INL/EXT-12-27526

Milestone Report #5: Prototype Test

Modifications and Optimization of the Organic Rankine Cycle to Improve the Recovery of Waste Heat

September 2013

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/EXT-12-27526

Milestone Report #5: Prototype Test

Modifications and Optimization of the Organic Rankine Cycle to Improve the Recovery of Waste Heat

Work Performed Under Agreement
DOE Industrial Technologies Program
Energy Intensive Processes
FWP 1275
CPS 19861
Agreement 17879

Report Authors
Jalal Zia[1], Jennifer Jackson[1], Paul Wickersham[1], Robert Benson[1], and Donna Post Guillen[2]

[1]General Electric Corporation, Global Research Center
Research Circle, Niskayuna, NY 12309

[2]Idaho National Laboratory
P.O. Box 1625, Idaho Falls, Idaho 83415

September 2013

Prepared for the
U.S. Department of Energy
Assistant Secretary for Energy
Efficiency and Renewable Energy
Under DOE Idaho Operations
Office
Contract DE-AC07-05ID14517

INTENTIONALLY BLANK

CONTENTS

FIGURES

TABLES

ACRONYMS

BSC	Building Support Center
EES	Engineering Equation Solver
ESD	emergency shutdown
FMEA	Failure Mode and Error Analysis
GC	gas chromatography
GT	gas turbine
HAZOP	Hazards and Operability Analysis
HX	heat exchanger
LEL	lower explosive limit
ORC	Organic Rankine Cycle
TC	thermocouple

INTENTIONALLY BLANK

Milestone Report 5 – Prototype Test Modifications and Optimization of the Organic Rankine Cycle to Improve the Recovery of Waste Heat

1. INTRODUCTION, PURPOSE, AND SCOPE

The opportunity for recovery of lost energy in thermal processes is estimated to be approximately 80 GW in the United States. In other words, this could save approximately 450 MM tons of CO_2 from entering the atmosphere. A significant fraction of this energy (about 10.7 GW) is emitted as exhaust (waste) heat from gas turbines at temperatures between 450 and 600°C.

Existing waste heat recovery processes (e.g., the OREGEN Organic Rankine Cycle [ORC]) attempt to recover this energy from such high-temperature exhaust streams by employing an intermediate heat transfer oil that protects the ORC working fluid from exposure to the high temperatures in the exhaust stream because the high temperatures (about 300°C) would cause thermal breakdown of the organic working fluid in the ORC.

The direct evaporator technology developed as part of this project allows direct contact between the hot exhaust and the ORC working fluid and mitigates the risk of fluid degradation by employing a "protective staging" (shown in Figure 1). The direct evaporator experiment conducted as part of this work aims to validate the premise of the direct evaporator in an ORC cycle: heat transfer from a hot exhaust gas at 500°C to a cyclopentane working fluid at conditions representative of an ORC cycle with boiling and superheating of the cyclopentane without risking thermal degradation. In addition, the following related data were collected for the 300-hour duration test:

- Data that show the temperature of the working fluid did not exceed 300°C
- Degradation data from samples of the working fluid collected at various times during the test
- A measure of fouling in the heat exchanger (HX) tubes (caused by thermal breakdown of the working fluid).

2. TEST FACILITY AND HARDWARE DESCRIPTION

2.1 Direct Evaporator Heat Exchanger Design

2.1.1 Direct Evaporator Requirements

A successful design of the direct evaporator must satisfy the required duty (i.e., the amount of heat to be transferred per unit time given the inlet temperatures and mass flows) and meet certain constraints specific to the working fluid and application. For extraction of heat from a low-pressure gas by a high-pressure fluid, finned-tube HXs were employed because of their suitable characteristics of low-pressure loss on the gas side, along with high surface area ratio between the fins (where the heat transfer coefficient is low) and the tube inside (where the heat transfer coefficients of the dense fluid are typically about two orders of magnitude larger). This leads to a high overall heat transfer coefficient in a relatively compact volume.

Generally, HX design is about finding a compromise between size (i.e., capital-intensive heat exchange area) and tolerable pressure losses of the fluids. However, in this case, specific constraints require a *distinctive* approach in regard to dimensions, geometry, and layout.

2.1.2 Constraints Imposed By the Working Fluid

The primary constraints imposed by the working fluid to the direct evaporator's HXs are as follows:

- Fluid temperature upper limit
- Safety in the event of leaking fluid

- Fin surface temperature lower limit.

By far, the most severe design constraint is the fluid temperature upper limit, above which decomposition starts. This limit, determined by experimental and theoretical means, is 300°C. Because the highest fluid temperature is found in the boundary layer of the fluid close to the wall of an externally heated duct, the inside wall temperature of all HX pipes must stay below this temperature limit at all times.

2.1.3 Strategies for Temperature Control

The inside wall temperature depends on the fluid bulk temperature, the heat transfer coefficient, and the heat flux. All three of these parameters are specified such that the inside wall temperature remains below 300°C.

To enhance the internal heat transfer coefficient, the velocity of the fluid inside the tubes must be high, putting a limit on the number of parallel tube passes and, at the same time, necessitating a certain pressure loss to be tolerated even when the tube length is kept as short as the aspect ratio and manufacturing costs allow. Internal heat transfer coefficients are highest in the evaporator section, where a nucleate and convective boiling regime prevails. The lowest heat transfer coefficients are found in the economizer section. The working fluid bulk temperature design point at the HX outlet was set to 250°C to allow ample margin for the wall temperature to stay below 300°C. The highest fluid temperature (i.e., 230 to 250°C) is encountered in the superheater section of the boiler.

Within the concept of "protective staging," the superheater section is placed in the exhaust gas stream behind the evaporator section (see Figure 1), where the exhaust gas is already cooled but it is still hot enough to ensure reasonable heat transfer performance in a counterflow layout. The evaporator section is placed first in the exhaust stream in a parallel flow arrangement, such that the highest exhaust gas temperature is met by a fluid bulk temperature at the boiling point, but at low vapor quality. In this regime, the heat transfer coefficients are highest and can only increase with the heat flux. The danger of local wall dryout (that leads to sharp wall temperature spikes as the heat transfer coefficient collapses) is minimal because of the low vapor quality. As the vapor quality increases along the evaporator, the exhaust gas temperature and the heat flux decrease. By the time dryout is expected, the high-volume flow rate has increased the gas phase heat transfer coefficient, while the exhaust gas temperature is low enough the wall temperature limit is not exceeded.

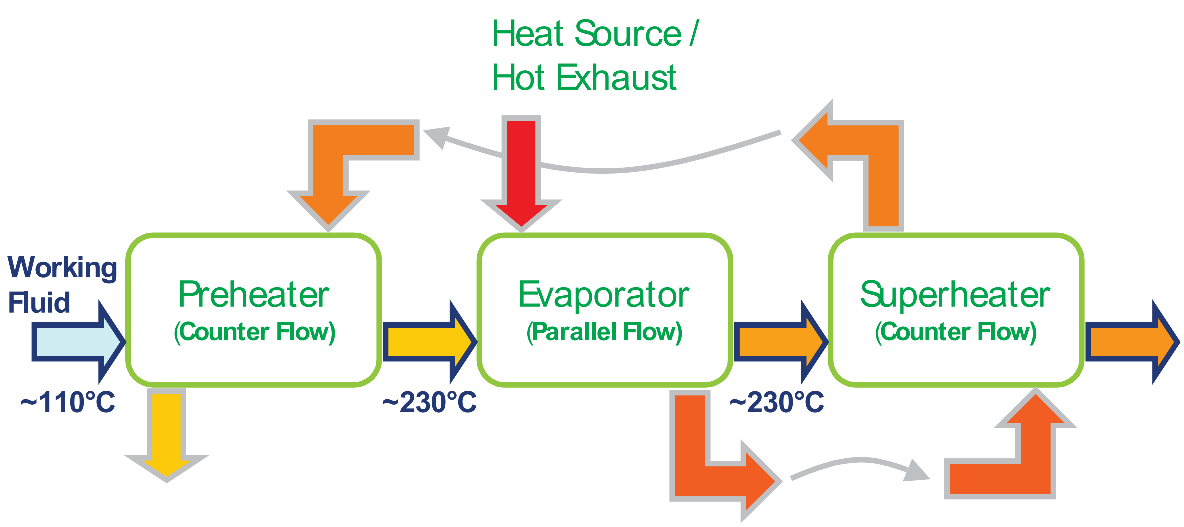


Figure 1. Concept of protective staging applied to a gas turbine exhaust stream.

Implementation of this concept is schematically shown in Figure 2. A further measure for limiting the heat flux and decreasing the inner wall temperature where it can become critical is to reduce the number and area of fins on the tube's outside. This concept of "variable finning" of the tubes (see Figure 3) throughout the length of the HX includes smaller and less densely spaced fins in the superheater and evaporator section, where the temperatures are high and the internal heat flux must be limited. However, in the economizer (i.e., preheater) section, where the temperatures are lower and the wall temperature is not critical, larger diameter and serrated fins with tighter fin spacing are used to improve heat transfer performance and reduce the number of rows necessary to achieve the required duty.

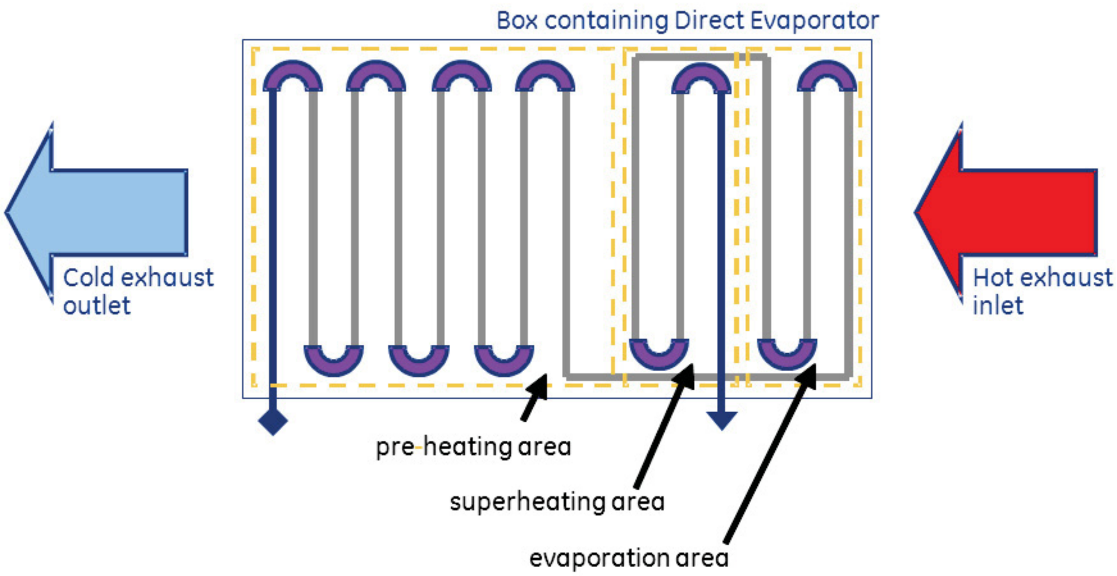


Figure 2. Implementation of protective staging (evaporator in parallel setup).

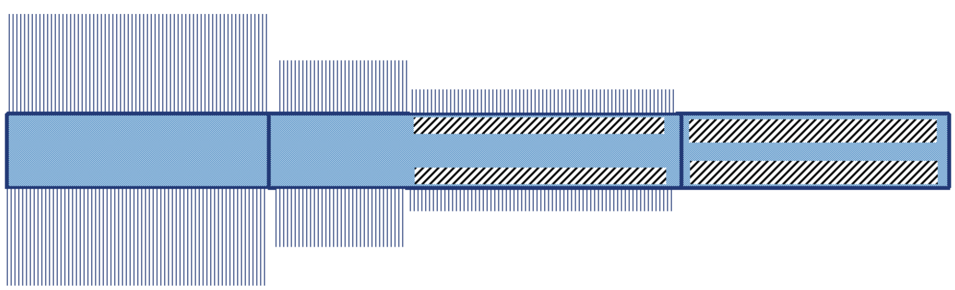


Figure 3. Variable finning of the tube and enhancements of the internal heat transfer surface to control heat flux and the tube-side film temperature.

2.1.4 Heat Exchanger Modeling Results

A detailed thermodynamic model has been set up for the entire HX in the program Engineering Equation Solver (EES) (F-Chart Software Inc.) to design and simulate the HX performance for a direct evaporator using the protective staging concept. The output of this model includes all heat flows, heat fluxes, and temperatures at the inlet and outlets of each section on the working fluid and the exhaust gas side. It contains detailed correlations for the pressure loss and heat transfer coefficient of the fin tubes measured in-house. The current preliminary design is based on these data. The outputs of this tool were compared to the outputs of the commercial HX design program ASPEN ACOL Exchanger Design and Rating and they agreed very well (see Figure 4). The wall temperatures are predicted to stay well below the critical limit, and the pressure losses of the exhaust gas and the working fluid are less than the design limits as well. An off-design mass flow/pressure loss calculation carried out for each section of the boiler indicated stable flow behavior, without the danger of oscillations characteristic for once-through steam boilers that are caused by maldistribution in parallel flow passes. Flow stability is attained when the gradient of pressure over mass flow is always positive throughout the range of operation, which was shown in the calculations.

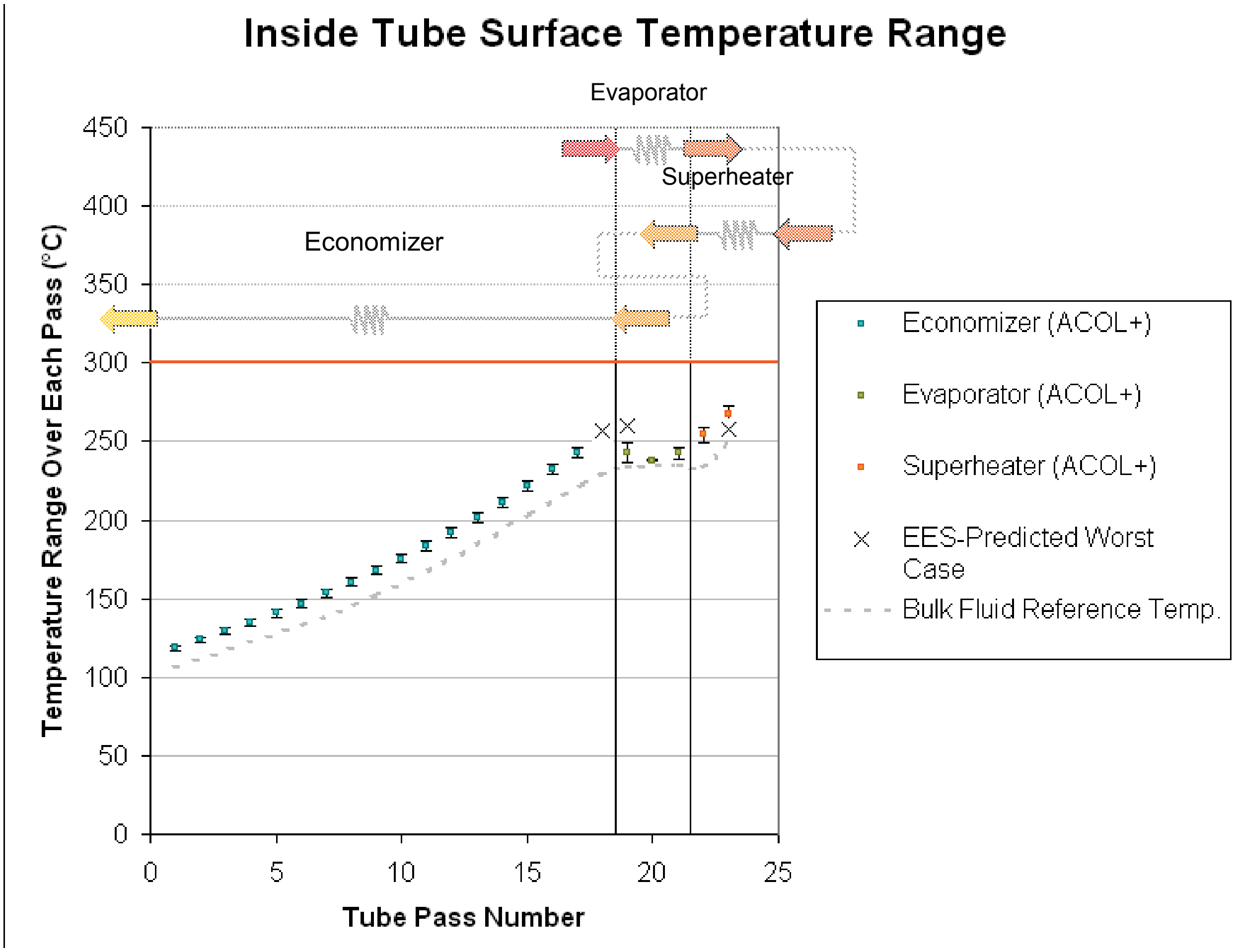


Figure 4. Working fluid side surface temperature in direct evaporators.

2.1.5 Heat Exchanger Design Summary

The preliminary design of the boiler includes three harps of fin tube bundles, the economizer, the superheater, and the evaporator suspended in a rectangular duct. The number of rows is 24, 2, and 2, respectively, giving a total of 28 rows with 60 tubes per row. The economizer section only has two rows per pass for the lower pressure loss, the economizer and superheater are in counterflow to the exhaust gas, and the two evaporator rows are arranged in parallel flow. The headers are laid out as manifolds on top of the tube bundles, with each bundle having a once-through flow path. The headers are tentatively placed outside the duct to prevent having zones of hot, slow moving fluid near walls and headers with weld seams, which could increase the risk of auto ignition in case of a leak. A simple schematic of the design is shown in Figure 5.

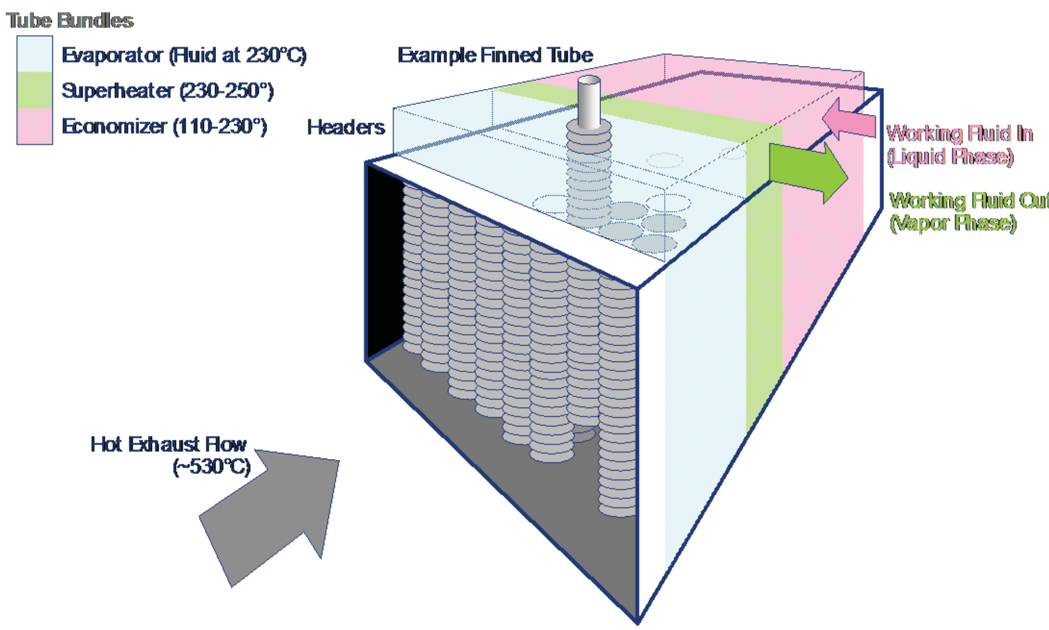


Figure 5. Direct evaporator design schematic.

2.2 Testbed Design

2.2.1 Design for Safety

The direct evaporator is focused on developing a HX that transfers heat from a high-temperature gas turbine exhaust gas to the working fluid of an ORC. Besides technical issues (such as working fluid decomposing at elevated temperatures), safety is a major concern because the working fluid of choice is cyclopentane, which is a hydrocarbon. Cyclopentane is flammable and has an auto-ignition temperature of 361°C (Gallant and Yaws 1993), which is significantly lower than the gas turbine exhaust temperature of up to 530°C. To mitigate any risks upfront, Failure Mode and Error Analysis (FMEA) and Hazards and Operability Analysis (HAZOP) safety studies were performed.

The safety analysis of the direct evaporator consisted of the following three stages:

1. At the beginning of the project, all conceivable risks were reviewed and it was decided what risks deserved the most attention due to not being easily mitigated (preliminary FMEA)
2. Once the initial research phase was complete and before the development effort transferred over to the business element, HAZOP was conducted along with business operations to agree upon a detailed plan for addressing hazards in every mode of operation
3. Finally, FMEA was performed specifically for the performance test planned in Niskayuna, New York.

2.2.2 Preliminary Failure Mode and Error Analysis

At the beginning of the direct evaporator research effort, the most serious risks anticipated from heating the cyclopentane working fluid in direct proximity to a hot gas turbine exhaust were as follows:

1. Thermal fatigue
2. Mechanical vibration
3. Corrosion of the tube banks
4. Manufacturing defects
5. Leak ignition.

These major risks correspond to the items identified in red in Table 1.

Table 1. Initial Failure Mode and Error Analysis for anticipated risks to the direct evaporator.

#	Risk	Details	Probability	Impact	Detectability	Risk Rating	Abatement	New Probability	Impact	New Detectability	New Risk Rating
1	unburned fuel in exhaust duct	Potential explosion hazard, Leakage	1	5	1	5	NONE - Existing unburned gas sensor of GT	1	5	1	5
2	hot cinder from GT	Potential ignition source	1	5	5	25	Avoid Leakage, Fresh Air Ventilation, HC sensor	1	1	5	5
3	transient thermal gradient in exhaust	Mechanical integrity (cyclic fatique), Leakage	5	5	5	125	HX design to withstand GT transient operation	1	1	1	1
4	exhaust temperature over HX design limit	Overheat HX, Overheat Fluid, Mechanical integrity	5	3	1	15	HX design to withstand Highest GT exhaust temperature	5	1	1	5
5	projectile from GT (blade)	Big Leakage	1	5	5	25	Position of HX no radially to GT	1	1	5	5
6	resonance from GT exhaust	Mechanical integrity (cyclic fatique), Leakage	3	5	3	45	HX design/check to avoid resonance of flow	1	5	3	15
7	resonance from GT (machine)	Mechanical integrity (cyclic fatique), Leakage	3	5	3	45	NONE - GT on one fundation, isolated duct	1	5	3	15
8	Corrosion of tubes	Small Leakage	5	3	5	75	Corrosion Allowance, Regular Checks, HC sensor	5	1	1	5
9	overpressure	Big Leakage	5	3	1	15	Safety Valve for boiler, Pump max pressure < than design pressure	1	1	1	1
10	Manufacturing Defect (welding, mounting etc.)	Small Leakage	3	3	5	45	HC sensor	3	1	1	3
11	over-temperature	Due to ORC failure, Big Leakage	5	3	1	15	Close Baffles; conduct exhaust directly to the chimney	1	3	1	3
12	cyclopentane released to ambient from safety valve	safety valve opening	5	1	1	5	Safety Valve for boiler releasing to condenser, controls	3	1	1	3
13	Flame as a consequence of a leakage	Leakage produces combustible mixture with a more or less stable flame	1	5	5	25	Fire Sensor (UV)	1	5	1	5
14	Explosion as a consequence of a lekage	Produce a explosive mixture in the HX (baffle closed)	3	5	3	45	Ventilate isolated part of stack when baffle closed	1	5	1	5
15		Produce an explosive mixture in the HX (major leakage during normal operation)	3	5	3	45	additional HC sensor located just downstream of HX	1	5	1	5

2.2.2.1 Thermal Fatigue. Following a cold start of the direct evaporator, metal temperatures increase over a range of hundreds of degrees Celsius. Differential thermal expansion in the various materials used in the construction of the evaporator can put large stresses on the material interfaces, especially on welded joints between the working fluid tubes and the frame. Over the life of the evaporator unit, repeated cycles of startup and shutdown can eventually aggravate small imperfections in the weld to open cracks through which working fluid under high-pressure escapes from the tube into the hot exhaust flow. A large leak would be noticed immediately from the measurable loss of working fluid; however, the smallest leaks could persist for weeks or months before they are recognized and repaired.

2.2.2.2 Mechanical Vibration. The boiling process within the tubes, as well as the aerodynamic buffeting experienced by the tube banks during steady-state exhaust flow, contribute to vibration that can eventually fatigue and weaken the tube joints. Excessive strain of fatigued members might open cracks in the tube material or welded joints, allowing a release of working fluid into the hot exhaust flow.

2.2.2.3 Tube Corrosion. Although substantially depleted of oxygen, the residual oxygen content, as well as the water content, of the exhaust flow from the gas turbine have a non-negligible potential to corrode the carbon steel of the direct evaporator fluid tubes over time. The risk of corrosion is already significantly reduced by observing a minimum exhaust temperature to prevent so-called “acid gas” exhaust components from precipitating out of the gaseous phase to corrode metal surfaces. The concern arising from corrosion of the evaporator tubes is that it may ultimately open pinhole leaks in the tube wall or simply weaken the wall sufficiently that thermal or mechanical stresses could cause a rupture.

2.2.2.4 Manufacturing Defects. Defects in the piping material or welded seams, if not discovered through pressure tests during commissioning, remain as potential nucleation points for cracks throughout the lifetime of the evaporator.

2.2.2.5 Leak Ignition. Various more serious effects could result from leaks in any of the above scenarios, including ignition of the fluid that causes hot spots and gradual weakening of the structure, as well as the possibility that leaks would feed larger cells of combustible gas, which could explode suddenly and cause catastrophic failure.

The estimated magnitude of these risks was necessarily quite provisional because no research had yet been performed on the detailed mechanism for each of the failure mechanisms. However, reports on steam boiler technology provide examples of rupture mechanisms originating from corrosive interactions with the tube steel. For many boiler applications, leaks are described in the boiler literature as an inevitable symptom of ageing. The project strategy changed after a review of leakage as an industry phenomenon. From initially proposing to guarantee a leak-free system, the focus changed to designing a system in which leaks would have no effect other than (harmlessly) signalling the need for boiler maintenance.

By identifying a safe means of recognizing and handling leaks in general, all particular leak scenarios, including corrosion and thermal or mechanical strain failure, can be simultaneously addressed. A safety mechanism that could anticipate and “disarm” leaks, allowing no opportunity for ignition or explosion, would conclusively mitigate all conceivable leak scenarios at once. In line with this approach, subsequent analysis and experiments focused on setting safe limits on the range of velocities and temperature of hot exhaust in which no amount of leaked working fluid could ignite. It was found that even at exhaust temperatures up to 600°C and flow rates as low as 24 kg/s (or about one-third of the normal operating level), any leaked fluid in the freestream would be expelled from the system before it had the chance to ignite.

A contingency plan for the possibility of fluid leaking into the hot exhaust flow must take account of several different operating modes, all of which imply different criteria for safe operation of the system:

1. Gas turbine (GT) and ORC in normal, steady-state operation
2. GT operating normally, ORC in emergency shutdown (ESD), diverter switching from “open” to “bypass” condition
3. GT in ESD, ORC in ESD, diverter moving from “open” to “bypass”
4. GT operating normally, ORC in ESD, diverter fully in “bypass”
5. GT in ESD, ORC in ESD, diverter fully in “bypass”
6. GT operating normally, ORC cold (shutdown), diverter fully in “bypass”
7. GT operating normally, ORC cold beginning startup, diverter initially in “bypass”
8. GT operating normally, ORC hot beginning startup, diverter initially in “bypass”
9. GT operating normally, ORC cold starting up, diverter switching from “bypass” to “open”
10. GT operating normally, ORC hot starting up, diverter switching from “bypass” to “open”
11. GT shutdown, preparing to restart, ORC boiler cleared by purge with GT crank and diverter “open”
12. ORC shutdown for maintenance, diverter fully in “bypass.”

During a formal HAZOP review in December 2009, GE Global Research and GE Oil and Gas developed a comprehensive strategy for safe operation of the evaporator under each of the above regimes. In this analysis, the review committee conservatively assumed that leaks would be possible in any operating mode and identified specific steps to neutralize the ignition risk under that assumption. Leak experiments at GE Global Research Munich established that leaks would not auto-ignite under the conditions of temperature (about 500°C) and flow (60 to 70kg/s) prevailing in the exhaust stream during steady-state operation. In the final product, flame and hydrocarbon detectors would be installed so that persistent leaks can be promptly identified and repaired, but the steady-state exhaust flow would generally prevent streams of leaked fluid from residing for long enough within the hot section of the evaporator to permit auto-ignition. However, the small risk remains that a leak should occur during a transition state when the gas turbine is in the process of shutting down, or when the diverter is in the course of opening or closing. Under these circumstances, residence times at high temperature may increase several fold as the bulk exhaust flow is throttled by a partially open diverter baffle. For this contingency, the HAZOP review calls for the following supplementary equipment to be installed:

- A draft fan should be activated for the duration of the diverter's transit from "open" to "bypass" or from "bypass" to "open." The fan would be located upstream of the evaporator and serve to cool and reinforce the flow of air through the evaporator, thereby carrying any leaked material completely through before it can auto-ignite.
- In case the fan malfunctions and fails to come on at the required time, a tank of compressed inert gas (CO_2 or nitrogen) of sufficient size to maintain a minimum flow through the evaporator should be discharged into the unit until the switching of the diverter from one setting to the other is complete. This precaution should disperse and render non-flammable any leak of working fluid that may have arisen within the evaporator tubes.

Using the above approach, a robust airflow can be maintained within the evaporator whenever hot exhaust gas is present. These systems also would engage after the diverter has been fully closed if the seal is not complete and the presence of exhaust gas in the evaporator can be inferred by thermocouples (TCs) measuring the upstream flow temperature. The logic diagram for the complete safety system is shown in Figure 6.

2.2.3 Testbed Design and Safety

Figure 7 shows a simplified schematic for the experiment. The direct evaporator unit was externally mounted on a concrete pad with support braces guarding against wind loads. The vitiated natural gas heater also was externally mounted. Utility air flow was obtained from a facility compressor. Cooling water circulation also was a utility from a facility-operated cooling tower. All other experimental hardware was mounted inside a 'trailer' indicated by the dashed orange lines in Figure 7.

In a separate study completed by GE Global Research in Niskayuna, New York in June 2009, an FMEA was conducted by a team assembled from the environmental health and safety organization, fire protection organization, principal researchers, veteran technicians, and the experimental team. The group reviewed each subsystem of the prototype and identified common and uncommon risks that needed to be addressed. The most pressing risks (noted in red in Table 2) were those pertaining to a leak of the working fluid, either into the exhaust stream or into the experimental area. A description of each subsystem and the associated risks is presented in the following subsections. For a detailed description of all equipment installed on the test loop, refer to the piping and instrumentation diagram in Appendix A and the equipment description in Appendix B.

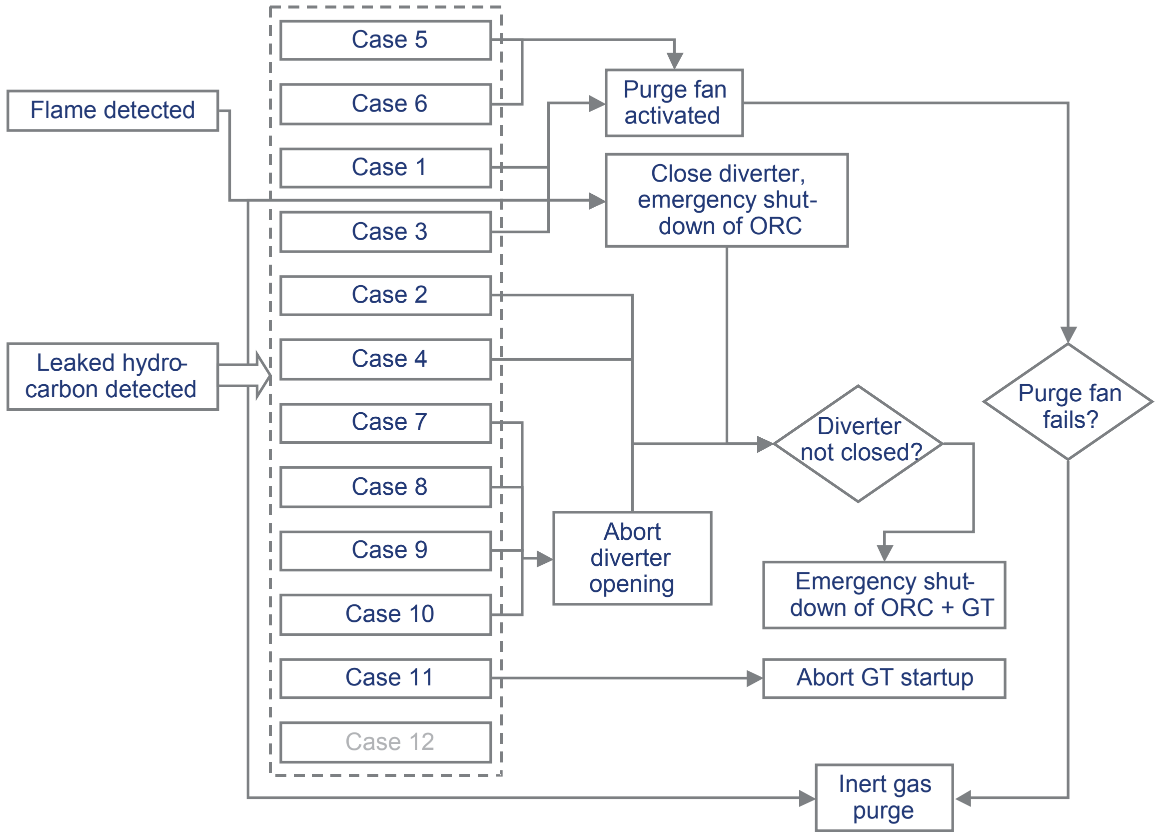


Figure 6. Safety system logic diagram.

2.2.3.1 Cooling Water Loop. The primary mechanism to condense the superheated vapor exiting the test HX is a shell and tube HX with the coolant being tower water that is circulated via an onsite loop. This cooling water loop supplies numerous experiments in the building; therefore, the usage demands change daily.

Two mechanisms of failure were identified, with the first being a loss of cooling flow, which would result in the working fluid not being condensed in the condenser and eventually vaporized fluid will enter the test HX, leading to overheating of the fluid and pressurization of the loop. Four scenarios could result in this situation, a pipe failure within the cooling loop, a loss of flow control or failure of a valve upstream, a failure of the tower water circulation pump, and too high of a demand on the water supply due to concurrent experiments. The first three scenarios will be handled by careful monitoring of the system and use of ESD procedures should the need arise. The fourth scenario will be avoided by communicating and coordinating with other experiments prior to and during testing.

The second mechanism of failure would result from too high a cooling flow rate, resulting in overcooling the working fluid. This scenario is far less severe than the previous situations and is ranked accordingly in FMEA.

2.2.3.2 Direct Evaporator Prototype. As noted above, the primary goal of this program is to remove the indirect oil loop separating the hydrocarbon HX and the hot exhaust gas. In doing so, there is an elevated risk of an ignition event occurring. The prototype HX has been designed, under the supervision of the GE technical team, by an outside vendor with extensive experience in heat recovery steam generators and hydrocarbon applications. With the currently selected hydrocarbon, a risk of overheating the film of the working fluid exists, resulting in hastened chemical decomposition, change in thermal and chemical properties, and potential for fouling on the heat transfer surfaces. To reduce this risk, a margin of 30°C was placed on the limit of the film temperature, along with contracting an experienced vendor to perform and to confirm GE’s calculations of the film temperature.

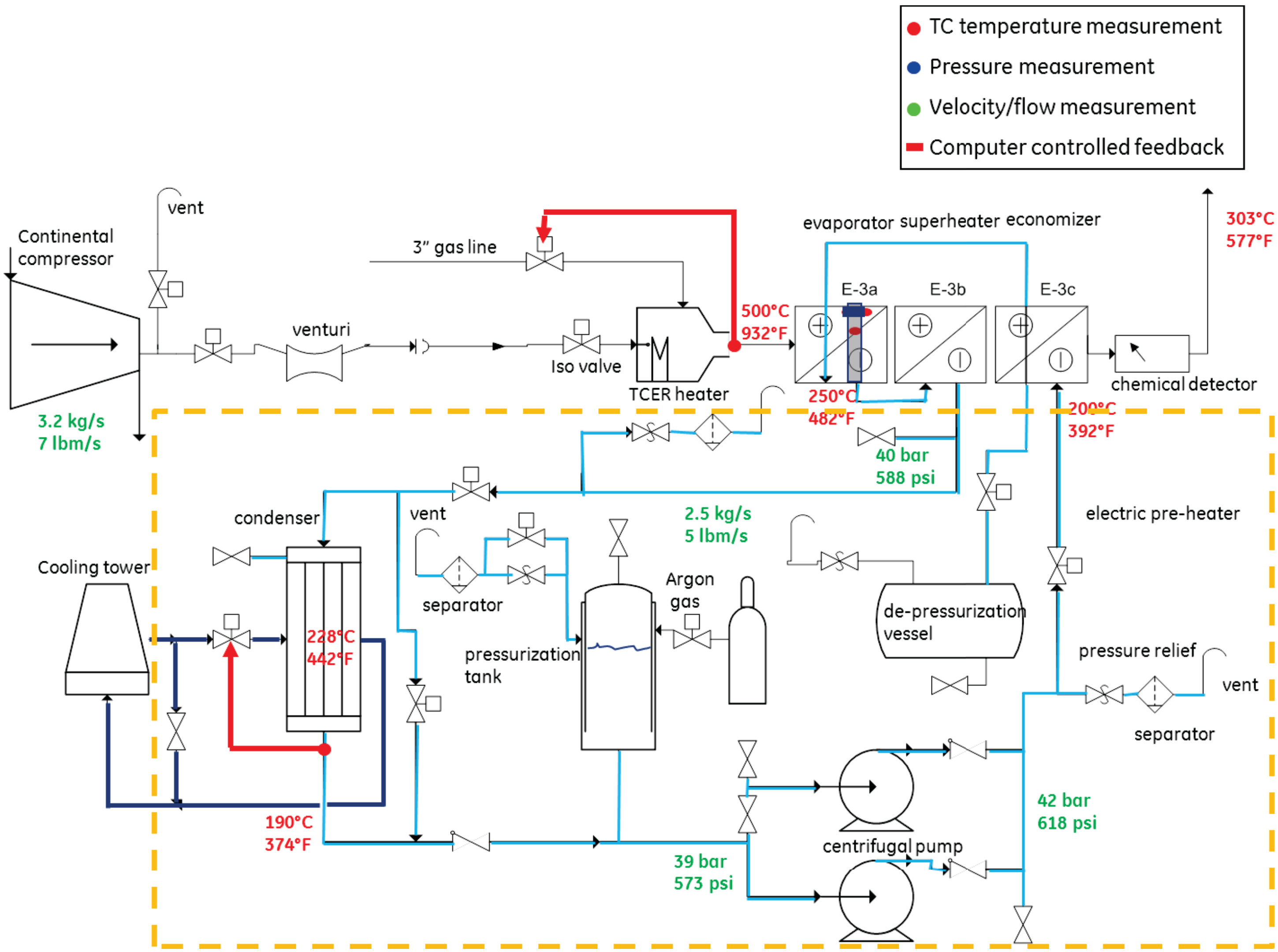


Figure 7. Simplified schematic for the performance test.

Table 2. Failure Mode and Error Analysis for Niskayuna performance test setup.

Item	Potential failure modes	Potential Effect(s)	Sev	Potential Cause(s)	Occ	Design Controls	Det	RPN	Action(s)	New Sev	New Occ	New Det	New RPN
Cooling water loop	Pipe burst	Loss of cooling	7	Freezing, mtl. defect, installation defect	2	Continuous water circulation; space heater	3	42	Test bypass/space heater prior to op.	7	2	3	42
	Loss of flow control	Too high cooling flow	3	Control valve failure, control system defect, wiring defect	3	Control valve-positioner through PLC controller box	4	36	Test control system to decrease flow at a drop in temperature	3	3	4	36
		Too low cooling flow	7	Wiring defect; leak in cooling line; loss of tower water	4	ESD of system	3	84	Test ESD procedures	7	4	3	84
	Cooling pump failure	Too low cooling flow	7	Motor failure, bearing failure, improper installation	2	ESD of system	3	42	Test ESD procedures	7	2	3	42
	Inadequate cooling flow	Too low cooling flow	7	High demand for tower water	5	Coordinate testing days with other high demand tests	3	105	Keep researchers apprised of the testing needs; consult Samuels	7	5	2	70
Direct Evaporator	Chemical decomposition of working fluid	Change in thermal properties	7	Overheating of fluid film temperature	4	Frequent fluid sampling	4	112	Working with HRSG vendor to ensure margin in film temp. calculations	6	4	4	96
	Working fluid leak into exhaust gas	Flame/explosion	10	Pin-hole in tube/tube rupture	4	Design of HRSG by certified vendor with hydrocarbon experience	5	200	Leak/rupture test completed in Munich; CO_2 system head for heat-ex	6	4	4	96
	Metal dusting	Significant leak of working fluid into exhaust stream	8	Metal dusting, reaction between metal and hydrocarbon	3	Design short operating lifetime; monitor working fluid for any evidence of metal dusting	3	72	Determine expected evidence of metal dusting; include on decomposition screening	8	3	3	72
	Fin meltdown	Improper heat transfer, leak into exhaust stream	10	Improper design, material failure	3	Proper tubewall sizing/material for temp	5	150	Consult HRSG manufacturer for input on tubewall/fin spacing/mtl.	10	2	4	80
Exhaust gas system	Exhaust gas leakage to ambient	Combustion gases released into container/exhaust stream	3	Leaks in flanges/heat exchanger casing	3	Appropriate notifications will be sent prior to running the test to minimize employee exposure	3	27	CO test point located at potential source	3	3	3	27
	Loss of air flow control	Too much flow to heat exchanger; overheating working fluid; over pressurize	7	Control valve failure; air flow rate measurement failure	4	Control system monitoring of flow; ESD	3	84	Photohelix will measure dP across heater, inline venturi will measure air flow	7	4	3	84
		Too little flow to heat exchanger; lower fluid temp; loss of efficiency; under pressurize	4	Control valve failure; air flow rate measurement failure	4	Control system monitoring of flow	3	48	Photohelix will measure dP across heater, inline venturi will measure air flow	4	4	3	48
Inline heater	Flame out	Fuel gas will exit heater unburnt; enter heat exchanger	6	Loss of flame, ignition problems	4	Flame detector/heater control panel	4	96	O_2 monitoring; ventilation in container; pre-operation system purge	6	4	4	96
	Uncombusted natural gas in exhaust	Flame/explosion in exhaust	4	Leakage, flameout conditions, improper operation	4	Purge at evaporator start-up; max start temp	4	64	UV detector in heat exchanger casing	4	4	3	48
Working fluid loop	Valve, fitting leak	Spill of hydrocarbon, build-up of flammable/explosive gases in container	7	Material failure, improper installation	4	Secondary containment with gas detection/ventilation system	6	168	Leak test prior to running; X-ray 10% of welds	6	3	5	90
	Loss of pressure control	Overpressurize working fluid - gas leak	7	Computer failure	3	Pressure monitoring; over-pressure reliefs; ESD	4	84	Test all pressure reliefs/transducers	7	3	4	84
		Underpressurize working fluid liquid state; boiling in tubes	7	Insufficient inert gas; computer failure	4	Pressure monitoring; ESD	4	112	Manifold 3 bottles of N_2 w/ pressure regulating valve	7	3	3	63
	Pump failure	Loss of flow	8	Motor failure, bearing failure	3	ESD of system	3	72	Routine maintenance of pump as required by manufacturer	8	3	3	72
	Superheater temperature higher than expected	High pressure in loop	6	Improper heat transfer in heat exchanger	3	Variable water flow through condenser to control temp	3	54	Additional tube rows in HRSG design to allow for slight adjustment	6	3	3	54
Continental compressor trip	Loss of power; trip	Heater trip	3	Power outage; trip; power surge; low oil; operator error	3	Verified flow to heater or immediate shutdown	3	27	Regular maintenance of compressor according to manufacturer instructions	3	3	3	27
Container	Fire	Explosion/equipment damage	8	Leak, fire in evaporator	3	Fire extinguishing system, CO monitor, gas detection, ventilation	3	72	Test UV detectors prior to running	8	3	3	72
	Exhaust gas leak	Toxic gas released	8	Leak between heat exchanger casing	4	CO/gas monitoring system; ventilation	3	96	Unmanned test; O_2 sensors detecting dangerous levels	7	4	3	84
	Working fluid leak	Fire, potential for fired explosion	8	Component leak	4	Fluid containment, ventilation, depressurization	4	128	Leak test prior to running; detailed ESD procedures	5	4	4	80
Containment	Leak of working fluid from containment vessel	Release of hydrocarbon into water stream, flammable mixture	5	Improper sizing of vessel, crack, failure of vessel	3	Welded lip around secondary containment sized to hold fluid	4	60	Check for any leakage prior to and after each day of testing	5	3	4	60

Perhaps the more pressing risk is a tube rupture or a pinhole, resulting in cyclopentane spraying into the exhaust gas where the temperature would be higher than the auto-ignition point. Additional causes for such a leak were identified, one being a hole resulting from metal dusting. This phenomenon occurs when in the presence of a high-carbon concentration, a metal alloy absorbs carbon atoms that result in a supersaturation of the alloy and a weakening or degradation of the metal. The rate at which this occurs depends on the alloy composition, the gas environment, the temperature, and the pressure. Although this is known to occur, the team felt there was a low risk of this occurring in the current test. A second cause of the leak could be fin meltdown. Drawing on the experience of a well-established vendor and GE experience, the thickness, material, and construction were specified to minimize this risk.

Detailed drawings of the HX can be found in Appendix C.

2.2.3.3 Hot Exhaust Gas Supply. In the HX test, a supply of hot air is necessary to provide the required heat input. A vitiated inline natural gas heater is employed to supply approximately 10 lbm/s of hot gas at 500°C. This heater is fed from an upstream, low-pressure compressor.

The primary concern of this system is leakage of hot gas to an area where a person could be injured or exposed. Also, to reduce the risk of a burn due to a release of hot gases from the supply line, signs were posted to limit foot and vehicle traffic during operation and e-mail reminders were sent to the building employees. To prevent any incidental burns, all pipes carrying hot gas were insulated to maintain a safe touch temperature of 49°C.

A final concern for the exhaust side supply is loss of control that results in too much or too little flow. Changes in flow and temperature on the exhaust side will directly impact the temperatures of the working fluid exiting the HX. Flow will be measured and controlled upstream of the inline heater using a venturi flow. Furthermore, ESD procedures will be initiated if flow control is lost.

The inline heater operates using natural gas and supplies the hot gas side of the HX. Because it is a vitiated heater, the hot gas is a mixture of combustion products with some unburnt hydrocarbons. The risks associated with this item stem from natural gas flowing downstream into the HX as the result of a flame out and the risk of an ignition event due to natural gas in the HX at the time of startup. To reduce these risks, a purge process prior to startup will be performed to ensure the HX does not contain a combustible mixture upon ignition of the heater. Further, the heater is capable of detecting a flameout and will begin shutdown procedures if this were to occur.

2.2.3.4 Working Fluid Loop. The working fluid loop circulates through the test HX, into a condenser, through a pump, and back into the test HX. All piping, along with all instrumentation containing the hydrocarbon, will be enclosed in the container to prevent release. The piping in this loop is made of carbon steel with numerous valves and instrumentation ports along the distance. All connections are potential weak points from which leaks can develop; this is addressed as the first risk, wherein a leak from the piping/valves would result in the build-up of an explosive mixture of flammable gas. To prevent any release of liquid cyclopentane outside of the trailer (shown as the orange dashed line in Figure 7), a secondary containment floor, with a lip, will be installed under all equipment in the trailer. To reduce the risk of a build-up of explosive fumes, two hydrocarbon sensors calibrated to detect cyclopentane will be positioned in the trailer, and elevated levels of hydrocarbon (10 to 25% of the lower explosive limit [LEL]) will trigger increased ventilation and ESD procedures.

A second concern for the release of the hydrocarbon is that through a computer malfunction or inadequate pressure control, the hydrocarbon would be released. This would be possible due to either an over or an under-pressure event. During an over-pressurization of the system, control of the nitrogen pressurization system would be compromised and the system pressure would increase. The pressure sensors throughout the loop would measure this increase; however, if system control cannot be regained, over-pressure valves will release nitrogen to reduce pressure. In the second scenario, an under-pressure event could occur as a result of low pressure in the nitrogen tanks. This loss of pressure could lead to boiling in the pipes of the loop. To reduce this risk, three bottles of compressed nitrogen gas will be tied together using a manifold, and daily checks of the pressure in the bottles will ensure that adequate pressure is maintained.

A final concern of overheating of the working fluid is loss of flow through the loop due to a malfunction or cavitation of the large circulating pump. This decrease in flow rate would allow for longer residence time in the test HX, which in turn would lead to overheating of the working fluid in the film regions. It is thought to be a minor risk and the system would enter ESD procedures if this event were to occur.

2.2.3.5 Compressor. A low-pressure compressor will supply air to the heater, which will then form the hot exhaust gas used in the test. This compressor can supply up to 20 lbm/s of air at 15 psig. In the event the compressor would trip, the heater would no longer receive the necessary flow signal and would shut down.

2.2.3.6 Container/Trailer. The container/trailer procured for this test is a 28-ft long × 8-ft tall × 10-ft wide container previously used to house an engine. The container has been retrofitted with several safety systems to contain and control any foreseeable hazardous condition. A CO_2 fire suppression system using ultraviolet sensors will detect a flame present in the container and trigger release of the suppression element. Further, a temperature sensor that measures increases in the exhaust gas temperature will be used to determine an event occurring within the test HX and will dispense the suppressant. Using the temperature sensor versus a line-of-sight detection system will have better results because much of the HX surface will be blocked from the line of sight by narrowly spaced rows of tubes.

An additional risk is leakage of the hot exhaust gas from the HX and into the container. A CO sensor will be installed to detect combustion by-products while an O_2 sensor will measure levels and display warning signals to personnel prior to entering the container and auditory alerts while inside the container. The chance anyone would be exposed to CO during this test is very slight, because no personnel will be permitted in the trailer during operation.

Lastly, as noted above, the container will have two points measuring the hydrocarbon levels to detect small leaks and to maintain safe levels for operation. Ten percent of LEL (i.e., an increase from 2,500 to 5,000 cfm) will trigger additional ventilation. Twenty-five percent of LEL will trigger shutdown of all non-explosion proof electrical components and an ESD of the system.

2.2.3.7 Leak Containment. The final risk assessed was a leak of working fluid from the container. As noted above, the secondary containment will be constructed below all components containing the hydrocarbon and will have a lip large enough to contain the total amount of hydrocarbon in the system (100 gal). There will be strict protocols for ensuring that no leaks are present at the start or completion of each test day.

The team has very thoroughly addressed the concerns for this complex and challenging test and is confident that the end goal of running a safe, productive HX test can be successfully achieved. The systematic approach of assessing each component of the system, although potentially redundant, offers assurance that risks are not overlooked. Lastly, although not every risk can be completely avoided, much effort was spent in developing ESD procedures to quickly isolate and remove threats to the test and personnel.

3. TEST CONDITIONS

3.1 Shakedown Testing and Prototype Test Procedure (Standard Operating Procedure)

This test and setup were designed to characterize an experimental HX with the working fluid cyclopentane in the direct path of an exhaust stream to simulate the HX behind a PGT25 gas turbine. The working fluid cycled in a loop consisting of the test HX, a heat recovery vapor generator (Deltak, Inc.), a condenser (Thermal Products Inc.), and a pump (ChemPump). The pressure in the system was maintained by a rack of hydraulic piston accumulators (Pearse Bertram). The maximum temperature of the vapor exiting the HX superheater (I-16) was 250°C and the system pressure was controlled at 508 psia (35 bar) as measured at the inlet to the HX. Prior to entering the pump, fluid is condensed and subcooled to approximately 165°C.

This test was run via a remote station located in Room No. ES 154, with remote monitoring cameras on the HX and on the inside of the container. Further, after a short performance characterization test, the system was run for approximately 300 hours, with periods for ramping and deramping the system with predetermined sampling intervals to measure the degradation products.

Prior to starting full-scale tests with flammable cyclopentane, a detailed shakedown plan was drawn up to test the various subsystems and procedures with a benign chemical (10% alcohol/water mixture). Performing a full subsystems and procedures shakedown test with the above fluid allowed a further benefit of precleaning the test rig before finally charging with cyclopentane.

The following shakedown procedures were documented, reviewed, and approved prior to a run through with the alcohol/water mixture:

- Charging of the HX and piping (Appendix D)
- Standard operating procedure (Appendix E)
- System event response checklist (Appendix F)
- Trailer entry procedure (Appendix G)
- Draining of HX and piping (Appendix H)
- Hot sample collection procedure (Appendix I)
- Inert gas purge procedure (Appendix J)
- Heated drying protocol (Appendix K).

3.2 Derating the Test Pressure

The design operating conditions of the test cycle were chosen to match the OREGEN cycle product from GE Oil and Gas. The design conditions called for a maximum cycle pressure of 43 bar (downstream of the pump), where the liquid cyclopentane should be at a temperature of 190°C. The HX exit pressure was expected to be 40 bar at a temperature of 250°C.

During installation of the condenser, it was noticed that the rating plate stated a maximum operating pressure of only 38 bar (absolute). Therefore, it was not possible to achieve the original design conditions of 43 bar downstream of the pump. After prolonged discussions with the vendor, the team of engineers, and the prime contractor, it was decided to derate the maximum operating pressure in the rig to a maximum operating pressure of 37 bar, 190°C downstream of the pump. As a result, the expected HX exit pressure was 34 bar and a superheater output temperature of 250°C. However, in many cases, the amount of superheat could easily be varied by controlling the hot resource flow rate and temperature. The upper temperature limit on the cyclopentane working fluid was still 300°C. It was surmised that lowering the operating pressure in this manner would not limit the ability to test for fluid degradation because the amount of superheat could still be varied when required. The risk of degradation was actually higher in this case due to the lower saturation pressure (and lower saturation temperature of 220°C) of the working fluid. It was decided this increased risk of fluid degradation would be managed by careful monitoring of the HX tube wall temperatures and control system alarms for possible temperature excursions. Table 3 shows a comparison of the original and derated operating conditions.

