Development, Construction, and Operation of a Non-Nuclear Microreactor Experimental Capability

A Thesis
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with a
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Abstract

Idaho National Laboratory has constructed the microreactor non-nuclear experimental test bed (MAGNET) to reduce uncertainty and risk for microreactor developers, users, and regulators. MAGNET will provide verification and validation data for dynamic models and system scaling allowing demonstration and validation of microreactor systems, components, and auxiliary systems. The system was designed around typical air-Brayton parameters with a hot design temperature of 650°C and a maximum allowable working pressure of 22 bar. The differential temperature through the microreactor test article was assumed to be 290°C. MAGNET is compatible with compressed air, nitrogen, or helium as the cooling fluids. Testing to date comprises a single heat pipe proof of concept test and a prototype helium-to-air heat exchanger test for a commercial developer.

Keywords: microreactor, non-nuclear testing, heat pipe, verification and validation.

Acknowledgments

I would like to acknowledge Idaho National Laboratory (INL) for fostering an atmosphere of continuous professional development and for providing the financial support that enabled me to pursue a graduate degree. I would like to thank Dr. Mike McKellar for sometimes simultaneously pushing and encouraging me when I needed it. Finally, I would like to thank Dr. Shannon Bragg-Sitton for her unwavering support of my continuing education.

Dedication

I would like to thank my wife for putting up with me no matter how grouchy I got as the sometimes challenging and time-consuming course work added time to my already long days. Thank you, Elisa, for taking care of so much cooking, cleaning, and dog walking while I was struggling to remember how math worked!

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Chapter 1: Introduction

Microreactors are a class of small modular reactors targeted to provide heat and power for non-conventional nuclear markets such as remote communities, mining sites, remote defense bases, back up generation for nuclear power plants, humanitarian assistance, and disaster relief missions (Idaho National Laboratory, 2023).

Figure 1-1. Definition of a Microreactor (Idaho National Laboratory, 2023)

These factory-fabricated, transportable, self-regulating reactor designs, while offering many advantages, are largely untested and unproven. Non-nuclear system and component testing capability was needed to demonstrate that these designs are safe and to convince customers that the systems are robust, reliable, and efficient.

Idaho National Laboratory has built a non-nuclear experimental facility to help develop, demonstrate, and validate microreactor components and systems. Non-nuclear testing can be used to evaluate operations of integrated systems and provide input to overall microreactor system designs (Bragg-Sitton & Morton, 2006). The microreactor agile non-nuclear experimental test bed (MAGNET) will support microreactor technology maturation to reduce uncertainty and risk relative to the operation and deployment of this unique class of systems. Stakeholders for this testbed include microreactor developers, energy users, and regulators. Regulators will be engaged early in the design and testing of microreactor concepts to expedite regulatory approval and licensing.

Within MAGNET, microreactor systems and components can be safely tested in a non-nuclear environment, providing valuable information on operating regimes, failure modes, and thresholds. Various microreactor designs have been proposed and classified according to their core cooling method; heat pipes, gas (pebble bed or prismatic), molten salt, and liquid metal. MAGNET was designed to test gas and heat pipe cooled microreactor concepts (Idaho National Laboratory, 2023). Each reactor type poses a diverse set of design and operational challenges and performance claims stated by commercial vendors that have not been independently verified and validated through rigorous testing. The initial set of tests to be performed in MAGNET will demonstrate the feasibility and performance of heat-pipe-cooled reactors, since this concept is unique to small nuclear reactors.

1.1 Functions

To further the technological maturity of microreactors, MAGNET is designed to fulfill the following functions (Morton, Sabharwall, & Hartvigsen, 2022):

1. Provide a general-purpose testbed for performance evaluation of microreactor design concepts,
2. Provide detailed reactor core and heat removal section thermal-hydraulic performance data for prototypical geometries and operating conditions,
3. Enhance the readiness of novel reactor components such as heat pipes,
4. Provide test article and flow loop temperature-time histories during reactor startup, shutdown, steady-state, and off-normal operations,
5. Provide displacement and temperature field data for potential design performance verification and accompanying analytical model validation,
6. Evaluate the interface between simulated reactor components and the heat removal heat exchanger for geometric compatibility, functionality, and heat transfer capability,
7. Test the interface of the reactor heat removal section to auxiliary systems, such as power conversion systems or process heat applications,
8. Evaluate concepts for passive decay heat removal,
9. Measure the effects of non-uniform heating profiles,
10. Demonstrate the effects of heat pipe or flow channel single and cascading failures,
11. Identify and develop advanced sensors and power conversion equipment for autonomous operation and for in-operando data collection and monitoring,
12. Assess structural integrity of the core block, (i.e., thermal stress, strain, aging/fatigue, creep, and deformation),
13. Study the effects of cyclic loading on materials and components,

14. Demonstrate the applicability of advanced manufacturing techniques, such as additive manufacturing and diffusion bonding, for nuclear reactor applications,
15. Enhance the technical readiness level of components and help address technical knowledge gaps to support high-temperature reactor components and systems.

Performance testing of systems or relevant components in MAGNET will be conducted under prototypical conditions that ensure safe operation of the microreactor. This performance testing will focus on thermal and structural performance. MAGNET was designed to allow integration of auxiliary systems (for example, a power conversion unit [PCU], desalination equipment, chemical processes [such as electrolysis], and district heating). This integrated system testing capability is a hallmark feature of MAGNET. Not all physical processes and phenomena will be emulated, rather only some that yield important safety and performance data.

MAGNET enables a plug-and-play arrangement with relatively easy integration of experiments and flexible operating modes. In addition, MAGNET will provide verification and validation data for modeling and simulation (M&S) efforts such as hybrid system modeling (Ho, et al., 2022) and dynamic system scaling (Yoshiura, Fischler, Epiney, & Ketrow, 2022). The information from these M&S efforts is helpful in guiding the placement of instrumentation and predicting operating performance under a range of normal or accident conditions. M&S will also prove useful in the scaling of prototypical hardware for each test. The use of computational control and model feedback allows emulation of typical nuclear thermal response times and magnitudes (Bragg-Sitton & Morton, 2006).

1.2 Similar Testing Capabilities or Facilities

Other test facilities with similar capabilities include the Early Flight Fission Test Facility (EFF-TF) at NASA's Marshall Space Flight Center (Van Dyke, Houts, Godfroy, & Martin, 2003). It was designed and operated to provide realistic, non-nuclear testing of space fission reactors with a 0.09 to 0.2 kg/s flow of a helium-argon mix at pressures of up to 25 bar. Test article inlet temperatures of 326.85°C to 701.85°C and outlet temperatures of 576.85°C to 701.85°C and electric power of 480 kW were supported at EFF-TF. The High Temperature Test Facility at Oregon State (Gutowski, 2019) supported high-temperature gas-cooled reactor (HTGR) experiments at temperatures up to 760°C and pressures of approximately 64 bar. This test facility was intended to examine HTGR performance and provide fundamental understanding of their hydraulic behavior, but it is no longer in operation. Sandia National Laboratories (SNL) developed a 30 kWe, closed-loop Brayton cycle for compressed nitrogen to research coupling it with a microreactor and document its performance (Wright, Lipinski, Vernon, & Sanchez, 2006). None of these facilities are currently in operation. However, SNL has constructed and run a recuperated, closed-loop, Brayton cycle using supercritical carbon dioxide as the working fluid (Energy.gov, n.d.) to evaluate potential power generation from microreactors.

Chapter 2: System Design

A small set of design inputs, design bases, were used to design MAGNET and its individual components. Those design bases and the approach used to determine required flow rate, establish appropriate pipe sizing, and select components are described below.

2.1 Design Bases

MAGNET was designed to support gas-cooled test articles of 250 kW or less with temperatures of 750°C or less. The closed-loop cooling system was designed to remove the same 250 kW of heat from the test article using compressed air, N_2, or He. Temperatures and pressures typical of various microreactors were examined and are summarized in Table 2-1. The heat-pipe-cooled microreactor is somewhat agnostic in terms of the heat removal section pressure, so pressures and temperatures are reflective of a typical air Brayton cycle.

A desire to stay with conventional stainless-steel alloys (316 and 304) instead of using Inconel alloys for cost and schedule concerns drove the choice for an outlet temperature from the test article (T_H) of 600°C and an inlet temperature to the test article (T_C) of 360°C.

These values are consistent with those from a single-stage turbine design, such as the Sandia-Brayton Test Loop and a steam-Rankine bottoming cycle (Wright, Lipinski, Vernon, & Sanchez, 2006). The cooling loop was broken into three design areas, T1 (650°C), T2 (300°C), and T3 (60°C), which are denoted by color on the flow diagram in Figure 2-1.

Table 2-1. Summary of Coolant Pressures and Temperatures for Typical Microreactor Designs

Type	Coolant Outlet Temperature (T_H) (°C)	Coolant Pressure (bar)	Reference
HTGR	750 – 950	11 - 48	(Iwatsuki, et al., 2021)
Heat Pipe (sodium)	600	20	(Gaspar, et al., 2023)

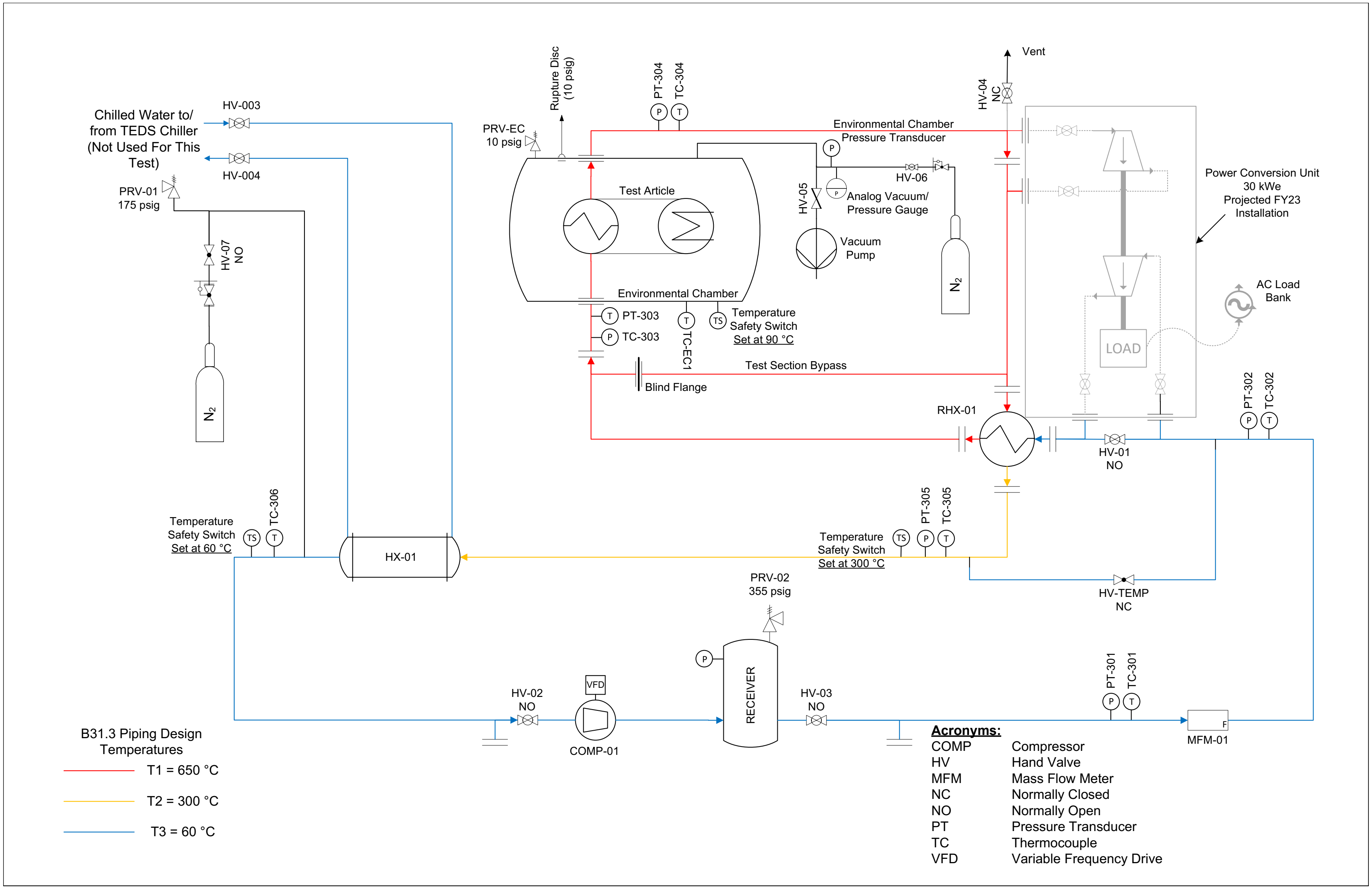


Figure 2-1. MAGNET Process and Instrumentation Diagram (P&ID)

2.2 Flow Rate Determination

To determine a flow rate for MAGNET, design values had to be selected for maximum reactor power (250 kW), coolant gas (N_2), and bounding temperatures T_H (600°C) and T_C (360°C).

