lord & Sons	100	ft	P1001C10PG	Ten 10' lengths of P1001C channel strut	6.59	716.66
McMaster	1	EA	2129T13	Clear FEP Tubing, 3/16" ID, 1/4" OD, .030" Wall Thickness, 360 ft. Length	532.80	579.42
McMaster	8	EA	4866K75	1" ball valve	64.40	560.28
McMaster	14	EA	45395K131	1/4" ball valve	34.60	526.79
Lord & Sons	38	EA	P1726EG	5 hole plate tee	12.68	524.00
Conax Buffalo Technologies, LLC.	2	EA	MHC2(SWM2/S316L)-020	1/4" NPT MHC2 Sealing Gland with 316L Weld Neck, 020 OD, A Cap, 4 Elements, Viton Sealant	237.00	515.48
Lord & Sons	100	ft	P100110PG	Ten 10' lengths of P1001 channel strut	4.45	483.94
McMaster	20	EA	7468A63	Pliobond Contact Adhesive, #25, 16 oz Can	21.74	472.85
McMaster	4	EA	86145K23	Lightweight Melamine Insulation, 1/2" Thick, 48" x 96", Light Gray	106.26	462.23
ALCO Iron and Metal Works	1	EA	N/A	4'x10' sheet of 304 stainless steel 14 gauge plate	389.34	423.41
McMaster	4	EA	5793T22	High-Temp Type 316SS Braided Air & Water Hose W/Female X Female Fittings, 1" ID, 300 PSI, 18" length	91.06	396.11
Automation Direct	3	EA	GS1-10P5	GS1 0.5 HP AC Drive 120V 1 Ph Input 3 Ph Out	117.00	381.71
Wireandsupply	88	ft	N/A	4/0 cci royal excelene welding cable black made in USA	3.95	378.02
USA Metals	1	EA	N/A	6"x6"x1/2" Angle iron, 2"x2"x1/4" angle iron, cuts	367.20	367.20
USA Scales	3	EA	CVC-NCL-CA	No Contract Labor	122.00	366.00
Lord & Sons	8	EA	P1944HG	Unistrut, stair tread support	42.00	365.40
McMaster	9	EA	4866K73	1/2" ball valve	36.47	356.95
McMaster	32	EA	5182K94	Type 316 SS Yor-Lok Tube Fitting Adapter for 1/4" Tube OD X 1/4" Butt Weld Male Pipe	9.40	327.12

McMaster	1	EA	1067A43	Fire-Rated Adhesive-Backed Rubber Bulb Seal, Charcoal, 1/2" Overall Width, 1/4" Overall Height, 300 ft	300.00	326.25
McMaster	4	EA	2190K42	Unthreaded Bronze Socket-Weld Pipe Fitting 1 Pipe Size, 4-1/4" OD, Flange	72.98	317.46
McMaster	19	EA	8967K591	Multipurpose Copper Tubing 5/16" OD, .249" ID, .032" Wall, 6' Length	15.11	312.21
McMaster	70	ft	52355K58	Durable White Tubing Made with Teflon FEP, 5/16" ID, 3/8" OD, 1/32" Wall Thickness - 70 ft	3.71	282.42
Nick Franco Pipe and Supply	8	EA	INLSE53	1" Sharpe Non-Locking Stem Extension	29.85	259.70
McMaster	24	EA	5182K94	Type 316 SS Yor-Lok Tube Fitting Adapter for 1/4" Tube OD X 1/4" Butt Weld Male Pipe	9.40	245.34
McMaster	3	EA	2129T13	Clear FEP Tubing, 3/16" ID, 1/4" OD, .030" Wall Thickness, 50 ft. Length	74.00	241.43
McMaster	8	EA	5520K123	1" Cast Bronze Companion Flange	27.58	239.95
McMaster	14	EA	8967K591	Multipurpose Copper Tubing 5/16" OD, .249" ID, .032" Wall, 6' Length	15.11	230.05
McMaster	125	ft	5239K12	Extreme-Temp Tubing Made with Teflon® PTFE 3/16" ID, 1/4" OD, 1/32" Wall, Semi-Clear White	1.69	229.73
Lord & Sons	350	EA	P1010EG	Unistrut nut w/spring. 1/2"-13 bolt thread	0.59	224.57
McMaster	1	EA	4982K94	Easy-Set Needle Valve 303 Stainless Steel, 1/2" NPTF (Dryseal) Female	204.49	222.38
McMaster	150	ft	1067A43	Fire-Rated Adhesive-Backed Rubber Bulb Seal 1/2" Overall Width, 1/4" Overall Height, Charcoal – 150 ft	1.35	202.50
McMaster	50	ft	52355K58	Durable White Tubing Made with Teflon, 5/16" ID, 3/8" OD, 1/32" Wall Thicknes	3.71	201.73
McMaster	5	EA	4866K73	Easy-Maintenance Type 316SS Ball Valve with 316 Stainless Steel Ends, 1/2" Socket Weld	37.02	201.30
McMaster	125	ft	2129T13	Clear FEP Tubing 3/16" ID, 1/4" OD, .030" Wall Thickness	1.48	201.19
McMaster	2	EA	5182K366	Type 316 Stainless Steel Yor-Lok Tube Fitting, Reducing Inline Tee for 1/2" x 3/8" Tube OD	87.45	190.20
McMaster	1	EA	9293T63	Chemical-Resistant Polypropylene Perforated Sheet, Straight, Thick, Diameter, 10% Open,	172.21	187.28
McMaster	1	EA	9293T63	Chemical-Resistant Polypropylene Perforated Sheet, Straight, .25" Thick, .1875" Diameter, 10% Open	172.21	187.28
A&N Corporation	2	EA	S-125-KM-V	1 1/4 Thin Wall SS Quick Coupling Viton	81.90	178.13
Pace Plumbing	2	EA	010416G3	Bronze companion flanges	88.71	177.42
McMaster	2	EA	3383T682	Polyester Web Sling, Eyeless, 2" Wide, 10000 lb. Choker Capacity, 10 Feet Long	81.34	176.91
McMaster	7	EA	6111K63	Swivel Leveling Mount, Nickel-Plated Steel, 3/4"-10 Thread, 4" Bolt, 7400 lb Load	22.71	172.88
Mr. Supply	6	EA	M46603	Aluminum Mechanical Lug, Dual Rated, 250 kcmil - 6 AWG Conductor Range, 1/2 Bolt Size, 0.31" Hex Size	26.31	171.67
Fluid Gauge Company	1	EA	62-505-A1	Soft-seated check valve, 1" NPTF, stainless steel, less spring	153.91	167.38
McMaster	3	EA	5676T26	High-Temperature Type 321SS Braided Air & Water Hose with Female x Female Fittings, 18" Long, 1/2" ID	50.14	163.58
McMaster	1	EA	2129T13	Clear FEP Tubing, 3/16" ID, 1/4" OD, .030"	148.00	160.95

				Wall Thickness, 100 ft. Length		