Table 3. Comparison of original and revised operating conditions.

Cycle Location	Original Design Conditions	Revised Conditions
Circulation pump	190°C, 42 bar	190°C, 37 bar
HX exit	250°C, 40 bar (Tsat: 232°C)	250°C, 34 bar (Tsat: 220°C)
Condenser exit	190°C, 39 bar	190°C, 33 bar

3.3 Reduction of Test Run Time

The purpose of the experiment was to demonstrate low/no degradation of the cyclopentane working fluid after a continuous 1,000 hours of cycle run time. Degradation of the working fluid is known to be determined by the "residence time" of the fluid in the hot zone of the HX (i.e., the evaporator and superheater). This residence time is determined by the mass flow rate of the working fluid and the overall volume inventory of the HX. For the current system, calculations suggest the residence time in the HX is about 5% of the total experimental run time. In other words, per the original plan, 1,000 hours of run time translates to about 50 hours of hot residence time.

The project's prime contractor (i.e., Idaho National Laboratory) performed laboratory-scale residence time versus decomposition testing of cyclopentane samples at temperatures and pressures representative of the cycle conditions. A plot of the results of one such test is shown in Figure 8. Figure 8 shows that at a total hot residence time of 15 hours at 240°C and 43 bar, a linear trend in the degradation products of cyclopentane was well established. This was functionally equivalent to approximatley 300 hours of test time in the experimental rig. Therefore, it was concluded that a test run time of no more than 300 hours was needed to establish a degradation profile for the cyclopentane working fluid. The originally proposed test run time was reduced from 1,000 hours to 300 hours.

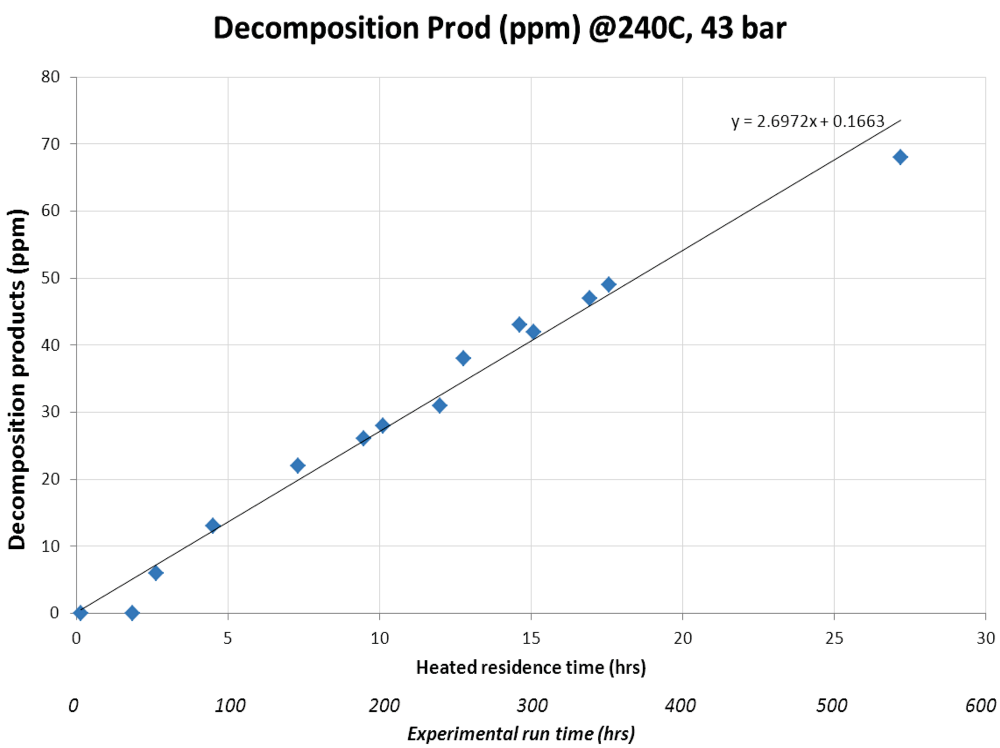


Figure 8. Results of laboratory-scale degradation testing by Idaho National Laboratory.

The target temperature-time profile of the superheater exit temperature also was altered so the temperature stayed at or below 250°C for the first 300 hours of operation. After this, the temperature was deliberately raised to 270°C and 280°C, respectively, for another 10+ hours each. Sample collection frequency per Figure 9 ensured any degradation triggered by the step increment in temperatures would be captured in the samples collected.

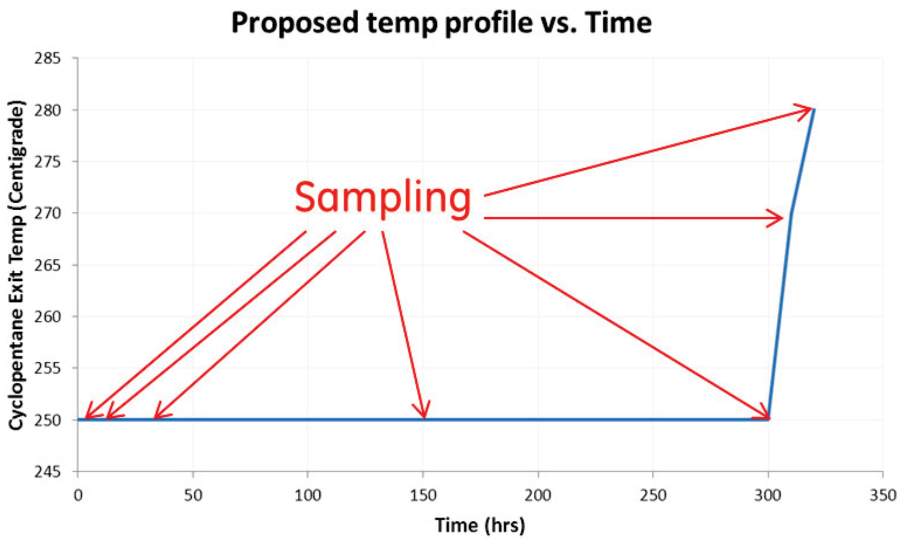


Figure 9. Superheater exit temperature vs. time profile for the test. Samples taken at t = 0, 5, 10, 30, 150, 300, 310 (overtemp), and 320 (overtemp) hours.

4. DATA COLLECTION AND ANALYSIS

At a high level, data collected from the experiment consisted of the following:

- HX inlet flow profiles to determine flow uniformity at the HX inlet
- Calorimetric data to measure heat leak from the HX shell to the environment
- Calorimetric data to measure net heat transfer from hot exhaust gas into the working fluid
- Wall temperature of the tubes to monitor excursions into high temperatures that risk fluid decomposition
- Chemical tests of the samples to determine the level of decomposition products.

Much more detail on the data collected and nomenclature of the temperature, pressure, and flow probes used can be found in Appendix L.

4.1 Heat Exchanger Inlet Flow Profiles

Velocity profiles in the HX were measured with a TSI Velocicalc Plus Multi-Parameter Ventilation Meter 8386 with a thermal hot film probe. A photo of the instrument is shown in Figure 10. The probe extends to a length of 36 in. and the unit has an overall accuracy of ±3% of reading.

Access to flow inside the HX was obtained by removing the air side TCs and inserting the velocity probe into the access ports. A total of five velocity traverses were performed in different locations, which were tagged T1 through T5. Velocity was measured starting from the back wall of the HX to the front in 1- in. increments. The probe is well marked; therefore, positional accuracy is greater than ±0.1 in. The first measurement was located approximately 1/4 in. from the back wall because that is the distance from the tip of the probe shroud to the thermal sensor. Each point measurement was averaged for 20 seconds. Figure 11 is a drawing of the HX, showing the ports where each of the traverses were performed.

Figure 10. TSI Velocicalc Plus Mult-Parameter Ventilation Meter 8386 (from TSI website).

The velocity traverses were done with cold (i.e., unheated) flow because the hot film probe is incapable of measuring fluid velocity at the high temperatures present during testing (i.e., testing the inlet temperature of the air was about 465°C). In order to match the Reynolds number of the cold flow used during velocity traverses with that of the hot flow used during testing, the mass flow rate for the cold flow was set to 6 lbm/s versus 9 lbm/s for the hot flow cases.

An overall summary of the results can be gathered by comparing the traverse locations in Figure 11 to the velocity profiles obtained in Figures 12, 13, and 14. It is clear from the average velocities at T5 and T1 (1.41 m/s and 1.88 m/s, respectively) that despite the two different types of flow conditioning at the HX entrance, there is still about 25% less flow at the top of the HX at T5 than in the center at T1. This situation is corrected by the time the flow travels midway through the HX in streamwise direction X, because the average velocities at T4 and T2 are nearly equal (2.16 and 2.18 m/s). Further downstream at T3, the average velocity appears to drop to about 1.79 m/s, but this is really an artifact of the tube wakes and coarse traverse spacing (addressed below in more detail). The expected average velocity for cold flow in the HX duct was calculated to be about 1.92 m/s using EES software (see Appendix M). This compares very well with the measured values.

Figures 12, 13, and 14 are comparative plots of the velocity profiles obtained from the five traverses. Figure 12 compares the two inlet traverses T1 and T5. T1 is located in the vertical center near the HX inlet and T5 is located at the top just downstream of where the flow first begins to bend. The two ports are located just downstream of a perforated plate with 3/4-in.-diameter holes. Two things are clear from the profiles:

1. The profiles are similar in shape, indicating the local geometries are similar
2. T5 is clearly offset lower than T1, indicating that flow is piling up more at the bottom than at the top as it makes the turn.

This is despite two flow-conditioning devices installed at the HX entrance: a bulkhead with three columns of 1-1/2 in. pipe sections welded in place and the previously mentioned perforated plate with 3/4-in.-diameter holes and 50% open area.

Figure 13 compares the top and mid profiles obtained half-way downstream through the HX (i.e., fixed X coordinate, different Y). These profiles match very closely and suggest that the distribution of flow between the top and middle has evened out at this point. Both traverses clearly show three wakes behind the three rows of tubes.

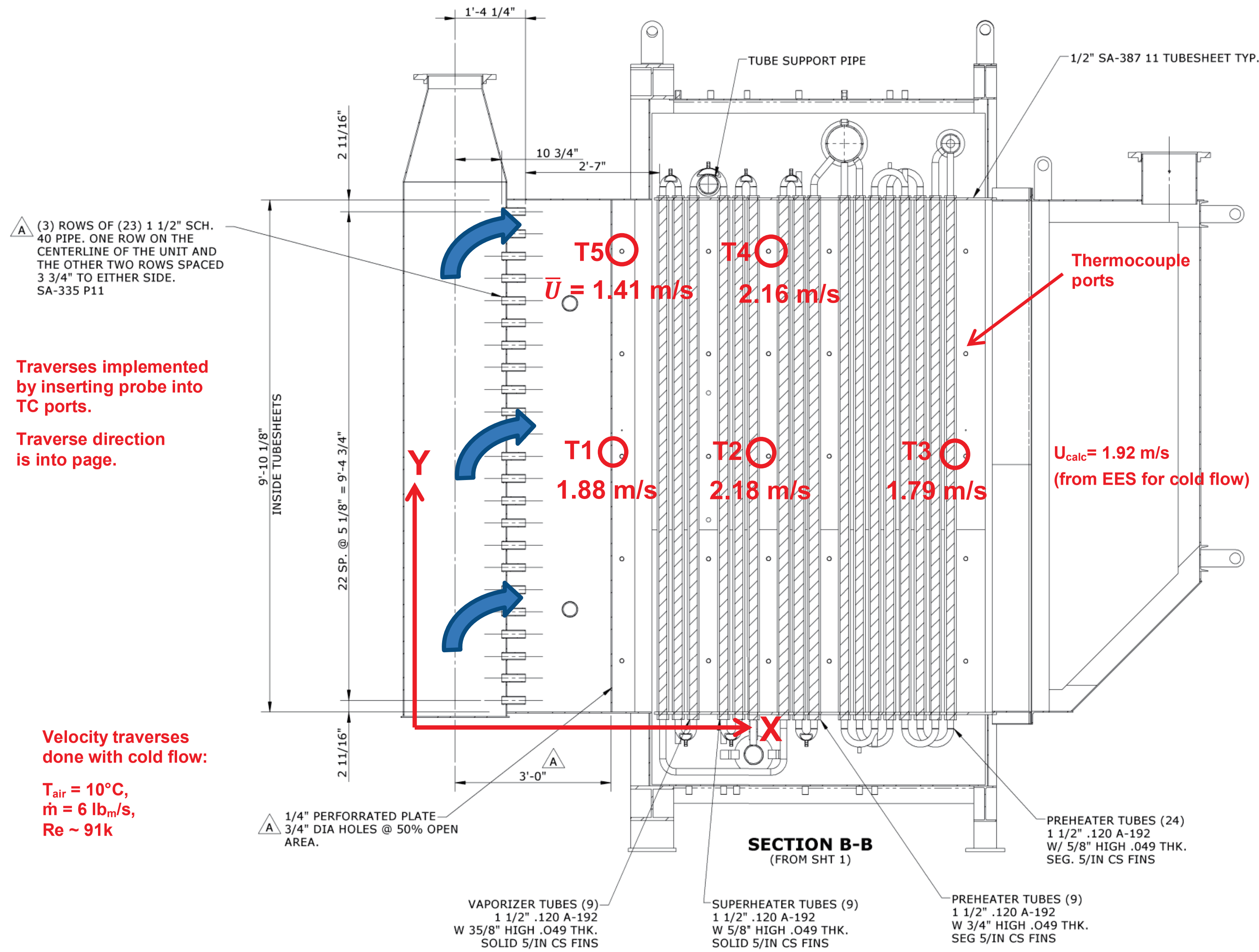


Figure 11. Schematic of the main heat exchanger and summarized air flow results.

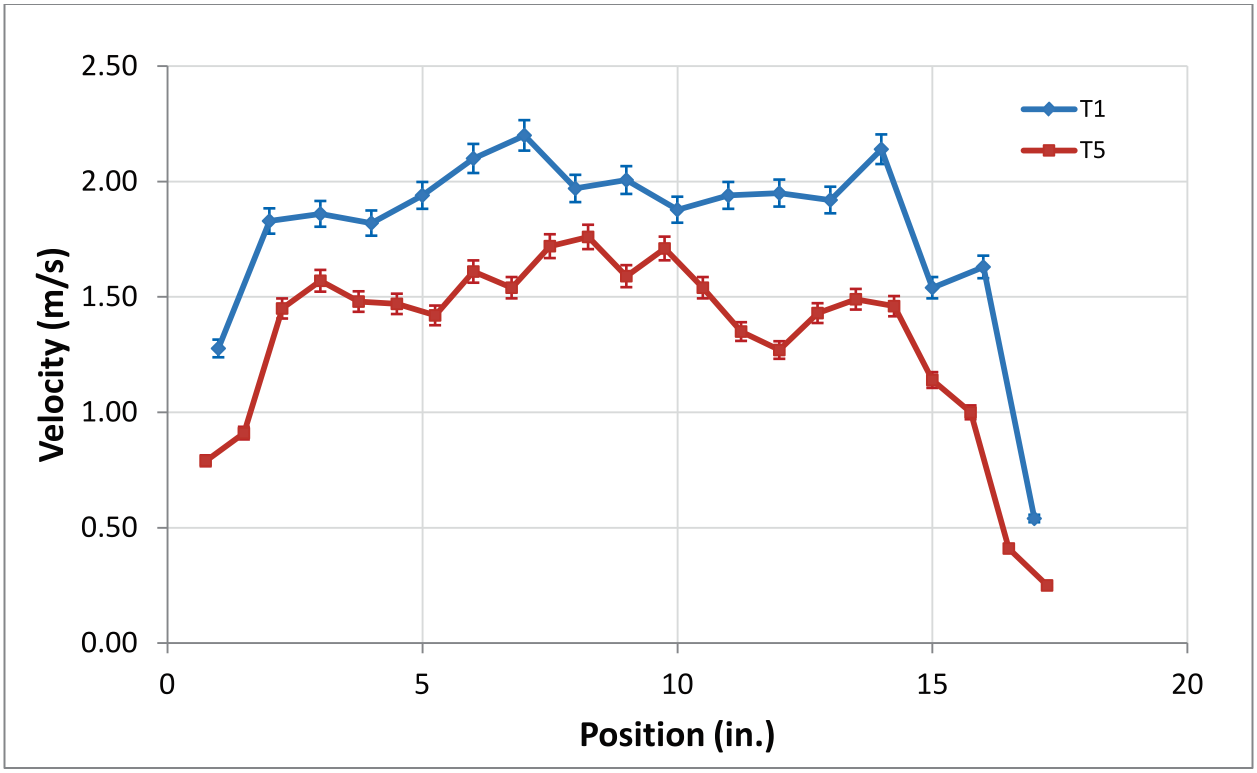


Figure 12. Comparison of inlet velocity traverses T1 (center) and T5 (top).

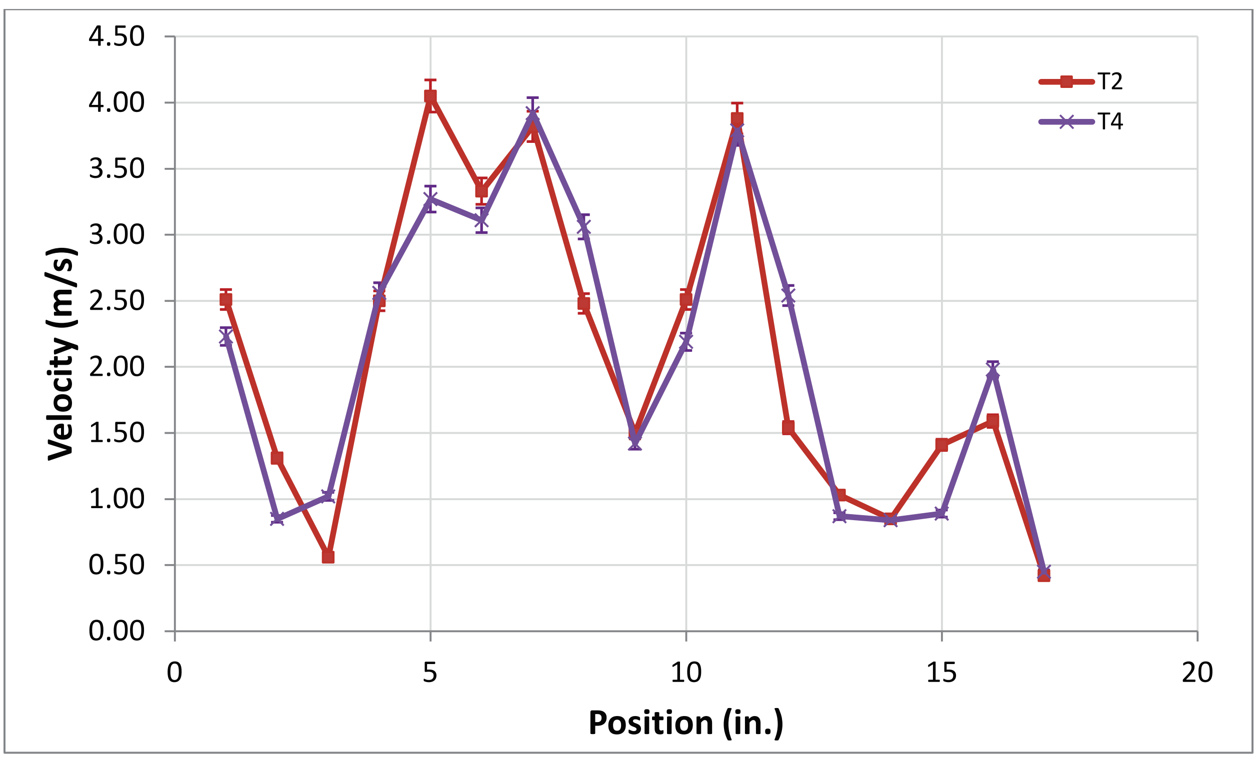


Figure 13. Comparison of mid-volume velocity traverses T2 (center) and T4 (top).

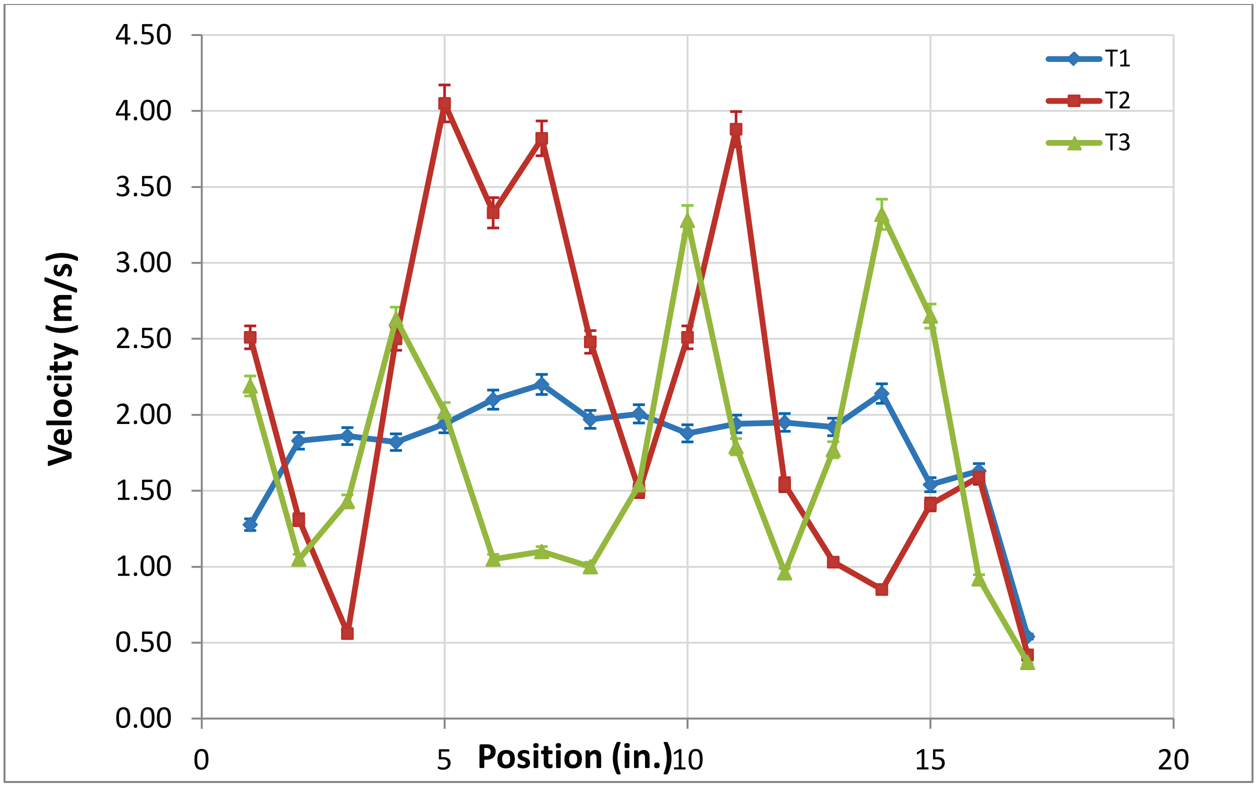


Figure 14. Comparison of mid-row velocity traverses T1 (inlet), T2 (mid), and T3 (outlet).

Figure 14 compares the profiles obtained in the vertical center of the HX moving downstream with the flow (fixed Y, changing X). Once again, the wakes are very clear for the two traverses performed just downstream of tube rows and the size of the wakes for T3 appear to be much larger than for T2. This is not surprising given the large quantity of tubes bundled together for the preheater in this region of the HX. Although, at first glance, the profile at T3 may seem to suggest that the average flow velocity in this region is lower than at T2, this is likely not the case. It would likely be necessary to use much finer traverse increments (probably on the order of a couple millimeters) to get a more accurate estimate of the true means and to capture the velocity peaks. For example, in Figure 14 it is likely that the peaks for T3 are higher than shown in the plot. They simply are not captured because the traverse resolution was not fine enough.

4.2 Test Data

4.2.1 Data Analysis Methodology

This section presents the data acquired from the prototype test. The test was performed in discrete segments, usually over weekends, rather than as a continuous test. The schedule of test runs, including the start and stop time for each run, is given in Table 4. The test rig was operated for a cumulative time of over 333 hours. A graphical comparison of the relative length of each test run is presented in Figure 15. Each run took approximately 30 minutes to bring up to operating temperature and about 15 minutes to cool down. The test rig has a significant thermal mass that takes time to settle into equilibrium.

Data from each test run was written into a separate Microsoft Excel spreadsheet. Because of the enormous size of the spreadsheets, it was not feasible to analyze the entire data set within Excel. The sheer amount of data made it impossible to perform statistics across different test runs and perform filtering operations. Also, the time stamp in the Excel spreadsheets is not consecutive. The data are not very well-behaved, with lots of spikes and data out of physical range, which makes analysis and distillation of the data difficult. The data were originally processed using Matlab, but even this approach proved unwieldy. Therefore, SAS Enterprise Guide 4.3 was used to compare the performance of the test rig across the 29 test runs. SAS code was written to overlay the measured variables from each run as a function of elapsed time during the run. The date-time stamp was reconfigured into elapsed time to facilitate comparison between the runs. Data from the 21st runs performed on 9/10/2012 were eliminated, because the test was not run long enough for the rig to settle into equilibrium. As discussed in Section 3, the exhaust gas temperature was intentionally increased during the last two test runs.

Table 4. Schedule of the Organic Rankine Cycle test runs.

Test Run	Time		Run duration	
	Start time	End time	H:M:S	Seconds
08152012_1st	8/15/2012 18:48:05	8/16/2012 6:11:43	11:23:38	41018
08162012_2nd	8/16/2012 18:38:25	8/17/2012 6:06:16	11:27:51	41271
08172012_3rd	8/18/2012 1:10:54	8/18/2012 5:09:44	3:58:50	14330
08182012_4th	8/18/2012 19:03:41	8/19/2012 6:54:32	11:50:51	42651
08202012_5th	8/20/2012 17:43:04	8/21/2012 5:19:47	11:36:43	41803
08212012_6th	8/21/2012 18:22:57	8/22/2012 6:09:32	11:46:35	42395
08222012_8th	8/22/2012 18:28:24	8/23/2012 5:55:39	11:27:15	41235
08232012_9th	8/23/2012 18:00:04	8/24/2012 5:58:06	11:58:02	43082
08292012_10th	8/29/2012 19:38:09	8/30/2012 6:06:52	10:28:43	37723
08302012_11th	8/30/2012 20:26:28	8/31/2012 5:55:48	9:29:20	34160
08312012_12th	8/31/2012 18:28:39	8/31/2012 23:28:21	4:59:42	17982
09012012_13th	9/1/2012 19:21:15	9/2/2012 5:25:59	10:04:44	36284
09022012_14th	9/2/2012 19:19:17	9/3/2012 5:51:19	10:32:02	37922
09032012_15th	9/3/2012 18:37:56	9/4/2012 5:56:01	11:18:05	40685
09042012_16th	9/4/2012 18:39:14	9/5/2012 5:39:38	11:00:24	39624
09052012_17th	9/5/2012 18:28:55	9/6/2012 6:09:39	11:40:44	42044
09062012_18th	9/6/2012 18:27:49	9/7/2012 5:42:33	11:14:44	40484
09072012_19th	9/7/2012 18:59:51	9/8/2012 17:26:54	22:27:03	80823
09092012_20th	9/9/2012 6:43:12	9/10/2012 5:59:55	23:16:43	83803
09102012_21st_a	9/10/2012 18:33:29	9/10/2012 19:15:06	0:41:37	2497
09102012_21st_b	9/11/2012 0:12:55	9/11/2012 1:02:03	0:49:08	2948
09122012_23rd	9/12/2012 19:43:19	9/13/2012 5:41:34	9:58:15	35895
09142012_25th	9/14/2012 20:25:00	9/15/2012 18:17:50	21:52:50	78770
09162012_26th	9/16/2012 6:29:26	9/17/2012 3:55:31	21:26:05	77165
09172012_27th	9/17/2012 15:24:55	9/18/2012 2:58:03	11:33:08	41588
09182012_28th	9/18/2012 12:09:01	9/18/2012 23:52:55	11:43:54	42234
09202012_29th	9/20/2012 1:15:25	9/20/2012 11:57:31	10:42:06	38526
09202012_30th	9/20/2012 21:24:41	9/21/2012 8:48:31	11:23:50	41030
09212012_31th	9/21/2012 18:44:39	9/22/2012 6:09:35	11:24:56	41096
		Total test time	333:37:48	

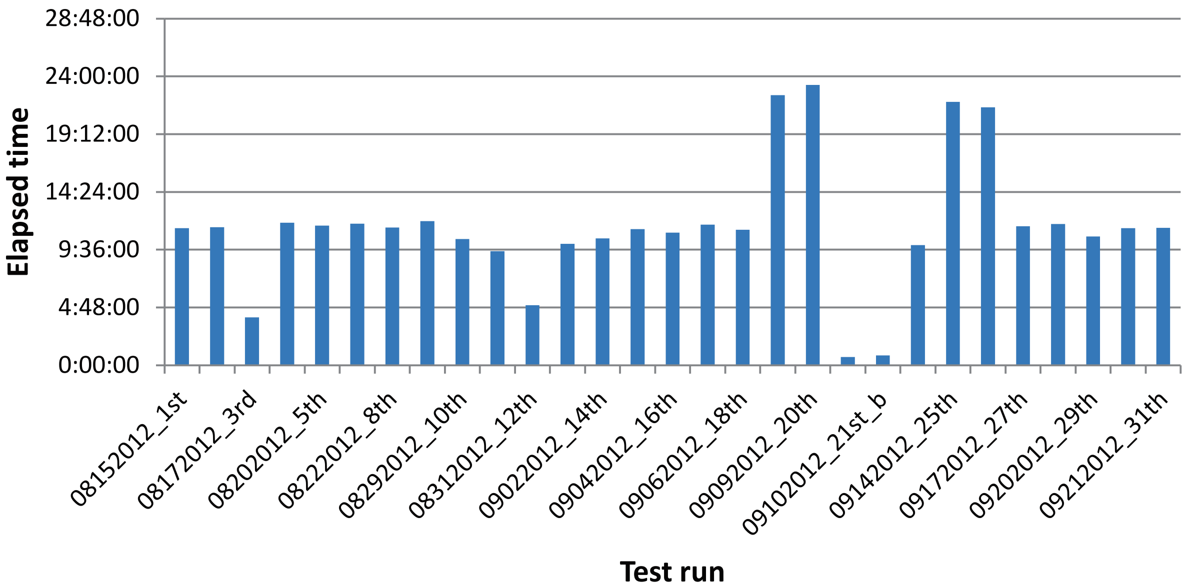


Figure 15. Length of the Organic Rankine Cycle test runs.

4.2.2 Analysis of the Entire Data Set

Figures 16 through 19 overlay the measured data from the test runs as a function of elapsed time. The time-date stamp in the Excel files was converted to elapsed time using SAS code to enable comparison of the variables between runs. Statistics were computed to summarize the overall pressure drop, flow rates, and temperatures in the HX. The mode better represents the steady-state condition, because the mean value is skewed by the startup and shutdown conditions, as well as by spikes in the data.

Figure 16 shows an overlay plot of the pressure drop in the exhaust gas. The exhaust gas pressure drops are 0.09 (mode and median) and 0.12 psi (maximum). Anomalies in the data occur from approximately 10,000 to 15,000 seconds into the 30th test run.

Figure 17 shows the variation of working fluid mass flow rate as a function of elapsed time as the flow travels through the HX piping. Large spikes in the measured values occurred during startup and shutdown. The data were clipped to only include positive values. The cyclopentane mass flow rates were generally around 2.5 kg/s, except for the last two runs, which were much lower (1.6 to 1.7 kg/s) than the preceding test runs.

Figure 18 shows the working fluid pressure drop as a function of elapsed time as the flow travels through the HX piping. Spikes in the measured values occurred during startup and shutdown. The data were clipped to only include positive values. The measured cyclopentane pressure drop for all but the 1st, 30th, and 31st ORC runs is 15.0 (mode). The cyclopentane pressure drop for the last two runs is around 12.5 psi.

Figure 19 shows the variation of exhaust gas inlet temperature as a function of elapsed time for all of the test runs. Table 5 lists the inlet and outlet exhaust gas temperatures for nominal and overtemperature conditions. The inlet nominal temperature is the mode value over the set of runs of the average values of four TC measurements just upstream of the evaporator section. The peak inlet temperature is the maximum exhaust gas temperature for the specified set of runs. The outlet temperature is the median over the set of runs of the average of the four TC measurements at the exit of the economizer section. Data that were out of range (especially for the 1st and 30th runs) were filtered, so as to not skew the results.

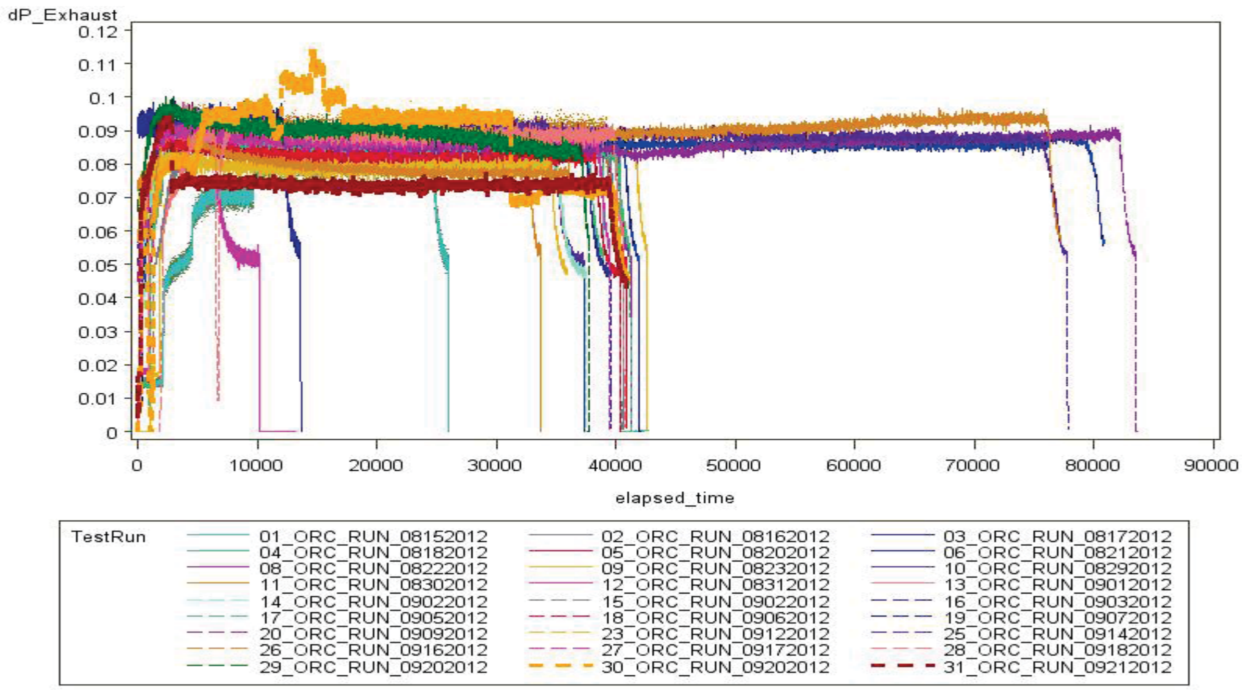


Figure 16. Exhaust gas pressure drop (psi) across the heat exchanger as a function of elapsed time (s).

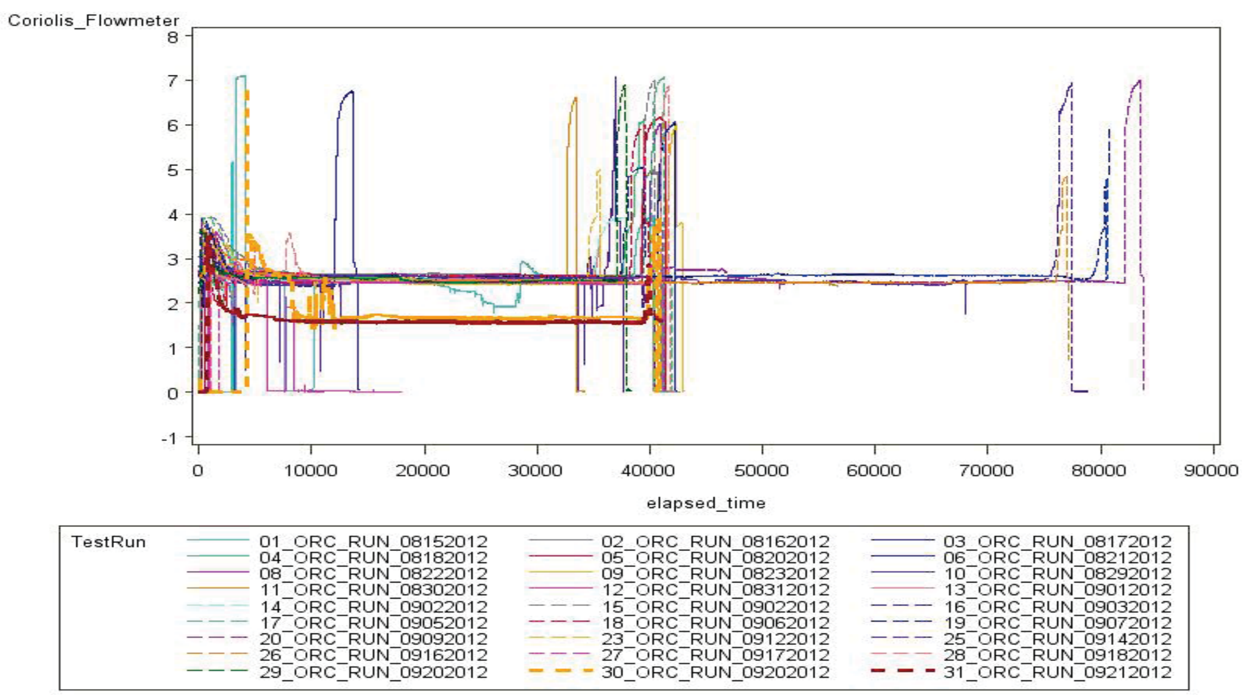


Figure 17. Cyclopentane mass flow rate (kg/s) in the heat exchanger as a function of elapsed time (s).

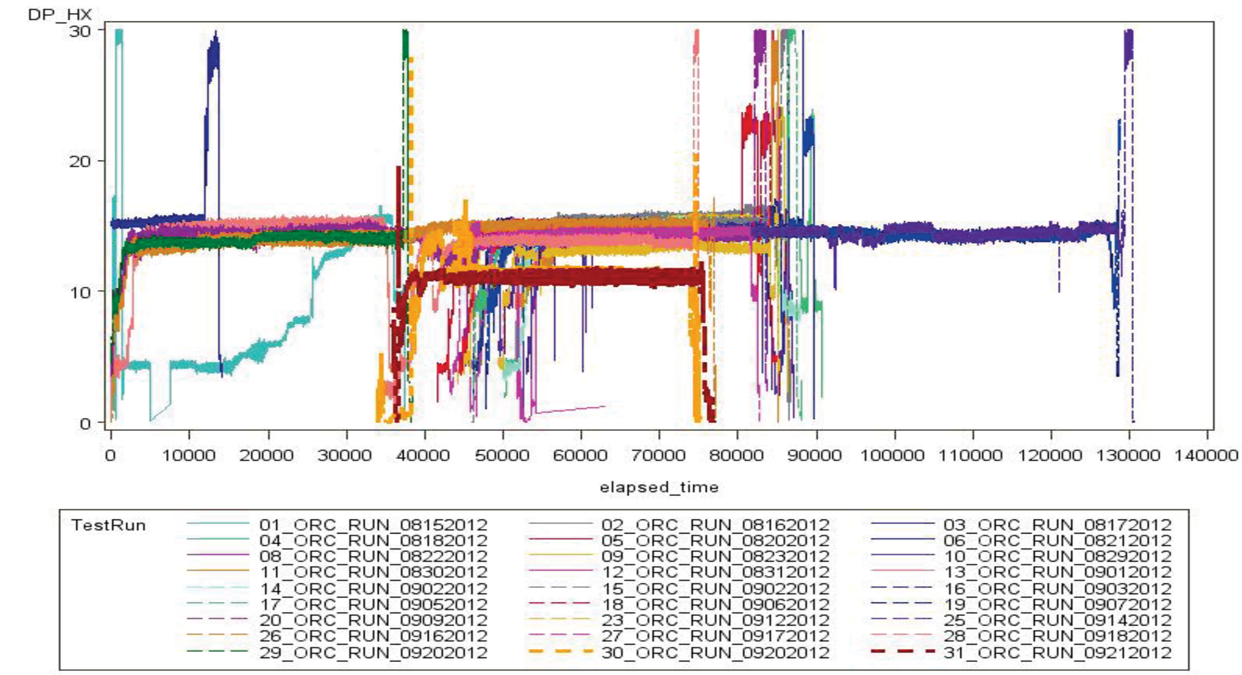


Figure 18. Cyclopentane pressure drop (psi) through the heat exchanger as a function of elapsed time (s).

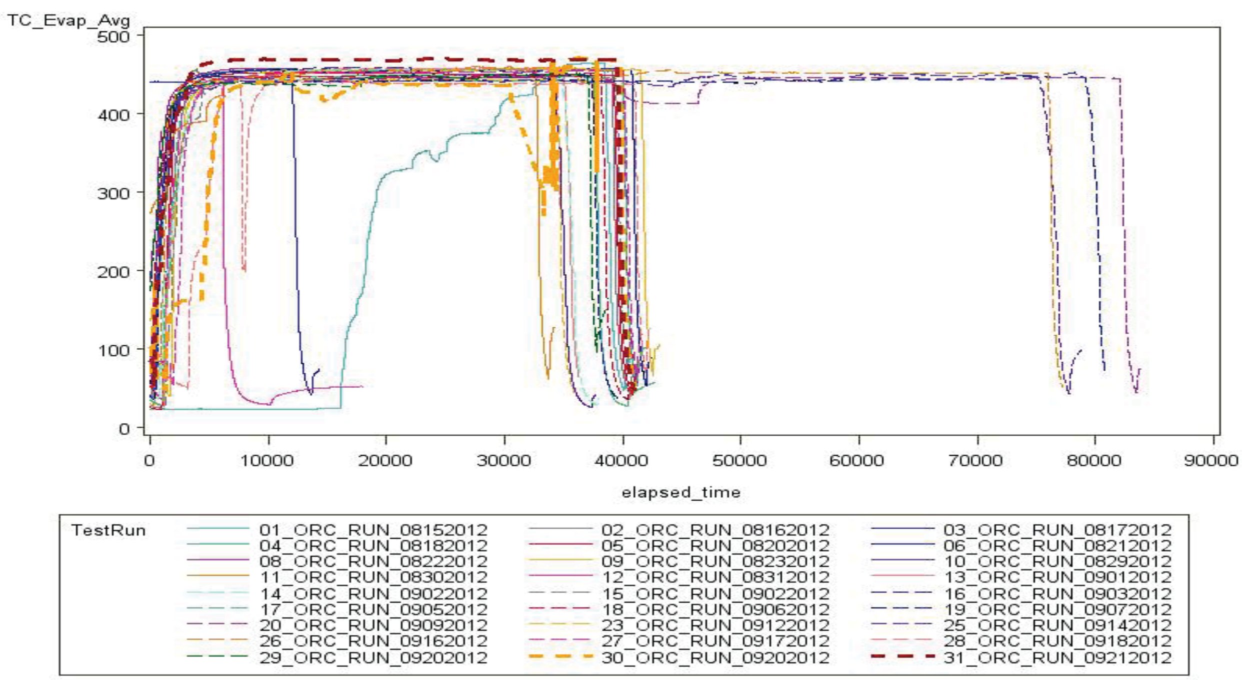


Figure 19. Average exhaust gas inlet temperature (°C) as a function of elapsed time (s).

Table 5. Exhaust gas temperatures (°C).

Type	Run	Inlet Nominal	Inlet Peak	Outlet
Nominal	1st through 29th	445.8	464.8	198.4
Overtemp	30th	437.0	471.7	211.8
	31st	468.8	469.8	210.4

4.2.3 Exhaust Gas and Working Fluid Mass Flow Rates

Table 6 lists the steady-state exhaust gas and working fluid mass flow rates for the 8th and 19th test runs.

Table 6. Exhaust gas and working fluid mass flow rates (kg/s).

Test Run	Exhaust Gas	Working Fluid
08/22/2012	4.1	2.4
09/07/2012	4.1	2.6

4.2.4 Measured Temperature Profiles

One of the main features of the protective staging concept is that it mitigates the risk of high wall temperatures in the working fluid loop. Furthermore, variable fin density in each of the three sections of the HX (i.e., economizer, evaporator, and superheater) on the outside of the working fluid tubes was used to control the heat flux into each section.

It generally was observed during the experiment that even where the hot exhaust temperature was greater than 400°C, the wall temperature of the finned tubes remained below 300°C. Therefore, the fluid was not exposed to temperatures high enough to cause fluid degradation; this validated the effectiveness of the protective staging design of the HX.

Figure 20 shows the steady-state temperature profile from the HX for operating runs on two different dates. From the data plots, it can be seen that although the hot gas temperature at the HX inlet was greater than 450°C, the working fluid temperature remained well below 250°C. It was found that the fluid temperature could be controlled by manipulating its flow rate and/or the flow rate of the hot exhaust gas.

Tube wall temperatures were not available in the economizer. However, the tube wall temperatures in the evaporator and superheater suggested that the wall temperature was much closer to the working fluid temperature than the local combustion gas temperature. In most cases, wall temperatures remained below 270°C. However, as mentioned in above, during the last two runs, the wall temperatures were deliberately raised to about 320°C to examine the effect on fluid decomposition (reported in Section 4.4).

Figure 21 shows the variation of median and maximum values of working fluid temperature measured by the immersed TCs as the fluid flows through the HX. There were some anomalies with the measured TC data for the 1st and 12th ORC runs that skewed the results; therefore, these runs were eliminated from the analysis shown in Figure 20, as were the last two runs. The TC data were filtered to eliminate large, unphysical spikes in temperature recorded at the end of the runs. Because the data included measurements during startup and shutdown, the median temperature represents the temperature of the working fluid during the majority of the test. Figure 22 shows the order in which the working fluid flows past the immersed thermocouples. Figure 23 illustrates the thermocouple locations in the protectively staged HX.

The test was run for just over 311 hours at conditions that produced a nominal average (through the HX) working fluid temperature of 185°C (average of the 11 median TC measurements) and median exit temperature of 216°C. Based on the computed median values, the nominal working fluid temperature increases by 75°C as it flows from the inlet to the outlet of the HX.The maximum temperature reached by the cyclopentane was limited to 234°C during the runs at nominal conditions.

Working fluid temperature was deliberately raised for the final 22+ hours of the test campaign. The working fluid temperature was increased to a higher average temperature of 213°C (throughout the length of the HX) during the last two runs. Table 7 compares the maximum cyclopentane temperature for the runs at nominal operating conditions to those for the last two runs.

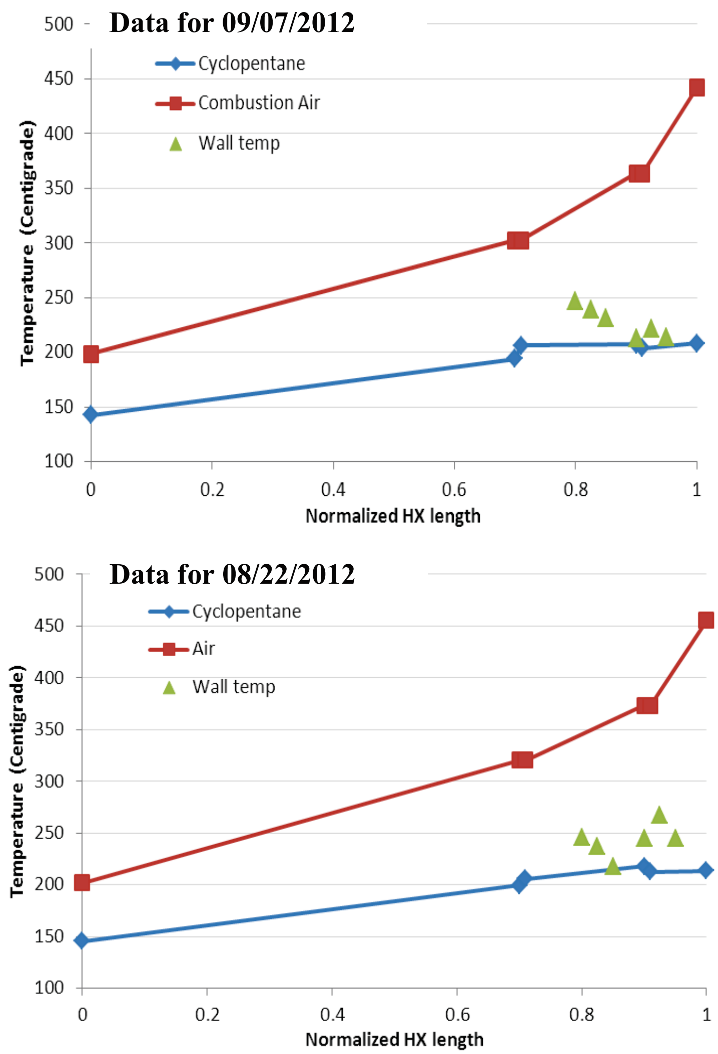


Figure 20. Temperature profile data from two operating runs (8th and 19th).

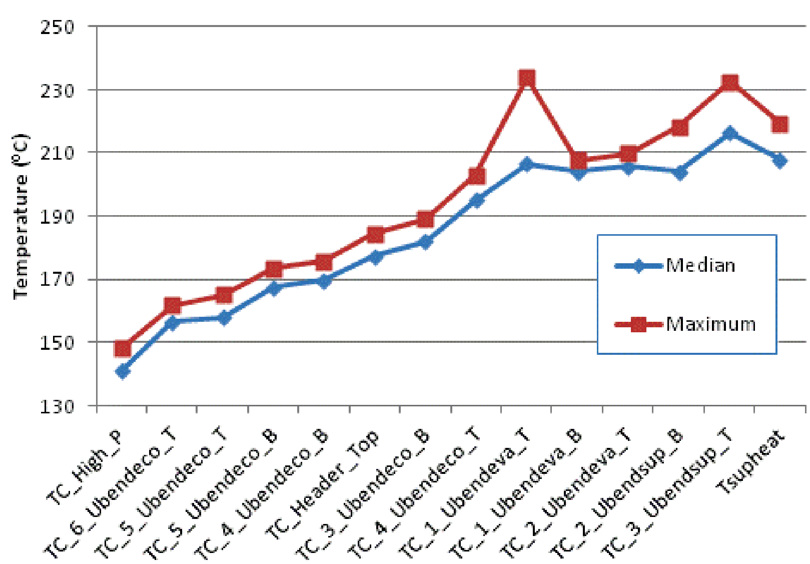


Figure 21. Median and maximum working fluid temperature through the heat exchanger.

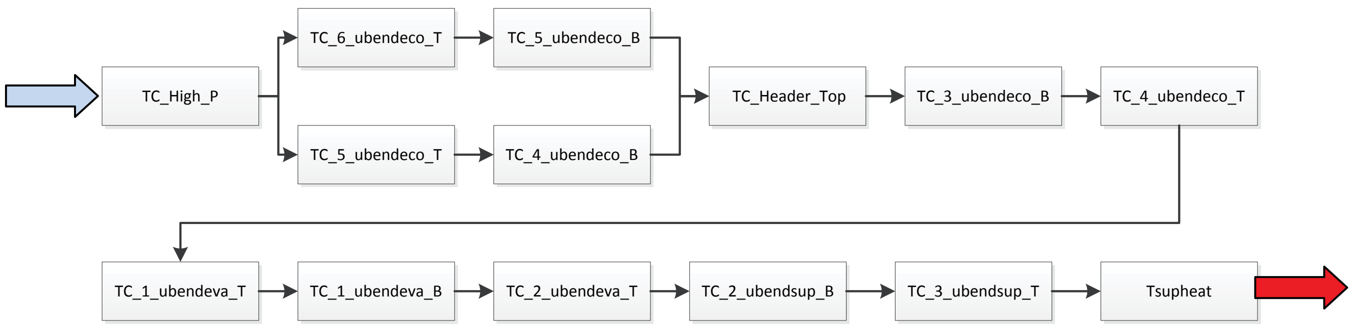


Figure 22. Sequence of thermocouples measuring working fluid temperature.

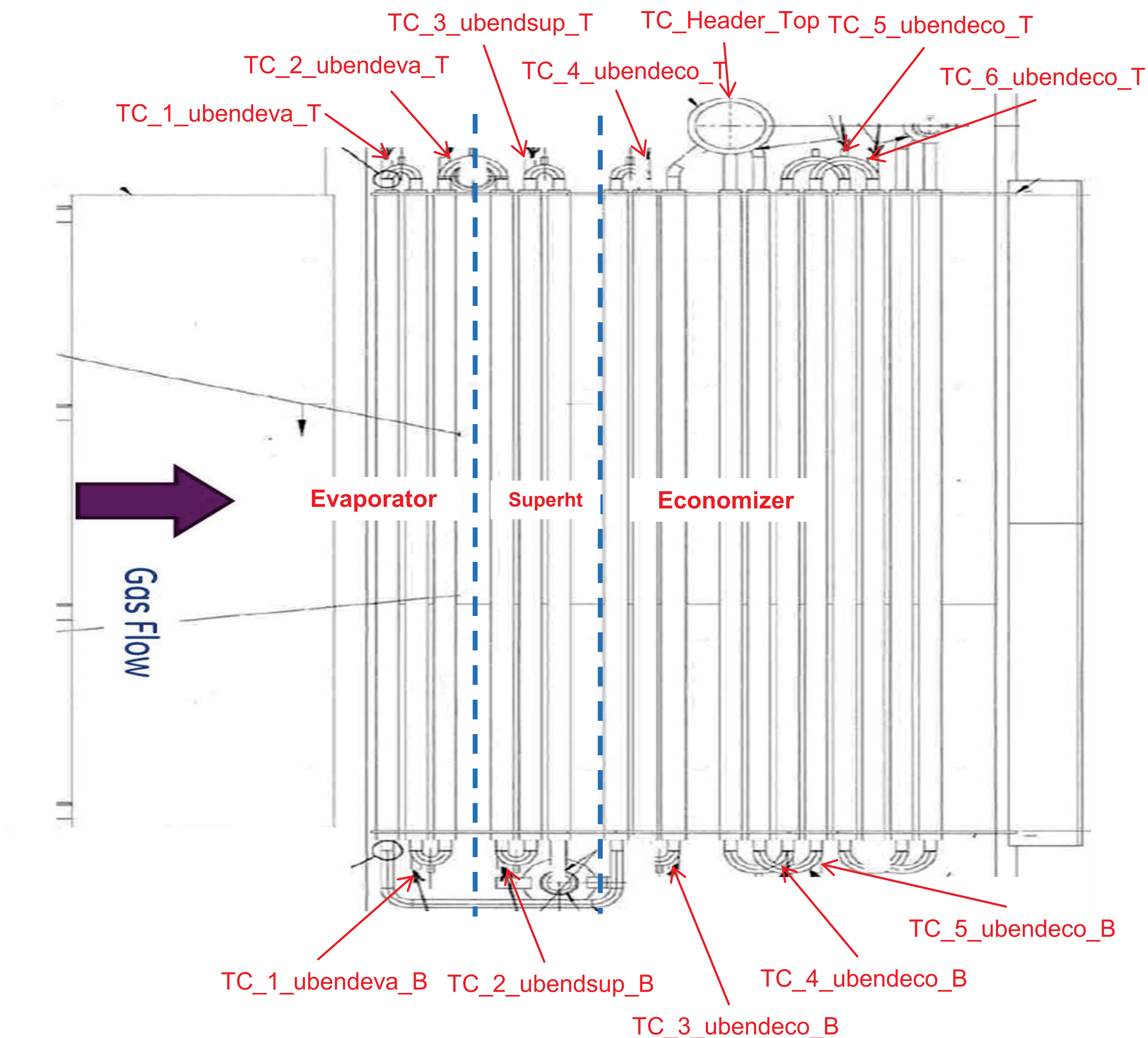


Figure 23. Schematic of thermocouples inserted in working fluid flow.

