



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

WASTE HEAT RECOVERY ANALYSIS OF A GAS TURBINE HEAT EXCHANGER

by

Denzel Reina

March 2021

Thesis Advisor:

Garth V. Hobson

Second Reader:

Douglas L. Seivwright

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC, 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE March 2021	3. REPORT TYPE AND DATES COVERED Master's thesis		
4. TITLE AND SUBTITLE WASTE HEAT RECOVERY ANALYSIS OF A GAS TURBINE HEAT EXCHANGER			5. FUNDING NUMBERS R7NL1	
6. AUTHOR(S) Denzel Reina				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) NSWC Carderock Division, West Bethesda, MD 20817			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) The U.S. Department of Defense has employed an initiative to become more conservative and efficient regarding uses of energy across all military services. The Naval Postgraduate School supported development toward this initiative by studying the possibility of electrical power generation using waste heat recovery within shipboard engine exhaust. This research included the development of a heat exchanger to use compressed carbon dioxide gas as the working fluid to run within a Brayton cycle. This thesis is built upon previous research using a Rolls Royce M250 helicopter engine and previously modified heat exchangers that were installed on the engine's dual exhaust. The effects that the modified heat exchangers had on the engine were measured and analyzed to determine new baseline efficiency and effectiveness parameters for the engine and heat exchanger, respectively. Nitrogen and carbon dioxide were used to develop baseline results. Additionally, an independent study was performed on the performance of an Organic Rankine Cycle waste heat recovery system at Cal Maritime Academy onboard its training ship, and results were presented and discussed.				
14. SUBJECT TERMS waste heat recovery, heat exchanger, carbon dioxide, gas turbine			15. NUMBER OF PAGES 169	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

**WASTE HEAT RECOVERY ANALYSIS OF A GAS TURBINE HEAT
EXCHANGER**

Denzel Reina
Lieutenant, United States Navy
BSE, U.S. Naval Academy, 2013

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

**NAVAL POSTGRADUATE SCHOOL
March 2021**

Approved by: Garth V. Hobson
Advisor

Douglas L. Seivwright
Second Reader

Garth V. Hobson
Chair, Department of Mechanical and Aerospace Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The U.S. Department of Defense has employed an initiative to become more conservative and efficient regarding uses of energy across all military services. The Naval Postgraduate School supported development toward this initiative by studying the possibility of electrical power generation using waste heat recovery within shipboard engine exhaust. This research included the development of a heat exchanger to use compressed carbon dioxide gas as the working fluid to run within a Brayton cycle. This thesis is built upon previous research using a Rolls Royce M250 helicopter engine and previously modified heat exchangers that were installed on the engine's dual exhaust.

The effects that the modified heat exchangers had on the engine were measured and analyzed to determine new baseline efficiency and effectiveness parameters for the engine and heat exchanger, respectively. Nitrogen and carbon dioxide were used to develop baseline results.

Additionally, an independent study was performed on the performance of an Organic Rankine Cycle waste heat recovery system at Cal Maritime Academy onboard its training ship, and results were presented and discussed.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I.	BACKGROUND	1
A.	ENERGY NEEDS OF THE U.S. NAVY	1
B.	WASTE HEAT RECOVERY ON U.S. NAVY SHIPS.....	1
C.	PRECEDING THESIS WORK	3
1.	“Waste Heat Recovery System for a Gas Turbine Engine and Carbon Dioxide Compression Simulation”: Coria Buck.....	3
2.	“Waste Heat Recovery from a Gas Turbine Engine Using a Heat Exchanger and Associate Centrifugal Compressor Volute Design and Simulation”: Michael Kaim.....	4
D.	GOALS AND OBJECTIVES	6
II.	TS GOLDEN BEAR TEHC SYSTEM EVALUATION	7
A.	INTRODUCTION.....	7
B.	THE ORGANIC RANKINE CYCLE.....	7
C.	ORC ADVANTAGES.....	9
D.	ORC DISADVANTAGES	10
E.	TS GOLDEN BEAR TEHC SYSTEM ANALYSIS	10
1.	Fixed Therminol Flow Rate Test	13
2.	Adjusted Therminol Flow Rate Test/Adjusted Blower (Fan) Speed Test.....	18
3.	Observations/Improvements for Navy Integration.....	20
4.	Conceptual Take-Aways for the Closed-Loop CO ₂ Brayton Cycle	22
III.	HEAT EXCHANGER MODIFICATION	25
A.	PREVIOUS THESIS WORK	25
B.	HEAT EXCHANGER MODIFICATIONS.....	26
IV.	DATA ACQUISITION SYSTEM AND UPGRADES.....	29
A.	PREVIOUS WORK.....	29
B.	DATA ACQUISITION UPGRADES	29
V.	ENGINE AND HEAT EXCHANGER TESTING ANALYSIS AND RESULTS	31
A.	INTRODUCTION.....	31
B.	INSTRUMENTATION	31
C.	TESTING AND RESULTS.....	39

1.	Choked Flow Theory and Calculations	39
2.	Carbon Dioxide Hot Run Mass Flow Calculations.....	43
3.	Carbon Dioxide Hot Run Effectiveness Calculations	46
4.	Heat Transfer Rate Calculations and Dittus-Boelter Theory	49
5.	Dittus-Boelter Analysis.....	53
 VI.	 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK	 57
A.	CONCLUSIONS	57
B.	FUTURE WORK.....	58
 APPENDIX A.	 Peltier Cooler Design Concept	 59
A.	BACKGROUND: THE Peltier Effect	59
B.	THE Peltier Design Concept.....	60
 APPENDIX B.	 MATLAB Data Acquisition Script	 77
A.	CURRENT MATLAB Script.....	77
 APPENDIX C.	 N ₂ Testing Data and Calculations.....	 91
A.	Nitrogen Cold Run Results	91
B.	Nitrogen Hot Run Results	91
C.	Nitrogen Hot Run Reynolds Calculations.....	92
1.	1.5875 mm (1/16") Nozzle Diameter	92
2.	2.3813 mm (3/32") Nozzle Diameter	92
D.	Nitrogen Heat Transfer Calculations.....	92
1.	1.5875 mm (1/16") Nozzle Diameter (Heat Absorbed by Nitrogen)	92
2.	2.3813 mm (3/32") Nozzle Diameter (Heat Absorbed by Nitrogen)	92
3.	1.5875 mm (1/16") Nozzle Diameter (Heat Radiated by Exhaust)	92
4.	2.3813 mm (3/32") Nozzle Diameter (Heat Radiated by Exhaust)	92
E.	Nitrogen Heat Transfer Rate Delta Q's (W).....	93
1.	1.5875 mm (1/16") Nozzle Diameter Heat Transfer Rate Delta's.....	93
2.	2.3813 mm (3/32") Nozzle Diameter Heat Transfer Rate Delta's.....	93
F.	Nitrogen Heat Effectiveness Comparisons	93

APPENDIX D. MASS FLOW RATE AND PRESSURE MAP TRENDS FOR N ₂ AND CO ₂ HOT RUNS.....	95
APPENDIX E. FLOW METER MASS FLOW RATE DATA.....	99
A. INDIVIDUAL FLOW METER ASSESSMENT DATA	99
B. INDIVIDUAL FLOW METER CHARTED DATA.....	100
APPENDIX F. HEAT EXCHANGER GASKET SOLIDWORKS DRAWINGS ...	105
APPENDIX G. PELTIER DESIGN SOLIDWORKS DRAWINGS.....	107
A. TEG CLAMSHELL DRAWING	107
B. COOLING BLOCK CAVITY DRAWING.....	108
C. COOLING BLOCK COVER DRAWING	110
D. TEG BLOCK BOTTOM DRAWING	111
E. TEG BLOCK TOP DRAWING	113
F. COOLING BLOCK SUPPORT SCREW DRAWING	114
APPENDIX H. THERMOCOUPLE AND PRESSURE BRICK PORT LOCATIONS	115
A. THERMOCOUPLE INSTRUMENTATION	115
B. PRESSURE BRICK INSTRUMENTATION	116
APPENDIX I. RAW DATA	117
A. N ₂ NOZZLE COLD RUN TEST DATA.....	117
1. Temperature Data for All 3 Nozzle Dimensions	117
2. Pressure Data for All 3 Nozzle Dimensions	119
B. N ₂ HOT RUN DATA.....	123
1. N ₂ Hot Run Temperature Data for 1/16-Inch Nozzle	123
2. N ₂ Hot Run Pressure Data for 1/16-Inch Nozzle	124
3. N ₂ Hot Run Temperature Data for 3/32-Inch Nozzle	126
4. N ₂ Hot Run Pressure Data for 3/32-Inch Nozzle.....	127
C. CO ₂ COLD RUN DATA.....	129
1. CO ₂ Cold Run Temperature Data for 1/16-Inch Nozzle	129
2. CO ₂ Cold Run Pressure Data for 1/16-Inch Nozzle	130
3. CO ₂ Cold Run Temperature Data for 3/32-Inch Nozzle	132
4. CO ₂ Cold Run Pressure Data for 3/32-Inch Nozzle	133
D. CO ₂ HOT RUN DATA	135
1. CO ₂ Hot Run Temperature Data for 1/16-Inch Nozzle	135
2. CO ₂ Hot Run Pressure Data for 1/16-Inch Nozzle.....	136
3. CO ₂ Hot Run Temperature Data for 3/32-Inch Nozzle.....	138

4.	CO ₂ Hot Run Pressure Data for 3/32-Inch Nozzle.....	139
E.	N ₂ INDIVIDUAL FLOW METER ASSESSMENT DATA	141
1.	N ₂ Temperature Data for All 4 Flow Meters	141
2.	N ₂ Pressure Data for All Four Flow Meters	143
LIST OF REFERENCES.....		147
INITIAL DISTRIBUTION LIST		149

LIST OF FIGURES

Figure 1.	Proposed Closed Loop CO ₂ Brayton Cycle. Source: [6].	3
Figure 2.	Buck's Fabricated Heat Exchanger Installed. Source: [7].	4
Figure 3.	Kaim's Solidworks Sketch of Volute. Source: [6].	5
Figure 4.	Kaim's 3D Printed Volute. Source: [6].	5
Figure 5.	General ORC Representation. Source: [9].	8
Figure 6.	ORC T-S diagram and ORC System Diagram. Source: [10].	8
Figure 7.	General ORC System Components. Source: [9].	9
Figure 8.	TS Golden Bear TEHC ORC Diagram. Source: [12].	11
Figure 9.	ORC Digital Printout. Source: [12].	12
Figure 10.	Power Efficiency vs. Therminol Inlet Temp (Fixed Flow Rate)	14
Figure 11.	Therminol Temp vs. Bypass Valve Position (Fixed Therminol Flow Rate)	15
Figure 12.	Heat Input (Qdot) vs. Bypass Valve Position (Fixed Therminol Flow Rate)	15
Figure 13.	Delta T vs. Therminol Inlet Temp (Fixed Therminol Flow Rate)	16
Figure 14.	ORC Blower and Therminol Pump Interface	21
Figure 15.	Side View Displaying Turbine-Generator Coupling	23
Figure 16.	Kaim's Modified Heat Exchanger. Source: [6]	25
Figure 17.	Kaim's Modified Heat Exchanger Installation. Source: [6].	26
Figure 18.	Modified Heat Exchanger Disassembly	27
Figure 19.	Close-Up View of Heat Exchanger with Installed Gaskets	28
Figure 20.	Heat Exchanger Full Reassembly with Installed Gaskets	28
Figure 21.	MODBUS Construct. Source: [16].	30
Figure 22.	T63 Rolls Royce Gas Turbine Helicopter Engine. Source: [17]	31

Figure 23.	Static Pressure and Temperature locations. Adapted from [6].	32
Figure 24.	Compressed CO ₂ Tanks	34
Figure 25.	Pressure Tap Port 5 Physical Location	34
Figure 26.	Pressure Tap Port 6 Physical Location	35
Figure 27.	Heat Exchanger Inlet Instrumentation	37
Figure 28.	Heat Exchanger Exit Instrumentation	37
Figure 29.	1.5875 mm (1/16") Exit Nozzle Diameter	38
Figure 30.	1.5875 mm (1/16") Exit Nozzle Diameter Installed.	38
Figure 31.	Choked Flow for Converging Nozzle. Source: [18].	39
Figure 32.	3.175 mm (1/8") Nozzle Diameter Solidworks Drawing	40
Figure 33.	Camera Setup for 4-inch Coil Flow Meter Monitoring	44
Figure 34.	Heat Exchanger Effectiveness vs. Pressure Nitrogen and Carbon Dioxide Comparison for 1.5875 mm (1/16") Nozzle	47
Figure 35.	Logarithmic Plot of Dittus-Boelter and Heat Transfer Rate Relationship	55
Figure 36.	General Peltier Element Arrangement. Source: [22].	59
Figure 37.	TEGpro Peltier Device. Source: [20].	60
Figure 38.	TEGpro Peltier Device Dimensions. Source: [20].	61
Figure 39.	Design Component 1, Clamshell Piece Isometric View	62
Figure 40.	Design Component 1, Clamshell Piece Side View	63
Figure 41.	Design Component 1, Clamshell Piece Back View	63
Figure 42.	Design Component 2 Part 1, TEG Block Bottom Isometric View	64
Figure 43.	Design Component 2 Part 1, TEG Block Bottom Front View	65
Figure 44.	Design Component 2 Part 1, TEG Block Bottom Back View	65
Figure 45.	Design Component 2 Part 2, TEG Block Top Isometric View	66

