

NIST Technical Note 1933

Intelligent Building Agents Laboratory: Hydronic System Design

Dr. Amanda J. Pertzborn

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Abstract

Achieving national goals of net zero energy buildings requires substantial reduction in the energy consumption of commercial building systems. In 2015, commercial buildings consumed 18 % of the total energy consumed in the U.S. [1]. Although significant progress has been made in the integration of building control systems through the development of standard communication protocols, such as BACnet and BACnet/IP, little progress has been made in making them “intelligent” about optimizing building system-level performance.

The purpose of this project is to demonstrate the potential for distributed, intelligent software agents to perform this optimization and to develop a research infrastructure suitable for development and testing of advanced agent-based optimization techniques that can improve the energy and comfort performance of building systems. Towards that goal, the Intelligent Building Agents Laboratory (IBAL) has been constructed to act as a testbed for these intelligent control algorithms. This note describes the design of a portion of that facility.

Acknowledgements

The wiring, instrumentation, and data rack design of the laboratory are primarily the efforts of Glen Glaeser. Glen has been instrumental in bringing the laboratory online. Dan Veronica was the main in-house designer of the laboratory and has been a key consultant regarding its operation. Cynthia Hudson oversaw the construction and helped us through some miscommunications with the contractor regarding the design. I would also like to thank former SURF students Nusrat Molla and Philip Hoddinott for the work they were able to complete during the summers of 2015 and 2016, respectively. Harrison Skye assisted with brainstorming parts of the LabVIEW code and was a sounding board for uncertainty calculations, as was James Yen. Greg Cala also consulted on the design of the LabVIEW code. Farhad Omar, Vance Payne, and Mark Kedzierski have all provided assistance in solving problems that arose during commissioning. John Wamsley, Art Ellison, and Luis Luyo have all assisted at various points installing instrumentation and wiring in the lab. Finally, I would like to thank the reviewers of this document, Steve Bushby, Ashwinkumar Patel, and Greg Linteris for their feedback and suggestions.

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Nomenclature

ρ	Density
Δ	Difference
\dot{m}	Mass flow rate
\dot{Q}	Heat transfer
\dot{V}	Volumetric flow rate
c_p	Specific heat
dt	Time step
t	Value of the t-distribution for a given number of samples
u	Local control signal
A	Control direction: 1 – direct, -1 – reverse
AHU	Air handling unit
AOM	Advanced optimization method
AS	Air separator
B	Position feedback
CF	Chemical feeder
CHWR	Chilled water return
CHWS	Chilled water supply
CL	Condensing loop
CWR	Condenser water return
CWRV	Condenser water regulating valve
CWS	Condensing water supply
DAQ	Data acquisition
DP	Differential pressure
E	Control error
EU	Engineering unit
F	Flow
GUI	Graphical user interface
HVAC	Heating, ventilating, and air conditioning
HX	Heat exchanger
IBAL	Intelligent Building Agents Laboratory
K	PID gain coefficient
O	On/off
OS	Operating system
P	Pressure

PG	Propylene glycol
PI	Proportional integral
PID	Proportional integral derivative
PL	Primary loop
PV	Process variable
Q	Power
RT	Real-time
S	Speed
SCHW	Site chilled water
SCR	Silicon controlled rectifier
SHW	Site hot water
SL	Secondary loop
S/N	Serial number
SOM	Simple optimization method
SP	Set point
T	Temperature
TMC	Thermal mass coil
TS	Thermal storage
V	Valve
VAV	Variable air volume
WSE	Water side economizer
ZS	Zone simulator

Subscripts

accum	Accumulated
high	High level
low	Low level
rate	Rate
P	Proportional
I	Integral
d	derivative
bias	Bias
min	Minimum
max	Maximum

Superscripts

-	Previous time step
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1. Introduction

Achieving national goals of net zero energy buildings requires substantial reduction in the energy consumption of commercial building systems. In 2015, commercial buildings consumed 18 % of the total energy consumed in the U.S. [1]. Although significant progress has been made in the integration of building control systems through the development of standard communication protocols, such as BACnet and BACnet/IP, little progress has been made in making them “intelligent” about optimizing building system-level performance. The focus of this project is to demonstrate the potential for distributed, intelligent software agents to perform this optimization and to develop a research infrastructure suitable for development and testing of advanced agent-based optimization techniques that can improve the energy and comfort performance of building systems.

An intelligent agent can take many forms, but the basic concept is that it acquires information about the state of the system, makes an optimal or near-optimal control decision, and communicates that decision to another agent or to an actuator that executes the decision. The agent can represent a piece of heating, ventilating, and air conditioning (HVAC) equipment such as a chiller, and learn how that chiller operates over time in order to produce an optimal or near-optimal operating point given the current or forecast system conditions. An HVAC system would contain a number of agents that communicate in order to make choreographed control decisions that lead to optimal or near-optimal operation of the overall system. In this way the decision making process is distributed.

Kelly and Bushby [2] completed a feasibility study to determine if intelligent agent technology could lead to significant savings in HVAC energy consumption. Their study was comprised of 17 agents:

- 8 – VAV (variable air volume) box agents
- 2 – AHU (air handling unit) agents
- 2 – Chiller agents
- 2 – Cooling tower agents
- 1 – Agent to coordinate the actions of the other agents
- 1 – Agent to quantify the operating cost of the system
- 1 – Agent to control the simulation

In order to simulate the learning that an agent would have to do in the real world to understand how a given piece of equipment operates, models of each HVAC component were developed and used to provide data to the agent under a variety of conditions. Regression models were developed based on the data and these models were incorporated into the agents in order to predict equipment performance. With the agents now capable of estimating the performance of their equipment, the next step was to develop a method to optimize system performance.

Kelly and Bushby tested two methods, a simple optimization method (SOM) and an advanced optimization method (AOM). Only the SOM will be presented here because the AOM was more complicated and did not lead to a significant increase in savings relative to

SOM. In SOM, each of the HVAC agents takes turns optimizing the operation of their equipment. It should be noted that often the optimal operation of one piece of equipment is in conflict with the optimal operation of another piece of equipment. For example, the AHU may have optimal performance when the chiller provides it with water at 1.7 °C (35 °F), but the chiller may have better performance producing water at 12.8 °C (55 °F). In each time step, one agent determines how it would like to operate its equipment, calculates the cost of that operation, and communicates with the other agents to determine what the impact of that operation is on the other equipment in the system and the overall system cost. The agent can then decide if, given the overall impact on the system, it should change its set point as proposed. In the next time step, a different agent leads this process.

In a simulation of a single day of operation, the cost savings over a reference case without optimization was 21 %. Although the authors note that these savings are dependent on the details of the reference case, this proof of concept study was promising enough to justify constructing a laboratory to test the concept using actual HVAC equipment. The Intelligent Building Agents Laboratory (IBAL) is the culmination of that effort. The IBAL contains an air system that emulates a building and a hydronic system that emulates the plant. The air system is located on a mezzanine and the hydronic system is located underneath the mezzanine. There is an AHU dedicated to conditioning outdoor air to produce repeatable test conditions and zone simulators to emulate building loads. All of the equipment are monitored and controlled from a central data acquisition (DAQ) system. This technical note will describe the design and construction of the hydronic system and a future technical note will describe the air system in detail.

Section 2 is a high level review of some of the control concepts that are deployed in the IBAL, Section 3 is a description of the design of and equipment in the IBAL, Section 4 is a description of the data collection and operation, and Section 5 details the instrumentation and uncertainty of the measurements in the IBAL. Section 6 is a look towards the future operations of the IBAL.

2. Background on Local Loop Control in the IBAL

Control systems can be thought of as having two levels, local and supervisory. Supervisory control is the level that makes big picture decisions, such as which of two chillers to use to meet the current building load and what the set point temperature of the water from the chiller should be. Local control is used to control a single action based on the system conditions. In a typical application, for example, a valve, V , modulates to control a temperature, T , to a set point temperature calculated by the supervisory level. Numerous local control loops are used throughout the IBAL. The intelligent agent technique described in the introduction will be applied to the supervisory level while the local control will use traditional proportional-integral-derivative (PID) control. This report will not address the supervisory level in detail, leaving that topic to future publications, but PID control will be presented in some detail.

The local control loop has four parts [3]:

- 1) a measurement of the state of the system (process variable or PV),

- 2) a controller that makes a control decision based on the state of the system and the desired state of the system (set point or SP),
- 3) an actuator that executes the control decision, and
- 4) a process that is being controlled.

Figure 1 is an example of a typical local control loop in the IBAL. A temperature sensor provides a measurement of the state of the system, a PID controller compares that measurement to the SP, provided by the supervisory level, and determines the control action that needs to be taken by the control valve in order to bring the process closer to the set point. The disturbance in the process could be a change in chiller operation or pump speed, for example, which will cause the temperature in the loop to change, which will require the control valve to respond.

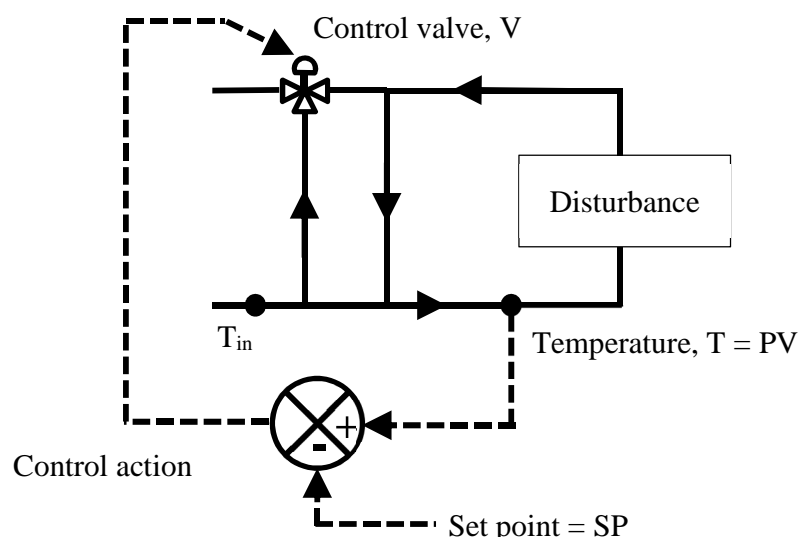


Figure 1. Example of a local control loop between a temperature and control valve.

In the IBAL local controllers use proportional-integral (PI) control, though derivative control is programmed into the software and can be added if necessary. For proportional control, the error between PV and SP is calculated and the control action is determined by multiplying the error by the proportional gain, hence the control action is proportional to the error. The problem with using proportional control by itself is that the error can reach a steady non-zero value, so although the system is stable, it is stable at the wrong set point. When this is the case, integral control, in which the integrated or accumulated error is multiplied by the integral gain, is added to proportional control in order to move the system closer to the set point. If the error is currently at a steady state, the proportional term is constant, but if it has been changing over time then the integral term will nudge the control action towards the set point. Derivative control is added to provide stability. The error rate is multiplied by the derivative gain; the derivative term anticipates the change in the system. Derivative gain has the significant disadvantage of being very sensitive to noise in the system [4]. In most temperature control applications derivative gain is not used.

The proportional, integral, and derivative gains are free parameters that must be determined for each system. The process of determining these values is called tuning. Although in some cases the values can be theoretically estimated, in most cases there are too many variables in the real system to capture in a model and the only way to set these values is to tune the system in operation. Tuning can be more of an art than a science, but one approach is to start by setting the integral and derivative gains to zero and the proportional gain to a large number, such as 100. This will likely cause the system to be unstable and oscillate around the set point. The proportional gain is decreased until the system no longer oscillates. At this point, however, the PV is usually offset from the SP, so the integral gain is slowly increased until the offset is removed. If the integral gain is too large, oscillations can again occur.

Figure 2 shows some temperature profiles that can be encountered during tuning. The horizontal line indicates the set point temperature. Oscillation is generally an indicator that the proportional gain is too high – the system is too responsive to the error. The figure shows two cases of overshoot, one that overshoots the SP, oscillates around the SP a couple of times, and slowly settles to the SP and one that overshoots the SP and then slowly settles to the SP. Both of these situations indicate that proportional gain is too high, but not so high that the system will never stabilize. The fourth profile shows the temperature increase to the SP without over or undershooting. Of all the profiles in this figure, this is the “best” case because it reaches the SP in the least time. However, depending on the situation, it may take too long for even this case to reach SP. In such a situation it may be better to increase the gain to overshoot the SP, but then stabilize to the SP more quickly after the overshoot.

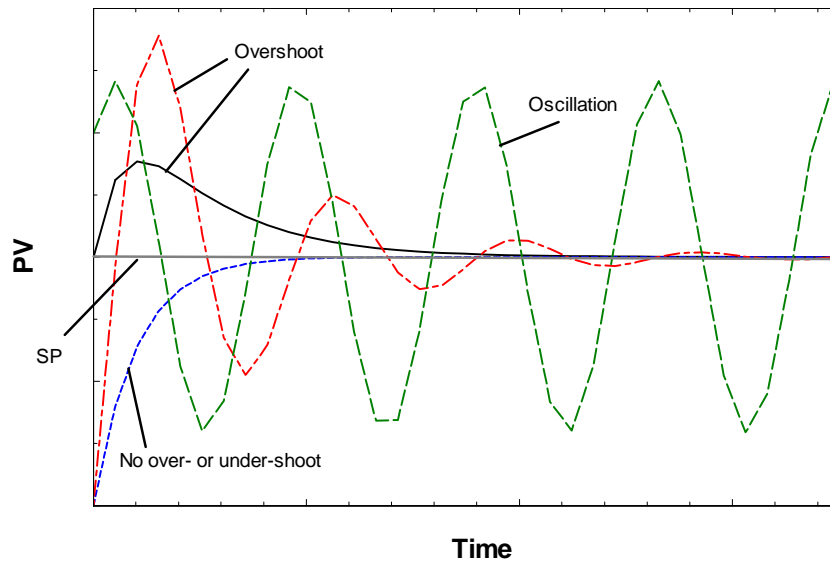


Figure 2. Possible temperature profiles under PI control.

The details of the implementation of PID in the IBAL are shown in Eqs. (1) through (5). Eq. (1) is the error calculation, where E is the error, SP_{high} is the largest value of the SP and SP_{low} is the lowest value. The various loops throughout the IBAL have SPs and PVs of different magnitudes, so by normalizing the error by the range of SP values, the magnitude of the gains will be similar even though the loops are very different.

$$E = \frac{PV - SP}{SP_{high} - SP_{low}} \quad (1)$$

The accumulated error, E_{accum} , is defined in Eq. (2), where dt is the control time step (10 s typical) and E_{accum}^- is the accumulated error at the start of the time step. The error rate, E_{rate} , is defined in Eq. (3), where $E - E^-$ is the difference between the error of the current time step and the error of the previous time step.

$$E_{accum} = E \cdot dt + E_{accum}^- \quad (2)$$

$$E_{rate} = \frac{E - E^-}{dt} \quad (3)$$

The control signal, u_{raw} , is calculated as shown in Eq. (4), where K_p , K_I , and K_d are the proportional, integral, and derivative gains, respectively. A is used to indicate if the control loop is direct (+1) or reverse acting (-1). Direct acting means that in order to increase temperature, the control action increases; reverse acting means that in order to increase temperature, the control action decreases. For example, looking back at Figure 1, if $T_{in} < T$, then in order to increase T , V needs to close, so the loop is reverse acting ($A = -1$). If, on the other hand $T_{in} > T$, V needs to open to increase T and the loop is direct acting ($A = 1$). The IBAL contains both direct and indirect control loops. u_{bias} is a bias control term that is used to provide coarse control on the system while the rest of the equation provides fine control – the bias term quickly brings the system near the SP and the PI terms refine the control action to bring the system to SP. In practice the bias term can be different for different operating conditions.

Eq. (5) is used to scale the raw signal to the engineering units required by the actuator. For example, the valves modulate from 2 to 10 V, but the control action from Eq. (4) outputs a value from $u_{min} = 0$ to $u_{max} = 1$. The control action has to be scaled to instead take a value between EU_{high} (10 V, for example) and EU_{low} (2 V, for example). This scaled value is the one that is written out by the DAQ system.

$$u_{raw} = A \cdot (K_p E + K_I E_{accum} + K_d E_{rate}) + u_{bias} \quad (4)$$

$$u_{scaled} = \frac{EU_{high} - EU_{low}}{u_{max} - u_{min}} (u_{raw} - u_{min}) + EU_{low} \quad (5)$$

The PI loops in the IBAL are continually being refined. As more tests are run additional complexity, such as adding feedforward control to anticipate the change in the control action based on something occurring elsewhere in the system, may have to be added to the calculation in order to bring the system under tighter control.

3. Description of the IBAL

The intent of the IBAL is to emulate a small office building in terms of the magnitude of building loads and the type of HVAC equipment that would typically be present. Since the primary purpose of the facility is to test the performance of different control algorithms, the equipment selection was designed to provide as many control options as possible. For example, rather than meeting all of the cooling load via a single chiller, the IBAL includes two chillers with different capacities, a water side economizer, an air side economizer, and thermal storage in the form of an ice tank. The control algorithm will have to determine which equipment or combination of equipment to use under the given conditions. This section will describe the mechanical design of the hydronic system of the IBAL in detail and will touch on components of the air system as needed. The air system will be described in more detail in a future technical note.

3.1. Overview

The IBAL contains the following equipment:

- Air system
 - 4 – Zone simulators (see Section 3.5)
 - 4 – Variable air volume terminals
 - 2 – Air handling units
 - 2 – Exhaust fans
 - 1 – Outdoor air simulation unit
- Hydronic system
 - 2 – Chillers (see Section 3.6)
 - 1 – Thermal storage tank (see Section 3.7)
 - 3 – Heat exchangers (see Section 3.8)

This technical note will focus on the hydronic system (aka chilled water plant), but there is a section about the zone simulators because the hydronic system ultimately is required to meet the loads generated in the zone simulators. In the IBAL, the hydronic system is on the lower level and the air system is on a mezzanine above the hydronic system. The entire laboratory is controlled from a central DAQ system.

Figure 3 shows the system as it was built. The hydronic system contains three main loops, the condensing loop (CL), the primary loop (PL), and the secondary loop (SL). Each loop is described in more detail in the following sections.

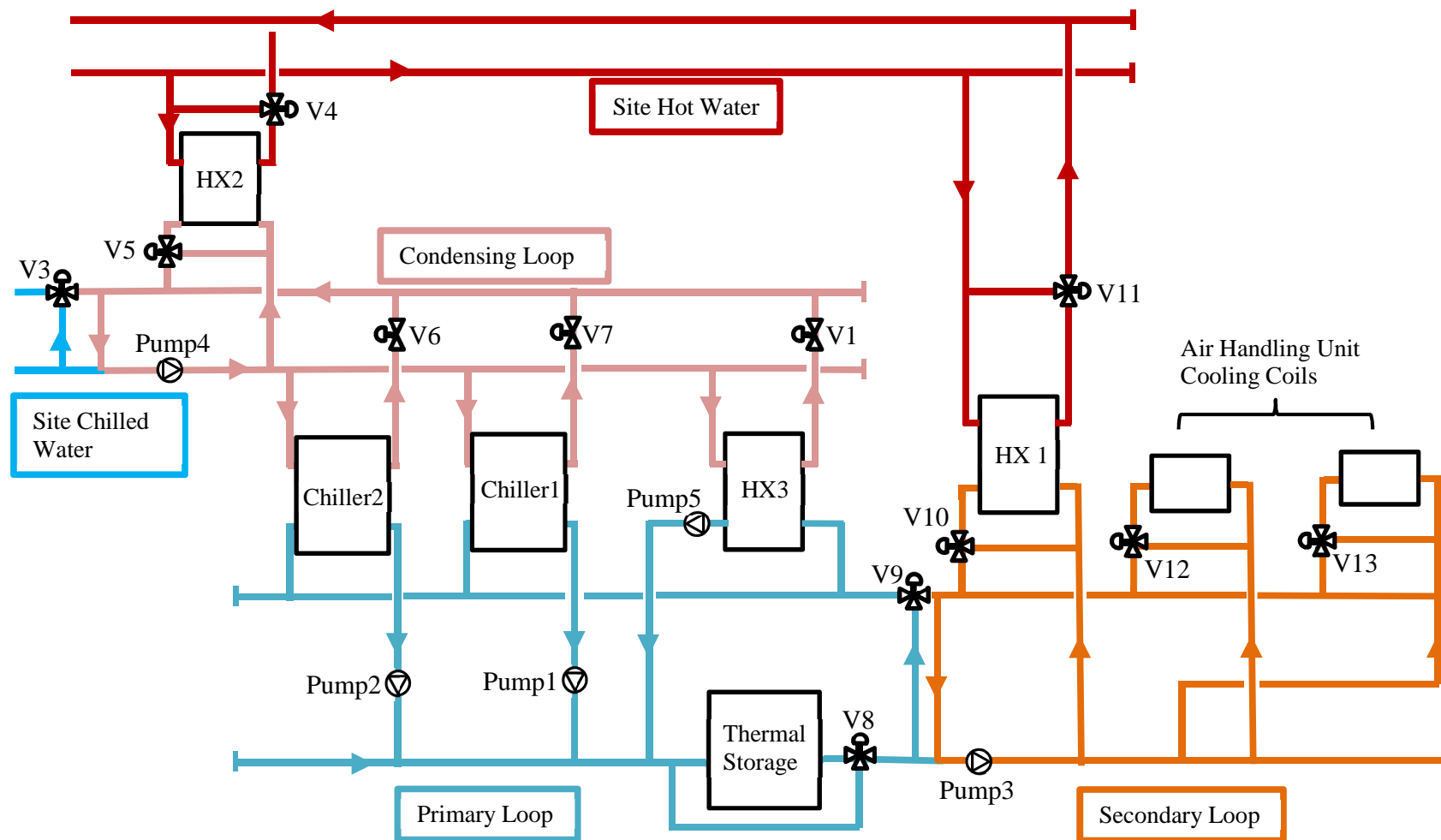


Figure 3. Schematic of the hydronic system as built.