Table 7. Maximum measured cyclopentane temperature (°C).

Type	Run	Maximum Cyclopentane Temperature (°C)
Nominal	1st through 29th	234.0
Overtemp	30th	277.2
	31st	281.7

Table 8 compares the design versus measured median temperatures of the working fluid within the various tube bundle sections under nominal operating conditions. These values are computed from the average of the steady-state measured temperatures through each the three stages (i.e., economizer, evaporator, and superheater) of the HX. The highest cyclopentane temperature occurs in the superheater. The cyclopentane temperature profile demonstrates the effectiveness of the protective staging (and variable fin density) design of the HX. Fluid degradation tests reported in Section 4.4 indicate insignificant decomposition of the working fluid.

Table 8. Comparison of the design with actual test temperature ranges for working fluid in the heat exchanger.

	Temperature (°C)	
Tube Bundle	Design	Measured
Economizer	110 to 230	169.3
Evaporator	230	205.3
Superheater	230 to 250	208.1

4.2.5 Working Fluid Phase

As the cyclopentane travels through the HX and is heated, it first turns to vapor in the superheater. As the test section heats up, the vapor bubble moves into the evaporator. The location of the vapor bubble can be found by using the Antoine equation for vapor pressure (Williamham et al. 1945, where the coefficients for cyclopentane are as follows:

A = 4.00288

B = 1,119.208

C = 42.412

The Antoine equation can be solved for temperature T in °C as a function of pressure in bars:

$$T = (B/(A-\log_{10}P)) - C \qquad (1)$$

The vapor pressure curve for cyclopentane (shown in Figure 24) is obtained by solving Equation 1.

The state of the working fluid was estimated based on the measured pressure, pressure drop, and temperature in the HX for the 8th ORC test run. The Antoine equation was used to calculate the vaporization temperature based on the measured working fluid pressure. If the measured temperature (T_{meas}) is lower than the calculated temperature (T_{calc}), then the working fluid is in a liquid state, otherwise it is vapor. Because the working fluid temperature was not measured at the exact same location as the pressure, the TC reading at the nearest location was used. It is seen in Table 9 that the working fluid has transitioned from liquid to vapor phase by the time it reaches the outlet of the superheater. As a cross check, the sum of the measured pressure drops at specified locations within the HX is within 4% of the overall measured HX pressure drop of 15.2 psi.

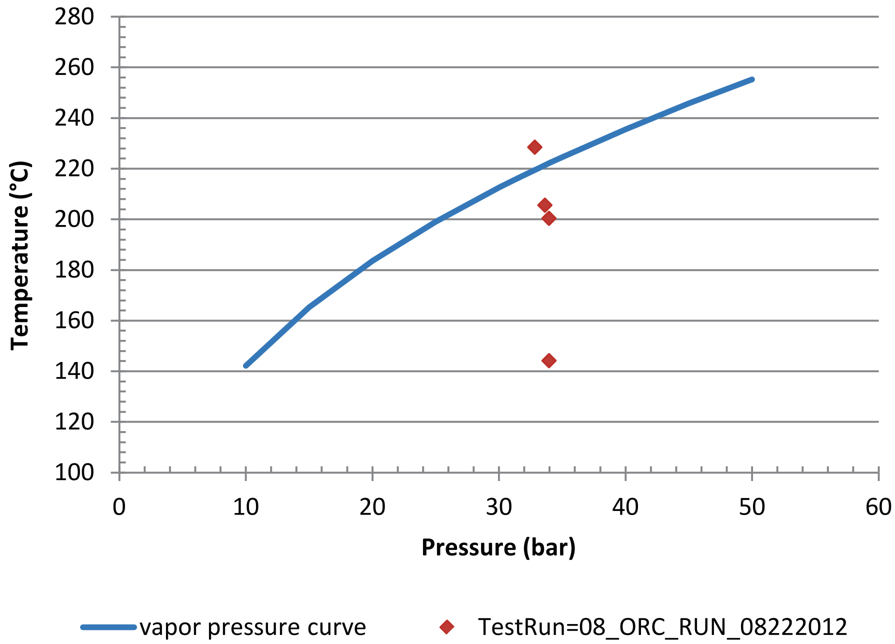


Figure 24. Relationship between vapor pressure and temperature for cyclopentane.

Table 9. State of working fluid within the heat exchanger.

TestRun=08_ORC_RUN_08222012		T_{meas} (°C)	T_{calc} (°C)	Phase
Cyclopentane pressure at inlet of HX (bar)	33.9	144.3	222.1	Liquid
Pressure at outlet of economizer (bar)	33.9	200.7	222.1	Liquid
Pressure at outlet of evaporator (bar)	33.6	205.6	221.4	Liquid
Pressure at outlet of superheater (bar)	32.8	229.0	219.5	Vapor
Sum of individual pressure drops (psi)	14.6			
Measured total pressure drop (psi)	15.2			

4.3 Heat Balance

4.3.1 Cyclopentane Heat Balance

Calorimetric data on the working fluid flow rate, inlet temperature, and associated pressures into the HX and outlet temperature were collected over the course of 300+ hours of hot runs. Using known NIST property databases for cyclopentane, the temperature and pressure data were converted to enthalpy change for the cyclopentane across the HX.

Given a steady-state average cyclopentane inlet temperature of 144 to 147°C, an average steady-state outlet temperature around 210 to 220°C, and an average steady-state flow rate of 2.4 to 2.5 kg/s, the nominal enthalpy change (including vaporization) of the cyclopentane was 980 to 1,000 kW.

4.3.2 Hot Exhaust Gas Heat Balance

The enthalpy change of the hot exhaust gas can be calculated based on the temperature difference of the exhaust gas as it travels across the finned tubes. To obtain an accurate measurement of the gas enthalpy, the following assumptions were made in regards to the operating conditions of combustion in the natural gas-fired inline heater:

1. Stoichiometric combustion

2. Relative humidity of 50% for incoming air.

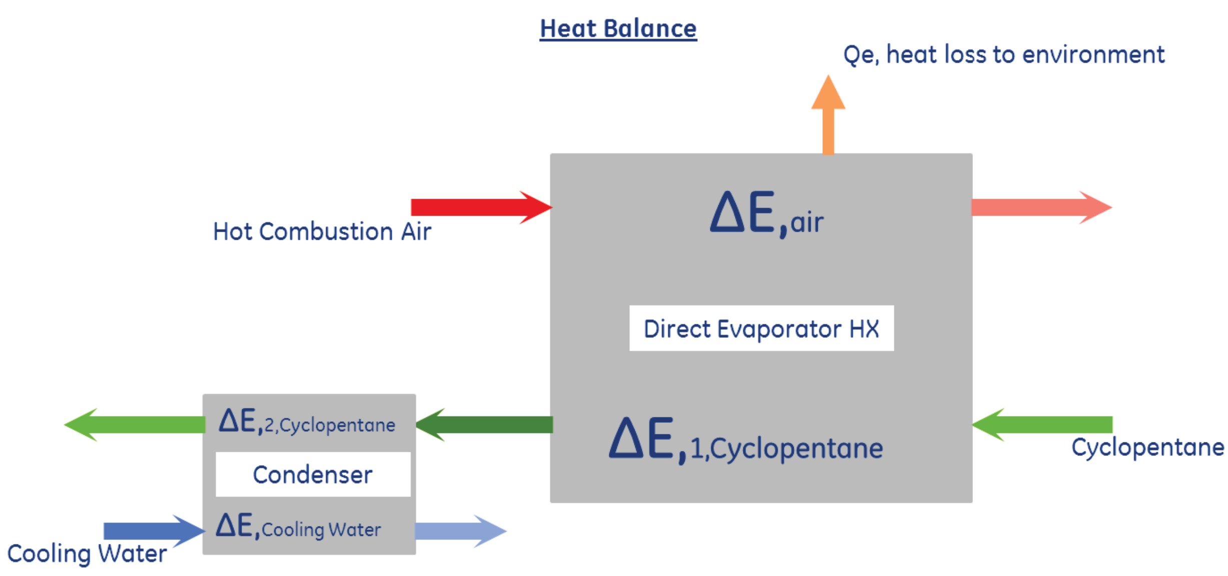
Details of this calculation are provided in Appendix N. The nominal flow rate of the incoming air was 9 to 10 lb/s. With an average steady-state HX inlet air temperature of 420°C (in most runs) the outlet steady-state temperature was typically around 200°C. In accordance with the calculations shown in Appendix N, the average steady-state enthalpy change of combustion air products through the HX was approximately 1,080 kW.

4.3.3 Condenser Cooling Water Heat Balance

The flow rate and temperature change of the cooling water also were known. Therefore, the enthalpy change of the cooling water for each run also could be calculated. During the average steady state for each run, the cooling water inlet temperature was about 295K and the outlet temperature was about 320K, with a flow rate of 10 to 12 kg/s. This corresponds to an average enthalpy change of approximately 1,200 kW.

4.3.4 Discussion, Measurement Accuracy, and Calculation Errors

The heat lost by the combustion product gas must balance with the enthalpy gain of the cyclopentane and heat losses to the environment. Furthermore, because there was no turboexpander in this fluid loop, all enthalpy gained by the cyclopentane must be removed by the cooling water. Figure 25 is a schematic illustration of this heat balance.



$$\Delta E_{,air} = \Delta E_{,1,Cyclopentane} + Qe$$

$$\Delta E_{,1,Cyclopentane} = \Delta E_{,2,Cyclopentane} = \Delta E_{,Cooling\ Water}$$

Figure 25. Schematic illustration of the heat balance across the experimental system.

Figure 26 illustrates the transient enthalpy change of each of the three fluids (i.e., combustion air, cyclopentane, and cooling water) for an 11.5-hour experimental run performed on 08/22/2012. Subtracting the steady-state enthalpy deltas of the combustion air from the cyclopentane gives the average steady-state heat loss to the environment, Qe ~ 140 kW, or 13% of the total enthalpy change of the air. This is a rather large number. However, the thin, long design of the HX provided an exceptionally large surface area to the outside; therefore, this could have contributed to the large heat loss. In an industrial implementation, the HX will likely have a square aspect ratio and the proportional heat loss to the surroundings is expected to be much smaller.

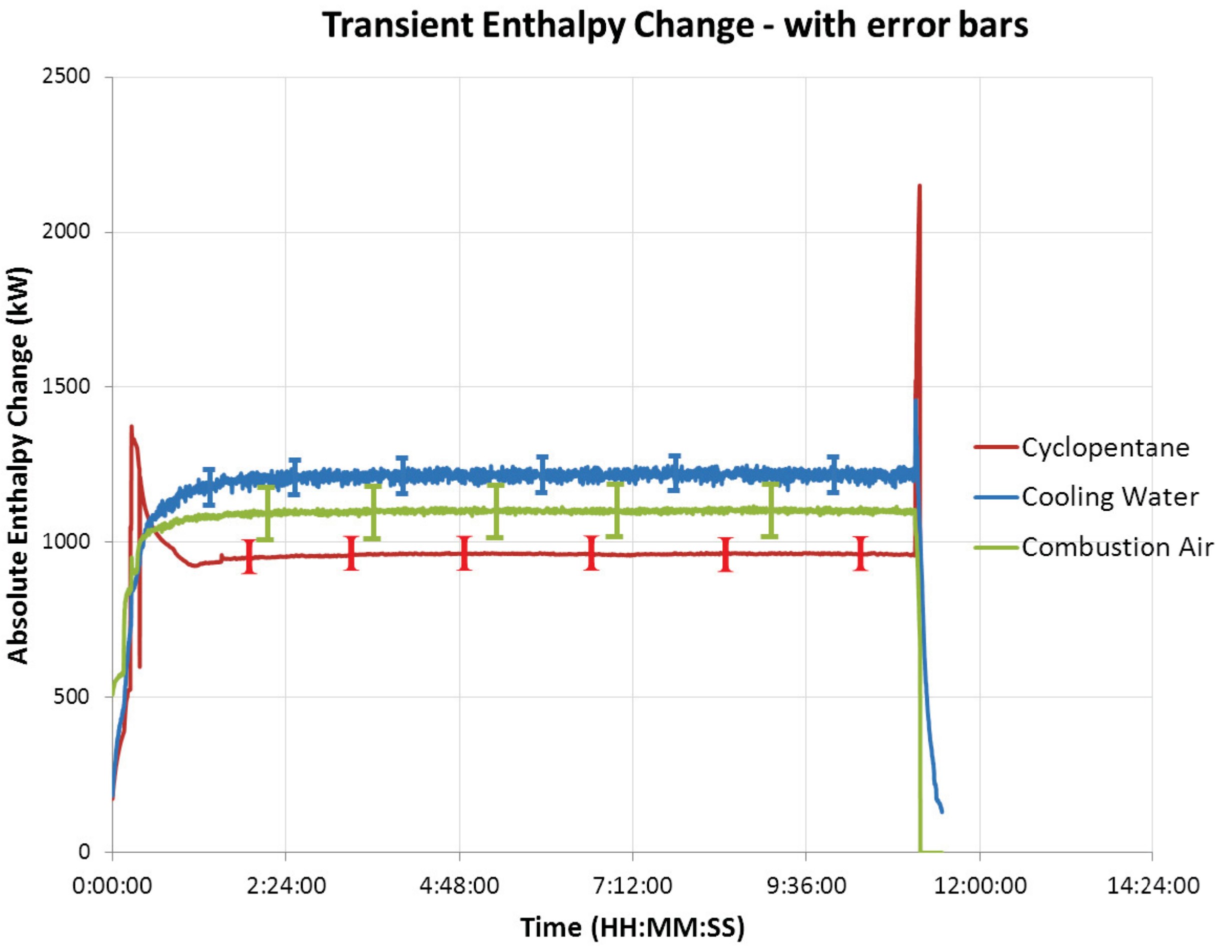


Figure 26. Enthalpy deltas for the three fluids vs. time for a typical experimental run.

Another factor to consider is the experimental error in the calculation that may mask the real heat loss. In order to examine this further, another method of calculating the heat loss was employed by using the outside surface temperatures of the HX shell and applying known free convection heat transfer coefficients to determine the heat flux and the total heat loss. This calculation method (shown in Appendix O) yields an estimated heat loss of 0.4 to 5.1 kW, which is significantly lower than the heat balance method.

The error propagation study is reflected in the error bars in Figure 25. There is a significant amount of overlap in the enthalpy change when considering the error spread. Therefore, the heat balance method of calculating the environmental heat loss is probably not accurate. The free convection heat transfer method is seemingly more accurate.

4.4 Working Fluid Degradation

4.4.1 Chemicals

Cyclopentane working fluid was obtained from Acros Organics (Belgium). Virgin fluid straight from the barrel was delivered to the test.

4.4.2 Analytical Methods

The sampling procedure and hardware are discussed in Appendix I**.** Samples were analyzed by gas chromatography (GC) using an Agilent 6890 GC equipped with an auto injector, a 30-meter J&W DB-1 column, and a flame ionization detector. The temperature program consisted of an initial temperature of 40°C for 4 minutes, a 16°C/minute ramp to 250°C, and then a hold for 20 minutes. Peaks were identified by retention time match and analysis by GC/mass spectrometry.

4.4.3 Results and Discussion

The feed was measured by GC to have a composition of 98.1 wt% cyclopentane with the remainder consisting of n-butane (0.1 wt%), n-pentane (0.7 wt%), and iso-hexane (1.1 wt%). Samples were taken from the test system at the times-on-stream identified in Table 10. During the course of the experiment, the samples were found to contain the same basic concentration of cyclopentane and other hydrocarbons as the fresh feed.

No impurities were detected in the samples up to Sample 11, corresponding to 153 hours of hot runs. Trace quantities of impurities totaling 29, 30, and 30 ppm (±7 ppm), respectively, were measured at 300 hours (Sample13), 310 hours (Sample 15), and 320 hours (Sample 16), respectively.

Table 10. Sample times and decomposition product concentrations.

Sample Number	Date and Time Collected	Time on Stream (hours)	Equivalent 'Hot' Time (hours)	Impurity Concentrations (ppm)
1	8/16/2012, 2:30 AM	0	0	n.d.
3	8/17/2012, 1:00 AM	8	6	n.d.
5	8/17/2012, 7:44 PM	13	9.75	n.d.
7	8/20/2012, 6:45 AM	32	24	n.d.
9	8/31/2012, 11:18 PM	93	70	n.d.
11	9/07/2012, 1:40 AM	153	115	n.d.
13	9/20/2012, 11:23 AM	300	225	29
15	9/21/2012, 8:05 AM	310	232.5	30
16	9/22/2012, 5:44 AM	320	240	30

n.d. = not detected

This result correlates very well with the measured temperature profiles in the cyclopentane and the wall temperatures; it remained well below the threshold of 300°C through most of the experiment. Only in the last two runs, corresponding to Samples 13, 15, and 16, the wall temperature was taken beyond 300°C. These samples show a small resulting decomposition of the working fluid. This outcome was expected.

4.5 Fouling Analysis

At the end of the experiment, four cotton swab samples of residue from the HX tubes were collected from the pressure ports of the working fluid tubes. The cotton swabs were extracted with methylene chloride and the solution was black in color. The GC temperature was ramped from 40°C to 300°C. However, no decomposition/fouling products were found using this method. The black residue in the system appeared to be carbon (from the carbon steel tubes), which apparently did not take part in any reaction with the working fluid.

5. LESSONS LEARNED

The purpose of this section is to document some of the most important lessons learned during the construction, shakedown, and testing of the ORC direct evaporator. These lessons should serve as a useful tool to aid in the design of a full-scale system. A number of design recommendations also are given. These recommendations are by no means the final word, but the designers would be wise to understand the problems encountered and at least make a comparable design choice to address the issues documented. In some instances, problems were encountered and resolved by making some sort of hardware or software change. At other times, the problems were manageable with the existing system, but recommendations were made for improvement on the next design iteration.

This section on lessons learned is divided into two subsections: Safety Issues and Operational Considerations. The safety issue subsection focuses on issues that are critical to safe operation of the rig, whereas the operational considerations subsection covers general practical knowledge gained during the 31 runs, which should prove useful for designing a system capable of smooth and reliable operation.

5.1 Safety Issues

Overall, the design of the ORC direct evaporator test rig was very successful. However, as is the case with all new technologies, issues were encountered that had to be dealt with. All of the safety issues encountered are listed first, followed by a description of the overall safety strategy. Finally, the best practices and recommendations are summarized.

5.1.1 Safety Issues

The safety issues encountered include the following:

1. Fire system dampers. The fire dampers (louvered windows) on the ORC trailer did not close, which was necessary to contain the CO_2, during the first fire suppression system test. This turned out to be a controls system issue and was quickly fixed. The key lesson learned from this event was to put the dampers under hardware control and not rely on software control.
2. Manual fill vent valve failure. A manual ball valve that served as a vent during the fill began to leak cyclopentane. The leak occurred through the valve body and not the stem; therefore, the team capped the valve off to seal the system. It was later discovered that this valve was not a high-temperature valve. The key lesson learned here was to verify that all valves in the hot path are high-temperature valves.
3. Solenoid failure. The solenoid used to actuate isolation valve V-8 failed during testing, causing the valve to suddenly shut. Fortunately, the operators noticed the pressure spike and shut the pump off before an E-stop or overpressure situation occurred. The cause of the solenoid failure was water leaking into the trailer during a rainstorm; the water was dripping directly onto the solenoid connector and caused it to corrode. The key lessons learned from this event were to leak check the trailer before commissioning and to modify the control software to monitor for sudden pressure spikes and initiate a soft stop in the event that one occurs to prevent a release of refrigerant through the pressure relief valves due to overpressure.
4. Pressure drop out/accumulators bottoming out. At one point while the team was pressurizing the rig on a cold night, the pressure suddenly dropped off. Initially, it was thought to be a leak. However, it was later discovered that the liquid cyclopentane, upon entering the HX, cooled and contracted enough that it completely emptied from the hydraulic accumulators and began to condense, resulting in a partial vacuum in the loop, and no longer allowed pressure control. As a short-term remedy, the team was able to heat the cyclopentane in the HX to re-expand it, which gave back pressure control. The key lesson learned was the importance of filling the accumulator cylinders with enough fluid in order to avoid this situation in the first place.

5.1.2 Overall Safety Strategy

The overall strategy for operating the system safely was to house all of the capital equipment in the refrigerant flow loop, with the exception of the Deltak HX in a trailer. The trailer contained a dedicated fire suppression system and was sealed during testing. The trailer was only to be entered under specific conditions as outlined in Appendix G. Overall, this was a very successful strategy.

Another key component that led to safe operation and that cannot be emphasized enough is the importance of filling the system with a surrogate fluid for shakedown prior to filling it with cyclopentane. In our case, the surrogate fluid was a mixture of approximately 90% water and 10% ethanol by volume. This provided us the opportunity to test out all of the equipment and gain operational experience using a non-flammable fluid. This fluid mixture also had the purpose of flushing the system of any dirt and rust prior to the fill.

A final key safety component was the use of tiered warnings and emergency stops and the proper training of operators on how to use them. The first line of defense was a set of operator-defined ranges for all of the measured parameters at steady-state operation. If a system parameter drifted out of this range, the software triggered an audible alarm and a red light on the control screen would indicate which parameter had drifted. The ranges were learned from experience and purposefully set tight around the desired steady-state values. The next line of defense was a series of software limits that would trigger a soft shutdown if exceeded (e.g., an absolute maximum temperature and pressure). This soft shutdown consisted of depressurizing the hydraulic accumulators and shutting off the Gastech heater, eliminating the heat source. These two shutdowns could easily be recovered from if needed. The final line of defense was the hardware safety features, including pressure relief valves, over temperature limit controls, and the manually actuated E-stop, which was considered a last resort. Additionally, the system had an emergency valve and reservoir tank that could be used to rapidly depressurize the system in the event of a major emergency (such as a fire in the trailer). This was tied into the fire suppression system, but also could be manually actuated from the control room using a pneumatic valve. We nicknamed this valve the “ejection button,” because it would eject a majority of the cyclopentane from the system into the reservoir tank and bring the experiment to an end.

The importance of proper operator training cannot be emphasized enough. We spent a lot of time during the design and build phase going over worst case scenarios and figuring out the proper response for each. Appendix F provides a reference for the recommended responses to various scenarios and shut down procedures.

One drawback of this test rig was the fact that a hard E-stop (i.e., one triggered by hitting a mushroom button) would terminate all power to the trailer. As a result, all operator control would be lost and it could not be quickly regained. In retrospect, we believe that it would be better to continue making measurements and to maintain control of the loop components (e.g., pump speed, valves, etc.), even during an E-stop; therefore, the operator would not be blind and measures could be taken to bring the system back to a safe state if possible.

5.1.3 Best Practices

A summary of best practices for the prototype test are summarized by the following:

1. Use of a trailer with fire suppression system to contain all equipment
2. Testing/shakedown with a surrogate fluid
3. Tiered safety system/Estops
4. Thorough operator training and emergency checklists.

5.1.4 Recommendations

The test team provides the following recommendations:

1. Maintain measurement and control capability in the event of a hard E-stop
2. Use video cameras with night vision in the trailer or have sufficient lighting such that it is not needed.

5.2 Operational Considerations

This section is a compilation of general knowledge gained during the month and half of testing on the ORC direct evaporator test rig.

5.2.1 Filling the Loop

To fill the system with cyclopentane, our team first purged the flow loop with nitrogen and then drew a partial vacuum on it. Because of safety concerns and limitations on filling equipment, the team used pneumatically powered drum pumps to pump the cyclopentane from 50-gallon metal drums directly into the flow loop. With the system in partial vacuum, the flow rate was high, but as the system filled the drum, the pumps had difficulty pushing the liquid into the system, resulting in not getting much fluid into the cylinders of the hydraulic accumulators. In retrospect, we believe a better method would have been to transfer the cyclopentane into a sufficiently large tank or pressure vessel and then use an explosion-proof, recirculating refrigerant pump to pull cyclopentane vapor from a high point in the loop and use it to push liquid into a low point in the loop. This should have provided sufficient pressure to fill the accumulators. Alternatively, nitrogen could have been used to push the additional liquid into the loop after some fluid was drawn in and vacuum was lost. For safety purposes, we recommend using a hands-off approach to filling where the fill system is engineered to operate without a user present at the fill site. All connections could be made in advance and the system could be remotely operated from the control room using pneumatically actuated valves and controls. Once the system is filled, the valves can be closed and the operator can disconnect the fill plumbing.

As previously mentioned, the hydraulic accumulators were barely filled with cyclopentane, resulting in the fluid completely evacuating from them during cold ambient conditions. We recommend filling the accumulator from one-fourth to one-half full with fluid. Additionally, the hydraulic pistons used for the experimental rig were not always reliable and sometimes the pistons would get stuck. We recommend using an accumulator tank with a gas blanket to avoid this problem.

5.2.2 First Run

A best practice that worked well for our team (which we recommend when running for the first time) is "burping" the system to get rid of any dissolved gasses in the cyclopentane. We circulated the fluid slowly while under pressure in order to keep it in the liquid phase, applied some heat, and then opened up a high point valve in order to vent off any desorbing gases. This helps to maintain the purity of the working fluid and also helps suppress pump cavitation. We also recommend pressurizing the system sufficiently with the accumulators before starting the pump to help avoid cavitation. It is common to experience some sporadic cavitation and/or vapor lock of the pump during the first startup after filling, but with enough pressurization and venting, the gas bubbles can be removed and subsequent startups should go smoothly.

5.2.3 Cold Starts

Cold temperature startup should not be an issue if the accumulators are sufficiently full, but in the event they are not full due to fluid loss, it is still possible to start the rig, even when the pressure is under partial vacuum by first gently heating the fluid in the HX and waiting for the system pressure to come back up. Once it does, the pump may be started and startup may commence as normal.

5.2.4 Cyclopentane Leak Monitoring

We believe that we experienced some weeping of fluid through the pressure relief valves because we were slowly losing cyclopentane over time. Therefore, we recommend thoroughly testing all relief valves and adding gas monitoring to the relief manifold. We also recommend adding capped ports downstream of each relief valve so, if a leak is found, it will be possible to determine exactly which relief valve is leaking fluid. A manual ball valve just upstream of each pressure relief valve would allow isolation, allowing replacement or maintenance to be performed without contaminating or losing cyclopentane in the event that a problem is found.

5.2.5 Reaching and Maintaining Steady-State Conditions

It took the test rig about 2 hours to reach temperature and to get close to steady state; however, the rig continued to heat slowly for much longer than that. We also noticed a certain amount of drift in the system pressure due to the pressure control system used. This occasionally triggered an alarm, but became less frequent as we gained operational experience. Some amount of drift should be expected. Some parameters will drift over time due to changing ambient conditions. For example the ambient conditions will affect both the heat loss through the HX and the cooling tower performance. In our case, we shared our cooling water system with several other large experiments; therefore, we occasionally experienced system fluctuations due to variations in the flow rate of our cooling water. We recommend that new installations have a dedicated cooling system.

5.2.6 Use of a Surrogate Fluid for Shakedown and Cleaning

As discussed at length in the safety section, we recommend filling with a surrogate fluid for shakedown and cleanout. The fluid can be circulated and cleaned with an inline filter. This may require removal of the filter, cleaning, and replacing a number of times depending on how clean the loop is. We recommend thoroughly cleaning the system before toggling the valves to keep them from getting dirty and not closing properly. If a water mixture is used, it is important to note that it may take some time to completely dry out the loop after emptying it. We alternately vacuumed and pressurized the loop with dry nitrogen. We monitored humidity of the nitrogen leaving the system and it took several days to completely dry it out. One way to avoid this situation is to use pure ethanol (or another fluid with a low boiling point) as the surrogate. This way a few vacuum and pressurization cycles would be sufficient to dry out the loop. If the decision is made to fill with water or a water mixture, we recommend using a strong vacuum pump capable of a deep vacuum to help speed up the dry out process.

5.2.7 System Pressure Control

Our system relied on two nitrogen cylinders, a pressure regulator, and a mechanical backpressure regulator to set the pressure of the accumulators. While functional, it was sometimes a struggle to balance the pressure settings so we were not losing nitrogen too fast. We strongly recommend using the following:

1. A bulk source of nitrogen or other inert gas to avoid frequent cylinder changes
2. An electronic flow controller to set the pressure flow rate of nitrogen into the system
3. An electro-pneumatic backpressure regulator for pressure control.

We also recommend flow metering on the nitrogen pressure relief line to detect when it is activated and how much nitrogen is being lost.

5.2.8 Sampling System

One of our test requirements was to take periodic samples of cyclopentane to check for degradation. We recommend using a similar system for periodic fluid inspection because fluid stability is critical to system performance and the sampling system was very easy to operate. Appendix I contains a schematic of our sampling system and procedures on how to operate it. Though our sampling system was manual, it would be very easy to make the same system operate automatically using pneumatically actuated valves, without a user having to go near the loop.

6. SUMMARY AND CONCLUSIONS

The following have been shown by means of this experiment:

- The temperature of a boiling (and superheating) ORC working fluid can be controlled by using protective staging when the hot resource temperature is significantly higher than the working fluid decomposition temperature.
- The heat transfer rate into the working fluid can be controlled be using variable fin densities in the evaporator, superheater, and economizer.
- The working fluid degradation/decomposition after 320 hours of hot run time was 30 ppm – an insignificant amount – suggesting the protective staging and variable finning approach was very effective.
- The safety hazard of direct exposure of a flammable fluid to a hot combustion gas was effectively mitigated in this experiment. There were no safety incidents involving the flammable fluid throughout this experiment.

In a full scale industrial setting, the following are recommended:

- The safety FMEA and flammability hazard mitigation steps in this experiment can be used to design a cost-effective safety system for commercial deployment.
- An online sampling system for working fluid quality analysis (similar to that used in this experiment) can be used to periodically check the working fluid for degradation. This sampling system does not require any downtime and can be automated.
- It seems a piston-based fluid accumulator (i.e., buffer tank) would be impractical in an industrial setting. Argon gas should be used as the blanket fluid.
- Flow uniformity on the hot combustion gas side remained a concern; therefore, in an industrial implementation, additional flow straightening should be implemented in order to make the most effective use of the tube heat transfer area.
- The test rig was comprised of three parallel flow passages for the cyclopentane. When the liquid was heated and changed phase to vapor, there was nothing to present one channel from being vapor locked. Using orifice plates at the inlet to the evaporator would help make the flow more uniform.

7. REFERENCES

Gallant, R. W. and C. L. Yaws, 1993, *Physical Properties of Hydrocarbons* 2, 3rd ed., 176 Houston, TX: Gulf Publishing Co.

INL, 2010, *Milestone Report #3 − Direct Evaporator FMEA & Hazop Study*, report to the U.S. Department of Energy, INL/LTD-10-19666, August 2010.

Williamham, C. B., W. J. Taylor, J. M. Pignocco, and F. D. Rossini, 1945, "Vapor Pressures and Boiling Points of Some Paraffin, Alkylcyclopentane, Alkylcyclohexane, and Alkylbenzene Hydrocarbons," *J. Res. Natl. Bur. Stand. (U.S.)*, 35, 219-244.

8. ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, Industrial Technologies Program, under Contract No. DE-PS36-08GO98014.

9. APPENDICES

Appendix A, Final Piping and Instrumentation Diagram Schematic

Appendix B, Detailed Equipment Description

Appendix C, Detailed HX Drawings, Specifications, and Bill of Materials

Appendix D, Rig Charging Procedure

Appendix E, Standard Operating Procedure

Appendix F, System Event Response Checklist

Appendix G, Trailer Entry Procedure

Appendix H, Draining of HX and Piping

Appendix I, Hot Sample Collection Procedure

Appendix J, Inert Gas Purge Protocol

Appendix K, Heated Drying Protocol

Appendix L, Data Collection Schematics

Appendix M, Calculation of Average Velocity and Reynolds Number in the ORC Main Heat Exchanger

Appendix N, Calculation of Enthalpy of Combustion Product Gas

Appendix O, Calculation of Q_E: Heat Flux to the Environment

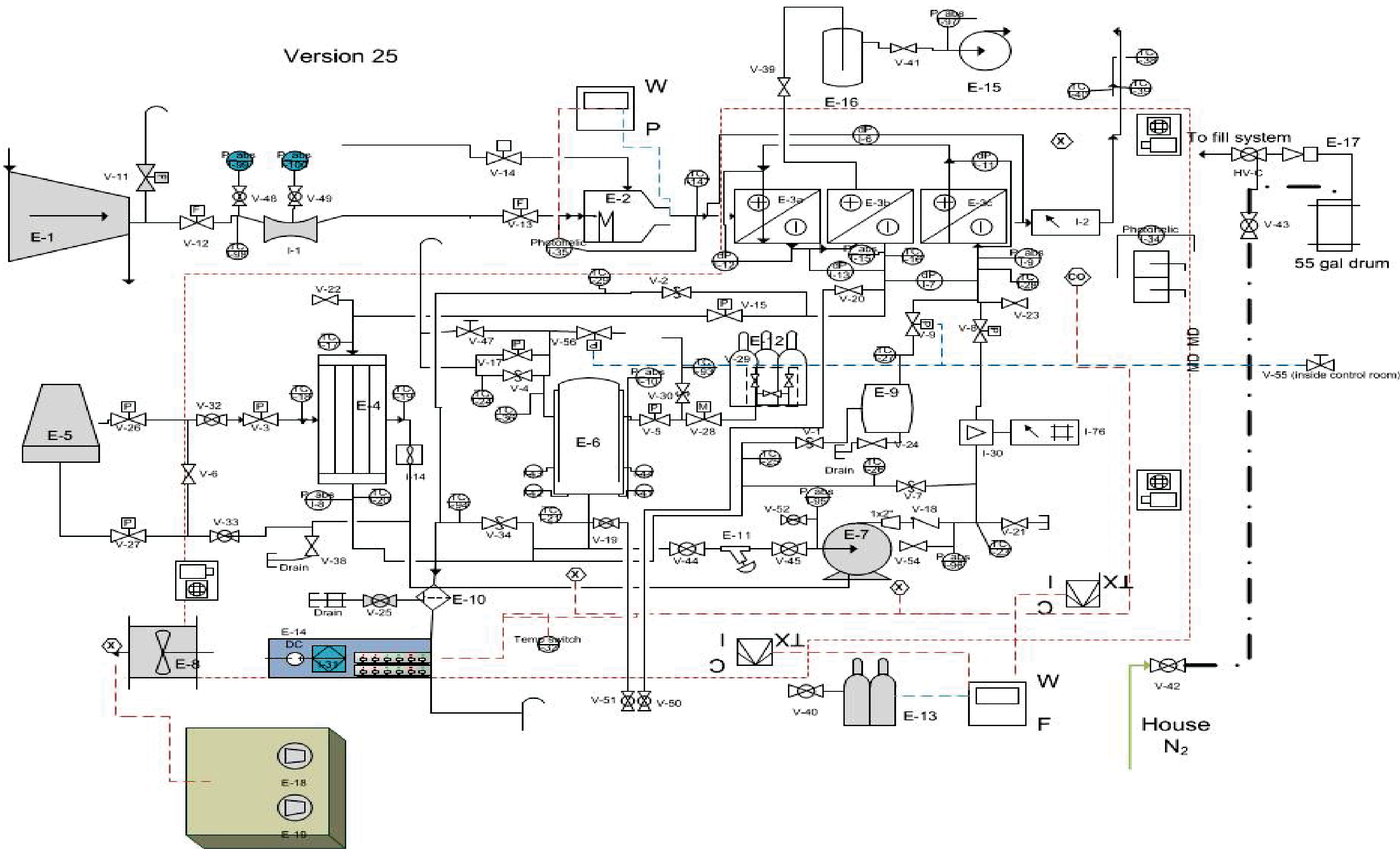
Appendix P, Data Analysis using SAS Enterprise Guide

Appendix Q, Data Dictionary

Appendix R, Test Rig Instrumentation Locations and Identifiers

Appendix A

Final Piping and Instrumentation Diagram Schematic



INTENTIONALLY BLANK

Appendix B

Detailed Equipment Description

B1. SYSTEM DESCRIPTION

B1.1 Automatic Controls

Working Fluid Flow Control

I-16 (HX WF Outlet Temp) is controlled at 250°C during steady-state operation by varying the speed of the Circulation Pump (E-7) using proportional control. I-16B is the backup for I-16.

Cooling Water Flow Control

I-20 (Condenser WF Outlet Temp) is controlled at operator-selected temperature during steady-state operation by varying the position of the cooling water throttle valve (V-3). The control temperature of I-20 will be established during initial cyclopentane S/U to allow I-16 to be controlled at 250°C.

System Pressure Control

Accumulator pressure is normally controlled by the Backpressure Regulator, V-47, which is adjusted manually outside the trailer. However, an overpressure condition (greater than 620 psia) sensed on Accumulator Pressure, I-10, will cause the following:

- The Ar Isolation Valve, V-5, to shut
- The Accumulator Depressurization Valve, V-17, to open
- Dumping all argon off the top of the accumulator pistons.

B2. MAJOR COMPONENTS

The HX (shown in Figure B-1) was manufactured by Hamon Deltak, Inc. in 2010/2011. It is a once-through boiler design with three sections. The section to the far left in the picture is the evaporator, next is the superheater, and the far right section is the economizer. There are three tube rows along the width of the HX. All experimental data are taken from the center row. The evaporator has three finned tube rows in the gas path, the superheater has three finned tube rows, and the economizer has 11 finned rows for a total of 17 rows long, by three rows wide. Detailed drawings of the HX can be found in Appendix C.

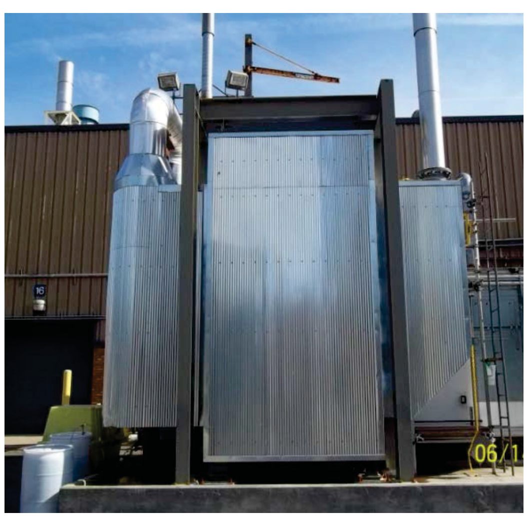


Figure B-1. Test heat exchanger (E-3).

The condenser, (Figure B-2) provided by Thermal Products Inc., is a shell and tube HX, where the working fluid (cyclopentane) is on the shell side and the cooling water, provided by the tower water system, is flowing through the tubes. This unit was stamped to operate at 450 psig; however, the vendor has communicated that it can be run at 500 psig and 500°F.

The pump (Figure B-3), provided by ChemPump, is a centrifugal pump with an explosion proof motor. It runs off a 480-V, 30-hp motor, which is driven by a Frenic VFD housed in the Hoffman panel in ES 154. The pump must be primed as instructed in the manual after each fill of the system.

The accumulator (Figure B-4), provided by Pearse-Bertram, is composed of a rack of four piston accumulators connected at the top and bottom by manifolds. The accumulator maintains pressure in the system by using a high-pressure gas to compress the pistons and force the cyclopentane out of the bottom and into the test loop. The pressurizing gas was supplied by a rack of nitrogen bottles.

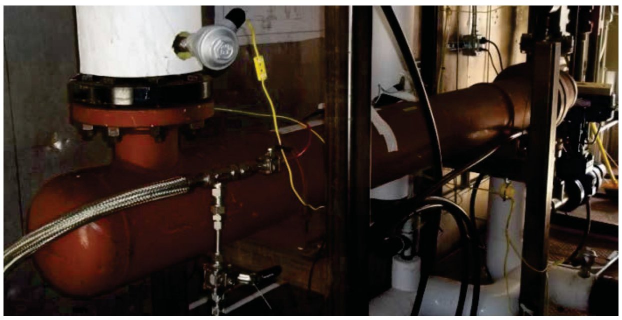


Figure B-2. Condenser (E-4).

Figure B-3. Pump (E-7).

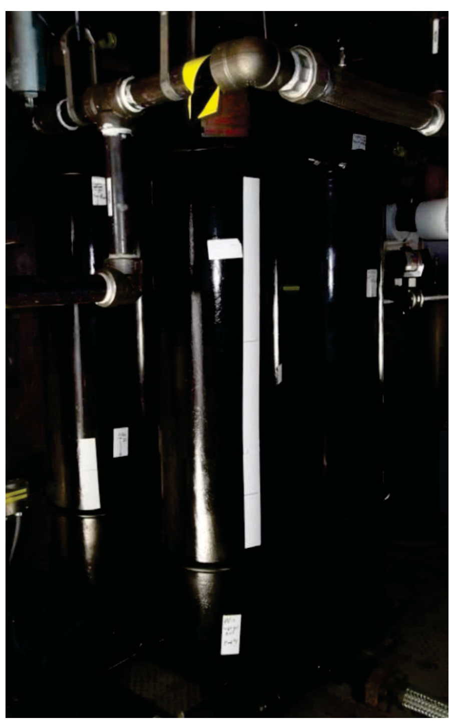


Figure B-4. Accumulator (E-6).

The depressurization vessel, (Figure B-5) provided by American Boiler, is used to drain cyclopentane or other fluid from the HX if V-8 and V-15 are closed or from the HX and the loop if the above valves are open. This vessel has a capacity of 50 gallons.

The separator (Figure B-6) was supplied by Eaton Process, Inc. The vessel is downstream of all the pressure relief lines coming off the cyclopentane line. The unit is a cyclone separator placed in line to remove the liquid portion of cyclopentane that is discharged. The vapor port is vented out through the top of the trailer. The liquid portion is collected and emptied via a drain in the base of the vessel.

The final critical piece of equipment to run this experiment is the GasTech, inline vitiated heater (Figure B-7). This is a natural gas heater capable of producing 500°C gas at a flow rate of 10l bm/s. This heater is fed off the continental blower/compressor. The GasTech heater is controlled from a panel mounted on the ES 154 wall by Door 17.

Figure B-5. Depressurization vessel (E-9).

Figure B-6. Separator (E-10).

Figure B-7. GasTech heater (E-2).

Images of the Valves in Safe Startup Position

Valves V-1, V-2, V-4, V-7, V-30, and V-34 are pressure relief valves. The valves are connected to the cyclopentane line and discharge to a common header, which then directs the vapor through a separator and out the top of the trailer. V-2 is set to a lower pressure to protect the condenser, which is rated to run at 500 psig.

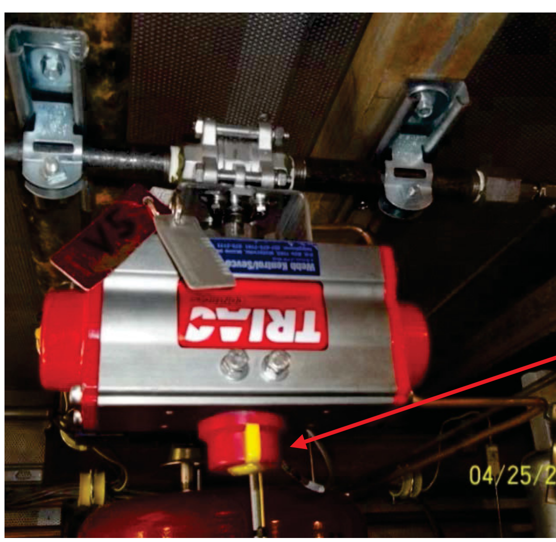
Valve V-3 is the tower water control valve with a pneumatic positioner, which is marked in red. Currently, the positioner/valves are closed. The position of this valve is controlled on the “Test” screen of the LabView VI by changing the percentage that the valve is open.

Valve V-5 is the solenoid located upstream of the accumulator, which allows the user to stop pressurizing the system and maintain pressure in the system at the current level. The pneumatic feed for V-5 and V-17 is located on the wall of the trailer. V-5 is controlled from the “Test” screen of the LabView VI. Currently, the valve is shown in the closed position, as noted by the yellow actuator at the bottom of the valve.

V-1

V-3

V-5



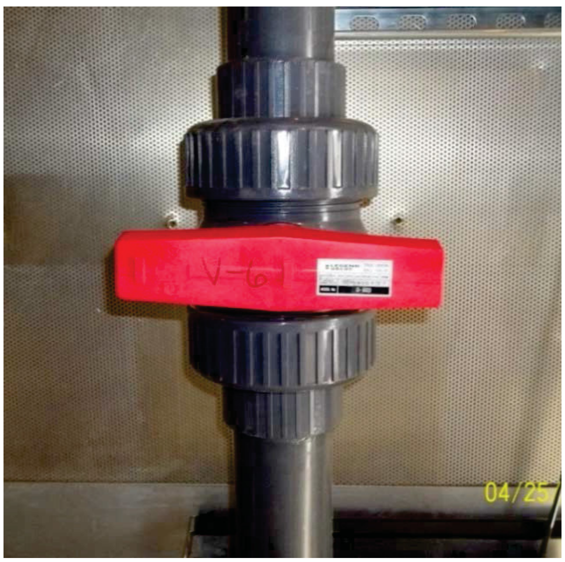
Valve is closed

Valve V-6 is the tower water bypass valve and, in the open position, it allows the tower water to circulate through the trailer and return to the building. This valve should be open prior to opening V-26 and V-27 in ESB 154. This will allow the tower water to return to the building during the initial condenser fill. This valve is manually actuated from the trailer on the west wall.

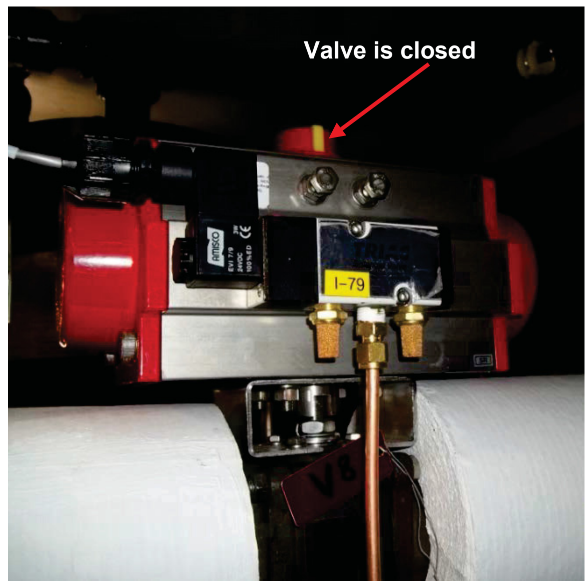
Valve V-8 is the 2-in. pneumatic isolation valve on the cyclopentane line. This valve is used to isolate the HX from the rest of the system. It is controlled from the "Test" screen on the LabView VI and should be actuated with V-15, which is the 4-in. isolation valve. The valve currently is shown in the closed position, as noted by the yellow bar on the actuator.

Valve V-9 is a 2-in. pneumatic valve used to drain the liquid portion of the cyclopentane out of the HX as required by the operator. It is controlled from the "Test" screen on the LabView VI. Valve V-8 should be closed prior to attempting to drain the HX. This valve currently is shown in the closed position.

V-6



V-8



V-9

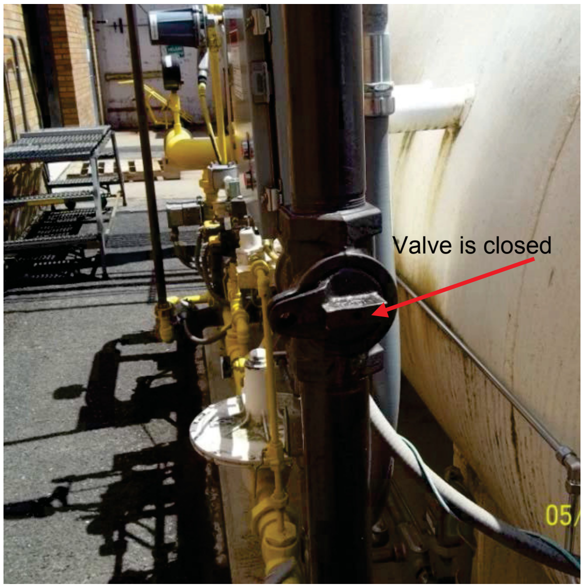
Valve is closed

Valve V-10 is the main natural gas supply to the GasTech heater. It should be opened prior to running the heater and be closed at the end of use.

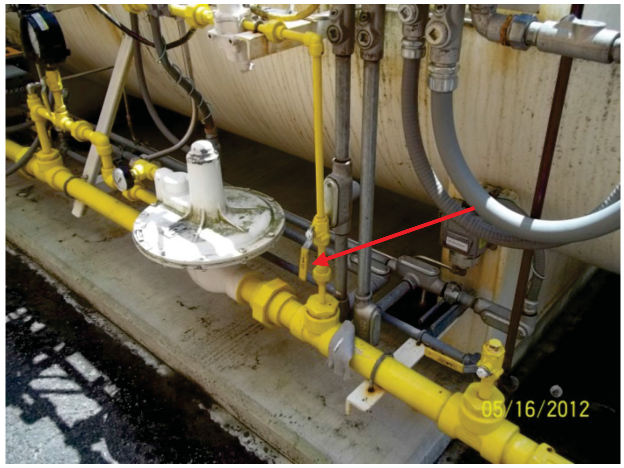
Valve V-11 is the natural gas supply to the pilot of the GasTech heater. This valve can remain open when the unit is not in operation if the main supply, V-10, has been closed.

Valves V-12 are the two blocking valves that control the flow of natural gas to the heater. These valves are controlled by the GasTech control panel and do not need adjustment.

V-10



V-11



V-12

Valve V-13 is an electric valve that opens the airline off the Continental out to the GasTech heater. This valve is powered by the GasTech control panel, but the switch to open/close the valve is to the left of the panel. Note that this valve should be closed before turning off the power to the GasTech panel.

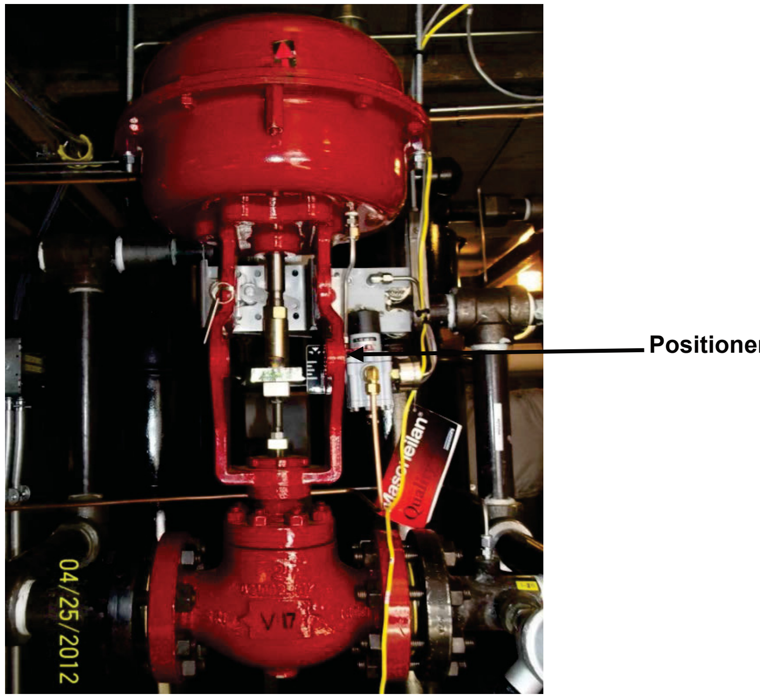
Valve V-15 is the 4-in. pneumatic isolation valve on the cyclopentane line. This valve is used to isolate the HX from the rest of the system. It is controlled from the "Test" screen on the LabView VI and should be actuated with V-8, which is the 2-in. isolation valve. The valve currently is shown in the closed position, as noted by the green bar on the actuator.

V-13

V-15

Valve V-17 is a 2-in. pneumatic positioner on the argon line. It is used to perform a controlled depressurization of the system. This would be used in conjunction with V-5, which is a solenoid valve to stop the flow of argon into the accumulator. This valve would, in turn, slowly release the argon to the vent system.

V-17



Valve V-18 is the check valve on the high-side of the pump, designed to maintain the head at the high-side of the pump and prevent flow from passing back in the reverse direction. It has a cracking pressure of 0.5 psi.

V-18

Valve V-19 is a manual ball valve used for filling and draining the loop. It inserts into the 2-in. line running between the condenser exit piping (covered with insulation in the photo) and the accumulator exit piping. This valve is connected to a 1/2-in. CS line that exits the trailer and terminates at the barrel grounding location at the west end of the trailer.

Valve V-20 is a manual ball valve used to fill/drain the cyclopentane from the 4-in. pipe exiting the superheater. This valve is connected to an extension line to the fill location, which terminates in another valve, V-50.