To determine flow rate, the test article (heat source) was selected as a control volume to which the First Law of Thermodynamics, also known as the conservation of energy, was applied (Incropera, Dewitt, Bergman, & Lavine, 2007):

$$\Delta E_{ST} = Q - W \quad \text{Equation 1}$$

Where: ΔE_{ST} = change in energy stored in the system
Q = net heat transferred into the system
W = net work done by the system

$$\Delta E_{ST} = E_{IN} - E_{OUT} + E_G \quad \text{Equation 2}$$

Where: E_{IN} = energy into the system
E_{OUT} = energy out of the system
E_G = energy generated in the system

The derivative of $\Delta E_{ST} = E_{IN} - E_{OUT} + E_G$ Equation 2 with respect to time gives the same equation but with terms shown as rates rather than static values.

$$\Delta \dot{E}_{ST} \stackrel{\text{def}}{=} \frac{dE_{ST}}{dt} = \dot{E}_{IN} - \dot{E}_{OUT} + \dot{E}_G \quad \text{Equation 3}$$

Assuming the test article (control volume) is at steady state (dE/dt = 0), the gas flow does no pressure work, and there is no internal thermal energy generation, $\Delta \dot{E}_{ST} \stackrel{\text{def}}{=} \frac{dE_{ST}}{dt} = \dot{E}_{IN} - \dot{E}_{OUT} + \dot{E}_G$ Equation 3 can be reduced to the following equation.

$$\dot{Q} = \dot{m} \int_{T_C}^{T_H} c_p \, dT \quad \text{Equation 4}$$

Where: $\dot{Q}$ = *power* in kW
$\dot{m}$ = mass flow rate in kg/s
c_p = isobaric specific heat in kJ/kg-K

Nitrogen flow rate was calculated first since, of the three coolant gases, it has the lowest specific heat and therefore the highest mass flow rate. Since nitrogen has a temperature-dependent heat capacity, the Shomate equation ($C_p = A + BT + CT^2 + DT^3 + \frac{E}{T^2}$ Equation 5) and appropriate constants from the National Institute for Standards and Technology Chemistry WebBook were used to integrate the specific heat capacity for $\dot{Q} = \dot{m} \int_{T_C}^{T_H} c_p \, dT$ Equation 4 (Chase, 1998).

$$C_p = A + BT + CT^2 + DT^3 + \frac{E}{T^2} \qquad \text{Equation 5}$$

Where: c_p = Heat capacity in J/mol-K

T = temperature in K/1000

The values for constants A, B, C, D, and E are shown in Table 2-2. Integrating the Shomate equation from T_C to T_H and dividing by the temperature difference gave an average specific heat of 0.0311 J/mol-K (1.111 kJ/kg-K) and a mass flow rate of 0.938 kg/s N_2.

Table 2-2. Gas Phase Heat Capacity (Shomate Equation) for T = 500 to 2000 K

Constant	Value
A	19.50583
B	19.88705
C	-8.598535
D	1.369784
E	0.527601

2.3 Pipe Sizing

A design temperature of 650°C and maximum allowable working pressure (MAWP) of 22 bar represent the maximum, nominal operating values for temperature and pressure plus a margin of approximately 10%. The design temperature and MAWP drove the selection of 304H stainless steel (SA-312) (UNS S30409) piping in line with the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code material specifications in Section II (American Society of Mechanical Engineers, 2019). Schedule 40 piping was chosen after verifying that it met minimum wall thicknesses in DN80 (3-inch) nominal pipe size (NPS) and DN100 (4-inch) piping according to UG-27(c)(1) of Section VIII of the Boiler and Pressure Vessel Code (American Society of Mechanical Engineers, 2019). 3” stainless steel, ASTM A312 grade TP304H, seamless, schedule 40 piping has an outside diameter of 3.500 inches and a wall thickness of 0.216 inches (Oberg, Jones, Horton, & Ryffel, 2000) for an inside diameter of 3.068 inches. The same standard and material of 4” schedule 40 piping has an outside diameter of 4.500 inches and a wall thickness of 0.237 inches (Oberg, Jones, Horton, & Ryffel, 2000) for an inside diameter of 4.026 inches. The UG-27(c)(1) calculation indicates a minimum required wall thickness, t_{min}, of 0.008 inches for the 3” piping and 0.010” for the 4” piping.

$$t_{min} = \frac{P\,R}{S\,E - 0.6\,P} \qquad \text{Equation 6}$$

Where: *P* = pressure in psig (320) (MAWP)

R = inside radius minus 12.5% tolerance (Section II, Part A, SA-312, Table 3),

S = minimum tensile strength in psi (75,000) (Section II, Part D, Table 1A)

E = 0.60 (Table UW-12 weld type 3, single butt weld without backing strip)

With flow rate, temperature, pressure, and piping materials and dimensions, piping sizes required for the system were calculated. For cost considerations, pipe sizing was minimized as much as possible. To minimize flow noise, piping was sized piping to maintain a flow velocity of < 18 m/s (60 ft/s) (Society of Petroleum Engineers, 2015).

2.4 Component Selections

Below is a discussion of the criteria that were used to search for components and the methodology used to make selections where there were multiple choices.

2.4.1 Compressor (COMP-01)

A bounding flow rate and a desire to keep system pressure loss below ~10% of system static pressure set some guidelines for a compressor/blower search. A system differential pressure (dP) of 3 bar was selected, which provides the 10% of system static pressure plus a 50% margin should components or the test article have a higher dP than anticipated. Roots-type blowers, screw-type compressors, and reciprocating compressors were all considered to overcome system head.

Roots-type blowers are positive displacement compressors that use two or three lobes rotating in opposite directions with small tolerances to trap and compress pockets of gas providing motive force for the gas (see Figure 2-2 for diagram of how a two-lobed, Roots-type blower moves gas). Two-lobed compressors are typically used for process gas applications (Roots Systems, Ltd., 2023).

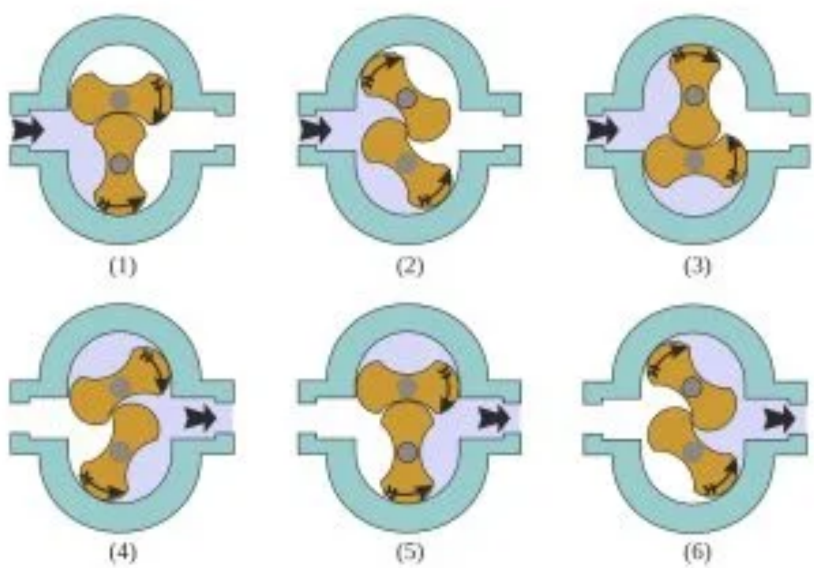


Figure 2-2. Two-Lobed, Roots-Type Blower General Operating Principal Diagram (Roots Systems, Ltd., 2023)

Screw-type compressors may or may not be positive displacement depending on whether or not oil is injected into the screws. Dry compressors (no oil injected into the screw housing) are not positive displacement and therefore have a flowrate that varies along a curve as a function of discharge pressure. Both oil-injected and dry screw-type compressors operate much like Roots-type blowers. Instead of simple lobes, however, screw-type compressors have helical lobed “screws” to trap and move volumes of gas providing motive force (Gardner Denver, n.d.).

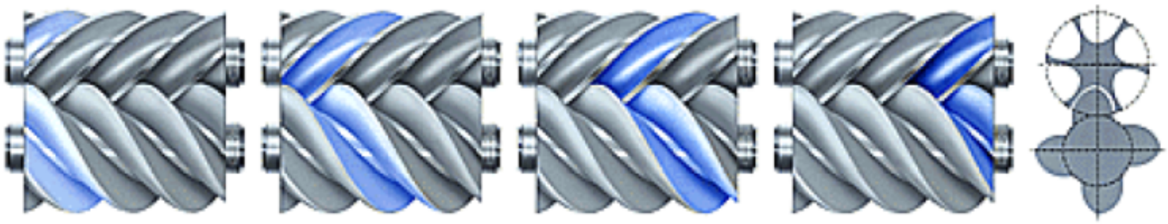


Figure 2-3. Twin-Screw Compressor General Operating Principal Diagram (Gardner Denver, n.d.)

Reciprocating compressors vary from simple, single-cylinder, single-acting compressors that pull a fixed volume of air in on the suction cycle, compress that air into a smaller volume, and then discharge it. The drawback to reciprocating compressors is that, since they send discreet pulses of compressed gas, the flow downstream of them pulses.

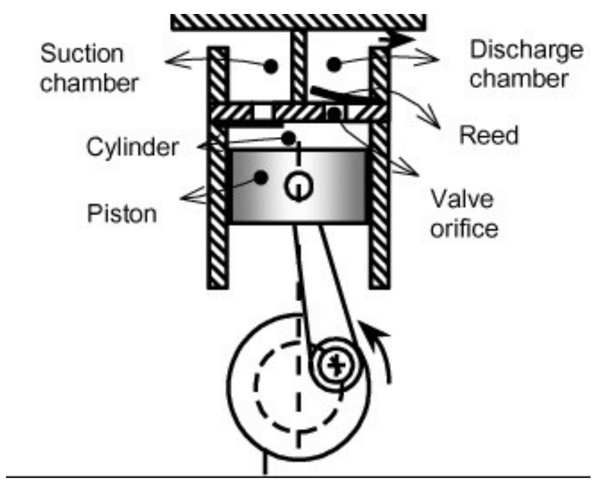


Figure 2-4. Diagram of a Single Cylinder Reciprocating Compressor (Linquip, 2023)

Long lead times and high prices led to the decision to purchase an off-the-shelf, reciprocating compressor despite the inherent pressure pulsation. The roots-type blowers are primarily custom-built units with a considerable lead time. A variable speed compressor rated for approximately half of the required system flow and a variable frequency drive (VFD) allowing flow rate control was chosen.

The manufacturer of the selected compressor lists the compressor performance with compressed, dry nitrogen at 74.3 m^3/h (43.7 actual cubic feet per minute (ACFM)) at 20 bar (290 psig). The manufacturer also provided performance parameters with compressed, dry helium upon request; these are 73.7 m3/h (42.4 ACFM) at 20 bar (290 psig).

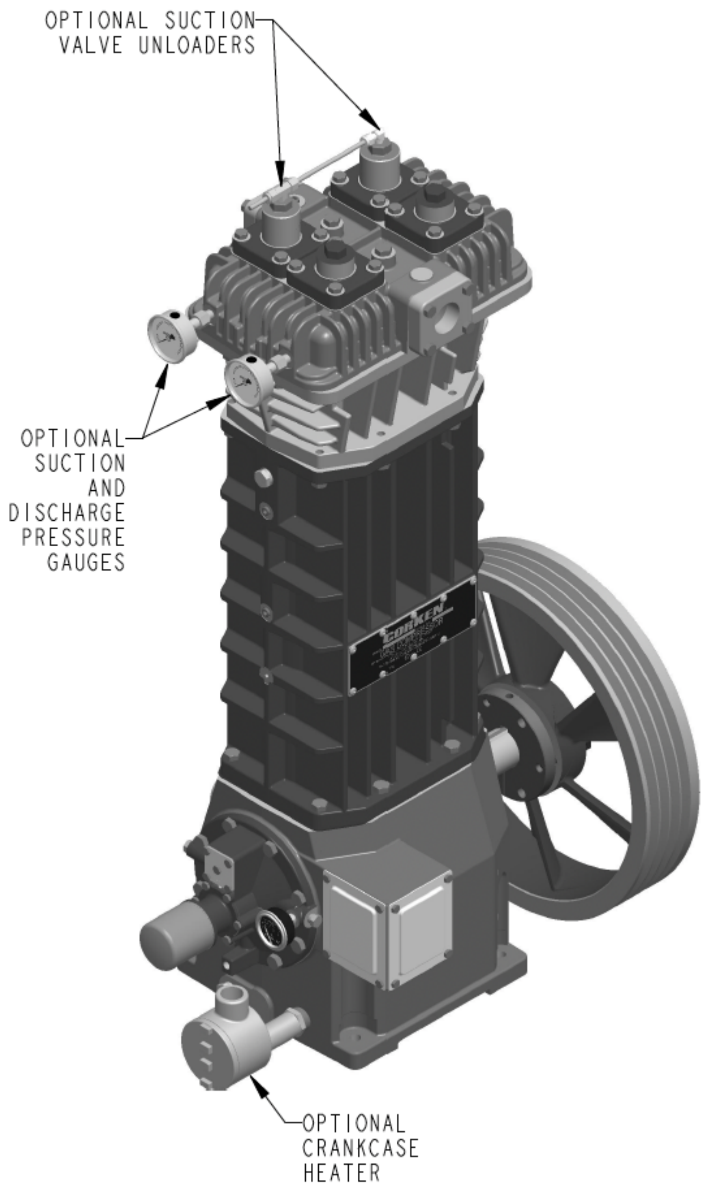


Figure 2-5. Rendering of CAD Model of Corken Compressor from Product Installation and Operation Manual

Since the piping was sized for approximately double this flow rate, tees on either side of the compressor allow the installation of a second compressor in parallel or a compressor bypass if a PCU with an integral compressor is added.

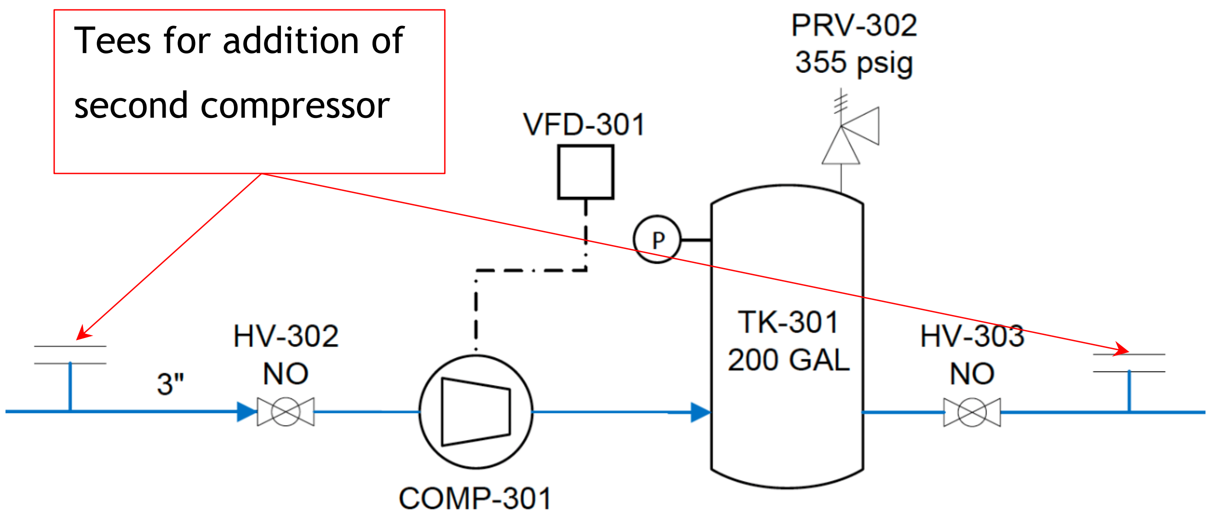


Figure 2-6. Section of P&ID Denoting Location of Tees for Additional Compressor

2.4.2 Recuperative Heat Exchanger (RHX-01)

A recuperative heat exchanger was desired in MAGNET to recover some of the heat coming from the test article outlet and reduce the amount of heat input. Without a recuperator a process heater would have been needed to preheat inlet gas to the desired 360°C to reduce the thermal stress on the test article. The recuperative heat exchanger, or recuperator, was one of the more difficult components to select, as discussed further below.