3.2. Condensing Loop

The CL provides a heat sink to the chillers. In a real commercial building, this loop would include a cooling tower, but in the case of the IBAL the heat sink is chilled water produced by the NIST plant facility (SCHW). The CL in the IBAL includes the SCHW, a three way mixing control valve (V3), a pump (Pump 4), the condenser for Chiller 2 and Chiller 1, and a heat exchanger (HX3) that serves as the water side economizer (WSE). The CL is shown in Figure 5; the legend for this schematic and the other loop schematics is in Figure 4. The figure shows the channel numbers associated with measurements at different locations (e.g., C356AO is a control signal for a valve and is identified by channel number 356AO).

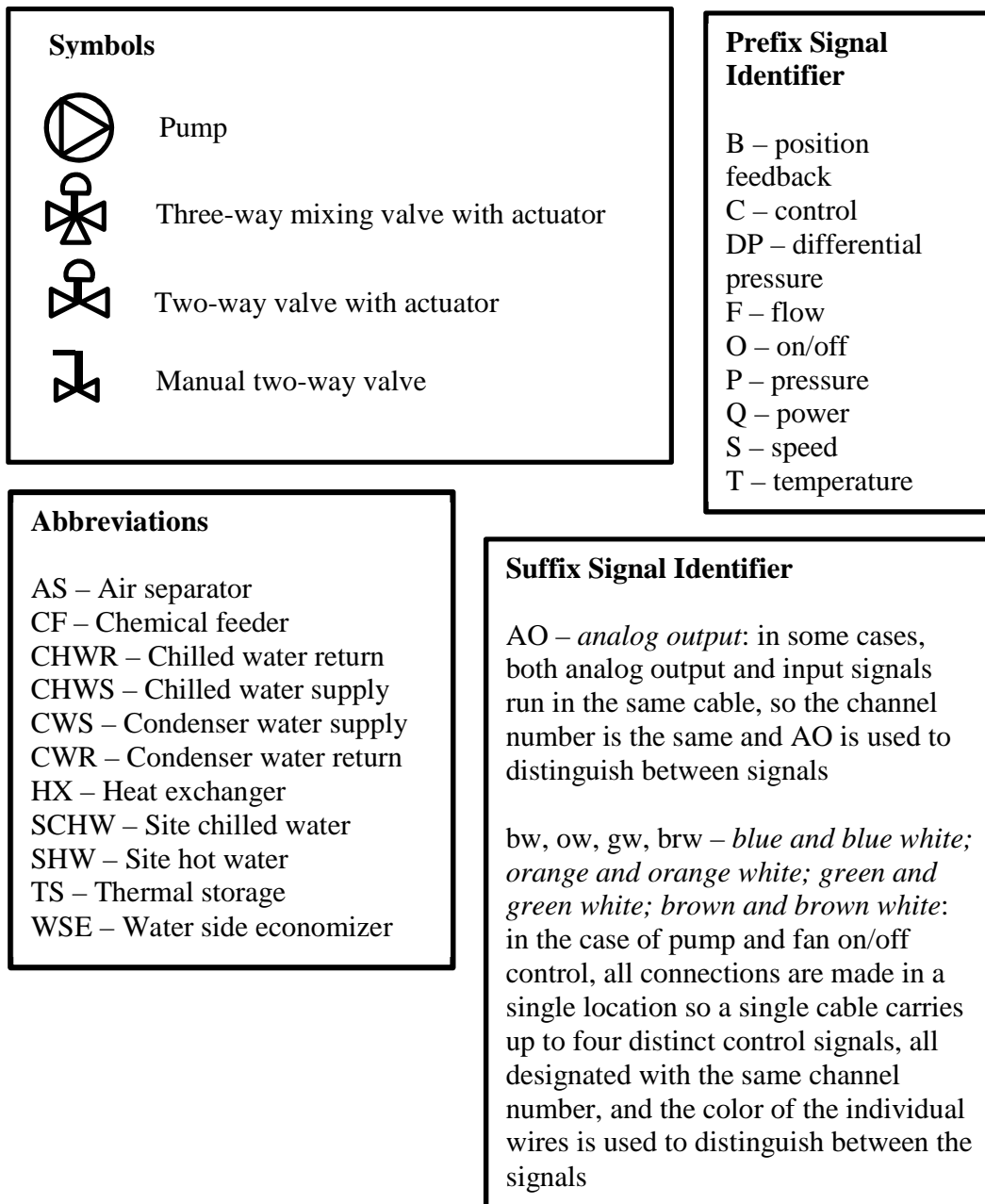


Figure 4. Legend for the loop schematics.

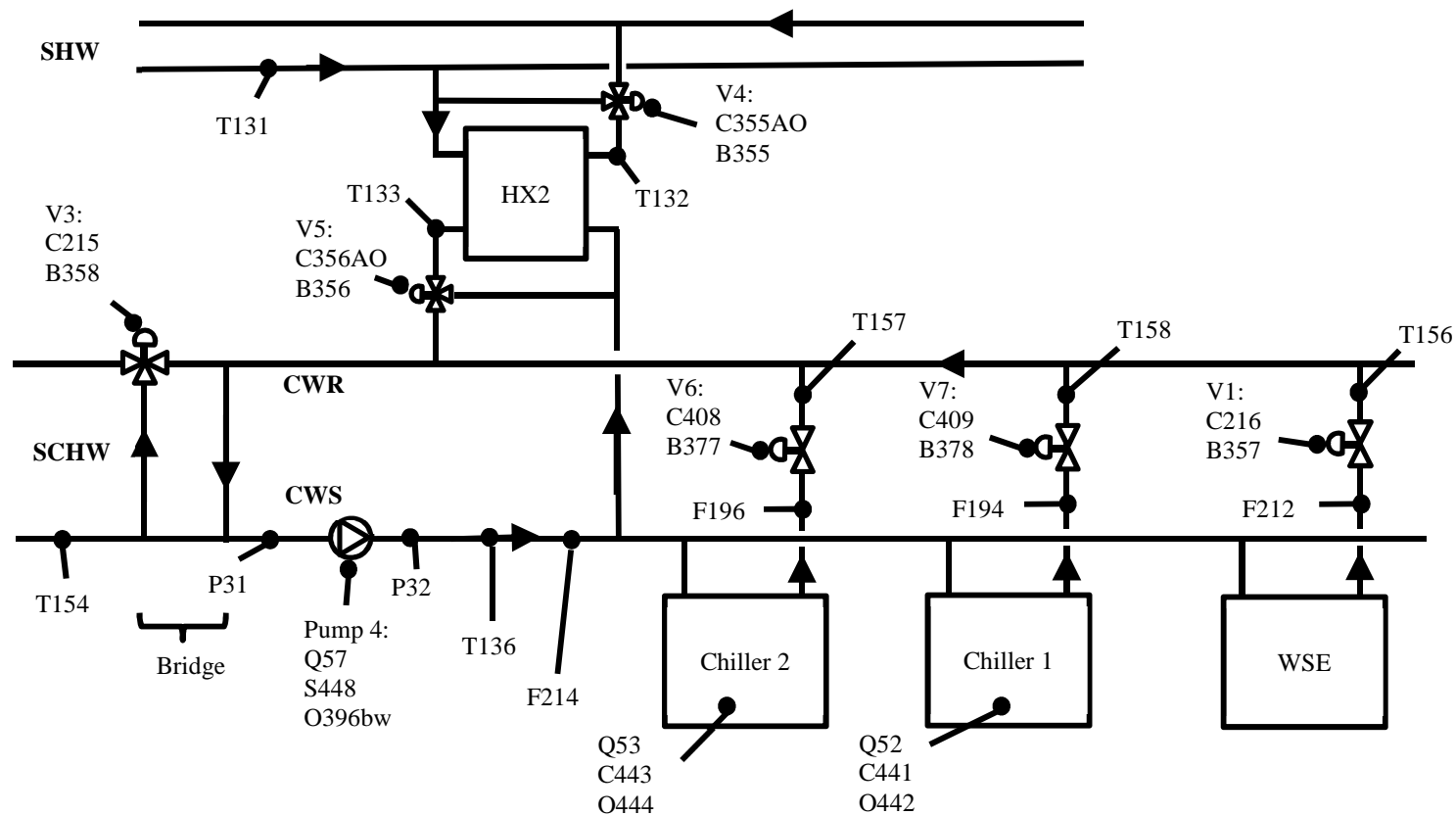


Figure 5. Schematic of the condensing loop.

At the far left of the CL is a bridge system that serves two purposes: 1) control temperature T136 and 2) hydraulically separate the SCHW loop from the lab CL. This system is shown in more detail in Figure 6. In Case 1, V3 is 50 % open, so there is partial flow through the bypass and through the common pipe. T136, which is the condenser water supply (CWS) temperature, T_{CWS} , is calculated as shown in Eq. (6). In Case 2, V3 is 0 % open, so all of the SCHW goes through the bypass and T136 is equal to the condenser water return (CWR) temperature, T_{CWR} . In Case 3, V3 is 100 % open, so no SCHW flows through the bypass and T136 is again calculated from Eq. (6). In this case, the flow through the common pipe, \dot{m}_{CP} , is simply $\dot{m}_{SCHW} - \dot{m}_{BYP}$. If $\dot{m}_{BYP} = \dot{m}_{SCHW}$, $\dot{m}_{CP} = 0$, and if $\dot{m}_{BYP} = 0$, $\dot{m}_{CP} = \dot{m}_{SCHW}$. The position of V3 is set to achieve the desired T136 via an automated control loop.

$$T_{136} = \frac{\dot{m}_{BYP} T_{BYP} + \dot{m}_{CP} T_{CP}}{\dot{m}_{BYP} + \dot{m}_{CP}} \quad (6)$$

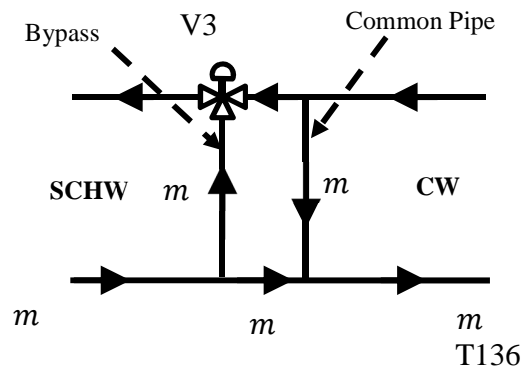


Figure 6. Illustration of the function of the bridge system.

HX2 (Figure 5) is a plate heat exchanger between the site hot water (SHW) and the CL. It is not currently being used, but it has two possible purposes. First, it can be used to set a predetermined loop temperature at T136 prior to activating the chillers; second, it can be used to apply an additional load to the CL if the load from the chillers or WSE are insufficient for the purposes of a test.

When Chiller 2 is operating, control valve V6 is fully open, allowing flow through the chiller. When Chiller 1 is operating, control valve V7 is fully open. The chiller control system consists of two parts, an internal controller provided by the manufacturer and the IBAL external controller. The internal controller determines how the compressor operates and protects the chiller components from damage by modifying the operation to keep pressure, for example, within specified limits. The external controller determines the set point temperature and when the chiller should be on or off. The internal chiller control includes a condenser water regulating valve (CWRV) that controls the discharge pressure. If the heat exchange in the condenser is such that the refrigerant is being overcooled by the CL, the discharge pressure will drop below the set point and the water flow through the condenser

will be throttled back by the CWRV, potentially to the point of completely shutting off flow. This can occur if the water flow rate is too high and/or the temperature of the water is too cold given the magnitude of the load being met. In order to avoid excessive modulation of the flow through the condenser, the set point for T136 is no less than 24 °C (75 °F) and the speed of Pump 4 is set to produce only the necessary flow.

When the WSE is operating, control valve V1 is open. The WSE, aka HX3, is a plate heat exchanger that sits between the CL and the PL. It is plumbed in parallel with the chillers, which means that it will likely only be used when it can meet the full building load.

For more information about:

- Chillers – see Section 3.6,
- WSE – see Section 3.8,
- Pump 4 – see Section 3.9.

3.3. Primary Loop

The primary loop produces the cold fluid in order to meet the building load in the SL and is shown in Figure 7. In this system the fluid is a 30 % propylene glycol (PG) solution because the minimum temperature for making ice is approximately -6.7°C (20°F). Although this loop contains PG, it is referred to as the chilled water loop by convention. As shown in the figure, the “water” from the PL to the SL is referred to as the chilled water supply (CHWS) and the water returning to the PL is the chilled water return (CHWR).

The PL contains Chiller 2, Chiller 1, and the WSE all in parallel, while a thermal ice storage tank (TS) is plumbed in series. Each chiller and the WSE have a dedicated pump. The pumps typically operate as single speed, but all of the pumps in the IBAL are operated from variable frequency drives (VFDs), so the PL can be variable speed. When not in use, the TS can be bypassed by closing control valve V8. AS is the air separator and is just downstream of the TS. CF is a chemical feeder that is plumbed between the PL and the SL.

This portion of the system presents a number of challenges to a control system. The control algorithm has to determine when to use which chiller, whether to use one or both, whether to use the WSE, when to charge and discharge the TS, etc.

For more information about:

- Chillers – see Section 3.6,
- TS – see Section 3.7,
- WSE – see Section 3.8,
- Pump 1, 2, and 5 – see Section 3.9,
- AS and CF – see Section 3.10.

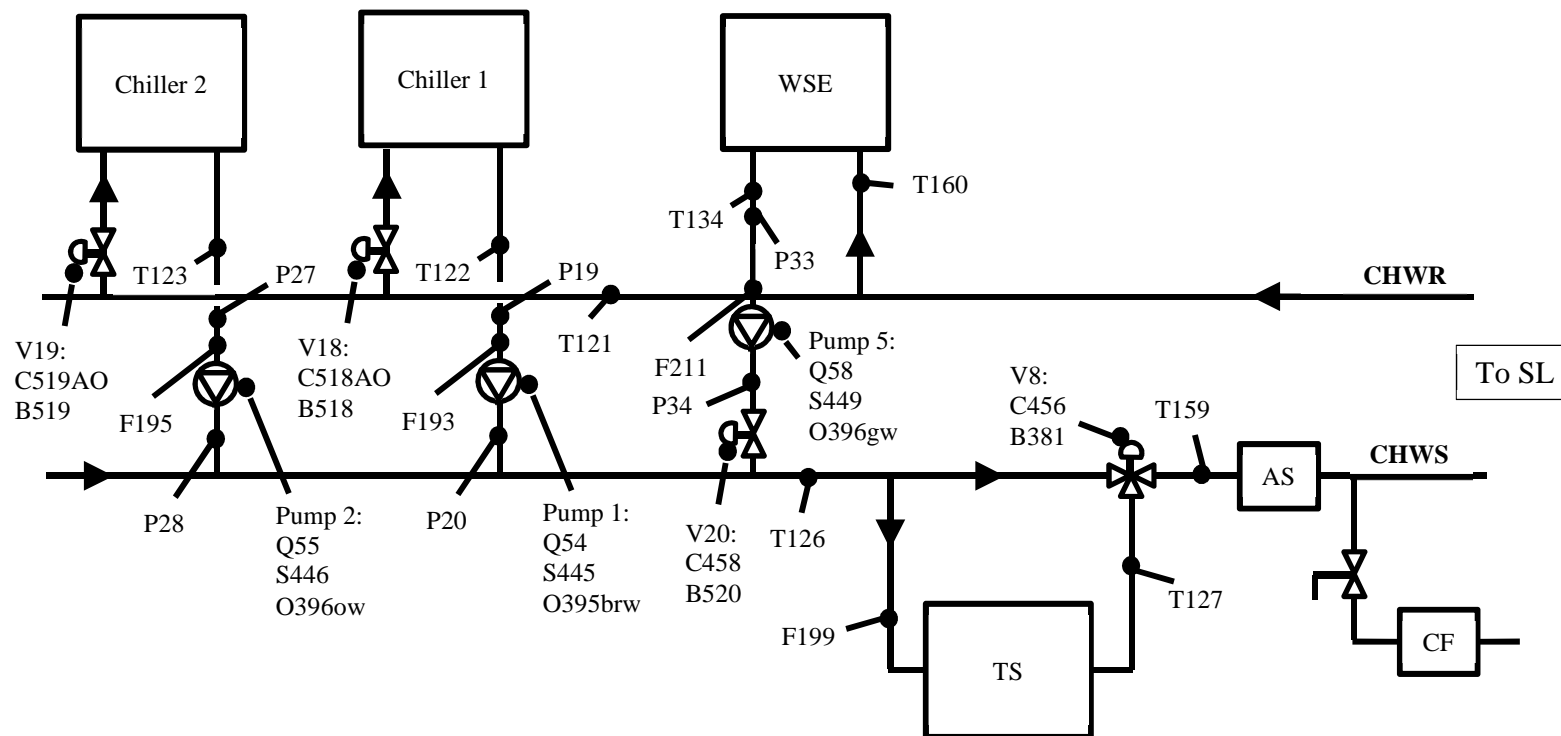


Figure 7. Schematic of the primary loop.

3.4. Secondary Loop

The secondary loop is where the hydronic system connects to the “building” through the cooling coils in the air handling units (AHUs) and is shown in Figure 8. The PL connects to the SL at another bridge like the one in the CL. This bridge serves the same purpose as that one; control valve V9 controls temperature T135 and there is a common pipe to allow the PL and SL to have different flow rates.

The SL contains HX1 and the cooling coils for AHU2 and AHU1. The cooling coils in AHU2 and AHU1 each have a control valve (V13 and V12, respectively) that can operate as either a three-way valve or, by closing off the bypass, a two-way valve. These valves will be controlled from the air system in order to deliver the right flow rate of chilled water to meet the air set point temperature and/or dehumidification needs. HX1 connects between the SL and the SHW. This heat exchanger will be used to place a cooling load on the SL either independently of the cooling coils or in addition to the coils.

If the cooling coils need less chilled water either because the building load is low or the water temperature is cold, control valves V13 and V12 will close down. This will lead to an increase in flow resistance, which is seen as an increase in the head that the pump must deliver. If the pump was constant speed, it would respond by simply moving along its pump curve to a higher head – lower flow point, but the SL pump is variable speed, so instead it can respond by decreasing its speed and thereby reducing its power consumption (which is proportional to the cube of the speed). In order to automate this process, a control loop is established between the pump speed and the pressure drop in the system.

The best location to measure the pressure drop in the SL is across the most distant significant load in the system [5] because the measurement will be sensitive to small changes in cooling coil valve position and the pump energy savings will be maximized. AHU2 is the most distant load in the system, but its pipes are located right next to those for AHU1, so one differential pressure (DP) sensor, DP493, measures the pressure drop across both AHU cooling coils. A separate DP sensor, DP362, was installed to measure the total pressure drop across the SL. This sensor can be used when the AHU cooling coils are not in use and HX1 is providing the entire system load. As of writing, DP362 is a 25 psi sensor and DP493 is a 10 psi sensor, but the final sensor selection will have to be determined at a future date once enough data has been collected to decide the optimal DP range for each location.

Prior to commissioning of the air system, HX1 will provide the entire load so that the hydronic system can be commissioned independent of the air system. When in use, control valve V10 is opened and control valve V11 modulates to produce the desired temperature T128. HX1 is designed to provide a load to the system, so a load set point, Q_{SP} , is requested and the temperature set point, $T128_{SP}$, is calculated from that load by use of Eq. (7). c_p [kJ/kg-K] is the specific heat of the PG, ρ [kg/m³] is the density, \dot{V} [m³/s] is the flow rate in the SL, and T135 is the temperature of the PG into the SL. Q_{SP} is, therefore, the total “building load.”

$$128_{SP} = \frac{Q_{SP}}{c_p \dot{V} \rho} + T135 \quad (7)$$

3.5. Zone Simulators

Building HVAC systems are designed based on the expected building loads. The IBAL does not include an actual building or rooms due to space constraints, but zone simulators (ZSs) were designed to provide a load to be met by the HVAC system. There are four ZSs, each containing an electric heating element, a steam spray humidifier, a cooling coil, and a thermal mass coil. The electric heating element provides the sensible cooling load, the steam spray humidifier supplies the latent cooling load, the cooling coil provides a heating load, and the thermal mass coil (TMC) provides a source of thermal mass. Note that the focus of the IBAL is to study control systems to meet cooling loads with the underlying belief that the developed methodologies can be adapted to heating loads, so the cooling coil is not currently used.