Figure 46.	Design Component 2 Part 2, TEG Block Top Front View	66
Figure 47.	TEG Block Top and Bottom Assembly with Installed Peltier Devices Side View	67
Figure 48.	TEG Block and Clamshell “Fit-up”	68
Figure 49.	Design Component 3, Cooling Block Cavity Front Isometric View	69
Figure 50.	Design Component 3, Cooling Block Cavity Back Isometric View	70
Figure 51.	Cooling Block Cavity NPT Fitting Locations	71
Figure 52.	Design Component 3, Cooling Block Cover Isometric View.....	72
Figure 53.	Design Component 3, Cooling Block Cover Back View	72
Figure 54.	Peltier Design Full Assembly Isometric Front View	73
Figure 55.	Peltier Design Full Assembly Isometric Back View	74
Figure 56.	Peltier Design Full Assembly Side View.....	75
Figure 57.	Peltier Design Screw Support Isometric View	76
Figure 58.	Peltier Design Screw Support Side View	76

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 1.	ORC Recorded Results at Various Bypass Valve Positions.....	14
Table 2.	ORC Recorded Results at Adjusted Blower Speeds and Adjusted Therminol Flow Rates (Cells Hidden).....	19
Table 3.	Pressure Tap Numbering and Locations.	33
Table 4.	Thermocouple Numbering and Locations	36
Table 5.	Nozzle Cold Run Results (Nitrogen)	41
Table 6.	N ₂ Mach Number and Mass Flow Calculation Cold Run Results	42
Table 7.	Carbon Dioxide Cold Run, Nozzle Diameter 1.5875 mm (1/16”)	45
Table 8.	Carbon Dioxide Hot Run, Nozzle Diameter 1.5875 mm (1/16”)	45
Table 9.	Carbon Dioxide Cold Run, Nozzle Diameter 2.3813 mm (3/32”)	45
Table 10.	Carbon Dioxide Hot Run, Nozzle Diameter 2.3813 mm (3/32”)	45
Table 11.	CO ₂ Hot Run Reynolds Calculations, 1.5875 mm (1/16”) Nozzle Diameter.....	48
Table 12.	CO ₂ Hot Run Reynolds Calculations, 2.3813 mm (3/32”) Nozzle Diameter.....	49
Table 13.	Heat Transfer Rate Calculations for Carbon Dioxide, 1.5875 mm (1/ 16”) Diameter (Heat Absorbed by Carbon Dioxide)	51
Table 14.	Heat Transfer Rate Calculations for Carbon Dioxide, 2.3813 mm (3/ 32”) Diameter (Heat Absorbed by Carbon Dioxide)	51
Table 15.	Heat Transfer Rate Calculations for Carbon Dioxide, 1.5875 mm (1/ 16”) Diameter (Heat Radiated by Engine Exhaust).....	52
Table 16.	Heat Transfer Rate Calculations for Carbon Dioxide, 2.3813 mm (3/ 32”) Diameter (Heat Radiated by Engine Exhaust).....	52
Table 17.	Carbon Dioxide Delta Q's, 1.5875 mm (1/16”) Diameter Nozzle.....	52
Table 18.	Carbon Dioxide Delta Q's, 2.3813 mm (3/32”) Diameter Nozzle.....	52

Table 19.	Carbon Dioxide Heat Effectiveness Comparisons, 1.5875 mm (1/16") Nozzle	53
Table 20.	Revised Carbon Dioxide Heat Transfer Rate Calculations for the 1.5875 mm (1/16") nozzle data.....	54

LIST OF ACRONYMS AND ABBREVIATIONS

CFD	Computational Fluid Dynamics
CO ₂	Carbon Dioxide
CSUMA	California State University Maritime University
DAQ	Data Acquisition
DOD	Department of Defense
DON	Department of the Navy
DSA	Digital Sensor Array
HP	Horsepower
HRU	Heat Recovery Unit
ICR	Intercooler Recuperation
Kg/h	Kilogram Per Hour
MATLAB	MATrix LABoratory
N ₂	Nitrogen
ORC	Organic Rankine Cycle
Pa	Pascals
PSID	Pounds Per Square Inch
RPM	Revolutions Per Minute
TEHC	Thermal Energy Harvesting and Conversion

THIS PAGE INTENTIONALLY LEFT BLANK

I. BACKGROUND

A. ENERGY NEEDS OF THE U.S. NAVY

The U.S. Department of Defense (DOD) has the highest energy consumption as compared to any other federal agency in the United States—approximately 77% of the federal government’s entire energy use [1]. From operating bases and training facilities to powering naval vessels and aircraft, the use of energy is integral and heavily relied upon in maintaining military operational readiness [1].

Across the military departments, the Department of the Navy (DON) consumes approximately 30% of all DOD energy use [1]. The Navy consumes around 80,000 barrels of oil afloat on U.S. naval platforms daily. [2]. Roughly 75% of the energy expended by the Navy is used at sea on its ships, aircraft, and vehicles, and close to 60% can be credited to liquid petroleum-based fuels [2]. These rates of consumption represent strategic and operational vulnerabilities as there is an over-reliance on petroleum and hence a need for higher efficiency in today’s Navy.

To combat this vulnerability, the then–Secretary of the Navy Ray Mabus in 2010 announced five aggressive energy initiatives for the DON as part of DOD’s master plan to push for energy efficiency across all military departments. As part of these initiatives, the Navy aspires to have alternative energy sources to reach 50% of total consumption by 2020 [1]. The ultimate goal is to decrease liquid petroleum dependence and increase energy efficiency “while providing the same or improved level of service with less energy” [1]. Over time, this will reduce agency expenses and decrease operational vulnerability in future Naval assets.

B. WASTE HEAT RECOVERY ON U.S. NAVY SHIPS

From 1960 to present day, the United States Navy has invested over \$100 million in waste heat recovery developments for shipboard gas turbines [3]. During these years, there were three major waste heat recovery programs that were funded. The first program was the 45,000-Watt (600 Hp) Oreanda gas turbine recuperation system for minesweepers. The recuperators were essentially counterflow heat exchangers that used exhaust heat

from the gas turbines to preheat compressor airflow. Because the air flow is preheated going into the combustion chambers, the turbines required considerably less fuel to bring the air to proper operating temperatures [4]. Though the recuperation design saved large amounts of fuel throughout the Navy, it did not reach reliability expectations enough for the Navy to continue the program [3].

The second program was the use of RACER Waste Heat Boilers on Ticonderoga class cruisers and Arleigh Burke class destroyers. This design used LM2500 gas turbine engine exhaust as a medium to heat distilled feedwater within a Waste Heat Boiler in the engine room. Once the boiler flashed the feedwater into wet steam, the boiler then distributed the steam through a steam header to be used for ship customer services. Unfortunately, the Waste Heat Boiler design proved to be exceedingly difficult to troubleshoot, and very costly to maintain and repair due to corrosion in ship steam piping [3]. Electrical Heaters were eventually installed as part of an “All Electric Modification” to combat the corrosion issues, thus terminating the Waste Heat Boiler program.

The third and final program funded was the use of an intercooler in conjunction with a recuperator to recover heat from gas turbine exhaust in a 20-MW (26,250 Hp) Rolls Royce Intercooler Recuperation (ICR) gas turbine engine. This engine was designed to be backfitted into existing ship classes in the early 1990s, and forward fitted into future ship classes [5]. The ICR design was expected to save 30% in annual fuel costs across the fleet, as well as increased range and time on station for operable ships in the fleet. Unfortunately, due to thermal fatigue and expansion deformation within the exhaust and compressor inlet ducting, the Navy had to venture away from the program, eventually selling it to the Royal Navy [5].

This project will focus on improving upon the previously funded Waste Heat Exchanger program by using compressed Carbon Dioxide as the working fluid instead of wet steam by use of a modified Brayton Cycle. Additionally, this project seeks in end-state to create a closed loop system where the compressor and turbine are decoupled and run independently at their designed parameters. With the idea that both the turbine and compressor are powered by electric motors, the closed loop design serves as dual purpose

as energy will be recovered in the form of electricity locally at the heat exchanger. This saves time, weight, and space as recovering energy in the form of electricity locally at the heat exchanger prevents the need of installing intricate piping systems to run the working fluid throughout the ship. This design also should optimize the Brayton Cycle for maximum efficiency at the expense of added complexity and weight. A visual representation of the Closed-Loop CO₂ Brayton cycle at project end state is shown in Figure 1.

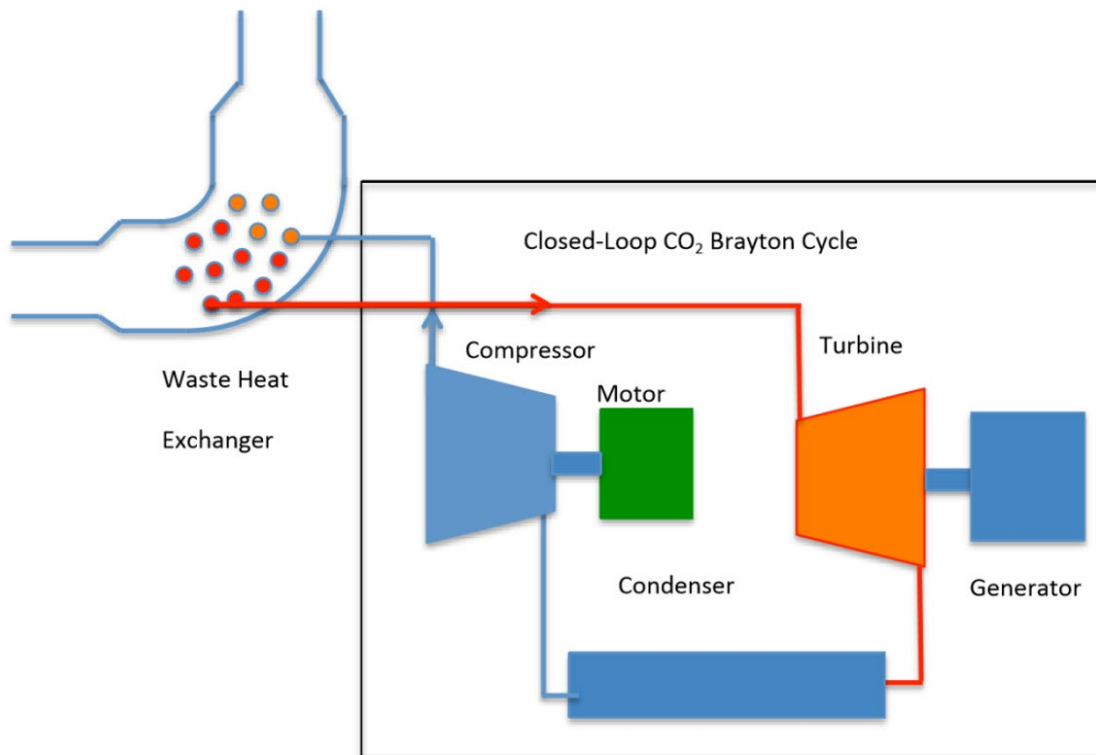


Figure 1. Proposed Closed Loop CO₂ Brayton Cycle. Source: [6].

C. PRECEDING THESIS WORK

1. “Waste Heat Recovery System for a Gas Turbine Engine and Carbon Dioxide Compression Simulation”: Coria Buck

Buck’s thesis [7] concentrated on fabricating and modifying the first prototype of the Waste Heat Exchanger designed by Polsinelli [8] in the thesis developed prior. Once fabricated, the heat exchanger was installed and baseline measurements for temperature

and pressure were acquired while running the gas turbine engine. With installed pressure taps along the engine exhaust duct and the outlet of the Waste Heat Exchanger itself, experimental measurements of back-pressure effects were taken on the engine. Lastly, Buck did an engineering analysis on the compressor that will be used in the eventual Closed-Loop CO₂ Brayton cycle. Computational Fluid Dynamics (CFD) was also used to predict Heat Exchanger and Engine performance. Buck's fabricated Waste Heat Exchanger is shown in Figure 2.



Figure 2. Buck's Fabricated Heat Exchanger Installed. Source: [7].