Scott Peterson Fluid Gauge Company	1	EA	62-505-A1	Apollo soft-seated check valve, 1" NPTF, stainless steel, less spring	146.58	159.41
McMaster	6	EA	5182K86	Type 316 SS Yor-Lok Tube Fitting Adapter for 5/8" Tube OD X 1/2" Butt Weld Male Pipe	24.11	157.32
McMaster	2	EA	4537K22	Type 316 Stainless Steel Ball Valve with Yor-Lok Fittings, and Lockable Lever, for 3/8" Tube Outside	71.62	155.77
McMaster	16	EA	5272K241	Brass Yor-Lok Tube Fitting, 90 Degree Elbow for Tube OD	8.63	150.16
McMaster	1	EA	7081K31	Ultra-Flexible Neoprene Rubber Power Cable, 600V AC (SOOW), 16 Gauge, 4 Wires, Black, 100 ft. Length	137.00	148.99
McMaster	16	EA	5182K111	Type 316 SS Yor-Lok Tube Fitting Adapter for 1/4" Tube OD X 1/4" NPT Male Pipe	8.16	141.98
McMaster	6	EA	7468A63	Pliobond Contact Adhesive, #25, 16 oz Can	21.74	141.85
McMaster	16	EA	5182K807	Type 316 Stainless Steel Yor-Lok Tube Fitting, Straight Adapter for Tube OD x 1/8 NPT Male	8.05	140.07
McMaster	2	EA	4866K75	Easy-Maintenance Type 316SS Ball Valve with 316 Stainless Steel Ends, 1" Socket Weld	64.40	140.07
McMaster	8	EA	3050T87	1" aluminum pipe clamp	15.59	135.63
McMaster	6	EA	1223A2	Roller Track Set for Bypassing Door 60-lb Cap, 4'9" L Track, for 3/4"-1-3/8" Thk Doors	20.54	134.02
McMaster	2	EA	46425K14	Easy-Set Needle Valve Brass, 1/2" NPTF (Dryseal) Female	60.02	130.54
APG Glass	3	EA	4SRL100X36	Redline Gage Glass, custom length: 4-1/8"	38.60	125.93
McMaster	14	EA	5182K111	Type 316 SS Yor-Lok Tube Fitting Adapter for 1/4" Tube OD X 1/4" NPT Male Pipe	8.16	124.24
McMaster	2	EA	5175K35	Copper Tubing for Drinking Water Med Pressure Type L, 1-1/2" Tube Sz, 1-5/8" OD, 5'L	54.38	118.28
McMaster	4	EA	68185K112	Low-Pressure Threaded Flange 1 Pipe Size x 4-1/4" OD	24.30	105.71
APG Glass	2	EA	4SRL100X36	1” Redline Gage Glass (custom length: 2 x 30")	47.50	103.31
McMaster	4	EA	6111K63	Swivel Leveling Mount, Nickel-Plated Steel, 3/4"-10 Thread, 4" Bolt, 7400 lb Load	22.71	98.79
Omega Engineering	2	EA	CO3-T	"CEMENT-ON" T/C	45.00	97.88
McMaster	4	EA	7468A63	Pliobond Contact Adhesive, #25, 16 oz Can	21.74	94.57
Swagelok	32	EA	SS-405-3	Compression fitting tube insert. For OD 3/16"ID tubing.	2.71	94.31
McMaster	1	EA	5793T22	High-Temp Type 316SS Braided Air & Water Hose W/Female X Female Fittings, 1" ID, 300 PSI, 12" Length	85.60	93.09
McMaster	2	EA	5182K231	Type 316 Stainless Steel Yor-Lok Tube Fitting, Reducing Straight Connector for 5/8" X1/2" Tube OD	39.87	86.72
McMaster	4	EA	8982K88	Multipurpose 6061 Aluminum, 90 Degree Angle, 1/8" Thick, 1" x 2" Legs	19.93	86.70
APG Glass	2	EA	4SRL100X36	1” Redline Gage Glass (custom length: 2 x 4-1/8")	38.60	83.96
Wire and Supply, Co.	20	ft	WC-4/0-01		3.85	83.74
McMaster	1	EA	5676T26	High-Temperature Type 321SS Braided Air	76.60	83.30

				& Water Hose with Female x Female Fittings, 72" Long, 1/2" ID		
McMaster	5	EA	8975K597	Multipurpose 6061 Aluminum, Rectangular Bar, 1/4" x 1-1/4", length of 6'	15.11	82.16
McMaster	1	EA	41945K57	Panel-Mount Flowmeter for Air W/Brass Valve, 6-60 Scfh, 1/4" NPT Female	74.00	80.48
McMaster	2	EA	46425K12	Easy-Set Needle Valve Brass, 1/4" NPTF (Dryseal) Female	36.20	78.74
McMaster	2	EA	7468A8	Pliobond Contact Adhesive, #25, 32 oz Can	36.12	78.56
McMaster	2	EA	51205K121	Extreme-Pressure 316 Stainless Steel Threaded Pipe Fitting, 1/4 Pipe Size, 45° Female x Male	35.25	76.67
McMaster	1	EA	5793T16	High-Temp Type 316SS Braided Air & Water Hose W/Female X Female Fittings, 1/2" ID, 300 PSI, 39" Length	70.42	76.58
Grainger	1	EA	3ERJ8	AQUATROL Safety Relief Valve,1/2 In,15 psi,Brass	70.35	76.51
Lord & Sons	350	EA	39105060125	1/2"-13 x 1 1/4 grade 2 SAE bolts	0.20	76.13
McMaster	2	EA	45395K131	Low-Profile Type 316 SS Ball Valve 1/4" NPT Female	34.60	75.26
McMaster	2	EA	5182K798	Type 316 Stainless Steel Yor-Lok Tube Fitting, Straight Adapter for 1/2" Tube OD x 3/4 NPT Female	34.51	75.06
McMaster	1	EA	8547K45	Tube Made of Teflon PTFE, 1.315" OD x 1.005" ID, 12" Length	68.50	74.49
McMaster	1	EA	8955K36	Multipurpose Copper Tubing 1/4" Tube Sz, 3/8" OD, .245" ID, .065" Wall, 10'Coil	68.50	74.49
McMaster	2	EA	5182K359	Type 316 Stainless Steel Yor-Lok Tube Fitting, 45 Degree Elbow for 3/8" Tube OD x 1/8 NPT Male	34.25	74.49
Automation Direct	1	EA	SC181808	N1 SCRW CVR WALL MT PULL 18X18X8 IN KO 7 DAY	67.00	72.86
McMaster	7	EA	7196K31	Straight-Blade, Three-Blade Male Plug, NEMA 5-15	9.48	72.17
Swagelok	2	EA	SS-8-UT-A-12	Stainless Steel Ultra-Torr Vacuum Fitting, Adapter, 1/2 in. Ultra-Torr Fitting x 3/4 in. Tube Stub	33.15	72.10
McMaster	1	EA	5175K91	Copper Tubing for Drinking Water Low Pressure Type M, 2" Tube Sz, 2-1/8" OD, 5'L	64.65	70.31