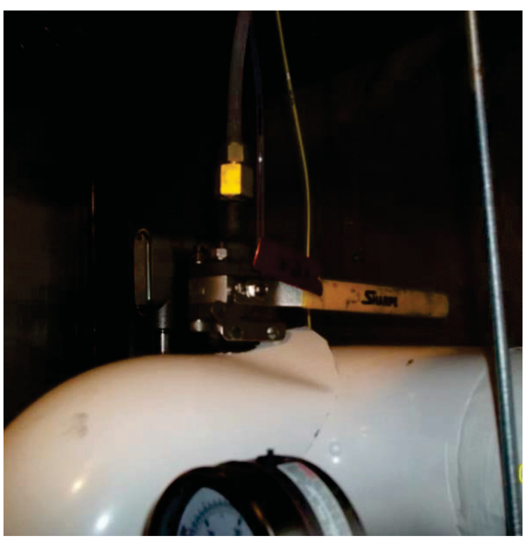
Valve V-21 is located at the high side of the pump and is the high point in the 2-in. cyclopentane liquid piping, where a vacuum can be drawn and vent slugs of air that become trapped during the fill process. This valve can be connected to a 1/2-in. poly line, which is for venting and is run outside through the north wall of the trailer. This valve can be used for any off-line sampling desired from the liquid side.

Valve V-22 is located at the high side of the condenser (E-4) and is the high-point in the 4-in. cyclopentane line. The condenser is pitched 1/4-in. up at this side to allow for non-condensable gas to accumulate and be vented out the side of the trailer through the same hole mentioned above. This valve can be connected to the vacuum system and be used for any off-line sampling required.

V-19

V-20

V-21



V-22

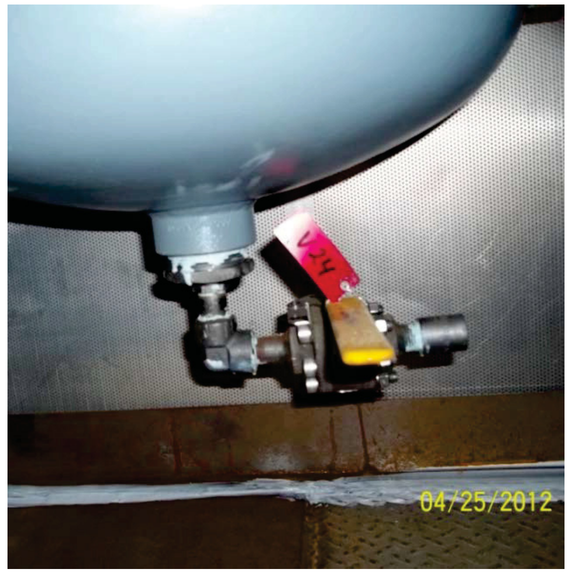
Valve V-23 is located in the 2-in. cyclopentane liquid pipe that feeds the preheater/economizer. This valve is accessed by climbing to the second level of the scaffolding and is manually actuated. This valve can be used to vent the cyclopentane and to draw vacuum on the system (as shown in the picture). This valve also is available to do online sampling because it is accessible without entering the trailer.

Valve V-24 is connected to the cyclone separator to be used as a drain after any discharge of the pressure relief valves. This should be drained into a metal catch pan.

Valve V-25 is a manual ball valve acting as a drain for the 50-gallon, de-pressurization vessel. There is a hose bib fitting attached to this valve to allow for easier draining from the tank. When draining cyclopentane or a fluid with flammability issues, a metal catch tank should be used and plastic/rubber or insulating hoses should be minimized.

V-23

V-24



V-25

Valve V-26 and V-27 are electro-pneumatic wafer valves that allow tower water to flow to the trailer. These valves have been modified with a slow release regulator to prevent them from slamming shut. They are activated using a single switch under the GasTech control panel. This switch is seen in the picture on the right (V-27).

Valve V-28 is a manual regulator, attached to the outside of the north wall of the trailer. This regulator is used to control the pressure of the argon/pressurizing gas going to the system. It can be manually adjusted prior to and during testing to increase/decrease the pressure on the accumulator; however, the set pressure of the regulator limits the amount of pressure in the accumulator.

V-26

V-27

V-28

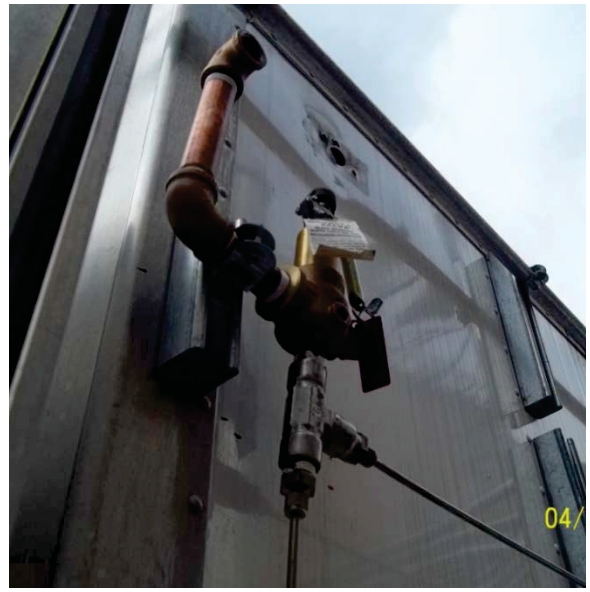
Valve V-29 is a manifold to connect four cylinders to the 1/4-in. argon/inert gas fill line to the high side of the accumulator. The manifold has gages attached to each bottle to verify acceptable pressure in each. V-28, the gas regulator, can be seen at the left end of the manifold.

Valve V-30 is the inert gas pressure relief, which will discharge if the inert gas regulator fails for any reason. This will discharge over the heads of anyone in the area to reduce the risk to personnel. This pressure relief is set to discharge at 44 bar (638 psi).

Valves V-32 and V-33 are manual butterfly valves that allow the tower water to flow to the condenser. These valves are both shown in the closed position. They should be opened well before heat is applied to the system and the flow in the loop verified by I-14.

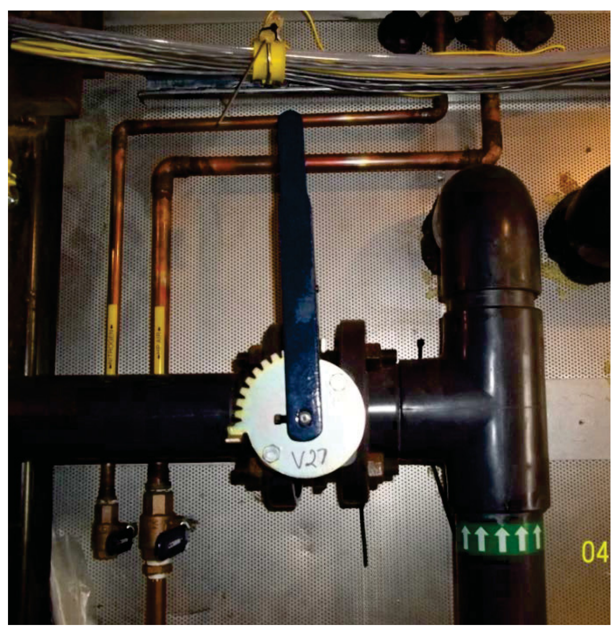
V-29

V-30



V-32

V-33

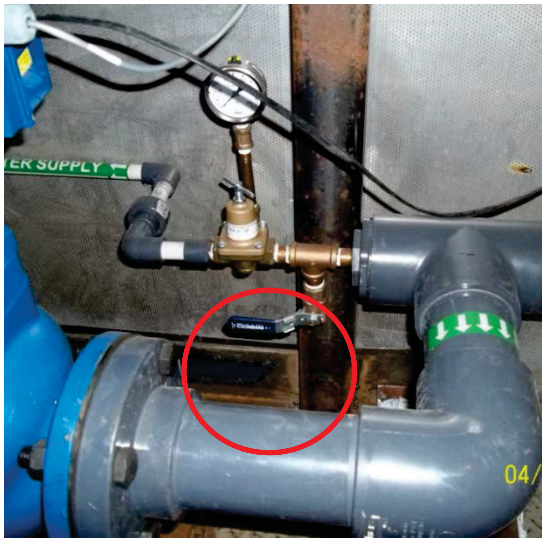


V-38 is the tower water drain. This valve has a hose bib on it that allows the user to drain the tower water that is in the condenser and in the lines from the building. Note that V-32 and V-33 should be closed prior to draining the lines. Also, to create the needed air draw-in, the TC fitting on the condenser exit, I-19, was loosened to enable draining.

V-39 is a venting valve connected to the intermediate header of the HX. This header is before the final three passes in the preheater/economizer. This header ensures even distribution of the fluid in each of the three tube rows and the three remaining passes in the exhaust stream. It is manually actuated by climbing to the second level of the scaffolding and is located at the top of the HX. It also can be used as a second vacuum port as necessary.

Valve V-40 is the lockout valve for the CO_2 fire suppression system. This valve should only be locked by a member of the Building Support Center (BSC) or the fire brigade. If the need arises to enter the trailer when the system is charged with cyclopentane, call x6118 to have someone come down and lock out the valve.

V-38



V-39

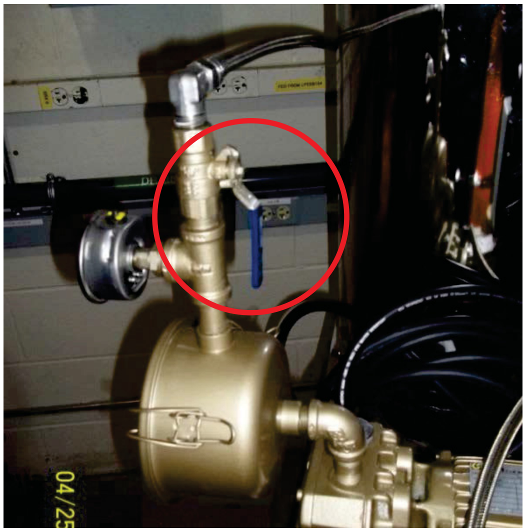
V-40

V-41 is the inlet vacuum valve. It is connected to the vacuum tank and the vacuum pump via a flex hose. This system is mobile and is stored in the trailer when not in use.

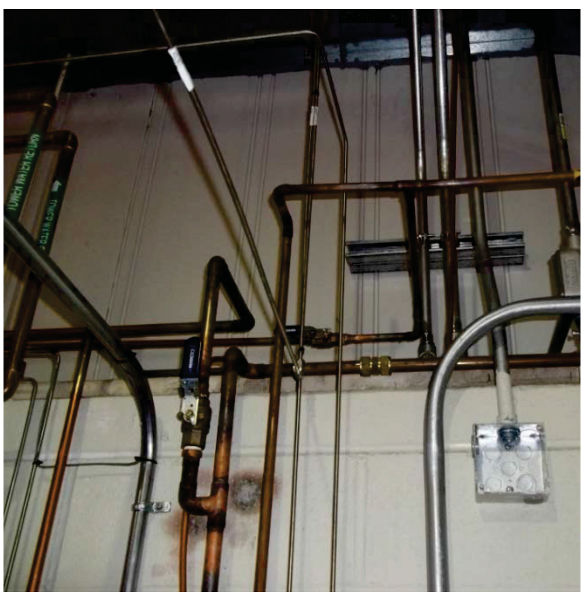
V-42 is the house nitrogen inlet valve that supplies the trailer with nitrogen at (about 40 psi). This valve is located in ES 154 on the south wall of the laboratory. This line has a check valve downstream of this valve to prevent anything from backing up into the building supply. This valve remains open during the duration of the testing and the flow of nitrogen is controlled at the trailer. However, it can be used for lockout/tagout, if necessary.

Valve V-43 is the house nitrogen valve on the outside of the trailer that can be connected to the barrels for the fill procedure. This valve also can be used to run N_2 into the piping to dry the loop as noted in the protocols.

V-41



V-42

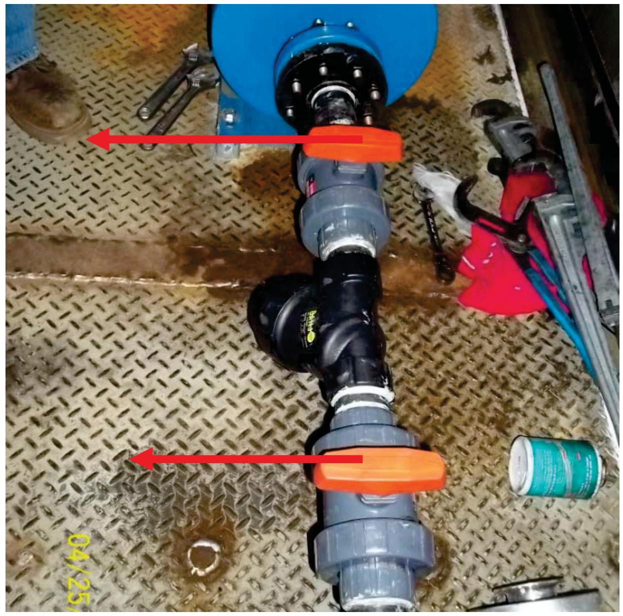


V-43

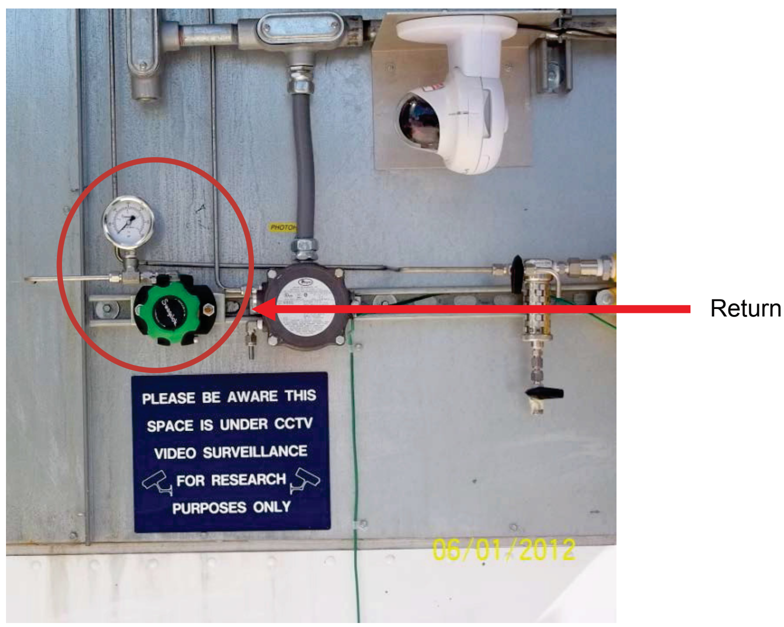
V-44 is the y-strainer inlet (seen at the bottom) and V-45 is the y-strainer exit (seen at the top). Both of these valves are polyvinyl chloride and are intended for use only during a water cycling/clean-out procedure. These valves are rated for 150 psi, as is the y-strainer. These should be opened to allow for water to flow through the strainer set-up and can be closed to drain and clean out debris in the strainer.

Valve V-47 is the back pressure regulator that is run in parallel with V-4 and V-17 to add fine control to the pressurizing system. This will be adjusted manually prior to heating the test to maintain the desired pressure in the accumulator.

V-44/V-45



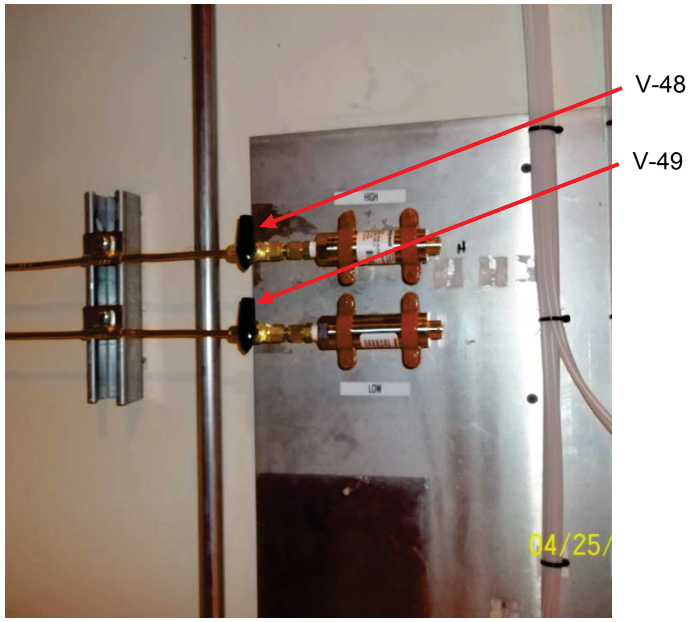
V-47



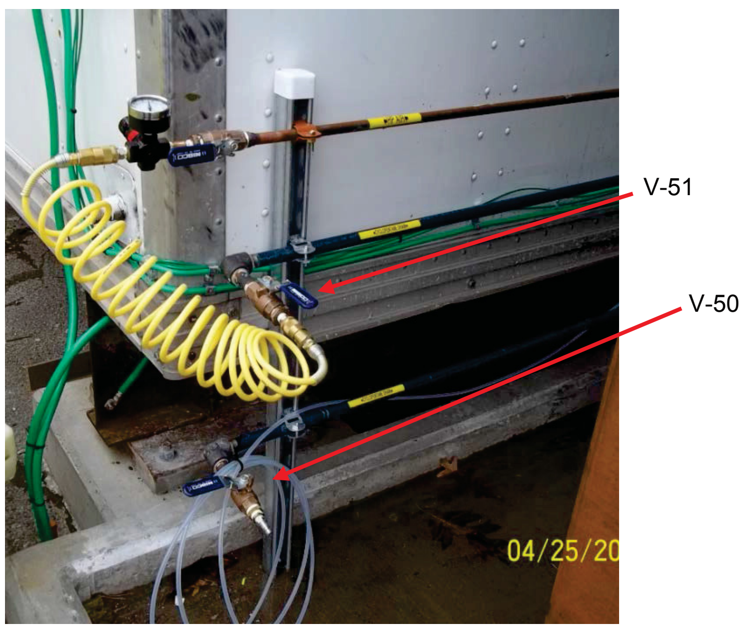
Valve V-48 opens the pressure transducer line from the venturi tap on the high side (shown as the top valve in the picture). Valve V-49 opens the pressure transducer line from the venturi tap at the contraction (shown as the lower valve). These valves must be opened to read the mass flow in the system.

Valve V-50 is a fill/drain extension line that connects to V-20, which is the manual ball valve used to fill and drain the HX side of the loop when the isolation valves V-8 and V-15 are closed. Valve V-51 is a fill/drain extension line that connects to V-19 inside the trailer. These manual ball valves are used to fill/drain the piping side of the loop.

V-48/V-49



V-50/V-51



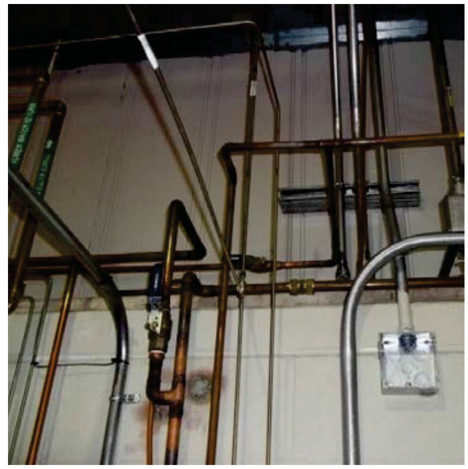
Valve V-52 is a vent off the 2-in. line running to the suction side of the pump. This valve is used during the fill procedure and to verify the pump has no air pockets at the suction side. In the photo, the valve is set up for the suck-blow dryout procedure. The tee would not be inline during actual operation.

Valve V-53 is the house air inlet valve that supplies the trailer with air at about 89 to 90 psi. This valve is located in ES 154 on the south wall of the laboratory. This line has a check valve downstream of this valve to prevent anything from backing up into the building supply. This valve remains open during the duration of the testing and the flow of air is controlled at the trailer. However, it can be used for lockout/tagout, if necessary.

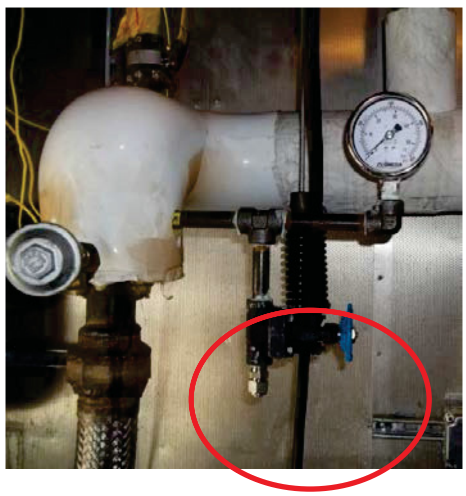
Valve V-54 is an additional drain valve off the high side of the pump. This valve can be utilized to drain the 2-in. line. The pressure gauge see is reading the discharge pressure of the pump. It is not rated for the highest temperatures seen in the look, thus it is over 12-in. from the hot pipe. This should be considered when using V-54.

V-52

V-53



V-54

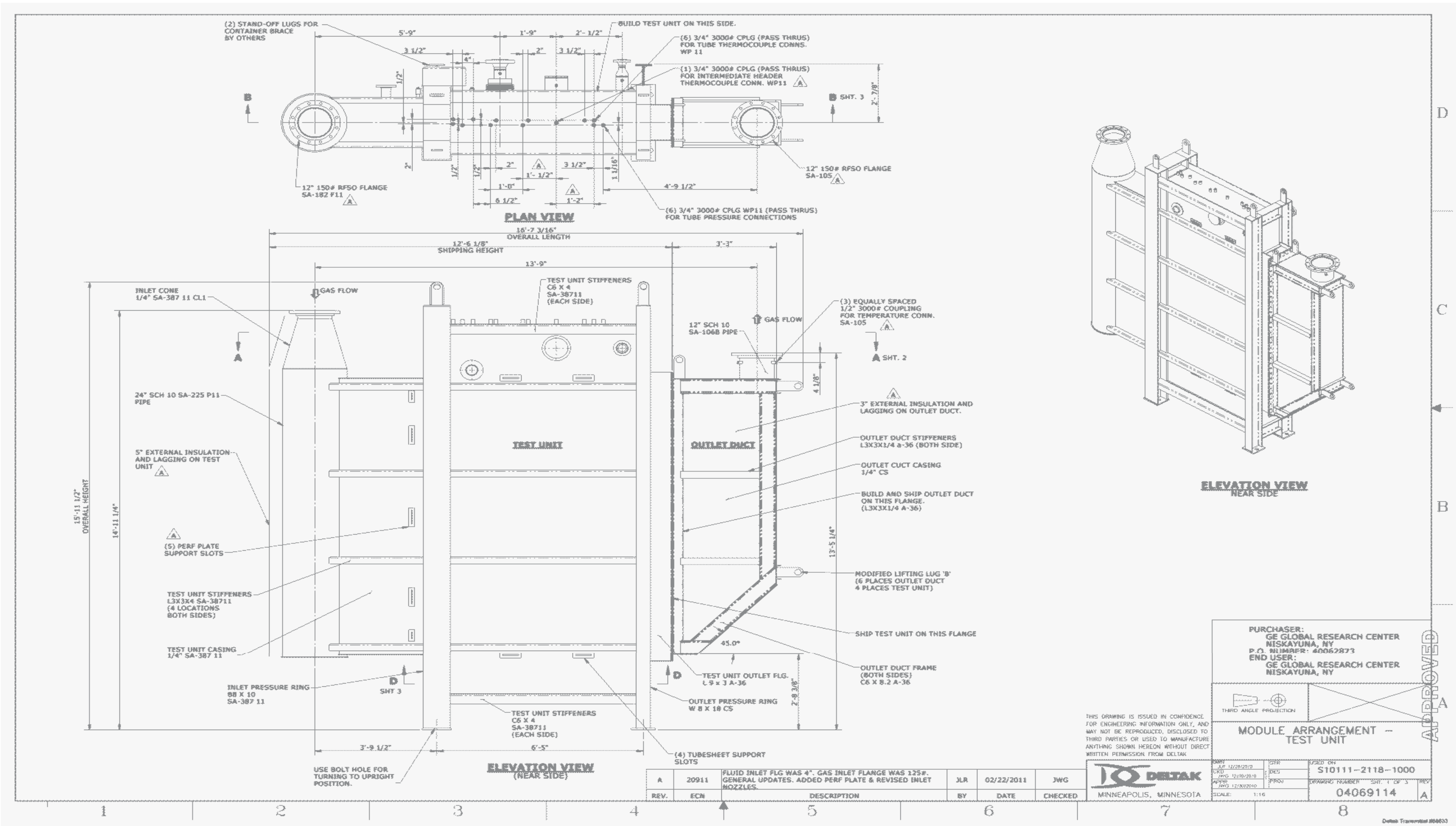


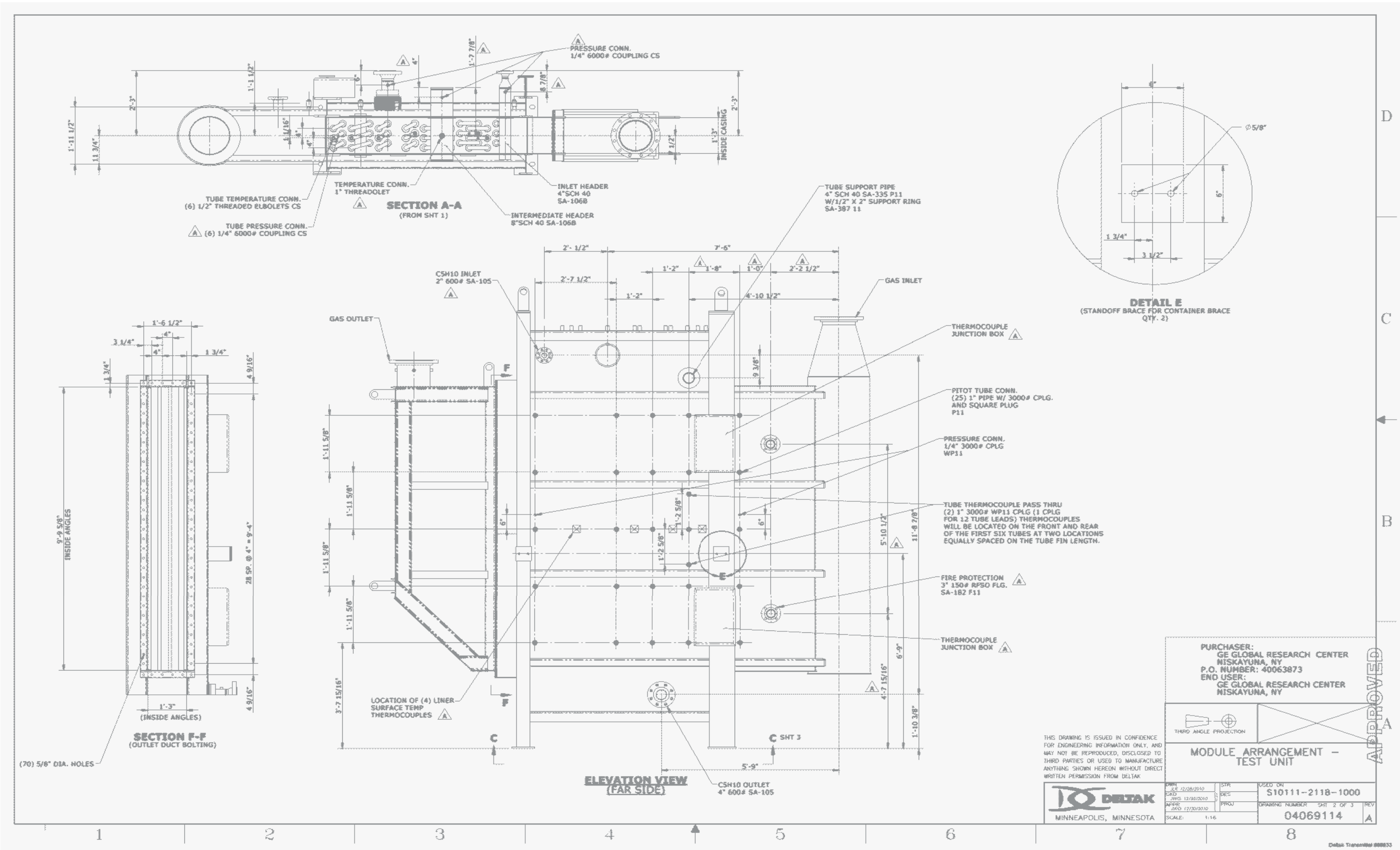
Valve V-100 is a manual ball valve set into the concrete containment around the HX. This valve should be closed any time cyclopentane is in the loop. Furthermore, this valve should only be opened to drain water that has accumulated in the containment after it is verified that no hydrocarbon has leaked out of the system.

V-100

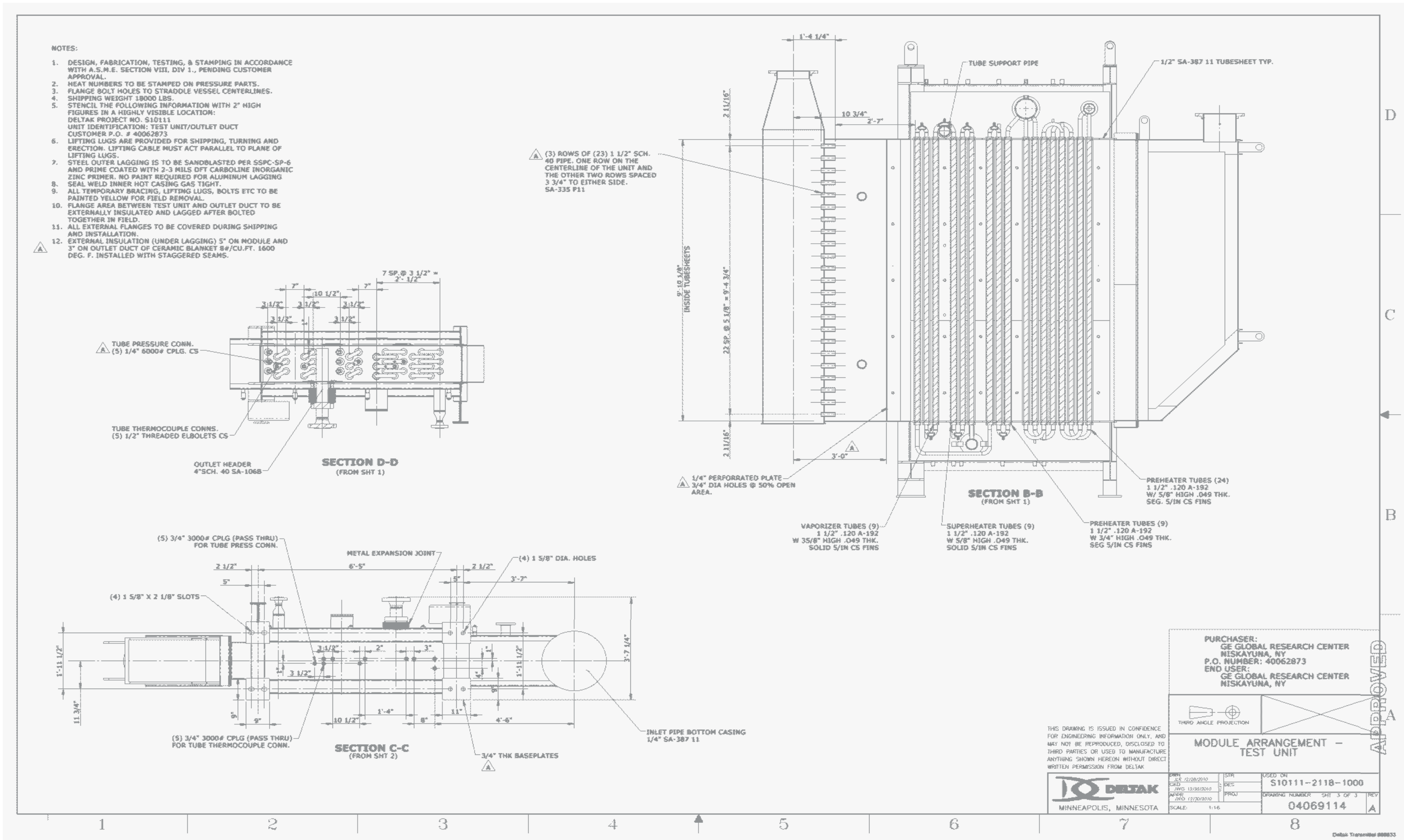
INTENTIONALLY BLANK

Appendix C
Detailed HX Drawings, Specifications, and Bill of Materials





PRESSURE CONN.
1/4" 6000# COUPLING CS
TUBE TEMPERATURE CONN.
(6) 1/2" THREADED ELBOLETS CS
TUBE PRESSURE CONN.
(6) 1/4" 6000# COUPLING CS
TEMPERATURE CONN.
1" THREADOLET
SECTION A-A
(FROM SHT 1)
INLET HEADER
4"SCH 40
SA-106B
INTERMEDIATE HEADER
8"SCH 40 SA-106B
INSIDE CASING
TUBE SUPPORT PIPE
4" SCH 40 SA-335 P11
W/1/2" X 2" SUPPORT RING
SA-387 11
DETAIL E
(STANDOFF BRACE FOR CONTAINER BRACE
QTY. 2)
CSH10 INLET
2" 600# SA-105
GAS OUTLET
GAS INLET
THERMOCOUPLE
JUNCTION BOX
PITOT TUBE CONN.
(25) 1" PIPE W/ 3000# CPLG.
AND SQUARE PLUG
P11
PRESSURE CONN.
1/4" 3000# CPLG
WP11
TUBE THERMOCOUPLE PASS THRU
(2) 1" 3000# WP11 CPLG (1 CPLG
FOR 12 TUBE LEADS) THERMOCOUPLES
WILL BE LOCATED ON THE FRONT AND REAR
OF THE FIRST SIX TUBES AT TWO LOCATIONS
EQUALLY SPACED ON THE TUBE FIN LENGTH.
FIRE PROTECTION
3" 150# RFSO FLG.
SA-182 F11
THERMOCOUPLE
JUNCTION BOX
INSIDE ANGLES
28 SP. @ 4" = 9'-4"
(INSIDE ANGLES)
SECTION F-F
(OUTLET DUCT BOLTING)
(70) 5/8" DIA. HOLES
LOCATION OF (4) LINER
SURFACE TEMP
THERMOCOUPLES
ELEVATION VIEW
(FAR SIDE)
CSH10 OUTLET
4" 600# SA-105
C SHT 3
PURCHASER:
GE GLOBAL RESEARCH CENTER
NISKAYUNA, NY
P.O. NUMBER: 40063873
END USER:
GE GLOBAL RESEARCH CENTER
NISKAYUNA, NY
THIRD ANGLE PROJECTION
MODULE ARRANGEMENT –
TEST UNIT
THIS DRAWING IS ISSUED IN CONFIDENCE FOR ENGINEERING INFORMATION ONLY, AND MAY NOT BE REPRODUCED, DISCLOSED TO THIRD PARTIES OR USED TO MANUFACTURE ANYTHING SHOWN HEREON WITHOUT DIRECT WRITTEN PERMISSION FROM DELTAK
DELTAK
MINNEAPOLIS, MINNESOTA
S10111-2118-1000
SHT 2 OF 3
04069114
APPROVED


NOTES:
1. DESIGN, FABRICATION, TESTING, & STAMPING IN ACCORDANCE WITH A.S.M.E. SECTION VIII, DIV 1., PENDING CUSTOMER APPROVAL.
2. HEAT NUMBERS TO BE STAMPED ON PRESSURE PARTS.
3. FLANGE BOLT HOLES TO STRADDLE VESSEL CENTERLINES.
4. SHIPPING WEIGHT 18000 LBS.
5. STENCIL THE FOLLOWING INFORMATION WITH 2" HIGH FIGURES IN A HIGHLY VISIBLE LOCATION:
DELTAK PROJECT NO. S10111
UNIT IDENTIFICATION: TEST UNIT/OUTLET DUCT
CUSTOMER P.O. # 40062873
6. LIFTING LUGS ARE PROVIDED FOR SHIPPING, TURNING AND ERECTION. LIFTING CABLE MUST ACT PARALLEL TO PLANE OF LIFTING LUGS.
7. STEEL OUTER LAGGING IS TO BE SANDBLASTED PER SSPC-SP-6 AND PRIME COATED WITH 2-3 MILS DFT CARBOLINE INORGANIC ZINC PRIMER. NO PAINT REQUIRED FOR ALUMINUM LAGGING
8. SEAL WELD INNER HOT CASING GAS TIGHT.
9. ALL TEMPORARY BRACING, LIFTING LUGS, BOLTS ETC TO BE PAINTED YELLOW FOR FIELD REMOVAL.
10. FLANGE AREA BETWEEN TEST UNIT AND OUTLET DUCT TO BE EXTERNALLY INSULATED AND LAGGED AFTER BOLTED TOGETHER IN FIELD.
11. ALL EXTERNAL FLANGES TO BE COVERED DURING SHIPPING AND INSTALLATION.
A 12. EXTERNAL INSULATION (UNDER LAGGING) 5" ON MODULE AND 3" ON OUTLET DUCT OF CERAMIC BLANKET 8#/CU.FT. 1600 DEG. F. INSTALLED WITH STAGGERED SEAMS.
A TUBE PRESSURE CONN. (5) 1/4" 6000# CPLG. CS
TUBE THERMOCOUPLE CONNS. (5) 1/2" THREADED ELBOLETS CS
OUTLET HEADER 4"SCH. 40 SA-106B
SECTION D-D
(FROM SHT 1)
A (3) ROWS OF (23) 1 1/2" SCH. 40 PIPE. ONE ROW ON THE CENTERLINE OF THE UNIT AND THE OTHER TWO ROWS SPACED 3 3/4" TO EITHER SIDE. SA-335 P11
TUBE SUPPORT PIPE
1/2" SA-387 11 TUBESHEET TYP.
9'-10 1/8" INSIDE TUBESHEETS
22 SP. @ 5 1/8" = 9'-4 3/4"
A 1/4" PERFORATED PLATE 3/4" DIA HOLES @ 50% OPEN AREA.
SECTION B-B
(FROM SHT 1)
VAPORIZER TUBES (9) 1 1/2" .120 A-192 W 35/8" HIGH .049 THK. SOLID 5/IN CS FINS
SUPERHEATER TUBES (9) 1 1/2" .120 A-192 W 5/8" HIGH .049 THK. SOLID 5/IN CS FINS
PREHEATER TUBES (9) 1 1/2" .120 A-192 W 3/4" HIGH .049 THK. SEG 5/IN CS FINS
PREHEATER TUBES (24) 1 1/2" .120 A-192 W/ 5/8" HIGH .049 THK. SEG. 5/IN CS FINS
(5) 3/4" 3000# CPLG (PASS THRU) FOR TUBE PRESS CONN.
METAL EXPANSION JOINT
(4) 1 5/8" DIA. HOLES
(4) 1 5/8" X 2 1/8" SLOTS
(5) 3/4" 3000# CPLG (PASS THRU) FOR TUBE THERMOCOUPLE CONN.
SECTION C-C
(FROM SHT 2)
3/4" THK BASEPLATES
INLET PIPE BOTTOM CASING 1/4" SA-387 11
PURCHASER:
GE GLOBAL RESEARCH CENTER
NISKAYUNA, NY
P.O. NUMBER: 40062873
END USER:
GE GLOBAL RESEARCH CENTER
NISKAYUNA, NY
THIRD ANGLE PROJECTION
MODULE ARRANGEMENT – TEST UNIT
APPROVED
THIS DRAWING IS ISSUED IN CONFIDENCE FOR ENGINEERING INFORMATION ONLY, AND MAY NOT BE REPRODUCED, DISCLOSED TO THIRD PARTIES OR USED TO MANUFACTURE ANYTHING SHOWN HEREON WITHOUT DIRECT WRITTEN PERMISSION FROM DELTAK
DELTAK
MINNEAPOLIS, MINNESOTA
DWN JLR 12/28/2010
CKD JWG 12/30/2010
APPR JWG 12/30/2010
SCALE: 1:16
USED ON S10111-2118-1000
DRAWING NUMBER 04069114 SHT 3 OF 3
REV A

INTENTIONALLY BLANK

Appendix D

Rig Charging Procedure

Piping, HX Fill, and Pump Priming Protocol

V	3	TW control valve	Electric positioner valve	Closed		Closed	
V	5	Ar pressure solenoid	Ball valve w/ solenoid	Closed		Closed	
V	6	TW bypass valve	Manual valve	Open		Open	
V	8	Econ. Iso valve	Ball valve w/ solenoid	Open		Open	
V	9	Econ. Drain	Ball valve w/ solenoid	Closed		Closed	
V	13	Cont. air flow	Electric valve	Closed		Closed	
V	15	Iso-hot; solenoid	Ball valve w/ solenoid	Open		Open	
V	17	Depress positioner	Plug and stem w/ positioner	Closed		Closed	
V	19	Fill valve – piping side	Manual ball valve	Closed		Closed	
V	20	Fill valve - low point	Manual ball valve	Closed		Closed	
V	21	High P; sampling	Manual ball valve	Closed		Closed	
V	22	Noncondensable vent/sampling valve	Manual ball valve	Closed		Closed	
V	23	Vent valve - high point	Manual ball valve	Closed		Closed	
V	24	Separator drain	Manual ball valve	Closed		Closed	
V	25	Depress. drain	Manual ball valve	Closed		Closed	
V	26	TW inlet	Electrical control valve	Open		Open	
V	27	TW return valve	Elect act valve	Open		Open	
V	28	Argon regulator	Manual gas regulator	Closed		Closed	
V	32	Trailer - TW inlet iso	Manual butterfly valve	Closed		Closed	
V	33	Trailer - TW exit iso	Manual butterfly valve	Closed		Closed	
V	38	TW condenser line drain	Manual ball valve	Closed		Closed	
V	39	Vent off int. header	Manual ball valve	Closed		Closed	
V	40	CO2 system lock-out valve	Manual ball valve	LOTO		LOTO	
HV	A	Vacuum inlet valve	Inlet isolation valve	Closed		Closed	
V	42	House N2 inlet	Manual ball valve	Closed		Closed	
V	43	House N2 to equipment	Manual ball valve	Closed		Closed	
V	44	Y-strainer inlet	PVC Manual ball valve	Rem.		Rem.	
V	45	Y-strainer exit	PVC Manual ball valve	Rem.		Rem.	
HV	C	Transfer hose valve	Manual ball valve	Closed		Closed	
V	47	Back pressure regulator	Manual BPR	Closed		Closed	
V	50	Fill/drain hex exten	Manual ball valve	Closed		Open	
V	51	Fill/drain piping exten	Manual ball valve	Closed		Closed	
V	52	Pump – low vent	Manual ball valve	Closed		Closed	

Procedures for Loop Fill

LabView software should be running continuously and the ventilation fan set to 75%. If you need to restart the LabView software, turn the fan to “Purge” on the Hoffman panel to avoid losing power to the trailer.

All valves listed above refer to the numbers assigned for the ORC test; separate valve numbers have been assigned for the Continental valves. It should be noted that V-13, according to the ORC test, is labeled as V-15, associated with Drop15 for the Continental control.

1. Send e-mail to team providing notification of test plans.
2. Read the attached MSDS carefully before handling cyclopentane.
3. Take dry chem fire extinguisher and place it next to the diesel tanks.
4. Ensure operators are wearing appropriate safety gear (i.e., nitrile gloves, safety glasses, flame-resistant clothing, face shield, and Nomex).
5. Check status of all valves (see list above, ensure that V-8 and V-15 are open).
6. Ground the cyclopentane barrel, transfer hose, vacuum pump, and vacuum system per the recommendations of NFPA 30.
7. Run purge/vent lines from all the high-point bleed valves (V-21, V-52, V-22, V-39, and V-23) back into the main cyclopentane barrel per Figure D-1.
8. Set up the auxiliary cyclopentane feed drums in connection with the main drum as shown in Figures D-2, D-3, and D-4.
9. Connect house N_2 from V-43 through a regulator set for 5 psig to the top of the cyclopentane barrels with a 1/4-in. flexible hose.
10. Start N_2 flowing into the system by setting the regulator in the line to 5 psig and opening the manual ball valve downstream. Note that this will pressurize feed drums 1 and 2. It also will create a blanket of N_2 over the main cyclopentane drum, but not pressurize it because the drum pump connection allows slow venting of the drum. This will create a small pressure difference between the cyclopentane feed drums and the main drum.
11. Connect the electrostatically safe fill hose to the drum pump on the main cyclopentane barrel and ensure the hose has no initial static charge.
12. Connect the transfer hose to V-21, but do not open HV-C on the transfer hose.
13. Connect house air supply to the regulator for the drum pump but do not turn it on.
14. Close the inlet valve on the vacuum pump (HV-A).
15. Turn on the vacuum pump and wait until the vacuum gage is reading about10 Torr.
16. Open the inlet valve (HV-A) of the pump.
17. Ensure HV-B, HV-C, HV-D, HV-F, and HV-G are now closed.
18. Open V-21, V-52, V-22, V-39, and V-23 to allow vacuum to be drawn on the entire loop and the transfer lines.
19. Once an acceptable vacuum level is established in the loop, close HV-A and turn off the vacuum pump.
20. Close valves V-52, V-22, V-39, and V-23, but <u>not V-21</u>.
21. Allow approximately 50 psig of nitrogen or argon into the 1/4-in. pressure transducer line off I-10(the top of the pistons in the accumulator) to ensure the pistons are bottomed out.
22. Open HV-C to start cyclopentane flowing to the loop through V-21. Monitor the flow rate of the cyclopentane using the flow meter on the transfer hose.
23. Monitor the cyclopentane level in the main cyclopentane drum using the UT probe. If it falls below 1/3 full, then close HV-B, open HV-G, and HV-F to refill the main drum from the first and second drums. Repeat this procedure as needed throughout the fill/purge process.

24. After the flow rate of the cyclopentane falls below 1.5 GPM, start the air flow to the drum pump to turn the unit on.
25. Monitor the pressure in the loop. It should start to rise to ambient pressure and above. When pressure is slightly above ambient (about 15 psia), open V-52 and HV-B.
26. Continue to fill the system until liquid cyclopentane is seen at the site tube at V-52.
27. Close V-52, bleed the pressure from the top of the accumulator, and then draw a vacuum on the top of the accumulator to allow the pistons to move all the way up. This should draw in more volume of cyclopentane from the drum pump.
28. Open V-23, V-39, V-22, and V-52 one at a time until clear liquid is seen at each corresponding sight tube. Then close each valve.
29. After approximately 100 gallons of cyclopentane have been transferred into the system, close V-21 and stop running the drum pump.
30. Slightly pressurize the top of the accumulator pistons (about 10 psig) to allow cyclopentane to be pushed through the loop and move vapor pockets to the high-point vents.
31. Open the high-point vent valves V-52, V-22, V-39, and V-23 in turn to bleed out vapor pockets safely into the cyclopentane barrel.
32. Repeat Steps 27 through 29 until no more vapor pockets are seen when the high-point vent valves are opened.
33. Now close V-21, V-23, V-39, V-22, and V-52 to isolate the loop from the fill piping.
34. Pressurize the top of the accumulator pistons with a small positive pressure of approximately 50 psig.

Pump Priming

35. Restore power to the trailer.
36. Close V-8 and start the loop circulation pump at about 30 Hz.
37. Now open V-8 and monitor the flow rate reading on the Coriolis meter for evidence of cavitation.
38. Cavitation will manifest itself by a sudden fall in the flow rate accompanied by a characteristic cavitation noise from the pump (however, the noise may not be audible if there are other noise sources in the vicinity).
39. If cavitation is detected, immediately turn off the circulation pump and bleed vapor bubbles from bleed valves V-23, V-39, V-22, and V-52.
40. Repeat Steps 36 through 40 until no evidence of cavitation is seen in the circulation pump when running at design flow rates.
41. Now warm the cyclopentane in the loop using the GasTech heater to approximately100°C with an accumulator/loop pressure of about 10 bar. Ensure circulation pump is running during the warming process.
42. Heating the cyclopentane will cause it to “de-aerate” and will produce cavitation in the pump. When this happens, immediately turn off the circulation pump and repeat Steps 36 through 40.

Disconnecting Fill Piping

43. Disconnect the transfer hose from the HV-C and allow the cyclopentane from the line to drain into a metal catch pan.

44. Remove drum pump carefully and catch any cyclopentane drips into a metal catch pan. Replace pump with the appropriate bung.
45. Turn off the N_2 to the cyclopentane barrel by closing HV-E.
46. Store the hose in ESB 154.
47. Safely dispose of the cyclopentane drawn into the metal catch pan with chem waste services.

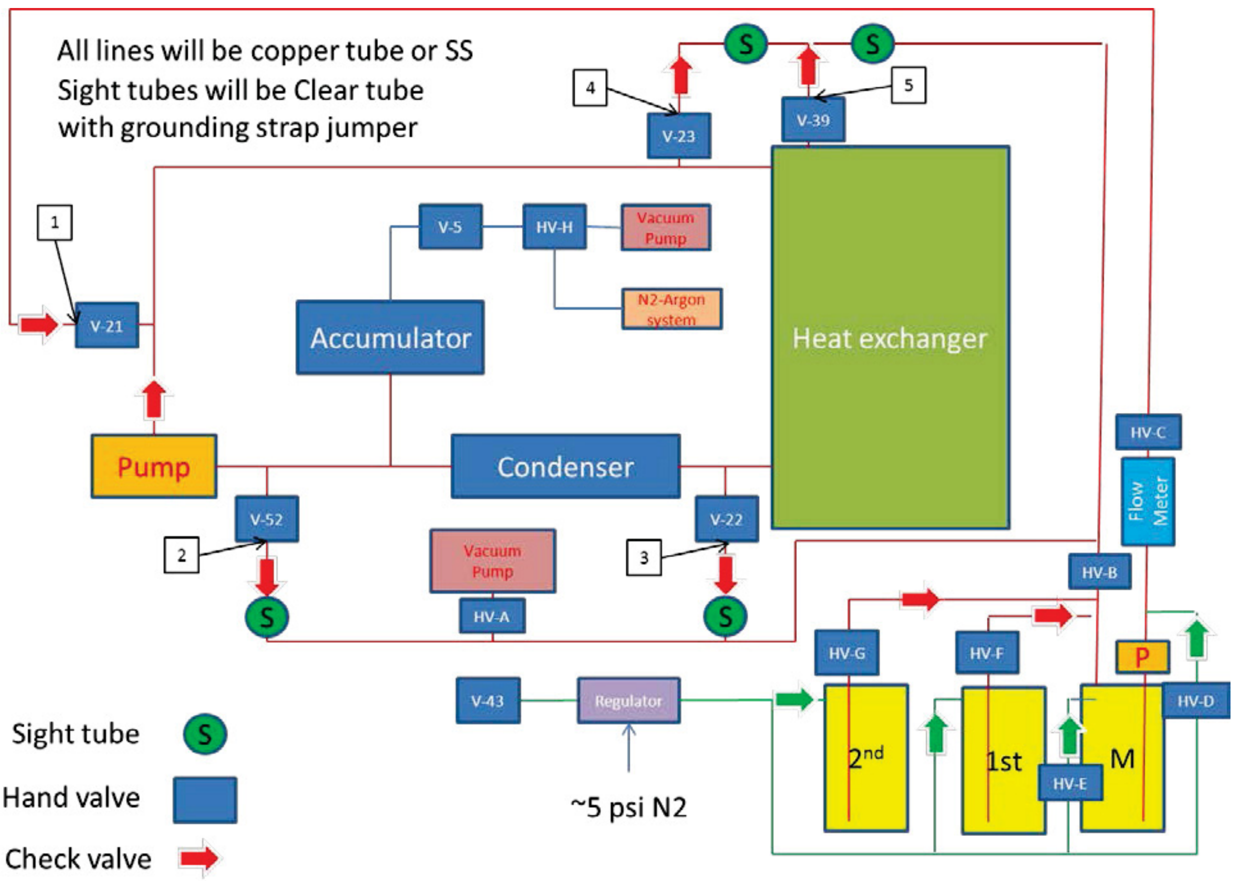


Figure D-1. Overall fill system schematic.

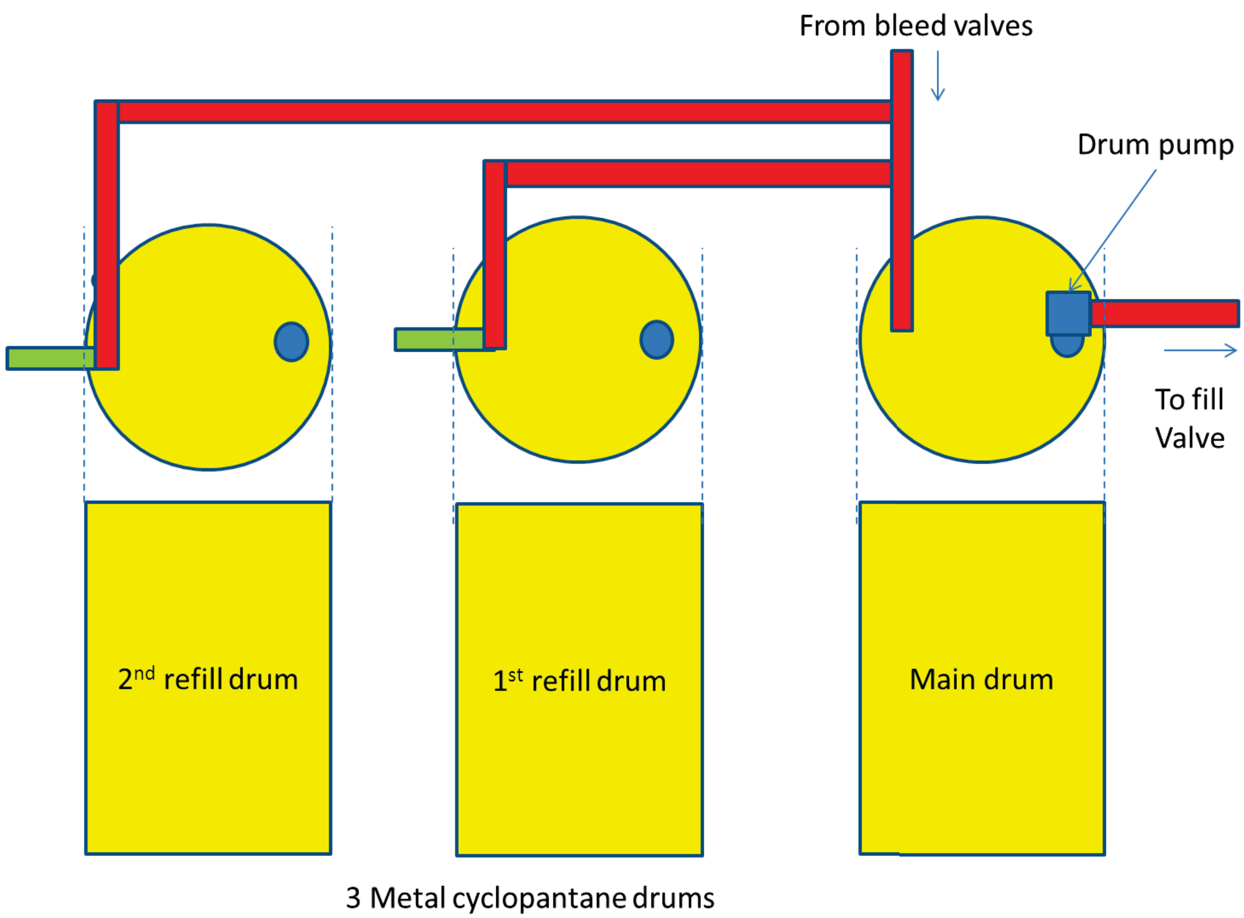


Figure D-2. More detail of fill setup for cyclopentane drums.