2. "Waste Heat Recovery from a Gas Turbine Engine Using a Heat Exchanger and Associate Centrifugal Compressor Volute Design and Simulation": Michael Kaim

Kaim's thesis [6] concentrated on developing baseline data for Heat Exchanger and engine performance with modified Waste Heat Exchangers installed on both engine

exhaust ducts. Kaim developed and improved the data acquisition program via MATLAB so that raw engine data could be placed into a file format that allowed greater flexibility in data analysis.

Kaim also developed a prototype for a centrifugal compressor design for the Closed-Loop CO₂ Brayton Cycle. A CFD model for the volute was developed to predict compressibility performance for potential design adaption and improvement in the future. Kaim's volute design is displayed in Figures 3 and 4.

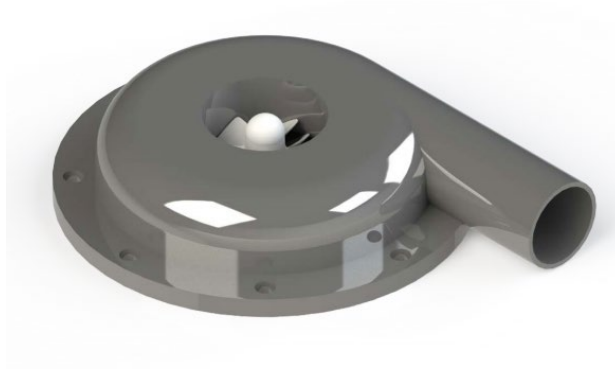


Figure 3. Kaim's Solidworks Sketch of Volute. Source: [6].



Figure 4. Kaim's 3D Printed Volute. Source: [6].

D. GOALS AND OBJECTIVES

This thesis research project contained three primary objectives. The first was to further analyze the concept of heat extraction from waste heat recovery Systems by conducting a separate study on Training Ship (TS) Golden Bear at California State University Maritime Academy (CSUMA) in Vallejo, California. The waste heat recovery design onboard TS Golden Bear used the Organic Rankine Cycle (ORC) as a basis for recovered heat energy to generate electric potential. Though TS Golden Bear used the Organic Rankine Cycle as compared to the Brayton Cycle used at Naval Postgraduate School, the ultimate objective was to learn and obtain key concepts that could be applied toward the Closed-Loop CO₂ Brayton Cycle project.

The second objective was to repeat baseline data achieved in Michael Kaim's [6] thesis and build upon it by adding pressure taps on the inlet side of the heat exchanger from the CO₂ supply, as well as making small modifications to the heat exchanger itself. The addition of pressure taps at the inlet side of the exchanger provides the ability to track relationships in pressure and flow rate of the CO₂ through the coils. As the mass flow rate of CO₂ is increased or decreased entering the Waste Heat Exchanger by use of a throttling valve, pressures can be tabulated at each flow rate change for further analysis. This involved adding another pressure sensing array and modifying the data acquisition system to support additional MODBUS protocol devices. Back pressures in the engine exhaust were recorded and analyzed as well for future modification of the heat exchanger exit nozzle.

The third and final objective was to create a design for heat extraction to generate electric potential in addition to the Closed Loop CO₂ Brayton Cycle to maximize recoverable energy from Gas Turbine exhaust. This design would involve the use of Peltier Coolers that use the "Seebeck Effect" to produce electricity. The theory behind the Peltier Coolers and how they work will be further explained later in the appendices.

II. TS GOLDEN BEAR TEHC SYSTEM EVALUATION

A. INTRODUCTION

The waste heat recovery System installed onboard TS Golden Bear CSUMA, which CSUMA refers to as the “Thermal Energy Harvesting and Conversion” (TEHC) system is an innovated system that uses the Organic Rankine Cycle (ORC) to create thermo-electric potential. This Harvesting system extracts heat from onboard Diesel Generator exhaust, and through a series of heat exchangers and associated equipment, enables the conversion of thermal energy into electric power. TS Golden Bear uses this electric potential for an adsorption chilling system to cool desired spaces throughout the ship. To further understand the study of this concept, representatives from the Naval Postgraduate School contacted California State University Maritime Academy (CSUMA) regarding the waste heat recovery system onboard their training ship. The goal was to analyze the intricacies of the system onboard TS Golden Bear in hopes of translating that knowledge to re-engineer the waste heat recovery process with the Brayton Cycle using a gas turbine engine at the Naval Postgraduate School.

B. THE ORGANIC RANKINE CYCLE

The Organic Rankine Cycle is one of four modifications of the Ideal Rankine cycle and it is known for using a high molecular mass fluid with a boiling point occurring at a lower temperature than a water-steam phase change [9]. Ideally, it is a four-stage heat engine thermodynamic cycle that substitutes an organic refrigerant as a working fluid instead of water in the commonly known Steam Rankine Cycle [9]. The term “organic” refers to the makeup of the working fluid in compounds of carbon, hydrogen, and oxygen [9]. A general representation of an ORC cycle is displayed in Figures 5 and 6.

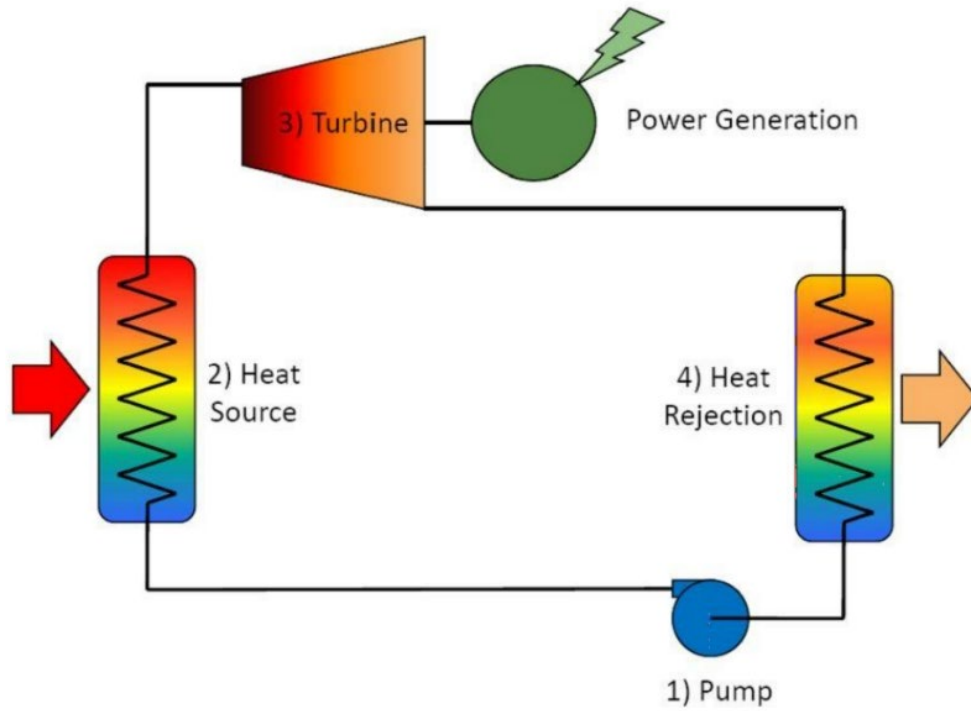


Figure 5. General ORC Representation. Source: [9].

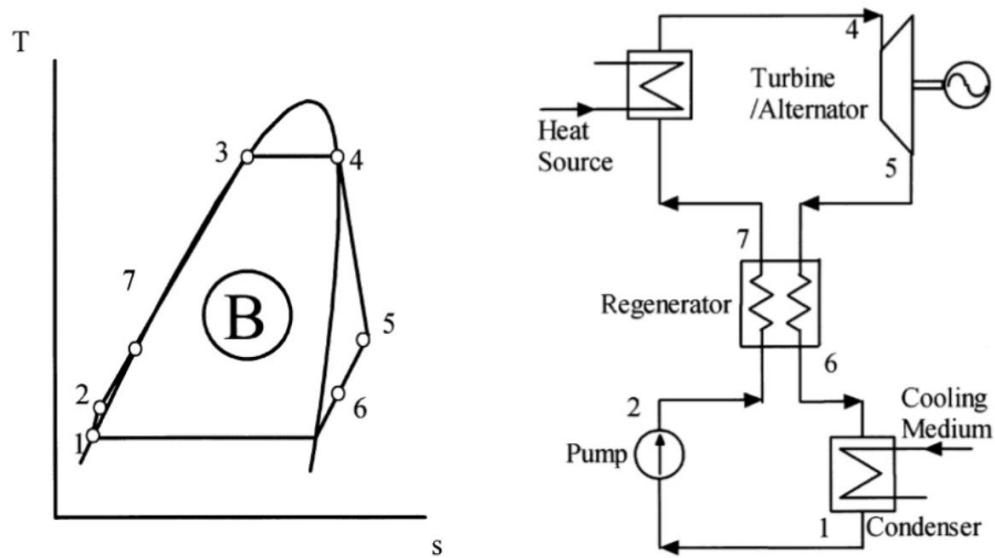


Figure 6. ORC T-S diagram and ORC System Diagram. Source: [10].

In the Organic Rankine Cycle represented in Figure 6, the working fluid is first pumped from a low pressure to a higher pressure (2-7), then the high-pressure fluid is pumped into a heat Source: where it is heated at constant pressure (3) [9]. At this point, the fluid becomes a dry saturated vapor and then expands through a turbine where mechanical work is produced and converted into electrical potential (3-5) [9]. From the turbine, the vapor of the working fluid enters a chilled water condenser at which it is condensed back into a saturated liquid and sent to a reservoir to start the cycle over again (5-1). Components of a general ORC system are shown are Figure 7.

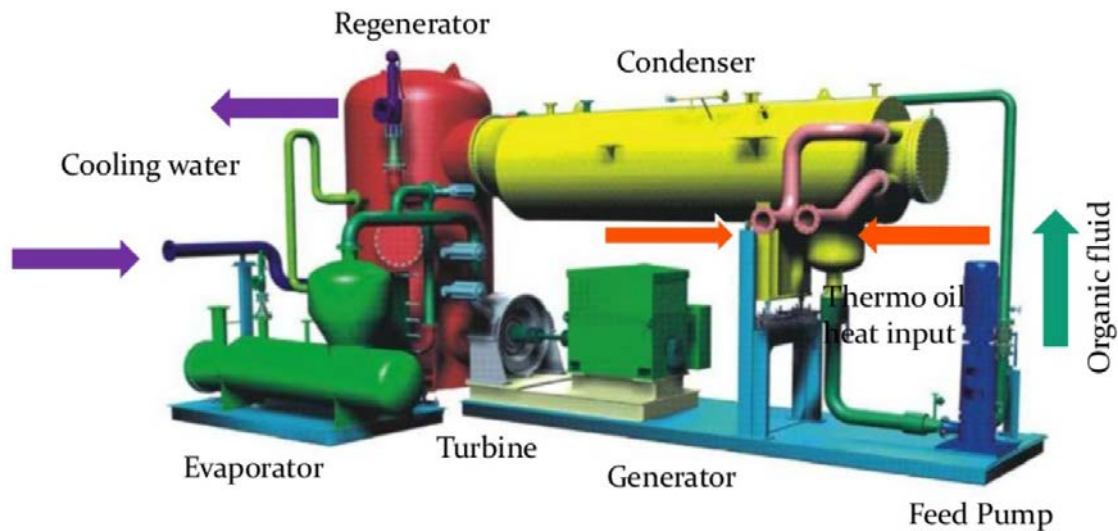


Figure 7. General ORC System Components. Source: [9].

C. ORC ADVANTAGES

There are several advantages to this type of system. Because the temperature of evaporation is relatively low in the working fluid, the heat needed to boil can be extracted from gases at lower temperatures as compared to the steam cycle [11]. Another advantage is the ability of the system to convert low-grade waste heat into reusable electrical power [9]. Though using a Steam Rankine Cycle to recover electrical potential from low-grade waste heat would be very inefficient and expensive, the Organic Rankine Cycle makes the waste heat recovery process economically feasible and worthwhile [9].

Because the Organic Rankine Cycle operates at lower temperatures and pressures, there are limited moving mechanical components. Therefore, the cost of maintenance is greatly reduced as comparable to fossil-fuel (gasoline or diesel powered) generators [9].

D. ORC DISADVANTAGES

Though the Organic Rankine Cycle has several advantages, as with any fluid mechanical system, there can be a few disadvantages. The Organic Rankine Cycle will generate less power than a steam cycle operating with similar conditions, and the fluids used within the cycle are very toxic—therefore if leakages were to occur, an environmental hazard could result [11]. Another disadvantage is that in order to generate proper heat transfer, ORC's require higher mass flows of the working fluid and therefore require bigger feed pumps which can have a negative impact on net power generated.