The four ZSs are stacked one above the other at one end of the mezzanine; Figure 9 shows one ZS. Beginning at the far left and moving right are an electric heater, a steam spray humidifier, an access door, a cooling coil, and a TMC (the copper pipe runs from the TMC to a water tank). The zone temperature and humidity are measured at the outlet of the ZS.

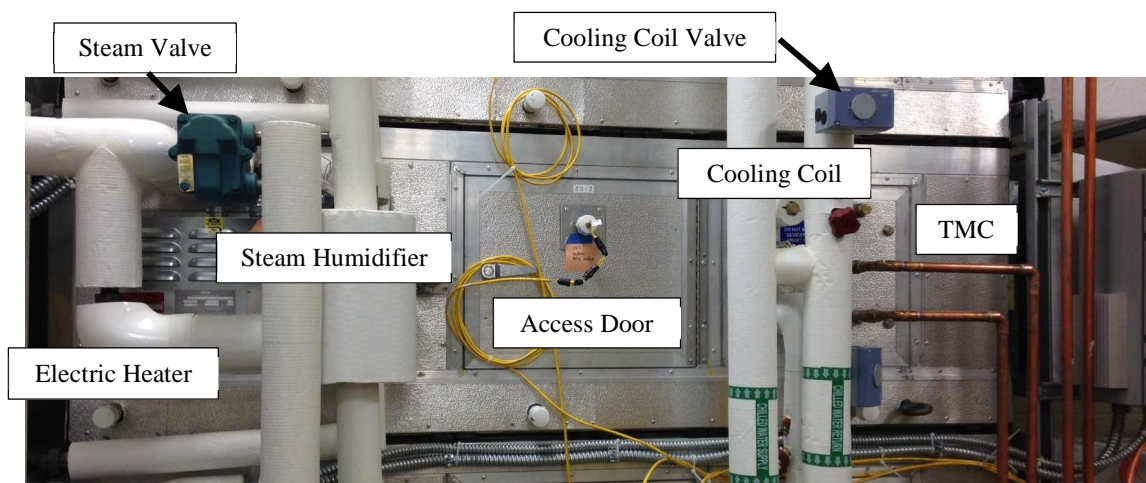


Figure 9. Zone Simulator 2.

Each ZS represents a 65 m² (700 ft²) room in an office building and the equipment within the ZS was sized to provide the loads defined by each of two cases: (1) open office space and (2) conference room. The design engineer based the magnitude of the loads on the tables in the ASHRAE Handbook Fundamentals [6]. For Case 1, there are 6 occupants, each performing office work. The room has a 32.5 m² (350 ft²) exterior wall with 7 m² (75 ft²) of glass that faces southwest and the magnitude of the heat gain through the envelope is based on conditions in Maryland. A summary of the loads for this zone is provided in Table 1.

Table 1. Loads for Case 1: open office space.

Source	Type of Load	Load	Total Load
Person	Sensible heat	72 W (245 BTU/hr)	430 W (1470 BTU/hr)
	Latent heat load	60 W (205 BTU/hr)	360.5 W (1230 BTU/hr)
Equipment	Workstation	175 W (597 BTU/hr)	1050 W (3583 BTU/hr)
Lighting	Lighting	11.8 W/m ² (1.1 W/ft ²)	770 W (2627 BTU/hr)
Envelope	Heat gain	2344 W (8000 BTU/hr)	2344 W (8000 BTU/hr)
		Total	4955 W (16,910 BTU/hr)

For Case 2 (see Table 2) there are 18 people performing office work in the conference room. There is one projector and one workstation and the envelope is the same as in Case 1.

Table 2. Loads for Case 2: conference room.

Source	Type of Load	Load	Total Load
Person	Sensible heat	72 W (245 BTU/hr)	1292 W (4410 BTU/hr)
	Latent heat load	60 W (205 BTU/hr)	1081 W (3690 BTU/hr)
Equipment	Workstation + projector	500 W (1706 BTU/hr)	500 W (1706 BTU/hr)
Lighting		11.8 W/m ² (1.1 W/ft ²)	770 W (2627 BTU/hr)
Envelope	Heat gain	2344 W (8000 BTU/hr)	2344 W (8000 BTU/hr)
		Total	5987 W (20,433 BTU/hr)

The latent load is provided by a steam spray humidifier that is connected to the site steam supply. For Case 1, the design steam flow rate is 0.6 kg/hr (1.25 lbs/hr) and for Case 2 the design steam flow rate is 1.8 kg/hr (4 lbs/hr).

The electric heater and steam spray humidifier were selected to meet either of these two scenarios as a minimum, but the ZS operation will not be limited to these scenarios. The electric heater is a 5 W open coil heater with a minimum air flow requirement of 187 m³/hr (110 SCFM). The amount of heat generated by the unit is controlled with a silicon controlled rectifier, or SCR. The steam spray humidifier can deliver up to 1.8 kg/hr (4 lbs/hr).

The electric heater and steam spray humidifier will provide a means to simulate the cooling loads in a zone, but a real zone also has thermal mass that acts to damp out changes in the temperature of the zone. For example, in a real room if an additional person (additional load) enters the room, the room temperature does not immediately increase. If there is no equivalent thermal mass in the zone simulator, an increase in the heater level will lead to an immediate change in temperature. The TMC is designed to provide the zone simulator with a means to damp out temperature changes. It was sized to mimic the effect of adding an occupant and workstation to the zone such that the temperature of the room would rise by 0.56 °C (1 °F) in 120 seconds. The volume of water required to achieve this effect is calculated as shown in Eq. (8), where $Q = 72 + 175 = 247$ W, $t = 120$ s, $c_p = 4.18$ kJ/kg-K, $\Delta T = 0.56$ K, and $\rho = 998$ kg/m³. In order to achieve the desired effect, a water volume of 0.013 m³ (3.35 gallons) is required.

$$Voldme [m^3] = \frac{Q [kW] [s]}{c_p [kJ/kg - K] \Delta T [K] \rho [kg/m^3]} \quad (8)$$

Rather than just placing a container of water in each ZS that will heat up over time, fluid circulates through the TMC so that at any given moment there is a volume of water in the TMC, but since it is not stagnant it has an opportunity to release heat outside of the ZS. Each TMC is independently supplied by a 76 L (20-gallon) water tank with a dedicated circulating pump. The flow rate of the water through the coil will be adjusted in order to achieve the desired effect. Figure 10 shows the water tanks and circulating pumps that supply the TMC.



Figure 10. The black tanks hold water for the thermal mass coils in the zone simulators. Above the tanks are the red circulating pumps that move the water through the TMCs. The flow rate is determined by manually setting a valve.

The four zone simulators together can generate a sensible load of 20 kW (5.7 ton) and a latent load of approximately 4.3 kW (1.2 ton), for a total load of 24 kW (6.9 ton).

3.6. Chillers

The chillers are AC Series water-cooled process chillers from Precise Cooling Solutions and use digital scroll compressors from Copeland. The Chiller 2 compressor is ZP120KCE-TFD-250 and has a nominal cooling capacity of 10.25 tons and the Chiller 1 compressor is ZP90KCE-TFD-250 and has a nominal cooling capacity of 7.5 tons. Table 3 contains design data for the chillers. Note that when the chillers are used to charge the TS, the capacity is degraded because the temperature they are required to deliver is so low.

Table 3. Design data for the chillers.

	Chiller 1	Chiller 2
Refrigerant	R-410A	
Nominal capacity [kW] (ton)	26.4 (7.5)	36 (10.25)
De-rated capacity during TS charging [kW] (ton)	16.2 (4.6)	22 (6.2)
Condenser water flow [m ³ /hr] (gpm)	5 (22)	6.8 (30)
Condenser supply temperature [°C] (°F)	29.4 (85)	
Leaving fluid temperature range [°C] (°F)	-6.7 to 26.7 (20 to 80)	
Chiller flow [m ³ /hr] (gpm)	4 (18)	5 (22)

Figure 11 shows the manufacturer data for nominal capacity as a function of leaving fluid temperature, assuming that the condenser supply temperature is 29.4 °C (85 °F). Figure 12 shows the corresponding EER for each chiller.

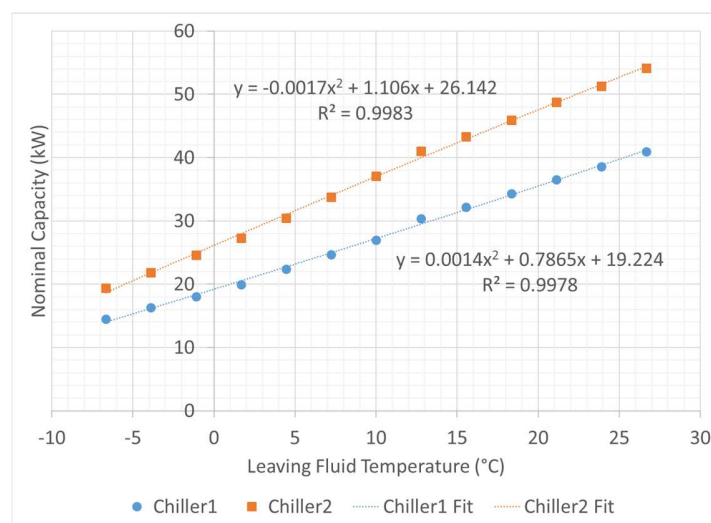


Figure 11. Chiller capacity as a function of leaving fluid temperature.

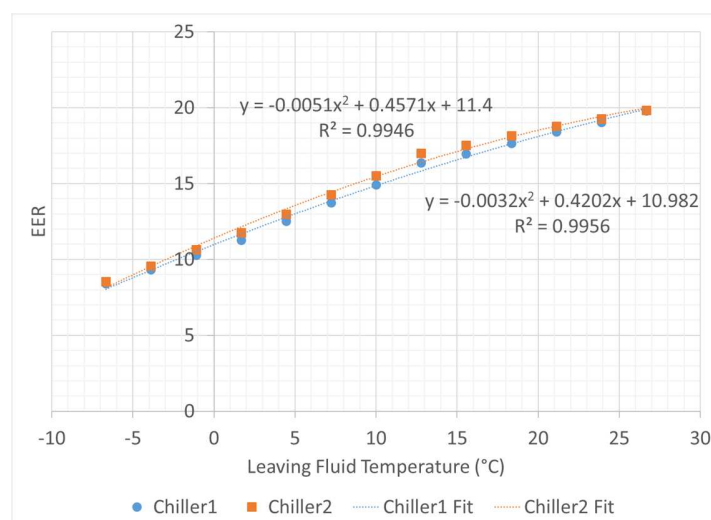


Figure 12. Chiller efficiency as a function of leaving fluid temperature.

The chillers have remote start/stop and remote temperature reset, so they can be activated and the temperature set point can be changed from the control program on the DAQ. The operation of the chiller itself is controlled internally and is described in detail in the users' manual [7]. The chiller has two controls that impact the rest of the system. The condenser water regulating valve (CWRV) was discussed earlier. If the CL temperature and flow rate are not appropriately adjusted, there will be excessive oscillation of the CWRV, which will lead to oscillation in the flow rate through the condenser and the return temperature from the condenser, which makes it more difficult to control the supply temperature to the condenser (T136). By keeping the flow rate in the CL well matched to the chiller and maintaining T136 above 24 °C (75 °F), the oscillations are less likely to occur.

The second control is the hot gas bypass, which is affected by the CWRV; if the CWRV is fluctuating the hot gas bypass typically does as well. Under conditions of partial loading, the hot gas bypass will open so that the load on the compressor remains relatively constant. This prevents excessive cycling of the compressor [7]. The intent is to operate the CL so that CWRV and hot gas bypass are of limited use and therefore the system is more stable overall.



Figure 13. The two process chillers in the IBAL. Chiller 1 is on the left and Chiller 2 is on the right. HX2 is just visible on the far right.

3.7. Thermal Storage Tank

The thermal storage tank (TS) is Calmac part number 1082A. It is specified to discharge 274 kWh (78 ton-hours) of ice over an eight-hour period with an inlet temperature of 10 °C (50 °F). The tank contains 3105 L of water (820 gallons) and is located outside of the lab as shown in Figure 14. Figure 15 shows the interior of the TS. The heat exchanger is spiral wound polyethylene tube and is filled with 295 L (78 gallons) of PG. The tank was designed to be fully charged during a single 8-hour off-peak period with a flow rate of 9.5 m³/hr (42 gpm) and charge temperature of -3.9 °C (25 °F). However, in operation the flow through the TS is provided only by the chiller pumps and/or WSE pump and these pumps do not provide that level of flow. In order to maximize the amount of ice that can be made during a given charging period, the charging temperature has been dropped to -6.7 °C (20 °F). The time required to fully freeze the tank as well as the amount of the tank frozen in 8 hours will be determined during future experiments.



Figure 14. Thermal storage tank.

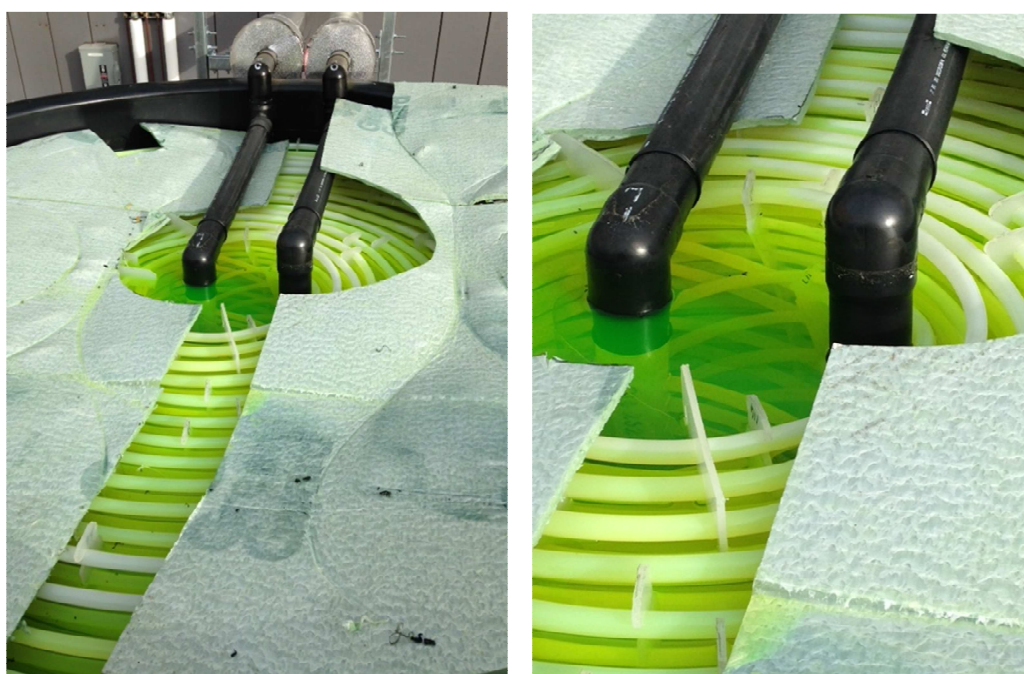


Figure 15. Interior of the thermal storage tank. The small tubes contain PG.

3.8. Heat Exchangers

There are three brazed plate heat exchangers in the IBAL. The plate material is 316L stainless steel and the brazing material is copper. All three heat exchangers are shown in Figure 16.



Figure 16. Left: HX3 and HX1; HX3 is the larger heat exchanger on the left. Right: HX2.

HX2 acts as an additional load on the CL and can be used to pre-heat the temperature in the CL before the rest of the system runs. HX2 has 50 plates and one side of the heat exchanger is hot water while the other side is CL water. Some key specifications are provided in Table 4.

Table 4. Specifications of HX2.

	Hot Water	Water
# of Passes * channels	1*24	1*25
Internal Volume [L] (ft ³)	2.5 (0.08758)	2.58 (0.09123)
Flow [m ³ /hr] (gpm)	5.1 (22.5)	6.8 (30)
Inlet Temperature [°C] (°F)	82.2 (180)	7.2 (45)
Outlet Temperature [°C] (°F)	71.1 (160)	15.3 (59.59)
LMTD [°C] (°F)	65.38 (117.68)	
Overall Heat Transfer Coefficient, Clean/Dirty [kW/m ² -K] (BTU/hr-ft ² -F)	3.60 (1142.26)	
Overall Heat Transfer Coefficient, Service [kW/m ² -K] (BTU/hr-ft ² -F)	0.22 (68.70)	
Effective Surface Area [m ²] (ft ²)	2.52 (27.17)	

The WSE is HX3, which has 70 plates. One side of the heat exchanger is PG and the other side is CL water. Some key specifications are provided in Table 5.

Table 5. Specifications of the WSE (HX3).

	PG	Water
# of Passes * channels	1*34	1*35
Internal Volume [L] (ft ³)	9.06 (0.31997)	9.327 (0.32938)
Flow [m ³ /hr] (gpm)	5.45 (24)	5.45 (24)
Inlet Temperature [°C] (°F)	15.6 (60)	7.2 (45)
Outlet Temperature [°C] (°F)	10 (50)	12.5 (54.54)
LMTD [°C] (°F)	2.91 (5.23)	
Overall Heat Transfer Coefficient, Clean/Dirty [kW/m ² -K] (BTU/hr-ft ² -F)	0.96 (304.53)	
Overall Heat Transfer Coefficient, Service [kW/m ² -K] (BTU/hr-ft ² -F)	0.96 (304.26)	
Effective Surface Area [m ²] (ft ²)	6.72 (72.28)	

HX1 is used to simulate a building load and has 30 plates. One side of the heat exchanger is hot water and the other side is PG. Some key specifications are provided in Table 6.

Table 6. Specifications of HX1.

	Hot Water	PG
# of Passes * channels	1*14	1*15
Internal Volume [L] (ft ³)	3.73 (0.13175)	4.00 (0.14116)
Flow [m ³ /hr] (gpm)	4.54 (20)	9.54 (42)
Inlet Temperature [°C] (°F)	82.2 (180)	7.2 (45)
Outlet Temperature [°C] (°F)	71.1 (160)	12.6 (54.70)
LMTD [°C] (°F)	66.7 (120.08)	
Overall Heat Transfer Coefficient, Clean/Dirty [kW/m ² -K] (BTU/hr-ft ² -F)	2.45 (776.71)	
Overall Heat Transfer Coefficient, Service [kW/m ² -K] (BTU/hr-ft ² -F)	0.17 (54.63)	
Effective Surface Area [m ²] (ft ²)	2.77 (29.76)	

3.9. Pumps

There are nine Bell & Gossett centrifugal pumps in the IBAL. Four of the pumps are small circulation pumps for the zone simulator TMCs and the other five pumps are in-line process pumps.

Pump 1 is the pump dedicated to Chiller 1, Pump 2 is the pump dedicated to Chiller 2, and Pump 5 is the pump dedicated to the WSE. All three of these pumps are plumbed in parallel in the PL, and therefore pump PG. Pump 3 pumps PG in the secondary loop and Pump 4 pumps water in the CL. Figure 17 shows Pump 3 installed in the SL; the other four pumps have the same appearance, though they are slightly different sizes. Table 7 contains the key specifications for these five pumps. Although the table contains the pump speed in RPM, all of these pumps are powered by a variable frequency drive (VFD), which outputs power at 15 to 60 Hz, and can therefore be operated at speeds determined by the control program.



Figure 17. Pump 3. The other in-line pumps have the same appearance.

Table 7. Key specifications for the in-line pumps in the IBAL.

	Pump 1	Pump 2	Pump 3	Pump 4	Pump 5
P/N	90 1-1/2A	90 1AA	90 1-1/2A	80 1-1/2x1-1/2x9-1/2	90 1-1/2A
Flow [m ³ /hr] (gpm)	4.1 (18)	5.45 (24)	9.5 (42)	11.8 (52)	5.45 (24)
Head [kPa] (ft of head)	167.4 (56)	167.4 (56)	119.6 (40)	224.2 (75)	119.6 (40)
Motor size [kW] (hp)	1.1 (1.5)	1.1 (1.5)	1.1 (1.5)	2.2 (3)	0.75 (1)
RPM [rpm]	1725	3450	1725	1750	1725
Max flow [m ³ /hr] (gpm)	13.4 (59)	11.1 (49)	13 (57)	23.2 (102)	12 (53)
Impeller diameter [cm] (in)	17.8 (7)	10.8 (4.25)	16.8 (6.625)	21.9 (8.625)	15.9 (6.25)
Fluid	PG	PG	PG	Water	PG

The four circulating pumps for the TMCs in the zone simulators are shown in Figure 18. They are constant speed, but, as can be seen in Figure 18, the flow rate can be varied by partially closing one of the red handled valves. These pumps currently are operated manually and are not connected to the DAQ. The pumps are capable of producing 0 - 9 m³/hr (0 - 40 gpm) at 120 - 0 kPa (40 - 0 ftH₂O). The design calls for 0.45 m³/hr (2 gpm), which corresponds to a head pressure of approximately 105 kPa (35 ft H₂O).