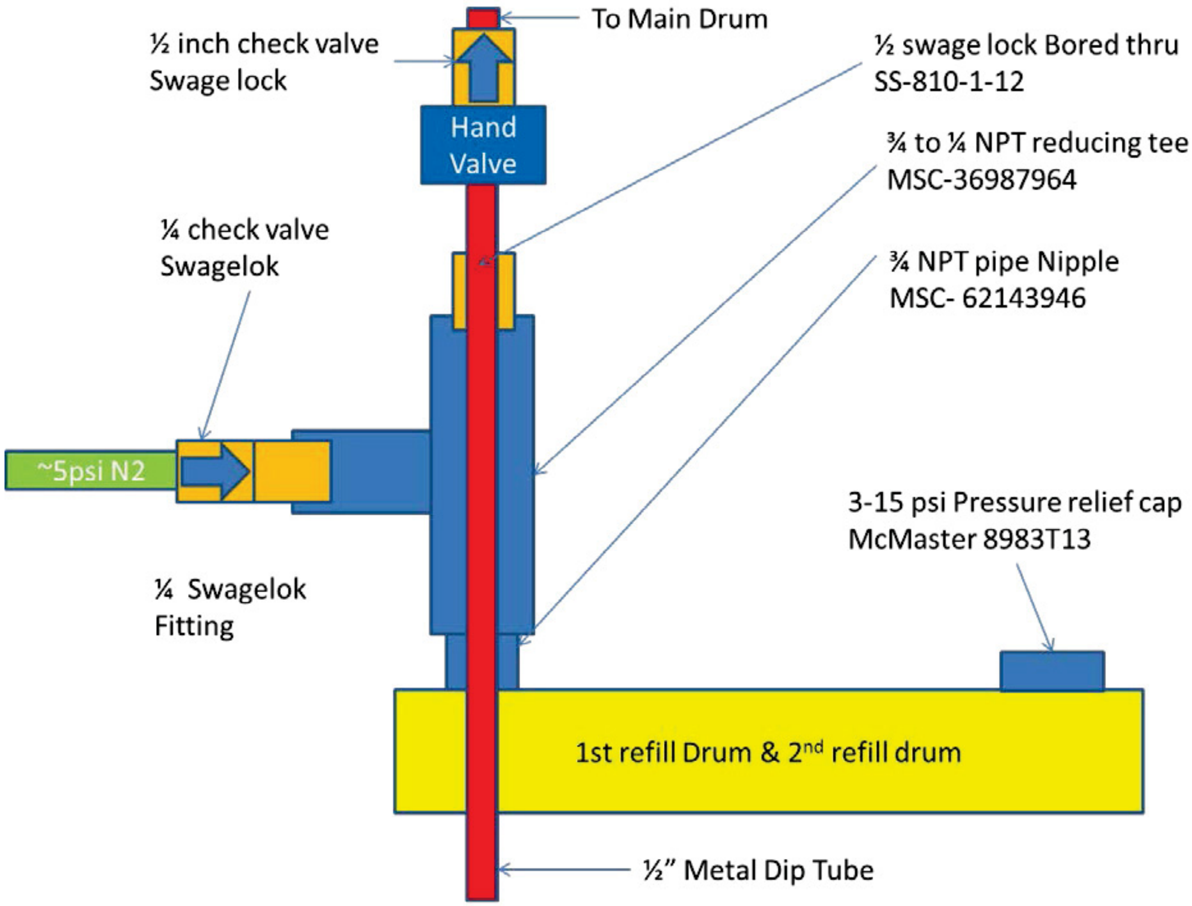


Figure D-3. Fill piping setup for cyclopentane feed drums.

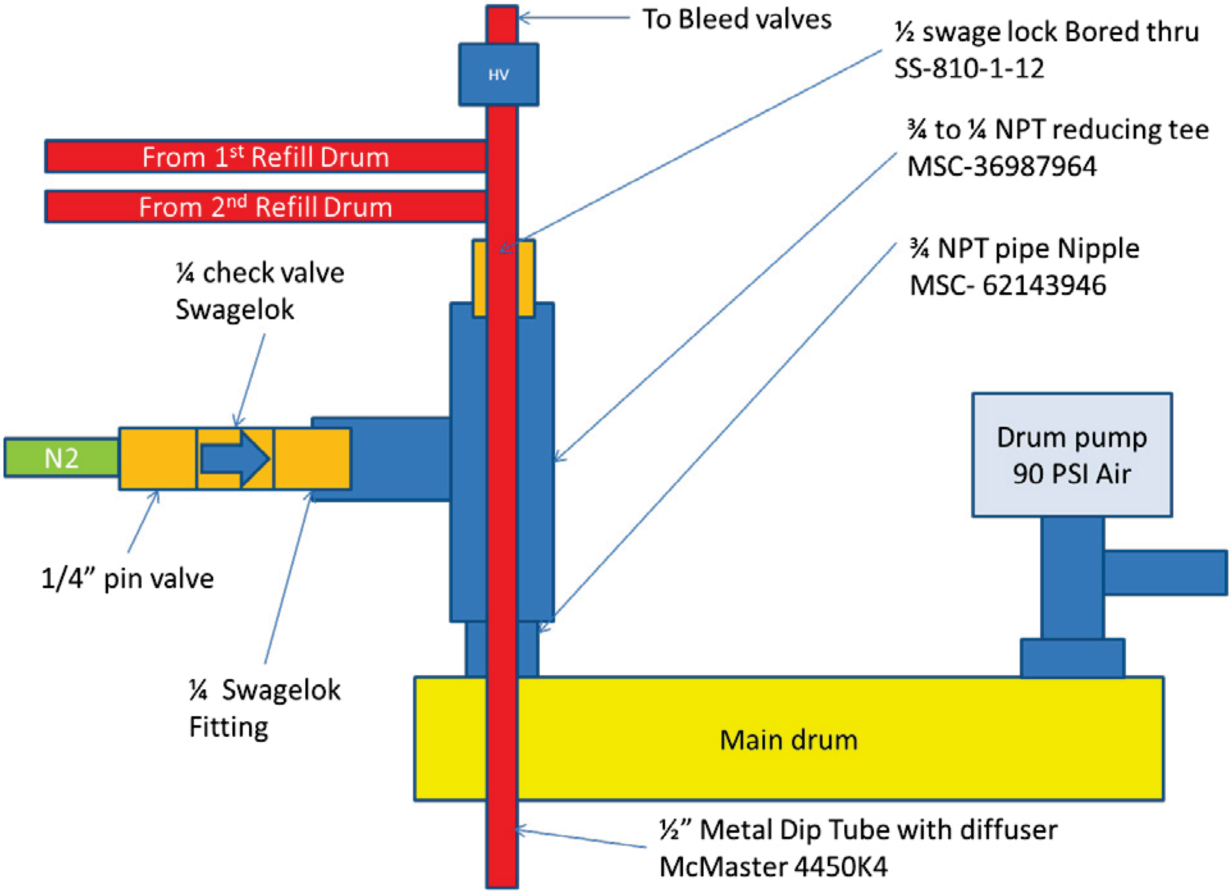


Figure D-4. Fill piping setup for main cyclopentane drum.

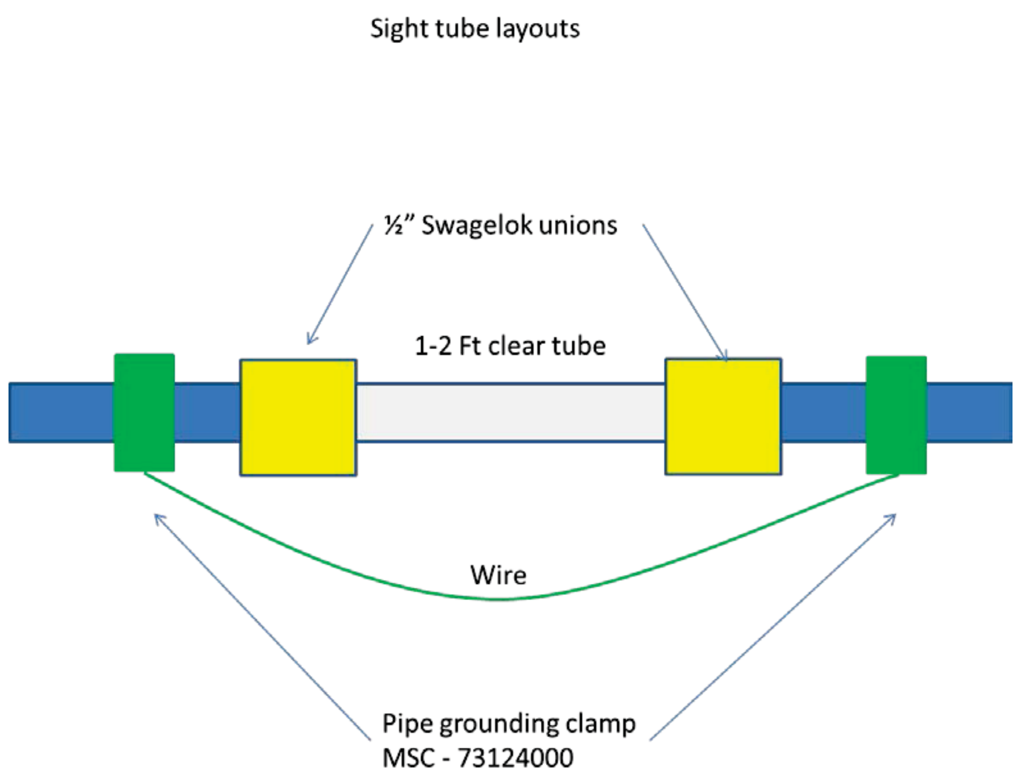


Figure D-5. Layout of clear sight tubes, including grounding wire.

Appendix E

Standard Operating Procedure

Direct Evaporator SOP Revision 2K

Standard Operating Procedure (SOP)

Direct Evaporator ORC Loop (ESB courtyard)

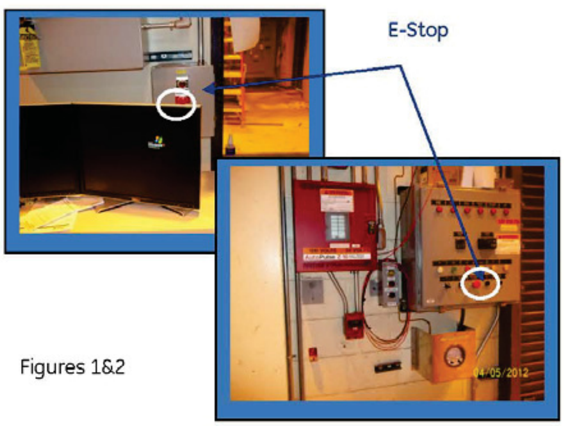
Prepared By: ____________________ Date: Emergency Ph: x7097

Approved By: ____________________ Date: __________ Emergency Ph: __________

(Acting Manager, RESL)

Expiration Date: ______________

EMERGENCY SHUTDOWN PROCEDURES:



Figures 1&2

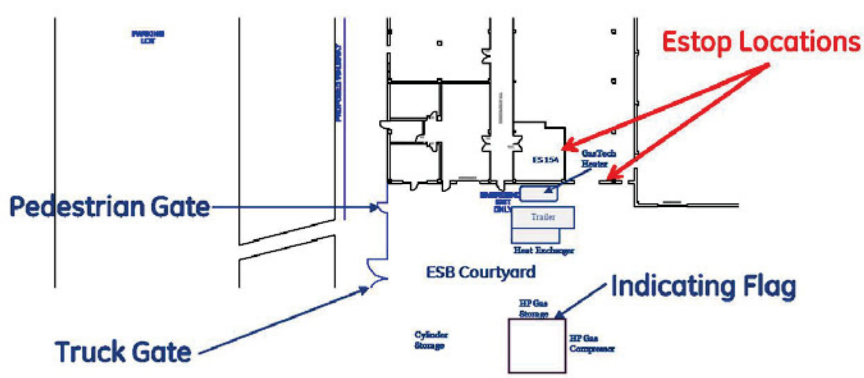
Hard-wired E-stop

1. Push E-Stop mushroom button by computer
2. Verify that the temperature of I-3 is dropping; if temperature does not drop within 10 seconds, check the Gas Tech Heater is E-stopped at the panel.

If Gastech not stopped:

- Push E-stop on GasTech control panel, or
- Push GasTech stop button on computer 'Test' screen.

Appendix A contains a detailed description of the E-Stop system.



imagination at work

1
9/6/2013

I. EQUIPMENT DESCRIPTION AND TEST SCOPE:

A. Documentation

The Direct Evaporator ORC Loop uses documentation that is under revision control. These documents are listed in \\Nas07crd\ocr_otb\Users\Controls\Contolled Documents\ORC_Controlled_Documents_List.xlsx

The documents themselves are located in following folder: \\Nas07crd\ocr_otb\Users\Controls\Contolled Documents

Throughout this document and other controlled documents, the following conventions and abbreviations will be used:

- Ar – the pressurization gas for the Accumulator pistons, normally Argon.
- CA – Compressor Air, air coming from the Continental Compressor.
- CW – Cooling Water (also called Tower Water in some places)
- HX – Heat Exchanger or Vaporizer (made up of three sections: Preheater, Vaporizer and Superheater).
- WF – Working Fluid, the fluid inside the main loop. This can be either Cyclopentane (under normal circumstances, or during certain commissioning/shakedown tests, it will be water).
- All temperatures are given in degrees Celsius unless marked otherwise.
- All pressures are given in absolute values unless marked otherwise. So, "psi" is understood to be mean "psia". Any gage pressure or differential pressures will be specifically marked "psig" and "psid" respectively. Where appropriate, the bar value for pressures will be given in parenthesis.
- Main Loop – The main working fluid circulation loop consisting of the working fluid side of the Heat Exchanger, Condenser, Accumulator, Circulation Pump, and connecting piping.
- Hot Side – The portion of the Main Loop on the Heat Exchanger side of the V-8 and V-15
- Cold Side – The portion of the Main Loop on the Condenser side of V-8 and V-15.

B. Test Scope and General Equipment Description

This test and set-up are designed to characterize an experimental heat exchanger with the working fluid cyclopentane in the direct path of an exhaust stream to simulate the heat exchanger behind a PGT25 gas turbine. The working fluid will be cycling in a loop consisting of the test heat exchanger, an HRVG (Deltak, Inc.), a condenser (Thermal Products Inc.), and a pump (ChemPump). The pressure in the system will be maintained by a rack of hydraulic piston accumulators (Pearse Bertram). The maximum temperature of the vapor exiting the Heat Exchanger (HX) superheater (I-16) is 250°C, and the system pressure will be controlled at 508psia (35bar) as measured at the inlet to the Heat Exchanger. Prior to entering the pump, fluid is condensed and subcooled to approximately **165°C**.

This test will be run via a remote station located in ES 154 with remote monitoring cameras on the heat exchanger and on the inside of the container. Further, after a short performance characterization test, the system will be run for 300 hours with periods for ramping and de-ramping the system with predetermined sampling intervals to measure the degradation products.

A detailed equipment description is provided in Appendix D.

II. SPECIFIC SAFETY AND HEALTH HAZARDS/ PRECAUTIONS, REQUIRED PPE:

- Large scale chemical handling, safety glasses with side shields, nitrile gloves, static resistant clothing or Nomex (required for Protocols 3 and 7)
- Excessive noise, hearing protection worn through duration of testing
- Safety shoes when working in the lab

Hazard checklist: (check which apply)

	Hazard Name:	Extra attention required:
	Small Scale Chemical Handling	N/A
✓	Large Scale Chemical Handling >3L Reactions >5 Gallon container transfers	100 gal of highly flammable cyclopentane
	Procedure 19 Chemicals	
	Pyrophoric Materials	
	Base/Acid Bath	
	Nano Materials	
✓	Pressurized Liquids	Pressures up to 36bar in system, tower water at 3bar
✓	Toxic Gas	Inline vitiated heater may produce CO
✓	Asphyxiating Gas (outside of hood)	Argon, Nitrogen
	N_2 Storage Box	
	Glove Box – Pyrophoric/P-19 chemicals	
✓	Flammable Gas	Cyclopentane vapor in 4" line at 250°C; significant static discharge concerns during filling/draining – see separate SOP for detailed instructions
✓	Equipment or Process with an SOP	
✓	High Pressure (> 15 PSIG)	Pressures up to 550psia
✓	Mechanical Hazards (rotating parts, springs, pinch, crush, drive	Centrifugal pump

	mechanisms, etc.)	
	Robotics	
✓	High/Low Temp, inc. cryogenics (below -20C, above 150C)	Process side temperatures of 250°C and hot gas temperatures of 500°C
	Electrical Disconnect Actuation	
	Exposed Electrical >50V	
	Radiation (Ionizing)	
	Laser	
	RF-High voltage, spark used to light laser tube, plasma	
	UV radiation	
	Biological	
✓	Air/Water Emissions	Pressure relief valves set at 35bar and 47bar for the low and high sides of the system discharge into a main header, enter a separator and then discharge through a vent in the roof
✓	Confined Space	When fire system deploys, the trailer louvers will close and a confined space will be created in the trailer.
	Cranes/Slings	
	Magnetic Fields-strong	
✓	Sharp Objects (razor blades, drill bits, band saws, knives, etc)	Tools used in shakedown
✓	Trip hazards	System containment, low piping presents a trip hazard
	Exposure to superheated steam	
✓	Noise Hazard	Continental compressor produces noise in excess of 85dB; hearing protection must be worn during testing
✓	Vacuum condition	Initial system fill will utilize a vacuum down to 1psia
✓	Ergonomics	Fall hazard
✓	Other	Low equipment hazard poses several locations where head may be impacted, operator is cautioned when moving around in trailer and on scaffolding; Fall hazard when climbing to 2nd level of scaffolding

III. LOCKOUT/TAGOUT PROCEDURES:

The fire protection agent is CO_2 for this test space. The system is inactivated by placing the switching the control panel to "Disarmed" and by locking V-40 in the open position; both these operations are conducted by the Fire Department / BSC. This is not a formal LOTO Lockout, but rather locking a normally inactive system to prevent inadvertent discharge of the CO_2.

Primary sources of energy to be isolated are hot air source, the electrical power, and the pressurized working fluid, which is to be kept at 48 psi (3 bar) when the system is not running to prevent the ingress of air/oxygen to the working fluid.

To isolate the hot air supply, LOTO the GasTech heater control panel to prevent operation and close the valve on continental compressor drop 15 (labelled V-13 on the ORC P&I) to prevent air flow to the heater. The heater has an internal flow sensor that will prevent ignition without air flow. This will allow other users to run the Continental without issue.

Isolation of the electrical power, if needed, will require switching the breaker in the ORC panel to prevent energizing the system. Only electrical trades will be allowed to perform electrical LOTO on this experiment.

Note

The following ORC distribution panels are ***touch safe*** and may be opened for instrumentation and controls diagnostics:

The working fluid is to be maintained at 48 psi (3 bar) of pressure and thus, to LOTO the pressure system will require that the fluid be drained and the test to be restarted. Without maintaining a positive pressure in the system, O_2 may interact with the working fluid and speed degradation. This will skew the results of the test.

IV. SPECIALIZED TRAINING REQUIRED:

- The operator of this test must be trained in the use of the Continental compressor, the GasTech heater and have electrical safety training.
- Operators must be trained and comfortable in using a fire extinguisher
- Operators must be trained and familiar with each protocol to be used on the ORC Direct Evaporator system.
- Operators must be trained in safe handling/storage of cyclopentane. Refer to \\Nas07crd\ocr_otb\Users\Controls\Contolled Documents\Reference Docs\cyclopentane_safe_handling_and_use.pdf
- Operators/engineers must have completed current LOTO training.
- In addition to acknowledging having read and understood this SOP, all operators must be trained on the Casualty Immediate Actions contained in this SOP and in the ***ORC Response Actions Table***

V. NORMAL SYSTEM START UP/OPERATION/SHUTDOWN:

During the following procedures, please refer to the current version of the P&ID.
\\Nas07crd\ocr_otb\Users\Controls\Contolled Documents

A. Start-up

Initial Conditions

Main Loop

- Filled with cyclopentane according to the latest revision of the Piping_and_HX_fill_Protocol.
- Normal shutdown conditions.

Pressurization System

- A minimum manifold pressure (as read at the local gage) of 1000 psi.
- Lined up with regulator pressure set to 48 psi.

Procedure

1. Complete Start-up Checklist (Appendix E) to ensure all systems are in position for safe start-up
2. Verify the control system is operational – NI system
3. Verify the data acquisition system is operational – Yokagawa (MX100)
4. Prime and vent the pump as necessary
5. Open V-13 (Drop 15) of Continental line
6. Start Continental Compressor following the SOP provided and using the Continental checklist – attached and set flow to 5lbm/s, verify with Venturi (I-1) reading on LabView "Test" vi
7. Take baseline data for 5 minutes from Yokagawa system
8. Save data as Baseline_DD_MM_YYYY_JJ(operator initials)
9. Start the VFD for the pump (circulating at 1 lb/s)
10. Increase the pressure incrementally to 460psi (32bar) using V-5, on the Argon tanks (V-28) over a period of 3-5 minutes
11. Set conditions according to "ORC_Checklist_TrailerEntry", and walk through container and outside courtyard to ensure no leaks from the cyclopentane piping are noted
12. Increase pump VFD to 5.51 lb/s
13. Set Backpressure Regulator, V-47, to control HX Inlet Pressure, I-9, at 508 psi (35 bar), verify that the system pressure in the accumulator is stable
14. Open Cooling Water Valve (V-3) to 25%
15. Record flow reading from I-14
16. In the LabView Test.vi, set the controls to **Manual**
17. Verify that V-17 is fully closed
18. Start heater following the SOP for the GasTech heater with the temperature set to 250°Farenheit.

19. Ramp heater to increase the Evaporator CA Exit Temperature (I-16) to 210°C by increasing 25°C per 5 minutes to monitor system response. Hold for temperature stabilization. Check for normal system single-phase operation.
20. Start taking ramping data with Yokagawa.
21. Continue to raise temperature I-16 slowly until there is indication of a gas phase in the evaporator. This will be indicated by constant temperature in the boiling section of the HX

    *Note pump should be manually adjusted as the temperature exiting the 4" line reaches 222°C (boiling point).

22. Continue to raise temperature I-16 to 250° ± 2.5°C.
23. Save data as Ramping_DD_MM_YYYY_JJ(operator initials)
24. Allow temperatures I-16 and I-8 to reach steady state conditions (temperature variation is < 3°C per minute)
25. In the LabView Test.vi, set the controls to **Automatic**

Steady State procedures

1. Save data as Test__DD_MM_YYYY_JJ(operator initials)
2. Monitor all readings and note any variations above/below expected readings by 5-10% or any temperatures with a variation greater than 5°C.
3. Run test for target number of hours.
4. Sample as necessary using the latest version of the sampling protocol.

Shutdown procedures

1. Refer to the Shutdown checklist in Appendix F.
2. In the LabView Test.vi, set the controls to **Manual**
3. Carefully collapse the two phase system (bubble) by ramping down the heater temperature.

    Note: The objective is to avoid an accumulator out-surge that will cause a system pressure decrease beyond the capacity of the supply pressure regulator. Monitor system pressure I-8. If the pressure falls below __, the heater temperature should be maintained until nominal operating pressure of 500 psia.

4. Once the bubble is collapsed as indicated by re-establishing of a temperature gradient in the evaporator and a loss of mass in the accumulator, ramp the heater down to achieve an I-16 cool down rate of 50°C per 10 minutes to reduce thermal stresses on the system.
5. Monitor temperature drop via portable radios with the control stand.
6. Turn off the heater following the detailed instructions in the SOP
7. Continue to operate the Continental blower to further cool the system
8. When temperatures of the working fluid reaches 50°C (as indicated by I-16), reduce the pressure in the system to 48 psig (3 bar) by closing V-5 and ramping down the back pressure regulator.
9. Stop the Circulation Pump (E-7)

10. Using the Argon positioner (V-17), slowly decrease the pressure in the accumulators to 48 psi (3 bar).
11. Stop the Continental Compressor
12. Stop Cooling Water flow to the Condenser:
    a. Open V-6, the CW bypass valve
    b. Close V-32, the Condenser CW Inlet, to stop the tower water from flowing to the condenser,
    c. Maintain V-33 Open
13. Initiate HX Nitrogen purge flow at I-19 TC port.
14. Draw samples from the system following the latest rev of the sampling protocol.
15. Establish conditions for trailer entry according to ***ORC_Checklist_TrailerEntry***.
16. If an extended shutdown is required, contact the BSC to have the FSS disabled.
17. Check for leaks from any of the equipment

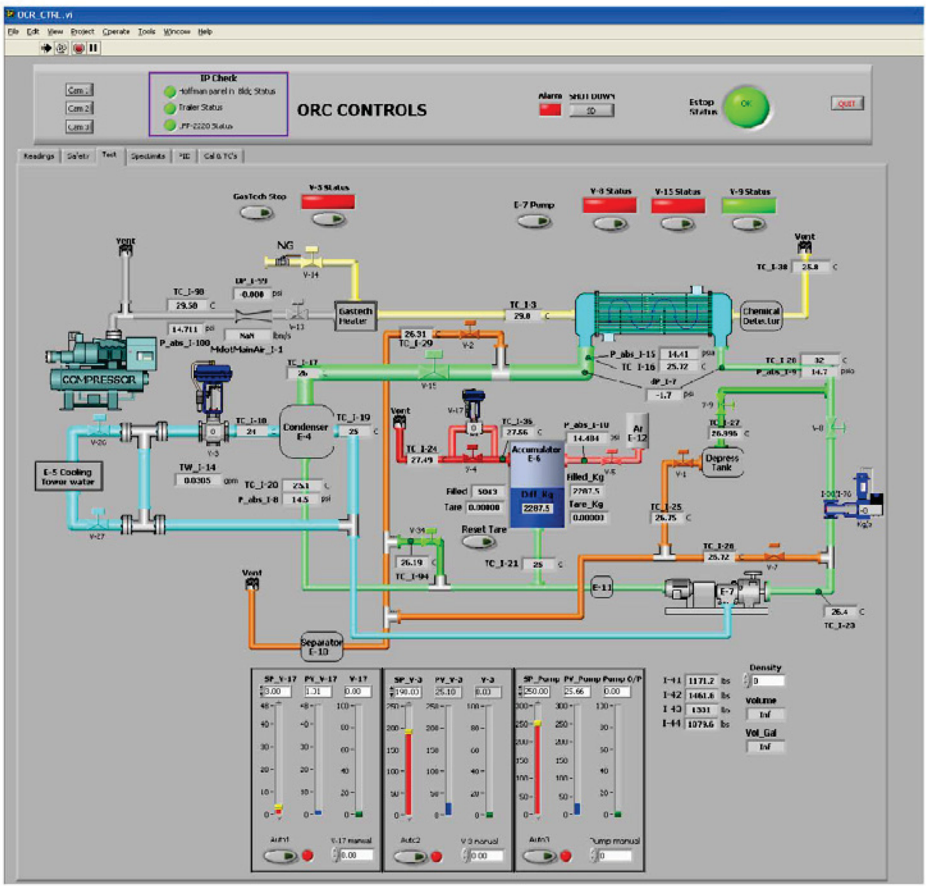


Figure 11. Screen shot of LabView Test vi.

VI. CASUALTY & ABNORMAL OPERATING PROCEDURES

A. Casualty Procedures: Major casualties and the appropriate response procedures are discussed below. The immediate actions for all casualties are given in ***ORC_Response_Actions_Table***

1. Hard E-Stop:

Discussion: See Appendix A.

Indications: E-Stop notification on Control System Screen/ Estop mushroom button light is on.

Immediate Actions:

1. Verify the GasTech Heater is off.
2. Identify the cause of the E-Stop
3. Call the BSC with the cause of the E-Stop; if the BSC is automatically notified (as in the case of a fire) then the call will be used to verify that the BSC did receive the automatic notification.

Follow-up Actions:

1. Restore indications and control.
2. Assess Main Loop temperatures and pressures.
3. In the LabView Test.vi, set the controls to **Manual**
4. Re-establish Main Loop flow as follows:

    a. Set V-28, Ar Pressure Regulator, to match HX Pressure, I-9.

    b. Shut V-47.

    c. Open V-5.

    d. Open V-8 and V-15; allowing the Hot Side and Cold Side pressures to equalize.

    e. At V-28 raise Accumulator Pressure to 460 psi; allow pressures to stabilize around the Main Loop and in the Accumulator.

    f. Set V-47 to 460 psi.

    g. Start the Circulation Pump at minimum speed.

5. Allow the Main Loop to circulate at minimum speed for 10 minutes.
6. If it is desired to restart the test, conduct a Normal Startup commencing at step 11, otherwise, conduct a normal system shutdown.

2. Power/Facilities Service Failure:

Discussion: In the event of a power failure, the Continental compressor will trip and this loss of flow will cause the GasTech heater to E-stop. The tower water flowing from the building is dependent on an independent circulation pump, number 1. All the actuated valves will return to their fail-safe positions, for the isolation valves the fail safe position is closed with the exception of Condenser CW Control Valve (V-3) which has a fail-safe position of Throttled. Upon re-energizing the system, the Continental will remain off, the valves will return to the start-up default positions while the Main Loop Circulation Pump will remain off until reset by user. The tower water pump will be re-energized and will restart pumping. The impact of loss of site power is similar to a Hard E-Stop except that there will be no cooling flow or heat addition to the system. So the system should fail "as is".

Immediate Actions:

1. Follow the immediate actions for a Hard E-Stop. Verify that the GasTech Heater is off.

Follow-up Actions: Once power is restored:

1. Restore indication and control.
2. Conduct a system shutdown to bring all systems to a known state.

3. Loss of Main Loop (working fluid) Flow

Discussion: Loss of working fluid flow in the main loop has no associated automatic system action. It creates a hazardous condition where heat is being added to the HX without any associated heat removal in the condenser. Without immediate operator action to shut down the GasTech Heater, all the liquid in the HX will flash to vapor causing a rapid in-surge to the Accumulator, and an associated pressure spike that may well exceed the set point of one or more of the system relief valves. Therefore, the most critical operator action will be to shut down the GasTech Heater. A shutdown of just the heater is preferred so that system indication and control is maintained, but in the event that a rapid shutdown cannot be achieved any other way, then a Hard E-Stop should be initiated.

Indications: Low Flow alarm on the Flow Meter I-30.

Possible causes: Loss of power to or motor/VFD malfunction on Pump E-7.

Immediate Actions

1. Stop the GasTech heater.
2. Verify GasTech heater is shut down by verifying decreasing temperatures on I-3.
3. Increase ventilation fan speed to maximum.

Follow-up Actions: Once the cause of the loss of flow is found and corrected:

1. Review TC's around the Main Loop. If the maximum temperature differential is greater than 50°C, then allow further ambient cooling. The concern is thermal shock to the system upon restart of main loop flow.
2. Restart main loop flow at minimum allowable pump speed.
3. Allow temperatures to equalize within 5 degrees around the loop.
4. After circulating the fluid for a minimum of 10 minutes to allow mixing, sample the working fluid according to Protocol 11 to re-baseline the working fluid's chemical constituents. (If necessary, sampling can be delayed until ready to restart the system.)
5. Conduct a normal system shutdown.

4. Loss of Cooling Water Flow

Discussion: Loss of cooling water to the condenser is similar in effect to the Loss of Main Loop flow. The most critical operator action is shutting down the GasTech.

Indications: Low Flow Alarm on I-14 (Cooling Water Flow) as well as High Temperature alarms on I-20 (Condenser Exit Temperature)

Possible Causes: Loss of power to the Circ Pump #1 in the Tower Water Cooling System.

Immediate Actions:

1. Stop/E-Stop the GasTech Heater.
2. Verify GasTech Heater is off by decreasing temps on I-3.

Follow-up Actions:

1. Maintain flows in the main loop and Continental air supply until the system temperatures and pressures are stable.
2. Conduct a normal system shutdown.

5. Major Working Fluid Leak

Discussion: A major leak of cyclopentane working fluid can occur in three locations: In the trailer, in the HX and outside both the HX and the trailer. Since all the major working fluid piping has been hydrostatically tested, the only places where there is a significant probability of leaks are flanges and threaded fittings. One of the key objectives of the final Main Loop water fill is to check the entire system at temperature and pressure. That test will be followed by a hot re-torque of all the fluid joints, flanges and unions.

There are two principal concerns about a major leak of cyclopentane.

- First, the environmental impact of an inadvertent discharge of cyclopentane.
- Second, and much more importantly, the danger of the cyclopentane igniting.

The casualty procedure is designed to address the second threat; the environmental impact will only be considered in the follow-up actions.

Although a major leak is defined as anything besides a slow drip from a union, if an operator should be concerned about a borderline leak, the conservative action is to call it a major leak, and take the appropriate actions.

<u>Detectability</u>: If a leak happens in the trailer, the Toxic Gas Monitoring System will detect the leak, and either give a warning level (10 to 25%) or an alarm level (>25%). In the case of a leak in the HX, during operation it will be detected by the Unburned Hydrocarbon Detector. For the limited portion of working fluid piping outside these two spaces, the most like method of detection will be visual...probably by the technician.

<u>Automatic Protection</u>: There are two automatic protective actions for a leak.

- In the trailer, an LEL alarm (25%) will trigger a Hard E-Stop. This will result in a condition where there is no flow in the loop, the Hot and Cold Sides are isolated from one-anther, the GasTech is shutdown, there is unheated CA supplied to the HX and CW supplied to the Condenser, and ventilation to the trailer is maximized. It is important to note that all control and indication power are lost as part of the e-stop response.

- The other automatic protective action will be a Soft E-Stop triggered by a high UHC concentration in the CA flow indicating a leak in the WF piping inside the HX. In this case, the GasTech is tripped and V-5 is closed, but no other action is taken.

Immediate Action Philosophy: There are two principles that form the basis for the Immediate Actions for a Major Leak. First, maximize dilution by increasing air flow and second, reduce system pressure to reduce the leak rate.

Indications: As discussed above, LEL alarm, UHC alarm or visual depending on location.

Possible Causes: Leaking flange or union, cracked weld, etc.

Immediate Actions:

Case 1: Below the Alarm Limit (LEL or UHC)

1. Stop the GasTech Heater.
2. Maximize dilution by increasing CA flow to maximum or increasing the ventilation fan to 100%.
3. Increase CW flow to maximum by fully opening V-3.
4. Close V-5
5. Reduce system pressure by venting Accumulator Ar through V-47.

Case 2: LEL alarm (Hard E-Stop)

1. Carry out actions for a Hard E-Stop.
2. Ensure ventilation fan is running at 100% to maximize dilution in the trailer.
3. Maximize CA flow to maximize the depressurization rate in the HX.

Note

Do not secure CA flow to the HX without specific authorization from the leader of the emergency response team.

4. Reduce system pressure by venting Accumulator Ar through V-47.
5. When LEL Alarm clears, restore indications and controls.

Case 3: UHC Alarm (Soft E-Stop)

1. Verify GasTech Heater is stopped.
2. Maximize dilution and HX cooling (bubble collapse) by increasing CA flow to maximum.

Note

Do not secure CA flow to the HX without specific authorization from the leader of the emergency response team.

3. Maximize WF cooling in the Condenser by fully opening V-3.

4. If UHC level cannot be brought below the alarm limit by the above actions, then vent the Accumulator by fully opening V-3, and as a last resort, open V-9 and dump the working fluid to the Depressurization Tank.

Follow-up Actions:

Case 1

1. Complete the shutdown being careful to monitor for pump cavitation.
2. Develop a plan to locate the leak.

Case 2

1. When indications and controls have been restored,
   a. Monitor TGMS levels; if levels remain high (above the warning level), go to Item 2 below.
   b. Restore Main Loop flow according to the procedure under Hard E-Stop Follow-up Actions above with the exception of repressurizing the system.
   c. Complete a system shutdown taking system pressure down to 30 psia.
   d. Set conditions for a trailer entry with the FSS enabled.
   e. Enter the trailer and look for the site of the leak. If necessary, raise the system pressure incrementally to make the leak site more identifiable.
2. If the TGMS levels remain above the warning level, then initiate a rapid depressurization.
   a. Open V-8 and V-15. This will allow the Cold Side fluid to expand into the depressurized HX.
   b. Fully depressurize the Accumulator pistons by venting the Ar using V-17.
   c. Maximize WF cooling in the condenser by fully opening V-3.
   d. Restore flow to the Main Loop by restarting the Circulation Pump (E-7) at minimum speed. Watch for cavitation.
   e. If additional depressurization is required, open V-9 and allow the WF to expand into the Depressurization Drum.

Case 3

1. Complete the system shutdown while keeping the CA flow maximized.
2. Provide higher Nitrogen flow to the HX to ensure that an inert atmosphere is present until the leak location procedure can be started.

6. Cyclopentane Fire

Discussion: A Cyclopentane fire during normal operations will require a Working Fluid Leak of some type. If a fire occurs inside the trailer (*Case 1*), then a Hard E-Stop will be initiated, and the Fire Suppression System will be initiated. Because the trailer is sealed and the ventilation fan is stopped as part of the FSS sequence, any fire in the trailer will be quenched, and all the components in the trailer will be cooled reducing the probability of a reflash even after the CO2 is vented from the trailer.

Manual deployment of the Fire safety system can be initiated by pulling the pin and actuating a lever on the red Carbon Dioxied cylinders located outside the trailer. Additionally, the fire pull station by the control computer (in the control room) will also activate the fire system in the trailer. See picture below that identifies the fire pull station.

FSS pull switch

FSS deployment pin + lever

Note

If the FSS is initiated, the trailer shall not be opened or ventilated without the express permission of the Fire Department.

If a fire occurs outside the trailer (*Case 2*), then no automatic protective actions will be initiated, and it will be up to the operators to notify the BSC and combat the casualty by reducing system pressure and using handheld fire extinguishers to fight the fire until the Fire Department arrives.

Indications:

- **Case 1**: UV Flame Detection Units
- **Case 2**: Visual

Probable Cause: Working Fluid Leak accompanied by an ignition source.

Immediate Actions:

Case 1:

1. Carry out immediate actions for a Hard E-Stop
2. Clear the courtyard.

3. Increase CA flow to maximum the system depressurization rate.
4. Coordinate any further actions with the Fire Team on-site leader.

Case 2: The Immediate Action philosophy for Case 2 is to notify the emergency response team, and to as rapidly as possible reduce the leak rate by depressurizing the system.

1. Initiate a Soft E-Stop
2. Notify the BSC of the fire and the nature of the fire.
3. Clear the courtyard.
4. Verify the GasTech Heater is stopped.
5. ~~Maximize CA flow~~. Fight the fire with handheld fire extinguishers if safe to do so until the Fire Department arrives.
6. Maximize CW flow by fully opening V-3.
7. Slow the Circulation Pump (E-7) to 25% to avoid cavitation during depressurization.
8. Open V-17 to dump the accumulators.
9. Open V-9 to dump part of the working fluid to the Depressurization Tank.

Follow-up Actions: The follow-up course of action should be as directed by the Fire Team leader.

B. Abnormal Operating Procedures

The Abnormal Operating Procedures are covered by the ORC Protocols.

VII. MAINTENANCE/TROUBLE SHOOTING PROCEDURES:

- **WF Circulating Pump** (E-7) is to receive regular maintenance per the manufacturer's instructions after reaching 1500 hours of operation or after reaching 3 months of service.
- **Inspections for Leakage:** Daily inspection of the valves and connections for any leakage is part of the start-up procedures. Any leakage will be handled according to the spill protocol.
- **Trailer Entry Procedures**: To conduct most maintenance and troubleshooting on the system it is necessary to enter the trailer. This experiment/experimental space is considered dangerous and thus certain conditions must be set prior to allowing access to the trailer during any stage of shakedown/testing. Potential hazards associated with trailer entry include:
    - Electrical hazard 480V power in controls cabinet in 154
    - Excessive noise from Continental compressor
    - Asphyxiating gas, CO2 CO - heater
    - Flammable fluid

- LEL of fluid 1.1%, 11,000ppm
- Pressurized fluid up to 43 bar (630 psia)
- Heated/vaporized fluid (250°C, 482°F)
- Inert gases, argon

Conditions for manned operation/maintenance in trailer; the following conditions will be verified by the operator making the entry by the use of the ***ORC_Checklist_TrailerEntry***.

Note

There are a set of daily checks that must be performed prior to entry even when the system is shutdown, cooled down and depressurized.

VIII. POLLUTION CONTROL & WASTE DISPOSAL PROCEDURES:

The exhaust gas exiting the heat exchanger is vented well away from building ventilation inlets and no additional measures will be required. The tower water cooling loop is a closed system and will not be contaminated. After the required testing interval, the cyclopentane will be drained from the system into the Center's hazardous waste containers and arrangements will be made for proper disposal.

IX. ACCURACY AND TOLERANCES:

The test instrumentation in this experiment is composed of type J and K thermocouples. The sensitivity as per the manufacturer is ±1°C.

The pressure transducers have an accuracy of ±.05% FSR which then depends on the transducer. The transducers were calibrated using a nitrogen cylinder and a dead weight tester in their final location to give the total system error for the measurements.

The Coriolis mass flow meter has an accuracy of ±.2% and the transmitter ±1% for a total accuracy of sqrt(flow meter^2+ transmitter^2).

The uncertainty of the Venturi flowmeter was calculated based on the uncertainty of the pressure transducers, TC, and the Venturi itself. This was found to be +/- 0.2 lbm/s

The load cells used to measure the level of cyclopentane in the accumulator can resolve to ±1lb.

All calibration sheets are stored in the ORC binders for future reference.

X. SCHEDULE REVIEW HISTORY:

Safety Review Date: ____________

Follow up actions complete Date: _______________

I have read and understand the above information:

User's Name: ______________________/______________________ Date: _________
print signature

User's Name: ______________________/______________________ Date: _________
print signature

User's Name: ______________________/______________________ Date: _________
print signature

User's Name: ______________________/______________________ Date: _________
print signature

User's Name: ______________________/______________________ Date: _________
print signature

User's Name: ______________________/______________________ Date: _________
print signature

User's Name: ______________________/______________________ Date: _________
print signature

User's Name: ______________________/______________________ Date: _________
print signature

XI. APPENDIX A: Emergency Systems and Protective Functions

A. E-Stop System

1. Hard E-Stop

a. The following stimuli will trigger the hard Estop:

- Hard-wired push buttons
- TGMS – LEL alarm levels
- Fire system – UV Sensors or the Manual Fire Alarm in the Control Room and by the Trailer.
- Loss of ventilation – low reading for I-34
- NI controller health – not responding (loss of control)
- Unburned Hydrocarbon Detector (I-2) health bit

b. Actions Triggered by a Hard E-Stop

- Send alarm to BSC/operator
- E-stop gas heater
- Remove power from circulation pump (E-7)
- Remove 120V from trailer (Will cause valves to return to fail safe position)

V-8	HX Inlet	Closed
V-15	HX Outlet	Closed
V-9	Main Loop Dump Valve	Closed
V-3	Condenser CW In	Throttled
V-5	Accumulator Ar Supply	Shut
V-17	Accumulator Ar Dump	Shut
V-47	Accumulator BP Regulator	As Is

- Remove 24V from trailer resulting in loss of all system indication.

Additional actions if Estop is triggered by an LEL alarm in the TGMS system:

- MD-1/D1&D2 shall open
- EF-1 and VFD-1 energized

Additional actions if Estop is triggered by Fire detectors in the trailer:

- EF-1 and VFD-1 de-energized
- MD-1/D1&D2 shall close
- Dispense CO2 into container

c. Conditions following Hard E-Stop: A hard E-Stop will result in a condition where:

- There is no flow in the main loop

- The Heat Exchanger (HX) is isolated from the rest of the Main Loop
- Compressor (Continental) Air is still flowing through the GasTech and the Heat Exchanger removing residual heat
- Cooling water continues to flow through the Condenser, although at a reduced rate
- Gas supply and dump will be isolated from the top of the accumulators, but the Back Pressure Valve will continue to provide some limited overpressure protection in the non-HX side of the Main Loop
- All electronic temperature and pressure indication is lost

Main Loop Hot Side: Since the heat exchanger is isolated by V-8 and V-15, the pressure in the heat exchanger will be controlled by the temperature and state of the fluid in the HX. Since working fluid flow will stop immediately, but residual heat from the GasTech Heater will continue to be added to the system, it is expected that there will be a pressure spike immediately following the E-stop initiation. That portion of the piping is protected by the pressure relief V-2 which has a setpoint of 550 psia, and it is likely that the pressure spike will exceed that setpoint and V-2 will lift as necessary to relieve pressure. As the Compressor Air (CA) cools, it will begin to condense the working fluid in the HX, and the pressure in the HX will equilibrate and the temperature will be approximately the compressor discharge temperature.

Main Loop Cold Side: The Cold Side of the Main Loop consists primarily of the Condenser, Accumulator and Pump, and following a Hard E-Stop it will be isolated from the Hot Side by V-8 and V-15. The working fluid will be a vapor from V-15 to the Condenser, and a subcooled liquid from the condenser to V-8. Since CW flow is maintained to the Condenser through a throttled V-3, vapor will condense in the condenser. As the vapor condenses, the Accumulator will supply additional liquid working fluid to the system, and Condenser will slowly fill with liquid. Once the condenser is filled with liquid, the rest of the vapor in the cold side will condense very slowly due to ambient/conductive losses. The liquid in the Condenser will eventually equilibrate at the supply temperature of the CW. Because of the relative volumes of the components, the accumulator is not projected to empty.

Pressure Control: Following a Hard E-Stop, V-5, and V-17 will fail shut. This means that operator controlled means of pressure control are:

1. V-47, the Accumulator Backpressure Regulator. V-47 only provides protection against slow pressure increases in the Cold Side.
2. Emergency pressure/dump valve, V-55 (located inside the control room on the North facing wall). Actuating V-55 will result in opening V-9 and V-56. As a result the working fluid (cyclopentane) will flow into E-9, the 50 gallon emergency holding tank and the accumulator pressure will be vented.

d. Hard E-Stop Recovery:

Once the cause of the Hard E-Stop has been corrected, indication should be restored as the top priority, and control as the second priority. Once indication has been restored, the conditions existing in the Main Loop should be assessed before deciding on what further recovery actions should be taken.

- The size of the differential pressure between the Hot Side and the Cold Side should be considered before attempting to open V-8 and V-15.
- The potential for thermal shock should be considered prior to re-initiating Main Loop flow.

2. Soft Estop

a. The following stimuli will trigger the soft Estop:

- Control system SD button → 

- Elevated temperature from exhaust stack thermal switch/thermocouple
- Elevated readings from UHC detector

b. What are the specific actions that are triggered by a Soft E-Stop

- E-stop gas-tech heater
- Close V-5 (This valve pressurizes the accumulator pistons).

B. Fire Suppression System

1. System Description

The Fire Suppression System (FSS) is designed to flood the trailer with Carbon Dioxide in the event that flames are detected by the UV Fire Detectors. The FSS has two operational states: Normal (enabled) and Disabled. To place the system in the active state, the Fire Department will:

- the Tank Isolation Valve (V-40) is unlocked and opened, and
- the system is switched to the Normal mode at the FSS control panel.

When the operator is ready to enable the system, the BSC is contacted, and they will in turn contact the Fire Department.

The FSS is required to be active for the following conditions:

1. The main loop is filled with Cyclopentane and either 2 or 3 below obtain.
2. Any main loop temperature exceeds 40°C
3. System pressure exceeds 75 psi.

Criteria for Trailer Entry with FSS Active

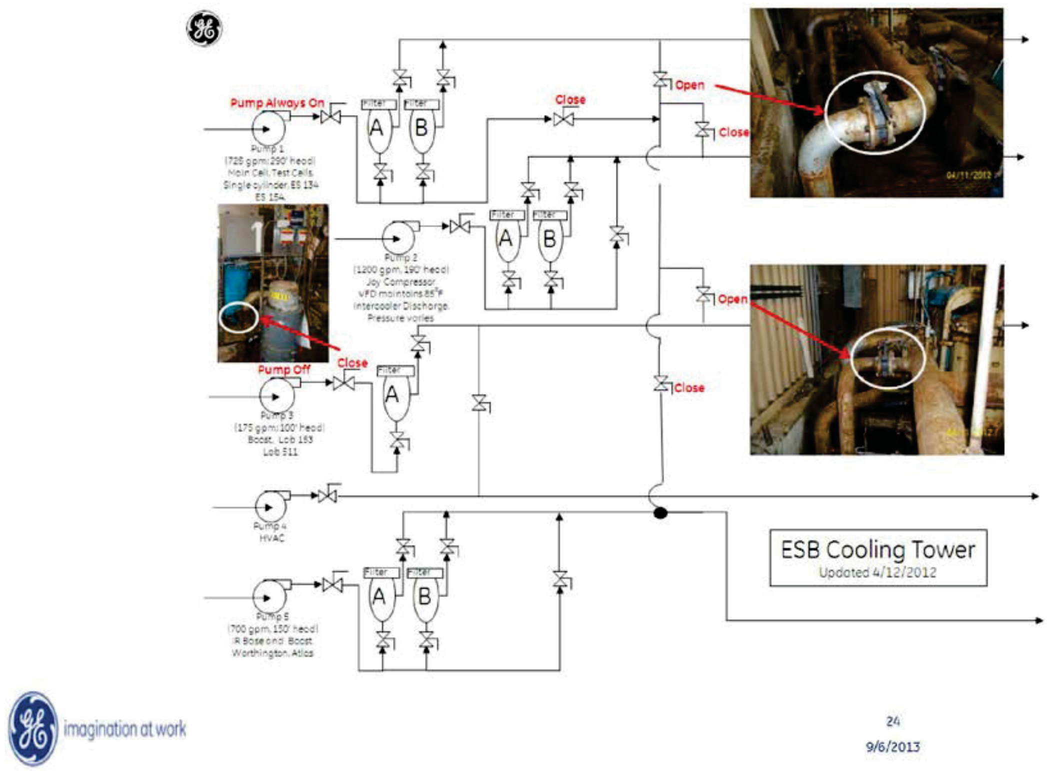
*In general, personnel entry into the trailer is not allowed if the FSS is active. <u>However</u>, for certain commissioning or shake-down operations such as system or pump venting, it is permissible to enter the trailer if the **ORC_Checklist_TrailerEntry**, Case 2, conditions are met. Specifically, a safety observer with no other duties than to monitor the operator entering the trailer is required to be stationed outside the open door of the trailer in case the operator encounters an emergency situation. There is specific concern that there may be inadvertent activation of the FSS (asphyxiation hazard).*

C. Protective Functions

The protective functions are described in the revision controlled document ***ORC_Protocol-06_Protective_ Functions.***

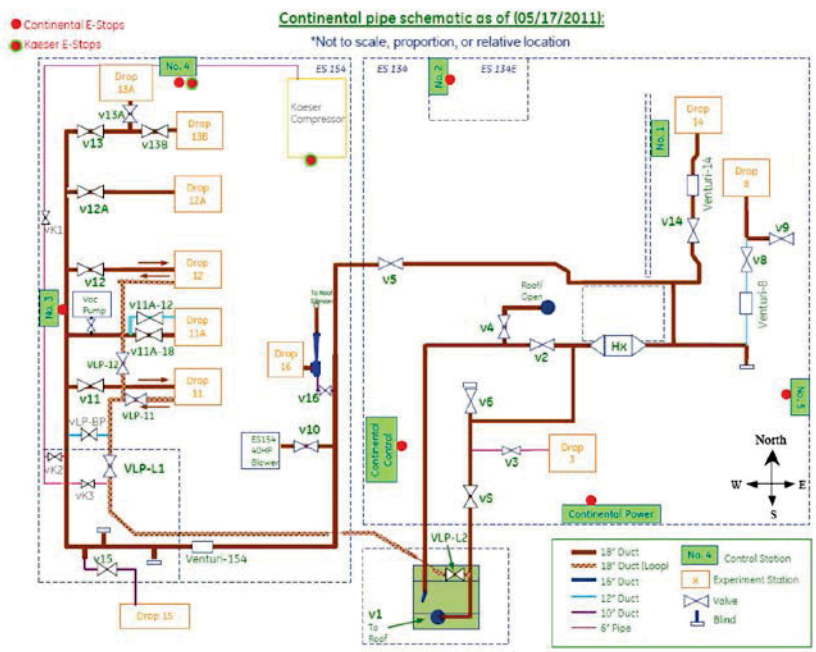
APPENDIX B

Pump house valve configuration



Appendix C

Continental valve configuration



Continental Compressor Checklist

Prestart **Operator:** ______ **Date:** ______ **Time:** ______

1 ___ Walk continental line - Valve checklist
2 ___ Oil level in two drippers viewable
3 ___ Condensate drain is closed
4 ___ Burst disk at rig is in tact
5 ___ Warn personnel of hazards
6 ___ Select modes (manual/auto, pressure/suction)
7 ___ Set V-1 <10%, V-4 = 100%
8 ___ Start machine

See SOP for detailed start-up procedures

Machine Periodic Walk-around

	Time/init.
Walk around Continental and check for abnormal noises	
Check Continental screen for alarms/warnings	
Drain condensate	
Air discharge pressure <14 psig or <9" H2O	
Bearing temperature <220°F	
Air discharge temperature <240°F	
Vibration <.45"/s	
Amp >90A and <140A	

Shutdown

1. Stop or E-stop machine (*if using with GasTech heater, must be run for 10 minutes after heater shutdown)*
2. Close drop
3. Set V-1 <10%, V-4 = 100%, Switch off
4. Drain condensate

NAME	***CONTROL LOCATION***	***FUNCTION***
V1	ES134 (by door 19), Control Screen (+remote stations)	Controls inlet flow to compressor
V2	ES134 (by door 19), Control Screen	Controls flow to heat exchanger (Auto)
V3	ES134 (by door 19), Control Panel	Controls flow to 6" line
V4	ES134 (by door 19), Control Screen (+remote stations)	Controls flow to exhaust pipe
V5	ES134 (near southwest blue tank), Hand valve with chain	Controls flow to ES154
Vs	ES134 (by door 19), Control Screen	Controls flow to change to suction system (Auto)
V6	ES134, Electronic, ES134D west wall	Nowhere, Blind!
V7	ES134, Hand valve	N/A
V8	ES134, Hand valve, No. 8 drop	Controls flow to 18"OD drop #8
V9	ES134, Hand valve, fuller cross over	Always closed.
V10	ES154, hand valve, low speed fan	Controls flow from low speed ES154 blower
V11	ES154, hand valve with chain, No. 11 drop	Controls flow to 18"OD drop #11
VLP-L1	ES154A, hand valve with chain, (Return Section)	Controls return of Low Pressure loop flow
VLP-L2	Continental Block House (Return Section)	Controls return of Low Pressure loop flow
VLP-11	ES154, hand valve with chain, (Return Section)	Controls return of Low Pressure Loop Flow to drop 11
VLP-12	ES154, hand valve with chain, (Return Section)	Controls return of Low Pressure Loop Flow to drop 12

V11a-12	ES154, Hand wheel, Drop 11	Controls flow to 12" section of Drop 11A
V11a-18	ES154, Hand wheel, Drop 11	Controls flow to 18" section of Drop 11A
V12	ES154, hand valve, No. 12 drop	Controls flow to 18"OD drop #12
V12a	ES154, Electric No. 12a drop	Controls flow to 18"OD drop #12a
V13	ES154, Electronic, ES154 north wall	Controls flow to 18"OD drop #13
V13A	ES154, hand valve with chain, No. 13A drop	Controls flow to 18"OD drop #13A
V13B	ES154, hand valve with chain, No. 13B drop	Controls flow to 18"OD drop #13B
V14	ES134, Electronic, west wall near drop	Controls flow to 18"OD drop #14
V15	ES154, Electronic, next to door high bay door 17	Shut off for 12" drop #15 (ORC Trailer)
V16	ES154, hand valve w/ chain, behind 40HP blower	Controls flow to 10" drop #16 (ejector to MR rig)
Vac Pump	ES154, hand valve above vacuum pump behind drop 11a	Controls vacuum pump tied into 18" Continental System
VK1	ES154, hand valve with chain, Kaeser Line	Isolation of Kaeser flow in ES154
VK2	ES154, hand valve with chain, Kaeser Line (in TCER)	Controls Kaeser flow in ES154 Continental Duct
VK3	ES154, hand valve with chain, Kaeser Line (in TCER)	Controls Kaeser flow in ES154 Continental Loop

APPENDIX D: Equipment Description

1. *System Description*

   a. Automatic Controls

Working Fluid Flow Control

I-16 (HX WF Outlet Temp) is controlled at 250C during steady state operation by varying the speed of the Circulation Pump (E-7) using Proportional Control. I-16B is the backup for I-16.