McMaster	2	EA	47065T101	Aluminum Inch T-Slotted Framing System, Four-Slot Single, 1" Solid Extrusion, 10' Length	31.59	68.71
McMaster	1	EA	8547K45	Tube Made of Teflon PTFE 1" OD X 1/2" ID, 2ft. Length	68.50	68.50
McMaster	1	EA	1270T48	Laminating Document Protector 24" High, 25' Wide, 0.003" Thick, Roll, Clear Finish	60.97	66.30
McMaster	1	EA	5793T16	High-Temp Type 316SS Braided Air & Water Hose W/Female X Female Fittings, 1/2" ID, 300 PSI, 22" Length	60.90	66.23
McMaster	2	EA	1067A51	Fire-Rated Adhesive-Backed Rubber Bulb Seal, Charcoal, 1/2" Overall Width, 1/4" Overall Height, 25'	30.07	65.40
McMaster	4	EA	5520K75	Solder-Joint Copper Tube Fitting for Water Tee, Sckt X Sckt X Sckt for 1-1/2" Tube Size	14.56	63.34
ALCO Iron and Metal Works	2	EA	N/A	20' length of 2" x 1.5" 304 stainless steel angle iron. 1/8" thick.	29.08	63.25
McMaster	1	EA	5793T16	High-Temp Type 316SS Braided Air & Water Hose W/Female X Female Fittings, 1/2" ID, 300 PSI, 12" Length	55.30	60.14

Lord & Sons	16	EA	P1023SEG	Unistrut nut for 3/4"-10 threading	3.45	60.03
Swagelok	20	EA	SS-405-3	Stainless Steel Tubing Insert, 1/4 in. OD x 3/16 in. ID	2.71	58.94
McMaster	2	EA	47065T101	Aluminum Inch T-Slotted Framing System, Four-Slot Single, 1" Solid Extrusion, 8' Length	26.38	57.38
McMaster	16	EA	5182K504	Front & Back Sleeve for 1/4" Tube OD Type 316 Stainless Steel Yor-Lok Tube Fitting	3.25	56.55
McMaster	1	EA	7081K22	Ultra-Flexible Neoprene Rubber Power Cable, 600V AC (SOOW), 16 Gauge, 3 Wires, Black, 50 ft. Length	51.50	56.01
McMaster	1	EA	8349T25	Ultra-Clear Tygon PVC Tubing, 3/8" ID, 1/2" OD, 1/16" Wall Thickness, 25 ft. Length	51.25	55.73
McMaster	8	EA	5520K304	Solder-Joint Copper Tube Fitting for Water Reducing Cplg W/Ctr Stop 1-1/2" Sckt X 1" Sckt	6.36	55.33
McMaster	2	EA	6759T28	High-Dexterity Synthetic Leather Work Glove, Heavy Duty, Oil Resistant, Large	25.36	55.16
McMaster	2	EA	5182K86	Type 316 Stainless Steel Yor-Lok Tube Fitting, Straight for 5/8" Tube OD x 1/2 Male Butt Weld Pipe	24.71	53.74
Lord & Sons	2	EA	P1728EG	Unistrut, 5-hole angular fitting EG	24.61	53.53
Amazon	10	EA	N/A	Silhouette Double-Sided Adhesive Paper	4.89	53.18
McMaster	2	EA	68185K112	Low-Pressure Threaded Flange, 1 Pipe Size x 4-1/4" OD	24.30	52.85
Pro Audio Stash	4	EA	R1285/4UK	Flat Steel Plain 4U Rack Panel	12.00	52.20
McMaster	16	EA	95630A500	Low-Friction PTFE Flat Washer 1/2" Screw Size, 1.25" OD, .093"-.107" Thick	2.97	51.68
APG Glass	1	EA	4SRL100X36	1" redline gage glass (custom length: 30")	47.50	51.66
Lord & Sons	6	EA	P1377EG	Unistrut, 4-hole splice clevis	7.88	51.42
McMaster	4	EA	5182K794	Type 316 Stainless Steel Yor-Lok Tube Fitting, Straight Adapter for Tube OD x 1/8 NPT Female	11.56	50.29
McMaster	2	EA	90322A220	High Strength Grade 8 Alloy Steel Threaded Rod, 1/2"-13 Thread, 6' Length	22.88	49.76
USA Metals	1	EA	N/A	Grey primer + Sanding discs	49.49	49.49
Amazon	1	EA	B00FJWDHSQ	Bosch GLL 1P Combination Point and Line Laser Level	45.19	49.14
McMaster	25	EA	3043T78	1" U-bolt clamp	1.79	48.67
McMaster	4	EA	91104A033	Znc Yellow Pltd STL Hvy Dty Split Lock Washer 1/2" Screw Size, 0.87" OD, 0.12" min Thick, Packs of 1	11.15	48.50
McMaster	2	EA	6100K152	Precision Stainless Steel Tubing 9/32" OD, .251" ID, .015" Wall, 28" Length	21.61	47.00
McMaster	2	EA	5182K913	Type 316 Stainless Steel Yor-Lok Tube Fitting, Straight Adapter for 3/8" Tube OD x 3/4 NPT Male	21.20	46.11
McMaster	2	EA	2829T43	High-Performance Rubber-Tread Wheel, 8" x 2", 1/2" Axle, Roller Bearing, 675 lb Capacity	21.10	45.89
McMaster	3	EA	95630A248	Low-Friction PTFE Flat Washer, 1/2" Screw Size, 1.01" OD, .057"-.067" Thick	14.01	45.71
McMaster	3	EA	95630A248	Low-Friction PTFE Flat Washer, 1/2" Screw Size, 1.01" OD, .057"-.067" Thick	14.01	45.71
Swagelok	15	EA	SS-405-3	Stainless Steel Tubing Insert, 1/4 in. OD x 3/16 in. ID	2.71	44.21
McMaster	1	EA	5182K708	Type 316 Stainless Steel Yor-Lok Tube Fitting, Reducing Straight Connector for	40.55	44.10

				5/8" X3/8" Tube OD		
McMaster	1	EA	43935K25	1" bronze strainer	39.57	43.03
McMaster	3	EA	97083A330	Internally Threaded Anchor for Concrete, Zinc-Plated Steel, 1/2"-13 Screw Size, 2" Length, packs of	13.14	42.87
McMaster	1	EA	5182K417	Type 316 Stainless Steel Yor-Lok Tube Fitting, 90 Degree Elbow for 1/2" Tube OD	38.27	41.62
Lord & Sons	16	EA	P1031EG	Unistrut, 4 hole tee plate	2.33	40.54
McMaster	2	EA	8964K411	Multipurpose Copper (Alloy 110) 1/8" Thick, 2" Width, 1' Length	18.38	39.98
McMaster	1	EA	4866K73	Easy-Maintenance Type 316SS Ball Valve with 316 Stainless Steel Ends, 1/2" Socket Weld	36.47	39.66
McMaster	2	EA	5520K706	Solder-Joint Copper Tube Fitting for Water Reducing Tee 2" Sckt X 1" Sckt X 2" Sckt	18.12	39.41