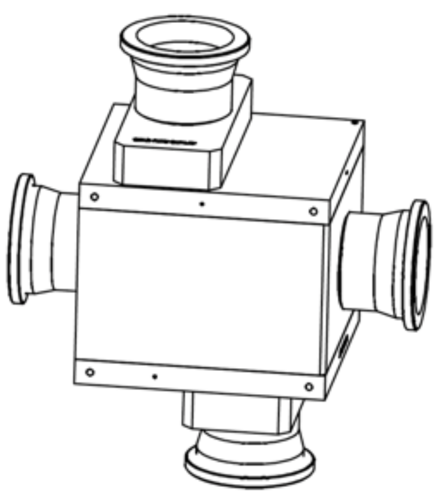
Many manufacturers either felt that the 600°C hot-side inlet temperature was too close to the creep limit of stainless steel or that the combination of pressure and temperature was too challenging. However, several compact platelet heat exchanger manufacturers bid on the project.

Compact platelet heat exchangers (CPHX) made an ideal choice for this application. CPHX are four to six times smaller than conventional heat exchanger designs. The small flow channels provide a large surface area per unit volume. In addition, those small flow channels present a smaller area on which high pressures can act, reducing stress and cyclic failure modes (Clean Energy Systems, Inc., n.d.).

Clean Energy Systems was selected to design and fabricate a compact-platelet, diffusion-bonded heat exchanger for RHX-01. The company was provided with the design parameters listed in Table 2-3 final design is shown in Figure 2-7.

Table 2-3. Recuperative HX Sizing Criteria

Parameter	Value
Gas	Compressed N_2
Mass Flow Rate (kg/s)	0.938
Maximum Allowable Working Pressure (MAWP) (barg)	22
Design Temperature (°C)	650
Cold Side	
Nominal Inlet Pressure (barg)	12
Desired Maximum dP (bar)	0.375
T_{COLDin} (°C)	38
$T_{COLDout}$ (°C)	360
Hot Side	
Nominal Inlet Pressure (barg)	10.625
Desired Maximum dP (bar)	0.375
T_{HOTin} (°C)	600
T_{HOTout} (°C)	Heat balance



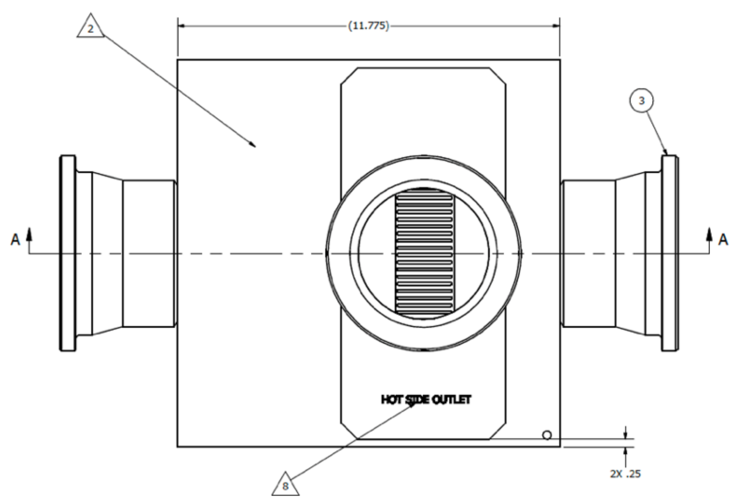


Figure 2-7. Isometric and Plan Views of HEXCES CPHX

2.4.3 Environmental Chamber

One of the first test articles planned for demonstration in MAGNET was a scale model of a sodium heat pipe cooled microreactor. Environmental and safety concerns with alkali metals required an environmental chamber (EC) to isolate any potential leakage of sodium from the surrounding occupied space.

The options for an environmental chamber investigated included vacuum chambers, waste storage tanks, and 20-foot shipping containers. Waste storage tanks comprise a wide range of shapes and sizes. Steel tanks are easy to fabricate and/or modify to meet project requirements. An example of a storage tank is shown in Figure 2-8.

Figure 2-8. Horizontal Storage Tank (Steel Tank and Fabricating Corp, 2021)

20-foot shipping containers are widely available, inexpensive, and easy to modify to specification. However, they are not airtight, and their size is fixed. Figure 2-9 shows an example of a modified shipping container designed to a customer’s specifications.

Figure 2-9. Custom Shipping Container (Container Technology, Inc., n.d.)

The primary requirements for the EC were the ability to run experiments on test articles in an inert atmosphere (i.e., the container needed to be mostly airtight) and the ability to house a test article of 2 m in length and 0.5 m in diameter with room for instrumentation and work. The size requirement was driven by an engineering-scale prototype of a hexagonal, heat-pipe-cooled reactor with a length of 2 m and a diameter of ~0.25 m.

The first proposed test article for MAGNET is shown in Figure 2-10. Its dimensions are 2 m in length by 0.2 m flat to flat. The test article, "eBlock37", is a subscale, electrically heated, heat-pipe-cooled prototype of a fast spectrum microreactor under development at Los Alamos National Laboratory. The prototype consists of an electrically heated core and gas-cooled heat exchanger. These subassemblies, both built from 316 L stainless steel, are thermally linked by an array of 37 sodium heat pipes designed to transfer a nominal 100 kW from the core at 700°C (Gaspar, et al., 2023).

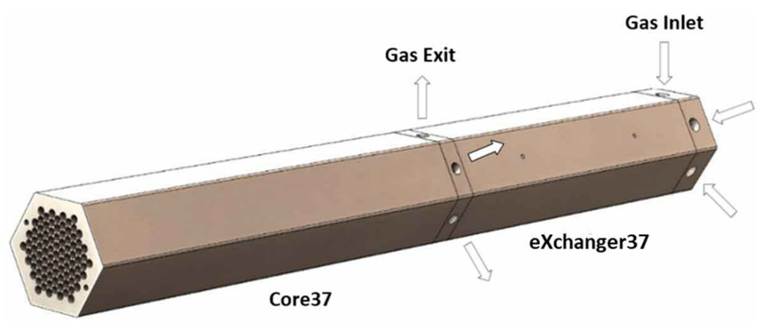


Figure 2-10. Rendering of Initial Proposed Test Article for MAGNET (Gaspar, et al., 2023)

Discussions on potential future test articles raised the proposition of potential tests on space power applications, so a vacuum chamber was chosen to support running experiments in a low vacuum, ≤ 10^{-3} torr. In order to accommodate the test article described above and provide room to connect gas coolant piping, insulation, and instrumentation, a rectangular vacuum chamber of 1.5 m in height x 1.5 m in width x 3 m in length was chosen. A cooling jacket was added to the design to keep surface temperatures on the outside of the chamber below 51.7°C (125°F), which is the threshold temperature at which a surface is considered a thermal hazard to personnel by INL safety. Figure 2-11 shows photos of the environmental chamber installed on the MAGNET skid.

Figure 2-11. Photos of Installed Environmental Chamber

2.4.4 Final Heat Sink (HX-01)

The final heat sink for the MAGNET gas cooling loop, HX-01, is not subject to exceptional temperatures or pressures and multiple choices were available. After investigating selections from multiple manufacturers, a shell-and-tube type, counter-flow HX was chosen for its low cost and small size.

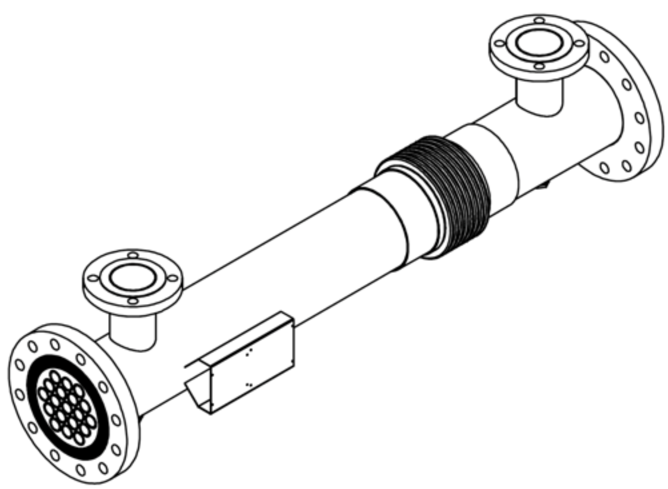


Figure 2-12. Isometric Rendering of HX-01

Figure 2-12 shows a rendered wire frame of the CAD model of HX-01 from the manufacturer, and Figure 2-13 shows a drawing side view of the HX with dimensions (in inches) from the approved shop fabrication drawing.

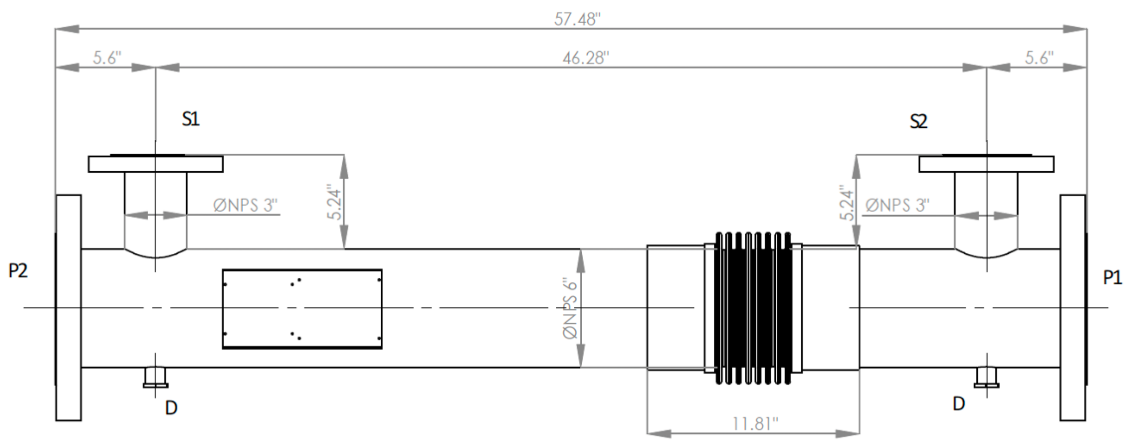


Figure 2-13. Side View of HX-01 With Dimensions

Table 2-4 presents the bounding design parameters provided to vendors for the selection of HX-01. Shell-side cooling is provided by a pre-existing chilled water system with a 50% ethylene glycol by volume-water solution. The 50% ethylene glycol prevents the chilled water from freezing at That chilled water removes heat from the system prior to the compressor inlet.

Table 2-4. HX-01 Sizing Criteria

Parameter	Value
Tube Side	
Fluid	Compressed N_2
MAWP (barg)	22
Nominal Inlet Pressure (barg)	12
Mass Flow Rate (kg/s)	0.938
T_{N2in} (°C)	275
T_{N2out} (°C)	20
Shell Side	
Fluid	50% Ethylene Glycol
Nominal Inlet Pressure (barg)	1
Desired Maximum dP (bar)	0.375
T_{CWin} (°C)	6.67
T_{CWout} (°C)	17.8

2.4.5 Instrumentation

To provide data for thermal hydraulic performance and for model verification and validation, a suite of sensors and a data acquisition system were chosen to record appropriate data and to control both MAGNET and the test article.

2.4.5.1 Flow Rate

For system flow, a thermal mass flow meter was selected for its high turndown and low pressure loss. A thermal mass flow meter determines gas velocity by measuring the amount of current required to keep a heated element at a certain temperature. The flowing gas cools the element, and the meter must apply a current to maintain the temperature. This type of flow measurement is specific to one gas, so if the coolant gas is switched from N_2 to He, the flow meter must be switched.

An inline flow meter from Kurz Instruments with an accuracy of ±1.23% of meter reading was chosen for MAGNET. The accuracy is a function of the meter flow area plus a standard error for the Coriolis effect velocity measurement. The flow meter includes a flow conditioner – a section of pipe that ensures a fully-developed flow, which allows a reasonable assumption for a uniform velocity profile. See Figure 2-14 for an outline drawing of the flow meter. See Table 2-5 for dimensions referenced in the drawing.