Cooling Water Flow Control

I-20 (Condenser WF Outlet Temp) is controlled at operator selected temperature during steady state operation by varying the position of the Cooling Water throttle valve (V-3). The control temperature of I-20 will be established during initial Cyclopentane S/U to allow I-16 to be controlled at 250C.

System Pressure Control

Accumulator pressure is normally controlled by the Backpressure Regulator, V-47, which is adjusted manually outside the trailer. However, an overpressure condition (>620 psia) sensed on Accumulator Pressure, I-10, will cause:

- the Ar Isolation Valve, V-5, to shut, and
- the Accumulator Depressurization Valve, V-17, to open

dumping all the Argon off the top of the accumulator pistons.

2. *Major Components*

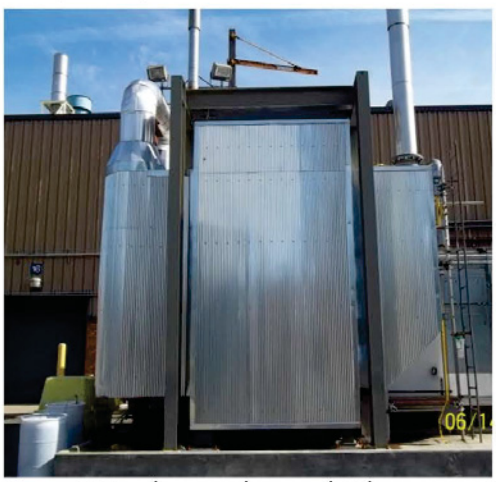


Figure 3. Test heat exchanger (E-3)

The heat exchanger, shown in Figure 3, was manufactured by Hamon Deltak, Inc in 2010-2011. It is a one through boiler design with three sections. The section to the far left in the picture being the evaporator, the next being the superheater and the far right section being the economizer. There are three tube rows along the width of the heat exchanger. All experimental data is taken from the center row. The evaporator has 3 finned tube rows in the gas path, the superheater has 3 finned tube rows and the economizer has 11 finned rows for a total of 17 rows long, by 3 rows wide.

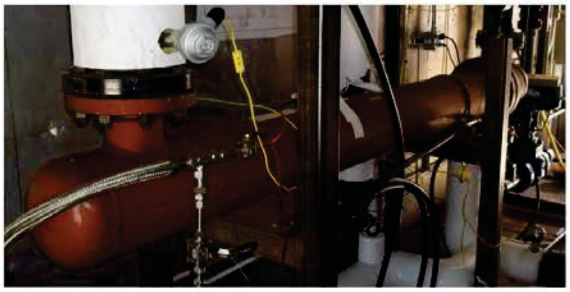


Figure 4. Condenser (E-4)

The condenser, seen in Figure 4, provided by Thermal Products Inc., is a shell and tube heat exchanger where the working fluid (cyclopentane) is on the shell side and the cooling water, provided by the tower water system, is flowing through the tubes. This unit was stamped to operate at 450psig, however the vendor has communicated that it can be run at 500psig and 500°F.

Figure 5. Pump (E-7)

The pump, Figure 5, provided by ChemPump is a centrifugal pump with an explosion proof motor. It runs of a 480V, 30hp motor which is driven by a Frenic VFD housed in the Hoffman panel in ES 154. The pump must be primed as instructed in the manual after each fill of the system.

Figure 6. Accumulator (E-6)

The accumulator, Figure 6, provided by Pearse-Bertram, is composed of a rack of 4 piston accumulators connected at the top and bottom by manifolds. The accumulator maintains pressure in the system by using a high pressure gas to compress the pistons and force the cyclopentane out of the bottom and into the test loop. The pressurizing gas will be supplied by a rack of XXX.

The depressurization vessel, Figure 7, provided by American Boiler, is used to drain cyclopentane or other fluid from the heat exchanger if V-8 and V-15 are closed or from the heat exchanger and the loop if the above valves are open. This vessel has a capacity of 50 gallons.

Figure 7. Depressurization vessel (E-9)

Figure 8. Separator (E-10)

The separator, Figure 8, was supplied by Eaton Process Inc. The vessel is downstream of all the pressure relief lines coming off the cyclopentane line. The unit is a cyclone separator placed in line to remove the liquid portion of cyclopentane that is discharged. The vapor port is vented out through the top of the trailer. The liquid portion is collected and emptied via a drain in the base of the vessel.

Figure 9. GasTech heater (E-2)

The final critical piece of equipment to run this experiment is the GasTech, inline vitiated heater, shown as Figure 9. This is a natural gas heater capable of producing 500°C gas at a flow rate of 10lbm/s. This heater is fed off the Continental blower/compressor. The GasTech heater is controlled from a panel mounted on the ES 154 wall by Door 17?? For additional information, see the SOP for the GasTech heater.

Images of the valves in safe start-up position

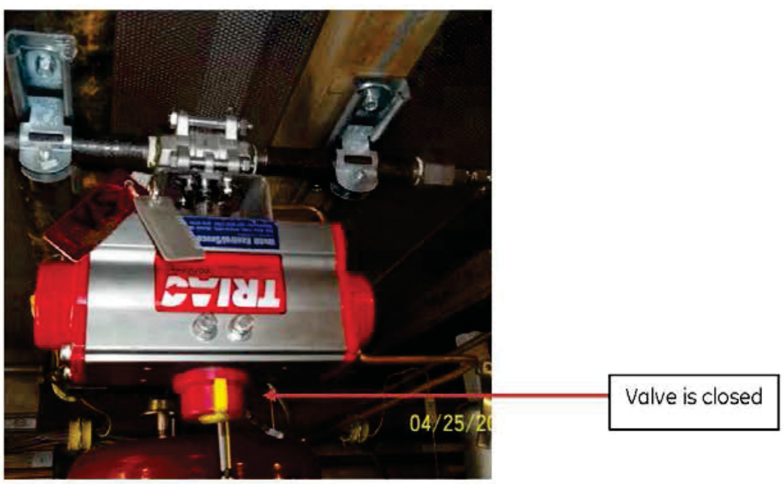
V-1(shown)

Valves V-1, V-2, V-4, V-7, V-30, V-34 are pressure relief valves. The valves connected to the cyclopentane line, all but V-XX, discharge to a common header which then directs the vapor through a separator and then out the top of the trailer. V-2 is set to a lower pressure to protect the condenser which is rated to run at 500psig.

V-3

Valve V-3 is the tower water control valve with a pneumatic positioner, marked in red. Currently the positioner/valve are closed. The position of this valve is controlled on the "Test" screen of the LabView VI by changing the percentage that the valve is open.

V-5

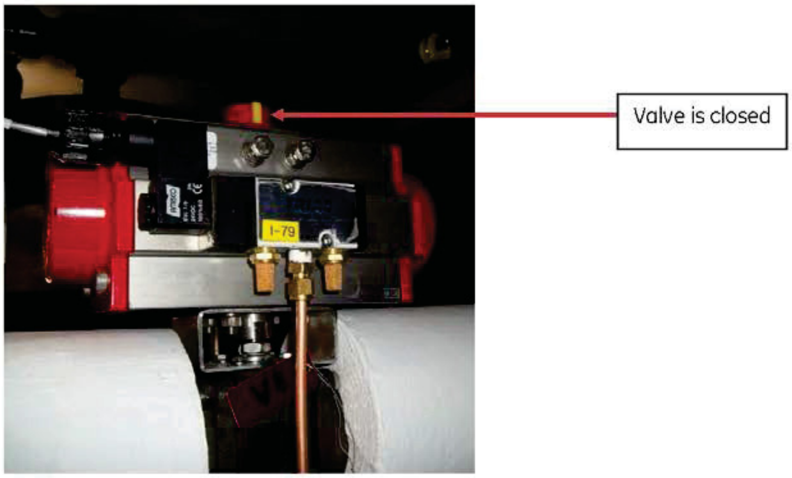


Valve V-5 is the solenoid located upstream of the accumulator which allows the user to stop pressurizing the system and maintain the pressure in the system at the current level. The pneumatic feed for V-5 and V-17 are shown as V-XX and is located on the East?? wall of the trailer. V-5 is controlled from the "Test" screen of the LabView VI. Currently the valve is shown in the closed position as noted by the yellow actuator at the bottom of the valve.

V-6

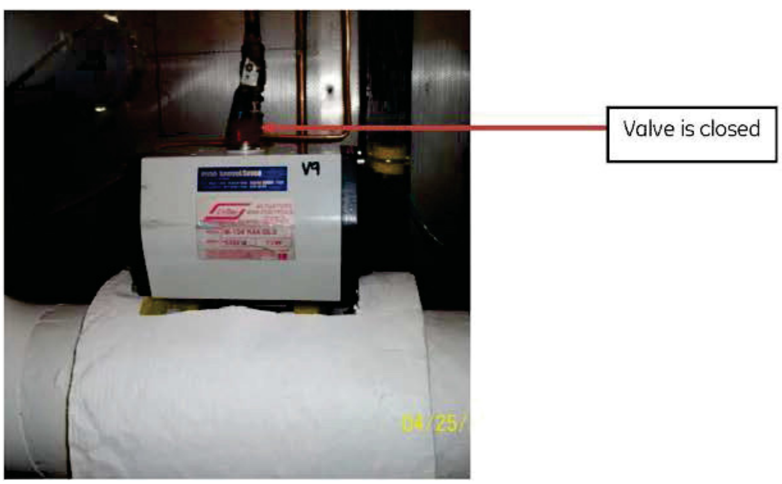
Valve V-6 is the tower water bypass valve and in the open position allows the tower water to circulate through the trailer and return to the building. This valve should be open prior to opening V-26 and V-27 in ESB 154. This will allow the tower water to return to the building during the initial condenser fill. This valve is manually actuated from the trailer on the West wall.

V-8



Valve V-8 is the 2" pneumatic isolation valve on the cyclopentane line. This valve is used to isolate the heat exchanger from the rest of the system. It is controlled from the "Test" screen on the LabView vi and should be actuated with V-15 which is the 4" isolation valve. The valve is currently shown in the closed position as noted by the yellow bar on the actuator.

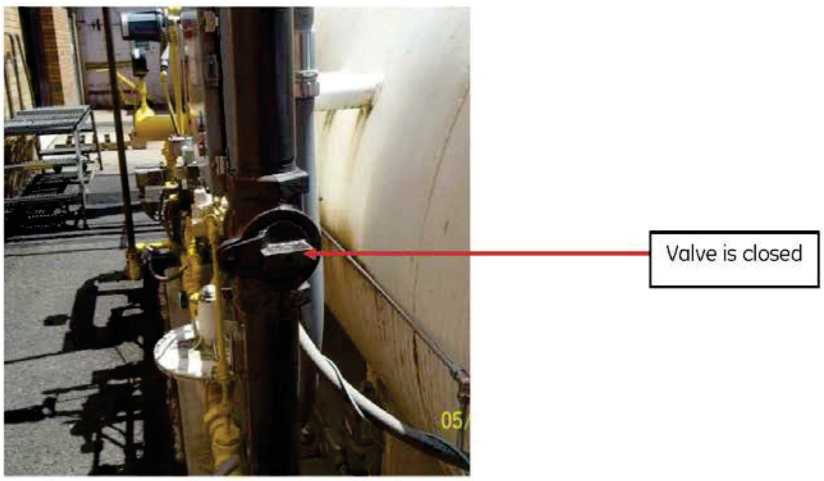
V-9



Valve V-9 is a 2" pneumatic valve used to drain the liquid portion of the cyclopentane out the heat exchanger as required by the operator. It is controlled from the "Test" screen on the LabView vi.

Valve V-8 should be closed prior to attempting to drain the heat exchanger. This valve is currently shown in the closed position.

V-10



Valve V-10 is the main natural gas supply to the GasTech heater. It should be opened prior to running the heater and closed at the end of use.

V-11

Valve V-11 is the natural gas to the pilot of the GasTech heater. This valve can remain open when the unit is not in operation if the main supply, V-10, has been closed.

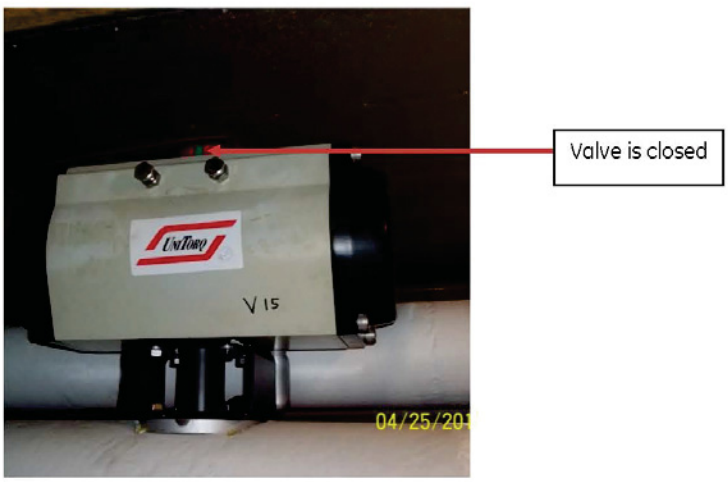
V-12

Valves V-12 are the two blocking valves which control the flow of natural gas to the heater. These valves are controlled by the GasTech control panel and do not need adjustment.

V-13

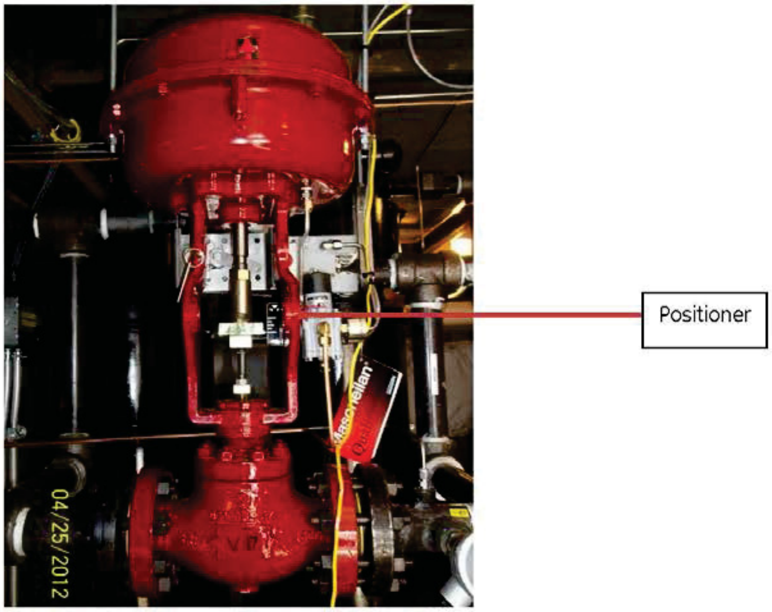
Valve V-15 is an electric valve which opens the airline off the Continental out to the GasTech heater. This valve is powered by the GasTech control panel but the switch to open/close the valve is to the left of the panel. Note, this valve should be closed before turning off the power to the GasTech panel.

V-15



Valve V-15 is the 4" pneumatic isolation valve on the cyclopentane line. This valve is used to isolate the heat exchanger from the rest of the system. It is controlled from the "Test" screen on the LabView vi and should be actuated with V-8 which is the 2" isolation valve. The valve is currently shown in the closed position as noted by the green bar on the actuator.

V-17



Valve V-17 is a 2" pneumatic positioner on the Argon line. It is used perform a controlled depressurization of the system. This would be used in conjunction with V-5 which is a solenoid valve to stop the flow of Argon into the accumulator. This valve would in turn slowly release the Argon to the vent system

V-18

Valve V-18 is the check valve on the high side of the pump, designed to maintain the head at the high side of the pump and prevent flow from passing back in the reverse direction. It has a cracking pressure of .5psi.

V-19

Valve V-19 is a manual ball valve used for filling and draining the loop. It inserts into the 2" line running between the condenser exit piping (covered with insulation in the photo) and the accumulator exit piping. This valve is connected to a ½" CS line which exits the trailer and terminates at the barrel grounding location at the west end of the trailer.

V-20

Valve V-20 is a manual ball valve used to fill/drain the cyclopentane from the 4" pipe exiting the superheater. This valve is connected to an extension line to the fill location which terminates in another valve, V-50.

V-21

Valve V-21 is located at the high side of the pump and is the high point in the 2" cyclopentane liquid piping where a vacuum can be drawn as well as venting slugs of air which become trapped during the fill process. This valve can be connected to a ½" poly line which for venting is run outside through the North wall of the trailer. This valve can be used for any off-line sampling desired from the liquid side.

V-22

Valve V-22 is located at the high side of the condenser (E-4) and is the high point in the 4" cyclopentane line. The condenser is pitched ¼" up at this side to allow for non-condensible gas to accumulate and be vented out the side of the trailer through the same hole mentioned above. This valve can be connected to the vacuum system as well as be used for any off-line sampling required.

V-23

Valve V-23 is located in the 2" cyclopentane liquid pipe that feeds the preheater/economizer. This valve is accessed by climbing to the 2nd level of the scaffolding and manually actuated. This valve can be used to vent the cyclopentane as well as to draw vacuum on the system, as shown in the picture. This valve is also available to do on-line sampling because it is accessible without entering the trailer.

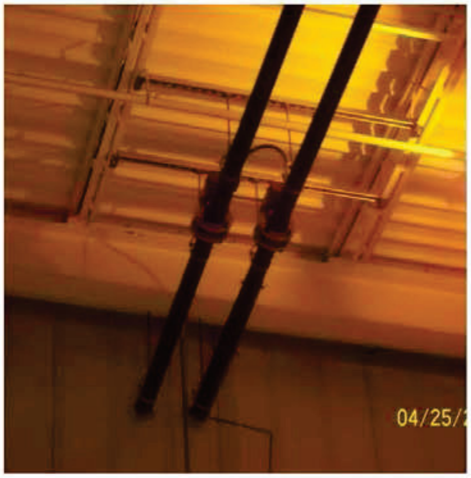
V-24

Valve V-24 is connect to the cyclone separator to be used as a drain after any discharge of the pressure relief valves. This should be drained into a metal catch pan.

V-25

Valve V-25 is a manual ball valve acting as a drain for the 50 gallon de-pressurization vessel. There is a hose bib fitting attached to this valve to allow for easier draining from the tank. When draining cyclopentane or a fluid with flammability issues, a metal catch tank should be used and plastic/rubber or insulating hoses should be minimized.

V-26/V-27



Valve V-26 and V-27 are electro-pneumatic wafer valves that allow tower water to flow to the trailer. These valves have been modified with a slow release regulator to prevent them from slamming shut. They are activated using a single switch under the GasTech control panel. This switch is seen in the picture on the right.

V-28

Valve V-28 is a manual regulator, attached to the outside of the North wall of the trailer. This regulator is used to control the pressure of the Argon/pressurizing gas going to the system. It can be manually adjusted prior to and during testing to increase/decrease the pressure on the accumulator, however, the set pressure of the regulator limits the amount of pressure in the accumulator.

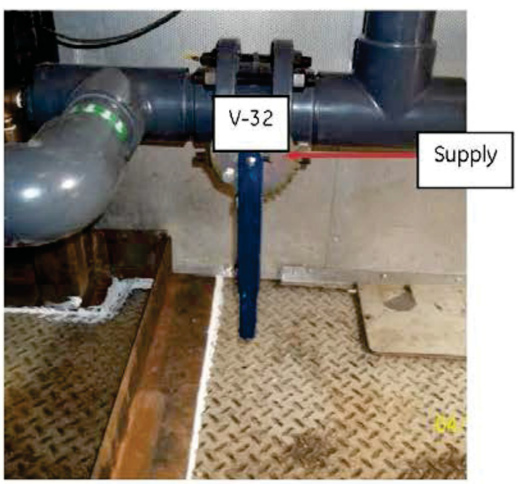
V-29

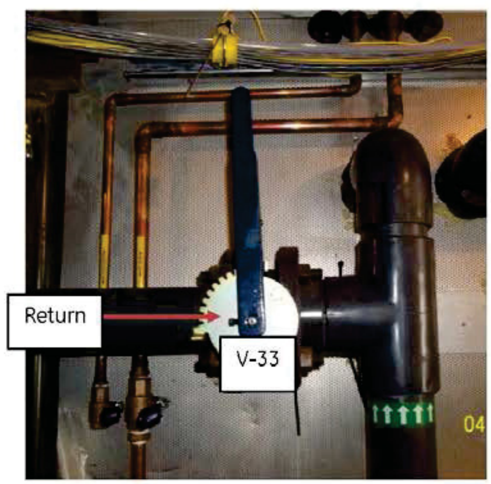
Valve V-29 is a manifold to connect 4 cylinders to the ¼" Argon/inert gas fill line to the high side of the accumulator. The manifold has gages attached to each bottle to verify acceptable pressure in each. V-28, the gas regulator can be seen at the left end of the manifold.

V-30

Valve V-30 is the inert gas pressure relief which will discharge if the inert gas regulator fails for any reason. This will discharge over the heads of anyone in the area to reduce the risk to personnel. This pressure relief is set to discharge at 44bar or 638psi.

V-32/V-33





Valves V-32 and V-33 are manual butterfly valves which allow the tower water to flow to the condenser. These valves are both shown in the closed position. They should be opened well before heat is applied to the system and the flow in the loop verified by I-14.

V-38

V-38 is the tower water drain. This valve has a hose bib on it to allow the user to drain the tower water that is in the condenser and in the lines from the building. Note, V-32 and V-33 should be closed prior to draining the lines. Also, to create the needed air draw-in, the TC fitting on the condenser exit, I-19 was loosened to enable the draining.

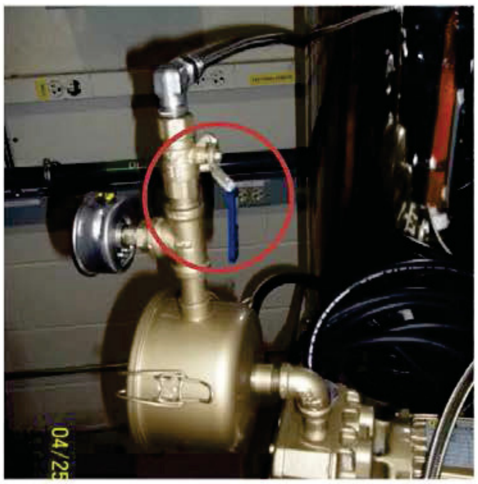
V-39

V-39 is a venting valve connected to the intermediate header of the heat exchanger. This header is before the final three passes in the preheater/economizer. This header ensures even distribution of the fluid in each of the three tube rows as well as the three remaining passes in the exhaust stream. It is manually actuated by climbing to the second level of the scaffolding and is located at the top of the heat exchanger. It can also be used as a second vacuum port as necessary.

V-40

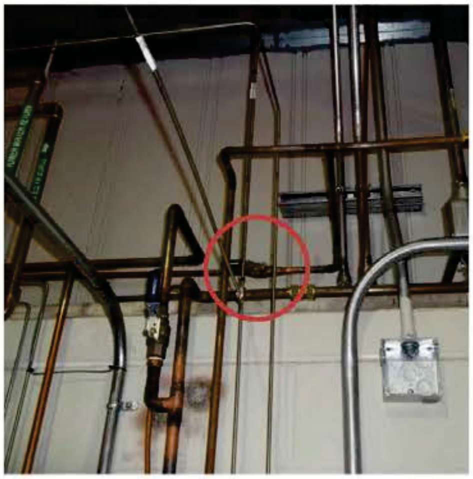
Valve V-40 is the Lock out valve for the CO_2 fire suppression system. This valve should only be locked by a member of BSC or the fire brigade. If the need arises to enter the trailer when the system is charged with cyclopentane call x6118 to have someone come down and lock-out the valve.

V-41



V-41 is the inlet vacuum valve. It is connected to the vacuum tank and the vacuum pump via a flex hose. This system is mobile and is stored in the trailer when not in use.

V-42

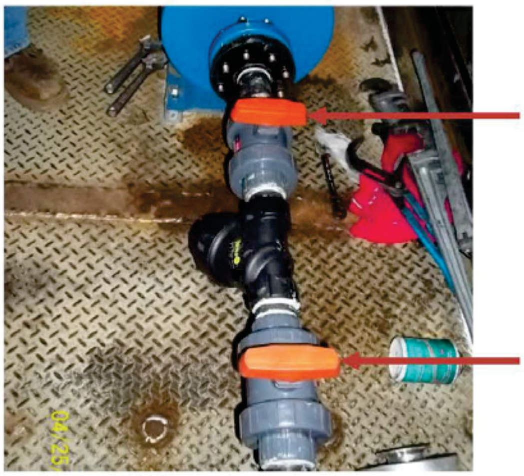


V-42 is the house nitrogen inlet valve which supplies the trailer with Nitrogen at ~40psi. This valve is located in ES 154 on the South wall of the lab. This line has a check valve downstream of this valve to prevent anything from backing up into the building supply. This valve remains open during the duration of the testing and the flow of nitrogen is controlled at the trailer. It can however, be used for LOTO if necessary.

V-43

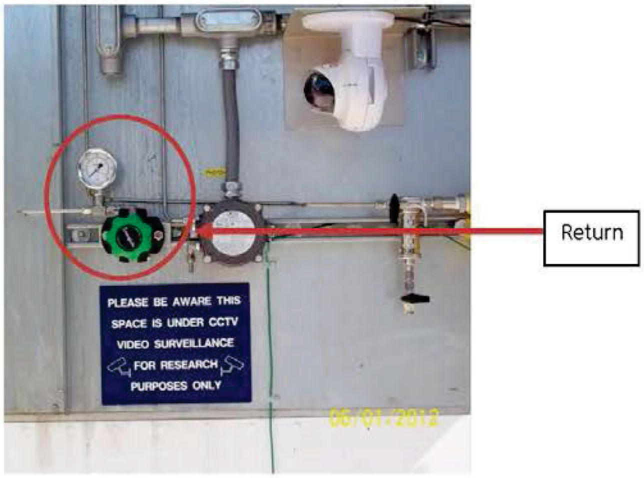
Valve V-43 is the house nitrogen valve on the outside of the trailer which can be connected to the barrels for the fill procedure. This valve can also be used to run N_2 into the piping to dry the loop as noted in the protocols.

V-44/V-45



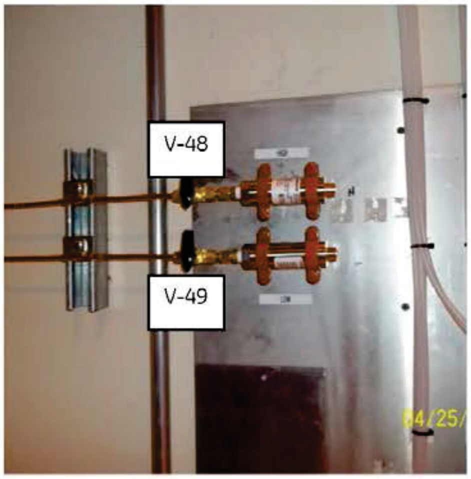
V-44 is the y-strainer inlet, seen at the bottom and V-45 is the y-strainer exit seen at the top. Both these valves are PVC and intended for use only during a water cycling/clean-out procedure. These valves are rated for 150psi as is the y-strainer. These should be opened to allow for water to flow through the strainer set-up and can be closed to drain and clean-out debris in the strainer.

V-47



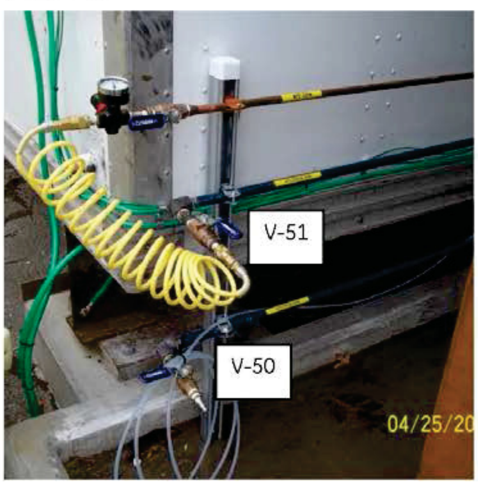
Valve V-47 is the back pressure regulator which is run in parallel with V-4 and V-17 to add fine control to the pressurizing system. This will be manually adjusted prior to heating the test to maintain the desired pressure in the accumulator.

V-48/V-49



Valve V-48 opens the pressure transducer line from the venturi tap on the high side, shown as the top valve on the picture. Valve V-49 opens the pressure transducer line from the venturi tap at the contraction, shown as the lower valve. These valves must be opened to read the mass flow in the system.

V-50/V-51

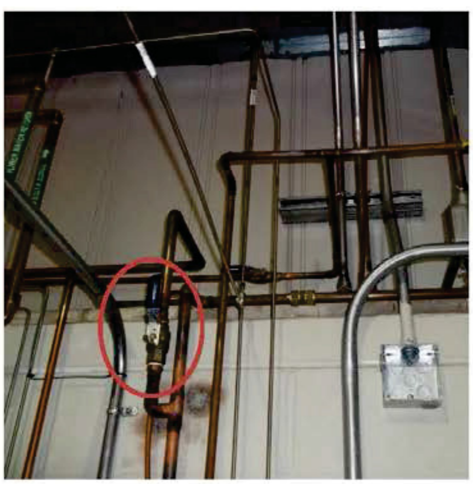


Valve V-50 is a fill/drain extension line that connects to V-20, the manual ball valve used to fill and drain the heat exchanger side of the loop when the isolation valves, V-8, V-15 are closed. Valve V-51 is a fill/drain extension line that connects to V-19, inside the trailer. These manual ball valves are used to fill/drain the piping side if the loop.

V-52

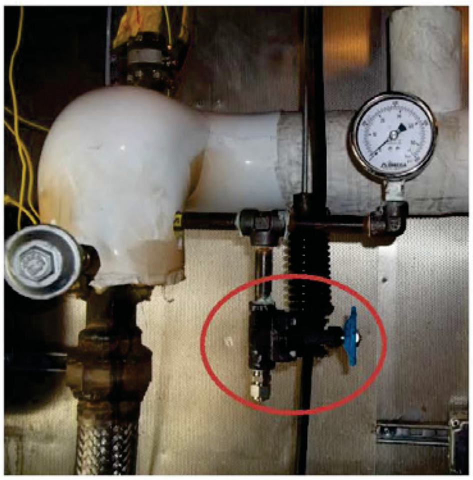
Valve V-52 is a vent off the 2" line running to the suction side of the pump. This valve is used during the fill procedure as well as to verify that the pump has no air pockets at the suction side. In the photo, the valve is set-up for the suck-blow dryout procedure. The tee would not be inline during actual operation.

V-53



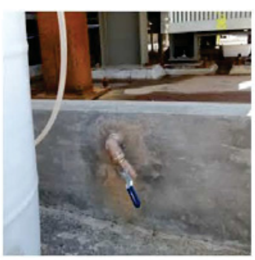
Valve V-53 is the house air inlet valve which supplies the trailer with air at ~89-90psi. This valve is located in ES 154 on the South wall of the lab. This line has a check valve downstream of this valve to prevent anything from backing up into the building supply. This valve remains open during the duration of the testing and the flow of air is controlled at the trailer. It can however, be used for LOTO if necessary.

V-54



Valve V-54 is an additional drain valve off the high side of the pump. This valve can be utilized to drain the 2" line. The pressure gauge see is reading the discharge pressure of the pump. It is not rated for the highest temperatures seen in the look and thus is over 12" from the hot pipe. This should be kept in mind with using V-54.

V-100



Valve V-100 is a manual ball valve set into the concrete containment around the heat exchanger. This valve should be closed any time that cyclopentane is in the loop. Furthermore, this valve should only be opened to drain water that has accumulated in the containment after it is verified that no hydrocarbon has leaked out of the system.

APPENDIX E: Startup Checklist

ORC Startup Check List			
	Rev:	0	
Operator:		Date:	
Device	Tag	Position	Verified
Signs posted on doors to courtyard, nuc lab hall, 154, 134, test cell control room (4-5)	Visual	Test in progress	
Gate to courtyard closed/locked	Visual	Locked	
ESB/MR email informing of testing/TW usage	Visual	Test in progress	
Pump house valves in operational position/signs posted	See photo, Visual	Test in progress	
Leak of cyclopentane from HRVG	Visual	No accumulation in secondary containment – shiny appearance	
HRVG containment valve closed	V-100	Closed/locked	
Leak of cyclopentane from equipment in trailer	Visual	No accumulation in secondary containment, fresh leaks on rags	
Pressure gages (4) on Ar bottles	Visual	Pressure should be 1000-2000psi	
Turn on power to Yokagawa systems/Start program	I-45/I-46	On	
Start LabView - if not already running		On	
Continental valve/Drop 15 open	V-13	Open	
Tower water return/supply-building valves open	V-26/27	Open	
Tower water return isolation open	V-33	Open	
Tower water inlet isolation open	V-32	Open	
Tower water bypass valve closed	V-6	Closed	
Tower water positioner valve open	V-3	Open (50%)	
Reading from water flow meter	I-14	100-200gpm	
Economizer isolation valve open	V-8	Open	
Economizer depressurization valve closed	V-9	Closed	
Superheater isolation valve open	V-15	Open	
Pressure release valve	V-17	Closed	
Review all TC readings	I-XX	Trailer – 7-25°C, ext – 0-25°C	
Review all P readings	I-XX	P_abs 14.7, 43.5 psia; dP = 0	
Review reading on load cells	I-41-I-44	1419 lbs	
Review readings from IR detectors	I-91, I-92	No incidents, responsive	
Review reading from CO, LEL, O2 detectors	I-83-I-90	<500 ppm	

Review reading from Exhaust gas LEL	I-2	<500 ppm	
Signals from three cameras	I-151 – 1-153	Operational, check with operator	
UPC_1 active	E-20	On	
Open pressure tap valves to venturi readings	V-48, V-49	Open	
Close readings valves to other drops (North wall)		Closed	
Current venturi reading	I-1		
All dampers are open		Open	
Ventilation fan is running at 100%	E-8		
Hoffman cooling fan is running		On	

APPENDIX F: Shutdown Checklist

ORC Shutdown Check List			
	Rev:	0	
Operator:		Date:	
Device	**Tag**	**Position**	**Verified**
Gastech Heater	E-2	Off	
Review all TC readings	I-XX	Trailer – 7-25°C, ext – 0-25°C	
Pressure release valve	V-17	Open	
Review all P readings	I-XX	1. P_abs 3 bar, 48 psia; dP = 0 (if temporary shutdown) 2. P_abs 1 bar, 14.7 psia; dP = 0 (if permanent shutdown)	
Circulation Pump	E-7	Off (VFD to zero)	
Continental Compressor	E-1	Off (use compressor shutdown procedure per continental SOP)	
Continental valve/Drop 15 open	V-13	Closed	
Tower water return/supply-building valves open	V-26/27	Closed	
Tower water return isolation open	V-33	Closed	
Tower water inlet isolation open	V-32	Closed	
Tower water bypass valve closed	V-6	Open	
Tower water positioner valve open	V-3	Closed (throttled to 10%)	
Reading from water flow meter	I-14	~ 0 gpm	
Economizer isolation valve open	V-8	Open	
Economizer depressurization valve closed	V-9	Closed	
Superheater isolation valve open	V-15	Open	
Signs posted on doors to courtyard, nuc lab hall, 154, 134, test cell control room (4-5)	Visual	Remove Signs	
Gate to courtyard closed/locked	Visual	OpenGate(Call BSC)	
ESB/MR email informing of testing/TW usage	Visual	Email test stoppage	
Pump house valves in operational position/signs posted	See photo, Visual	Remove Signs	
Leak of cyclopentane from HRVG	Visual	No accumulation in secondary containment – shiny appearance	
HRVG containment valve closed	V-100	Closed/locked	
Leak of cyclopentane from equipment in trailer	Visual	No accumulation in secondary containment, fresh leaks on rags	
Ventilation fan	E-8	maintain operation ~50%	

Appendix F

System Event Response Checklist

#	Stimulus	Primary Indications	Engineer Actions	Technician Actions	System Automatic Response
1	Hard E-stop	E-stop Alarm	1. Identify cause of E-stop, take other action as indicated 2. Notify Tech of cause of E-stop 4. Call BSC with verbal report of the cause of the E-stop 5. As soon as cause of E-stop is corrected, restore control by clearing E-stop	1. Ensure GasTech is stopped by pressing E-stop on GasTech control panel 2. Ensure trailer door is closed 3. Get cause of E-stop from Engineer 4. Take immediate actions for cause of E-stop	1. Send alarm to BSC/operator 2. E-stop gas heater 3. Remove power from circulation pump (E-7) 4. Remove 120 V from trailer (Will cause valves to return to fail safe position – closed) 5. Remove 24 V from trailer (will cause a loss of all indication)
2	Cyclopentane leak/release triggers LEL sensor	LEL Alarm	1. E-stop immediate actions 3. Allow the cyclopentane to cool for ~20 minutes 4. BSC/Fire personnel should arrive in response to LEL alarm 5. Using back pressure regulator outside the trailer, slowly depressurize the cyclopentane loop 6. Allow the LEL alarm to clear before taking any further action	1. E-stop immediate actions 2. Ensure ventilation louvers are open and fan is at 100% 3. Clear courtyard 4. Ensure Continental at full flow to cool down the HX section	1. E-stop 2. Audible LEL alarm 7. Resultant loss of instrumentation signals – LabView will go to E-stop 8. Louvers shall open 9. Ventilation Fan will go to 100% rpm 10. BSC/Fire personnel will arrive
3	UV sensors in trailer trigger Fire System		1. E-stop immediate actions If Cold Side Pressure (I-8) is >100 psi: 2. Open V-17 to dump the Accumulator argon 3. Open V-3 fully If further pressure reduction is needed: 4. Open V-8 or V-15 5. Open V-55 - this will cause V-9 and V-56 to open and further reduce pressure Main Loop Pressure	1. E-stop Immediate Actions 2. Clear the courtyard - if necessary 3. Using back pressure regulator outside the trailer, depressurize the Accumulator pistons (depressurizes the Cold Side Main Loop)	1. Hard E-stop Automatic Actions: • E-stop gas heater • Remove power from circulation pump (E-7) • Remove 120V from trailer (Will cause valves to return to fail safe position – closed [except V-3 is throttled]) • Remove 24 V from trailer • Send notifications to BSC/Operator 2. Resultant loss of instrumentation signals – LabView will go to E-stop 3. Audible horn outside the trailer and flashing light 4. Louvers will close and ventilation fan will turn off. 5. O_2 will start discharging after a 15-second delay.

#	Stimulus	Primary Indications	Engineer Actions	Technician Actions	System Automatic Response
					6. Discharge will be accompanied by a pneumatic horn inside the trailer 7. BSC/Fire personnel will arrive
4	UHC sensor warning/alarm		1. At the warning level of the UHC sensor, monitor the trend closely to determine if it is rising/falling/steady 2. If UHC level continues to rise beyond the alarm level, call BSC and initiate following actions 3. E-stop gas heater 4. Close accumulator pressurization valve (V-5) 5. Cooling water valve (V-3) opened 100% 6. If UHC levels continue to climb or remain above the alarm limit: Open V-55, this will cause V-56 and V-9 to open, dumping the accumulator pressure and decreasing the WF in the main Loop		1. System will indicate warning and alarms levels on the UHC sensor. 2. No additional automatic actions by the system
5	Loss of Controller Power		1. Determine if power loss is limited to the controller 2. Check to make sure GasTech is stopped 3. Ensure cooling water valves are open and continental compressor continues to run		1. Hard E-stop Automatic Actions * E-stop gas heater * Remove power from circulation pump (E-7) * Remove 120V from trailer (Will cause valves to return to fail safe position – closed [except V-3 is throttled]) * Remove 24V from trailer * Send notifications to BSC/Operator
6	Loss of Control Computer		1. E-stop the GasTech Heater at the panel 2. Restart the computer and LabView VI	1. E-stop the GasTech Heater at the panel	1. System will continue to run as-is if only the controls computer is affected 2. Upon restoration of computer (reboot or otherwise) the system will default to the E-stop state

#	Stimulus	Primary Indications	Engineer Actions	Technician Actions	System Automatic Response
7	Loss of Site Power		1. Carry out actions for Hard E-stop	1. Carry out immediate actions for Hard E-stop 2. Keep personnel clear of courtyard until power is restored	1. In case of total power loss, all systems will shut down 2. LabView computer is on UPS and will continue to run 3. LabView will go to E-stop state (loss of NI health bit) 4. System may start to vent cyclopentane through the relief valves due to overpressure in the loop
8	Loss of Trailer Power		1. Carry out actions for Hard E-stop 2. As soon as possible, open V-8 or V-15	1. E-stop GasTech at panel	1. Hard E-stop Automatic Actions * E-stop gas heater * Remove power from circulation pump (E-7) * Remove 120 V from trailer (Will cause valves to return to fail safe position – closed [except V-3 is throttled]) * Remove 24 V from trailer * Send notifications to BSC/Operator
9	Loss of Cooling Water/ Insufficient Cooling Water		1. Immediately upon loss in CW flow (or low CW flow) turn off the GasTech heater. 2. Run compressor at maximum flow to cool the system down.		1. Condenser temperature (I-20) will rise and pump may start to cavitate (loss of circulation flow). This may quickly exacerbate the problem. 2. System will warn the operator when temp limit on condenser is exceeded 3. System will not initiate any automatic response 4. If problem goes unchecked, cyclopentane volume will expand to fill the accumulator and safety valves will start to vent
10	Leak of Cyclopentane Outside the trailer (no LEL detected)		Small Leak (e.g., drip from a flange) 1. E-stop GasTech heater 2. Capture the leak using chemsorb powder or a pig mat 3. Allow the system to cool down 4. Using back pressure regulator outside the trailer, slowly depressurize the cyclopentane loop 5. Now address the source of the leak (tighten flange, etc.) Large Cyclopentane Leak/Spray 1. Call/Alarm BSC 2. E-stop GasTech heater		1. No response from system if LEL is not detected

#	Stimulus	Primary Indications	Engineer Actions	Technician Actions	System Automatic Response
			3. Clear Courtyard (if applicable) 4. Close V-5 (accumulator pressurization valve) 5. Open V-17 between 1% and 10% to slowly release pressure from accumulator 6. Standby for BSC response		
11	Leak of Cyclopentane into concrete containment (no LEL detected)		Small Leak (e.g., drip from a flange) 1. E-stop GasTech heater 2. Capture the leak using chemsorb powder or a pig mat 3. Allow the system to cool down 4. Using back pressure regulator outside the trailer, slowly depressurize the cyclopentane loop 5. Now address the source of the leak (tighten flange etc.) Large Cyclopentane Leak/Spray 1. Call/Alarm BSC 2. E-stop GasTech heater 3. Ensure drain valve on concrete containment is closed 4. Clear Courtyard (if applicable) 5. Close V-5 (accumulator pressurization valve) 6. Open V-17 between 1% and 10% to slowly release pressure from accumulator 7. Standby for BSC response		1. No response from system if LEL is not detected

#	Stimulus	Primary Indications	Engineer Actions	Technician Actions	System Automatic Response
12	Leak of cyclopentane into Trailer	**<u>Warning LEL (10% < LEL < 25%)</u>**	1. Monitor level and trend carefully. If rising, a. Stop the GasTech heater b. Close V-5 (accumulator pressurization valve) c. Slowly remove pressure from the accumulator using the back pressure regulator outside the trailer	1. Stop GasTech Heater if directed 2. Depressurize accumulators through V-47, if directed	1. TGMS system will detect concentrations and respond as follows: 2. When 10% < LEL < 25% - Warning level: a. Send alarm to operator b. Louvers will fully open c. Ventilation Fan will operate at full flow
		<u>Alarm LEL (LEL ≥ 25%)</u>	1. Carry out Immediate Actions for Hard E-stop	1. Slowly remove pressure from the accumulator using the back pressure regulator outside the trailer. 2. Clear the Courtyard (if applicable)	3. When LEL ≥ 25% - alarm level: System Initiates a Hard E-stop: * E-stop gas heater * Remove power from circulation pump (E-7) * Remove 120 V from trailer (Will cause valves to return to fail safe position – closed [except V-3 is throttled]) * Remove 24 V from trailer * Send notifications to BSC/Operator c. Louvers will fully open d. Ventilation Fan will operate at full flow. g. Accumulator pressurization valve (V-5) fails closed; Accumulator depressurization valve (V-17) fails closed
13	Loss of Cyclopentane circulation pump		1. Upon loss of circulation pump, immediately E-stop GasTech heater 2. Verify GasTech Heater is shut down by a decreasing trend on I-3 3. Shut V-5 3. Fully open V-3	1. E-stop GasTech Heater 2. Depressurize accumulators through V-47	1. System will provide warning when flow meter reading goes outside of user defined limits 2. No Further action from the system
14	Loss of compressor air flow		1. Maintain CW flow rate and allow the system to cool	1. Verify GasTech heater is stopped	1. GasTech heater will stop automatically
15	Loss of house air pressure		1. Continue to run circulation pump – but watch the coriolis flow meter for any sign of cavitation 2. If pump cavitation occurs, turn off circulation pump 3. Continue to run the compressor and allow the system to cool.		1. GasTech heater fuel control valves will shut – GasTech heater will stop 2. V26 and V27, the CW control valves will close resulting in loss of cooling water

#	Stimulus	Primary Indications	Engineer Actions	Technician Actions	System Automatic Response
16	Loss of Accumulator argon/ nitrogen	Unable to maintain pressure	1. Shut V-47 and V-5 to prevent further Ar loss, (locks Ar bubble on top of Accumulator pistons) 2. Conduct a normal shutdown 3. Carefully monitor system pressures (I-8 and I-9); if depressurization rate is too high, then slow the down-ramp on the GasTech heater 4. Monitor Circ Pump for cavitation. Slow flow rate as necessary to correct cavitation.		1. Slow fall in system pressure and loss in ability to build pressure 2. Accumulator pressure I-10 will be in a warning state 3. Condenser may not be able to condense all the cyclopentane – resulting in pump cavitation
17	HX tube wall temperature high (>**260**C)		1. Verify HX Exit Temp (I-16) and Condenser Inlet Temp (I-17); if within limits, continue operation 2. If either is out of limits, bring I-16 into limits by: a. Reduce compressor flow rate and/or b. Reduce the temperature setting at the GasTech heater	1. System will provide warning based on user defined temperature limits	
18	System High Pressure (>36 bar		1. Shut down gas tech heater 2. Turn compressor flow rate to max 3. Turn cooling water flow rate to max 4. Close V-5 (accumulator pressure control valve) 5. Open V-17 between 1% and 5% to slowly remove pressure from the accumulator		1. System will provide warning based on user-defined pressure limits 2. System will start to vent if pressure exceeds 38 bar
19	Loss of Indication: Main Loop Flow Meter (I-76)		1. Maintain the following parameters constant: a. GasTech temperature setting. b. All system flows (Main, CW, CA) 2. Maintain pressure control in automatic 3. Check Circ Pump suction and discharge pressures normal		None

#	Stimulus	Primary Indications	Engineer Actions	Technician Actions	System Automatic Response
20	Loss of critical instrumentation reading(s)		1. Loss of the following instrument readings is critical to the experiment: c. Condenser downstream temperature, I-20 d. Superheater exit temperature, I-16 e. Accumulator pressure, I-10 2. Shift to Manual Control 3. Conduct a Normal Shutdown		1. System will provide warning when instrumentation reading goes outside of user defined limits 2. No further action from system unless the faulty instrument corresponds to an E-stop trigger
21	Loss of All Liquid Leg Pressure Indication (I-8 and I-9)		1. Verify Vapor Leg pressure indication stable and normal (I-15) 2. Maintain all flows constant (Main, CW and CA) 3. Consider conducting a normal controlled shutdown. If continued operation is indicated, use Circ Pump suction pressure (I-95) as alternate pressure indication.		None

INTENTIONALLY BLANK

Appendix G

Trailer Entry Procedure

ORC Direct Evaporator Trailer Entry Protocol 11

This Protocol is disestablished. Refer to the controlled document below:

ORC Trailer Entry Checklist

	Case 1	Case 2	Case 3	Case 4
System Pressure (I-8 or I-9) psia	> 75 or	> 75 or	< 75 and	< 75 and
System Temperature (I-16, 16B, 17) degrees C	> 40	> 40	< 40	< 40
Working Fluid	Water	Cyclopentane	Any liquid	Any liquid
Initial entry after Operation (> 75 psia or > 40 C)	NA	NA	Yes	No
Daily Shutdown Check	No	No	No	Yes

Cyclepentane Short-Term Entry Checklist (FSS Active)

Operator:	Date:					
Note 1: Vent fan at 75% <u>or</u> (LEL 275ppm, CO < 12.5ppm, O2 Indicator - Green)	Time:					
		Position/Reading (circle case)				Verified by
Device	Tag	Case 1	Case 2	Case 3	Case 4	
Review cameras for unusual cues	I-151-153	Stable	Stable	NR	NR	
Ventilation fan is running at 75%	E-8	>75%	>75%	Note 1	Note 1	
LEL indicators (ppm)	I-83-I-86	< 275	< 275			
CO detector is below trouble levels (**12.5**ppm)	I-87					
O2 indicator	I-88	Green	Green			
Circulation pump	E-7	N/A	N/A	Off/Stopped	Off/Stopped	
GasTech heater	NA	T<200C	T<200C	Off	Off	
Headset on and working	NA	On	On	NR	NR	
Fire suppresion system is <u>active.</u>	V-40	Closed/Locked	Open	Closed/Locked	Closed/Locked	
Closed Door Initial Ventilation Conducted	NA	2 min.	2 min.	2 min.	2 min.	
Trailer door open	NA	Open	Open	NR	NR	
Safety Observer Outside Trailer Door	NA	NR	Stationed	NR	NR	

NR = Not Required NA = Not Applicable

INTENTIONALLY BLANK

Appendix H

Draining of HX and Piping

Procedure for Draining ORC Loop

				Start	Check	Finish	Check
V	3	TW control valve	Electric positioner valve	Closed		Closed	
V	5	Ar pressure solenoid	Ball valve w/ solenoid	Open		Open	
V	6	TW bypass valve	Manual valve	Open		Open	
V	8	Econ. Iso valve	Ball valve w/ solenoid	Open		Open	
V	9	Econ. Drain	Ball valve w/ solenoid	Closed		Closed	
V	13	Cont. air flow	Electric valve	Closed		Closed	
V	15	Iso-hot; solenoid	Ball valve w/ solenoid	Open		Open	
V	17	Depress positioner	Plug and stem w/ positioner	Open		Open	
V	20	Fill valve - low point	Manual ball valve	Closed		Closed	
V	21	High P; sampling	Manual ball valve	Closed		Closed	
V	22	Noncondensable vent/sampling valve	Manual ball valve	Closed		Closed	
V	23	Vent valve - high point	Manual ball valve	Closed		Closed	
V	24	Depress. drain	Manual ball valve	Closed		Closed	
V	26	TW inlet	Electrical control valve	Open		Open	
V	27	TW return valve	Elect act valve	Open		Open	
V	28	Argon regulator	Manual gas regulator	Closed		Closed	
V	32	Trailer - TW inlet iso	Manual butterfly valve	Closed		Closed	
V	33	Trailer - TW exit iso	Manual butterfly valve	Closed		Closed	
V	35	Pump filter inlet - BV	Manual ball valve	Open		Open	
V	36	Pump filter exit - BV	Manual ball valve	Open		Open	
V	37	Filter bypass	Manual ball valve	Open		Open	
V	38	TW condenser line drain	Manual ball valve	Closed		Closed	
V	39	Vent of int. heater	Manual ball valve	Closed		Closed	
V	40	CO_2 system lock-out valve	Manual ball valve	LOTO		LOTO	
V	41	Vacuum inlet valve	Inlet isolation valve	Closed		Closed	
V	42	House N_2 inlet	Manual ball valve	Closed		Closed	
V	43	House N_2 to equipment	Manual ball valve	Closed		Closed	
V	44	Y-strainer inlet	PVC Manual ball valve	Open		Open	
V	45	Y-strainer exit	PVC Manual ball valve	Open		Open	
V	46	Transfer hose valve	Manual ball valve	Closed		Closed	

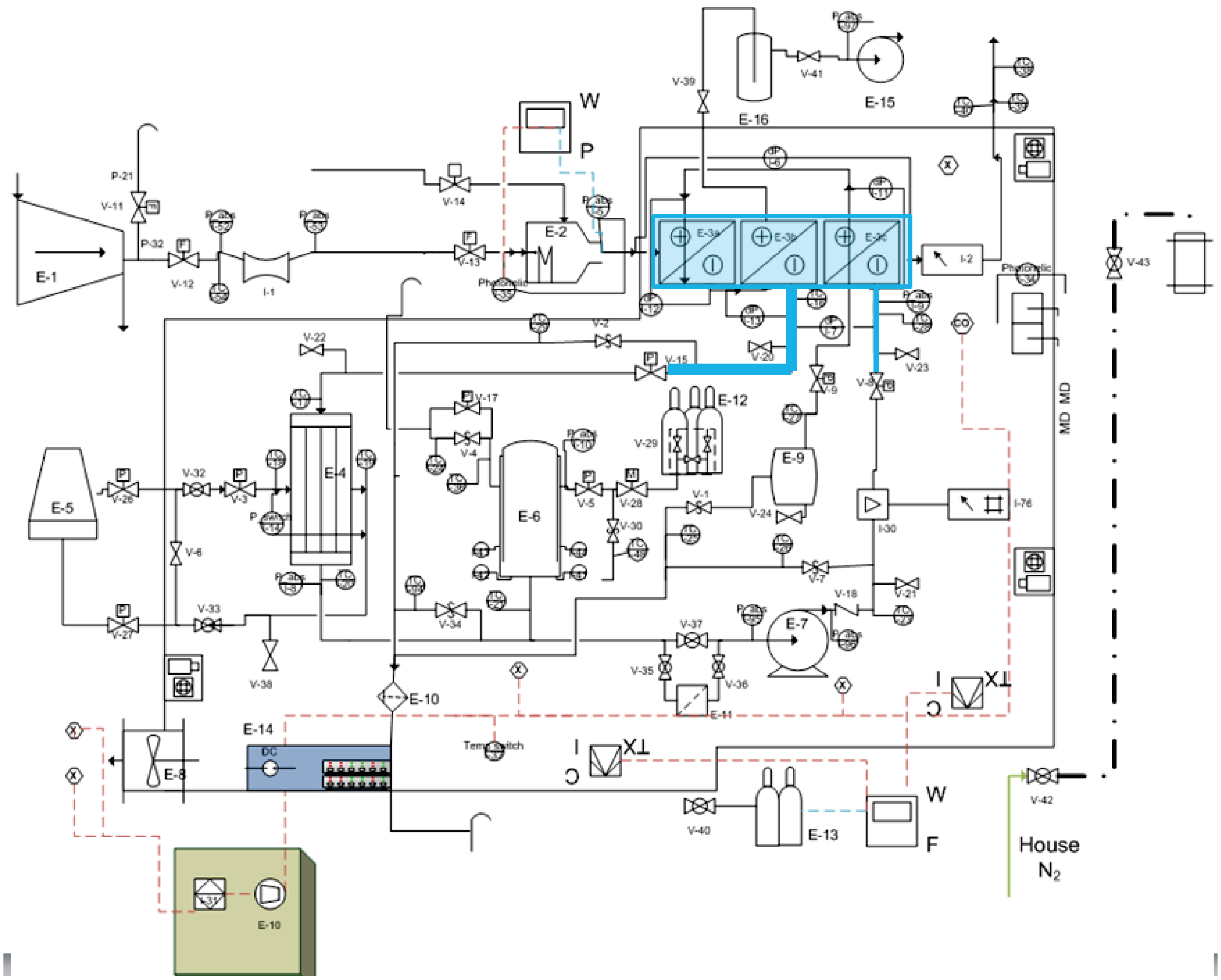


Figure H-1. Draining procedure.