McMaster	4	EA	91309A718	Low-Strength Zinc-Plated Steel Cap Screw, 1/2"-13 Fully Threaded, 1-3/4" Long, packs of 25	8.91	38.76
Amazon.com	2	EA	N/A	Woods 0592 16/2 SPT-2 Flat Vinyl Extension Cord, Yellow, 50-Feet	17.77	38.65
McMaster	4	EA	4457K116	Standard Wall Black Welded Steel Pipe, 1 Pipe Size X 18" Length, Threaded Ends	9.58	38.32
McMaster	1	EA	2129T17	Clear FEP Tubing, 1/4" ID, 3/8" OD, .062" Wall Thickness, 10 ft. Length	35.10	38.17
McMaster	1	EA	5182K436	Type 316 Stainless Steel Yor-Lok Tube Fitting, Tee for Tube OD	35.02	38.08
McMaster	1	EA	8547K45	Tube Made of Teflon PTFE, 1" OD x 1/2" ID, 1 ft. Length	34.25	37.25
McMaster	1	EA	7081K31	Ultra-Flexible Neoprene Rubber Power Cable, 600V AC (SOOW), 16 Gauge, 4 Wires, Black, 25 ft. Length	34.25	37.25
McMaster	1	EA	8964K412	Multipurpose Copper (Alloy 110) 1/8" Thick, 4" Width, 1' Length	34.20	37.19
McMaster	8	EA	8361T92	Nestable and Stackable Plastic Bin Box, Width x Depth x Height, Black	4.24	36.89
McMaster	7	EA	5016K911	White Polypro Compression Tube Fitting Adapter for 1/4" Tube OD X 1/8" NPT Female Pipe, packs of 5	4.84	36.84
McMaster	4	EA	91257A963	High-Strength Steel Cap Screw - Grade 8, 1"-8 Thread, 4-1/2" Long, Zinc-Plated	8.41	36.58
McMaster	4	EA	47065T101	Aluminum Inch T-Slotted Framing System, Four-Slot Single, 1" Solid Extrusion, 2' Length	8.35	36.32
McMaster	6	EA	77025T84	Direct-to-Metal Rust-Stopper Paint, Aerosol, Fast Dry, 12 oz., Gloss Yellow	5.50	35.89
McMaster	4	EA	91465K91	Brass Push-on Hose Fitting Adapter for 1/4" Hose ID X 1/4" NPTF Male Pipe, Packs of 5	8.22	35.76
Pace Plumbing	2	EA	010316B3	Bronze couplings	17.59	35.18
McMaster	2	EA	8967K933	Multipurpose Copper Tubing 1/4" Tube Size, 3/8" OD, .245" ID, .065" Wall, 3'L	16.04	34.89
McMaster	9	EA	4464K499	Type 304 Stainless Steel Threaded Pipe Fitting, 1/2 Pipe Size, Cap, 150 PSI	3.54	34.65
McMaster	8	EA	4464K254	Type 304 Stainless Steel Threaded Pipe Fitting, 1/2 Pipe Size, Hex Head Plug, 150 PSI	3.92	34.10
McMaster	1	EA	5288K11	Choose-A-Color Hose for Push-on Fitting Buna-N, 1/4" ID X 1/2" OD, 250 PSI, Blue, 25 ft. Length	31.00	33.71
McMaster	3	EA	91102A770	Zinc-Plated Steel Split Lock Washer, 1/2"	10.15	33.11

				Screw Size, .87" OD, .12" min Thick, packs of 100		
McMaster	1	EA	9246K13	Multipurpose 6061 Aluminum, 1/4" Thick, 12" x 12"	30.39	33.05
McMaster	1	EA	5182K368	Type 316 Stainless Steel Yor-Lok Tube Fitting, Reducing Straight Connector for 1/2" X3/8" Tube OD	29.78	32.39
McMaster	1	EA	5175K33	Copper Tubing for Drinking Water Med Pressure Type L, 1" Tube Size, 1-1/8" OD, 5'L	29.57	32.16
McMaster	1	EA	7631A33	High Temperature Aluminum Foil Tape, Width x 60 Yards Length, Thick	29.29	31.85
McMaster	4	EA	92865A841	Medium-Strg Zinc-Pltd STL Cap Screw - Grade 5 3/4"-10 Fully Threaded, 1-3/4" Long, Packs of 5	7.24	31.49
McMaster	1	EA	9293T63	Chemical-Resistant Polypropylene Perforated Sheet, Straight, .25" Thick, .1875" Diameter, 10% Open,	28.70	31.21
McMaster	1	EA	86145K21	Lightweight Melamine Insulation 1/2" Thick, 24" X 48", Light Gray	28.10	30.56
McMaster	2	EA	95630A248	Low-Friction PTFE Flat Washer 1/2" Screw Size, 1.01" OD, .057"-.067" Thick, Packs of 10	14.01	30.47
Newegg.com	1	EA	N82E16823126188	Logitech MK320 Black USB RF Wireless Standard Desktop	27.99	30.44
McMaster	1	EA	7081K22	Ultra-Flexible Neoprene Rubber Power Cable, 600V AC (SOOW), 16 Gauge, 3 Wires, Black, 25 ft. Length	27.57	29.98
McMaster	4	EA	47065T242	Aluminum Inch T-Slotted Framing System, Corner Connector, 90 Degree, for 1" Extrusion	6.83	29.71
McMaster	8	EA	47065T153	Aluminum Inch T-Slotted Framing System, Adjustable 90° Connector, for 1" Extrusion	3.39	29.49
McMaster	6	EA	77845T84	Touch-Up Miniature Paint Roller	4.39	28.64
McMaster	4	EA	5182K508	Front & Back Sleeve for Tube OD Type 316 Stainless Steel Yor-Lok Tube Fitting	6.43	27.97
McMaster	6	EA	90126A033	Zinc-Plated Steel Type A SAE Flat Washer 1/2" Screw Size, 1-1/16" OD, .07"-.13" Thick, Packs of 55	4.20	27.41
McMaster	2	EA	3505T12	Hinge for Strut Channel, 4-Hole, Zinc-Plated Steel	12.53	27.25
McMaster	4	EA	77025T84	Direct-to-Metal Rust-Stopper Paint, Aerosol, Fast Dry, 12 oz., Gloss Yellow	6.10	26.54
McMaster	1	EA	9936K16	Control Cable, Unshielded, Includes Two 18-Gauge Wires, 30 ft. Length	24.30	26.43
McMaster	2	ft	5033K37	Extreme-Temp Tubing Made with Teflon® PTFE 1/2" ID, 5/8" OD, 1/16" Wall, Semi-Clear White	11.83	25.73
McMaster	1	EA	5182K416	Type 316 Stainless Steel Yor-Lok Tube Fitting, 90 Degree Elbow for 3/8" Tube OD	23.25	25.28
McMaster	1	EA	3226K51	High-Temperature Melting Pot NO. 0000, 1 lb Red Brass Cap, 2-5/8" OD X 3-1/16" Ht	23.00	25.01