Figure 18. Circulating pumps for the zone simulator thermal mass coils.

3.10. Support Equipment

There are several other important pieces of supporting equipment that are not part of any experiment, but allow the system to operate. This section will briefly introduce the support equipment in the hydronic system.

In order to add additional PG into the system or change the concentration of PG, a 189 L (50 gallon) reservoir is placed in the PL. When work needs to be performed on a section of the system that requires draining pipe, the PG can be drained directly into the reservoir and, when the system later needs to be refilled, PG is pulled from the bottom of the reservoir by a dedicated pump and pumped back into the system.

The entire hydronic system is a closed loop, so an expansion tank is necessary to allow for changes in PG volume over the wide temperature range that will be used in the IBAL. The lowest temperatures will occur when the TS is being charged, -6.7°C (20°F), and the highest temperatures will occur in the SL at high loads. In theory, the SL temperature could reach the temperature of the site hot water, 82.2°C (180°F), due to the connection via HX1, though it is unlikely that this will be an intentional operating point. Based on estimates of the length of pipe in the IBAL, there is approximately 757 to 946 L (200 to 250 gallons) of PG in the system. In a worst case scenario where the temperature does range from -6.7°C to 82.2°C and the system volume is 946 L, the volume of PG would change by 45 L (12 gallons). The expansion tank has a volume of 200 L (53 gallons), so it is more than capable of compensating for the volume change. The system pressure can be set by adding compressed air to the expansion tank. Figure 19 shows both the PG reservoir and the expansion tank. The current system pressure is approximately 193 kPa (28 psi).



Figure 19. The PG reservoir is the white tank with yellow liquid and the expansion tank is the red object in the front of the picture.

A chemical feeder is included in the PL/SL in order to allow chemical treatment to be added to the PG as needed to avoid corrosion. This feeder is 19 L (5 gallons) and contains a replaceable filter bag. Figure 20 is a picture of the chemical feeder.



Figure 20. Chemical feeder.

In order to remove air from the system, an air separator and air vent, pictured in Figure 21, are incorporated into the PL just downstream of the TS. The air vent is the red device at the top. A copper pipe runs from the top of the air vent to the PG reservoir so that when the vent opens any PG that passes through has somewhere to go. The air separator, which is just below the air vent and covered with insulation, is designed with tangential inlet and outlet openings. This creates a vortex pattern in the flow, which allows the air to more readily separate from the fluid. The air is then purged from the system via the air vent. Some additional small air vents were added to other points in the system in order to enable more localized venting.



Figure 21. Air separator (covered by insulation) and air vent (red object at the top).

3.11. Fluid Properties

The hydronic system contains water in the condensing loop and a nominally 30 % PG solution in the primary and secondary loops. The density, ρ , and specific heat, c_p , of PG are required to calculate items such as mass flow rate and heat transfer. Eq. (9) and Eq. (10) and used for these calculations; ξ is the concentration of PG and T is the fluid temperature in K [8].

$$\rho \left[\frac{kg}{m^3} \right] = 508.41109 - 182.40820 \xi + 965.76507 \frac{273.15}{T} + 280.29104 \xi \frac{273.15}{T} - 472.22510 \left(\frac{273.15}{T} \right)^{2d} \quad (9)$$

$$c_p \left[\frac{kJ}{kg K} \right] = 4.47642 + 0.60863 \xi - 0.71497 \frac{273.15}{T} - 1.93855 \xi \frac{273.15}{T} + 0.47873 \left(\frac{273.15}{T} \right)^2 \quad (10)$$

The freezing temperature of 30 % PG is $-13.3\text{ }^{\circ}\text{C}$ ($8\text{ }^{\circ}\text{F}$) and the burst point is $-27.5\text{ }^{\circ}\text{C}$ ($-18\text{ }^{\circ}\text{F}$). At the freezing temperature, the PG is a slush, but at the burst point the fluid will freeze solid and can potentially burst pipes.

4. Data Collection and Operation

Commercial HVAC equipment typically arrives from the manufacturer with controllers that can be linked to a central control system. The IBAL, however, is designed to study different control algorithms and as such does not contain any proprietary manufacturer control systems on the major equipment (exceptions: the AHU that conditions outdoor air and the internal chiller controls). Instead, the IBAL is fully controlled from a LabVIEW program on an embedded computer system.

This section will describe the types of signals used in the IBAL, the data acquisition (DAQ) system, the database, and the architecture of the control software.

4.1. Signals

When completed, the IBAL will contain nearly 300 unique measurement and control signals, roughly split equally between the air and hydronic systems. This section will describe the types of signals that exist in the hydronic system. Other sections will discuss the details of how those signals are acquired or output.

There are 6 general categories of signal: pressure, control valve, power, temperature, flow, and control. The pressure devices output a 4 – 20 mA signal that is converted to a voltage at the DAQ by measuring the voltage drop across a 249 Ohm resistor (note: this method is used for all sensors that output current and are read by a DAQ device that measures voltage). The reason for using a current signal is that it is less susceptible to noise from other electrical equipment in the IBAL. The control valves have both a control signal and a position feedback signal. In both cases these signals are typically voltage because most of the valves use voltage by default. There are a couple of instances where the control signal for the control valve is generated by a DAQ card that only outputs current because of the limited availability of analog output (AO) channels that generate voltage. In those cases, the current is converted to a voltage at the valve via a 500 Ohm resistor ($4\text{ mA} = 2\text{ V}$, $20\text{ mA} = 10\text{ V}$).

The watt transducers that are used to measure power produce 4 – 20 mA signals that are converted to voltage at the DAQ. The temperature measurements all use 4-wire RTDs and are read by a DAQ card that is designed to read RTDs. The 4-wire design is used in order to minimize the effect of noise on the measurement. The flow meters output current and are read by a current reading DAQ card, so no conversion to voltage is necessary. Finally, there are a multitude of control signals (other than valve control) throughout the laboratory. For example, each pump is operated by a VFD. The VFD is operated remotely by sending 1) a digital signal to a relay that turns the VFD on or off and 2) a voltage signal that sets the frequency between 15 and 60 Hz and thereby sets the pump speed. The control signals are a mixture of voltage, current, and digital.

4.2. Data Acquisition System Hardware

The DAQ system uses the PXI and PXIe (PXI Express) standards for data acquisition and all of the hardware is from National Instruments. The system contains 2 PXI chassis: PXIe-1075 (C1) and PXIe-1082 (C2). C1 is the controlling chassis; it contains an embedded computer, PXIe-8135, which fills two of the 18 slots in C1. The 8135 is a 2.3 GHz quad-core Intel Core i7-3610QE computer that can be booted into the Windows 10 operating system (OS) or LabVIEW Real-Time OS (RTOS). Another slot in C1 contains a card that connects C1 to C2 in a master-slave type arrangement. Fourteen of the remaining slots in C1 contain DAQ cards and there is one open slot for future expansion. C2 is smaller than C1, containing only 8 slots. One slot contains the card that communicates with C1, and the remaining slots contain DAQ cards.

Table 8 is a list of the DAQ cards that are currently installed in C1 and C2. In this table AI is analog input, AO is analog output, DI is digital input, DO is digital output, and DIO is digital input or output (the functionality of the channel is software selectable). The 4300 is only capable of measuring voltage (± 10 V), while the 4357 is specifically designed to measure RTDs and the 6238 is designed to measure and output current (0 – 20 mA). The 6363 measures and outputs voltage (± 10 V), while half of the channels on the 6704 output voltage (± 10 V) and the other half output current (0 – 20 mA). The 6345 measures and outputs voltage (± 10 V). The digital channels output voltage in the range of 3 to 5.5 V when the channel is on and 0 when it is off.

For the cards that measure voltage, the sensors can be wired as either differential or single-ended. The differential configuration requires two wires for every sensor, whereas the single-ended configuration only requires one wire and the ground is shared. The advantage of the single-ended configuration is that twice as many channels are available; in this configuration, the 4300 would have 16 AI channels rather than 8. However, this configuration is more susceptible to noise, so all of the sensors in the IBAL are wired in the differential configuration.

Table 8. Specifications of DAQ cards.

P/N	Quantity	Chassis	AI channels	AO channels	DI channels	DO channels	DIO channels
PXIe-4300	7	C1	8				
PXIe-4357	5	C1	20				
PXI-6238	2	C1	8	2	6	4	
PXIe-6363	4	C2	16	4			48
PXIe-6704	2	C2		32			8
PXIe-6345	1	C2	40	2			24

The system to connect the sensors and equipment to the DAQ was designed and constructed at NIST. The signals are all carried on 24 AWG, stranded and shielded Cat5e cable with four twisted pairs of wire for a total of eight wires per cable. These cables also contain a shield wire that runs along the shield for the entire length of the cable. For the pressure, flow, and control valve signals, the measurement device requires power, so two of the eight wires are used to send power to the sensor. Two of the remaining wires are used to acquire the measurement. For the control valves, which have both measurement and control signals,

where possible a single cable is used and therefore two more wires are used for the control signal, resulting in the use of six of the eight wires. However, in some cases the control and measurement signals cannot be acquired by the same card (note that the number of AO and AI channels are not equal for any of the cards), so only four of the eight wires are used and a separate cable is required for the other two wires.

The DAQ hardware is all contained inside of two data racks, pictured in Figure 22 and Figure 23. The color of the Cat5e cables designates the type of signal carried by that cable. Blue is pressure, purple is power, red is temperature, black is flow, and orange is control. The other colors visible in the pictures are for signals in the air system and will not be addressed here. At the bottom of the data racks as seen from the front are four DC power supplies for the equipment that require DC power. In the left image of Figure 22, at the bottom of the data rack on the left is a gray box. This box contains an AC transformer that provides 24 VAC for the equipment that require AC power. The Cat5e cables run from the equipment to the data rack along cable trays as shown in Figure 23. At the data rack, the cables terminate in an RJ45 connector, which then plugs into a RJ45 coupler that is mounted in a patch panel on the front of the data rack.

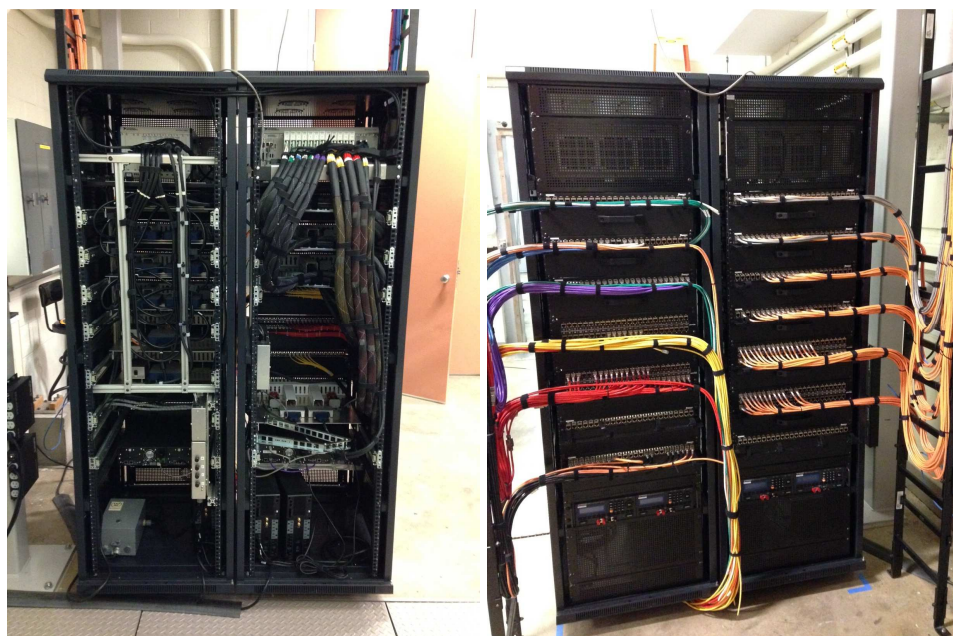


Figure 22. Left: Back of the two data racks. C1 and C2 are on the top shelf of the right and left data racks, respectively. Right: Front of the two data racks. The cables terminate in a shielded RJ45 connector that plugs into a shielded RJ45 coupler.

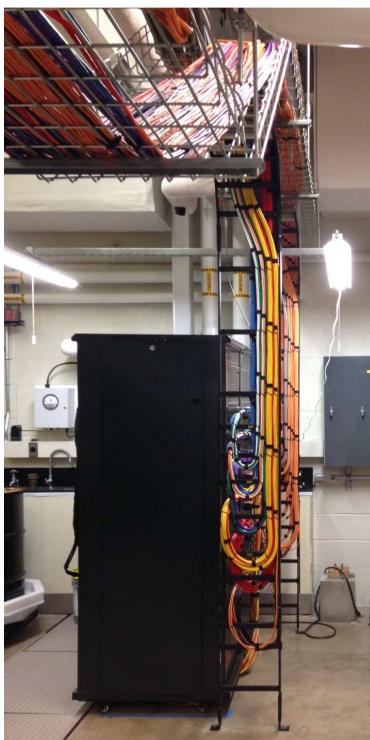


Figure 23. The Cat5e cables are placed in cable trays that run throughout the IBAL and then connect to the data racks.

Signals are connected to the DAQ cards via two different methods. Figure 24 shows the primary method used on C1. Cables are connected to the terminal blocks shown on the left and the terminal blocks are connected to the DAQ cards that are installed in C1 shown on the right. All of the connections in C2 use what are called breakout boxes. As can be seen in Figure 25, cables connect to the cards at C2. At the other end the cables connect to the breakout boxes visible in Figure 27.



Figure 24. In one style, cables are wired to terminal blocks (left), which are then connected to the DAQ cards that are installed in C1 (right).



Figure 25. In C2, all of the cables connect to breakout boxes that are separate from the chassis. The cables shown in this picture run from C2 to the breakout boxes.

Figure 26 is a close up of the front of the data rack. Underneath the top row of cables, a black drawer handle is visible. In the image at right, the cables have been removed from the front of the patch panel and the drawer has been pulled out to reveal a shelf. The breakout boxes are screwed onto this shelf. Inside the data rack, cables connect the breakout box to the inside of the RJ45 couplers. Figure 27 is a picture of the same shelf with the cables on the shelf exposed. At the middle left of the left figure is a set of screw terminal blocks that are connected to AC and DC power. This is the point at which power is connected to the wires that will deliver power to the sensors that need it. The picture at the right shows the wiring inside of the breakout box. At the middle right of this figure, the shield wires for the Cat5e cables are connected to a common ground. The shield wire is not connected to the sensor at the other end in order to avoid establishing a ground loop.

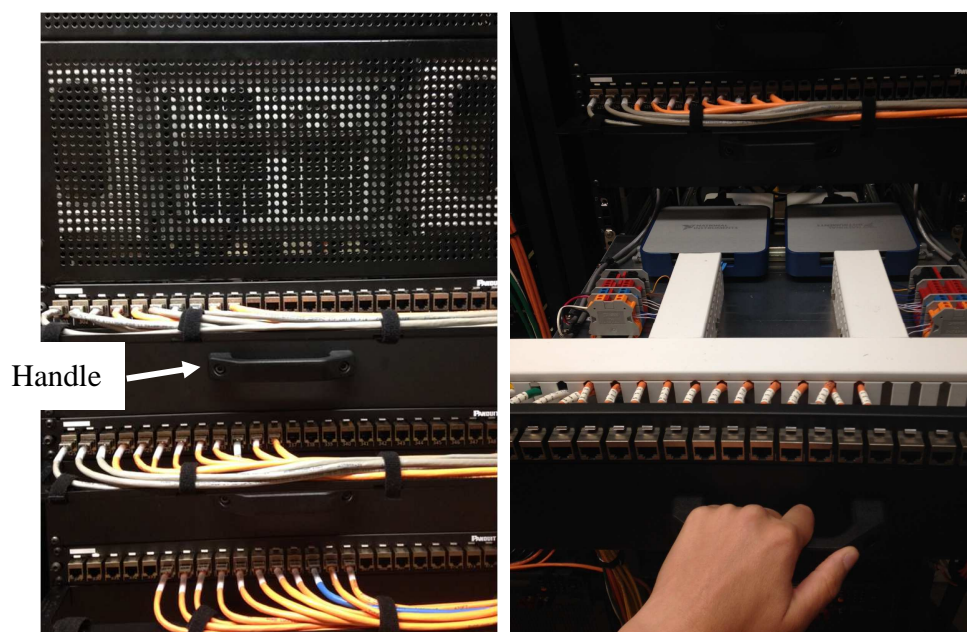


Figure 26. Left: Close up of the front of the data rack. Right: Two breakout boxes are mounted to a shelf.

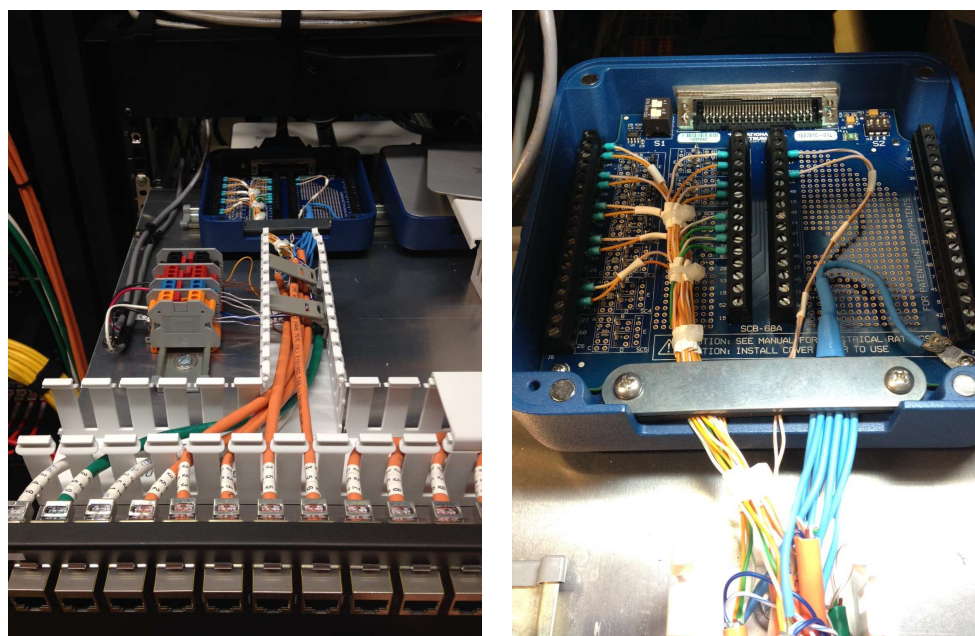


Figure 27. Left: Cat5e cables connected to the breakout box. Right: Close up of the wiring in the breakout box.

4.3. Data Collection

All of the measured and generated signals, as well as other experimental information, need to be recorded for eventual storage in a database. The DAQ system software writes five distinct files: metadata, experiment tags, process data, raw data, and scaled data. The metadata and experiment tags are written once for each test because they contain data that do not change during a single test. Process, raw, and scaled data files are written at a pre-determined interval during a test (10 minutes, for example) so that multiple files are generated. The experiment tags are entered into a graphical user interface (GUI) prior to running a test. At the start of a test, a file containing a list of all of the relevant signals that will be measured or generated during the test is loaded into the software; this file contains all of the metadata.

The following sections will describe the information presented in each file and briefly introduce the database structure.