Procedure for Draining ORC Loop 1 and 2

1. Check status of all valves (see list above); ensure that V-8 and V-15 are open using the controls computer in ES 154.
2. Connect the drain hose to manual ball valve V-20 and run to a waste disposal barrel located in a plastic containment dike.
3. Ground the drain hose, the plastic waste barrels, and the containment.
4. Ensure the operator is wearing appropriate flame-resistant personal protective equipment.
5. Set the nitrogen pressure regulator in ES 154 to 15 psig.
6. Open V-42.
7. Connect the 1/4-in. house N_2 line from V-42 on the wall of the trailer to the 1/2-in. vent valve upstream of the pump.
8. Alternately, connect the nitrogen line to valve V-39 (top of HX).
9. Open the vent valve (and/or V-39).
10. Open V-20.

11. Drain the fluid from the loop until nitrogen gas is heard exiting the loop through valve V-20.
12. While the cyclopentane is draining, pressurize the top of the pistons in the accumulator to ensure they are "bottomed out."
13. Place a catch pan under the HX and open the ports at the base of the HX one at a time to drain the fluid from the pipes.
14. Close each port after fluid no long drains from the system.
15. Continue to run N_2 through the piping for 24 hours to dry the piping.
16. While nitrogen is running through the system, start the GasTech heater at a temperature of 100°F and continue to run heated for 24 hours.
17. Shutdown the GasTech heater following the standard operating procedure.
18. Close V-20 and then V-23, trapping nitrogen in the cyclopentane line.
19. Disconnect the drain hose from V-20.
20. Connect the drain hose to manual ball valve V-19 and run out through the door to a waste disposal barrel located outside of the trailer and in a plastic containment dike.
21. Ground the drain hose, the plastic waste barrels, and the containment.
22. Ensure the operator is wearing appropriate flame-resistant personal protective equipment.
23. Open V-23.

INTENTIONALLY BLANK

Appendix I

Hot Sample Collection Procedure

Online Sampling Protocol

				Start	Check	Finish	Check
V	3	TW control valve	Electric positioner valve	Open		Open	
V	5	Ar pressure solenoid	Ball valve w/ solenoid	Open		Open	
V	6	TW bypass valve	Manual valve	Closed		Closed	
V	8	Econ. Iso valve	Ball valve w/ solenoid	Open		Open	
V	9	Econ. Drain	Ball valve w/ solenoid	Closed		Closed	
V	13	Cont. air flow	Electric valve	Open		Open	
V	15	Iso-hot; solenoid	Ball valve w/ solenoid	Open		Open	
V	17	Depress positioner	Plug and stem w/ positioner	Closed		Closed	
V	20	Fill valve - low point	Manual ball valve	Closed		Closed	
V	21	High P; sampling	Manual ball valve	Closed		Closed	
V	22	Noncondensable vent/sampling valve	Manual ball valve	Closed		Closed	
V	23	Vent valve - high point	Manual ball valve	Closed		Closed	
V	24	Depress. drain	Manual ball valve	Closed		Closed	
V	26	TW inlet	Electrical control valve	Open		Open	
V	27	TW return valve	Elect act valve	Open		Open	
V	28	Argon regulator	Manual gas regulator	Closed		Closed	
V	32	Trailer - TW inlet iso	Manual butterfly valve	Open		Open	
V	33	Trailer - TW exit iso	Manual butterfly valve	Open		Open	
V	35	Pump filter inlet - BV	Manual ball valve	N/A		N/A	
V	36	Pump filter exit - BV	Manual ball valve	N/A		N/A	
V	37	Filter bypass	Manual ball valve	Closed		Closed	
V	38	TW condenser line drain	Manual ball valve	Closed		Closed	
V	39	Vent of int. heater	Manual ball valve	Closed		Closed	
V	40	CO_2 system lock-out valve	Manual ball valve	LOTO		LOTO	
V	41	Vacuum inlet valve	Inlet isolation valve	Closed		Closed	
V	42	House N_2 inlet	Manual ball valve	Closed		Closed	
V	43	House N_2 to equipment	Manual ball valve	Closed		Closed	
V	44	Y-strainer inlet	PVC Manual ball valve	N/A		N/A	
V	45	Y-strainer exit	PVC Manual ball valve	N/A		N/A	
V	46	Transfer hose valve	Manual ball valve	Closed		Closed	

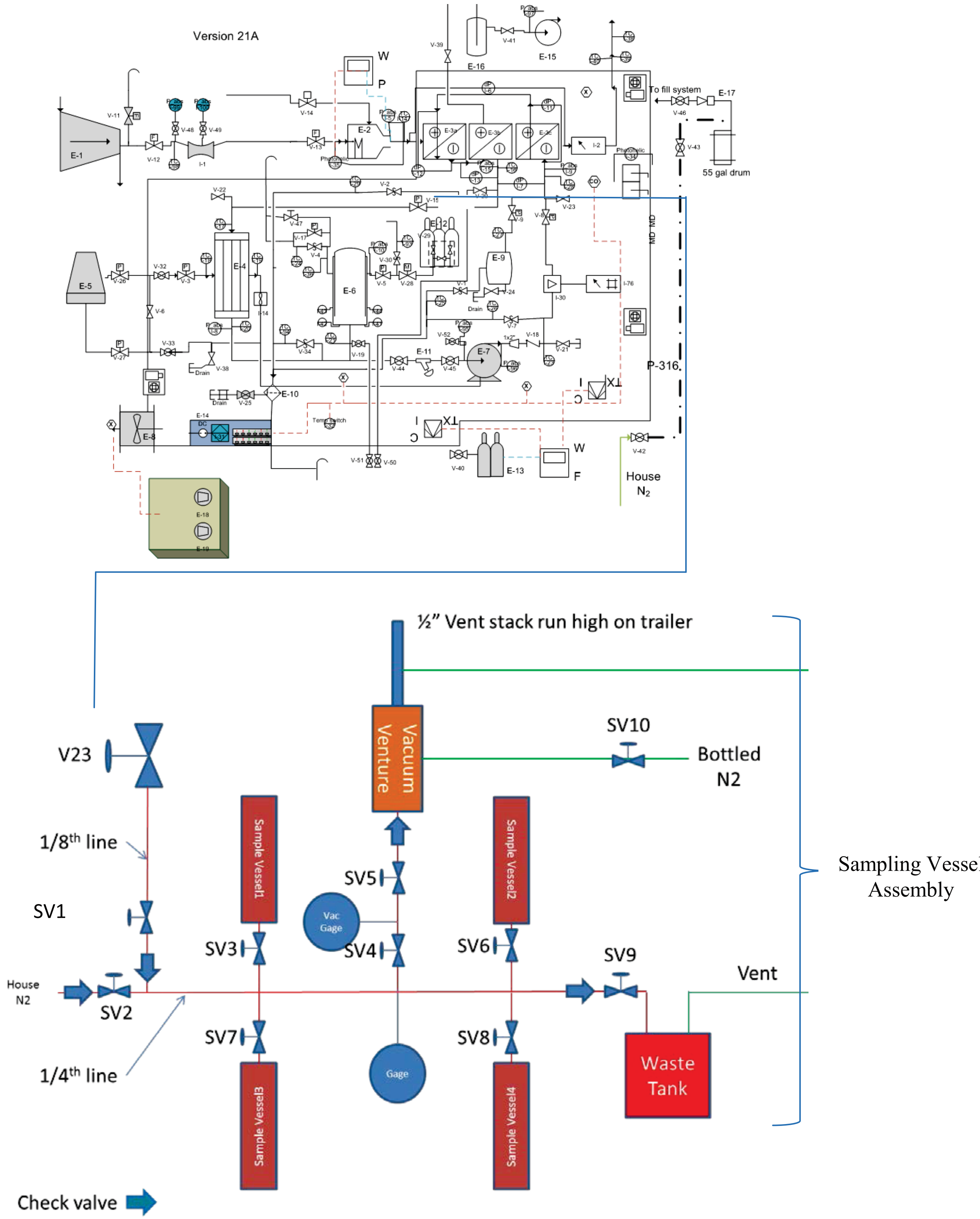


Figure I-1. Sample collection schematic.

The sampling vessel assembly is permanently attached to the outside of the trailer at the north facing wall. A 1/8-in. stainless line is run from V-23 (vent valve at the top of the scaffolding) down to the sampling vessel assembly. The advantage of this arrangement is that it is outside; therefore, any small amount of cyclopentane vapor vented from this setup will diffuse into the ambient air very easily.

1. Ensure operators are wearing appropriate safety gear (i.e., nitrile gloves, safety glasses, and flame-resistant clothing).
2. Open SV and SV3 to SV8. Then open SV10 to allow the vacuum venturi to evacuate the sampling system, lines, and vessels. Leave for 5 to 7 minutes.
3. Close SV5 and then close SV10.
4. Now open SV2 and allow house nitrogen to flood the sampling system, lines, and vessels.
5. Close SV2 after about1 minute.
6. Repeat Steps 2 through 5 three times to completely purge the sampling system of any air. The system should be in a state of vacuum after the final purge.
7. Now close SV1 and SV3 to SV8.
8. Slowly open V23, crack open SV1, and allow the sampling lines to fill with working fluid (cyclopentane). Crack open SV9 for about 10 seconds to allow an initial "stagnant" sample of working fluid to flow into the vented waste tank.
9. Close SV9 and open SV3 for about 10 seconds to fill the first sample vessel.
10. Close SV3 and then close V23. Now crack open SV9 to vent the residual working fluid into the vented waste tank.
11. Close SV9, open SV10 to activate the venturi, and then open SV4 and SV5 to remove any residual working fluid from the sampling assembly.
12. Steps 2 through 5 may be repeated at this point to ensure all the working fluid is removed from the sampling system.
13. Detach the first sampling vessel upstream of SV3 and send for analysis.
14. Replace the sampling vessel and valve if needed or cap the system at this point.
15. The system should be left with a blanket of house nitrogen until it is time for the next sample to be taken.
16. Sampling intervals are shown as follows:
    a. Take t = 0 sample
    b. Take samples at t = 5 hour, 10 hour, 30 hour, 150 hour, 300 hour, 310 hour (overtemp), and 320 hour (overtemp).

INTENTIONALLY BLANK

Appendix J

Inert Gas Purge Protocol

Inert Purge Protocol-Ver1

				Start	Check	Finish	Check
V	3	TW control valve	Electric positioner valve	Closed		Closed	
V	5	Ar pressure solenoid	Ball valve w/ solenoid	Closed		Closed	
V	6	TW bypass valve	Manual valve	Open		Open	
V	8	Econ. Iso valve	Ball valve w/ solenoid	Closed		Open	
V	9	Econ. Drain	Ball valve w/ solenoid	Closed		Closed	
V	13	Cont. air flow	Electric valve	Closed		Closed	
V	15	Iso-hot; solenoid	Ball valve w/ solenoid	Closed		Open	
V	17	Depress positioned	Plug and stem w/ positioner	Closed		Closed	
V	19	Accumulator low point	Manual ball valve	Closed		Closed	
V	20	Fill valve - low point	Manual ball valve	Closed		Closed	
V	21	High P; sampling	Manual ball valve	Closed		Closed	
V	22	Noncondensable vent/sampling valve	Manual ball valve	Closed		Closed	
V	23	Vent valve - high point	Manual ball valve	Closed		Closed	
V	24	Separator drain	Manual ball valve	Closed		Closed	
V	25	Depress. Drain	Manual ball valve	Closed		Closed	
V	26	TW inlet	Electrical control valve	Open		Closed	
V	27	TW return	Elect act valve	Closed		Closed	
V	28	Argon regulator	Manual gas regulator	Closed		Closed	
V	32	Trailer - TW inlet iso	Manual butterfly valve	Closed		Closed	
V	33	Trailer - TW exit iso	Manual butterfly valve	Closed		Closed	
V	38	TW condenser line drain	Manual ball valve	Closed		Closed	
V	39	Vent off int. header	Manual ball valve	Closed		Closed	
V	40	CO_2 system lock-out valve	Manual ball valve	LOTO		LOTO	
V	41	Vacuum inlet valve	Inlet isolation valve	Closed		Closed	
V	42	House N_2 inlet	Manual ball valve	Closed		Closed	
V	43	House N_2 to equipment	Manual ball valve	Closed		Closed	
V	44	Y-strainer inlet	PVC Manual ball valve	Open/Rem		Open/Rem	
V	45	Y-strainer exit	PVC Manual ball valve	Open/Rem		Open/Rem	
V	46	Transfer hose valve	Manual ball valve	Closed		Closed	
V	50	Fill/drain hex extension	Manual ball valve	Closed		Closed	
V	51	Fill/drain piping extension	Manual ball valve	Closed		Closed	
V	52	Pump-low vent	Manual ball valve	Closed		Closed	

Procedures for Inert Gas Purge

LabView software should be running continuously and the ventilation fan set to 75%. If you need to restart the LabView software, turn the fan to "Purge" on the Hoffman panel to avoid losing power to the trailer.

NOTE: *This procedure is for filling the loop with an inert gas, not for flowing an inert gas through the piping. Consult the heated dry down procedure.*

All valves listed above refer to the numbers assigned for the ORC test; separator valve numbers have been assigned for the Continental valves. It should be noted that V-13, according to the ORC test, is labeled as V-15, associated with Drop15 for the Continental control.

1. Send e-mail to the team providing notification of the test plan.
2. Start the Yokagawa software and verify that all the instruments are reading as expected.
3. Check status of all valves (see list above).
4. Open V-8 and V-15 from the "Test" VI of the LabView controller.
5. Connect house N_2 at V-43 to V-50/V-51, depending on whether you want to fill the loop through the HX or through the piping with a 1/4-in. flexible hose connected to the nitrogen on the outside of the trailer's south wall.
6. Open V-20 or V-19, depending on if you are filling from V-50 or V-51, respectively.
7. Set the regulator in the nitrogen line to 40 psi.
8. Open V-50 or V-51 to let N_2 flow into the test loop.
9. Allow system to fill with N_2 until the I-95 and I-96 pressure gauges on the low and high sides of the pump read 40 psi.
10. Close V-19 or V-20.
11. Turn off the N_2 by reducing the regulator to zero and relieving the pressure in the line.
12. Close V-43 on the wall of the trailer.
13. Disconnect the flexible hose running between V-43 and V- 50/V-51. Note that a small amount of N_2 may be released from the hose.
14. Store the hose in the trailer below the fan.

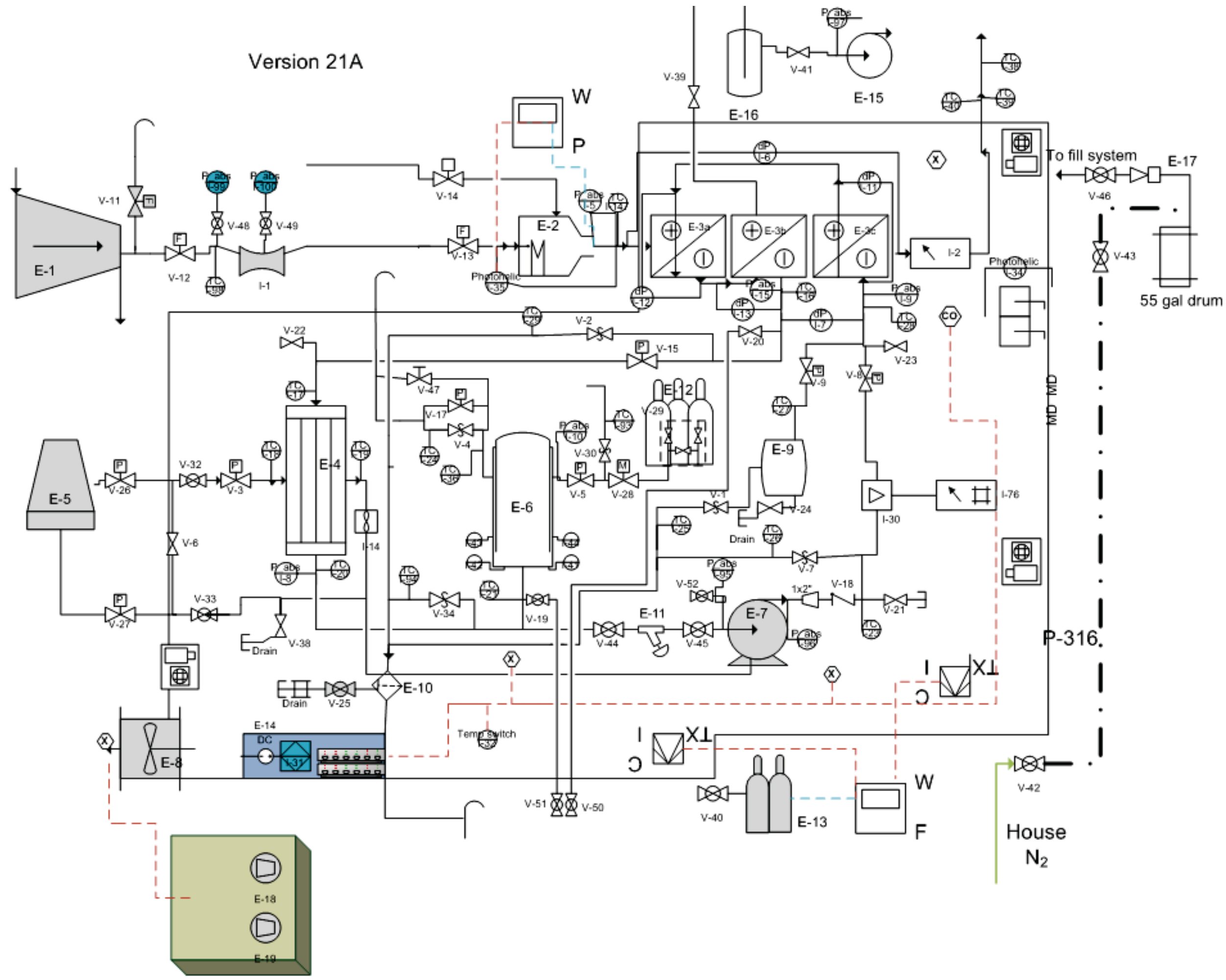


Figure J-1. Piping and instrumentation diagram of the loop showing valve locations.

Protocol was prepared by Jennifer Jackson ________________________________ 5-18-2012

Reviewed and approved by:

Marty Samuels ____ Date: _________

Matthew Boespflug ______________________________________ Date: _________

____ Date: _________

____ Date: _________

____ Date: _________

INTENTIONALLY BLANK

Appendix K

Heated Drying Protocol

Procedure for Drying Carbon Steel Loop-Ver1

				Start	Check	Finish	Check
V	3	TW control valve	Electric positioner valve	Closed		Closed	
V	5	Ar pressure solenoid	Ball valve w/ solenoid	Closed		Closed	
V	6	TW bypass valve	Manual valve	Open		Open	
V	8	Econ. Iso valve	Ball valve w/ solenoid	Closed		Open	
V	9	Econ. Drain	Ball valve w/ solenoid	Open		Closed	
V	13	Cont. air flow	Electric valve	Closed		Closed	
V	15	Iso-hot; solenoid	Ball valve w/ solenoid	Closed		Open	
V	17	Depress positioner	Plug and stem w/ positioner	Closed		Closed	
V	19	Accumulator low point	Manual ball valve	Closed		Closed	
V	20	Fill valve - low point	Manual ball valve	Closed		Closed	
V	21	High P; sampling	Manual ball valve	Closed		Closed	
V	22	Noncondensable vent/sampling valve	Manual ball valve	Closed		Closed	
V	23	Vent valve - high point	Manual ball valve	Closed		Closed	
V	24	Separator drain	Manual ball valve	Closed		Closed	
V	25	Depress. drain	Manual ball valve	Closed		Closed	
V	26	TW inlet	Electrical control valve	Open		Open	
V	27	TW return	Elect act valve	Open		Open	
V	28	Argon regulator	Manual gas regulator	Closed		Closed	
V	32	Trailer - TW inlet iso	Manual butterfly valve	Closed		Closed	
V	33	Trailer - TW exit iso	Manual butterfly valve	Open		Open	
V	38	TW condenser line drain	Manual ball valve	Closed		Closed	
V	39	Vent off int. header	Manual ball valve	Closed		Closed	
V	40	CO_2 system lock-out valve	Manual ball valve	LOTO		LOTO	
V	41	Vacuum inlet valve	Inlet isolation valve	Closed		Closed	
V	42	House N_2 inlet	Manual ball valve	Closed		Closed	
V	43	House N_2 to equipment	Manual ball valve	Closed		Closed	
V	44	Y-strainer inlet	PVC Manual ball valve	Open/Rem		Open/Rem	
V	45	Y-strainer exit	PVC Manual ball valve	Open		Open	
V	46	Transfer hose valve	Manual ball valve	Closed		Closed	
V	50	Fill/drain hex extension	Manual ball valve	Closed		Closed	
V	51	Fill/drain piping exten.	Manual ball valve	Closed		Closed	
V	52	Pump – low vent	Manual ball valve	Closed		Closed	

Procedure for Drying CS Loop

LabView software should be running continuously and the ventilation fan set to 75%. If you need to restart the LabView software, turn the fan to “Purge” on the Hoffman panel to avoid losing power to the trailer.

This procedure can be used to run a nitrogen or air purge through the cyclopentane piping by skipping Steps 12 and 13.

All valves listed above refer to the numbers assigned for the ORC test; separator valve numbers have been assigned for the Continental valves. It should be noted that V-13, according to the ORC test, is labeled as V-15, associated with Drop15 for the Continental control.

1. Send an e-mail to the team providing notification of the test plans.
2. Start the Yokagawa software and verify that all the instruments are reading as expected.
3. Check status of all valves (see list above).
4. Place the tower water loop on bypass (open the bypass valve) and open V-26, V-27, and V-33.
5. Connect V-21 to V-52 using a heat-resistant flexible hose. This will bypass the check valve after the pump.
6. Open V-8 and V-9 from the “Test” VI of the LabView controller.
7. Connect house N_2 at V-43 to V-50 to fill the loop through the HX or through the piping with a 1/4–in. flexible hose connected to the nitrogen on the outside of the trailer’s south wall.
8. Open V-20.
9. Connect a temperature-resistant flexible hose to V-22 at the high side of the condenser, and run the hose out of the trailer through the hole at the west end of the north wall.
10. Open V-43.
11. Set the regulator in the nitrogen line to 40 psi.
12. Open V-50 to let N_2 flow into the test loop; reduce the pressure until there is flow of gas from the hose exiting the trailer.
13. Allow nitrogen to run through the piping for 10 minutes.
14. While nitrogen is running through the system, start the Continental compressor and the GasTech heater at a temperature of 250°F and continue to run heated for 8 hours.
15. Shutdown the GasTech heater following the standard operating procedure and allow the Continental to continue to run for an additional 10 minutes.
16. Close V-22 then V-20, trapping nitrogen in the cyclopentane line.
17. Repeat Steps 3 through 9 for several days to ensure the piping is dry.
18. Turn off the N_2 by reducing the regulator to zero and relieving the pressure in the line.
19. Close V-43 on the wall of the trailer.
20. Disconnect the flexible hose running between V-43 and V-50. Note that a small amount of N_2 may be released from the hose.
21. Store the hose in the trailer below the fan.

NOTE: *The system will be under low pressure and filled with nitrogen.*

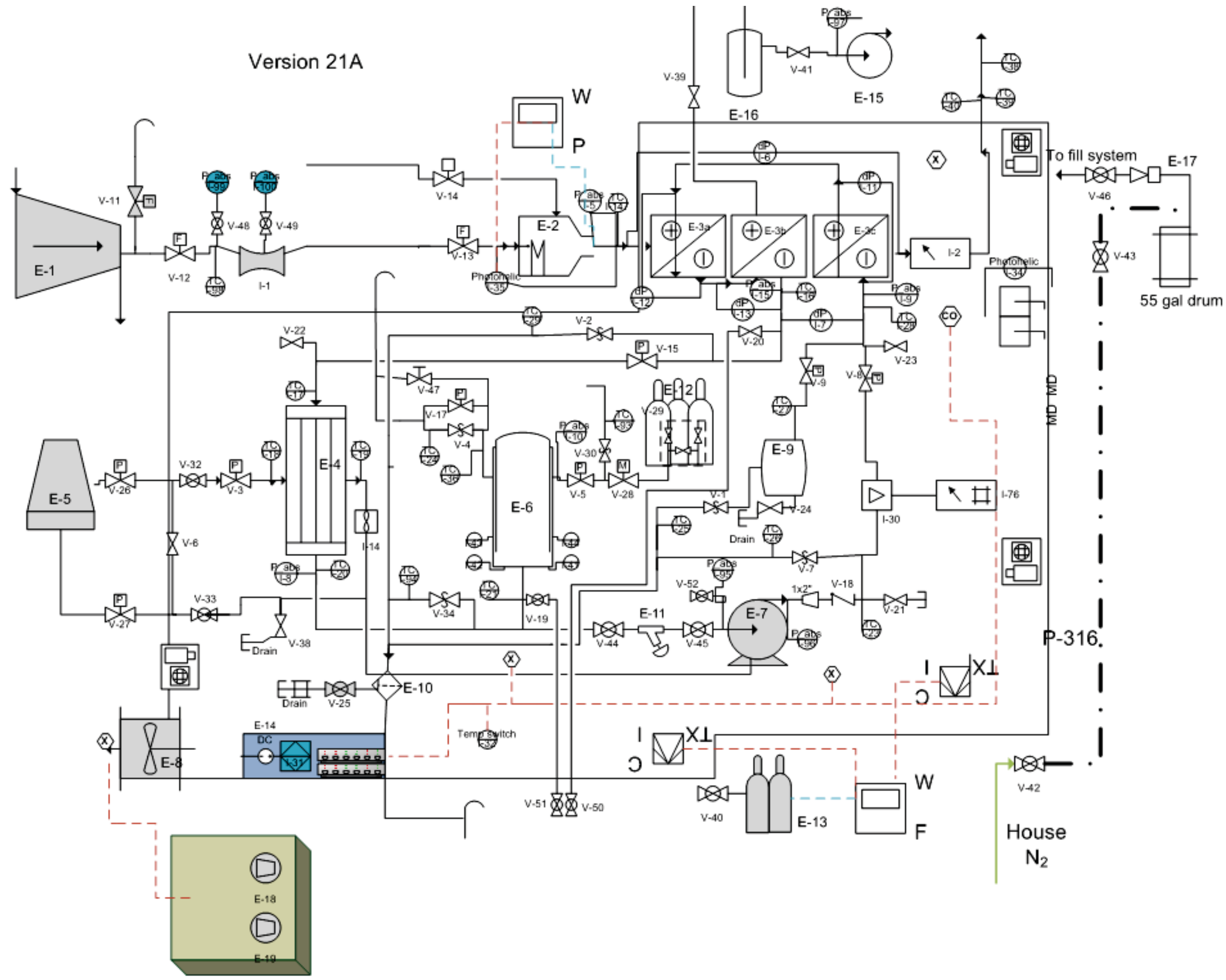


Figure K-1. Piping and instrumentation diagram of loop showing valve locations.

Protocol was prepared by Jennifer Jackson ____ 5-18-2012

Reviewed and approved by:

Marty Samuels ____ Date: __________

Matthew Boespflug ____ Date: __________

____ Date: __________

____ Date: __________

____ Date: __________

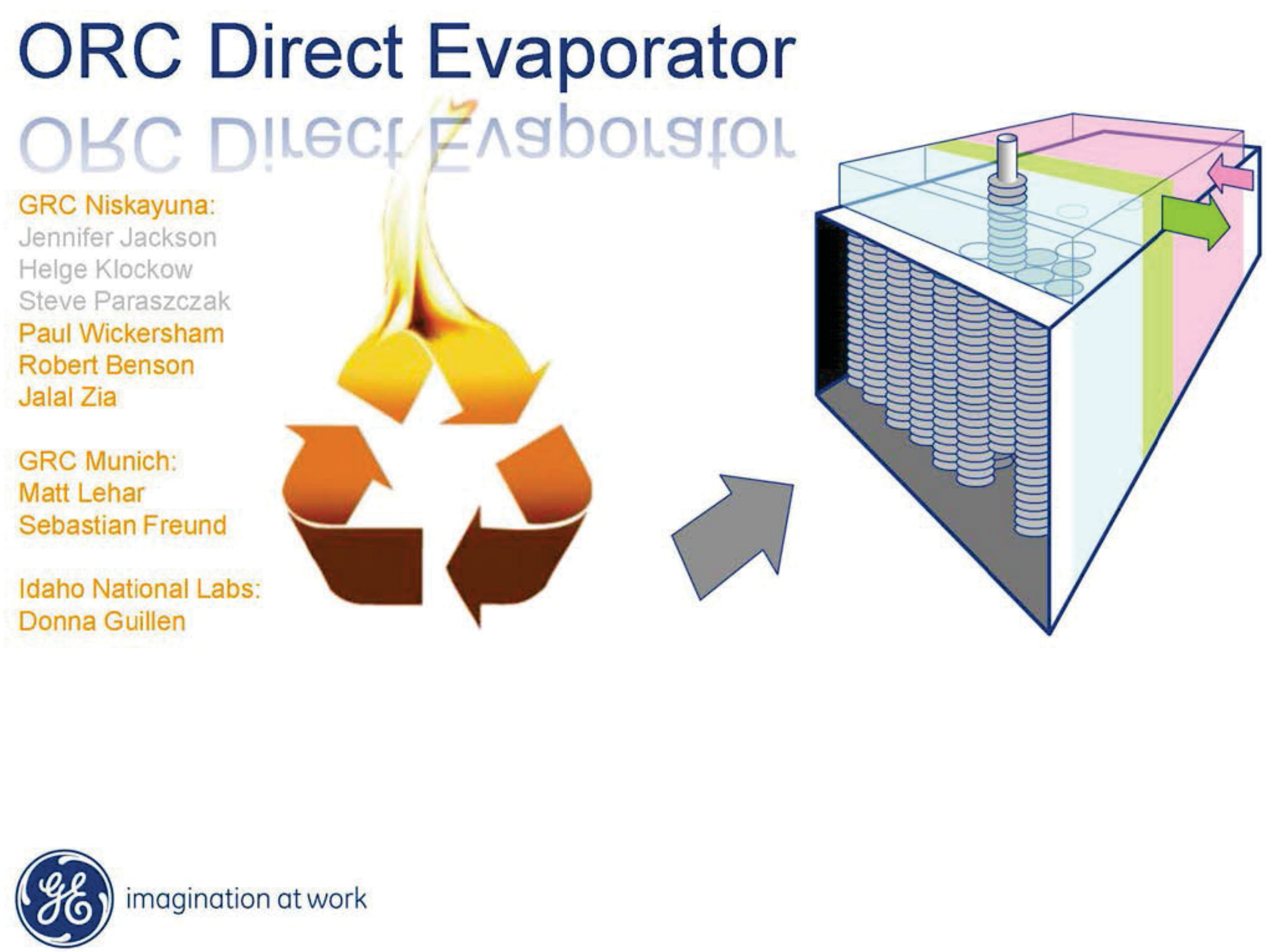
System Startup Checklist

Operator: ______________________________ Date: ____________

Device	Tag	Position	Verified
Signs posted on doors to courtyard - hallway	Visual	Test in progress	
Gate to courtyard closed/locked	Visual	Test in progress	
ESB/MR email informing of testing/TW usage	Visual	Test in progress	
Leak of cyclopentane from HRVG	Visual	No accumulation in secondary containment	
Leak of cyclopentane from equipment in trailer	Visual	No accumulation in secondary containment	
Pressure gages (4) on Ar bottles	Visual	Pressure should be 900-2000 psi	
Continental valve open	V-13	Open	
Economizer isolation valve open	V-8	Open	
Economizer depressurization valve closed	V-9	Closed	
Superheater isolation valve open	V-15	Open	
Tower water return isolation open	V-33	Open	
Tower water inlet isolation open	V-32	Open	
Tower water bypass valve closed	V-6	Closed	
Tower water return-building valve open	V-27	Open	
Tower water inlet building valve open	V-26	Open	
Turn on power to Yokagawa systems	I-45/I-46	On	
Review all TC readings	Relevant TC's	Trailer – 7-25°C, ext – 0-25°C	
Review all P readings	Relevant Press probes	P_abs 14.7, 43.5 psia; dP = 0	
Review reading on load cells	I-41-I-44	1419 lb	
Review readings from UV detectors	I-91, I-92		
Review reading from CO, LEL, O_2 detectors	I-83-I-90	<500 ppm	
Adjust LEL at base of HEX to read from outside	I-88	Sampling outside of hex	
Signals from three cameras	I-151 – 1-153	Operational, check with operator	

Appendix L

Data Collection Schematics

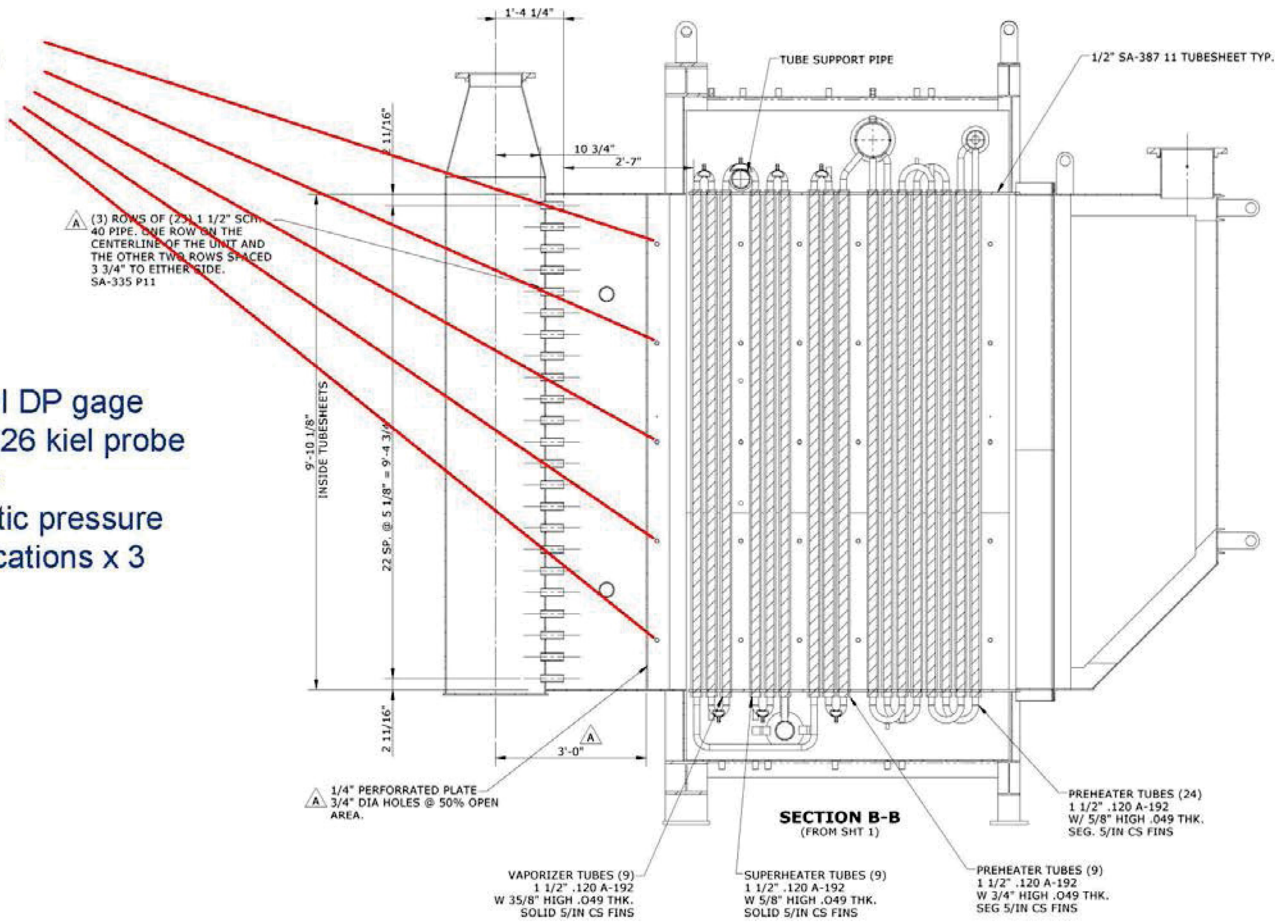


Experimental Plan

- Air Flow profile at HX inlet
- Heat Exchanger Performance
  - Heat Leak to the outside
  - Effectiveness (net heat transfer into working fluid)
- Working fluid film temperature
- Decomposition/fouling tests

Air Flow Profile at HX inlet

Kiel Probe Slots
(inlet Flow
Profiles)



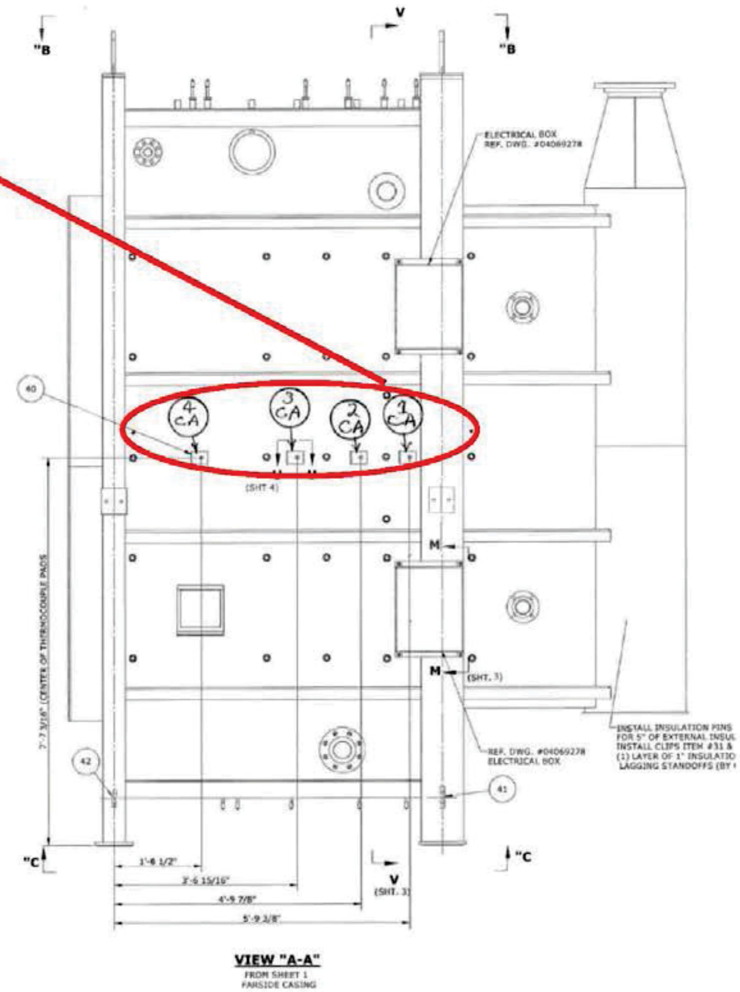
Data:

- Omega PX655-0.1DI DP gage
- United Sensor KAC-26 kiel probe
- Dynamic Pressure =
  Total pressure – Static pressure
- 5 slots x 5 sweep locations x 3
  repeatability runs

imagination at work

HX Performance/Effectiveness

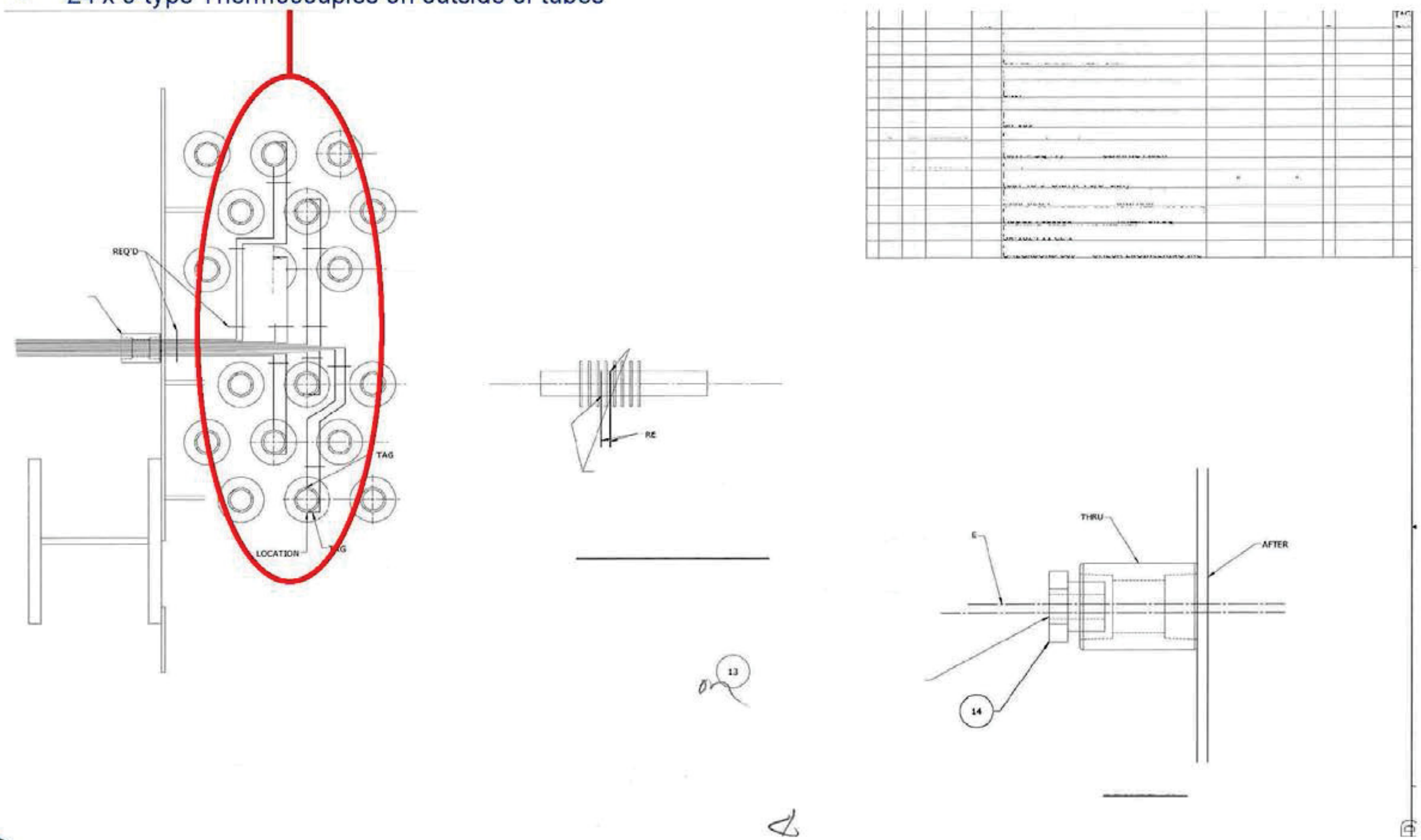
- Measurments:
  - 4 x J-type Thermocouples on the HX 'casing'
  - 1 x Ambient temperature measurement
  - Working fluid (cyclopentane) inlet & outlet temperature
  - Working Fluid Flow rate
  - Hot Air inlet & outlet temperature
  - Hot Air Flow rate
- Heat Balance:
  - Heat Leak to ambient=Heat absorbed by working fluid – Heat removed from hot air
  - Investigate for at least 3 air flow rates x 3 hot air temperatures x 2 repeatability runs
- Additional Data: *double click on image below*



imagination at work

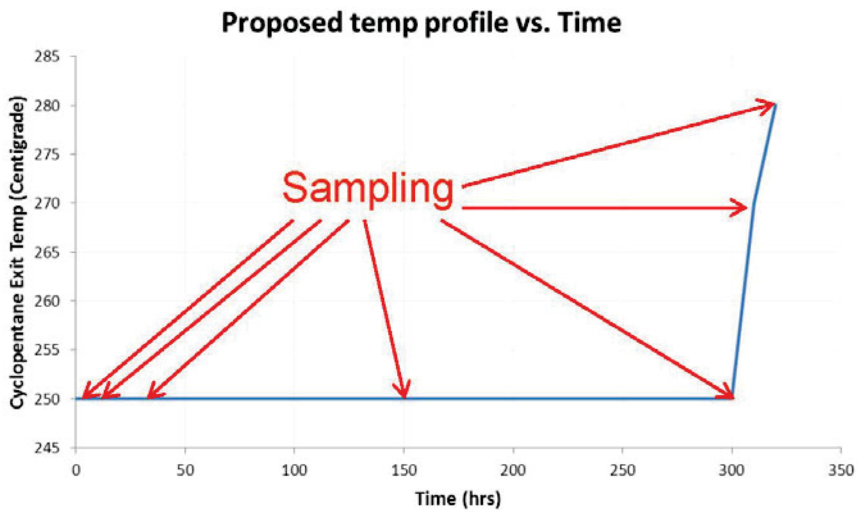
Working Fluid Film temperature

- Measurments:
  - 24 x J-type Thermocouples on outside of tubes



imagination at work

Decomposition tests



Degradation Test Protocol: High level

- 31 bar pressure: Start-up and ramp up to 500□C exhaust temp, 250□C cyclopentane outlet temp. over 2 hrs.
- T=0 to T=300 hours run time @ 250C outlet temp
- T=300 to T=310 hours @ 270□C outlet temp.
- T=310 to T=320 hrs @ 280□C outlet temp.
- Shutdown

imagination at work

Appendix M

Calculation of Average Velocity and Reynolds Number in the ORC Main Heat Exchanger

During testing, the temperature of the gas at the main HX inlet was approximately 465°C (869°F) and the outlet temperature was approximately 210°C (410°F). It was not possible to use the portable TSI hot film probe to measure velocities with air heated to these temperatures; therefore, the velocity traverses were done using cold air at ambient conditions, which happened to be 10°C on that day. A similar Reynolds number was chosen to get similar velocity profiles in the HX. For the hot flow case, the Reynolds number based on hydraulic diameter was 70,000 at the inlet and 93,000 at the outlet. For the cold flow case, the Reynolds number was fixed through the HX at about 91,000. The calculations were done using EES software. The code and results are shown in the pages that follow.

Calculations were performed for the following three cases:

1. Hot flow (465°C), inlet conditions
2. Hot flow (210°C), outlet conditions
3. Cold flow (10°C) conditions.

Simplifying assumptions are as follows:

1. Neglected pressure drop in HX (i.e., assumed inlet pressure was atmospheric)
2. Ignored combustion products in hot flow cases (i.e., assumed the gas properties were those of hot air).

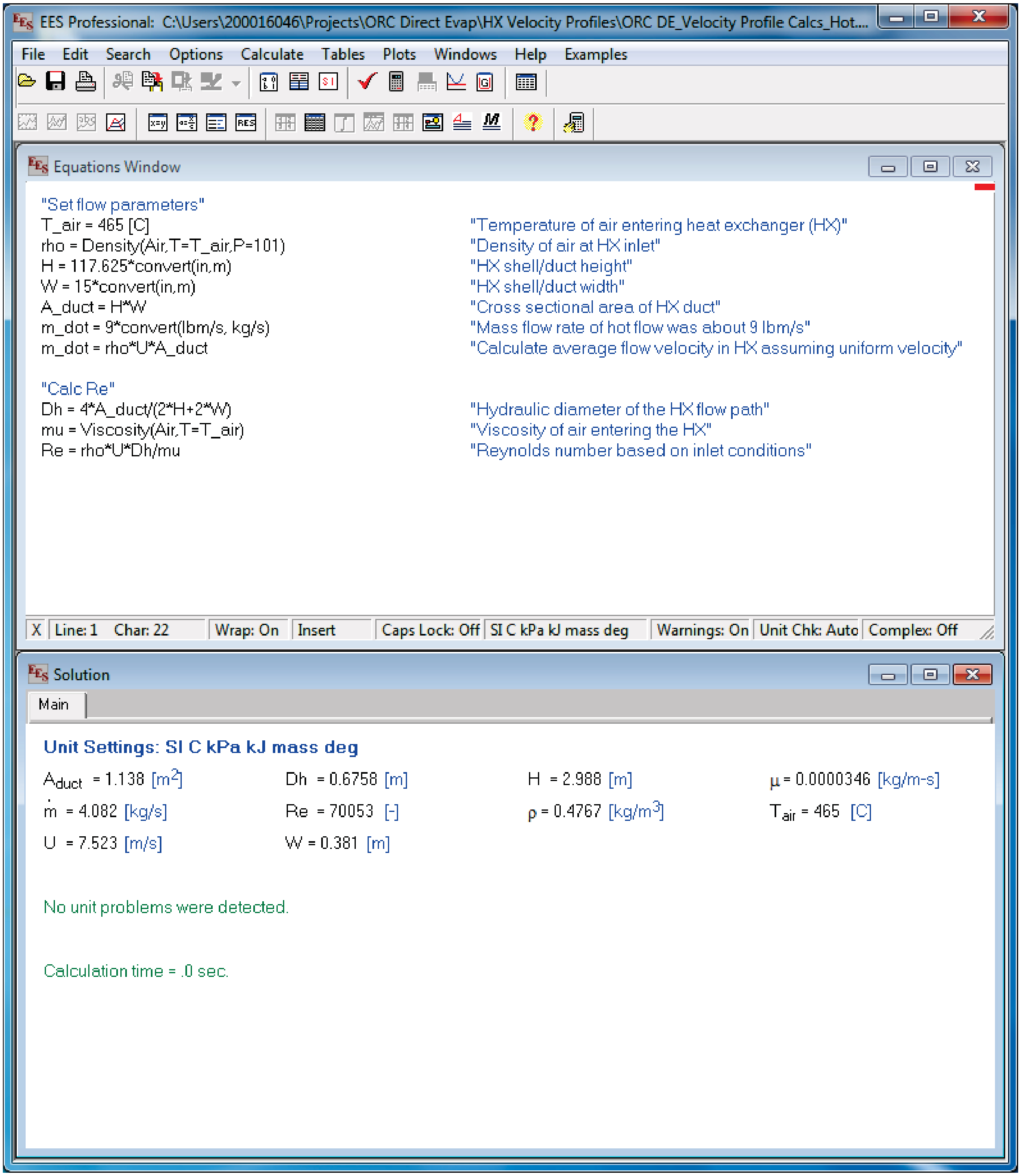


Figure M-1. Case 1, Calculation of Reynolds number for hot flow based on inlet conditions.