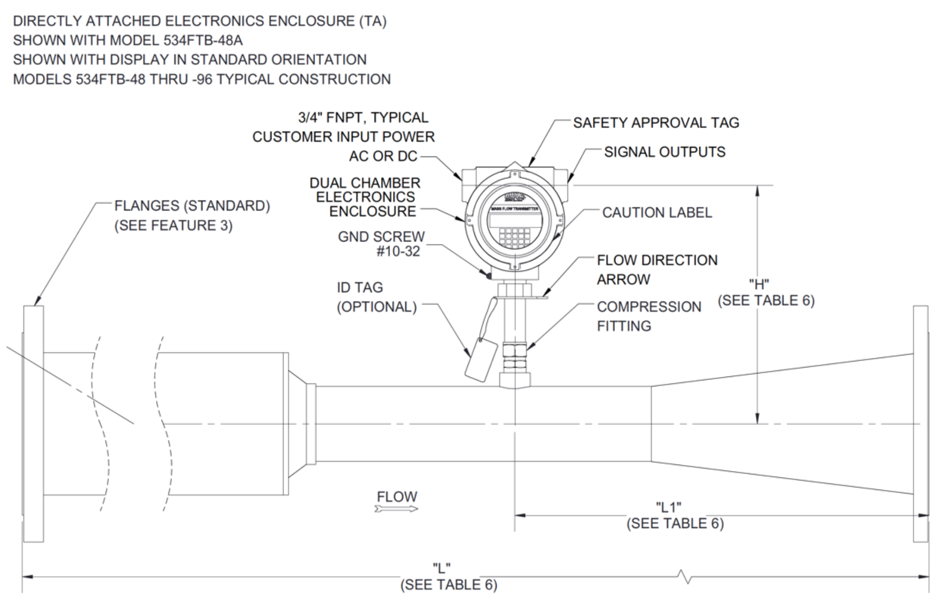


Figure 2-14. Outline Drawing of Kurz 534FTB

Table 2-5. Dimensions Information For Flow Meter

Model Number	Nominal Pipe Size (inches)	Dimensions (inches)		
		(L)	(L1)	(H)
534-FTB-64A	4	94.0	9.18	13.18

2.4.5.2 Pressure

Pressure transducers were chosen for locations up and downstream of each HX in the system and at the inlet of the flow meter in the event we needed to pressure compensate the flow rate to determine mass flow. We chose configurable pressure transducers from Omega with a 0-34.5 bar (0-500 psi) range, an accuracy ±0.08% of full range, a twist-lock (MIL spec) terminal, and a 4-20 mA output. These transducers were readily available and inexpensive.

2.4.5.3 Temperature

For temperature measurement, in the absence of any programmatic accuracy requirement, standard, ¼", sheathed, type K thermocouples from Omega Engineering were chosen. Standard type K thermocouples have an accuracy of ±2.2°C or 0.75%, whichever is greater (Omega Engineering, Inc., n.d.).

2.4.5.4 Data Acquisition and Control

For data acquisition and control, a National Instruments PXi chassis and Windows 10 based LabView was selected. All instruments and control devices interface with National Instruments input/output (I/O) cards, which are plugged into PXi modules. See Figure 2-15 for a photo of the computer, I/O cards, power supplies, and PXi modules.

A LabView virtual instrument (VI) was programmed to serve as the human machine interface (HMI). The VI contains all the subroutines required to read voltage or current from the sensors, convert that voltage or current to a value (pressure, temperature, or flow rate), and write it to storage. A screen shot of the primary control screen is shown in Figure 2-16.

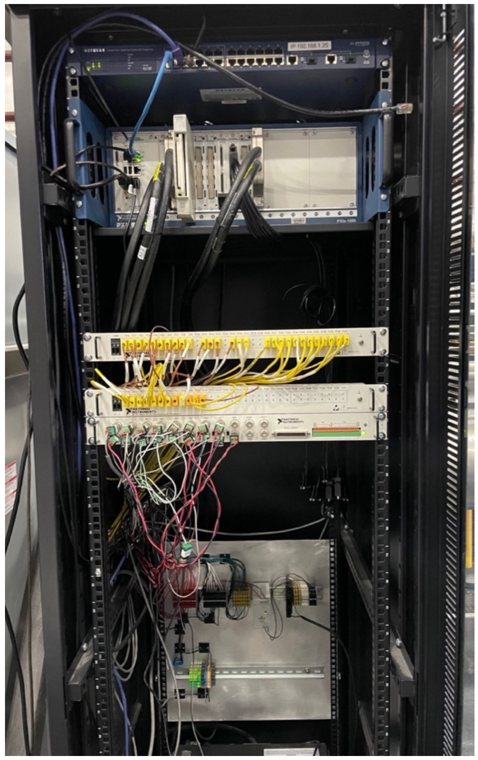


Figure 2-15. Data Acquisition Cabinet with Computer, Input/Output Cards, and Power Supplies

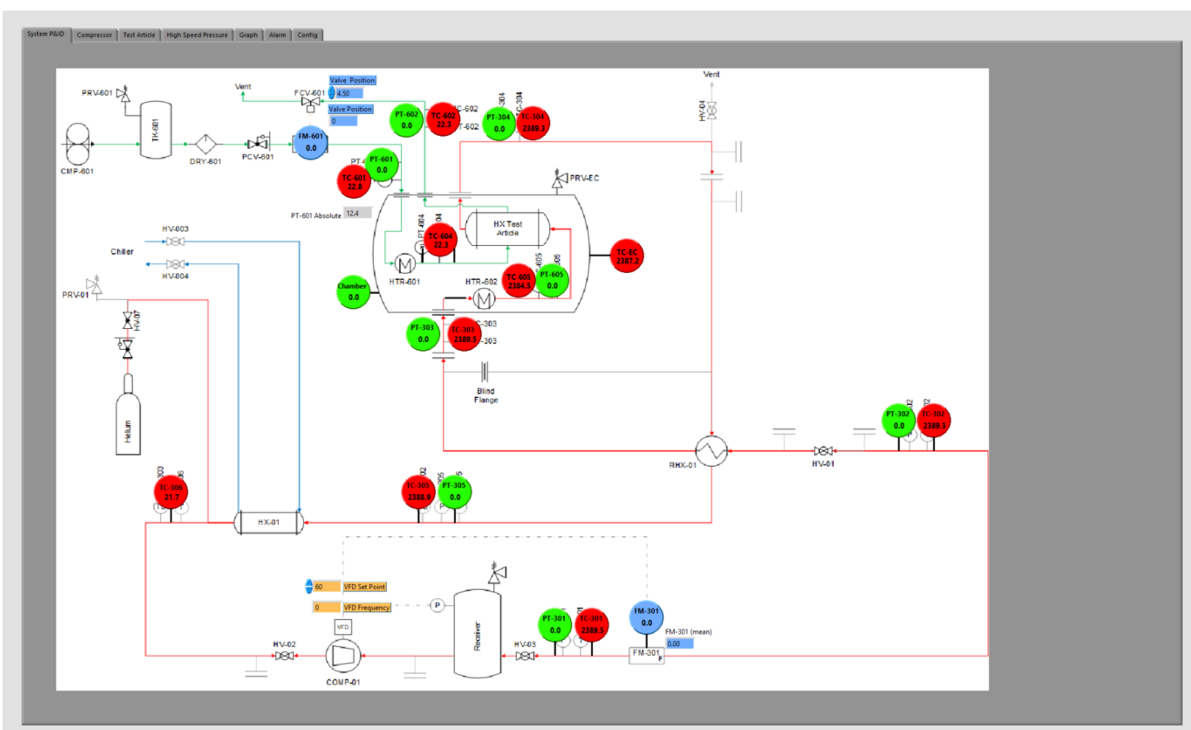


Figure 2-16. HMI for LabView VI (MAGNET Control Interface)

Chapter 3: ASPEN HYSYS Model of MAGNET

An ASPEN HYSYS model, using values from purchased equipment when available and engineering judgment bases when assumptions were made, was created to validate the MAGNET design. Piping geometry and dimensions were taken off from construction drawings in Figure A-1 through Figure A-5. The piping material is stainless steel ASTM A312, grade TP304H, seamless, schedule 40s with the properties shown in Table 3-1. The piping is insulated with two, two-inch layers of Thermo-1200 calcium silicate pipe insulation with stainless steel jacketing. The manufacturer specified thermal conductivity (Johns Manville, n.d.) was interpolated with a 3rd order polynomial data fit of data in Table 3-2.

Table 3-1. Piping Properties

Nominal Size	**2”**	**3”**	**4”**	**6”**
OD (inch)	2.375	3.5	4.5	6.625
Wall Thickness (inch)	.154	.216	.237	.28
ID (inch)	2.067	3.068	4.026	6.065
Commercial Steel Roughness (mm)			.09	
Thermal Conductivity (W/m-K)			14.4	

Table 3-2. Insulation Properties

Insulation (Thermo-1200 Ca-SiO$_3$)							
Mean Temperature (°C)	38	93	149	204	260	316	371
Thermal Conductivity (W/m-K)	0.05	0.056	0.063	0.07	0.078	0.085	0.093

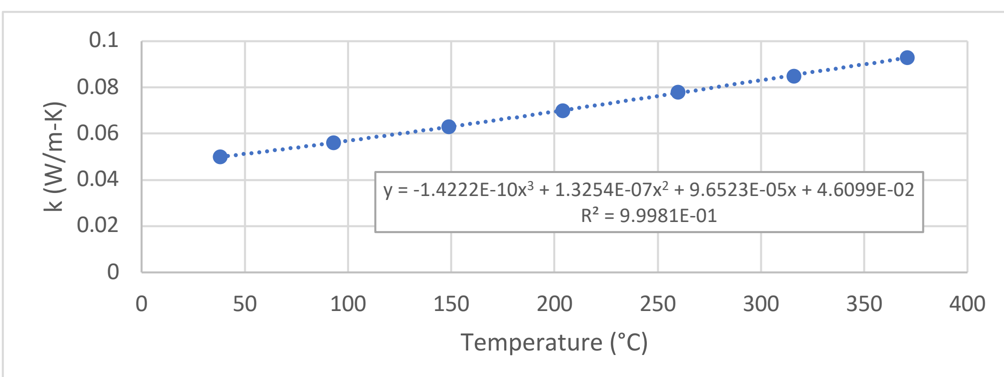


Figure 3-1. Curve Fit of Insulation Properties

COMP-01 was modeled as a reciprocating compressor with design conditions and parameters shown in the factory provided performance worksheet in Figure A-6. Discharge pressure was set at 12 bar and adiabatic efficiency at 47% to match overall efficiency listed in the performance worksheet. This resulted in compressor duty calculated by HYSYS that was close to the listed brake horsepower at design conditions.

RHX-01 was modeled as a simple weighted heat exchanger. A weighted model in Aspen HYSYS breaks up the heat curves into a default of 5 segments. It is intended for counter-current heat exchangers in which the overall heat transfer coefficient does not remain constant. The differential pressures were set as a percentage of inlet pressure, which was based on the design conditions supplied to the manufacturer as shown in Table 2-3. The cold side outlet temperature was set at 360 °C.

The test article was defined as a generic heat source with a duty of 250 kW and a pressure drop of 2% relative to its inlet pressure. There were no design specifics for the test article, so a general rule of thumb of 2% was used for pressure drop.

HX-01 was also modeled as a simple weighted heat exchanger based on the manufacturer's specifications and performance report shown in Figure A-7 and Figure A-8 respectively. Differential pressures were set as a percentage based on the design conditions shown in the performance report. A simple cooler and pump loop were modeled to simulate the chiller that supplies a 50% by volume ethylene glycol mix to cool HX-01 with pump head values based on equipment already procured to deliver a 20 °C gas outlet temperature.

An iterative solver, called a RECYCLE operation, was added between the last section of piping and the compressor so that the HYSYS model would converge without having to constrain the model with a fixed compressor inlet temperature and pressure. This solver allows HYSYS to use an estimated solution for compressor inlet temperature and pressure, but then iterates the calculations until the solution converges.

Calculated values for pressure drops compare favorably with those determined in an independent modeling effort (Frick, 2019). The outputs from this model are shown in Figure 3-2 with the flow diagram from the validating model shown in Figure 3-3.

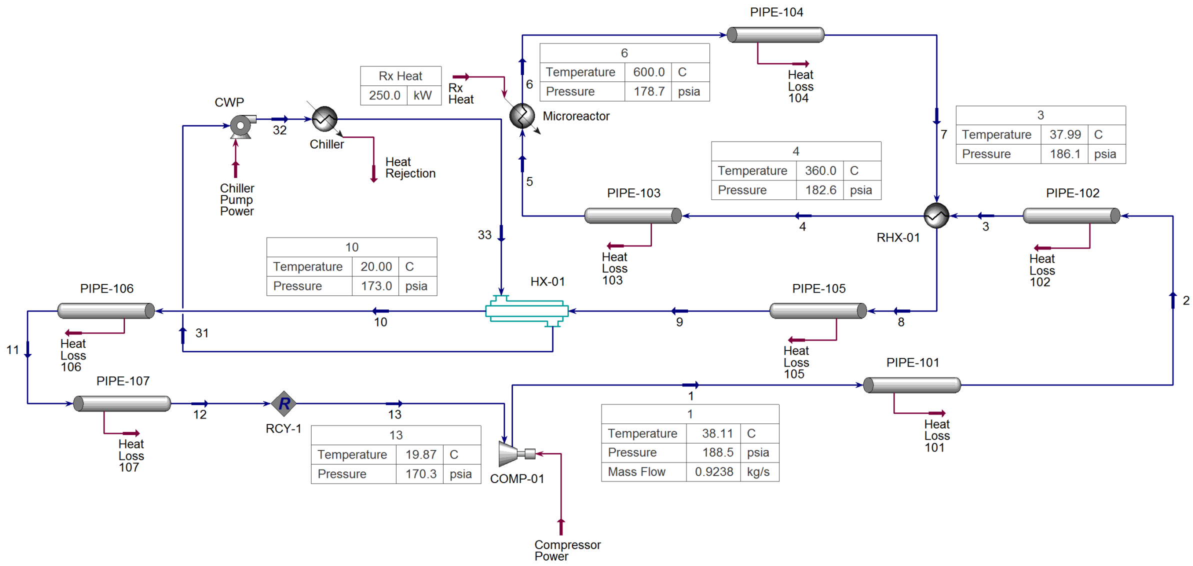


Figure 3-2. Aspen HYSYS Model Outputs

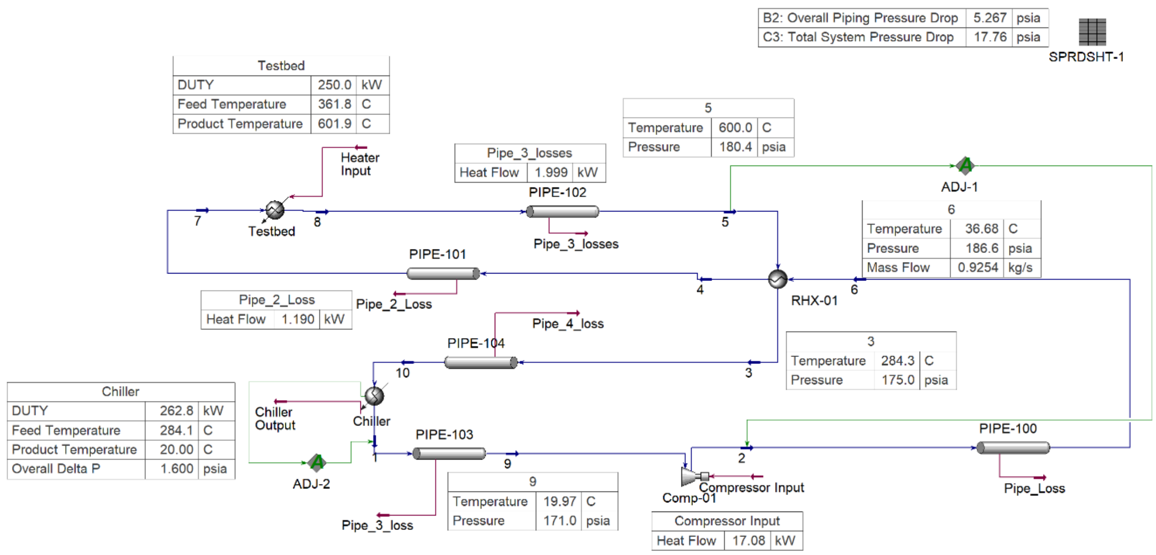


Figure 3-3. Aspen HYSYS Outputs From Independent Modeling Effort

Chapter 4: System Operations

This chapter provides a general operating strategy for the system and describes initial startup and system testing for a commercial reactor developer. Refer to Figure 2-1 for the MAGNET process and instrumentation diagram that provides a visual aid.