E. TS GOLDEN BEAR TEHC SYSTEM ANALYSIS

To analyze these advantages and disadvantages numerically, representatives from the Naval Postgraduate School planned to go underway on TS Golden Bear with CSUMA engineers and TEHC system designer, Bill Abrams, to observe the TEHC waste heat recovery system in full operation. Unfortunately, due to the Coronavirus-19 Pandemic with Shelter-In-Place orders, the underway had to be postponed and thus at sea data was unable to be obtained. Luckily, the opportunity presented itself in June of 2020 where TS Golden Bear was able to run its generators pier side to support ORC testing. A series of controlled tests were conducted with pre-planned ORC system configurations to analyze the bounds of the system and calculate overall system efficiency. A schematic of TS Golden Bear's TEHC waste heat recovery system is shown in Figure 8.

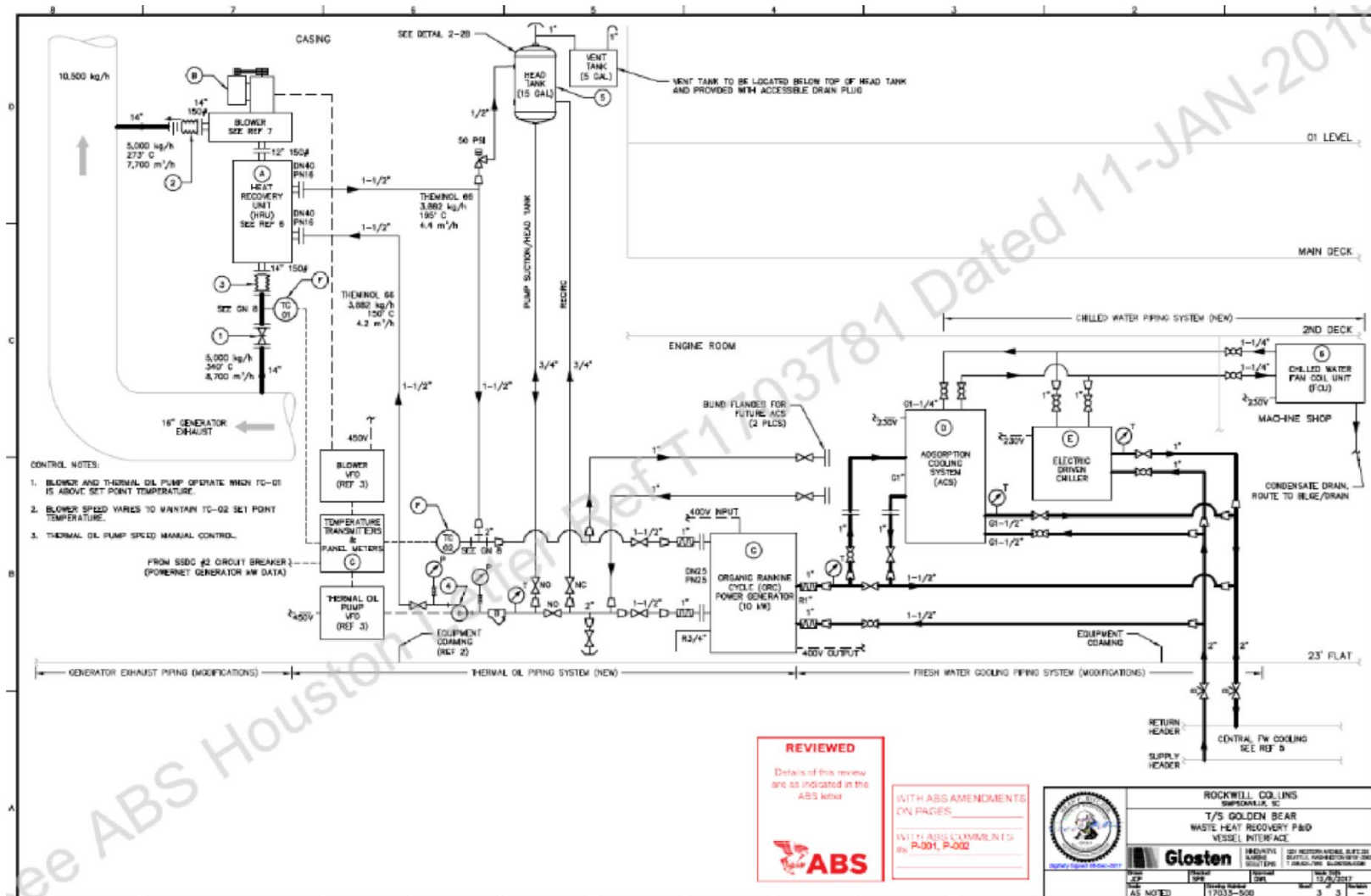


Figure 8. TS Golden Bear TEHC ORC Diagram. Source: [12].

The TEHC system onboard TS Golden Bear is initially operated by a manual bypass valve retrofitted into 1 of 3 Diesel Generator exhaust ducts onboard. Downstream of the bypass valve, there is a single pass counterflow heat exchanger at which the Diesel Exhaust flows through noted as the Heat Recovery Unit (HRU) in the diagram in Figure 8. In this heat exchanger (HRU) Diesel exhaust flows over the tubes inside the encasing, and by means of convection and conduction, transfers heat to Therminol (working fluid) flowing inside the tubes in the opposite direction. The Therminol carrying the absorbed heat from the diesel exhaust is then gravity fed into a plate heat exchanger within the ORC generator to transfer the heat to the refrigerant, R-245. The R-245 refrigerant vaporizes to a low pressure which then drives a mechanical piston generating electric potential through a series of coils. The internal system components of the ORC generator are shown in the digital diagram in Figure 9:

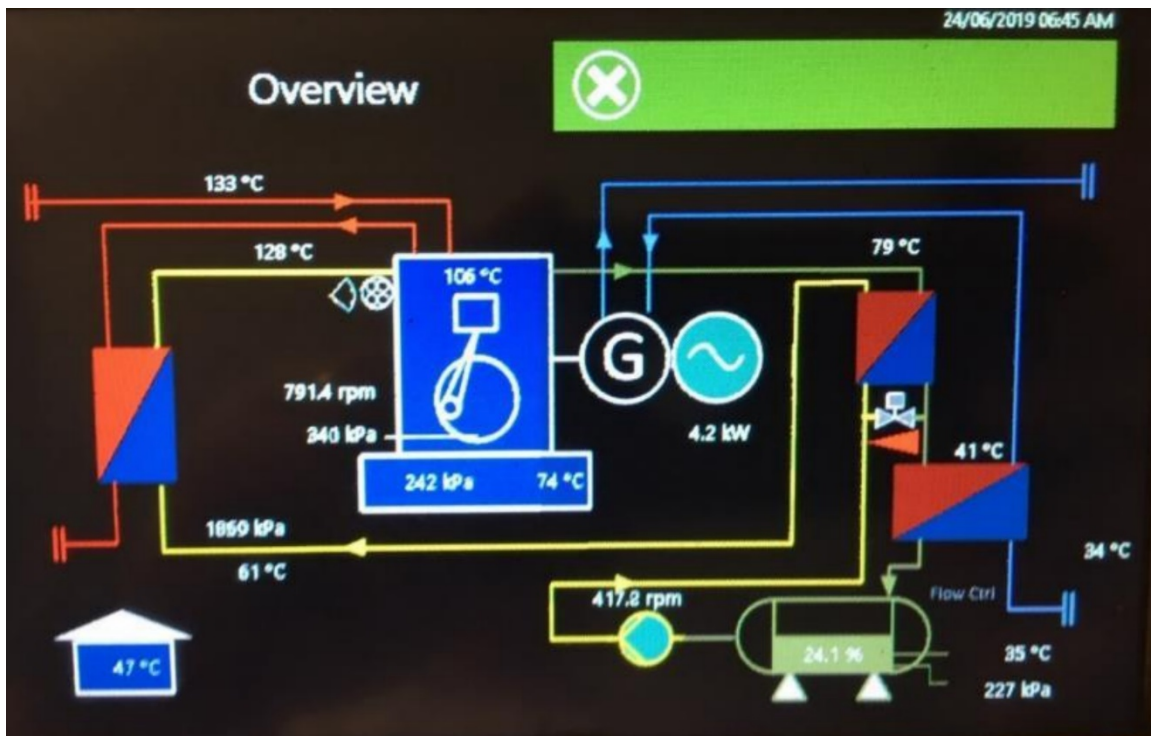


Figure 9. ORC Digital Printout. Source: [12].

To analyze the efficiency and other parameters of the TEHC system properly, accurate, instantaneous readings of Therminol flow rate, Therminol ORC inlet and outlet temperature, and ORC kilowattage need to be taken at pre-determined sample points while the system is in full operation in real-time. Because it would be the first time these types of tests were conducted on the system, three primary test parameters were developed to bound the problem. The test parameters are listed below:

1. Fixed Therminol Flow Rate

- With adjusted bypass valve positions of 33%, 50%, 66%, 75%, and 90%

2. Adjusted Therminol Flow Rates

- With bypass valve position constant at 75%

3. Adjusted Blower (Fan) Speeds

- With bypass valve position constant at 75%

1. Fixed Therminol Flow Rate Test

When the ORC system is at normal operation, the Therminol has a mass flow rate of 65.1 lpm (17.2 gpm). It was decided to keep the mass flow rate constant while adjusting the bypass valve positions to observe the change in the amount of heat transferred from the diesel exhaust to the Therminol. Keeping the mass flow rate constant allows the opportunity to set a form of control upon the system. By opening and closing the bypass valve, it increases and decreases the amount of diesel exhaust that can flow through the heat exchanger (HRU) respectively. This enables more heat flow over the Therminol inside the heat exchanger, thus increasing Therminol temperature as the bypass valve is opened. Data was taken at valve positions of 33%, 50%, 66%, 75%, and 90%. Results were recorded and are shown in Table 1.

Table 1. ORC Recorded Results at Various Bypass Valve Positions

Therminol Inlet Temp (C)	Therminol Density (kg/m ³)	Heat Capacity (kJ/kg-K)	Delta T (T1-T2) (C)	Flow Rate (Fixed) (gpm)	Mass Flow Rate (kg/s)	Heat Input (kW)	ORC Power Generated (kW)	Calculated Efficiency (%)	bypass valve position (%)
132	933.945368	1.948951696	28.1	17.2	1.013471626	55.50332353	4.5	8.11	33
141	927.628385	1.980972818	21.5	17.34	1.014810138	43.22169292	5.4	12.49	33
147	923.388173	2.002400969	28	17.22	1.00318061	56.24555515	6.5	11.56	50
149	921.969633	2.00955804	29	17.18	0.999312802	58.23713519	6.5	11.16	66
150	921.2594	2.013139266	29	17.42	1.012492366	59.11035604	7.5	12.69	75
151	920.548525	2.016722287	29	17.2	0.99893403	58.4226031	5.9	10.10	90

The first line of Table 1 represents the ORC system when it first reaches operating parameters as described by TEHC System designer, Bill Abrams. The following rows display the recorded Therminol density, Heat Capacity, Delta Therminol Temperature, Therminol flow rate, Heat transfer rate ($\dot{Q}$), overall calculated efficiency, and ORC power generated at each respective valve position. Trends from these recorded results are displayed on the graphs in Figures 10–13.