4.3.1. Metadata

Table 9 is a list of the metadata collected for every signal measured or generated. Not only are these values written to a file and used in the database as an identifier of the signal, but some of them are also used throughout the control software. The “measurement_id” is used as a convenient method to identify the signal and its location within the IBAL. Here are some examples to illustrate the concept:

- ch1_c_out_rtd = RTD measurement at the outlet of the condenser of Chiller 1
- ch1_f_c = Flow in the condenser of Chiller 1
- pump1_on = Digital output that turns Pump 1 on
- pump3_p_down = Pressure measurement downstream of Pump 3

Table 9. List of the metadata collected for each signal.

measurement_id	String identifier for the signal: Example - ch1_c_out_rtd
card	Number of the DAQ card used to make the measurement or generate the signal: Example - 4300
physical_channel	Channel used by the LabVIEW program to read/write to the DAQ channel: Example - PXI1Slot2/ai0
channel_number	Channel identifier for the signal: Example - 364
measurement_type	Type of signal: Example - temperature, flow
signal_type	Type of signal in terms of NI hardware: Example - RTD, AI, AO
subsystem	Identify what subsystem of the IBAL the signal belongs to: Example - chiller 1, condensing loop
instrument_m_n	Manufacturer part number if relevant
instrument_s_n	Device serial number if relevant
calibration_date	Calibration date for the device if relevant
accuracy_scaled	Accuracy of the device if relevant
unit_raw	Units of the raw signal: Example - V, A
unit_scaled	Units of the scaled signal: Example - gpm, W
range_lo_raw	Lowest allowable value of the signal
range_hi_raw	Highest allowable value of the signal
startup	Startup value of the signal if relevant (e.g., to ensure a damper is open, set the startup position to 1)
shutdown	Shutdown value of the signal if relevant (e.g., to ensure a damper is closed, set the shutdown position to 0)
scaling_coeff_a0	Used to convert from raw to scaled – this is the intercept
scaling_coeff_a1	Used to convert from raw to scaled – this is multiplied by the raw value
scaling_coeff_a2	Used to convert from raw to scaled – this is multiplied by the raw value squared

4.3.2. Experiment Tags

The experiment tags, which are listed in Table 10, have two purposes. First, they can be used to identify information about the test itself. For example, the title tag could be “Summer Day, Control Algorithm 1.” Later, when looking for a specific data set, the title could be queried for this phrase. Many tests will be run more than once, so more than one test may have the title “Summer Day, Control Algorithm 1.” This leads to the second use of the experiment tags, differentiation of tests. The tags such as day, month, and year, can be used to distinguish one test from another. If multiple tests with the same title are run on the same day, then the run and start_time tags can be used to filter the data to find the test data that are needed. These tags allow the data and metadata to be linked to a specific test.

Table 10. List of experiment tags written to file.

title	Title of the experiment
run	Run number in the event that multiple tests are conducted on the same day
comments	Any comments that the operator would like to have stored
year	Year of the test
month	Month of the test
day	Day of the test
start_time	Time at which the test began

4.3.3. Time Varying Data

The process data, raw data, and scaled data files all store time varying data. Process data is information about the test operation that is not a signal. Values such as set point temperatures and control loop parameters (see Section 2) fall under this category. Raw data is the measured or generated signal value and scaled data is calculated by multiplying the raw data by the scaling coefficients listed in Table 9. The raw and scaled data can be the same, in which case $scaling_coeff_a0 = scaling_coeff_a2 = 0$ and $scaling_coeff_a1 = 1$. These data are saved at every time step, written to file at the specified writing interval (10 minutes is typical), and deleted from the program after being written to file.

4.3.4. Database

The back-end of the database uses InfluxDB and the front end of the database uses Grafana. InfluxDB [9] is an open source database designed for use with time-series data. Grafana [10] is an open source program that can be used to query and display data from a database. In the future a version of the database will be available for public access.

4.4. Architecture of the LabVIEW Control Program

LabVIEW is a graphical programming environment that is well suited to data acquisition and control applications. LabVIEW Real-Time (RT) was selected for the operation of the IBAL because it guarantees real-time operation. An OS such as Windows is not designed to guarantee real-time operation in which a section of code will finish within a required time. Real-time is also referred to as on time every time or deterministic operation. Real-time control is a key concern in control systems where decisions must be made at a specified time [11]. The control software is written in the LabVIEW RT software on a standard desktop computer called the host and deployed onto the embedded computer in chassis C1, which is booted into the LabVIEW RTOS and is called the target.

The software is written by creating a new project that contains two levels. The top level contains LabVIEW codes that run on the host computer, which uses a Windows OS, and the lower level contains codes that run on the target computer, which uses the RTOS. The host computer has a graphical user interface (GUI). A user can enter commands into the GUI that are then transferred to the target as well as view data that are transferred from the target to the host. The target computer runs the code that reads and outputs signals, makes control decisions, writes data to file, etc. Figure 28 shows how the host and target are linked and what tasks take place on each computer. Note that the target contains non-deterministic and deterministic while loops. Processes such as data transfer and storage do not have to occur in real-time, so they are non-deterministic. Reading sensors and making control decisions are real-time processes and are therefore deterministic. A non-deterministic task can be interrupted when a deterministic task needs to execute, but not vice versa.

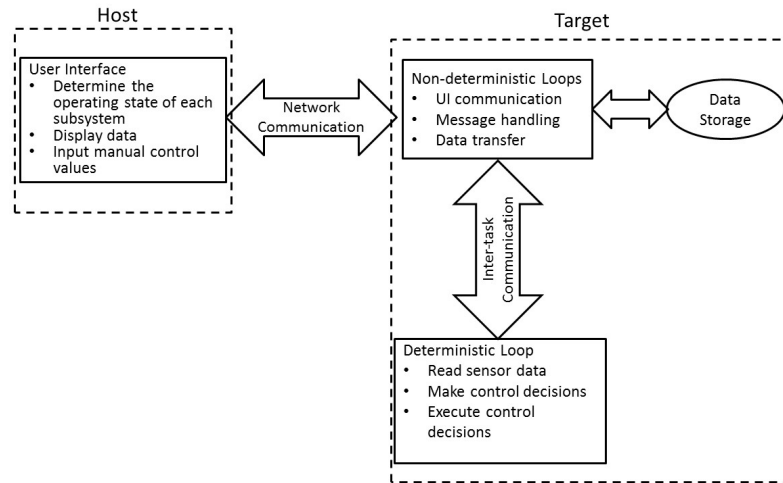


Figure 28. Architecture of the LabVIEW RT program.

5. Measurement Uncertainty Calculations

This section will provide an overview of the measurement uncertainty calculations performed to date for the sensors in the hydronic system of the IBAL. The same methodology will be applied to any new instrumentation added in the future.

5.1. Overview

According to the *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results* [12], uncertainty can be categorized as one of two types, Type A or Type B. Type A uncertainties can be determined from a statistical evaluation of data, such as calculating standard deviation from a series of independent measurements. Uncertainty calculated from calibration data is an example of Type A. Type B uncertainties are based on scientific judgement and prior data, such as manufacturer specifications. In the following sections, the manufacturer specifications are referenced and included in the overall uncertainty measurement as necessary. When there is more than one source of uncertainty, they are summed in quadrature as shown in Eq. (11).

$$o_{dal} = \sqrt{d_1^2 + \frac{2}{2} + \dots + \frac{2}{n}} \quad (11)$$

Table 11 contains the measurement uncertainties of the NI hardware in the DAQ. In the following sections, where these values are sufficiently large relative to the other Type A and B uncertainties, they are included in the total uncertainty calculation.

Table 11. Uncertainties of temperature, voltage, and current measurements of NI hardware.

NI Card	AI uncertainty	Units	AO uncertainty	Units
4357	0.126	°C		
4300	0.002460	V		
6238	0.0000188	A	0.0000523	A
6363	0.00166	V	0.00189	V
6704			0.00107	V
			0.000000448	A
6345	0.001520	V	0.00189	V

This section will present the measurement uncertainty calculations and summaries for the sensors in the hydronic system of the IBAL. Full sets of calibration data are in the Appendix.

5.2. Uncertainty of Calibration Curve Fit

This section contains the equations used to calculate the uncertainty of the curve fit derived from calibration data that relates the measured current or voltage signal to the engineering units of the sensor. In the case of pressure transducers, voltage is converted to psi and in the case of flow meters current is converted to gpm. For both sensor types the relationship between the measured signal and engineering units is linear. During calibration, pressure or flow is the independent x variable, while the voltage or current is the dependent y variable. Eq. (12) shows the relationship between the dependent and independent variables, where the slope m and intercept b are found from the calibration data as shown in Eqs. (13) and (14) [13].

$$y = mx + b \quad (12)$$

$$m = \frac{S_{xy}}{S_{xx}} \quad (13)$$

$$b = \bar{y} - m\bar{x} \quad (14)$$

$$\bar{x} = \frac{\sum_{i=1}^n x_i}{n} \quad (15)$$

$$S_{xy} = \sum x_i y_i - \frac{\sum x_i \sum y_i}{n} = \sum (x_i - \bar{x})(y_i - \bar{y}) \quad (16)$$

$$S_{xx} = \sum x_i^2 - \frac{(\sum x_i)^2}{n} = \sum (x_i - \bar{x})^2 \quad (17)$$

The standard error of the calibration is determined from the fit by first calculating the residual y_r between the fit \hat{y} and the measured y as shown in Eqs. (18) and (19).

$$\hat{y} = mx + b \quad (18)$$

$$y = y - \hat{y} \quad (19)$$

The standard error, se , is calculated by dividing the sum of the squares of the residuals, $SSResid$, by the number of degrees of freedom, ν , and taking the square root. The expanded standard error, se_e , which is the 95% confidence interval, is calculated by multiplying the se by the t statistic that corresponds to the degrees of freedom. See Eqs. (20) through (23). This final error is the calibration uncertainty.

$$Resid = \sum_{i=1}^n y_i^2 \quad (20)$$

$$\nu = n - 2 \quad (21)$$

$$se = \sqrt{\frac{Resid}{\nu}} \quad (22)$$

$$se_e = t \cdot se \quad (23)$$

In order to apply the calibration curve fit to experimental data, in which voltage or current is now the independent variable, the relationship defined by Eq. (12) has to be rewritten as shown in Eq. (24) to solve for the engineering units.

$$x = \frac{y - b}{m} \quad (24)$$

The slope and intercept that are part of the metadata for each channel, a_1 and a_0 , respectively, are derived from Eq. (24) and shown in Eq. (25). In the LabVIEW program, the measured voltage, for example, is converted to engineering units of psi for use in calculations and monitoring.

$$a_0 = -\frac{b}{m}, \quad a_1 = \frac{1}{m} \quad (25)$$

The uncertainty also has to be scaled, but prior to scaling any additional measurement uncertainties, such as the DAQ measurement uncertainty from Table 11 and the uncertainty in the calibration standard, have to be included as shown in Eq. (26). The final scaled uncertainty is shown in Eq. (27).

$$u_s = \sqrt{se^2 + \frac{2}{o} h} \quad (26)$$

$$cal = \frac{u_s}{m} \quad (27)$$

5.2.1. Example of Calibration Uncertainty Calculation

Ten hydronic pressure transducers were calibrated simultaneously using a pneumatic deadweight tester. Calibrated mass plates are set on a piston so as to establish a known pressure (force/area). Nitrogen gas, which is connected to both the deadweight tester and the sensor under test, is added to/removed from a bladder to perfectly balance the weight, thereby providing a known pressure to the sensor under test. Figure 29 is a picture of a technician operating the deadweight tester. Note that a new, more automated calibrator has been acquired and will be used in future calibrations.

Twenty-four pressures were randomly selected from a calibration range of 69 kPa to 1034 kPa (10 psi to 150 psi); the lower value was based on the limitations of the dead weight tester. Calibration was also performed at a pressure of 0 kPa by opening the pressure transducer to atmosphere for a total of 25 pressure measurements. The order in which the 25 pressures were measured was randomized.



Figure 29. A technician adjusts the pressure in the deadweight tester to just balance the weight on the piston. There is a stack of calibrated plates in the background.

The pressure transducer returns a 4 to 20 mA signal, which is converted to a voltage at the DAQ by measuring the voltage drop produced by the current signal as it passes through a 249 Ohm resistor. At each of the pressures, the DAQ acquired 12 measurements of voltage. The first and last data points were dropped and the mean of the remaining 10 voltages was used in the calculations. Table 12 shows the calibration data for Channel 19. The first column shows the 25 values of pressure that were selected and the order in which those pressures were applied and the last column shows the mean voltage for each pressure. Figure 30 shows a plot of the data.

Table 12. Calibration data for Channel 19 hydronic pressure transducer.

Pressure (kPa)	Pressure (psi)	Mean of 10 measurements (V)
x_i	x_i	y_i
627.4	91	3.40
537.8	78	3.07
406.8	59	2.57
579.2	84	3.23
137.9	20	1.53
172.4	25	1.66
441.3	64	2.71
655	95	3.51
0	0	0.99
262	38	2.00
682.6	99	3.64
317.2	46	2.22
358.5	52	2.39
703.3	102	3.72
289.6	42	2.12
344.7	50	2.34
82.74	12	1.31
103.4	15	1.39
510.2	74	2.96
489.5	71	2.89
365.4	53	2.41
255.1	37	1.99
689.5	100	3.66
751.5	109	3.90
627.4	29	1.77

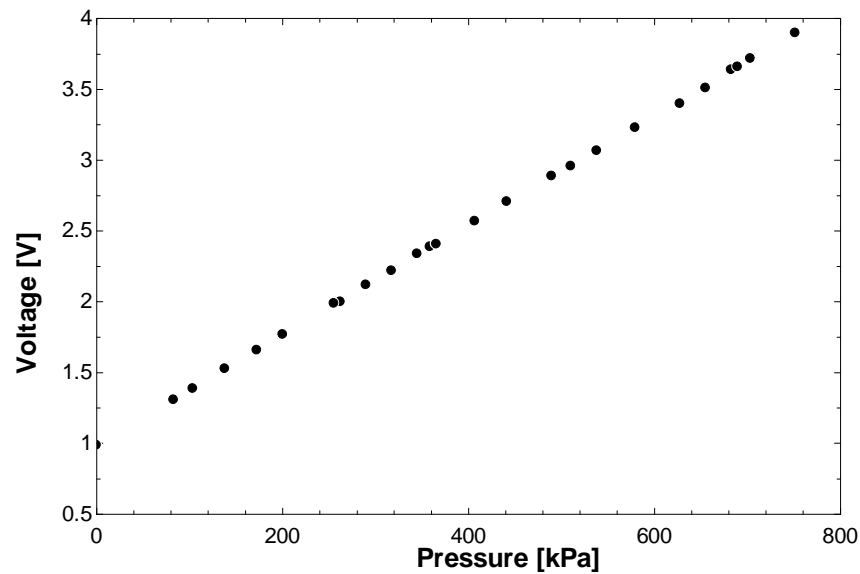


Figure 30. Channel 19 calibration data.

The results of applying the uncertainty calculations are given in Table 13. For this sensor, the calibration uncertainty, which includes the uncertainty of the voltage measurement, is 2.9 kPa (0.42 psi). The uncertainty of the calibration standard was neglected. Table 14 is a summary of the measurement uncertainty for all pressure transducers.

Table 13. Calibration uncertainty calculation results for Channel 19.

<i>n</i>	25		25	
\bar{x}	398.5	kPa	57.8	psi
\bar{y}	2.54	V	2.54	V
S_{xy}	4412	kPa *V	639.91	psi*V
S_{xx}	1.143e6	kPa ²	24046	psi ²
<i>m</i>	0.0039	V/ kPa	0.027	V/psi
<i>b</i>	0.997	V	0.997	V
<i>SSResid</i>	0.00067	V ²	0.00067	V ²
<i>ν</i>	23		23	
<i>se</i>	0.0054	V	0.0054	V
<i>t</i>	2.069		2.069	
<i>u_{us}</i>	0.011	V	0.011	V
<i>a₀</i>	-258.3	kPa	-37.46	psi
<i>a₁</i>	259.1	kPa /V	37.58	psi/V
<i>u_{cal}</i>	2.9	kPa	0.42	psi

Table 14. Calibration uncertainty results for pressure transducers. $n = 25$ measurements, $\nu = 23$ degrees of freedom.

Channel	S/N	\bar{x}	\bar{y}	S_{xy}	S_{xx}	m	b	$SSResid$	se	t	u_{us}	a_0	a_1	u_{cal}
		kPa	V	kPa*V	kPa ²	V/kPa	V	V ²	V		V	kPa	kPa/V	kPa
19	2058089.29	398.5	2.54	4412	1.143E+06	0.0039	0.997	0.00067	0.0054	2.07	0.011	-258.30	259.11	2.92
20	2058089.33	398.5	2.53	4402	1.143E+06	0.0039	0.991	0.0027	0.011	2.07	0.023	-258.38	259.73	6.01
27	2058089.32	398.5	2.54	4405	1.143E+06	0.0039	1.008	0.0012	0.0073	2.07	0.015	-258.46	259.45	3.94
28	2058089.31	398.5	2.54	4411	1.143E+06	0.0039	1.00	0.0014	0.0077	2.07	0.016	-258.53	259.17	4.20
29	2058089.25	398.5	2.53	4428	1.143E+06	0.0039	0.985	0.0010	0.0067	2.07	0.014	-258.61	258.21	3.67
30	071914D101	398.5	2.54	4402	1.143E+06	0.0039	1.004	0.00068	0.0054	2.07	0.011	-258.69	259.66	2.93
31	2058089.27	398.5	2.53	4399	1.143E+06	0.0039	0.997	0.00098	0.0065	2.07	0.014	-258.77	259.86	3.69
32	2058089.28	398.5	2.53	4404	1.143E+06	0.0039	0.995	0.00067	0.0054	2.07	0.011	-258.84	259.52	2.93
33	2058089.34	398.5	2.53	4430	1.143E+06	0.0039	0.986	0.0010	0.0066	2.07	0.014	-258.92	258.00	3.67
34	2058089.26	398.5	2.53	4405	1.143E+06	0.0039	0.998	0.00045	0.0044	2.07	0.0093	-259.00	259.45	2.42

5.3. Flow Meter Uncertainty

The IBAL uses two types of flow meters, 14 ultrasonic transducer (UT) meters and one magnetic flow meter. All of the meters were calibrated at an outside facility with water, although some of the meters are used to measure flow in 30 % propylene glycol. In addition, given the fact that temperature will differ from the calibration conditions during operation, an estimated uncertainty of 0.10 % is added to the calibration uncertainty in order to account for the difference in viscosity between the calibration and operation conditions [14].

The UT meters are transit time with transducers that are integral to the unit and a manufacturer specified accuracy of 1 % of reading for velocities greater than 0.3 m/s. The calibration summary for these meters is shown in Table 15. The error in the calibration standard (0.05 lpm) and the temperature error of 0.10 % make negligible contributions to the total error, which is dominated by the calibration curve fit error.

The magnetic flow meter is used to measure the flow rate in the condensing loop. This meter was calibrated with a gravimetric standard that has an uncertainty of 0.10 %. The meter was brought to within the manufacturer specified accuracy of 0.30 % of reading by adjusting the calibration factor (coefficient K_a) in the meter to 1.9464. Incorporating the three uncertainties (temperature uncertainty, calibration standard uncertainty, meter uncertainty), the total uncertainty of this meter is 0.33 % of reading as calculated in Eq. (28).

$$_{cal} = \sqrt{0.1^2 + 0.3^2 + 0.1^2} = 0.33 \% \quad (28)$$

Table 15. Calibration uncertainty results for ultrasonic flow meters. $n = 10$ measurements, $\nu = 8$ degrees of freedom.