McMaster	4	EA	44615K316	Standard-Wall Black Steel Threaded Pipe Nipple, 1 Pipe Size x Length	5.72	24.88
McMaster	4	EA	47065T235	Aluminum Inch T-Slotted Framing System, End-to-End Connector, for 1" Extrusion	5.66	24.62
Newegg.com	1	EA	N82E16833389005	NETIS WF-2113 PCI Express Wireless-N Adapter	21.99	23.91
McMaster	1	EA	7468A63	Pliobond Contact Adhesive, #25, 16 oz Can	21.74	23.64
McMaster	1	EA	7468A63	Pliobond Contact Adhesive, #25, 16 oz Can	21.74	23.64

Grainger	1	EA	9GE46	Cartridge/Filter Adapter, PK 2	23.32	23.32
McMaster	1	EA	5182K98	Type 316 Stainless Steel Yor-Lok Tube Fitting, Straight for 1/2" Tube OD x 1/2 Male Butt Weld	20.35	22.13
McMaster	3	EA	8965A61	Adhesive-Backed Polyester Horizontal Scale, Left-Right, mm Graduations, 1 Meter Long, Wide, Whi	6.76	22.05
McMaster	3	EA	68115K43	Low-Pressure Black Cast Iron Thread Pipe Fitting, 1 Pipe Size, Tee	6.59	21.50
McMaster	6	EA	91465K62	Brass Push-on Hose Fitting 90 Deg Elbow for 1/4" Hose ID X 1/4" NPTF Male Pipe, Packs of 1	3.28	21.40
McMaster	2	EA	5520K306	Solder-Joint Copper Tube Fitting for Water Reducing Cplg W/Ctr Stop 2" Sckt X 1" Sckt	9.77	21.25
McMaster	3	EA	1077T13	Brass Industrial-Shape Air Hose Plug 1/4" Push-on Hose ID, 1/4 Coupling Size	6.37	20.78
McMaster	3	EA	7631A92	High Temperature Aluminum Foil Tape, 2" Width X 5 Yards Length, .006" Thick	6.78	20.34
McMaster	1	EA	7338K35	Nylon Cable Tie 400-Piece 3-Size, Solid Colored Assortment	18.42	20.03
McMaster	1	EA	1223A999	Brass Floor Guide with Tan Plastic Guide, for, Bypass Sliding Door, Adjustable, Pack of 10	18.38	19.99
McMaster	2	EA	91104A047	Znc Yellow Pltd STL Hvy Dty Split Lock Washer 3/4" Screw Size, 1.27" OD, 0.18" min Thick, Packs of 2	9.11	19.81
McMaster	2	EA	93548A730	Round Head Square Neck Bolt, Zinc-Plated Grade 2 Steel, 1/2"-13, 4-1/2" Long	8.69	18.90
McMaster	1	EA	8703K125	Harsh Environment Heat-Shrink Tubing, ID Before Shrinking, . Length	16.46	17.90
McMaster	3	EA	6536K18	Industrial-Shape Hose Coupling Sleeve-Lock Sckt, Brass, 1/4" NPTF Male, 1/4 Cplg Sz	5.46	17.81
McMaster	5	EA	5182K504	Front & Back Sleeve for 1/4" Tube OD Type 316 Stainless Steel Yor-Lok Tube Fitting	3.25	17.67
McMaster	1	EA	5182K142	Type 316 Stainless Steel Yor-Lok Tube Fitting, 90 Degree Elbow for 1/4" Tube OD x 1/4 NPT Male	16.13	17.54
McMaster	1	EA	8569K25	Film Made with Teflon PTFE, 1/32" Thick, 6" Width, 1 ft. Length	15.94	17.33
McMaster	1	EA	89895K131	Type 304 Smooth-Bore Seamless SS Tubing 5/16" OD, .257" ID, .028" Wall, 3' Length	15.73	17.11
McMaster	3	EA	44605K156	Low-Pressure Threaded Fitting 1 Pipe Size, Tee	5.24	17.10
McMaster	1	EA	4172T8	Category 6 Cord, 25' Long, Gray	15.65	17.02
McMaster	1	EA	5182K126	Type 316 Stainless Steel Yor-Lok Tube Fitting, Straight Adapter for Tube OD x 1/2 NPT Male	15.62	16.99
McMaster	4	EA	9483K65	PTFE Flange Gasket, 1/8" Thick, for 1-1/2" Pipe, 1-7/8" ID, 3-3/8" OD	3.88	16.88
McMaster	4	EA	9483K65	PTFE Flange Gasket 1/8" Thick, for 1-1/2" Pipe, 1-7/8" ID, 3-3/8" OD	3.88	16.88
McMaster	1	EA	5182K797	Type 316 Stainless Steel Yor-Lok Tube Fitting, Straight Adapter for Tube OD x 1/8 NPT Female	15.40	16.75
McMaster	1	EA	8547K61	Tube Made of TeflonÂ® PTFE 5/8" OD X 1/2" ID, 2 ft. Length	15.20	16.53
McMaster	2	EA	5602K13	Industrial Shape Hose Coupling Set 1/4"	7.51	16.33

				Cplg Size, 1/4" Female NPTF X 1/4" Male NPTF		
McMaster	1	EA	47865K44	Brass Ball Valve, 3/4" NPT Connection, Female x Male	14.93	16.24
Battery Specialists	1	EA	N/A	Replacement battery for CIET scale	16.24	16.24
McMaster	10	ft	2129T13	Clear FEP Tubing 3/16" ID, 1/4" OD, .030" Wall Thickness	1.48	16.10
McMaster	1	EA	50915K247	Tube Support for 5/8" Tube OD X 3/8" Tube ID Brass Compression Tube Fitting, packs of 5	14.50	15.77
APG Glass	1	EA	4SRL050X16	1/2" Redline Gage Glass (custom length: 14-7/8")	0.00	15.33
McMaster	1	EA	89895K737	Type 304 Smooth-Bore Seamless Stainless Steel Tubing, 3/8" OD, .305" ID, .035" Wall, 3' Length	13.94	15.16
McMaster	1	EA	95462A033	Zinc-Plated Grade 5 Steel Hex Nut, 1/2"-13 Thread Size, 3/4" Width, 7/16" Height, packs of 100	13.77	14.97
McMaster	1	EA	95462A033	Zinc-Plated Grade 5 Steel Hex Nut, 1/2"-13 Thread Size, 3/4" Width, 7/16" Height, packs of 100	13.77	14.97
McMaster	2	EA	1556A48	Bracket, Galvanized Steel, Length of Sides	6.82	14.83
McMaster	1	EA	90473A223	Zinc-Plated Grade 2 Steel Hex Nut, 1/2"-13 Thread Size, 3/4" Width, 7/16" Height, packs of 100	13.45	14.63
McMaster	2	EA	90108A033	Zinc-Plated Steel Type A USS Flat Washer, 1/2" Screw Size, 1-3/8" OD, 0.086"-0.132" Thick, packs of	6.67	14.51
McMaster	1	EA	97083A330	Internally Threaded Anchor for Concrete, Zinc-Plated Steel, 1/2"-13 Screw Size, 2" Length, packs of	13.14	14.29