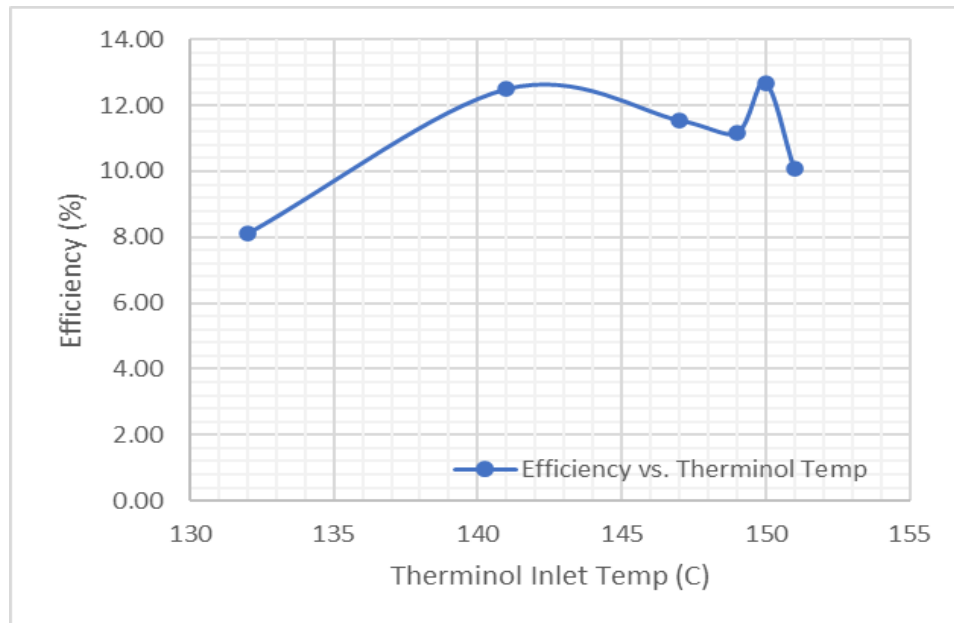


Figure 10. Power Efficiency vs. Therminol Inlet Temp (Fixed Flow Rate)

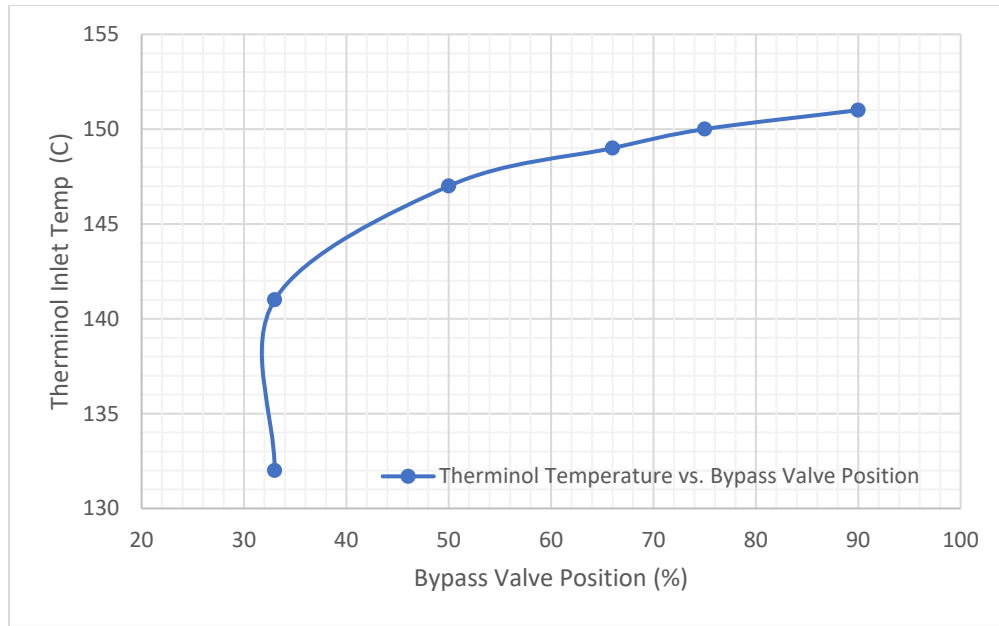


Figure 11. Therminol Temp vs. Bypass Valve Position (Fixed Therminol Flow Rate)

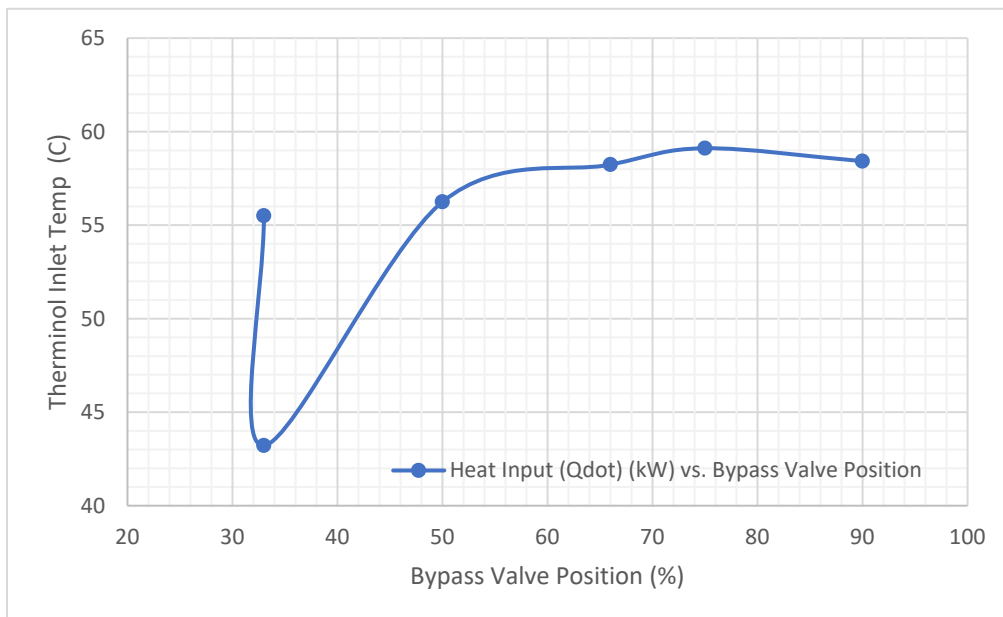


Figure 12. Heat Input (Qdot) vs. Bypass Valve Position (Fixed Therminol Flow Rate)

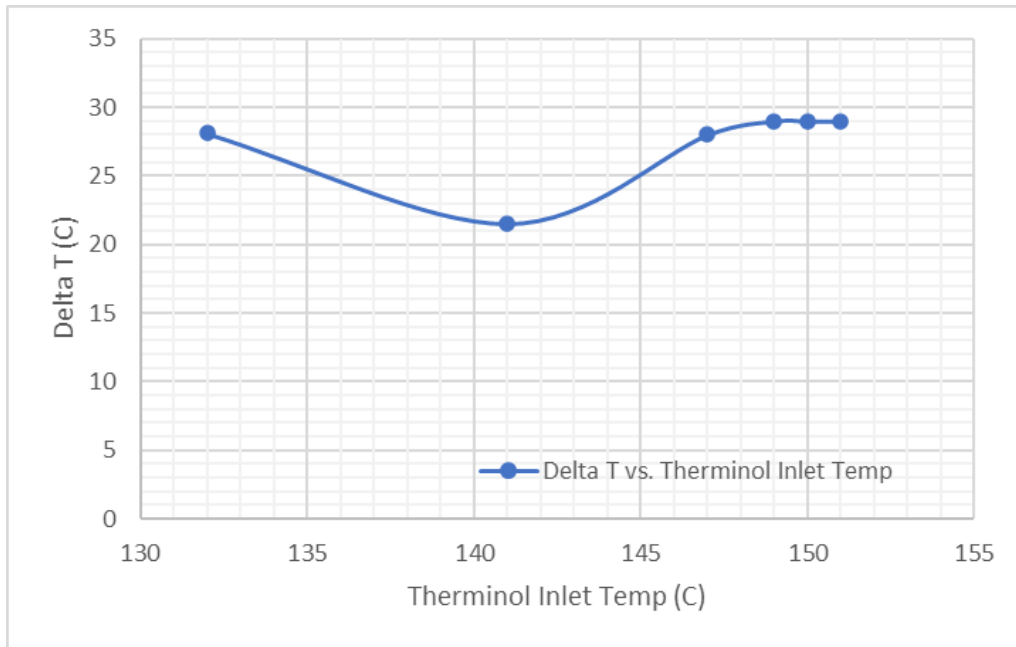


Figure 13. Delta T vs. Therminol Inlet Temp (Fixed Therminol Flow Rate)

In Figure 10, which displays the Power Efficiency vs. Therminol Temperature, the trend shows the efficiency gradually increasing as Therminol inlet temperature is increased. As stated before, in this system the Therminol inlet temperature directly depends on how far open the bypass valve is. This correlation is displayed in Figure 3. The highest power efficiency obtained while keeping the Therminol flow rate constant was 13.63% at a bypass valve position of 75%. This essentially is saying that 13.63% of waste heat from diesel exhaust was recaptured and used to generate power that can be re-used anywhere throughout the ship—which is quite an astounding feat.

Though the ORC system reached 13.65% at a 75% bypass valve position, once opened to 90%, efficiency decreased down to 10.1%. This can attribute to two factors. One, is that at 90% valve opening the flow of heat from the diesel exhaust into the heat exchanger might have been too volatile to create an environment for optimal heat transfer between the Therminol and diesel exhaust—thus reaching a system limitation. This theory could have been verified with an installed flow meter in the ducting downstream of the bypass valve into heat exchanger (HRU) to measure the actual diesel exhaust flow rate. Unfortunately, due to cost and time in retrofitting this into the system, it would have

to be a note for improvement for future test runs. Secondly, the decreased power efficiency to 10.1% at a 90% valve position can be attributed to human error. The data recording of power generated from the ORC proved quite challenging as there were fluctuations of the digital readout between 5.9 kW and 7.5 kW. This made it exceedingly difficult to make an accurate recording of actual power generated at 90% bypass valve position. The fluctuations in power generated from the digital readout could be due to low levels of R-245, which in turn slows the vaporization rate and affects the turnover rate of the mechanical piston inside the ORC. This piston within the ORC is the driving force behind creating the thermo-electric potential desired throughout the system. The installation of a sight glass, or a digital readout of the level of R-245 within the ORC generator could also be an improvement for future developments to verify this theory from an operator's standpoint.

Another item to note is that Delta T remains fairly consistent throughout the process of opening the bypass valve. From the recorded results in Figure 1, the average Delta in Temperature between Therminol inlet and outlet temperatures to the ORC generator is 27.1°C, which correlates to the average Delta in Temperature reported in the TEHC Underway Test Report at 28.1°C. Despite the outlier of 43.2kW of heat input shown in Figure 12, which is attributed to the system stabilizing itself after reaching operating parameters, the ORC generator also produced a consistent heat transfer rate of 56.74 kW. The heat transfer rate is calculated using the energy equation:

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

where $\dot{Q}$ is the heat transfer rate (W), $\dot{m}$ is the mass flow rate of the Therminol (gpm), C_p is the specific heat capacity (J/K) and Delta T is the difference in Therminol temperatures entering and exiting the ORC generator measured in Kelvin (K). By observing this equation, it should be obvious that generally the higher the Delta T and mass flow rate, the higher the heat transfer rate. The physical components that control these two parameters in this particular system is the Therminol pump and the normal operating conditions of the generator itself.

The ship's generator used onboard TS Golden Bear is a MAK diesel generator which, if fully loaded, can operate independently up to 900 kW. With that being said, it is not good engineering practice to load a ship's generator to full capacity under normal conditions. Typically, roughly half of a ship generator's full load capacity is specified as its normal operating condition. Therefore, the heat transfer rate calculated within the ORC system is dependent upon the temperature of the diesel exhaust, which is then dependent on the current load of the generator. The higher the generator load in kW, the more work is needed from the generator to keep up with the load demand, which in turn increases exhaust temperatures proportionately. This is important because ORC system efficiency, heat transfer rate, and kilowattage regenerated throughout the system is limited by the amount of heat that it can extract from its respective generator or prime mover's exhaust at normal operating conditions. The same idea can be said for the Therminol pump. The mass flow rate of Therminol is only limited to the capacity of the pump pushing it throughout the system. The more powerful the pump, the bigger the mass flow rate, thus leading to a larger heat transfer rate.

2. Adjusted Therminol Flow Rate Test/Adjusted Blower (Fan) Speed Test

The Adjusted Therminol Flow Rate test and Adjusted Blower (Fan) Speed test were originally supposed to be conducted as two separate sets of data, but due to time constraints tests had to be combined to analyze how changing Therminol flow rate, and diesel exhaust flow rate impacts overall ORC performance. Because there were only 3 speeds that the Blower could operate at in terms of rpm's, it was decided that the first 3 rows of data collected would represent the Blower at its 3 operable speeds while the Therminol pump operated at full capacity. The Blower speeds were roughly 1800 rpms, 2500 rpms and 3600 rpms; this essentially correlates to low, medium and high fan speeds. Once the first 3 rows of data were collected the blower would be left running constant at its highest speed (3600 rpm), and Therminol pump speeds would begin to be adjusted.

Unfortunately, the Therminol pump could only be adjusted back from 100%, to 90%, and then to 80% in terms of pump capacity. Any pump percentage lower than 80% would not produce enough pumping power to pump the Therminol throughout the ORC

system. It was the originally assumed that the 65.1 lpm (17.2 gpm) generated by the Therminol pump in the TEHC Test Report Results could be increased and decreased by operator input. Unfortunately, this assumption was false, and was not known until tests were actually conducted onboard. Since it was found previously that a bypass valve position of 75% produced the optimal ORC power efficiency during the Fixed Therminol Flow Rate Test, this position was used for control for all data collected in this data set. Results from the combined test are displayed in Table 2.