An inert gas is supplied by compressed gas cylinders via a regulator. The regulator maintains system pressure and compensates for gas contraction and/or leakage during system operation. A relief valve installed in the piping leading to MAGNET compensates for any gas expansion during heatup by venting pressure. COMP-01 provides head for the coolant to overcome system pressure losses. Its speed is controlled by a variable frequency drive (VFD) with the output signal from the mass flow meter (MFM-01) providing the process variable for control of the VFD to match the required mass flow rate for any given test. The compressed gas is pre-heated by rejected heat from the test article in RHX-01. The pre-heated, compressed gas flows into the environmental chamber, where it removes heat from the test article. A test section bypass line allows the system to run without flowing gas through the environmental chamber, if necessary, which allows system operation with no test article in place for shake down testing. Hot gas out of the test article flows through and rejects heat in RHX-01 before being cooled to ambient by HX-01. Heat is removed from the shell side of HX-301 by chilled water supplied by the co-located thermal energy distribution system (TEDS). No active cooling control is supplied for HX-01, other than the temperature of the inlet chilled water. COMP-01 and MFM-01 are in the low-temperature section of the flow loop.

4.1 System Startup and Shakedown Testing

Startup of a new system at Idaho National Laboratory requires a detailed hazard analysis. Those hazards, and any mitigations for them, are identified, reviewed by a range of subject matter experts, and then summarized in a table for inclusion in the work control that governs the system operation. The hazard identification and mitigation table is reproduced in Table B-1.

The first test performed in MAGNET was of a proprietary helium-to-air heat exchanger for a commercial reactor developer; this test was used as a shakedown test of the system. Since the testing called for pressures up to 20 bar and temperatures up to 650°C, the system was operated to the extent of its design pressure and temperature. In addition, the testing called for cycling of temperature and pressure, so bolted connections were examined and evaluated for adverse thermal cycling effects after the test.

4.2 Proprietary Helium-to-Air HX Testing

The first full-scale test performed in MAGNET was of an engineering-scale, prototype heat exchanger for a commercial developer. This test required additional capabilities for MAGNET. An open-circuit, compressed air system, two 80-kW process heaters, and additional pressure and temperature sensors were added. The compressed air circuit supplies up to 16.6 SLPM of air at 36 psig to the process heater and preheats that air to 335°C at the test article inlet. The compressed air piping out of the test article to its exhaust point outside the building is rated for the same 650°C as MAGNET. The helium process heater heats the helium stream up to 650°C. These modifications, dubbed the helium component test facility (He-CTF), provide the ability to test some high temperature helium components at MAGNET.

4.3 Performance Analysis of RHX-01

The experimental data available from this testing allowed us to determine the heat exchanger effectiveness of RHX-01 using the NTU method (Incropera, Dewitt, Bergman, & Lavine, 2007).

$$\epsilon = \frac{q}{q_{max}} \qquad \text{Equation 7}$$

Where: ϵ = effectiveness (dimensionless)

q = heat transfer rate (kW)

qmax = maximum heat transfer rate (kW)

Since the test data available for this heat exchanger used helium, an ideal gas, the ratio of the heat capacities is 1 and the mass flow rate is constant around the MAGNET cooling loop, $\epsilon = \frac{q}{q_{max}}$ Equation 7 simplifies to:

$$\epsilon = \frac{T_{co} - T_{ci}}{T_{hi} - T_{ci}} \qquad \text{Equation 8}$$

Where: T_{co} = cold side outlet temperature (°C)

T_{ci} = cold side inlet temperature (°C)

T_{hi} = hot side inlet temperature (°C)

As we have experimental data for temperature difference and mass flow rate, we calculated the duty of the HX with the logarithmic mean temperature difference and then the heat transfer proportionality constant, UA (Incropera, Dewitt, Bergman, & Lavine, 2007).

$$\dot{Q} = UA\Delta T_{lm} \qquad \text{Equation 9}$$

Where: $\dot{Q}$ = HX duty (kW) see $\dot{Q} = \dot{m}\int_{T_C}^{T_H} c_p\, dT$ Equation 4

U = overall heat transfer coefficient (W/m^2-K)

A = heat transfer area (m^2)

ΔT_{lm}= log mean temperature difference

$$\Delta T_{lm} = \frac{\Delta T_h - \Delta T_c}{ln\left(\frac{\Delta T_h}{\Delta T_c}\right)} \qquad \text{Equation 10}$$

Where: ΔT_h = temperature difference on the hot side of the HX

ΔT_c = temperature difference on the cold side of the HX

$$NTU = \frac{UA}{C_{min}} \qquad \text{Equation 11}$$

Where: NTU = number of transfer units (dimensionless)

C_{min} = minimum specific heat capacity (J/K) (helium is an ideal gas with constant specific heat capacity)

A plot with effectiveness and the number of transfer units is provided in Figure 4-1. At the start of the test all temperatures were at ambient. The error of the thermocouples combined to indicate an effectiveness greater than one, which is physically impossible. The uncertainty of the thermocouple measurements was carried through the calculation and is represented by the "Effectiveness Error" plot. The number of transfer units is also plotted.

In addition to the performance analysis of the HX, the Reynolds number and Prandtl number were calculated in the piping at the inlet to each side. These values are included in Table 4-1. The Reynolds number (Re), or the ratio of inertia to viscous forces, indicates whether flow is laminar or turbulent. Re at both inlets is >> 4000; this indicates that flow is turbulent in both instances. The Prandtl numbers for gases typically range between 0.7 and 1. As a ratio of momentum diffusivity to the thermal diffusivity, this result indicates that thermal and velocity boundary layers are similar in thickness (Incropera, Dewitt, Bergman, & Lavine, 2007).

Table 4-1. Dimensionless Parameters at Inlets to HX

	Reynolds Number	Prandtl Number
Cold Side Inlet (60°C and 20 bar)	$5.33x10^5$	0.71
Hot Side Inlet (650°C and 20 bar)	$2.12x10^5$	0.73

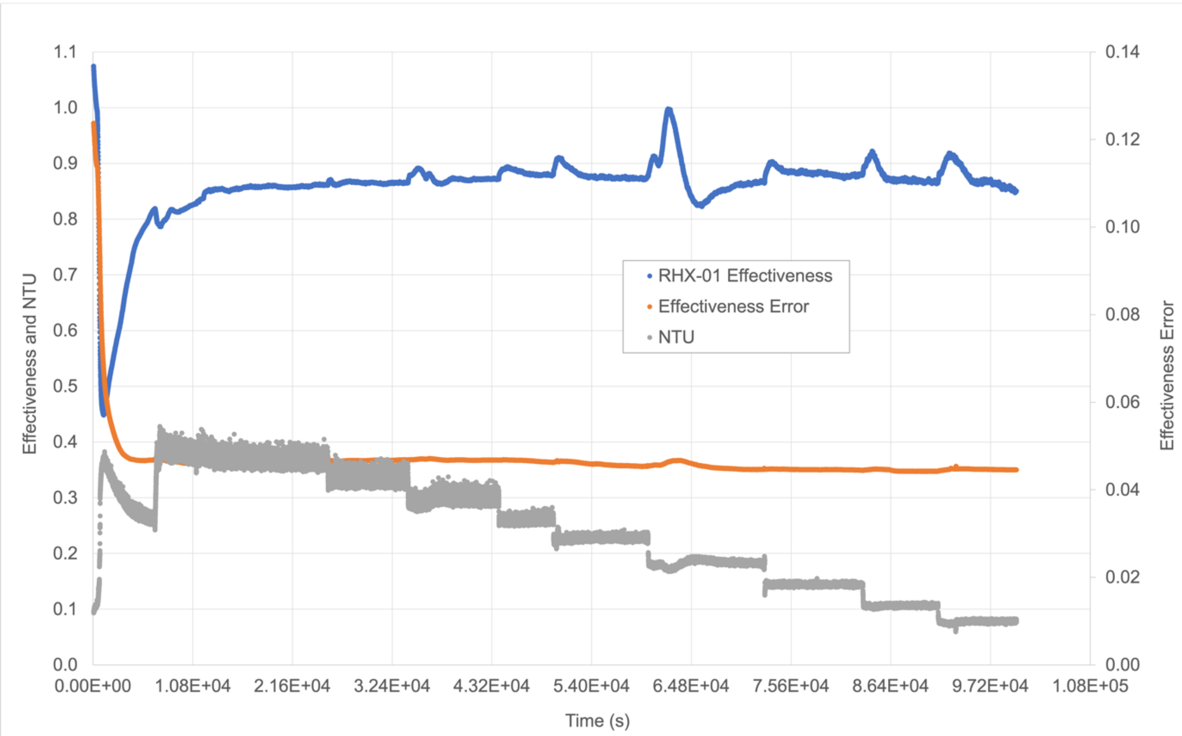


Figure 4-1. RHX-01 Effectiveness and Number of Transfer Units

Chapter 5: Future Work

Future work for MAGNET includes upgrading the controls from LabView to an industrial control system with some programmable logic controllers (PLC) and an industrial supervisory control and data acquisition (SCADA) system. LabView is not well suited for proportional integral derivative (PID) control loops, so switching to a more industrial-style control system with onboard PLC will enable PID control loops for flow rate and heater temperature control. The new control system will be based on the Opto22 groov® EPIC (Edge Programmable Industrial Controller) for instrumentation inputs and outputs and for the system control (Opto22, n.d.) and the SCADA HMI will be provided by Ignition software from Inductive Automation (Inductive Automation, 2023).

Design work to integrate a PCU with to MAGNET is in on-going. INL worked with SNL to obtain a gas turbine unit planned for disposal as excess. The PCU is a commercial, C30 gas turbine from Capstone Green Energy Corporation (Capstone Green Energy Coporation, n.d.) that was modified by Barber-Nichols (Barber-Nichols, n.d.) to run on compressed nitrogen heated with an electric heater. The integration of this PCU was evaluated and an Aspen HYSYS model was created in 2020 by INL researchers (Guillen & Wendt, 2021). A schematic of the system configuration with the PCU integrated is shown in Figure 5-2. The PCU is expected to run with heat supplied by a heater or test article in MAGNET. An integral recuperative heat exchanger is included in the PCU to preheat gas prior to its return to MAGNET and recover exhaust heat from the turbine. A final heat exchanger will cool the gas after the recuperator and prior to compression.

In addition, MAGNET will be integrated with the thermal energy distribution system (TEDS) by a helical coil heat exchanger to support integrated energy system testing.

The Aspen HYSYS evaluation (Guillen & Wendt, 2020) provides reasonable estimates of operating parameters for a 30 kWe output of the turbine. These parameters are shown in Figure 5-1.