Channel	S/N	\bar{x}	\bar{y}	S_{xy}	S_{xx}	m	b	SS_{Resid}	se	t	u_{us}	a_0	a_1	u_{cal}
		lpm	mA	lpm*mA	lpm ²	mA/lpm	mA	mA ²	mA		mA	lpm	lpm/A	lpm
193	100718	55.02	5.07	104.02	5351.82	0.019	4.00	0.0024	0.017	2.306	0.044	-205.75	51451.58	2.27
194	100716	51.38	5.02	85.13	4301.32	0.020	4.00	0.0020	0.016	2.306	0.041	-202.31	50529.33	2.05
195	100725	94.76	5.01	172.42	17256.92	0.010	4.06	0.0218	0.052	2.306	0.12	-406.37	100088.6	12.16
196	100724	71.99	4.73	73.40	7368.61	0.010	4.01	0.0004	0.007	2.306	0.025	-402.74	100393.3	2.48
197	100714	24.98	4.74	11.34	412.14	0.028	4.05	0.0003	0.006	2.306	0.023	-147.33	36359.25	0.85
198	100713	25.00	4.70	12.21	416.88	0.029	3.96	0.0008	0.010	2.306	0.029	-135.34	34139.44	0.99
199	100721	94.41	5.14	207.83	17198.41	0.012	4.00	0.0028	0.019	2.306	0.047	-331.30	82752.97	3.88
200	100722	104.10	5.12	238.32	22655.11	0.011	4.03	0.0046	0.024	2.306	0.059	-383.03	95061.28	5.62
207	100723	93.75	5.07	181.25	16645.96	0.011	4.05	0.0145	0.043	2.306	0.10	-371.59	91837.86	9.16
208	100720	54.98	5.08	103.02	5304.10	0.019	4.01	0.0024	0.017	2.306	0.044	-206.42	51487.37	2.28
210	100717	52.44	5.01	90.50	4634.38	0.020	3.99	0.0022	0.016	2.306	0.042	-204.15	51209.75	2.17
211	100715	47.55	4.96	67.58	3371.05	0.020	4.01	0.0027	0.018	2.306	0.046	-199.99	49880.85	2.30
212	100719	43.98	4.85	51.00	2581.06	0.020	3.98	0.0048	0.024	2.306	0.059	-201.21	50604.48	2.99
213	100727	71.89	4.83	85.59	7225.47	0.012	3.97	0.0016	0.014	2.306	0.038	-335.44	84415.65	3.21

5.4. RTD Uncertainty

Temperature measurements in the IBAL hydronic system are made with four-wire 100 Ohm platinum RTDs (resistance temperature detector). The RTDs have class A accuracy, which is defined in Eq. (29), where T is the measured temperature in °C.

$$RTD = (0.15 + 0.002 T) \text{ } ^\circ\text{C} \quad (29)$$

The RTDs are connected to National Instruments data acquisition card PXIe-4357. This card has a typical accuracy of 0.09 °C, however, the IBAL uses a faster data acquisition rate than normal, so an additional error of 0.036 °C must be added. These DAQ uncertainties, especially at low temperatures, are significant enough that they need to be considered in the evaluation of uncertainty as shown in Eq. (30). Figure 31 is a plot of the RTD uncertainty with and without the DAQ uncertainty as a function of temperature.

$$RTD, \text{ total} = \sqrt{\frac{2}{RTD} + (0.09 + 0.036)^2} \quad (30)$$

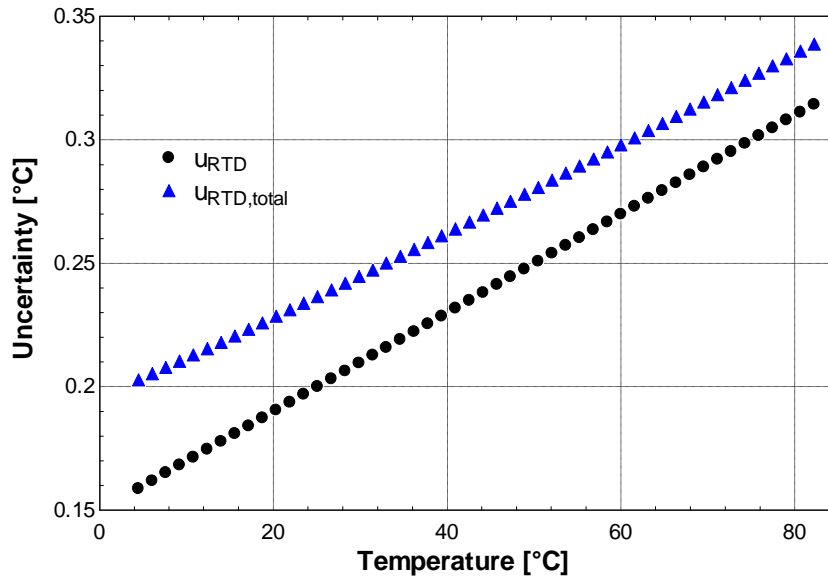


Figure 31. RTD uncertainty with and without the DAQ uncertainty.

The RTDs are inserted at the approximate mid-point of the pipe and, given the small diameter of the pipes in the IBAL (5 cm or less), temperature variation through the cross-section is neglected.

5.5. Power Measurement Uncertainty

The power consumption of pumps, fans, electric heaters, and chillers are measured by Ohio Semitronics watt transducers. The AGW-006E watt transducer can measure up to 600 VAC at 5 A and the AGW-002E watt transducer can measure up to 300 VAC at 5 A; both

transducers have a manufacturer specified accuracy of 0.2 %. Some of the equipment draw greater than 5 A and therefore a current transformer (CT) is used to step the current down to a level that can be measured by the watt transducer. The CT's have a manufacturer specified accuracy of 0.3 % and output a 4 – 20 mA signal that is converted to a voltage at the DAQ using a 249 Ohm resistor. Figure 32 is a picture of a watt transducer.



Figure 32. Watt transducer for the fan in AHU1.

Power is calculated from voltage by use of Eq. (31), where W is power in Watts, V is the measured signal in volts, a_0 [W] is the intercept and a_1 [W/V] is the slope. In Eq. (32), which is used to calculate the slope, W_{FS} is the full scale power in [W] and the denominator is the difference between 20 and 4 mA multiplied by 249 Ohm. The intercept is calculated as shown in Eq. (33).

$$W = a_0 + a_1 V \quad (31)$$

$$a_1 = \frac{W_{FS} - 0}{(0.020 - 0.004) [A] * 249[\Omega]} \quad (32)$$

$$a_0 = W_{FS} - a_1(0.020 [A]) \quad (33)$$

Table 16 contains information about the watt transducers for all of the power measurements that do not require a CT. All of these components are either fans or pumps. u_{meter} is the uncertainty based on the manufacturer specified accuracy and u_{total} is the uncertainty accounting for the uncertainty in NI card 4300's reading of the voltage. This uncertainty dominates the calculation.

Table 16. Power meter information for components that do not require a CT.

Component	P/N	S/N	W_{FS}	a_0	a_1	u_{meter}	u_{total}
OSU Fan	AGW-006E	14090243	4000	-1000	1004.016	0.2 %	0.00246 V
AHU1 Fan	AGW-006E	14090238	4000	-1000	1004.016	0.2 %	0.00246 V
AHU2 Fan	AGW-006E	14090246	4000	-1000	1004.016	0.2 %	0.00246 V
EF1	AGW-006E	14090235	4000	-1000	1004.016	0.2 %	0.00246 V
EF2	AGW-006E	14090236	4000	-1000	1004.016	0.2 %	0.00246 V
P1	AGW-006E	14090248	4000	-1000	1004.016	0.2 %	0.00246 V
P2	AGW-006E	14090245	4000	-1000	1004.016	0.2 %	0.00246 V
P3	AGW-006E	14090237	4000	-1000	1004.016	0.2 %	0.00246 V
P4	AGW-006E	14090244	4000	-1000	1004.016	0.2 %	0.00246 V
P5	AGW-006E	14090242	4000	-1000	1004.016	0.2 %	0.00246 V

W_{FS} is 4000 W and 1000 W for the AGW-006E and AGW-002E, respectively. When CT's are included W_{FS} is scaled from these nominal values based on the number of wraps through the transducer. Figure 33 is a picture of the CT's for Chiller 2. There is one CT for each phase and each CT has three turns (i.e., the wire carrying power is wound around the CT three times). Each CT has a current ratio of 100:5, so when a CT is used the nominal value of W_{FS} is multiplied by a factor of 20 (100/5). This leads to new W_{FS} of 80,000 W and 20,000 W for the AGW-006E and AGW-002E, respectively. The value of W_{FS} is then divided by the number of wraps and this is the final value of W_{FS} that is shown in Table 17.



Figure 33. Current transformers for Chiller 2. There is one CT for each phase and each CT has 3 wraps.

The error of the measurement takes into account the error of both the watt transducer and the current transformer by adding the individual errors as previously described. In the case that two CTs are used, the uncertainty of the CT is added in to the sum square error calculation twice. Even when the CT uncertainty is included, the uncertainty in the NI card reading dominates the calculation.

Table 17. Power meter information for components that do require a CT.

Component	P/N	S/N	Wraps	W_{ES}	a_0	a_1	u_{meter}	u_{total}
AHU 1 preheat	AGW-006E	15040368	6	13333.33333	-3333.33	3346.72	0.47 %	0.00247 V
AHU 2 preheat	AGW-006E	15040369	6	13333.33333	-3333.33	3346.72	0.47 %	0.00247 V
Chiller 1	AGW-006E	15040371	4	20000	-5000	5020.08	0.47 %	0.00247 V
Chiller 2	AGW-006E	15040370	3	26666.66667	-6666.67	6693.44	0.47 %	0.00247 V
VAV 1 reheat	AGW-002E	15040501	13	1538.461538	-384.615	386.16	0.36 %	0.00247 V
VAV 2 reheat	AGW-002E	15040502	13	1538.461538	-384.615	386.16	0.36 %	0.00247 V
VAV 3 reheat	AGW-002E	15040500	13	1538.461538	-384.615	386.16	0.36 %	0.00247 V
VAV 4 reheat	AGW-002E	15040499	13	1538.461538	-384.615	386.16	0.36 %	0.00247 V
Zone 1 heat	AGW-006E	15040366	15	5333.333333	-1333.33	1338.688	0.47 %	0.00247 V
Zone 2 heat	AGW-006E	15040372	15	5333.333333	-1333.33	1338.688	0.47 %	0.00247 V
Zone 3 heat	AGW-006E	15040373	15	5333.333333	-1333.33	1338.688	0.47 %	0.00247 V
Zone 4 heat	AGW-006E	15040367	15	5333.333333	-1333.33	1338.688	0.47 %	0.00247 V

5.6. Uncertainties of Derived Quantities

The heat transfer at various points in the system will be calculated in order to 1) assess how well energy conservation is obeyed, thereby revealing hidden sources of uncertainty in the system, 2) understand how the system is operating (i.e., how much load is being met by different equipment), and 3) make control decisions such as when to bring a second chiller online. Eq. (34) shows the calculation of heat transfer, \dot{Q} , [kW], where ρ is the fluid density (kg/m^3), \dot{V} is the volumetric flow rate (m^3/s), c_p [kJ/kg-K] is the specific heat, and ΔT [K] is the temperature change across the component.

$$Q = \rho \dot{V} c_p \Delta T \quad (34)$$

The uncertainty is determined from the Law of Propagation of Uncertainty [12], which is based on a Taylor series approximation of Eq. (34). The partial derivatives of the heat transfer rate with respect to each variable are provided in Eqs. (35) - (38). The total uncertainty is given in Eq. (39).

$$\frac{\partial Q}{\partial \dot{V}} = \rho c_p \Delta T \quad (35)$$

$$\frac{\partial Q}{\partial \Delta T} = \rho \dot{V} c_p \quad (36)$$

$$\frac{\partial Q}{\partial \rho} = \dot{V} c_p \Delta T \quad (37)$$

$$\frac{\partial Q}{\partial c_p} = \rho \dot{V} \Delta T \quad (38)$$

$$q = \sqrt{\left(\frac{\partial Q}{\partial \dot{V}}\right)^2 \dot{V}^2 + \left(\frac{\partial Q}{\partial \Delta T}\right)^2 \Delta T^2 + \left(\frac{\partial Q}{\partial \rho}\right)^2 \rho^2 + \left(\frac{\partial Q}{\partial c_p}\right)^2 c_p^2} \quad (39)$$

The uncertainty associated with the temperature difference, Eq. (40), is 0.18°C as calculated in Eq. (41).

$$\Delta T = T_1 - T_2 \quad (40)$$

$$\Delta T = \sqrt{\left(\frac{\partial \Delta T}{\partial T_1}\right)^2 T_1^2 + \left(\frac{\partial \Delta T}{\partial T_2}\right)^2 T_2^2} = \sqrt{(1)^2 T_1^2 + (-1)^2 T_2^2} = \sqrt{2} \, RTD = 0.18 \, ^\circ\text{C} \quad (41)$$

A similar analysis was completed for the density, Eq. (9), and specific heat, Eq. (10). That analysis showed that the uncertainty of the density and specific heat are dominated by the propylene glycol concentration, with the temperature contributing a very small amount to the specific heat and having almost no impact whatsoever on density. Figure 34 shows the relative uncertainty of specific heat, $u_{cp,rel}$, and density, $u_{\rho,rel}$, as a function of propylene glycol concentration. It is unlikely that the concentration will stray far from 30 %, but in a worst case scenario values of $u_{cp,rel} = 1.8 \, \%$ and $u_{\rho,rel} = 0.5 \, \%$ will be applied to the calculation of the uncertainty of \dot{Q} .

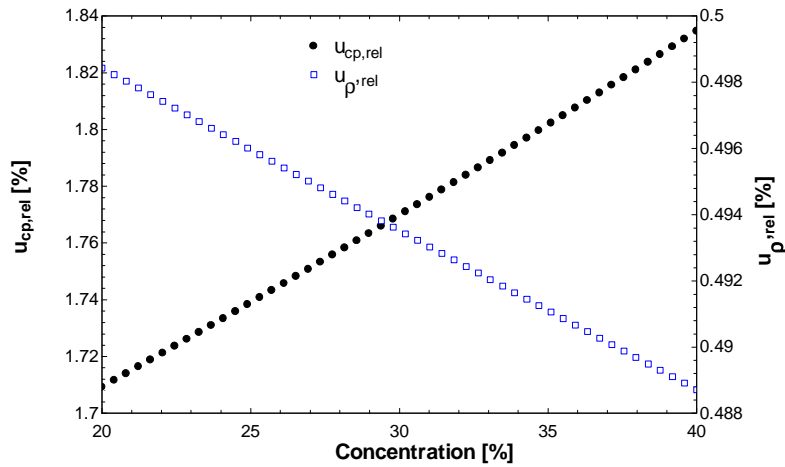


Figure 34. Relative uncertainty of specific heat ($u_{cp,rel}$) and density ($u_{\rho,rel}$) with respect to propylene glycol concentration.

The uncertainty in volumetric flow rate was discussed in Section 5.3 and varies with each meter. Based on some preliminary data, the uncertainty of heat transfer is on the order of 7 %. When the temperature change across the equipment is large, the uncertainty is dominated by the uncertainty of the flow meter reading, so improving the accuracy of the flow measurement would reduce the uncertainty of the heat transfer calculation. However, at low temperature differences, the temperature uncertainty dominates and although the flow meter uncertainty is not insignificant, improving that measurement will not have the same

impact. As more data are collected in the future the need to upgrade some of the sensors in order to reduce uncertainty will be evaluated.

6. Future Work

One of the major goals of the near term is to operate and more fully characterize the hydronic system by using HX1 to apply a variable building load. This will allow for the evaluation of the uncertainty and repeatability of system operation as well as the determination of what, if any, sensors need to be added or upgraded. The PI parameters and the sufficiency of the PI controllers to yield stable operation will be determined. System operating characteristics such as the time to fully charge/discharge the thermal storage, the amount of charge that can be achieved in an eight-hour charge period, will be established. In addition to further understanding the hydronic system, the air system will be commissioned, including integrating it into the control system.

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8. Appendix: Additional Calibration Data

8.1. Hydronic Pressure Transducer Calibration

The Kobold Sen 87 series pressure transducer uses an internal diaphragm and piezo-resistive ceramic sensing element to measure pressure. The manufacturer specifies an accuracy of 0.5% of full scale, which is 0.5 % of 1034 kPa (150 psi) for these transducers, or 5.17 kPa (0.75 psi). The transducer outputs a 4 to 20 mA signal that is converted to a voltage by sending it across a 249 Ohm resistor at the DAQ. Channels 19-20, 27-29, and 31-34 use this transducer. Channel 30 uses the PX319 transducer from Omega. This transducer also outputs a 4 to 20 mA signal and uses an internal diaphragm, but the sensing element is a silicon strain gage. The manufacturer specifies an accuracy of 0.25 % full scale (2.59 kPa or 0.375 psi). Table 18 contains the raw data for the calibration of ten pressure transducer calibrations and Table 19 contains all of the calibration uncertainty calculations.

Table 18. Pressure transducer raw calibration data.

Pressure (kPa)	Pressure (psi)	Channel	Data (V)											
627.4	91	19	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.40
627.4	91	20	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41
627.4	91	27	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43	3.43
627.4	91	28	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42
627.4	91	29	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42
627.4	91	30	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42
627.4	91	31	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42
627.4	91	32	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.39	3.39
627.4	91	33	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42
627.4	91	34	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42
537.8	78	19	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07
537.8	78	20	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07
537.8	78	27	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07
537.8	78	28	3.08	3.08	3.08	3.08	3.08	3.08	3.08	3.08	3.08	3.08	3.08	3.08
537.8	78	29	3.08	3.08	3.08	3.08	3.08	3.07	3.07	3.07	3.08	3.07	3.07	3.07
537.8	78	30	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07
537.8	78	31	3.06	3.06	3.06	3.06	3.06	3.06	3.06	3.06	3.06	3.06	3.06	3.06
537.8	78	32	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07
537.8	78	33	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07
537.8	78	34	3.07	3.07	3.07	3.07	3.07	3.06	3.06	3.07	3.07	3.07	3.07	3.06
406.8	59	19	2.57	2.57	2.57	2.57	2.57	2.57	2.57	2.57	2.57	2.57	2.57	2.57
406.8	59	20	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53
406.8	59	27	2.58	2.58	2.58	2.58	2.58	2.58	2.58	2.58	2.58	2.58	2.58	2.58
406.8	59	28	2.57	2.57	2.58	2.58	2.58	2.58	2.57	2.57	2.57	2.58	2.58	2.57
406.8	59	29	2.56	2.56	2.56	2.56	2.56	2.56	2.56	2.56	2.56	2.56	2.56	2.56

Pressure (kPa)	Pressure (psi)	Channel	Data (V)											
406.8	59	30	2.58	2.58	2.58	2.58	2.58	2.58	2.57	2.57	2.57	2.57	2.57	2.57
406.8	59	31	2.57	2.57	2.57	2.57	2.57	2.57	2.57	2.57	2.57	2.57	2.57	2.57
406.8	59	32	2.56	2.56	2.56	2.56	2.56	2.56	2.56	2.56	2.57	2.57	2.57	2.56
406.8	59	33	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
406.8	59	34	2.56	2.56	2.57	2.57	2.56	2.57	2.57	2.57	2.57	2.57	2.57	2.57
579.2	84	19	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23
579.2	84	20	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21
579.2	84	27	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25
579.2	84	28	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24
579.2	84	29	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23
579.2	84	30	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.21	3.21	3.22	3.22
579.2	84	31	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23
579.2	84	32	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23
579.2	84	33	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22	3.22
579.2	84	34	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24	3.24
137.9	20	19	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53
137.9	20	20	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51
137.9	20	27	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54
137.9	20	28	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54
137.9	20	29	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52
137.9	20	30	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52
137.9	20	31	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53
137.9	20	32	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53
137.9	20	33	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.52	1.53	1.53	1.53
137.9	20	34	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53
172.4	25	19	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
172.4	25	20	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65
172.4	25	27	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
172.4	25	28	1.68	1.67	1.67	1.67	1.67	1.68	1.68	1.68	1.68	1.68	1.67	1.68
172.4	25	29	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65
172.4	25	30	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
172.4	25	31	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
172.4	25	32	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
172.4	25	33	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
172.4	25	34	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66
441.3	64	19	2.70	2.70	2.70	2.71	2.71	2.71	2.71	2.70	2.71	2.71	2.71	2.71
441.3	64	20	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70
441.3	64	27	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71
441.3	64	28	2.69	2.68	2.68	2.68	2.68	2.68	2.68	2.69	2.69	2.69	2.69	2.69
441.3	64	29	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70

Pressure (kPa)	Pressure (psi)	Channel	Data (V)											
441.3	64	30	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71
441.3	64	31	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70
441.3	64	32	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70
441.3	64	33	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70
441.3	64	34	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70
655	95	19	3.50	3.50	3.51	3.51	3.51	3.51	3.52	3.52	3.52	3.52	3.52	3.52
655	95	20	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
655	95	27	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.54	3.54	3.54	3.54	3.54
655	95	28	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53
655	95	29	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
655	95	30	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.52	3.52	3.53
655	95	31	3.53	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
655	95	32	3.51	3.50	3.50	3.51	3.51	3.50	3.50	3.50	3.50	3.50	3.50	3.50
655	95	33	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53
655	95	34	3.52	3.53	3.53	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52	3.52
0	0	19	1.00	0.99	0.99	0.99	0.99	0.99	1.00	0.99	1.00	1.00	0.99	1.00
0	0	20	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
0	0	27	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
0	0	28	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
0	0	29	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
0	0	30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0	0	31	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0	0	32	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	0.99	0.99	0.99	1.00
0	0	33	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
0	0	34	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
262	38	19	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
262	38	20	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
262	38	27	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02
262	38	28	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01
262	38	29	1.98	1.98	1.99	1.99	1.99	1.99	1.99	2.00	2.00	2.00	2.00	2.00
262	38	30	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02
262	38	31	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
262	38	32	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
262	38	33	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01
262	38	34	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01
682.6	99	19	3.64	3.64	3.64	3.64	3.64	3.63	3.64	3.64	3.64	3.64	3.64	3.64
682.6	99	20	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63
682.6	99	27	3.64	3.64	3.64	3.64	3.63	3.63	3.64	3.64	3.64	3.63	3.63	3.63
682.6	99	28	3.64	3.64	3.64	3.63	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64
682.6	99	29	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63