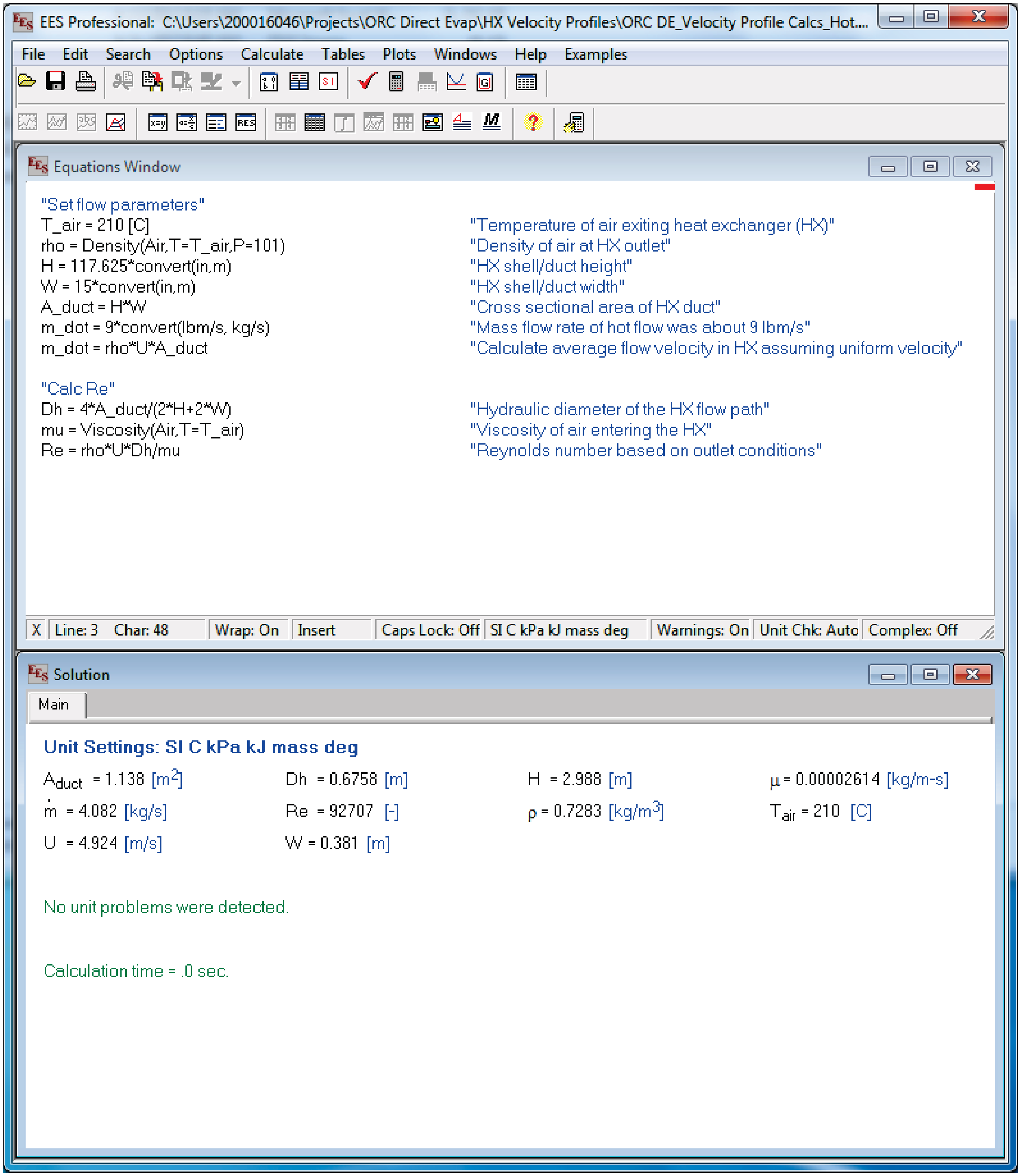


Figure M-2. Case 2, Calculation of Reynolds number for hot flow based on outlet conditions.

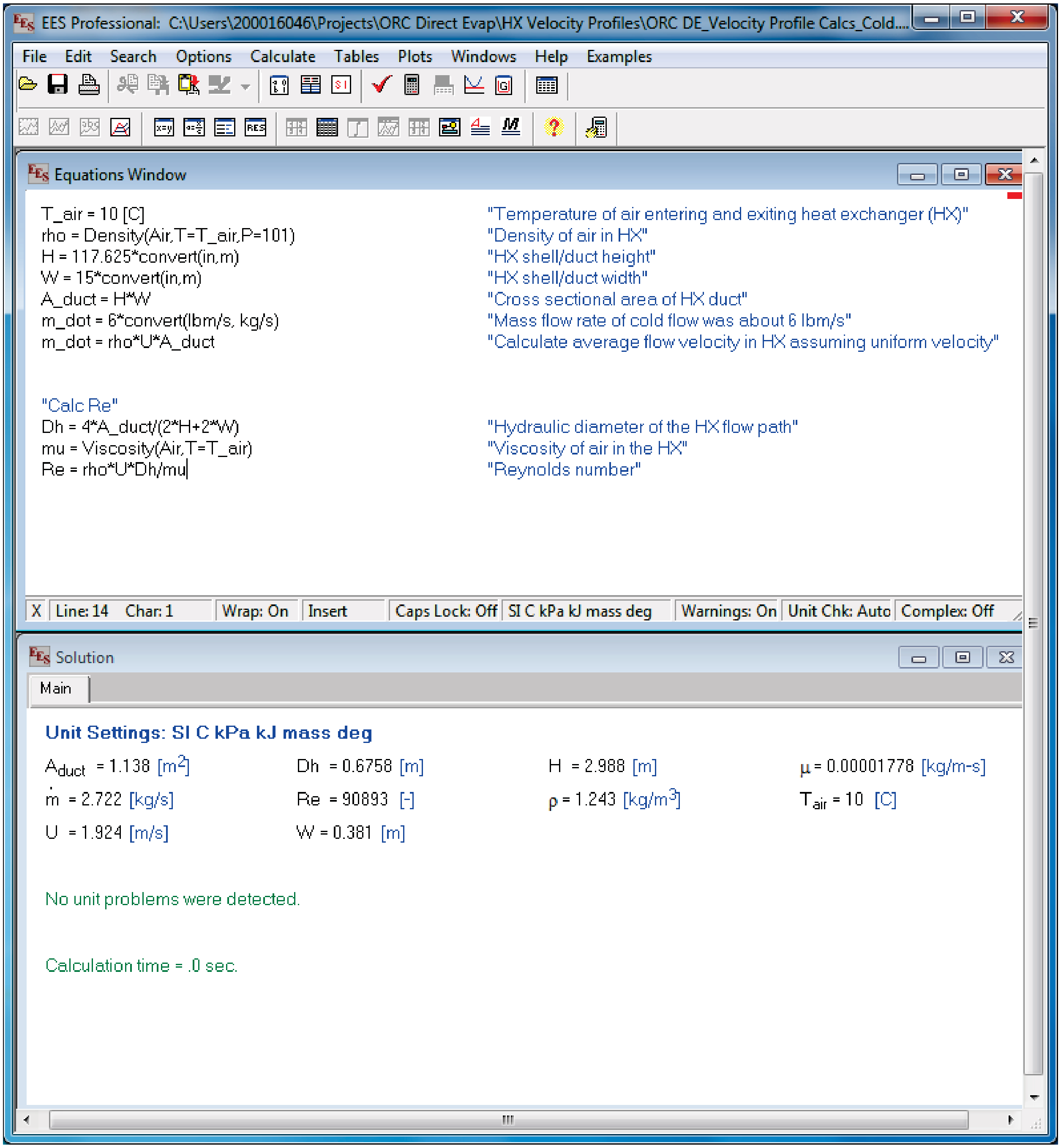


Figure M-3. Case 3, Calculation of Reynolds number based on cold conditions.

Appendix N

Calculation of Enthalpy of Combustion Product Gas

Fuel gas flow	36	lb/hr	0.01	lb/s									
Fuel gas combustion ratio													
Compound	Mole fraction	MW	N2	O2	CO2	H2O	Ar	SO2	Fuel gas molar flow	N2	O2	CO2	H2O
CH4	0.9567	16.04726	0	-2	1	2	0	0	2.0579	0	-4.11572	2.057858	4.115716
C2H6	0.01581	30.06964	0	-3.5	2	3	0	0	0.0340	0	-0.11903	0.068014	0.102022
Nitrogen	0.01883	28.01348	1	0	0	0	0	0	0.0405	0.040503	0	0	0
CO2	0.00866	44.0098	0	0	1	0	0	0	0.0186	0	0	0.018628	0
Mol. Weight	16.73643335	16.732								0.040503	-4.23474	2.1445	4.217737
Fuel gas molar flow	2.151												
Moist air for combustion	3.175904982	lb/hr											
	0												
Fuel gas heating value													
Fuel temperature	60	°F											
Compound	Mole fraction	MW	Heating value (Btu/lb)										
CH4	0.9567	16.04726	21503	19724.81									
C2H6	0.01581	30.06964	20432	580.3742									
Nitrogen	0.01883	28.01348	0	0									
CO2	0.00866	44.0098	0	0									
Mol. Weight	16.73643335	16.732											
Fuel gas ideal heating value	20305	Btu/lb											
Sensible heat of fuel	0.022711864												
Fuel net heating value	**20305**	Btu/lb											

Fuel gas combustion

Gas Turbine Exhaust Gas Composition											
Venturi air flow	18831.31765	lbm/hr	5.23092157	lbm/s							
	Moist air composition	Comb Moist air	Comb mole change	Steam inj.	Resultant	Mole weight		Gas Mass fraction	Balance of Moist air	Gas	Gas Composition
Nitrogen mole fraction	0.77409	0.085153835	0.041	0	0.125657	28.01348	3.520092	0.089874748	504.9140059	505.0397	0.771587593
Oxygen mole fraction	0.20767	0.022844225	-4.235	0	-4.2119	31.9988	-134.776	-3.441082148	135.4533148	131.2414	0.200507519
Argon mole fraction	0.00928	0.001021292	0.000	0	0.001021	39.948	0.040799	0.001041666	6.055683195	6.056704	0.009253289
Carbon dioxide mole fraction	0.00032	3.47883E-05	2.144	0	2.144535	44.0098	94.38054	2.409717365	0.20627474	2.350809	0.003591511
Water	0.00864	0.00095099	4.218	0	4.218688	18.01528	76.00085	1.940448368	5.638833786	9.857522	0.015060088
Average molecular weight	28.87052				2.278005	Total gas mas	39.16664			654.5461	
Total exhaust flow	**18870.5**	**lbm/hr**									

Combustion gas composition

	Flow rate		5.230922	lb/s							
Gas temperature	392	°F	200	°C	*From TC:						
	851.67	R									
	A1	A2	A3	A4	A5	A6	A7	A8	Sum		
Nitrogen	-5.961115742	-328.756	367.2477	-121.8496834	62.38428764	-15.38980296	1.524878292	123.567	82.76774349	Btu/lb	
Oxygen	8.087725924	365.3338	59.14614	53.69227285	-2.6964333	-2.832073564	0.5504904	-406.962	74.32022526	Btu/lb	
CO2	-8.486515996	-343.292	203.7495	22.76408716	-0.61007934	-0.782603179	0.109774253	199.5048	72.95680456	Btu/lb	
H20	16.55617178	770.5662	87.47811	160.4183245	-51.4409002	12.31881094	-1.25811365	-844.3	150.3385423	Btu/lb	
Argon	0	0	105.8451	0	0	0	0	-64.5843	41.26078625	Btu/lb	
	Gas Composition	h									
Nitrogen mole fraction	0.771587593	63.86256									
Oxygen mole fraction	0.200507519	14.90176									
Argon mole fraction	0.009253289	0.381798									
Carbon dioxide mole fraction	0.003591511	0.262025									
Water	0.015060088	2.264112									
Enthalpy at T = 200°C		**81.67226**	Btu/lb								

Gas enthalpy

INTENTIONALLY BLANK

Appendix O

Calculation of Q_E: Heat Flux to the Environment

Tventuri	20.2	C	Run starts on 9/17/2012 and finishes on 9/18/2012
Tamb	17	C	Weather Underground Historical Data, Albany Airport, 2:30 am
			Position (in)
Casing A	39.6	C	15.75
Casing B	26.9	C	38.5
Casing C	24.5	C	52.5
Casing D	25.7	C	66.5
Average	29.175		
Evap Mean	453.75	C	0
Sup Mean	373.91	C	31.5
Econ Mean	321.22	C	45.5
Econ Mean 2	270.29	C	59.5
Exh Mean	201.16	C	79.5

Estimated heat Loss

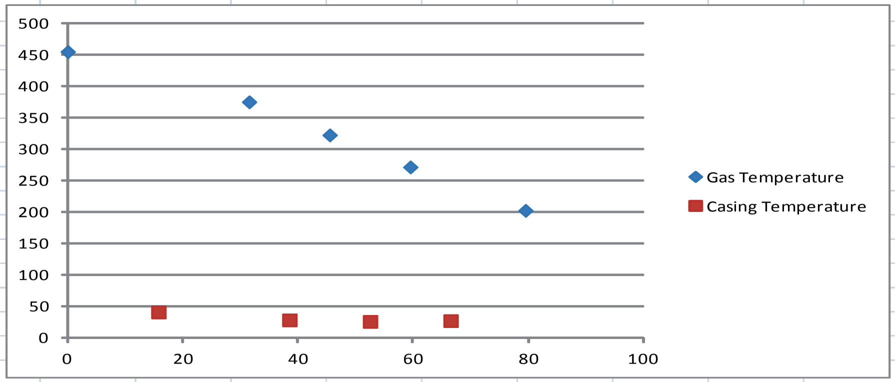
Typical Free Convection for gases

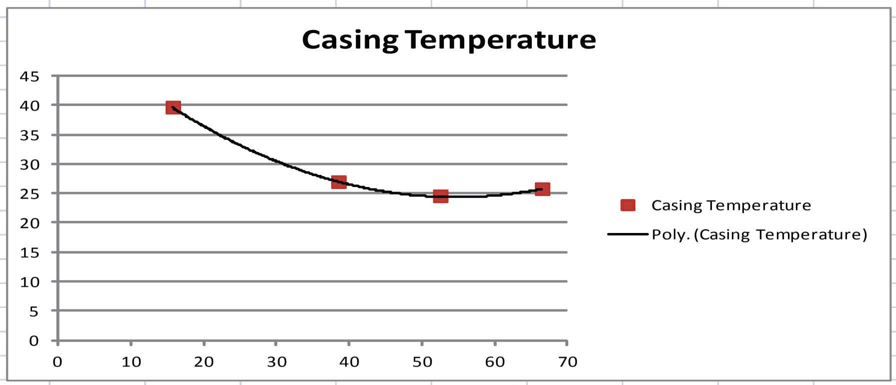
h = 2 - 25 W/m^2-K

	h	q'' (W/m^	Q (kW)
Case 1	2	24.35	0.4090746
Case 2	10	121.75	2.0453729
Case 3	25	304.375	5.1134322

Total Surface Area of HX:

height	9.82	ft
Width	1.542	ft
Length	6.625	ft
Estimated SA'	30.28488	
	130.115	
	20.4315	
Sum	**180.8314**	ft^2
	16.79978	**m2**





INTENTIONALLY BLANK

Appendix P

Data Analysis using SAS Enterprise Guide

Step 1 – Import data into SAS *(ORCData.egp)*

Import Excel spreadsheets into SAS and build a query to make an SQL database.

Step 2– Create SAS data sets *(ORCData.egp)*

Create a new variable called TestRun as the test run identifier. Then create data tables containing the data from the desired test runs, filtered as necessary. The code below was modified to produce customized data sets containing the desired data. The data can be filtered to exclude data out of range.

```
Data A1;
Set Guillen.First_ORC_RUN_08152012;
TestRun = "01_ORC_RUN_08152012";
run;
Data A2;
Set Guillen.SECOND_ORC_RUN_08162012;
TestRun = "02_ORC_RUN_08162012";
run;
Data A3;
Set Guillen.THIRD_ORC_RUN_08172012;
TestRun = "03_ORC_RUN_08172012";
run;
Data A4;
Set Guillen.FOURTH_ORC_RUN_08182012;
TestRun = "04_ORC_RUN_08182012";
run;
Data A5;
Set Guillen.FIFTH_ORC_RUN;
TestRun = "05_ORC_RUN_08202012";
run;
Data A6;
Set Guillen.SIXTH_ORC_RUN;
TestRun = "06_ORC_RUN_08212012";
run;
Data A8;
Set Guillen.EIGHTH_ORC_RUN;
TestRun = "08_ORC_RUN_08222012";
run;
Data A9;
Set Guillen.NINTH_ORC_RUN;
TestRun = "09_ORC_RUN_08232012";
run;
```

```
Data A10;
Set Guillen.TENTH_ORC_RUN;
TestRun = "10_ORC_RUN_08292012";
run;
Data A11;
Set Guillen.ELEVENTH_ORC_RUN_08302012;
TestRun = "11_ORC_RUN_08302012";
run;
Data A12;
Set Guillen.TWELFTH_ORC_RUN;
TestRun = "12_ORC_RUN_08312012";
run;
Data A13;
Set Guillen.THIRTEENTH_ORC_RUN;
TestRun = "13_ORC_RUN_09012012";
Data A14;
Set Guillen.FOURTEENTH_ORC_RUN;
TestRun = "14_ORC_RUN_09022012";
run;
Data A15;
Set Guillen.FIFTEENTH_ORC_RUN;
TestRun = "15_ORC_RUN_09022012";
run;
Data A16;
Set Guillen.SIXTEENTH_ORC_RUN;
TestRun = "16_ORC_RUN_09032012";
run;
Data A17;
Set Guillen.SEVENTEENTH_ORC_RUN;
TestRun = "17_ORC_RUN_09052012";
run;
Data A18;
Set Guillen.EIGHTEENTH_ORC_RUN;
TestRun = "18_ORC_RUN_09062012";
run;
Data A19;
Set Guillen.NINETEENTH_ORC_RUN;
TestRun = "19_ORC_RUN_09072012";
run;
Data A20;
Set Guillen.TWENTIETH_ORC_RUN;
TestRun = "20_ORC_RUN_09092012";
run;
Data A23;
Set Guillen.TWENTYTHIRD_ORC_RUN;
TestRun = "23_ORC_RUN_09122012";
run;
Data A25;
Set Guillen.TWENTYFIFTH_ORC_RUN;
TestRun = "25_ORC_RUN_09142012";
run;
Data A26;
```

```
Set Guillen.TWENTYSIXTH_ORC_RUN;
TestRun = "26_ORC_RUN_09162012";
run;
Data A27;
Set Guillen.TWENTYSEVENTH_ORC_RUN;
TestRun = "27_ORC_RUN_09172012";
run;
Data A28;
Set Guillen.TWENTYEIGHTH_ORC_RUN;
TestRun = "28_ORC_RUN_09182012";
run;
Data A29;
Set Guillen.TWENTYNINTH_ORC_RUN;
TestRun = "29_ORC_RUN_09202012";
run;
Data A30;
Set Guillen.THIRTIETH_ORC_RUN;
TestRun = "30_ORC_RUN_09202012";
run;
Data A31;
Set Guillen.THIRTYFIRST_ORC_RUN;
TestRun = "31_ORC_RUN_09212012";
run;
Data GUILLEN.PRESSUREDROPDATA;
length TestRun $ 25;
SET A2 A3 A4 A5 A6 A8 A9 A10 A11 A12 A13 A14 A15 A16 A17 A18 A19 A20
A23 A25 A26 A27 A28 A29;
If storetag = "IdNumber" then delete;
Format date date7. datetime datetime19. timex time12.;
/*If storetag = "IdNumber" then delete;*/
Len = length(asciitime)-4;
time = substr(asciitime,5,Len);
Mon_ = substr(time,1,3);
If mon_ = "Aug" then mon = "8";
If mon_ = "Sep" then mon = "9";
day =  substr(time,5,2);
year = substr(time,17,4);
hour = input(substr(time,8,2),2.0);
minute = input(substr(time,11,2),2.0);
sec = input(substr(time,14,2),2.0);
timex = hms(hour,minute,sec);
date = MDY(mon,day,year);
datetime = dhms(date,hour,minute,sec);
if dp_HX>30 then delete;
if dp_HX<0 then delete;
KEEP testrun timex date datetime dP_hx hour minute sec time;
run;
Data GUILLEN.C5H10TEMP;
length TestRun $ 25;
SET A1 A2 A3 A4 A5 A6 A8 A9 A10 A11 A12 A13 A14 A15 A16 A17 A18 A19
A20 A23 A25 A26 A27 A28 A29;
/*SET A30 A31;*/
```

```
/*removed low temps. A1 & A12 from dataset, also high A30 & A31*/
If storetag = "IdNumber" then delete;
Format date date7. datetime datetime19. timex time12.;
/*If storetag = "IdNumber" then delete;*/
Len = length(asciitime)-4;
time = substr(asciitime,5,Len);
Mon_ = substr(time,1,3);
If mon_ = "Aug" then mon = "8";
If mon_ = "Sep" then mon = "9";
day =  substr(time,5,2);
year = substr(time,17,4);
hour = input(substr(time,8,2),2.0);
minute = input(substr(time,11,2),2.0);
sec = input(substr(time,14,2),2.0);
timex = hms(hour,minute,sec);
date = MDY(mon,day,year);
datetime = dhms(date,hour,minute,sec);
/*if TC_High_P > 500 then delete;
if Tsupheat > 500 then delete;
if TC_Header_Top > 500 then delete;
if TC_1_Ubendeva_B > 500 then delete;
if TC_1_Ubendeva_T > 500 then delete;
if TC_2_Ubendeva_T > 500 then delete;
if TC_2_Ubendsup_B > 500 then delete;
if TC_3_Ubendeco_B > 500 then delete;
if TC_3_Ubendsup_T > 500 then delete;
if TC_4_Ubendeco_B > 500 then delete;
if TC_4_Ubendeco_T > 500 then delete;
if TC_5_Ubendeco_B > 500 then delete;
if TC_5_Ubendeco_T > 500 then delete;
if TC_6_Ubendeco_T > 500 then delete;
if Coriolis_Flowmeter>20 then delete;
if Coriolis_Flowmeter<0 then delete;
if air_mfr>200 then delete;
if air_mfr<0 then delete;*/
/*Convert from psi to mmHg*/
P_abs_hex_in=P_abs_hex_in*57.715;
dP_Eco=dP_Eco*57.715;
dP_Evap=dP_Evap*57.715;
dP_Sup=dP_Sup*57.715;
DP_HX_mm=DP_HX*57.715;
TC_Exit_Avg=(TC_Exit_Exh_11+TC_Exit_Exh_12+TC_Exit_Exh_14+TC_Exit_Exh_
15)/4;
TC_Evap_Avg=(TC_Evap_Exh_1+TC_Evap_Exh_2+TC_Evap_Exh_4+TC_Evap_Exh_5)/
4;
if TC_Exit_Avg>300 or TC_Evap_Avg>500 then delete;
dT_Exhaust=TC_Evap_Avg-TC_Exit_Avg;
Exhaust_TAvg=(TC_Evap_Avg+TC_Exit_Avg)/2;
cp_air=-4e-10*Exhaust_TAvg**3+9e-7*Exhaust_TAvg**2-
0.0004*Exhaust_TAvg+1.0477;
/*Convert from lbm/s to kg/s*/
air_mfr=air_mfr*0.45359;
```

```
H_Exhaust=air_mfr*cp_air*dT_Exhaust;
KEEP testrun date timex TC_High_P Tsupheat TC_Header_Top
TC_1_Ubendeva_B TC_1_Ubendeva_T TC_2_Ubendeva_T
TC_2_Ubendsup_B TC_3_Ubendeco_B TC_3_Ubendsup_T TC_4_Ubendeco_B
TC_4_Ubendeco_T TC_5_Ubendeco_B TC_5_Ubendeco_T TC_6_Ubendeco_T
P_abs_hex_in dP_Eco dP_Evap dP_Sup DP_HX DP_HX_mm
TC_Exit_Avg TC_Evap_Avg dT_Exhaust H_Exhaust Exhaust_TAvg
Coriolis_Flowmeter;
run;
Data GUILLEN.CORIOLIS;
length TestRun $ 25;
SET A1 A2 A3 A4 A5 A6 A8 A9 A10 A11 A12 A13 A14 A15 A16 A17 A18 A19
A20 A23 A25 A26 A27 A28 A29 A30 A31;
If storetag = "IdNumber" then delete;
Format date date7. datetime datetime19. timex time12.;
/*If storetag = "IdNumber" then delete;*/
Len = length(asciitime)-4;
time = substr(asciitime,5,Len);
Mon_ = substr(time,1,3);
If mon_ = "Aug" then mon = "8";
If mon_ = "Sep" then mon = "9";
day =  substr(time,5,2);
year = substr(time,17,4);
hour = input(substr(time,8,2),2.0);
minute = input(substr(time,11,2),2.0);
sec = input(substr(time,14,2),2.0);
timex = hms(hour,minute,sec);
date = MDY(mon,day,year);
datetime = dhms(date,hour,minute,sec);
/*if Coriolis_Flowmeter>20 then delete;
if Coriolis_Flowmeter<0 then delete;
if air_mfr>200 then delete;
if air_mfr<0 then delete;*/
/*Convert from lbm/s to kg/s*/
air_mfr=air_mfr*0.45359;
KEEP testrun timex date datetime Coriolis_Flowmeter air_mfr hour
minute sec time;
run;
Data GUILLEN.FLOWS;
length TestRun $ 25;
SET A8 A19;
If storetag = "IdNumber" then delete;
Format date date7. datetime datetime19. timex time12.;
/*If storetag = "IdNumber" then delete;*/
Len = length(asciitime)-4;
time = substr(asciitime,5,Len);
Mon_ = substr(time,1,3);
If mon_ = "Aug" then mon = "8";
If mon_ = "Sep" then mon = "9";
day =  substr(time,5,2);
year = substr(time,17,4);
hour = input(substr(time,8,2),2.0);
```

```
minute = input(substr(time,11,2),2.0);
sec = input(substr(time,14,2),2.0);
timex = hms(hour,minute,sec);
date = MDY(mon,day,year);
datetime = dhms(date,hour,minute,sec);
if Coriolis_Flowmeter>20 then delete;
if Coriolis_Flowmeter<0 then delete;
if air_mfr>200 then delete;
if air_mfr<0 then delete;
/*Convert from lbm/s to kg/s*/
air_mfr=air_mfr*0.45359;
KEEP testrun timex date datetime Coriolis_Flowmeter air_mfr hour
minute sec time;
run;
Data GUILLEN.EXHAUST;
length TestRun $ 25;
SET A1 A2 A3 A4 A5 A6 A8 A9 A10 A11 A12 A13 A14 A15 A16 A17 A18 A19
A20 A23 A25 A26 A27 A28 A29 A30 A31;
If storetag = "IdNumber" then delete;
Format date date7. datetime datetime19. timex time12.;
/*If storetag = "IdNumber" then delete;*/
Len = length(asciitime)-4;
time = substr(asciitime,5,Len);
Mon_ = substr(time,1,3);
If mon_ = "Aug" then mon = "8";
If mon_ = "Sep" then mon = "9";
day =  substr(time,5,2);
year = substr(time,17,4);
hour = input(substr(time,8,2),2.0);
minute = input(substr(time,11,2),2.0);
sec = input(substr(time,14,2),2.0);
timex = hms(hour,minute,sec);
date = MDY(mon,day,year);
datetime = dhms(date,hour,minute,sec);
if dP_Exhaust>20 then delete;
if dP_Exhaust<0 then delete;
KEEP testrun timex date datetime dP_Exhaust hour minute sec time;
run;
```

<u>Step 3 – Create elapsed time variable to enable overlay of test run data *(Plots.egp)*</u>

The examples below show the code used for the exhaust gas temperature data. Similar code was used for the other variables in the report.

```
proc sort data=guillen.c5h10temp;
by testrun date timex;
run;
data EXHAUST_TEMP;
set guillen.c5h10temp;
By testrun date timex;
format obs time12.;
```

```
obs = lag1(timex);
delt = timex - obs;
if delt<0 then delt=1;
if first.testrun then elapsed_time = 0;
if first.testrun then delt = 0;
/*elapsed_time + 1;*/
elapsed_time + delt;
run;
```

Step 4 – Filter results *(Plots.egp)*

```
%_eg_conditional_dropds(WORK.QUERY_FOR_EXHAUST_TEMP);

PROC SQL;
   CREATE TABLE WORK.QUERY_FOR_EXHAUST_TEMP AS
   SELECT t1.TC_Evap_Avg,
          t1.elapsed_time,
          t1.TestRun
      FROM WORK.EXHAUST_TEMP t1
      WHERE t1.TC_Evap_Avg < 500;
QUIT;
```

Step 5 – Create an overlay plot of all test runs *(Plots.egp)*

```
/* -------------------------------------------------------------------
   Code generated by SAS Task

   Generated on: Thursday, August 29, 2013 at 4:52:23 PM
   By task: Line Plot7

   Input Data: WORK.QUERY_FOR_EXHAUST_TEMP
   Server:  SASApp
   -------------------------------------------------------------------
*/

%_eg_conditional_dropds(WORK.SORTTempTableSorted);
/* -------------------------------------------------------------------
   Sort data set WORK.QUERY_FOR_EXHAUST_TEMP
   -------------------------------------------------------------------
*/
PROC SORT
     DATA=WORK.QUERY_FOR_EXHAUST_TEMP(KEEP=elapsed_time TC_Evap_Avg
TestRun)
     OUT=WORK.SORTTempTableSorted
     ;
     BY elapsed_time;
RUN;
SYMBOL1
     INTERPOL=JOIN
     HEIGHT=10pt
     VALUE=POINT
     LINE=1
     WIDTH=1
```

```
        COLOR=BIBG

        CV = _STYLE_
;
SYMBOL2
        INTERPOL=JOIN
        HEIGHT=10pt
        VALUE=POINT
        LINE=1
        WIDTH=1
        COLOR=bgr

        CV = _STYLE_
;
SYMBOL3
        INTERPOL=JOIN
        HEIGHT=10pt
        VALUE=NONE
        LINE=1
        WIDTH=1
        COLOR=BIB

        CV = _STYLE_
;
SYMBOL4
        INTERPOL=JOIN
        HEIGHT=10pt
        VALUE=NONE
        LINE=1
        WIDTH=1
        COLOR=BIG

        CV = _STYLE_
;
SYMBOL5
        INTERPOL=JOIN
        HEIGHT=10pt
        VALUE=NONE
        LINE=1
        WIDTH=1
        COLOR=CRIMSON

        CV = _STYLE_
;
SYMBOL6
        INTERPOL=JOIN
        HEIGHT=10pt
        VALUE=NONE
        LINE=1
        WIDTH=1
        COLOR=BLUE
```

```
      CV = _STYLE_
;
SYMBOL7
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=1
      WIDTH=1
      COLOR=BIP

      CV = _STYLE_
;
SYMBOL8
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=1
      WIDTH=1
      COLOR=BIOY

      CV = _STYLE_
;
SYMBOL9
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=1
      WIDTH=1
      COLOR=BIPB

      CV = _STYLE_
;
SYMBOL10
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=1
      WIDTH=1
      COLOR=BIO

      CV = _STYLE_
;
SYMBOL11
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=1
      WIDTH=1
      COLOR=BIPPK

      CV = _STYLE_
;
```

```
SYMBOL12
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=1
      WIDTH=1
      COLOR=LIGHTCORAL

      CV = _STYLE_
;
SYMBOL13
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=3
      WIDTH=1
      COLOR=AQUAMARINE

      CV = _STYLE_
;
SYMBOL14
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=3
      WIDTH=1
      COLOR=bgr

      CV = _STYLE_
;
SYMBOL15
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=3
      WIDTH=1
      COLOR=bIB

      CV = _STYLE_
;
SYMBOL16
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=3
      WIDTH=1
      COLOR=BIG

      CV = _STYLE_
;
SYMBOL17
      INTERPOL=JOIN
```

```
      HEIGHT=10pt
      VALUE=NONE
      LINE=3
      WIDTH=1
      COLOR=CRIMSON

      CV = _STYLE_
;
SYMBOL18
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=3
      WIDTH=1
      COLOR=BLUE

      CV = _STYLE_
;
SYMBOL19
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=3
      WIDTH=1
      COLOR=BIP

      CV = _STYLE_
;
SYMBOL20
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=3
      WIDTH=1
      COLOR=BIOY

      CV = _STYLE_
;
SYMBOL21
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
      LINE=3
      WIDTH=1
      COLOR=BIPB

      CV = _STYLE_
;
SYMBOL22
      INTERPOL=JOIN
      HEIGHT=10pt
      VALUE=NONE
```

```
        LINE=3
        WIDTH=1
        COLOR=BIO

        CV = _STYLE_
;
SYMBOL23
        INTERPOL=JOIN
        HEIGHT=10pt
        VALUE=NONE
        LINE=3
        WIDTH=1
        COLOR=BIPPK

        CV = _STYLE_
;
SYMBOL24
        INTERPOL=JOIN
        HEIGHT=10pt
        VALUE=NONE
        LINE=3
        WIDTH=1
        COLOR=LIGHTCORAL

        CV = _STYLE_
;
SYMBOL25
        INTERPOL=JOIN
        HEIGHT=10pt
        VALUE=NONE
        LINE=3
        WIDTH=1
        COLOR=GREEN

        CV = _STYLE_
;
SYMBOL26
        INTERPOL=JOIN
        HEIGHT=10pt
        VALUE=NONE
        LINE=2
        WIDTH=2
        COLOR=ORANGE

        CV = _STYLE_
;
SYMBOL27
        INTERPOL=JOIN
        HEIGHT=10pt
        VALUE=NONE
        LINE=2
        WIDTH=2
```

```
      COLOR=BROWN

      CV = _STYLE_
;
Legend1
      FRAME
      ;
Axis1
      STYLE=1
      WIDTH=1
      MINOR=NONE


;
Axis2
      STYLE=1
      WIDTH=1
      MINOR=NONE


;
TITLE;
TITLE1 "Line Plot";
FOOTNOTE;
PROC GPLOT DATA = WORK.SORTTempTableSorted
 NOCACHE ;
PLOT TC_Evap_Avg * elapsed_time = TestRun /
      VAXIS=AXIS1

      HAXIS=AXIS2

FRAME LEGEND=LEGEND1;
GOPTIONS cback=white ftext='arial' htext=10pt;
/* -------------------------------------------------------------------
   End of task code.
   -------------------------------------------------------------------
*/
RUN; QUIT;
%_eg_conditional_dropds(WORK.SORTTempTableSorted);
TITLE; FOOTNOTE;
GOPTIONS RESET = SYMBOL;
```

Step 6 – Analyze statistics of variables in test runs *(Graphs.egp)*

The code below prints out a report with the variable name and the mode, median and maximum values over the entire range of test runs contained in the data set.

```
PROC SORT
      DATA=GUILLEN.C5H10TEMP (drop=date timex)
      OUT=WORK.SORTTempTableSorted
```

```
      ;
      BY TC_1_UBENDeva_T;
      RUN;
proc means data=guillen.c5H10temp (drop=date timex) MODE MEDIAN MAX;
BY TestRun;
TITLE 'Measured TC Temperatures';
RUN;
proc means data=guillen.c5H10temp (drop=date timex) MODE MEDIAN MAX;
TITLE 'Summary';
RUN;
```

Appendix Q

Data Dictionary

Variable	Description	
Accumulator_Level1	#1 of 4 load cells under the Accumulator	
Accumulator_Level2	#2 of 4 load cells under the Accumulator	Add #1, #2, #3, #4 together to obtain total accumulator weight
Accumulator_Level3	#3 of 4 load cells under the Accumulator	
Accumulator_Level4	#4 of 4 load cells under the Accumulator	
Container_Temp	Ambient temp inside the trailer	
Coriolis_Flowmeter	Cyclopentane Liquid Flow rate	
DP_HX	Delta Pressure across the HX	
Exhaust_Fan_Speed	Speed of Ventilation fan on trailer	
Gastech_T1	Temp on outside body of vitiated heater, Centigrade	
Gastech_T2	Temp of vitiated air flowing out of heater, Centigrade	
LEL_CO	CO concentration inside trailer, ppm	
LEL_Courtyard_Value	Lower Explosive Limit in test Courtyard	
LEL_O2	O2 concentration inside trailer	
LEL_Pump_Value	Lower Explosive Limit next to cyclopentane circulation pump	
LEL_Vent_Value	Lower Explosive Limit next to ventilation fan	
LEL__Accumulator_Value	Lower Explosive Limit next to accumulator	
Main_Panel_Temp__hoff_	Temperature of main electrical supply/control panel	
PVenturi	Absolute pressure upstream of the venturi that measures air flow rate to the vitiated heater, psia	
P_Abs_Ar	Absolute pressure on the accumulator pistons, psia	
P_Abs_Subcool	Absolute pressure of the cyclopentane downstream of the condenser, psia	
P_abs_hex_in	Absolute pressure of cyclopentane at I-9, the inlet of the HX	
P_abs_superheater	Absolute pressure of cyclopentane at the outlet of the HX (downstream of superheater)	
T1BotFrEv	Temp on outside wall of HX tube - Refer to ppt schematic	
T1TopFrEv	Temp on outside wall of HX tube - Refer to ppt schematic	
T2BotFrEv	Temp on outside wall of HX tube - Refer to ppt schematic	
T2TopFrEv	Temp on outside wall of HX tube - Refer to ppt schematic	
T3BotFrEv	Temp on outside wall of HX tube - Refer to ppt schematic	
T3TopFrEv	Temp on outside wall of HX tube - Refer to ppt schematic	
TArgAccum	Temperature at I-36, the top of the accumulator	
TCEconPump	Temperature at I-27	

TC_1_CA_Eva	Refer to ppt schematic
TC_1_Ubendeva_B	Refer to ppt schematic
TC_1_Ubendeva_T	Refer to ppt schematic
TC_2_CA_Sup	Refer to ppt schematic
TC_2_Ubendeva_T	Refer to ppt schematic
TC_2_Ubendsup_B	Refer to ppt schematic
TC_3_CA_Eco	Refer to ppt schematic
TC_3_Ubendeco_B	Refer to ppt schematic
TC_3_Ubendsup_T	Refer to ppt schematic
TC_4_CA_Eco	Refer to ppt schematic
TC_4_Ubendeco_B	Refer to ppt schematic
TC_4_Ubendeco_T	Refer to ppt schematic
TC_5_Ubendeco_B	Refer to ppt schematic
TC_5_Ubendeco_T	Refer to ppt schematic
TC_6_Ubendeco_T	Refer to ppt schematic
TC_Casing_Ext_A	Thermocouples attached to the outside of the HX casing
TC_Casing_Ext_B	
TC_Casing_Ext_C	
TC_Casing_Ext_D	
TC_Condenser_A	Temperature at I-17, cyclopentane inlet to the condenser
TC_Eco_Exh_1	Refer to ppt schematic
TC_Eco_Exh_10	Refer to ppt schematic
TC_Eco_Exh_2	Refer to ppt schematic
TC_Eco_Exh_4	Refer to ppt schematic
TC_Eco_Exh_5	Refer to ppt schematic
TC_Eco_Exh_6	Refer to ppt schematic
TC_Eco_Exh_7	Refer to ppt schematic
TC_Eco_Exh_9	Refer to ppt schematic
TC_Evap_Exh_1	Refer to ppt schematic
TC_Evap_Exh_2	Refer to ppt schematic
TC_Evap_Exh_4	Refer to ppt schematic
TC_Evap_Exh_5	Refer to ppt schematic
TC_Exhaust	Temperature of hot gas at the outlet of the HX
TC_Exit_Exh_11	Refer to ppt schematic
TC_Exit_Exh_12	Refer to ppt schematic
TC_Exit_Exh_14	Refer to ppt schematic
TC_Exit_Exh_15	Refer to ppt schematic
TC_Header_Top	Refer to ppt schematic
TC_High_P	Temperature of cyclopentane at the inlet to the HX
TC_Inlet_Eco_B	Temperature at the inlet to the economizer section of the HX
TC_Low_Pressure	Temperature at I-21, the cyclopentane leg going to accumulator
TC_Super_Exh_1	Refer to ppt schematic
TC_Super_Exh_2	Refer to ppt schematic

TC_Super_Exh_4	Refer to ppt schematic
TC_Super_Exh_5	Refer to ppt schematic
TC_Superheat_B	Redundant TC at exit of HX (downstream of superheater)
TC_Water_Exit	Temperature at I-19, condenser cooling water exit
TC_Water_Inlet	Temperature at I-18, condenser cooling water inlet
TDeprRel	Temperature at I-27, downstream of V-9, the pressure dump valve
TEcoExit3	Refer to ppt schematic
TEcoExit8	Refer to ppt schematic
TEvapExit3	Refer to ppt schematic
TExhExit13	Refer to ppt schematic
TInEco	Redundant, temperature at I-28, inlet to the HX
TPressRel	Temperature at I-24, downstream of the accumlator pressure relief circuit
TPumpPR	Temperature at I-94, upstream of the cyclopentane loop pressure relief at the circulation pump
TPumpRel	Temperature at I-26, upstream of the cyclopentane loop pressure relief at the circulation pump
TSubcoolA	Temperature of cyclopentane at I-20, downstream of the condenser
TSupRel	Temperature at I-29, downstream of the superheater pressure relief valve
TSuperExit3	Same as TC_sup_exh3
TVenturi	Temperature of the air flow rate to the venturi supplying the vitiated heater
TW_flowmeter	Cooling water flow rate to condenser
Tsupheat	Same as TC_I-16
Tube1_Bottom_Back_Ev	Refer to ppt schematic
Tube1_Top_Back_Ev	Refer to ppt schematic
Tube2_Bottom_Back_Ev	Refer to ppt schematic
Tube2_Top_Back_Ev	Refer to ppt schematic
Tube3_Bottom_Back_Ev	Refer to ppt schematic
Tube3_Top_Back_Ev	Refer to ppt schematic
Tube4_Bottom_Back_Su	Refer to ppt schematic
Tube4_Bottom_Front_Su	Refer to ppt schematic
Tube4_Top_Back_Su	Refer to ppt schematic
Tube4_Top_Front_Su	Refer to ppt schematic
Tube5_Bottom_Back_Su	Refer to ppt schematic
Tube5_Bottom_Front_Su	Refer to ppt schematic
Tube5_Top_Back_Su	Refer to ppt schematic
Tube5_Top_Front_Su	Refer to ppt schematic
Tube6_Bottom_Back_Su	Refer to ppt schematic
Tube6_Bottom_Front_Su	Refer to ppt schematic
Tube6_Top_Back_Su	Refer to ppt schematic
Tube6_Top_Front_Su	Refer to ppt schematic

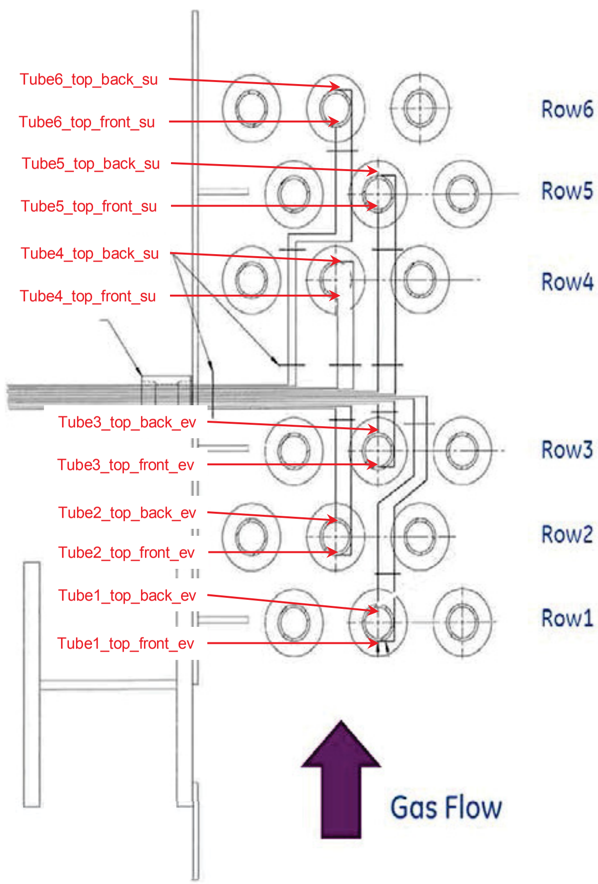
Unburned_Hydrocarbon_Det	reading of unburned HC detector at HX air exhaust stream, ppm of cyclopentane
dPVenturi	Differential pressure of the venturi that measures air flow rate to the vitiated heater, psi
dP_Eco	Differential pressure of cyclopetane across the economizer section of the HX, psi
dP_Evap	Differential pressure of the cyclopentane across the evaporator section of the HX, psi
dP_Exhaust	Differential pressure of hot air across the HX, psi
dP_Sup	Differential pressure of the cyclopentane across the superheater section of the HX, psi

Appendix R

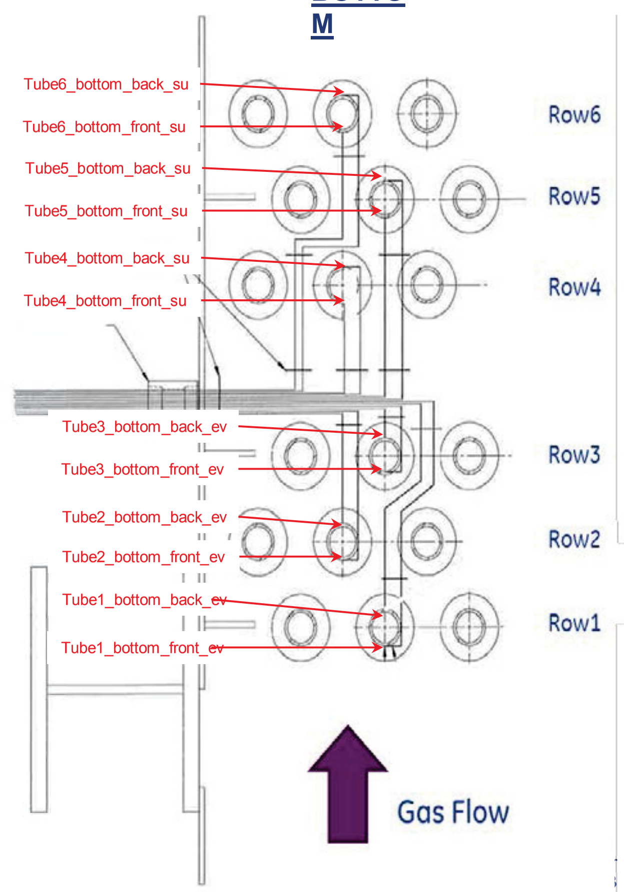
Test Rig Instrumentation Locations and Identifiers

Thermocouples outside the tubes

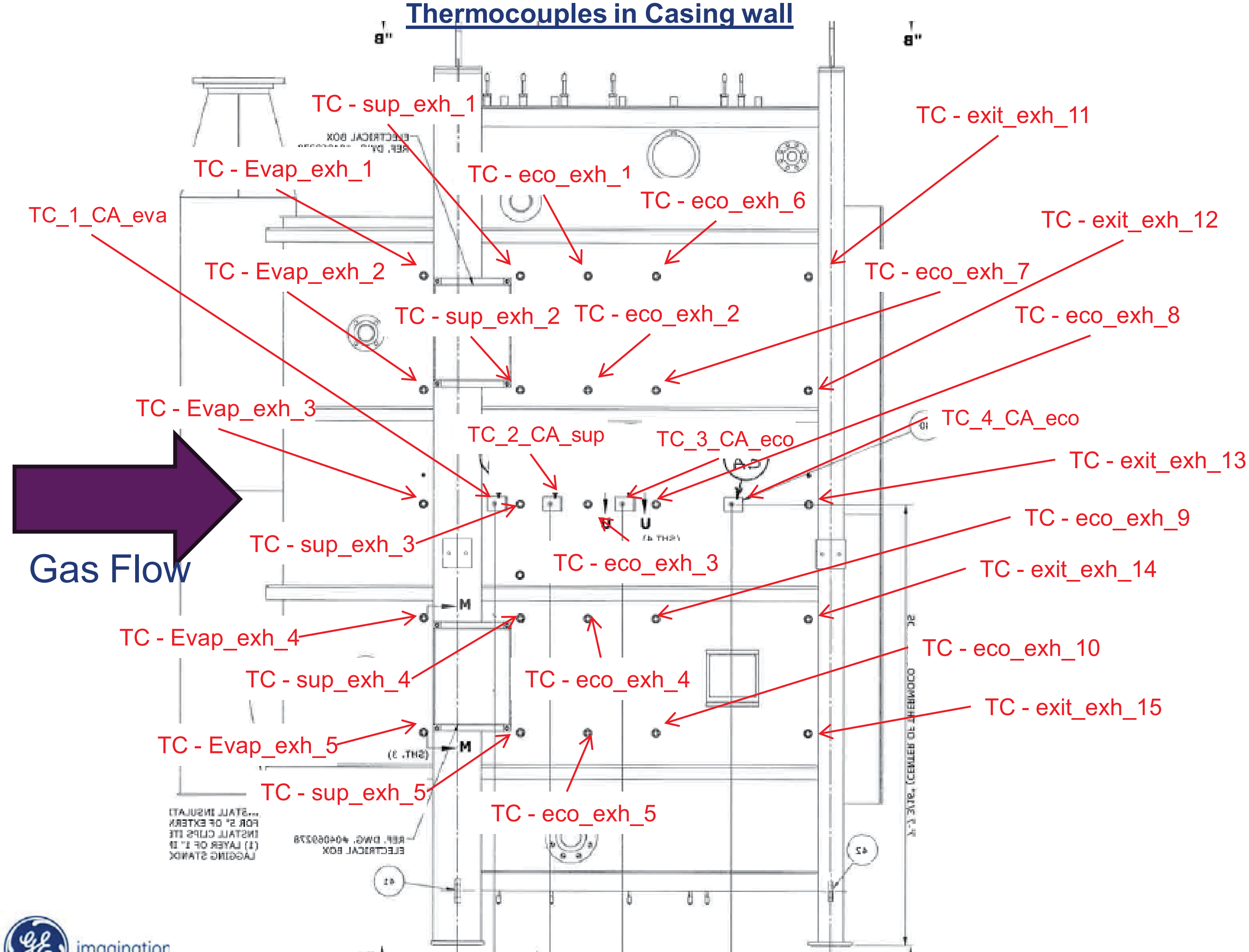
TOP



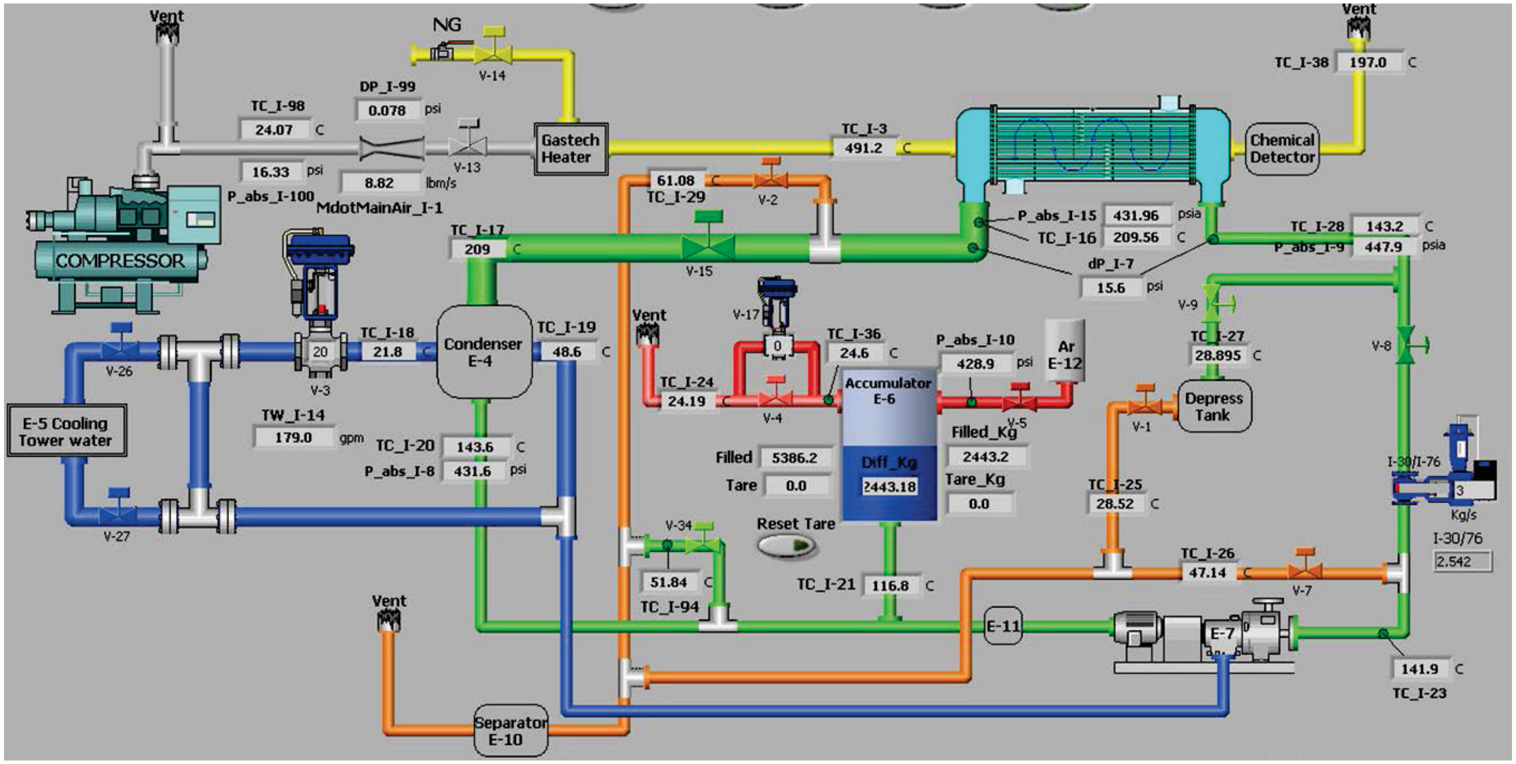
BOTTOM



Thermocouples in Casing wall



Diff Pressure Sensors



dP_Exhaust	P_Abs_Subcool	P_Abs_Ar	dP_Eco	dP_Evap	dP_Sup
I-6	I-8	I-10	I-11	I-12	I-13