McMaster	1	EA	89895K723	Type 304 Smooth-Bore Seamless Stainless Steel Tubing, OD, ID, Wall, Length	13.01	14.15
McMaster	2	EA	9657K124	Steel Compression Spring, Zinc-Plated Spring-Tempered, 3.0" Long,.688" OD,.047" Wire, packs of 12	6.44	14.01
McMaster	1	EA	93405A197	Pan Head Phillips Machine Screw with Split Washer, Zinc-Plated Steel, 8-32 Thread, 3/4" Length, pack	12.84	13.96
McMaster	1	EA	12365A72	Circuit Breaker Lockout, NO-Hole 480/600 VAC, 2-3/4" Long x 1-3/4" Wide x 1-13/16" Deep	12.77	13.89
McMaster	2	EA	91355K47	Brass Barbed Hose Fitting Tee for 1/4" Hose ID, Packs of 2	6.34	13.79
McMaster	1	EA	89325K862	Super Corrosion Resistant SS (Type 316/316L) 7/16" Diameter, 3' Length Rod	12.58	13.68
McMaster	7	EA	33125T126	Strut Channel Accessory, Flat Connecting Plate, 4-Hole, Zinc-Plated Steel	1.78	13.55
McMaster	1	EA	92865A716	Medium-Strength Zinc-Plated Steel Cap Screw - Grade 5, 1/2"-13 Fully Threaded, 1-1/2" Long, packs of	12.28	13.35
McMaster	5	EA	5182K554	Nut for 1/4" Tube OD Type 316 Stainless Steel Yor-Lok Tube Fitting	2.42	13.16
Lord & Sons	4	EA	P1325EG	Unistrut, 4 hole corner angle	3.01	13.09
McMaster	2	EA	4699A682	Flat Sanding Disc, Smooth Finish, Plain-Hole, Multipurpose, 4-1/2" Diameter - 120 grit	6.47	12.94
McMaster	1	EA	90322A215	High Strength Grade 8 Alloy Steel Threaded Rod, 1/2"-13 Thread, 3' Length	11.89	12.93
McMaster	5	EA	4591K12	Commercial Grade Pipe Thread Sealant	2.31	12.56

				Tape, 16 Yard L x Wide, Thick, 0.5 G/CC Density		
McMaster	1	EA	5182K119	Type 316 Stainless Steel Yor-Lok Tube Fitting, Straight Adapter for 3/8" Tube OD x 1/4 NPT Male	11.47	12.47
McMaster	1	EA	50915K246	Tube Support for 1/2" Tube OD x 3/8" Tube ID Brass Compression Tube Fitting, packs of 10	11.33	12.32
McMaster	1	EA	91465K951	Brass Push-on Hose Fitting Adapter for 1/4" Hose ID X 1/4" NPTF Female Pipe, Packs of 5	10.98	11.94
McMaster	4	EA	2190K47	Unthreaded Bronze Socket-Weld Pipe Fitting 1 Pipe Size, Ring	2.73	11.88
McMaster	2	EA	92141A056	18-8 Stainless Steel General Purpose Flat Washer, 3/4" Screw Size, 1-3/4" OD, .09"-.12" Thick, packs	5.36	11.66
McMaster	4	EA	9157K33	Std-Wall 304/304L SS Thrd One End Pipe Nipple 1/2 Pipe Size X 2" Length	2.65	11.53
McMaster	2	EA	5272K295	Brass Yor-Lok Tube Fitting, Straight Adapter for Tube OD x 1/8 NPT Male	5.25	11.42
McMaster	1	EA	89895K752	Type 304 Smooth-Bore Seamless Stainless Steel Tubing, 5/8" OD, .555" ID, .035" Wall, 1' Length	10.44	11.35
McMaster	1	EA	89895K744	Type 304 Smooth-Bore Seamless Stainless Steel Tubing, 1/2" OD, .43" ID, .035" Wall, 1' Length	10.35	11.26
McMaster	1	EA	4464K534	Type 304 Stainless Steel Threaded Pipe Fitting, 1 x 1/2 Pipe Size, Reducing Coupling, 150 PSI	10.25	11.15
McMaster	1	EA	91102A770	Zinc-Plated Steel Split Lock Washer, 1/2" Screw Size, .87" OD, .12" min Thick, packs of 100	10.18	11.07
McMaster	1	EA	93827A259	Ultra-Coated Grade 8 Steel Hex Nut 3/4"-10 Thread, 1-1/8" Width, 41/64" Height, Packs of 10	9.90	10.77
McMaster	8	EA	7798K42	Cord Grip for Building Cable, Screw Connector Style, 3/4 Trade Size	1.15	10.01
McMaster	8	EA	7798K42	Cord Grip for Building Cable, Screw Connector Style, 3/4 Trade Size	1.15	10.01
McMaster	4	EA	47065T142	Standard Zinc-Plated Steel End-Feed Fastener, for 1" Aluminum Inch T-Slotted Framing System, packs	2.30	10.01
McMaster	1	EA	92146A038	18-8 Stainless Steel Split Lock Washer, 1" Screw Size, 1.66" OD, .25" min Thick, packs of 5	9.19	9.99
McMaster	1	EA	93827A277	Ultra-Coated Grade 8 Steel Hex Nut, 1"-8 Thread Size, 1-1/2" Width, 55/64" Height, packs of 5	9.12	9.92
McMaster	1	EA	91104A047	Zinc Yellow Plated Steel Heavy Duty Split Lock Washer, 3/4" Screw Size, 1.27" OD, 0.18" min Thick	9.11	9.91
McMaster	2	EA	93250A440	Type 316 Stainless Steel Threaded Rod, 1/4"-20 Thread, 2' Length	4.35	9.46
McMaster	1	EA	92865A628	Medium-Strength Zinc-Plated Steel Cap Screw - Grade 5, 3/8"-16 Fully Threaded, 1-1/2" Long, packs of	8.48	9.22
McMaster	1	EA	9439T44	Steel Two-Hole Clamp for 1-1/16" OD, 3/4" Pipe/Rigid Conduit Size, packs of 50	8.29	9.02
Conax Buffalo Technologies, LLC.	2	EA	19-0001-001	Sealing Gland Lubrication Kit	4.00	8.70

McMaster	1	EA	95462A031	Zinc-Plated Grade 5 Steel Hex Nut, 3/8"-16 Thread Size, 9/16" Width, 21/64" Height, packs of 100	7.84	8.53
McMaster	1	EA	92141A038	18-8 Stainless Steel General Purpose Flat Washer, 1" Screw Size, 2" OD, .11"-.14" Thick, packs of 10	7.39	8.04
McMaster	1	EA	9657K435	Steel Compression Spring, Zinc-Plated Music Wire, 3.00" Long,.660" OD,.072" Wire	6.96	7.57
McMaster	4	EA	44615K446	Standard-Wall Threaded Pipe Nipple 1 Pipe Size x 2-1/2" Length	1.73	7.53