Pressure (kPa)	Pressure (psi)	Channel	Data (V)											
682.6	99	30	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63
682.6	99	31	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.61	3.61	3.62
682.6	99	32	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63
682.6	99	33	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63
682.6	99	34	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63
317.2	46	19	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22
317.2	46	20	2.22	2.21	2.21	2.21	2.22	2.22	2.22	2.22	2.22	2.21	2.22	2.22
317.2	46	27	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24
317.2	46	28	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22
317.2	46	29	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22
317.2	46	30	2.23	2.23	2.23	2.23	2.23	2.23	2.23	2.23	2.23	2.23	2.23	2.23
317.2	46	31	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22
317.2	46	32	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.21	2.21
317.2	46	33	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22	2.22
317.2	46	34	2.23	2.23	2.23	2.23	2.23	2.23	2.23	2.23	2.23	2.23	2.23	2.23
358.5	52	19	2.39	2.39	2.39	2.39	2.39	2.39	2.38	2.39	2.39	2.39	2.39	2.39
358.5	52	20	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38
358.5	52	27	2.39	2.39	2.38	2.38	2.38	2.39	2.39	2.38	2.38	2.38	2.38	2.38
358.5	52	28	2.38	2.38	2.38	2.38	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39
358.5	52	29	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38
358.5	52	30	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38
358.5	52	31	2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36
358.5	52	32	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38
358.5	52	33	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38	2.38
358.5	52	34	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37
703.3	102	19	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72
703.3	102	20	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70
703.3	102	27	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72
703.3	102	28	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72
703.3	102	29	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71
703.3	102	30	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71
703.3	102	31	3.69	3.70	3.69	3.70	3.70	3.69	3.69	3.70	3.70	3.70	3.70	3.70
703.3	102	32	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.70	3.71	3.71
703.3	102	33	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72	3.72
703.3	102	34	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71	3.71
289.6	42	19	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12
289.6	42	20	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11
289.6	42	27	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12
289.6	42	28	2.12	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.12
289.6	42	29	2.09	2.09	2.09	2.09	2.09	2.10	2.09	2.09	2.09	2.10	2.10	2.09

Pressure (kPa)	Pressure (psi)	Channel	Data (V)											
289.6	42	30	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12
289.6	42	31	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12
289.6	42	32	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11
289.6	42	33	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11
289.6	42	34	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11
344.7	50	19	2.33	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.33	2.34	2.34	2.33
344.7	50	20	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32
344.7	50	27	2.33	2.33	2.33	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34
344.7	50	28	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32
344.7	50	29	2.33	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.33	2.33	2.33
344.7	50	30	2.33	2.33	2.33	2.33	2.33	2.33	2.33	2.33	2.33	2.34	2.34	2.33
344.7	50	31	2.33	2.33	2.33	2.33	2.32	2.33	2.33	2.32	2.32	2.33	2.32	2.32
344.7	50	32	2.33	2.32	2.32	2.33	2.33	2.33	2.33	2.33	2.32	2.32	2.33	2.33
344.7	50	33	2.33	2.33	2.33	2.33	2.33	2.33	2.33	2.33	2.33	2.33	2.33	2.33
344.7	50	34	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32
82.74	12	19	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
82.74	12	20	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
82.74	12	27	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
82.74	12	28	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
82.74	12	29	1.31	1.31	1.30	1.30	1.30	1.30	1.30	1.30	1.31	1.30	1.30	1.30
82.74	12	30	1.32	1.32	1.32	1.32	1.33	1.33	1.32	1.32	1.32	1.32	1.32	1.32
82.74	12	31	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
82.74	12	32	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
82.74	12	33	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30
82.74	12	34	1.32	1.31	1.31	1.31	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
103.4	15	19	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39
103.4	15	20	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39
103.4	15	27	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
103.4	15	28	1.41	1.40	1.41	1.41	1.41	1.41	1.41	1.41	1.40	1.40	1.40	1.40
103.4	15	29	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.39	1.38	1.38
103.4	15	30	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
103.4	15	31	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39
103.4	15	32	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39
103.4	15	33	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38	1.38
103.4	15	34	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39
510.2	74	19	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96
510.2	74	20	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96
510.2	74	27	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98
510.2	74	28	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97
510.2	74	29	2.94	2.94	2.95	2.94	2.94	2.94	2.94	2.94	2.95	2.94	2.94	2.94

Pressure (kPa)	Pressure (psi)	Channel	Data (V)											
510.2	74	30	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97
510.2	74	31	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97
510.2	74	32	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96
510.2	74	33	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.96	2.97	2.96	2.96	2.96
510.2	74	34	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97
489.5	71	19	2.89	2.89	2.89	2.89	2.89	2.89	2.89	2.89	2.89	2.89	2.89	2.89
489.5	71	20	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88
489.5	71	27	2.89	2.89	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90
489.5	71	28	2.88	2.87	2.87	2.87	2.87	2.87	2.87	2.87	2.87	2.87	2.87	2.87
489.5	71	29	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88
489.5	71	30	2.89	2.89	2.89	2.89	2.89	2.89	2.89	2.89	2.89	2.89	2.89	2.89
489.5	71	31	2.87	2.87	2.88	2.88	2.88	2.87	2.88	2.88	2.88	2.88	2.88	2.87
489.5	71	32	2.88	2.89	2.88	2.88	2.88	2.88	2.89	2.89	2.89	2.89	2.88	2.88
489.5	71	33	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.89	2.89	2.89	2.88	2.88
489.5	71	34	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88
365.4	53	19	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41
365.4	53	20	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
365.4	53	27	2.42	2.42	2.42	2.42	2.42	2.42	2.42	2.42	2.42	2.42	2.42	2.42
365.4	53	28	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41
365.4	53	29	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39
365.4	53	30	2.42	2.42	2.42	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41
365.4	53	31	2.41	2.41	2.40	2.40	2.40	2.40	2.40	2.40	2.41	2.41	2.40	2.40
365.4	53	32	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
365.4	53	33	2.39	2.39	2.39	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40	2.40
365.4	53	34	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41
255.1	37	19	1.98	1.98	1.99	1.99	1.99	1.98	1.98	1.99	1.99	1.99	1.98	1.98
255.1	37	20	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98
255.1	37	27	1.98	1.98	1.98	1.98	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99
255.1	37	28	1.98	1.98	1.98	1.97	1.97	1.97	1.98	1.98	1.97	1.97	1.97	1.98
255.1	37	29	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98
255.1	37	30	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99
255.1	37	31	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.97
255.1	37	32	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98
255.1	37	33	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98
255.1	37	34	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98
689.5	100	19	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66
689.5	100	20	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61
689.5	100	27	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67
689.5	100	28	3.67	3.67	3.66	3.66	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67
689.5	100	29	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65

Pressure (kPa)	Pressure (psi)	Channel	Data (V)											
689.5	100	30	3.66	3.66	3.66	3.67	3.67	3.67	3.66	3.66	3.66	3.66	3.66	3.66
689.5	100	31	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66
689.5	100	32	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66
689.5	100	33	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65
689.5	100	34	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66
751.5	109	19	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90
751.5	109	20	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89
751.5	109	27	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.87	3.87	3.87
751.5	109	28	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90
751.5	109	29	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90
751.5	109	30	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90
751.5	109	31	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
751.5	109	32	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89
751.5	109	33	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89
751.5	109	34	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89	3.89

Table 19. Calibration uncertainty results for pressure transducers. $n = 25$ measurements, $\nu = 23$ degrees of freedom.

Channel	S/N	\bar{x}	\bar{y}	S_{xy}	S_{xx}	m	b	$SSResid$	se	t	u_{us}	a_0	a_1	u_{cal}
		psi	V	psi*V	psi ²	V/psi	V	V ²	V		V	psi	psi/V	psi
19	2058089.29	57.80	2.54	639.91	24046	0.027	0.997	0.00067	0.0054	2.07	0.011	-37.46	37.58	0.42
20	2058089.33	57.80	2.53	638.41	24046	0.027	0.991	0.0027	0.011	2.07	0.023	-37.32	37.67	0.87
27	2058089.32	57.80	2.54	638.93	24046	0.027	1.008	0.0012	0.0073	2.07	0.015	-37.93	37.63	0.57
28	2058089.31	57.80	2.54	639.69	24046	0.027	1.00	0.0014	0.0077	2.07	0.016	-37.58	37.59	0.61
29	2058089.25	57.80	2.53	642.16	24046	0.027	0.985	0.0010	0.0067	2.07	0.014	-36.90	37.45	0.53
30	071914D101	57.80	2.54	638.46	24046	0.027	1.004	0.00068	0.0054	2.07	0.011	-37.82	37.66	0.42
31	2058089.27	57.80	2.53	638.02	24046	0.027	0.997	0.00098	0.0065	2.07	0.014	-37.56	37.69	0.54
32	2058089.28	57.80	2.53	638.78	24046	0.027	0.995	0.00067	0.0054	2.07	0.011	-37.46	37.64	0.42
33	2058089.34	57.80	2.53	642.57	24046	0.027	0.986	0.0010	0.0066	2.07	0.014	-36.90	37.42	0.53
34	2058089.26	57.80	2.53	638.95	24046	0.027	0.998	0.00045	0.0044	2.07	0.0093	-37.57	37.63	0.35

8.2. Hydronic Differential Pressure Transducer Calibration

Differential pressure (DP) transducers will be used at several locations in the laboratory for control and to provide secondary flow measurements. To date, two DP sensors have been calibrated, though the final use of these sensors is to be determined. The DP sensors are the PX2300 series from Omega. The manufacturer stated accuracy is 0.25 % of full scale.

Table 20. Calibration data for a 344.5 kPa (50 psi) differential pressure sensor (S/N 6600605).

Pressure (kPa)	Pressure (psi)	Data (V)											
254.93	37	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92
144.69	21	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
323.83	47	4.71	4.71	4.71	4.71	4.71	4.71	4.71	4.71	4.71	4.71	4.71	4.71
130.91	19	2.49	2.49	2.49	2.50	2.50	2.50	2.50	2.50	2.50	2.49	2.50	2.49
103.35	15	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
124.02	18	2.42	2.42	2.42	2.41	2.42	2.41	2.42	2.41	2.42	2.42	2.41	2.42
234.26	34	3.68	3.68	3.68	3.68	3.68	3.68	3.68	3.68	3.68	3.68	3.68	3.68
227.37	33	3.60	3.61	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60	3.60
75.79	11	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86	1.86
337.61	49	4.87	4.87	4.86	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87	4.87
206.7	30	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36
316.94	46	4.63	4.63	4.63	4.63	4.63	4.63	4.63	4.63	4.63	4.63	4.63	4.63
172.25	25	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97
117.13	17	2.34	2.34	2.34	2.34	2.34	2.34	2.33	2.34	2.34	2.34	2.34	2.34
48.23	7	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54
0	0	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.98

Table 21. Calibration data for a 172.25 kPa (25 psi) differential pressure sensor (S/N 6600603).

Pressure (kPa)	Pressure (psi)	Data (V)											
48.23	7	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15
62.01	9	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47	2.47
124.02	18	3.89	3.89	3.89	3.89	3.89	3.90	3.90	3.90	3.90	3.90	3.89	3.89
82.68	12	2.94	2.95	2.94	2.94	2.94	2.94	2.95	2.94	2.95	2.95	2.95	2.94
137.8	20	4.21	4.21	4.21	4.21	4.21	4.22	4.21	4.21	4.21	4.21	4.21	4.21
117.13	17	3.73	3.73	3.74	3.74	3.74	3.74	3.74	3.74	3.74	3.74	3.74	3.74
165.36	24	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.84	4.85	4.85	4.85	4.85
55.12	8	2.31	2.31	2.31	2.31	2.31	2.31	2.31	2.31	2.31	2.31	2.31	2.31
103.35	15	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42	3.42
130.91	19	4.05	4.05	4.05	4.05	4.06	4.06	4.05	4.05	4.05	4.05	4.05	4.05
68.9	10	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63	2.63
110.24	16	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58
96.46	14	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.27	3.26
144.69	21	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37
75.79	11	2.78	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.78
172.25	25	5.01	5.01	5.01	5.00	5.01	5.00	5.00	5.00	5.00	5.01	5.01	5.01
0	0	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05

Table 22. Calibration uncertainty results for differential pressure transducers.

S/N	<i>n</i>	\bar{x}	\bar{y}	S_{xy}	S_{xx}	<i>m</i>	<i>b</i>	<i>SSResid</i>	<i>ν</i>	<i>se</i>	<i>t</i>	<i>u_{us}</i>	<i>a₀</i>	<i>a₁</i>	<i>u_{cal}</i>
		psi	V	psi*V	psi ²	V/psi	V	V ²		V		V	psi	psi/V	psi
6600605	16	25.56	3.01	255.09	3219.94	0.079	0.99	0.00023	14	0.0040	2.145	0.0090	-12.46	12.62	0.11
6600603	17	14.47	3.34	109.65	692.24	0.16	1.04	0.000030	15	0.0014	2.131	0.0039	-6.59	6.31	0.024

8.3. Hydronic Flow Meter Calibration

The flow meters in the IBAL are described in more detail in Section 5.3. This section contains the calibration report for each flow meter. Table 23 is a summary of results in imperial units (see Table 15 for SI units).

Table 23. Calibration uncertainty results for ultrasonic flow meters. $n = 10$ measurements, $\nu = 8$ degrees of freedom.

Channel	S/N	\bar{x}	\bar{y}	S_{xy}	S_{xx}	m	b	$SSResid$	se	t	u_{us}	a_0	a_1	u_{cal}
		gpm	mA	gpm*mA	gpm ²	mA/gpm	mA	mA ²	mA		mA	gpm	gpm/A	gpm
193	100718	14.54	5.07	27.48	374	0.074	4.00	0.0024	0.017	2.306	0.044	-54.36	13593.55	0.60
194	100716	13.57	5.02	22.49	300	0.075	4.00	0.0020	0.016	2.306	0.041	-53.45	13349.89	0.54
195	100725	25.04	5.01	45.55	1205	0.038	4.06	0.0218	0.052	2.306	0.12	-107.36	26443.48	3.21
196	100724	19.02	4.73	19.39	514	0.038	4.01	0.0004	0.007	2.306	0.025	-106.40	26523.99	0.65
197	100714	6.60	4.74	2.99	29	0.104	4.05	0.0003	0.006	2.306	0.023	-38.93	9606.14	0.23
198	100713	6.60	4.70	3.23	29	0.111	3.96	0.0008	0.010	2.306	0.029	-35.76	9019.67	0.26
199	100721	24.94	5.14	54.91	1200	0.046	4.00	0.0028	0.019	2.306	0.047	-87.53	21863.40	1.03
200	100722	27.50	5.12	62.96	1581	0.040	4.03	0.0046	0.024	2.306	0.059	-101.20	25115.26	1.48
207	100723	24.77	5.07	47.89	1162	0.041	4.05	0.0145	0.043	2.306	0.10	-98.18	24263.64	2.42
208	100720	14.53	5.08	27.22	370	0.074	4.01	0.0024	0.017	2.306	0.044	-54.54	13603.00	0.60
210	100717	13.85	5.01	23.91	323	0.074	3.99	0.0022	0.016	2.306	0.042	-53.94	13529.66	0.57
211	100715	12.56	4.96	17.86	235	0.076	4.01	0.0027	0.018	2.306	0.046	-52.84	13178.56	0.61
212	100719	11.62	4.85	13.48	180	0.075	3.98	0.0048	0.024	2.306	0.059	-53.16	13369.74	0.79
213	100727	18.99	4.83	22.61	504	0.045	3.97	0.0016	0.014	2.306	0.038	-88.62	22302.68	0.85

Flow Technology, Inc.

8930 S. Beck Av. Suite 107 Tempe, AZ 85284

AS-FOUND

Certificate of Calibration and Conformance

FINAL CALIBRATION

Certificate No. 68000796

Customer: NATIONAL INST OF STDS AND TECH

Ambient Temp. 75 °F
Ambient Pres: 14.1 PSIA
Humidity: 28%
Calib Fluid: WATER
Fluid Visc: 0.885 cSt
Fluid Dens: 8.319 Lb/Gal

Meter Tag #: N/A

Size: 1-1/2"

End Fitting: N/A

Bearing Type: N/A

Pickoff Type: N/A

Pickoff P/N: N/A

Job #: 49377.01
Meter Serial #: 100716
Meter Model #: DTFXL2-KN1-NN
P.O. Number: SB1341-15-S

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.656	84.282	84.25	0.04%	77.8
5.529	76.527	77.79	-1.65%	77.8
5.367	69.313	69.55	-0.34%	78.0
5.247	61.914	63.44	-2.47%	78.1
5.114	55.022	56.67	-3.00%	78.2
4.946	47.767	48.13	-0.76%	78.2
4.780	40.427	39.68	1.84%	78.3
4.657	33.398	33.42	-0.08%	78.2
4.522	26.266	26.56	-1.11%	78.3
4.388	18.908	19.74	-4.40%	78.3

Calib Inv #: 51868
Report No: 150225A
Calibrator Recal Date: 8/25/2015
Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR

Date: 5/19/2015

Procedure: CP-08

Certified By:

On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
Z540-1-1994

Flow Technology, Inc.
8930 S. Beck Av. Suite 107 Tempe, AZ 85284

AS-FOUND
FINAL CALIBRATION

Certificate of Calibration and Conformance
Certificate No. 68000799

Customer: NATIONAL INST OF STDS AND TECH


Meter Tag #: N/A
Size: 1-1/2"
End Fitting: N/A
Bearing Type: N/A
Pickoff Type: N/A
Pickoff PIN: N/A

Job #: 49377.01
Meter Serial #: 100719
Meter Model #: DTFXL2-KN1-NN
P.O. Number: S91341-15-S

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.321	69.508	67.206	0.033	79.0
5.268	63.555	64.510	-0.015	78.9
5.122	57.581	57.082	0.009	79.1
5.041	52.405	52.961	-0.011	79.1
4.870	46.591	44.261	0.050	79.2
4.764	41.192	38.869	0.056	79.2
4.676	35.668	34.392	0.036	79.2
4.562	30.005	28.592	0.047	79.2
4.467	24.537	23.759	0.032	79.2
4.362	18.805	18.417	0.021	79.2

Calib Inv #: 51868
Report No: 150225A
Calibrator Recal Date: 8/25/2015
Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR
Date: 5/19/2015
Procedure: CP-08
Certified By: 
On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCCL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
Z540-1-1994

Flow Technology, Inc.
8930 S. Beck Av. Suite 107 Tempe, AZ 85284

Certificate of Calibration and Conformance
Certificate No. 680009800

AS-FOUND
FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH
Job #: 49377.01
Meter Serial #: 100720
Meter Model #: DTFXL2-KV1-NN
P.O. Number: SB1341-16-S


Meter Tag #: N/A
Size: 1-1/2"
End Fitting: N/A
Bearing Type: N/A
Pickoff Type: N/A
Pickoff P/N: N/A

Ambient Temp. 75 °F
Ambient Pres: 14.1 PSIA
Humidity: 28%
Calib Fluid: WATER
Fluid Visc: 0.869 cSt
Fluid Dens: 8.3176 Lb/Gal

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.761	91.016	89.59	1.57%	79.3
5.633	83.169	83.08	0.11%	79.3
5.478	75.081	75.19	-0.15%	79.4
5.322	66.926	67.26	-0.49%	79.5
5.172	58.908	59.63	-1.22%	79.5
4.979	50.990	49.81	2.32%	79.5
4.820	42.954	41.72	2.88%	79.6
4.674	34.979	34.29	1.97%	79.5
4.538	26.906	27.37	-1.73%	79.6
4.393	18.909	19.99	-5.74%	79.5

Calib Inv #: 51868
Report No: 150225A
Calibrator Recal Date: 8/25/2015
Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR
Date: 5/19/2015
Procedure: CP-08
Certified By: 
On Behalf of Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
Z540-1-1994

Flow Technology, Inc.
 8930 S. Beck Av. Suite 107 Tempe, AZ 85284
Certificate of Calibration and Conformance
 Certificate No. 68000795

AS-FOUND
FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH
 Job #: 49377.01
 Meter Serial #: 100715
 Meter Model #: DTFXL2-KN1-NN
 P.O. Number: SB1341-15-S

Meter Tag #: N/A
 Size: 1-1/2"
 End Fitting: N/A
 Bearing Type: N/A
 Pickoff Type: N/A
 Pickoff P/N: N/A

Ambient Temp: 75 °F
 Ambient Pres: 14.1 PSIA
 Humidity: 28%
 Calib Fluid: WATER
 Fluid Visc: 0.691 cSt
 Fluid Dens: 8.3198 Lb/Gal

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.537	76.762	78.195	-1.87%	77.7
5.436	69.855	73.057	-4.56%	76.9
5.284	63.613	65.324	-2.69%	77.4
5.169	56.830	59.473	-4.65%	77.4
4.996	50.421	50.672	-0.50%	77.6
4.871	44.120	44.312	-0.43%	77.7
4.765	38.058	38.919	-2.26%	77.7
4.637	31.569	32.407	-2.66%	77.7
4.532	25.454	27.066	-6.33%	77.8
4.389	18.861	20.299	-7.62%	77.8

Calib Inv #: 51868
 Report No: 150225A
 Calibrator Recal Date: 8/25/2015
 Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR
 Date: 5/19/2015
 Procedure: CP-08
 Certified By:


 On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
 Z540-1-1994

Flow Technology, Inc.
 8930 S. Buck Av. Suite 107 Tempe, AZ 85284
Certificate of Calibration and Conformance
 Certificate No. 68000798

AS-FOUND

FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH

Job #: 49377.01
 Meter Serial #: 100718
 Meter Model #: DTFXL2-KV1-NN
 P.O. Number: SB1341-15-S

Meter Tag #: N/A
 Size: 1-1/2"
 End Fitting: N/A
 Bearing Type: N/A
 Pickoff Type: N/A
 Pickoff P/N: N/A

Ambient Temp: 75 °F
 Ambient Pres: 14.1 PSIA
 Humidity: 28%
 Calib Fluid: WATER
 Fluid Visc: 0.878 cSt
 Fluid Dens: 8.3184 Lb/Gal

Note:

Meter Output (mA)	Flow Rate (Lb/Min)	Calc Flow Rate (Lb/Min)	% Error	Meter Temp (°F)
5.758	92.029	89.44	2.82%	78.4
5.023	82.733	82.57	0.20%	70.5
5.482	75.306	74.38	1.23%	78.6
5.317	66.684	67.00	-0.48%	78.7
5.160	58.808	59.02	-0.35%	78.7
4.985	50.952	50.11	1.65%	78.8
4.813	42.833	41.36	3.44%	78.9
4.675	35.038	34.34	1.99%	78.9
4.521	27.070	26.51	2.08%	78.9
4.369	18.856	18.77	0.44%	78.9

Calib Inv #: 51868
 Report No: 150225A
 Calibrator Recal Date: 8/25/2015
 Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR
 Date: 5/19/2015
 Procedure: CP-08
 Certified By:


 On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
 Z540-1-1994

AS-FOUND

Certificate of Calibration and Conformance

Certificate No. 68000797

Ambient Temp.	75	°F
Ambient Pres:	14.1	PSIA
Humidity:	28%	
Calib Fluid:	WATER	
Fluid Visc:	0.883	cSt
Fluid Dens:	8.3188	Lb/Gal

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.654	86.499	84.15	2.72%	78.0
5.541	78.836	78.40	0.56%	78.0
5.361	71.119	69.24	2.64%	78.1
5.238	63.263	62.98	0.44%	78.3
5.089	56.036	55.40	1.13%	78.3
4.950	48.444	48.33	0.23%	78.4
4.798	41.298	40.80	1.69%	78.4
4.625	33.819	31.80	5.98%	78.4
4.491	26.336	24.98	5.15%	78.5
4.358	18.804	18.21	3.14%	78.4

Calibration Technician: CBJR
Date: 5/19/2015
Procedure: CP-08
Certified By:

On Behalf of FTI Flow Technology, Inc.