Table 2. ORC Recorded Results at Adjusted Blower Speeds and Adjusted Therminol Flow Rates (Cells Hidden)

Therminol Inlet Temp (C)	Therminol Density (kg/m ³)	Heat Capacity (kJ/kg-K)	Pump Percentage (%)	Blower RPM	Delta T (T1-T2) (C)	Flow Rate (Adjusted) (gpm)	Heat Input (kW)	ORC Power Generated (kW)	Calculated Efficiency (%)	Bypass valve position (%)
132	933.945368	1.948951696	100	1821	28	17.22	55.3701119	4.5	8.13	75
144	925.511168	1.99167882	100	2500	25	17.27	50.2105513	4.9	9.76	75
149	921.969633	2.00955804	100	3500	30	17.34	60.8063862	7.3	12.01	75
152	919.837008	2.020307102	90	3500	32	15.47	58.0403785	7.5	12.92	75
no data taken	no data taken	no data taken	80	3500	no data taken	no data taken	no data taken	no data taken	no data taken	75

As annotated in Table 2, no data was taken at pump capacity of 80% due to time constraints onboard TS Golden Bear. Unfortunately, a graphical trend would not be possible as two test parameters were combined into one data set. However, the data that was gathered was pertinent to the study. When the Blower was adjusted from its low speed to its high-speed setting in the first 3 rows of data, It was observed in the “Heat Input (Qdot)” Column and the “ORC Power Generated” column that Heat transfer rate and the power generated showed an increasing trend as the Blower speed was increased. This trend is consistent as an increase of flow rate of diesel exhaust is increased by the Blower over the Therminol coils within the heat exchanger.

The Blower is essentially a fan built into the ducting downstream of the Heat Recovery Unit (HRU) that draws the diesel exhaust through the heat exchanger from the bypass valve opening. This Blower ensures diesel exhaust re-routed from the bypass valve is forced back into the main diesel exhaust duct to be pushed back out downstream into the atmosphere through the ships exhaust stacks. The Blower also enables the operator the opportunity to change diesel exhaust flow rates through HRU over the

Therminol to find optimal heat exchange rates and power efficiencies. The only downside, as mentioned before in the analysis for the Fixed Therminol Flow Rate test, is that there is no flow meter installed in the exhaust ducting upstream or downstream of the HRU. With a flow meter to measure diesel exhaust flow rate, heat exchanger efficiencies could be calculated to optimize the design of the heat exchanger, which would inherently increase overall ORC system efficiency.

The second and final observation from Table 2 is the trends of data in the fourth and fifth rows where Therminol flow rates were adjusted back from 100% pumping capacity. At 90% the Therminol flow rate decreased to 58.5 lpm (15.47 gpm), yet it helped yield the highest ORC power generated compared to the rest of the data set. Even with the missing data at 80% pumping capacity, this result shows that flow rates between two fluids within a controlled volume have a limitation in terms of maximizing the heat transfer rate. In order to find that limitation, measurements of mass flow rate of diesel exhaust through the ORC system need to be measured and calculated against the heat exchanger geometry, given the Therminol flow rate, to find true heat exchanger efficiency to optimize the overall TEHC design. This would serve as a note for improvement on the way forward to the continued optimization of this revolutionary system.

3. Observations/Improvements for Navy Integration

From working with this system hands-on for approximately two days, from an operator's standpoint, if this system were to be accepted by the Navy and be installed onboard ships, user interface and buttonology needs to be at the forefront of the design in future models. There are many times in the fleet where a new state-of-the-art system is pushed out for installation on U.S. Navy vessels with no thought on how the operator has to adjust to new buttonology and new system interfaces, and, still be expected execute their job at a high level. It is just not feasible in an up-tempo work environment such as day-to-day operations on a U.S. Naval vessel.

For example, in adjusting Blower speeds and Therminol pump speeds, the process to do such an action is not as intuitive as one might think with this system. For the

Blower, it had to be placed in local control for manual input, and certain set points through a PID logic control loop had to be entered in to set a desired fan speed. See Figure 14. This action is not easily duplicatable for the average U.S. Navy sailor. To make the action of adjusting Blower speeds easier on the average operator in the fleet, designing the interface to include a knob, or digital screen that discernably states “Fan Speed” with “low,” “medium,” and “high” fan settings would greatly decrease ambiguity in system operation for a sailor. The same can be said for increasing and decreasing speeds for the Therminol pump in the system.



Figure 14. ORC Blower and Therminol Pump Interface

Another observation, as mentioned previously throughout the report, is that there is no way to track the flow rate of exhaust through the HRU. This has an impact on calculating heat transfer rates between the Therminol and diesel exhaust. If mass flow rates cannot be tracked for both fluids in a controlled volume such as a heat exchanger

while the system is in operation, valuable information is lost in determining optimization strategies for the heat exchanger, and the TEHC system.

Lastly, it is recommended that Navy approved refrigerants like R-134a, R-22, R-502, R-717, R-125, R-410A or R-12 be used as the vaporization medium in the ORC generator. *(even though R-12 will soon be phased out as part of the Ozone Protection and Clean Air Act due to its negative impact on the ozone)* [5] R-245 is not a commonly used refrigerant in the Navy and is highly unlikely to be circulated in the Navy stock system due to its toxicity [13].

4. Conceptual Take-Aways for the Closed-Loop CO₂ Brayton Cycle

One major take-away from the TEHC design on TS Golden Bear was how the system was able to extract thermal energy, turn it into mechanical energy and then produce electrical potential. As noted earlier in this chapter, this was accomplished by running Therminol through a heat exchanger, in which the Therminol extracted and absorbed heat from diesel generator exhaust. Through installed piping, the Therminol was pumped back to the ORC generator and run through another counterflow heat exchanger. In this smaller heat exchanger internal to the ORC generator, is where the absorbed heat from the Therminol vaporized the secondary fluid, refrigerant R-245, during heat transfer. The vaporized state of the R-245 refrigerant supplied enough pressure and energy to drive a mechanical piston within the ORC generator. This piston provided radial torque to a shaft with magnetic coils that when rotated, produced electricity to be used as desired throughout the ship.

This same concept of taking thermal energy and turning it into mechanical energy to produce electricity can be applied to the Closed Loop CO₂ gas turbine design at the Naval Postgraduate School. Instead of using the refrigerant as the working fluid as a means of extracting heat from gas turbine exhaust, the CO₂ in the Closed Loop CO₂ design in a high temperature super critical state can be used as a means to drive a turbine coupled with a generator to produce electricity. This is of course assuming that the appropriate piping is rigged and installed to withstand the associated pressures. As compared to the TEHC design on TS Golden Bear, a refrigerant would not be needed, as

CO₂ in a supercritical state with its high density and volumetric heat capacity is nearly twice as dense as steam, which also makes CO₂ more energy dense than most working fluids [14]. The high energy density of supercritical CO₂ provides the means to develop considerably smaller system components that lead to a smaller footprint and lower production costs [14]. Developed by a prior thesis student, by scale, an accurate representation of a reduced, turbine-coupled generator is displayed in Figure 15

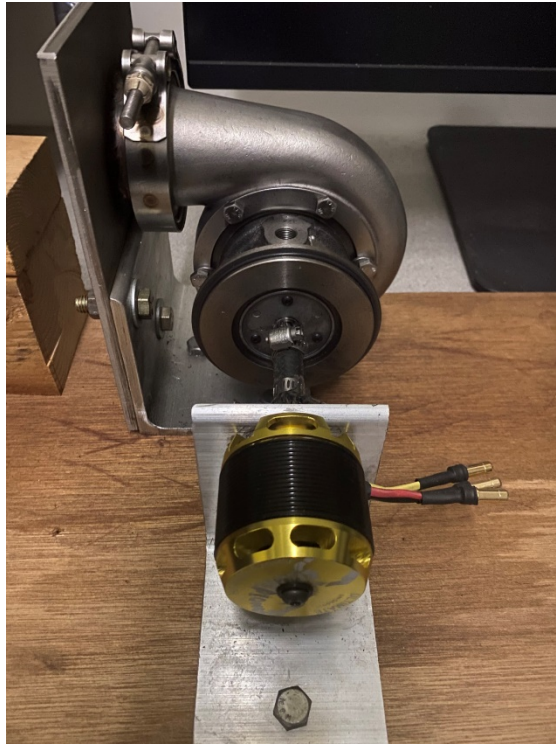


Figure 15. Side View Displaying Turbine-Generator Coupling

Another take away from the TEHC design is the working fluid having the ability to be stored and maintained the working fluid within the system, i.e. Closed Loop. The TEHC design had a reservoir for the Therminol (working fluid) built into the HRU enabling it to stay a “wet” closed-loop system even while not in operation. With the Closed-Loop CO₂ Brayton Cycle Design, maintaining compressibility of CO₂ proves to be quite a challenge, especially in a supercritical state. Reinforced piping and other

infrastructures would have to be put in place to withstand the associated temperatures and pressures. This will be a project to be researched in a follow-on thesis.

The last take away from the TEHC design is the consideration of how well the design integrates with current Navy shipboard systems. As mentioned before, the TEHC design uses R-245 refrigerant at its vaporized state within the ORC to provide thrust to an internal cylinder to create electric power. Unfortunately, Refrigerant R-245 is not used in the Navy, let alone present in the Navy stock system, so integration of the TEHC design onto current Naval vessels could prove to be highly unlikely unless a different refrigerant is used that is more commonly recognized by Navy Logistics. This is important to note with the Closed Loop CO₂ Brayton Cycle design as the project matures in the future. Integration must continue to be considered at the forefront of the project, because no matter how revolutionary a new system is, if it lacks the capability to integrate with current Naval shipboard systems, it would defeat the purpose of developing that new system as it would result in a lot of time, money, and resources wasted.

III. HEAT EXCHANGER MODIFICATION

A. PREVIOUS THESIS WORK

Improving upon Polsinelli and Buck's heat exchanger designs, as there were excessive bending and alignment issues in manufacturing the four coils inside the heat exchanger clamshell, Michael Kaim adjusted the tube sizing of the coils which allowed the tubing to enter and exit the clamshell assembly in a more tangential direction relative to each coil's circumference. Michael Kaim's modified heat exchanger with the smooth consistent coil bends is shown in Figure 16.



Figure 16. Kaim's Modified Heat Exchanger. Source: [6]

As soon as Kaim fixed the bending and alignment issues in the heat exchanger, he had a secondary heat exchanger manufactured to match his modified exchanger design. This was done to allow for predictable flow measurements across both engine exhaust ducts for future design modifications [6]. Once the second heat exchanger was fabricated, both heat exchangers were installed on the engine exhaust ducts in preparation for baseline testing. The installed heat exchangers are shown in Figure 17.



Figure 17. Kaim's Modified Heat Exchanger Installation. Source: [6].

B. HEAT EXCHANGER MODIFICATIONS

During Kaim's heat exchanger baseline testing, there were numerous exhaust leaks from the clamshell along the fastener locations. This led to hot exhaust gases escaping over test cell instrumentation. Several thermocouples along the exhaust ducting had to be replaced. In result, measured outlet temperatures in his data were compromised because of the hot gasses on the thermocouples during data collection. Kaim's final engine baseline run ended in four outlet thermocouples, and one pressure tap melting [6].

To combat the exhaust gas leakage in this current thesis, the heat exchangers were disassembled for analysis and corrective action. This is shown in Figure 18. It was determined that the best solution was to fabricate gaskets in between the clamshell mesh

points to seal the heat exchanger, and to prevent exhaust gas from leaking into the test cell. Gasket sheet material found in campus storage was ultimately chosen to fabricate the gaskets needed for the heat exchanger. SolidWorks drawings were created for the fabrication process and can viewed in Appendix F. The installed gaskets are shown in Figures 19 and 20 after heat exchanger reassembly.



Figure 18. Modified Heat Exchanger Disassembly



Figure 19. Close-Up View of Heat Exchanger with Installed Gaskets



Figure 20. Heat Exchanger Full Reassembly with Installed Gaskets

IV. DATA ACQUISITION SYSTEM AND UPGRADES

A. PREVIOUS WORK

Kaim [6] did thesis work in streamlining the MATLAB code used to take temperature, pressure, and mass flow measurements within the data acquisition (DAQ) system for this engine project. His modified MATLAB code was built off the foundation of Belna's thesis work [15] which involved creating a DAQ system for the NPS Transonic Compressor test rig. Belna used National Instruments (NI) hardware for temperature and mass flow measurements, Scanivalve Digital Sensor Arrays (DSAs) to record pressure readings. His program, along with Kaim's modified MATLAB code was the basis for this projects' DAQ system. Refer to Kaim's thesis [6] for detailed information on his code modification.

B. DATA ACQUISITION UPGRADES

At the start of this thesis, the goal was to be able to remotely feed mass flow measurements from four flow meters into the DAQ system. The current system could only read mass flow measurements from one flow meter at a time using a RS232 port. This was to be done using a MODBUS protocol device that allowed multiple slave devices to communicate and send information vice communicating with only one slave device. Unfortunately, due to lead time for ordered parts, the MODBUS device would not be received and installed for this work. However, cabling and wiring were re-rigged within the DAQ system to support the MODBUS device once it is delivered. A diagram of a nominal MODBUS construct is shown in Figure 21.

The MATLAB code used in this thesis is slightly modified from Kaim's code used in Kaim's work. Kaim's code had built in local functions that recorded temperature, pressure, and mass flow data into tab-delimited files that could be read into any program that accepts tab-delimited files, such as MATLAB or excel, depending on the preference of the user. Once the MATLAB code was run to record data, these archived files would be written into the current working directory. This proved to be very cumbersome when trying to open desired files, as all files for each data run was located in the same folder.