McMaster	4	EA	44615K446	Standard-Wall Black Steel Threaded Pipe Nipple, 1 Pipe Size x Length	1.73	7.53
McMaster	1	EA	4429K161	Low-Pressure Brass Threaded Pipe Fitting 1/4 Pipe Size, 90 Degree Elbow	6.80	7.40
McMaster	1	EA	92147A031	Type 316 Stainless Steel Split Lock Washer, 3/8" Screw Size, .68" OD, .09" min Thick, packs of 50	6.79	7.38
McMaster	1	EA	93827A211	Ultra-Coated Grade 8 Steel Hex Nut, 1/4"-20 Thread Size, 7/16" Width, 7/32" Height, packs of 100	6.74	7.33
McMaster	1	EA	9657K119	Steel Compression Spring, Zinc-Plated Spring-Tempered, 2.25" Long,.375" OD, .062" Diameter	6.71	7.30
McMaster	1	EA	50915K245	Tube Support for 3/8" Tube OD x 1/4" Tube ID Brass Compression Tube Fitting, packs of 10	6.30	6.85
McMaster	1	EA	8251T2	Solid Wire, 300V AC, 22 Gauge, 50 Feet, Red	5.91	6.43
McMaster	2	EA	7631A72	High Temperature Aluminum Foil Tape, 2" Width X 5 Yards Length, .003" Thick	3.19	6.38
McMaster	1	EA	4912K47	Miniature Chrome-Plated Brass Ball Valve Wedge Handle, 1/4" NPT Female Connections	5.74	6.24
McMaster	1	EA	4172T4	Category 6 Cord, 5' Long, Gray	5.65	6.14
McMaster	1	EA	9157K45	Standard-Wall 304/304L Stainless Steel Thread One End Pipe Nipple, 1 Pipe Size x Length	5.28	5.74
McMaster	1	EA	92147A029	Type 316 Stainless Steel Split Lock Washer, 1/4" Screw Size, .49" OD, .06" min Thick, packs of 100	5.21	5.67
McMaster	1	EA	97077A130	Installation Tool, for 1/2"-13 Screw Size Internally Threaded Anchor for Concrete	4.80	5.22
McMaster	1	EA	97077A130	Installation Tool, for 1/2"-13 Screw Size Internally Threaded Anchor for Concrete	4.80	5.22
McMaster	2	EA	9483K25	PTFE Flange Gasket, 1/16" Thick, for 1-1/2" Pipe, 1-7/8" ID, 3-3/8" OD	2.39	5.20
McMaster	2	EA	9483K25	PTFE Flange Gasket 1/16" Thick, for 1-1/2" Pipe, 1-7/8" ID, 3-3/8" OD	2.39	5.20
McMaster	1	EA	33125T82	Strut Channel Accessory, Cross Connecting Plate, 5-Hole, Zinc-Plated Steel	4.69	5.10
Staples	3	EA	IM1CL4558	Phone Line	1.49	4.86
McMaster	10	EA	1556A24	Bracket Zinc-Plated Steel, 7/8" Length of Sides	0.43	4.68
Pro Audio Stash	1	EA	U5200/5215KIT	25 x 10/32" Rack Screw (steel)	3.50	3.81
Home Depot	1	EA	N/A	High Temperature BBQ Black Spray Paint	3.76	3.76
McMaster	1	EA	8547K23	Tube Made of TeflonÂ® PTFE, 1/4" OD x 1/8" ID, 1 ft. Length	3.26	3.55
McMaster	1	EA	8251T2	Solid Wire, 300V AC, 22 Gauge, 25 Feet, Blue	3.25	3.53

McMaster	2	EA	1077T11	Brass Industrial-Shape Air Hose Plug 1/4" NPTF Female, 1/4 Coupling Size	1.48	3.22
McMaster	1	EA	90272A194	Zinc-Plated Steel Pan Head Phillips Machine Screw, 8-32 Thread, 1/2" Length	2.93	3.19
McMaster	1	EA	3043T79	Zinc-Plated Steel U-Bolt with Plate, 3/8"-16x1-1/8" Long Thread, for 1-3/4" OD, 1090 lb Work Load Li	1.92	2.09
McMaster	1	EA	3043T78	Zinc-Plated Steel U-Bolt with Plate, 3/8"-16x1-1/4" Long Thread, for 1-1/2" OD, 1090 lb Work Load Li	1.79	1.95
McMaster	1	EA	3043T77	Zinc-Plated Steel U-Bolt with Plate, 3/8"-16x1-1/4" Long Thread, for 1-1/4" OD, 1090 lb Work Load Li	1.72	1.87
McMaster	1	EA	90480A009	Zinc-Plated Steel Machine Screw Hex Nut, 8-32 Thread Size, 11/32" Width, 1/8" Height, packs of 100	1.49	1.62
McMaster	1	EA	5485K21	1/8" NPT Brass nipple	1.40	1.52
McMaster	1	EA	5182K574	Front Sleeve for 1/4" Tube OD Type 316 Stainless Steel Yor-Lok Tube Fitting	1.36	1.48
McMaster	1	EA	5182K584	Back Sleeve for 1/4" Tube OD Type 316 Stainless Steel Yor-Lok Tube Fitting	1.25	1.36
Johansing Iron Works	1	EA		Experimental oil loop	76,082.00	76,082.00
Johansing Iron Works	1	EA	N/A	Fill/drain tank per provided drawings	5,297.40	5,297.40
Piedmont Plastics	11	EA	PC CLR 0.500MGPP	.500X48X96 CLR MAKROLON GP PRP/PLP	300.00	3,588.75
Walter Mork Mobile Welding	1	EA	N/A	16ga stainless steel welded pan	2,500.00	2,718.75
Piedmont Plastics	6	EA	PC CLR 0.500MGPP	*.500X48X96 CLR MAKROLON GP PRP/PLP	320.00	2,088.00
Scot Industries	12	ft	N/A	1.750"OD x 1.503"ID x 10R12, 304 SS Honed, 12.00 ft	50.33	656.81
Piedmont Plastics	1	EA	PC CLR 0.500MGPP	.500 CLR MAKRO GP PRP/PLP cut to size: 22.813" x 23.688"	48.00	52.20
Siemens	1	EA	7ME4613-3LD11-1GA3-Z	SITRANS FC430 System w/ DN25 Sensor	10,643.00	10,643.00
Siemens	1	EA	7ME4613-3LD11-1GA3-Z	SITRANS FC430 System w/ DN25 Sensor	10,561.00	10,561.00
Siemens	1	EA	7ME4613-3LD11-1GA3-Z	SITRANS FC430 Systemw/ DN25 Sensor	10,528.00	10,528.00
Siemens	1	EA	7ME4613-3HD11-1GA3-Z	SITRANS FC430 System w/ DN15 Sensor	9,917.00	9,917.00
National Instruments	2	EA	776572-02B	SCXI-1102B 32-Channel Amplifier, 200 Hz Bandwidth. Signal Conditioning Module with gain and filters on each of 32 channels.	1,394.10	2,788.20
Eastman	55	gal	N/A	Therminol VP-1 (equivalent of Dowtherm A)	2,635.00	2,635.00