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTL Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTL Flow Technology, Inc.

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Flow Technology, Inc.
 8330 S. Beck Av. Suite 107 Tempe, AZ 85284
Certificate of Calibration and Conformance
 Certificate No. 68000789

AS-FOUND

FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH

Ambient Temp: 75 °F
 Ambient Pres: 14.1 PSIA
 Humidity: 28%
 Calib Fluid: WATER
 Fluid Visc: 0.902 cSt
 Fluid Dens: 8.3205 Lb/Gal

Job #: 49377.02
 Meter Serial #: 100724
 Meter Model #: DTFXL2-LN1-NN
 P.O. Number: SB1341-15-S

Meter Tag #: N/A
 Size: 2"
 End Fitting: N/A
 Bearing Type: N/A
 Pickoff Type: N/A
 Pickoff P/N: N/A

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.155	114.651	102.434	10.66%	76.0
5.078	105.958	95.605	9.77%	76.3
4.951	95.142	84.342	11.35%	76.4
4.865	85.845	76.715	10.64%	76.6
4.770	76.413	68.289	10.63%	76.8
4.674	66.750	59.775	10.45%	76.8
4.580	57.873	51.439	11.12%	76.9
4.503	48.573	44.610	8.16%	76.9
4.397	39.066	35.209	9.87%	77.0
4.314	29.684	27.848	6.18%	77.0

Calib Inv #: 51868
 Report No: 150225A
 Calibrator Recal Date: 8/25/2015
 Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR
 Date: 5/18/2015
 Procedure: CP-08
 Certified By:


 On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCISL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
 Z540-1-1994

Flow Technology, Inc.
 8930 S. Beck Av. Suite 107 Tempe, AZ 85284
Certificate of Calibration and Conformance
 Certificate No. 68000794

AS-FOUND
FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH

Ambient Temp. 75 °F
 Ambient Pres: 14.1 PSIA
 Humidity: 28%
 Calib Fluid: WATER
 Fluid Visc: 0.886 cSt
 Fluid Dens: 8.3191 Lb/Gal

Meter Tag #: N/A
 Size: 2"
 End Fitting: N/A
 Bearing Type: N/A
 Pickoff Type: N/A
 Pickoff P/N: N/A

Job #: 49377.02
 Meter Serial #: 100722
 Meter Model #: DTFXL2-LN1-NN
 P.O. Number: SB1341-15-S

Note:

Meter Output (mA)	Flow Rate (Lb/Min)	Calc Flow Rate (Lb/Min)	% Error	Meter Temp (°F)
5.980	181.200	173.83	4.07%	77.7
5.725	161.973	152.99	5.55%	77.8
5.564	145.438	136.71	4.63%	77.9
5.329	124.833	117.87	5.58%	78.1
5.178	112.231	104.47	6.91%	78.1
5.033	96.354	91.61	4.92%	78.2
4.863	79.782	76.54	4.07%	78.3
4.718	62.657	63.68	-1.63%	78.3
4.555	46.783	49.22	-5.21%	78.3
4.319	29.888	28.29	5.34%	77.3

Calib Inv #: 51868
 Report No: 150225A
 Calibrator Recal Date: 8/25/2015
 Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR
 Date: 5/19/2015
 Procedure: CP-08
 Certified By:

On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
 Z540-1-1994

Flow Technology, Inc.

8930 S. Beck Av. Suite 107 Tempe, AZ 85284

AS-FOUND

Certificate of Calibration and Conformance

Certificate No. 68000790

FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH

Meter Tag #: N/A

Ambient Temp: 75 °F
Ambient Pres: 14.1 PSIA
Humidity: 28%
Calib Fluid: WATER
Fluid Visc: 0.89 cSt
Fluid Dens: 8.3194 Lb/Gal

Job #: 49377.02

Meter Serial #: 100723

Meter Model #: DTFXL2-LN1-NN

P.O. Number: SB1341-15-S

Size: 2"

End Fitting: N/A

Bearing Type: N/A

Pickoff Type: N/A

Pickoff PIN: N/A

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.811	161.342	160.81	0.45%	77.0
5.613	142.509	143.05	-0.38%	77.2
5.358	124.215	120.44	3.04%	77.4
5.273	115.122	112.90	1.93%	77.6
5.107	101.677	98.18	3.44%	77.7
5.069	87.146	94.81	-8.79%	77.9
4.893	72.917	79.20	-8.61%	78.0
4.696	58.740	61.73	-5.08%	78.0
4.513	44.158	45.50	-3.03%	78.0
4.337	29.773	29.89	-0.39%	78.0

Calib Inv #: 51868
Report No: 150225A
Calibrator Recal Date: 8/25/2015
Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR

Date: 5/18/2015

Procedure: CP-08

Certified By:

On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
Z540-1-1994

Flow Technology, Inc.
 8930 S. Beck Av. Suite 107 Tempe, AZ 85284
Certificate of Calibration and Conformance
 Certificate No. 68000791

AS-FOUND
FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH
 Job #: 49377.02
 Meter Serial #: 100725
 Meter Model #: DTFXL2-LN1-NN
 P.O. Number: SB1341-15-S

Meter Tag #: N/A
 Size: 2"
 End Fitting: N/A
 Bearing Type: N/A
 Pickoff Type: N/A
 Pickoff P/N: N/A

Ambient Temp: 75 °F
 Ambient Pres: 14.1 PSIA
 Humidity: 28%
 Calib Fluid: WATER
 Fluid Visc: 0.876 cSt
 Fluid Dens: 8.3183 Lb/Gal

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.646	161.834	145.980	9.80%	78.4
5.472	145.317	130.548	10.16%	78.5
5.328	128.281	117.777	8.19%	78.7
5.235	116.344	108.529	5.86%	78.6
5.129	102.269	100.128	2.09%	78.8
4.991	87.446	87.889	-0.51%	78.8
4.867	73.043	76.892	-5.27%	78.9
4.650	58.786	57.647	1.94%	79.4
4.426	44.642	37.781	15.37%	79.1
4.325	29.731	28.823	3.05%	79.3

Calib Inv #: 51868
 Report No: 150225A
 Calibrator Recal Date: 8/25/2015
 Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR
 Date: 5/18/2015
 Procedure: CP-08
 Certified By:

[Signature]
 On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
 Z540-1-1994

Flow Technology, Inc.

8930 S. Beck Av. Suite 107 Tempe, AZ 85284

Certificate of Calibration and Conformance

Certificate No. 68000792

AS-FOUND

FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH

Job #: 49377.02

Meter Serial #: 100721

Meter Model #: DTFXL2-LN1-NN

P.O. Number: SB1341-15-S

Meter Tag #: N/A

Size: 2"

End Fitting: N/A

Bearing Type: N/A

Pickoff Type: N/A

Pickoff P/N: N/A

Ambient Temp: 75 °F

Ambient Pres: 14.1 PSIA

Humidity: 28%

Calib Fluid: WATER

Fluid Visc: 0.863 cSt

Fluid Dens: 8.317 Lb/Gal

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.961	161.697	173.916	-7.56%	79.4
5.750	143.226	155.203	-8.36%	79.7
5.592	130.919	141.191	-7.85%	79.8
5.370	114.403	121.502	-6.20%	79.9
5.206	101.514	106.957	-5.36%	80.1
5.044	87.274	92.590	-6.09%	80.1
4.898	72.782	79.641	-9.43%	80.2
4.729	56.269	64.553	-10.96%	80.3
4.516	44.362	45.763	-3.16%	80.3
4.378	29.766	33.524	-12.62%	80.2

Calib Inv #: 51868

Report No: 150225A

Calibrator Recal Date: 8/25/2015

Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR

Date: 5/18/2015

Procedure: CP-08

Certified By:

On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
Z540-1-1994

Flow Technology, Inc.
8930 S. Beck Av. Suite 107 Tempe, AZ 85284
Certificate of Calibration and Conformance
Certificate No. 68000793

AS-FOUND
FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH

Meter Tag #: N/A
Size: 2"
End Fitting: N/A
Bearing Type: N/A
Pickoff Type: N/A
Pickoff P/N: N/A

Ambient Temp: 75 °F
Ambient Pres: 14.1 PSIA
Humidity: 28%
Calib Fluid: WATER
Fluid Visc: 0.9 cSt
Fluid Dens: 8.3203 Lb/Gal

Job #: 49377.02
Meter Serial #: 100726
Meter Model #: DTFXL2-LN1-NN
P.O. Number: SB1341-15-S

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.642	161.806	145.62	10.00%	76.2
5.501	145.446	133.12	8.47%	76.4
5.382	129.377	122.57	5.26%	76.6
5.264	114.902	112.10	2.44%	76.7
5.122	102.003	99.51	2.45%	76.9
4.937	87.457	83.10	4.98%	77.0
4.795	72.442	70.51	2.67%	77.1
4.641	58.597	56.85	2.98%	77.1
4.466	44.469	41.33	7.06%	77.2
4.318	29.898	28.20	5.67%	77.3

Calib Inv #: 51868
Report No: 150225A
Calibrator Root Date: 8/25/2015
Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR
Date: 5/19/2015
Procedure: CP-08
Certified By:

On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
Z540-1-1994

Flow Technology, Inc.
8930 S. Beck Av. Suite 107 Tempe, AZ 85284

Certificate of Calibration and Conformance
Certificate No. 88000788

AS-FOUND
FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH
Job #: 49377.02
Meter Serial #: 100727
Meter Model #: DTFXL2-LN1-NN
P.O. Number: SB1341-15-S

Meter Tag #: N/A
Size: 2"
End Fitting: N/A
Bearing Type: N/A
Pickoff Type: N/A
Pickoff PIN: N/A

Ambient Temp: 75 °F
Ambient Pres: 14.1 PSIA
Humidity: 28%
Calib Fluid: WATER
Fluid Visc: 0.911 cSt
Fluid Dens: 8.3212 Lb/Gal

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.314	114.935	116.535	-1.39%	75.5
5.202	104.132	106.602	-2.37%	75.6
5.100	94.920	97.556	-2.78%	75.7
5.005	85.458	89.131	-4.30%	75.9
4.893	76.520	79.198	-3.50%	75.9
4.785	67.579	69.620	-3.02%	76.1
4.671	57.974	59.509	-2.65%	76.1
4.532	48.484	47.182	2.69%	76.1
4.432	39.224	38.313	2.32%	76.2
4.319	29.800	28.291	5.06%	76.2

Calib Inv #: 51868
Report No: 150225A
Calibrator Recal Date: 8/25/2015
Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR
Date: 5/18/2015
Procedure: CP-08
Certified By: 
On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
Z540-1-1994

Flow Technology, Inc.
 8930 S. Beck Av. Suite 107 Tempe, AZ 85284
Certificate of Calibration and Conformance
 Certificate No. 68000802

AS-FOUND

FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH

Meter Tag #: N/A
 Size: 1-1/4"
 End Fitting: N/A
 Bearing Type: N/A
 Pickoff Type: N/A
 Pickoff P/N: N/A

Ambient Temp: 75 °F
 Ambient Pres: 14.1 PSIA
 Humidity: 28%
 Calib Fluid: WATER
 Fluid Visc: 0.905 cSt
 Fluid Dens: 8.3208 Lb/Gal

Job #: 49377.03
 Meter Serial #: 100714
 Meter Model #: DTFXL2-JN1-NN
 P.O. Number: SB1341-15-S

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
5.009	35.006	36.26	-3.59%	76.1
4.953	32.808	34.25	-4.39%	76.1
4.892	30.724	32.06	-4.34%	76.3
4.837	28.259	30.08	-6.44%	76.4
4.779	26.116	28.00	-7.20%	76.4
4.709	23.758	25.48	-7.25%	76.4
4.644	21.659	23.14	-6.85%	76.5
4.589	19.416	21.17	-8.02%	76.5
4.528	17.270	18.98	-9.87%	76.5
4.453	14.857	16.28	-9.58%	76.5

Calib Inv #: 51868
 Report No: 150225A
 Calibrator Recal Date: 8/25/2015
 Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR
 Date: 5/20/2015
 Procedure: CP-08
 Certified By:

R. J. [Signature]
 On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSS Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
 Z540-1-1994

Flow Technology, Inc.
 8930 S. Beck Av. Suite 107 Tempe, AZ 85284
Certificate of Calibration and Conformance
 Certificate No. 68000801

AS-FOUND

FINAL CALIBRATION

Customer: NATIONAL INST OF STDS AND TECH

Ambient Temp: 75 °F
 Ambient Pres: 14.1 PSIA
 Humidity: 28%
 Calib Fluid: WATER
 Fluid Visc: 0.911 cSt
 Fluid Dens: 8.3212 Lb/Gal

Meter Tag #: N/A
 Size: 1-1/4"
 End Fitting: N/A
 Bearing Type: N/A
 Pickoff Type: N/A
 Pickoff P/N: N/A

Job #: 49377.03
 Meter Serial #: 100713
 Meter Model #: DTFXL2-JN1-NN
 P.O. Number: SB1341-15-S

Note:

Meter Output (mA)	Flow Rate (Lit/Min)	Calc Flow Rate (Lit/Min)	% Error	Meter Temp (°F)
4.995	35.243	35.76	-1.46%	75.7
4.939	32.863	33.75	-2.68%	75.7
4.860	30.480	30.91	-1.40%	75.8
4.785	28.332	28.21	0.43%	75.8
4.723	26.140	25.98	0.60%	75.9
4.689	23.908	24.04	-0.57%	76.0
4.586	21.528	21.06	2.18%	76.0
4.534	19.497	19.19	1.57%	76.0
4.455	17.076	16.35	4.24%	76.0
4.418	14.927	15.02	-0.63%	76.1

Calib Inv #: 51868
 Report No: 150225A
 Calibrator Recal Date: 8/25/2015
 Calibrator Uncertainty: +/- .05

Calibration Technician: CBJR
 Date: 5/19/2015
 Procedure: CP-08
 Certified By:


 On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994, as per customer request, and MIL-STD-45662A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Compliant to
 Z540-1-1994



FTI Flow Technology, Inc.
8930 South Beck Ave. Ste. 107, Tempe, AZ 85284
E-mail: ftimarket@ftimeters.com Website: www.ftimeters.com

Phone: (480) 240-3400 Fax: (480) 240-3401

Certificate No. 40001523

Customer: NATIONAL INSTITUTE OF STANDARDS & TECHNOLOGY
Job No.: 23731-01
Meter Serial No.: FAC1217
Meter Model No.: EL 2200
Elec. Serial No.: FCA2121
Elec. Model No.: 608A
Calibration Factor: 1.9464
P.O. No.: SANDY HECKMAN-CC
Ambient Temp.: 27.7 °C
Ambient Press.: 900.0 mb
Humidity: 35%
Cal. Fluid: H2O
Meter Size: 2.0"

Step No.	Nominal Flow [GPM]	Nominal Velocity [ft/sec]	Test Volume [Gal]	Master Volume [Gal]	Error [Gal]	Error [%]
1	93.363	9.843	266.972	266.762	0.21	0.08%
2	93.363	9.843	267.580	267.790	-0.21	-0.08%
3	46.681	4.921	133.407	133.577	-0.17	-0.13%
4	46.681	4.921	133.460	133.580	-0.12	-0.09%
5	23.340	2.461	67.126	66.924	0.20	0.30%
6	23.340	2.461	67.258	67.136	0.12	0.18%

Calibrator Inv. No.: 51840
Report No.: 140513A
Calibrator Recal Date: Oct 25, 2016
Calibrator Uncertainty: +/- 0.10%

Calibration Technician: CBJR
Date: Jun 27, 2016
Procedure: CP-100323

Certified By:

On Behalf of FTI Flow Technology, Inc.

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to the National Institute of Standards and Technology and through the Certificate Number listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request. FTI Flow Technology, Inc.'s calibration system is in compliance with ANSI/NCSL Z540-1-1994 and MIL-STD-45682A. Results apply only to the unit calibrated and shall not be reproduced, expect in full, without the written approval of FTI Flow Technology, Inc.

Magnetic Meter System - Serial Number Report

SALES ORDER: 23731

LINE: 1

MODEL NUMBER: 01-68704-AAA-BBA

Mag System Part Number	Flow Sensor	Flow Serial	Transmitter	Trans Serial
68754-AAA-BBA	EL2200-050A15FP5SA	FAC1217	MC608ACVA2F2S21NN	FCA2121



8930 South Beck Avenue, Suite #107
Tempe, Arizona 85284

Phone: (480) 240-3400

Fax: (480) 240-3401

e-mail: ftimarket@ftimeters.com

website: www.ftimeters.com

Electromagnetic Flow Meter Calibration Report

In accordance with ISO 9104

Model Number:
Serial Number:
Diameter (in)
Connection:
Coefficient Ka:
Coefficient Kb:
Test Fluid:
Temperature Fluid:
Test Bench:
Test Group:

EL 2200
FAC1217
2"
ANSI 150
+1.9464
+00000
H2O
25.2°C
2
3

Reference Instruments	WEIGHT SCALE "SIT" CERTIFIED
Part Number	E O065610
Verification Date	10/07/2015

Calibration Conditions				
Test #	Test Velocity (m/s)	Test Flow Rate (gpm)	Reference Volume (gal)	Error (%)
1	3.000	93.4	105.46	0.05
2	3.000	93.4	105.54	0.00
3	3.000	93.4	105.54	0.05
4	2.100	65.4	66.34	-0.08
5	2.100	65.4	66.24	0.11
6	2.100	65.4	66.32	-0.08
7	1.200	37.4	37.87	0.63
8	1.200	37.4	37.87	0.53
9	1.200	37.4	37.90	0.26
10	0.600	18.7	26.80	0.34
11	0.600	18.7	26.77	0.56
12	0.600	18.7	26.80	0.56

Operator:

Code:

3

Date:

06/15/2016

Statement of Calibration and Conformance

We hereby certify that the above unit conforms to the applicable specifications as referenced in, or furnished with this purchase order and has been calibrated using standards traceable to SIT and through the certified equipment listed above. Evidence of traceability is archived within the manufacturing plant and is subject to examination upon request.



8930 South Beck Avenue, Suite #107
Tempe, Arizona 85284

Phone: (480) 240-3400

Fax: (480) 240-3401

e-mail: flmarket@fitemeters.com

website: www.fitemeters.com

Transmitter Program Sheet

Description	Value
Converter Serial Number	FCA2121
Board Serial Number	016650
Flow Sensor Serial Number	FAC1217
Full Scale Flow Rate	gal/m 311.0625
Scaled Pulse Output Value	gal 15
Pulse Time Duration (ms)	10
Flow Meter Diameter (in)	2"
Ka Coefficient	1.9464
Kb Offset	000000
Current Output	4-20 mA
Language	English
Calibration Module	
Converter Model	608A
Note	ANSI 150

Technician Signature:

Date:

06/15/2016