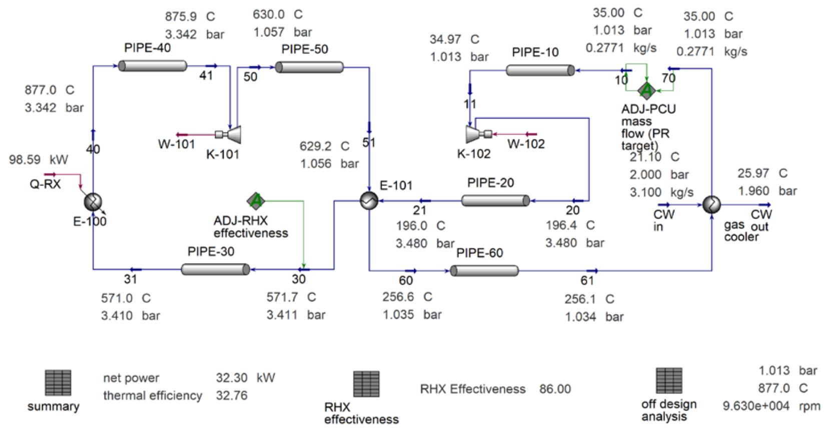


Figure 5-1. Aspen HYSYS Model Outputs for 30 kWe Operation of the PCU

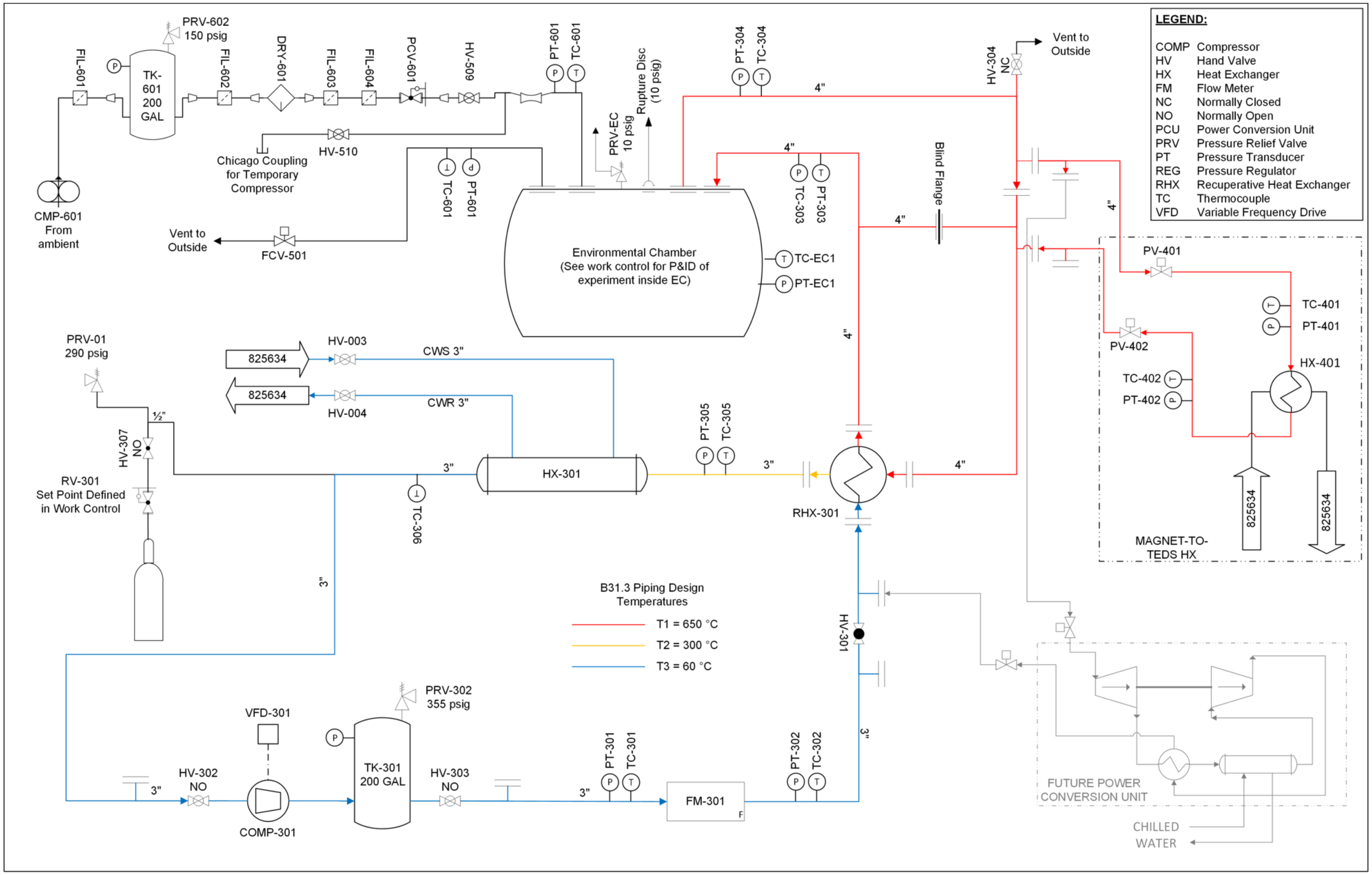


Figure 5-2. Schematic of MAGNET With PCU Integrated

Chapter 6: Conclusion

The MAGNET test bed provides a flexible platform in which demonstrators can test microreactor components or scaled models of microreactors in a non-nuclear environment. This testing can provide data for verification and validation of computational models, operational testing of components, and stress analyses of materials.

The system provides compressed nitrogen, helium, or air cooling at a maximum of 20 bar to remove heat from up to a 250 kW electrically heated test article. That cooling gas can reach temperatures of 650°C. Instrumentation and control is currently provided by National Instruments hardware and LabView software.

MAGNET design started in June 2019, construction finished in April 2022, and the first testing started in September 2022. Figure 6-1 shows the bulk of the test bed at the completion of construction. Future work includes the addition of a 30 kWe PCU and an Opto22 hardware with Inductive Automation’s Ignition SCADA software.

Figure 6-1. Photo of MAGNET Piping at the Completion of Construction

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Appendix A: Input Figures for HYSYS Model

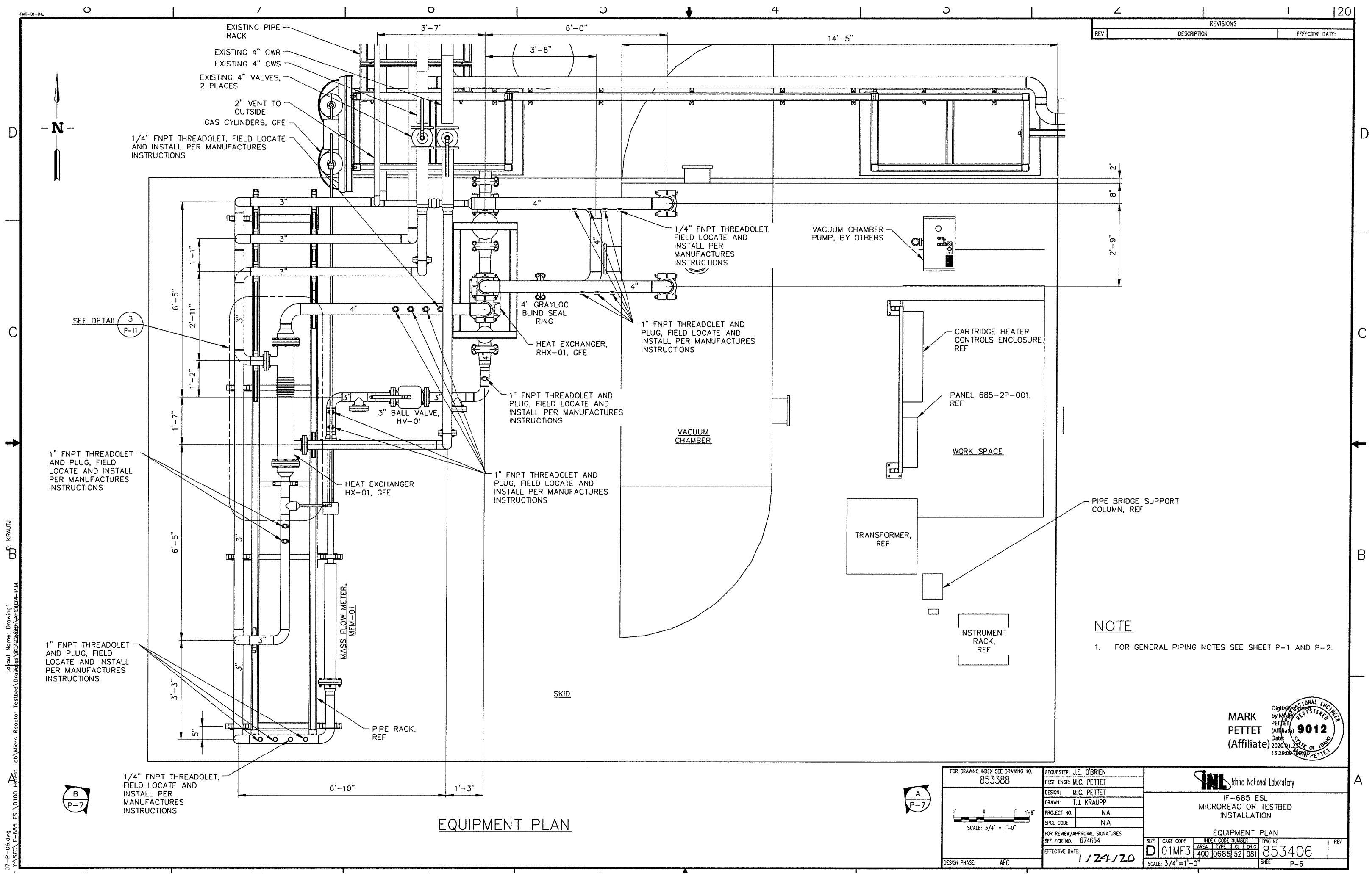


Figure A-1. Piping Construction Drawing (P-6)

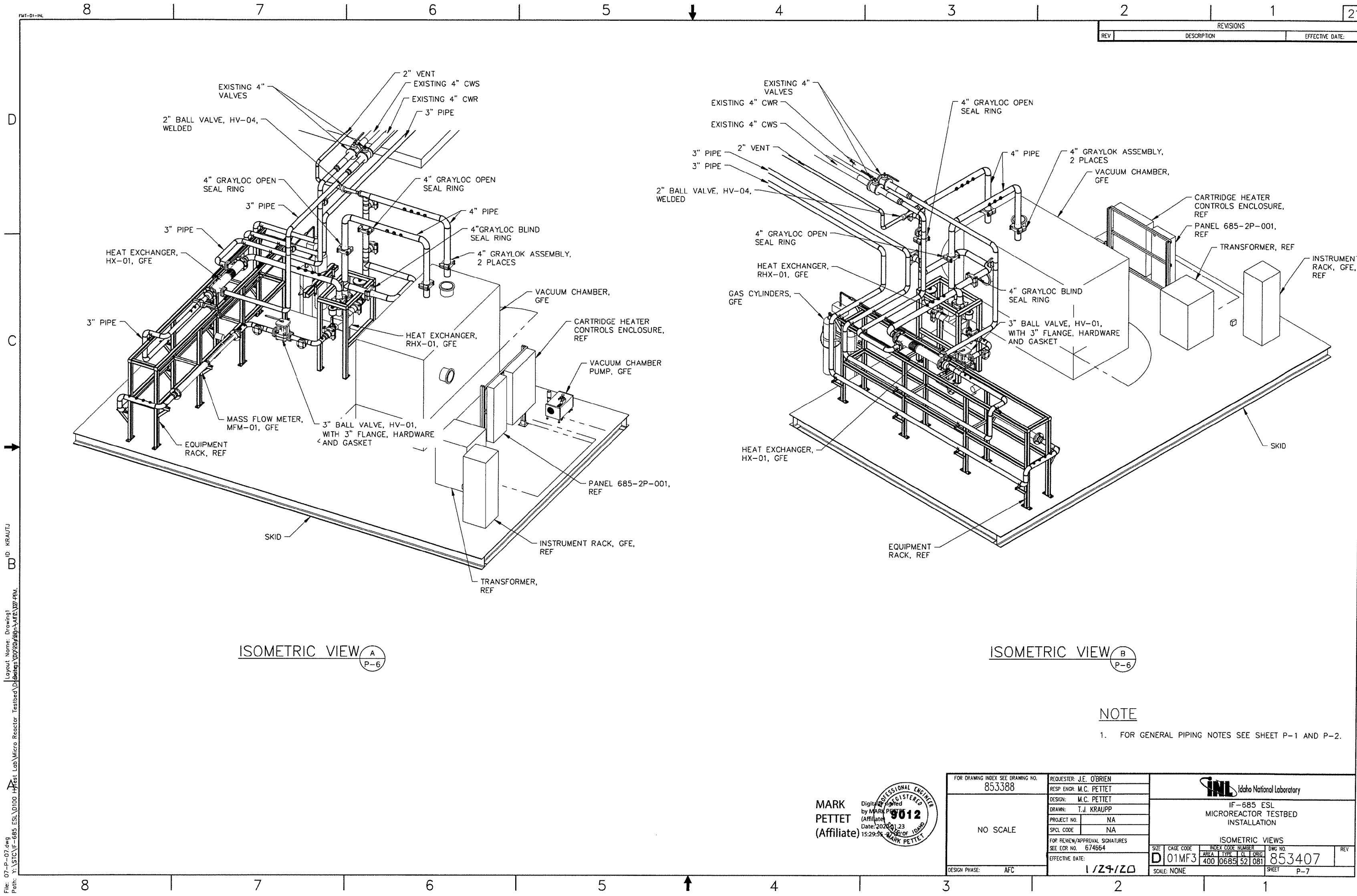


Figure A-2. Piping Construction Drawing (P-7)

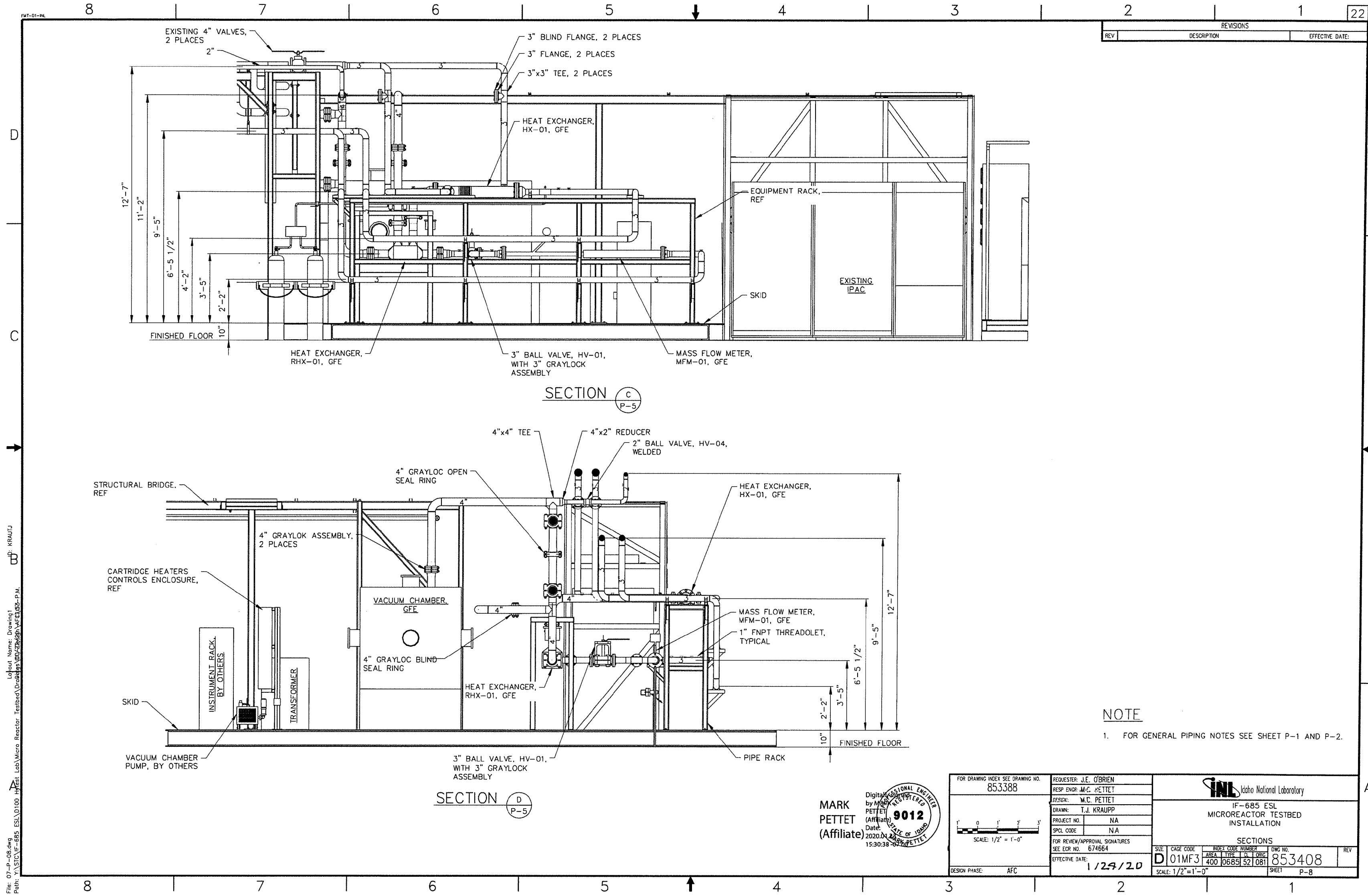


Figure A-3. Piping Construction Drawing (P-8)