Amazon.com	1	EA	N/A	FLIR E4-NIST: Compact Thermal Imaging Camera with 80 x 60 IR Resolution and MSX, with Certificate	1,299.99	1,413.74
Agilent Technologies	1	EA	G3388B	Helium leak detector	1,257.00	1,366.87
National Instruments	1	EA	776572-1600	NI SCXI-1600, USB DAQ and Control Module	1,115.10	1,115.10
Newegg.com	2	EA	N82E16830120506	Canon EOS REBEL T3 5157B002 Black 12.2 MP Digital SLR Camera with EF-S 18-55mm Lens	399.00	798.00
National Instruments	1	EA	776570-01	SCXI-1000 4-Slot Chassis, U.S. 120 VAC. 120V option.	791.10	791.10

National Instruments	2	EA	777687-03	SCXI-1303 32-Channel Isothermal Terminal Block. Connects TCs and signals to SCXI-1100/ SCXI-1102 Modules.	305.10	610.20
Omega Engineering	16	EA	TMTSS-020U-3	Subminiature transition joint probe, type T, 0.020" O.D. stainless steel sheath, 3" length, unground	33.00	574.20
Omega Engineering	16	EA	TMTSS-020U-4	Subminiature transition joint probe, type T, 0.020" O.D. stainless steel sheath, 4" length, unground	33.00	574.20
Omega Engineering	1	EA	EXTT-T-24-1000	PTFE-insulated T-type TC extension wire, 24 AWG, 1000 ft	365.00	396.94
Siemens	1	EA	A5E03914850	10m Cable for FCS40 w/M12 Plugs, Non-Ex	368.88	368.88
Newegg.com	2	EA	N82E168240094 84	Acer H226HQLbid Black 21.5" 5ms (GTG) HDMI Widescreen LED Backlight LED Backlit LCD Monitor, IPS Pan	149.99	326.23
Omega Engineering	8	EA	TMTSS-020U-6	Subminiature transition joint probe, type T, 0.020" O.D. stainless steel sheath, 6" length, unground	33.00	287.10
Omega Engineering	40	EA	SMPW-CC-T-MF	T-type TC connector pairs, 2 pins w/ integral cable clamp cap	5.40	234.90
Omega Engineering	1	EA	N/A	Calibration of OMEGA HH804U unit + PR-11-2-100-1/8-9-E-CONNECTOR	195.00	212.06
Duratherm	1	EA	Duratherm G	5 gal pail of Duratherm G heat transfer oil	177.00	192.49
Omega Engineering	1	EA	HH804U	4WIRE RTD 2 INPU, USB & AC JACK	159.00	172.91
Omega Engineering	2	EA	PR-21B-3-100-A-1/4-0	RTD ASSY 1/2"NPT CONNEC. 4"LEN	77.00	167.48
Omega Engineering	1	EA	N/A	SET UP CHARGE FOR MFG OF CUSTOM ITEM	150.00	163.13
Amazon.com	2	EA	N/A	Canon 5113B002 AC Adapter Kit for EOS (Black)	64.95	141.27
Cole Parmer	1	EA	EW-98934-51	Cannon® Cannon-Fenske routine viscometer, size 50	121.00	131.59
Automation Direct	1	EA	GS1-10P5	GS1 0.5 HP AC Drive 120V 1 Ph Input 3 Ph Out	117.00	127.24
Omega Engineering	1	EA	EXTT-T-24-200	PTFE-insulated T-type TC extension wire, 24 AWG, 200 ft	110.00	119.63
Omega Engineering	3	EA	TMTSS-020U-4	SUB MINI TJ W/FITTING	33.00	107.66
Omega Engineering	3	EA	TMTSS-020U-6	SUB MINI TJ W/FITTING	33.00	107.66
Amazon	1	EA	B001U89QBU	Bosch DLR130K Digital Distance Measurer Kit	89.00	96.79
Automation Direct	3	EA	RF220X00A	ZERO PHASE REACTOR FOR GS1/GS2/GS3	26.00	84.83
Omega Engineering	2	EA	1-260W-U21/2-304SS	Socket-Weld Design Thermowell for 1/4 Inch Diameter Elements	38.00	82.65
Omega Engineering	2	EA	TMTSS-020U-3	SUB MINI TJ W/FITTING	33.00	71.78
Omega Engineering	1	EA	M12C-PUR-4-S-F-HH804	M12 CBL ASY 35' WIRE FOR HH804	40.50	44.04
Amazon.com	2	EA	N/A	HDE 50 ft. High-Speed 480Mbps USB 2.0 Type A Male to A Female Extension Cable w/ Active Repeater (50	19.95	43.39
Omega Engineering	1	EA	M12C-PUR-4-S-F-HH804	M12 CBL ASY 20' WIRE FOR HH804	36.50	39.69
National Instruments	1	EA	776582-01	SCXI Process Current Resistor Kit	20.70	22.51
Trianglecables.c	1	EA	99-200-175	USB To Serial Adapter DB9 RS-232	16.75	18.22

om				Converter PC MAC 3 Foot 8 Inches Long		
Staples	1	EA	716299	GE 5-Jack Phone Line Splitter (White)	12.49	13.58
Trianglecables.c om	1	EA	DB9F-RJ45	DB9 Female to RJ45 Female RS232 Serial Terminal Modular Adapter	2.10	2.28
Agnitsch Electric	1	EA	N/A	Electrical work for CIET	24,663.0 0	24,663.00
Clifford Smith (campus lead insulator)	1	EA	N/A	Thermal insulation work for CIET	12,489.0 0	12,489.00
Hertz Rentals	1	EA	N/A	Forklift rental from Hertz Equipment Rental Co.	461.02	461.02
USA Scales, Inc.	1	EA	N/A	Scale calibration	451.00	451.00
General Grinding	1	EA	N/A	Centerless grinding of a 1.75" OD stainless steel tube	360.00	360.00
General Grinding	1	EA	N/A	Electrical heater tube machining at General Grinding	360.00	360.00
Walter Mork Mobile Welding	1	EA	N/A	Delivery	300.00	300.00
Piedmont Plastics	1	EA	CUTCHARGE	CUTTING CHARGES	165.00	179.44
Piedmont Plastics	1	EA	CUTCHARGE54	CUTTING CHARGES: cut to 40 pc. per provided drawings	165.00	179.44
USA Scales	1	EA	CMP-M	Min Charge Utility Truck, CA	150.00	150.00
ALCO Iron and Metal Works	1	EA		Shipping charge	75.00	75.00
Kuvacode	1	EA	N/A	Smart Shooter v2 License	50.00	50.00
Omega Engineering	1	EA	CAL-4-SYSTEM	CAL/CERT ITM1,2,4: 0,100,175C	35.00	38.06
Omega Engineering	1	EA	CAL-4-SYSTEM	CAL/CERT ITM1,3,4: 0,100,175C	35.00	38.06