The current code now takes these files and creates a time-date stamped folder for that day, then writes data into the designated folder for that day as well. This modification to the code prevents confusion in trying to retrieve the correct archived data when needed. The MATLAB Code used within this thesis can be found in Appendix B.

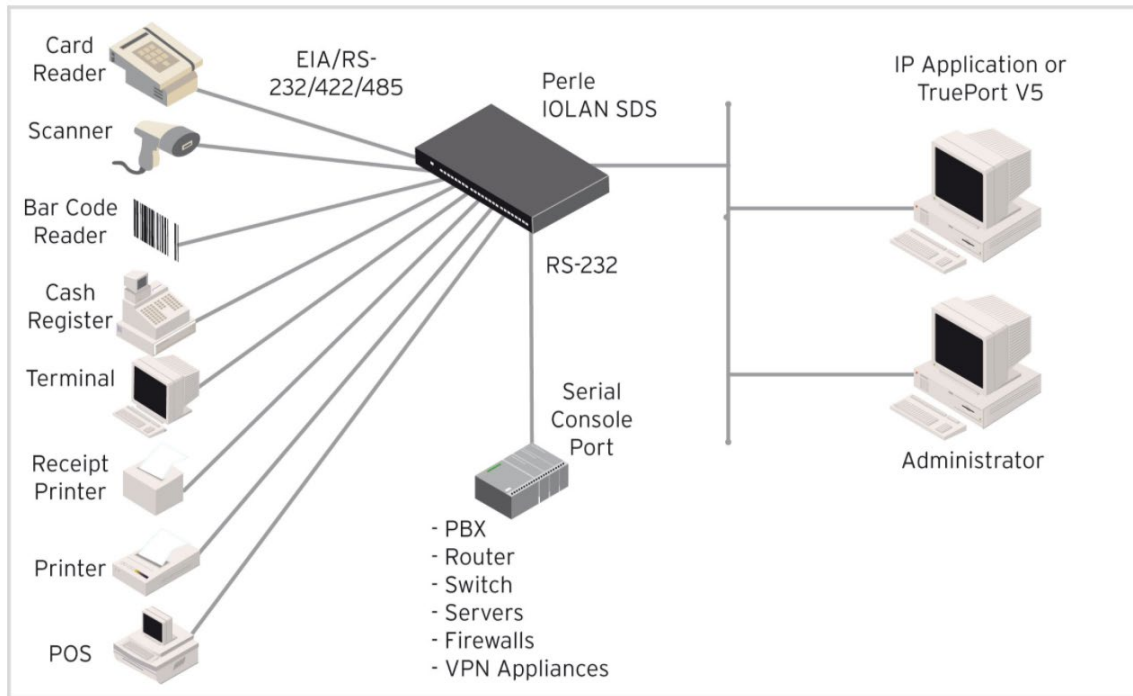


Figure 21. MODBUS Construct. Source: [16].

V. ENGINE AND HEAT EXCHANGER TESTING ANALYSIS AND RESULTS

A. INTRODUCTION

The goal behind this thesis was to create a pressure map with correlating efficiencies, effectiveness readings, and mass flow rates of all four coils within the heat exchanger while the engine was in operation. This pressure map, once created, would be the foundation of optimizing the design of the heat exchanger in the future as it would provide predicted performance parameters based off engine speed. As mentioned in the previous chapter, due to lead time in ordered equipment, only the 101.6 mm (4-inch) diameter coil was able to be monitored and analyzed for pressure map and efficiency calculations in this thesis.

B. INSTRUMENTATION

The engine used in this thesis was a T63 Rolls Royce M250 gas turbine helicopter engine shown in Figure 22. Pressure taps and thermocouples were installed along the engine exhaust duct to measure static pressure and temperature at desired locations when the engine is in operation. This is shown in Figure 23. As compared to the previous thesis (Michael Kaim) where tests were run from 2 different exhaust configurations, this thesis only tested 1 exhaust configuration with the modified heat exchangers installed.

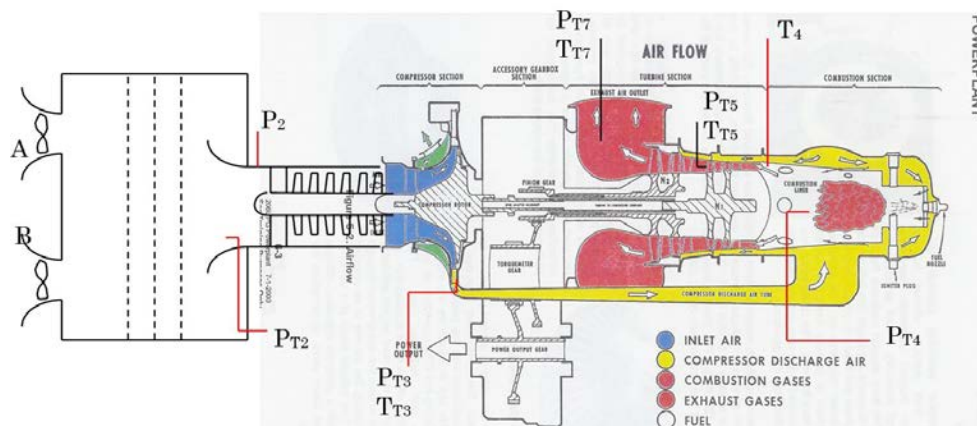


Figure 22. T63 Rolls Royce Gas Turbine Helicopter Engine. Source: [17].

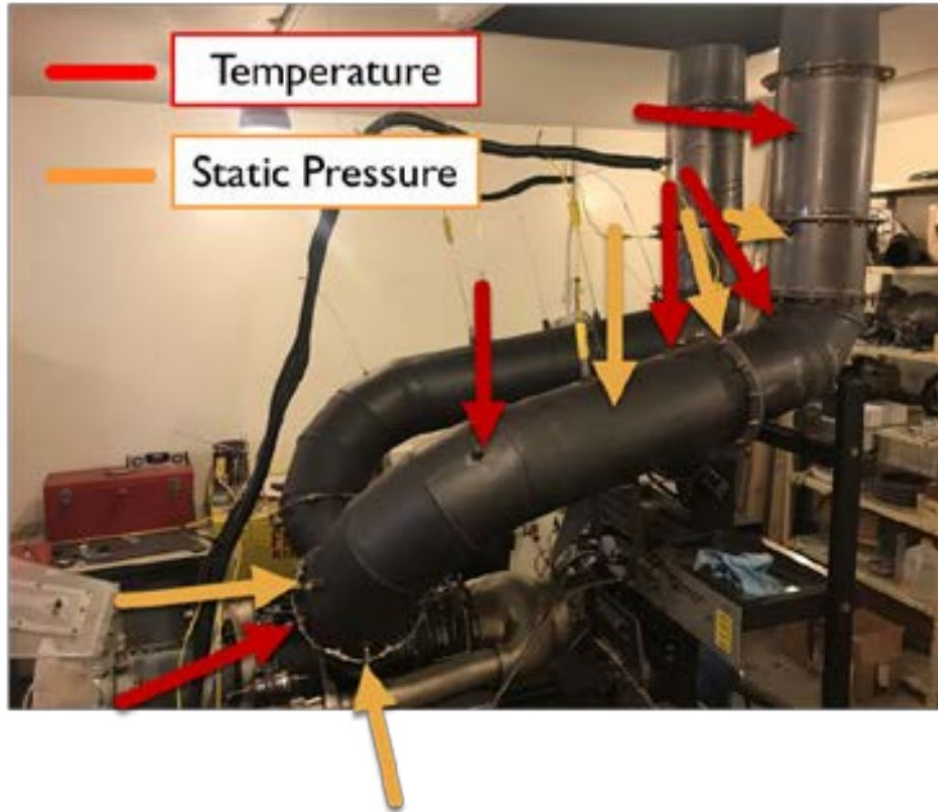


Figure 23. Static Pressure and Temperature locations. Adapted from [6].

There are 38 total pressure taps rigged to the engine in various locations, but only 2 pressure taps were needed for heat exchanger calculations in this thesis. All pressure taps were measured using 3 separate pressure bricks, each with a different maximum pressure, 10" H₂O, 2.5 PSID, and 100 PSID [7]. Each pressure brick had 16 different ports for use as pressure taps. The 2 pressure taps used in this thesis were fed from the 100 PSID pressure brick. For more details on pressure brick installation and initial configuration, refer to Coria Buck's thesis [7]. Current pressure tap (port) locations and numbering are shown in Table 3. The 2 pressure tap locations used for calculations in this thesis are highlighted in yellow and are shown in Table 3 as well.

Table 3. Pressure Tap Numbering and Locations.

Port	(Pressure Brick 1) 10" H ₂ O	(Pressure Brick 2) 2.5 PSID	(Pressure Brick 3) 100 PSID
1	Compressor Inlet Static	Compressor Inlet Static	Compressor Inlet Static
2	Compressor Inlet Total	Compressor Inlet Total	Compressor Inlet Total
3	<i>Not Assigned</i>	<i>Not Assigned</i>	Compressor Outlet Left
4	<i>Not Assigned</i>	<i>Not Assigned</i>	Compressor Outlet Right
5	<i>Not Assigned</i>	<i>Not Assigned</i>	Gas (CO ₂ /N ₂) Manifold Inlet Pressure
6	<i>Not Assigned</i>	<i>Not Assigned</i>	Gas (CO ₂ /N ₂) Manifold Outlet Pressure
7	Left Stack 1	Left Stack 1	Left Stack 1
8	Right Stack 1	Right Stack 1	Right Stack 1
9	Left Stack 0	Left Stack 0	Left Stack 0
10	Right Stack 0	Right Stack 0	Right Stack 0
11	Left Stack 2	Left Stack 2	Left Stack 2
12	Right Stack 2	Right Stack 2	Right Stack 2
13	Left Stack 3	Left Stack 3	Left Stack 3
14	Right Stack 3	Right Stack 3	Right Stack 3
15	Left Stack 4	Left Stack 4	Left Stack 4
16	Right Stack 4	Right Stack 4	Right Stack 4

Pressure tap ports 5 and 6 from pressure brick 3 were used to measure inlet and outlet manifold pressures of Carbon Dioxide and Nitrogen gas respectively as it entered and exited the heat exchanger while the engine was in operation. These were needed to calculate the mass flow rate of the pressurized Carbon Dioxide and Nitrogen gas as it flowed from the compressed tanks, shown in Figure 24, through the coils in the heat exchanger. Mass flow rate calculations will be explained more in depth later in this chapter. The physical locations of the pressure taps that measured the inlet and outlet Carbon Dioxide and Nitrogen gas manifold pressures are shown in Figures 25 and 26. Nitrogen gas was used because of its availability, as well as to ascertain the effect of charging gas during the experiment.