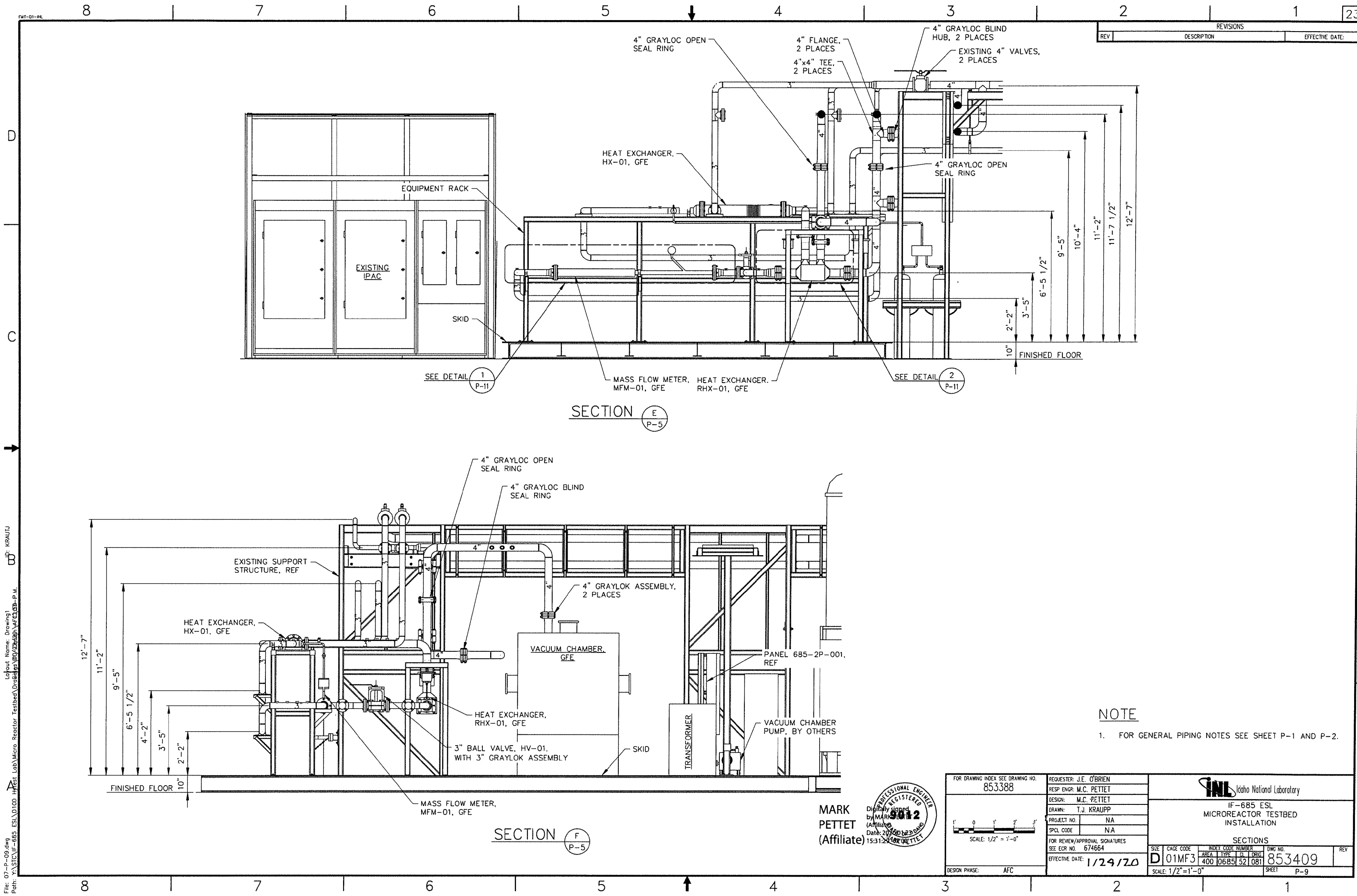


Figure A-4. Piping Construction Drawing (P-9)

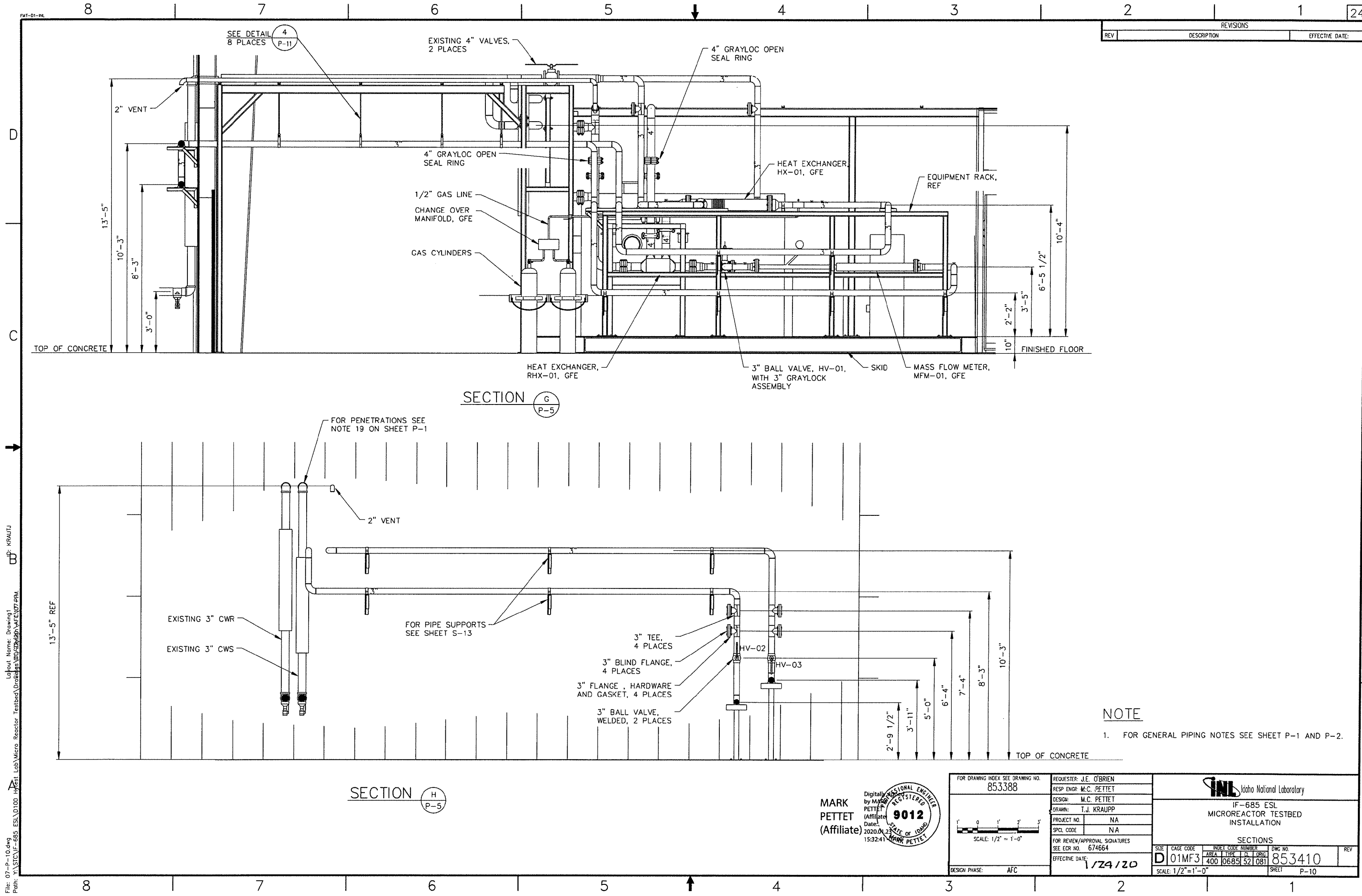


Figure A-5. Piping Construction Drawing (P-10)

Model: FD691-4

Input Data

RPM	Lube/Non-Lube Cyl.	Stroke	ATM Pressure	Speed Variation(%)	Std. Compressibility	Avg Thermo Torque	Avg Mech Torque	WK Sq.	Flywheel
825	Non-Lube	4	14.7	2.5	0.999	118.0	116.7	26.7	Standard Flywheel

Gas	n	Spec. Grav.	Crit. Press (psia)	Crit. Temp (Deg. R)
Nitrogen	1.40	0.97	493	228

Stage	Cyl. Dia.	Cyl.	Crankends	Headends
1	4	2	0	1

Output Data

	Piston Displacement	Suction Pressure	Discharge Pressure	Compress.	Inlet Temp.	Outlet Temp.	Volumetric Efficiency		
Stage	(CFM)	(PSIG)	(PSIG)	Ratio	Deg. F	Deg. F	Headend	Crankend	Overall
1	48.0	245.0	290.0	1.17	100.0	126	0.92	0.00	0.92

	Brake	Capacity					Efficiency			Inlet	Outlet
Stage	HP	ACFM	Discharge CFM	MCFD	SCFM	Lbs/Hr	Compress.	Mechanical	Overall	Comp.	Comp.
1	18.5	44.3	39.6	1054	731.8	3245	0.59	0.78	0.47	0.99	.99

	Deg Rod Reversal		Max Gas Rod Load		Max Inertial Rod Load		Max Total Rod Load		Max Continuous
Stage	Comp.	Tension	Comp.	Tension	Comp.	Tension	Comp.	Tension	Rod Load
1	290	70	1096	-155	658	1063	1684	809	7000

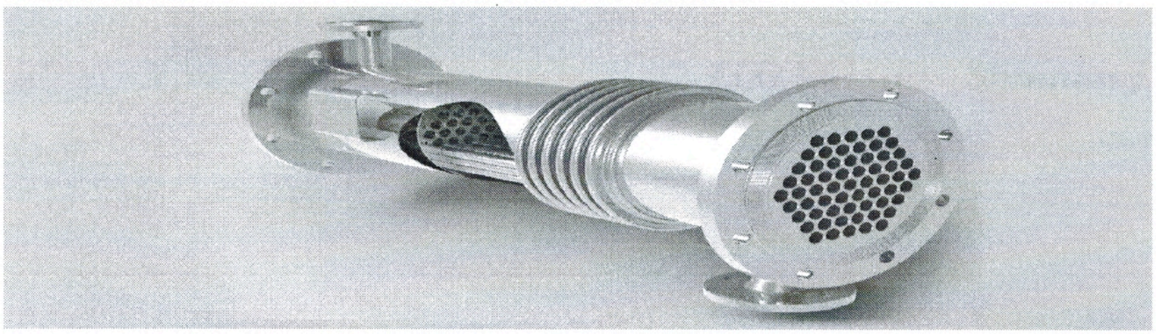
This Corken compressor program is designed to aid in showing the performance of Corken compressors at parameters of your choosing as long as they are within predetermined limits of operational parameters as set by Corken Engineering. These programs are not a substitute for sound engineering practices. Corken, Inc. hereby expressly disclaims any and all warrantees relating to this software including merchantability and fitness for use.

Version 050524

Figure A-6. Compressor (COMP-01) Performance Worksheet From Corken

XLG I-Series - Summary

Reference	
HEAT EXCHANGER	**XLG® I-SERIES**
No.Units x Model	XLG I-6"/19x1"-60"-304/304-X



GEOMETRY & FEATURES		
Channels	Shellside	Tubeside
Fluids	EG50	Nitrogen @11 barg
No.Parallel flow lines	1	1
No.Units in series per line	1	1
No.Passes	1	1
Shell & Tubes/Nominal length	6.63x0.11 inch / 4.92 ft	19 tubes 0.98x0.04" / 4.92 ft
Tube(s) pattern	Not corrugated	Corrugated
Material wetted areas	AISI-304	AISI-304
Inlet & outlet connections	ANSI#150 RFSO 3"	ANSI#300 RFSO 6"
Interconnections	-	-
Bonnets/Reducers/Bends	-	-
Gaskets	-	-
Inlet & outlet manifolds	-	-
Finish external / product side	Matt	Mill finish
Shellside baffles	8 segmental @45%	
Bellows	Included	
Mounting position	As wished	
Supports for installation	Not included	
Thermal insulation	Not included	
Side protection sheets	Not included	
Weight empty/full	-	
Footprint	-	

DESIGN CONDITIONS	Shellside	Tubeside
Operating/Design temperature	--/212°F	--/550°F
Operating/Design pressure	--/150 Psi	--/320 Psi
Fluid classification 97/23/EC	Not applicable	Not applicable
PED Category 2014/68/EU	Not applicable outside EU	
Design code	PED EN13445 Part 3	

Figure A-7. HX-01 Geometry and Design Parameters From XLG

XLG

Thermal Calculation

REFERENCE		
Customer		
Project		COMPRESSED NITROGEN COOLER
Item		

PROCESS		SERVICE	PRODUCT
Fluid		EG50	Nitrogen @11 barg
Channel		Shellside	Tubeside
Inlet temperature	[°F]	44.000	527.000
Outlet temperature	[°F]	64.000	68.000
Mass flow	[lb/h]	55 390.555	7 952.515
Volumetric flow	[gpm]	103.155	2 160.840
Velocity	[ft/s]	3.791	56.659
Pressure loss	[psi]	3.7875	1.6444

HEAT EXCHANGER		XLG® I-SERIES
Number of units / Model HEX	1	XLG® I-6"/19x1"-60"-304/304-X
Nominal length of units	[ft]	4.92
Flow arrangement		Counterflow

PERFORMANCE		
Heat load	[BTU/h]	912 613.665
Effective temperature difference	[°F]	203.408
K-value (clean)	[BTU/h·ft²·°F	168.422
Fouled K-value	[BTU/h·ft²·°F	168.422
Fitted heat transfer area	[ft²]	24.094
Overdesign	[%]	17.431

GEOMETRY AND DESIGN DATA		SHELLSIDE		TUBESIDE	
No. Units parallel/series flow		1	1	1	1
Diameter / wall thickness	[in]	6.63	0.11	0.98	0.04
No. Tubes per channel / passes		1	1	19	1
Working pressure (max/min)	[psi]	72.52	FV	174.05	FV
Working temperature (max/min)	[°F]	212.00	32.00	550.00	32.00
Design pressure	[psi]	150.00		320.00	
Volume	[USgal]	1.20		11.84	
PxV - PED	-	Not applicable		Not applicable	
Category 97/23/EC		Not applicable		Not applicable	
Metal Temp (average)	[°F]	54.00		117.47	
Metal material		AISI-304		AISI-304	
Connection type		ANSI#150 RFSO		ANSI#300 RFSO	
Gasket material		-		-	
Shellside baffles		8 segmental @45%		-	

FLUID DATA		EG50		Nitrogen @11 barg	
Channel		Shellside		Tubeside	
Density (in/out)	[lb/ft³]	66.946	66.582	0.45884	0.86452
Specific heat (in/out)	[BTU/lb·°F]	0.820	0.828	0.25359	0.24780
Latent heat	[BTU/lb]	-	-	-	-
Thermal conductivity (in/out)	[BTU/h·ft·°F]	0.240	0.241	0.02392	0.01410
Consistency index (in/out)	[cP]	5.997	4.099	1.00000	1.00000
Flow behaviour		1.000	1.000	1.00000	1.00000
Apparent viscosity (in/out)	[cP]	5.997	4.099	0.02733	0.01734
Fouling resistance	[h·ft²·°F/BTU	0.000000		0.000000	
Reynolds No.		2 194.081		132 927.584	
Prandtl No.		40.267		0.716	

Figure A-8. HX-01 Thermal Hydraulic Performance Calculation From XLG

Appendix B: Hazard Identification and Mitigation

Table B-1: Hazard Identification and Mitigation Measure Table

Activity/Task	Hazard	Engineering Control	Administrative Control	Personal Protective Equipment (PPE)
1) Transport and load compressed gas cylinders	Back injury or muscle strains and falling cylinders and foot crushing hazards		Use material handling devices whenever possible, get help to move heavy cylinders, do not bend or twist whilst lifting, do not lift more than 50 lbs, or 1/3 of body weight, whichever is less. Use cylinder cart to transport cylinders, secure cylinders to cylinder cart whilst moving, ensure cylinder cap is in place.	Protective footwear, leather gloves, safety glasses with side shields
2) Connecting cylinder gauges	Exploding or flying parts under pressure and/or cylinder damage	Gauge assemblies have integral pressure relief valves	Do not use oil on threads. Use correct gauges. Stand to side and open valve slowly.	Safety glasses with side shields and leather gloves
3) Storage of cylinders	Explosion or damage to cylinder	Cylinders have pressure relief	Store cylinders in designated storage area, secure cylinders to prevent them from falling. Move cylinders to storage area when not in use or empty. Store cylinders with caps on, ensure they are labeled correctly, and ensure that they have a full or empty tag. Ensure storage area is properly posted including any relevant hazard information for cylinders.	
4) Operation of pressurized vessels and systems	Incorrect selection of over-pressure safety relief device(s), improper	System designed by a competent pressure system designer/engineer. Documentation, traceability, and accountability maintained for each pressure system, including descriptions of design, pressure conditions,	Management of changes to ensure any system modifications meet or exceeds original design conditions. Follow ASME code for repair and commissioning of pressurized systems.	Contact IH SME for sound monitoring, and follow recommendations for hearing protection

Activity/Task	Hazard	Engineering Control	Administrative Control	Personal Protective Equipment (PPE)
(includes repairs, modifications, and reconfigurations of pressure systems)	material, or improper system operation, which can result in: • Uncontrolled release of energy • Creation of projectiles Release of helium Exposure to sound greater than threshold levels.	identification of pressure boundaries, testing, inspection, operation, repair, and maintenance. Specification of set point, capacity, and location of over-pressure protection devices where the source pressure can exceed the design pressure of the lowest rated components. Design documentation reviewed by a second pressure system designer/engineer and approved by line management. Pressure system leak testing in accordance with ASME B31.3. The compressed gas receiver on the COMP-01 skid is an ASME B&PV Section VIII, Division 1 pressure vessel protected by an installed pressure relief valve.	Refer to PLN-13115 and contact the ASME Pressure Vessel Program Manager prior to any work on, or modifications to, this vessel. Stamped vessels are placed on INL Pressure Vessel List Formal valve lineups as part of system start up and shut down	
5) Working on pressure system	Over pressurization	Use piping, tubing, valves, and fittings with pressure ratings greater than system design pressure. Install pressure relief devices where appropriate.	Qualification – QN000PSA Qualified Pressure System Assembler (PSA) Following assembly, system to be walked down by independent PSA. If affected components/piping are within the ASME code boundary, follow ASME code for modifications/repairs.	Safety glasses with side shields Level IV/A4 cut-resistant gloves for cutting
6) Operation of high-temperature piping/components. Working on	Surface temperatures > 125°F	Insulation and shielding as appropriate	"Caution, Hot" placards placed to alert personnel to hot surfaces and roped off boundaries	Thermal protection gloves

Activity/Task	Hazard	Engineering Control	Administrative Control	Personal Protective Equipment (PPE)
or near a high temperature system operating at temperatures > than 125°F				
7) Unattended experiments	Damage to equipment, failure of experiment	Upset or utility failure will not result in a situation that requires emergency actions. The test bed includes independent over-temperature limit controllers that will shut down the heaters in the event of overheating of the core block or the heat pipes.		
8) Use of portable step ladders or straight/extension ladders, portable stairs, and scaffolding.	Fall hazard		Use appropriate ladder (Type I or Type IA) or platform for task. Set or lock the wheels on the portable platform stairs. Prior to positioning the ladder, perform an inspection to ensure all hardware and fittings are securely attached, components are not corroded, and rungs are kept free of grease, oil, water, and other hazards. If ladder is found to be damaged or not working properly, immediately remove the ladder from service. If work is to be performed while standing on a rung more than 6 feet above the working surface, the work must be evaluated for fall protection. Qualification – QNSCAFUS	

Activity/Task	Hazard	Engineering Control	Administrative Control	Personal Protective Equipment (PPE)
			Inspect scaffolding by checking several randomly chosen fasteners for tightness.	
9) Assembly of electrical equipment	Electrical shock	Cord and plug isolation of electrical energy will be used as appropriate for servicing components	Qualification QNDREWT Research and Electronic Worker Safety De-energize by unplugging cord-connected devices/equipment and maintain exclusive control of plug and cord (within eyesight and arm's reach) or LO/TO. Only one person is allowed to work on a device or component under cord and plug control	Leather gloves may be worn
10) Use of electrical equipment	Electric shock, arc-flash, burn, fire, or blast	Equipment shall be: a. Listed by a nationally recognized testing laboratory (NRTL), e.g., UL, CSA, FM. b. Approved by INL National Electrical Code (NEC) authority having jurisdiction (AHJ) if there is not NRTL listing or if an NRTL-listed component/device has been modified by INL for a specific purpose. c. Approved by INL NEC AHJ if component/device was designed, fabricated, and assembled at INL.	Verify NRTL label/markings or INL NEC AHJ approval stickers are present prior to use.	
11) Voltage measurements – 50 V or less	Burn		Avoid bare-handed contact with energized conductors	None required
12) Voltage and/or current measureme	Electric shock, startle reaction, meter or lead	Use measurement equipment and probes rated as CAT III at 600 V or better	Establish a safe working condition, avoid contact per NFPA 70E 130.4 (F), ensure current rating of meter and leads exceeds that of the current to be	See LI-623 for PPE requirements.

Activity/Task	Hazard	Engineering Control	Administrative Control	Personal Protective Equipment (PPE)
nts (– 50 V to 300 V) that can only be performed while the equipment is energized such as trouble shooting.	overload, injury from arc		measured, ensure that meter and leads are connected such that a shock hazard is not present. A safe working condition must be established prior to connecting and/or disconnecting instrumentation for voltage and current measurements. Establish a safe working condition by use of exclusive control of cord/plug equipment or by LO/TO per LWP-9400 if exclusive control of the equipment cord/plug cannot be maintained or if the equipment is hardwired. Ensure that all scaling values are understood. Any work that exposes an employee to energized electrical circuit parts shall be justified per the requirements of NFPA 70E, approved by Laboratory Management and performed per LI-623, Energized Electrical Work.	
13) Perform soldering with soldering iron as necessary when fabricating, assembling, or repairing electronic devices	Thermal burns Exposure to rosin-cored solder fumes.	Use soldering tool guard when provided by the manufacturer.	Avoid direct contact of exposed skin with hot surfaces. Operate equipment in accordance with manufactures operating manual. If process requires more than incidental soldering (i.e., greater than 5 minutes), use local exhaust system. Do not breathe solder fumes. Do not eat or drink near soldering operations. Wash hands thoroughly after handling solder.	Safety glasses with side shields
14) Use of a pallet jack.	Tipping of loads and collision Foot injury Sprains and strains	Use correctly designed pallet jack with sufficient load capacity.	Loads in excess of the rated capacity must not be lifted. Inspect jack/truck prior to use. Keep hands and feet clear of lifted loads. Loads shall be evaluated by the operator to ensure they will not tip or collide with other objects or personnel.	Protective footwear when exposed to a foot crush hazard.

Activity/Task	Hazard	Engineering Control	Administrative Control	Personal Protective Equipment (PPE)
			Use proper pallet jack technique, pushing the load, not pulling the load, when possible. Use of company approved stretching program.	
15) General equipment assembly, component testing, calibration, and maintenance.	Pinch points and strains due to heavy lifting. Cuts and injuries from equipment, handling sharp objects, and/or when cutting or using powered or non-powered hand tools Head injury from bumping into equipment. Thermal burns from hot surfaces Electric shock / arc hazard from accessing electrical equipment or manipulating disconnects. Lab Ergonomics Falls	Use material handling devices, such as drum carts and drum dollies Ladders and elevated platforms are approved and in good working order. Platforms over four feet in height shall have railings installed to INL/BEA standards.	Do not lift more than 50 lbs or 1/3rd of one's body weight, whichever is less. When using utility knives, hand saws, maintain situational awareness and keep body parts from the cutting path Ensure cutting or drilling tools are de-energized by removing the battery or unplugging prior to changing the blade/bit. Remove or confine personal clothing, hair, jewelry, and attire that may become entangled with rotating parts. Workers must be properly trained and have the qualifications to work on elevated platforms and ladders. Check all portable ladders/stairs to ensure they are free from physical defects. Safety evaluation for fall protection is required when working above 6 feet on a ladder or 4 feet on platform or other elevated surfaces follow the Fall Hazard Prevention Analysis (FHPA) Personnel should maintain good situational awareness when working in areas with low overhead clearance Do not work on systems until they are below 125°F, except to remove insulation blankets to facilitate cooling. Use calibrated direct reading or IR tools to determine temperatures before handling.	Safety glasses with side shields. Leather palm gloves Level IV/A4 cut resistant gloves are to be used when handling sharp materials or bladed tools. Follow the Fall Hazard Prevention Analysis (FHPA) when on elevated platforms without railings or on ladders above 6 feet. Wear a bump cap when working in positions where bumping the head against solid materials is possible Wear leather gloves when removing insulation blankets. Protective clothing (non-melting natural fibers), hearing protection (ear plugs) with NRR rating of at least 30 dB, leather gloves are recommended.

Activity/Task	Hazard	Engineering Control	Administrative Control	Personal Protective Equipment (PPE)
			Maintain exclusive control of equipment power supply, e.g., cord plug or comply with INL/BEA LOTO procedures. Energy sources to affected areas shall be shown to be zero-energy prior to accessing electrical components Evaluate experimental configurations and workstations to identify ergonomic issues or actions that will be repetitive in nature. Consult with ergonomic TPOC to mitigate repetitive motion injuries and issues.	
16) Clearing and cleaning process equipment.	Mechanical motion Surfaces >125°F		Lock and tag out the equipment per INL procedures before engaging in exposed activities.	Thermal protective gloves
17) Temporary operation of equipment with exposed hazards.	Mechanical motion Surfaces >125°F Dust	Temporary guarding as applicable.	Perform a hazard analysis involving pertinent ES&H personnel to identify and mitigate temporary hazard exposure. Barriers as needed.	Thermal protective gloves Dust masks
18) Work in the environmental chamber	Asphyxiation Confined space		Isolation, lockout, and tagout of asphyxiant source The Environmental Chamber will be posted as a confined space. Prior to opening, coordinate with industrial hygiene (IH) to downgrade.	
19) System operation	Exceeding temperature limit of pressure sensors and	Over-temperature shut off with dedicated over-temp controller.	Administrative stop in test plan (when temperature exceeds 110°C at nearest TC to pressure transducer	

Activity/Task	Hazard	Engineering Control	Administrative Control	Personal Protective Equipment (PPE)
	potential leak of compressed nitrogen Exceeding temperature limit for electrical connections to Environmental Chamber		Administrative stop in test plan when temperature exceeds 120°C at power feedthrough on Environment Chamber	
20) General chemical use	Exposure to chemicals	See LI-845	See LI-845	See LI-845