Figure 24. Compressed CO₂ Tanks

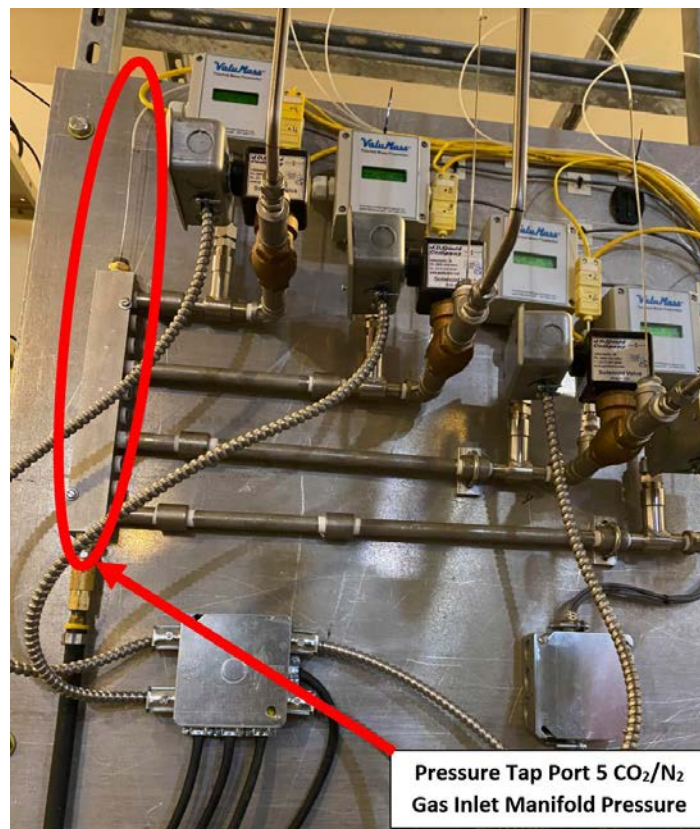


Figure 25. Pressure Tap Port 5 Physical Location

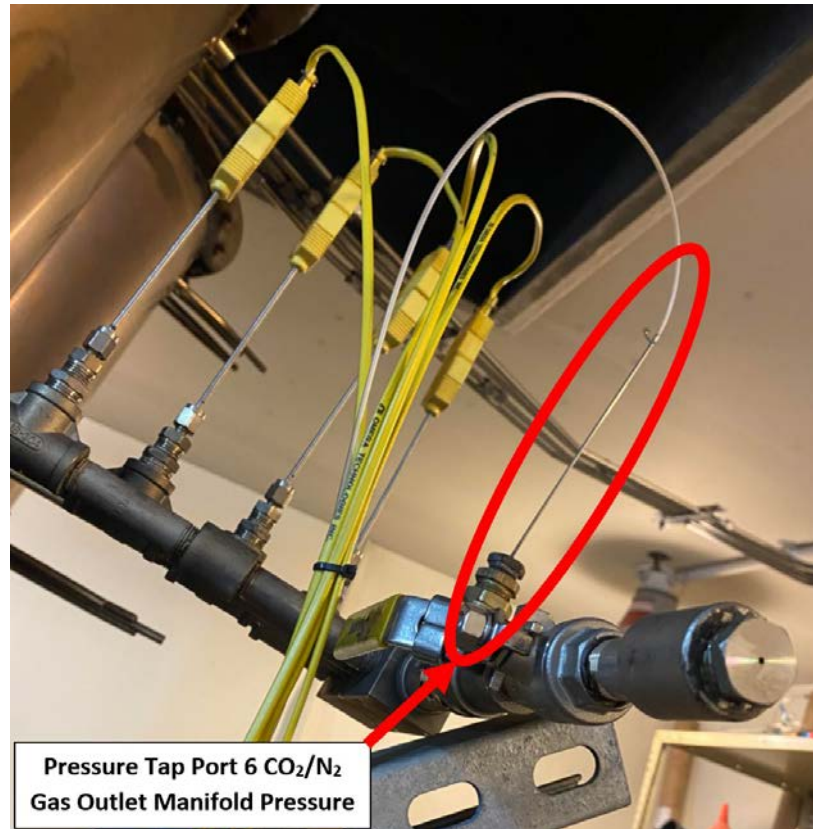


Figure 26. Pressure Tap Port 6 Physical Location

Regarding thermocouples and temperature readings, there were 32 K-type thermocouple sensors rigged along the engine, but only 10 thermocouples were monitored, and only 4 thermocouples were used for calculations in this thesis. Refer to Coria Buck's thesis for the thermocouples' initial installation and configuration [7]. The 10 thermocouples that were monitored measured inlet and outlet exhaust temperatures, as well as inlet and outlet Carbon Dioxide and Nitrogen gas temperatures for each of the 4 coil diameters within the heat exchanger. As mentioned in the introduction, only the 4-inch diameter coil readings for pressure and temperature were taken for calculations in this thesis, so only data from thermocouple ports 14, 15, 16, and 20 were considered. Current thermocouple locations and numbering are shown in Table 4. Temperature locations highlighted in yellow in Table 4 were temperatures that were monitored but not used in this thesis, and items highlighted in green in Table 4 were the items used for heat transfer rate and heat exchanger effectiveness calculations.

Table 4. Thermocouple Numbering and Locations

Thermocouple No.	Location
1	Compressor Inlet 1
2	Compressor Inlet 2
3	Compressor Outlet Left
4	Compressor Outlet Right
5	T5
6	Left Stack 1
7	Left Stack 2
8	Right Stack 1
9	Left Stack 3
11	<i>Not Assigned</i>
12	<i>Not Assigned</i>
13	Right Stack 3
14	HX Hot (IN)
15	HX Hot (OUT)
16	4" Coil (IN)
17	6" Coil (IN)
18	8" Coil (IN)
19	10" Coil (IN)
20	4" Coil (OUT)
21	6" Coil (OUT)
22	8" Coil (OUT)
23	10" Coil (OUT)

The cold side of the heat exchanger had additional instrumentation that monitored the temperature and mass flow rate of Carbon Dioxide and Nitrogen gas by use of four Eldridge Valumass Thermal Mass Flowmeters. These flow meters were located upstream of where each of the four coils entered the heat exchanger. Compressed Carbon Dioxide and Nitrogen gas fed into a manifold, was distributed amongst four different lines, one for each heat exchanger coil, and routed downstream into the inlet side of the heat exchanger. This is shown in Figure 27. At the exit of the heat exchanger, there were four more thermocouples, a throttling valve, and an additional pressure tap to measure manifold exit pressures and temperatures for each respective coil as well. This is shown in Figure 28.



Figure 27. Heat Exchanger Inlet Instrumentation

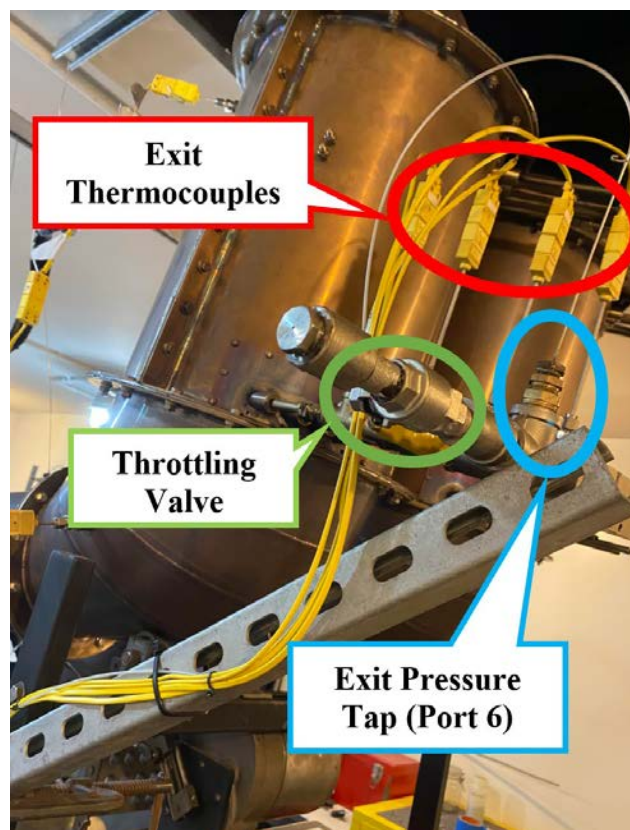


Figure 28. Heat Exchanger Exit Instrumentation

Each flow meter had the capability to measure mass flow rates and temperatures for its respective line when compressed Carbon Dioxide or Nitrogen was fed into the system. The flow meter readings were checked for accuracy by way of a throttling valve and a converging nozzle installed on the downstream side of the exit instrumentation for the heat exchanger. The nozzle marked the exit point of where the carbon dioxide and nitrogen gas were exhausted into ambient air. By choking the flow and measuring pressure and temperature ahead of the nozzle, a mass flow measurement could be made. These values were then compared to flow meter readings. See Figures 29 and 30.



Figure 29. 1.5875 mm (1/16") Exit Nozzle Diameter



Figure 30. 1.5875 mm (1/16") Exit Nozzle Diameter Installed.

There were three exit nozzles fabricated for experimentation, each with a different nozzle diameter of 1.5875 mm (1/16”), 2.3813 mm (3/32”) and 3.1750 mm (1/8”). This allowed variation of mass flows as a function of exit diameter and thus consistency between these mass flow measurements to those measured by the Valumass meter. This “choked flow” method of mass flow calculations will be further explained later in the next section

C. TESTING AND RESULTS

1. Choked Flow Theory and Calculations

At the beginning of this thesis, figuring out a method to calculate accurate mass flow readings was the biggest hurdle. After much discussion, calculating Carbon Dioxide mass flow rates by use of the “Choked Flow” method was the agreed upon solution and Nitrogen would be used to test the theory. Choked flow is a type of isentropic flow that occurs when the Mach number equals 1.0 at the minimum cross-sectional area, or throat, for a converging nozzle as shown in Figure 31 [18]. At this condition, there are extremely useful equations available to calculate mass flow within a converging-diverging nozzle. Here is where three fabricated exit nozzles become most beneficial and played a huge role in calculations throughout this thesis.

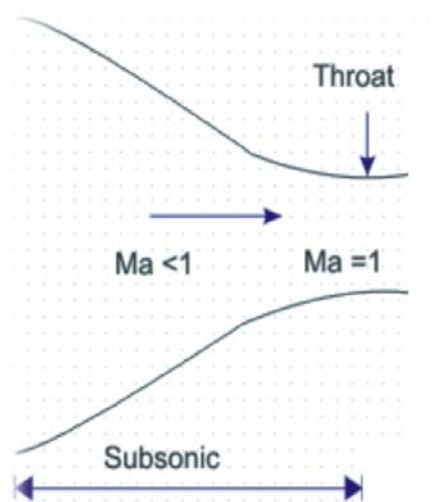


Figure 31. Choked Flow for Converging Nozzle. Source: [18].

There were 3 different nozzle sizes fabricated, 1.5875 mm (1/16”), 2.3813 mm (3/32”), and 3.1750 mm (1/8”). Each nozzle was designed to portray a converging-diverging geometry to replicate a choked flow condition. Refer previously to Figures 29 and 30 to see an example of one of the nozzles post-fabrication. The internal structure of the nozzles showing the converging geometry is shown in the Solidworks drawing in Figure 32.

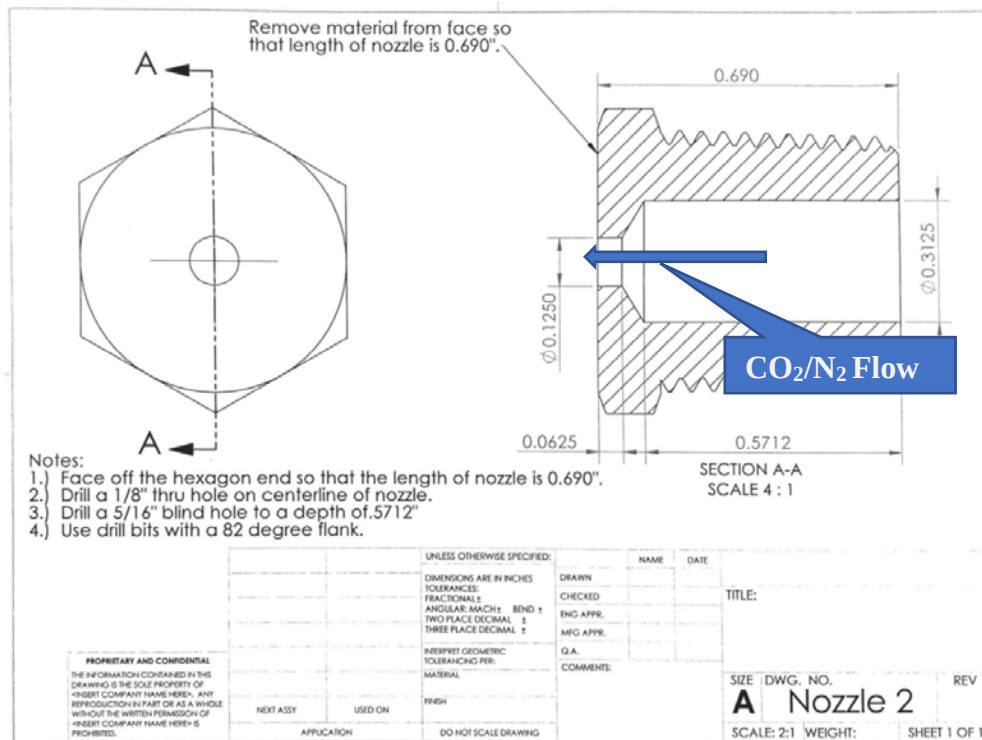


Figure 32. 3.175 mm (1/8”) Nozzle Diameter Solidworks Drawing

Cold run tests were conducted for each nozzle to determine which nozzle produced the best choked flow condition. Tests were run with Nitrogen for each nozzle at discharge pressures of 344738 Pa (50 psi), 517107 Pa (75 psi) and 689476 Pa (100 psi) while the flow rate for each run was recorded using the installed flow meters. Results are shown in Table 5. Once flow rates were recorded for each nozzle, choked flow calculations were conducted to determine which nozzle created a condition valid enough to be trusted for future mass flow rate calculations.

Table 5. Nozzle Cold Run Results (Nitrogen)

Flow Meter Valve 1 (4-inch Coil) COLD RUN 1			
Cold Run 1.5875 mm (1/16") Nozzle	Flow Rate (kg/h)		
Pa	Run 1	Run 2	Run 3
344738 (50 psi)	12.09	12.13	12.04
517107 (75 psi)	15.79	15.83	15.85
689476 (100 psi)	21.07	21.13	20.11

Flow Meter Valve 1 (4-inch Coil) COLD RUN 2			
Cold Run 2.3813 mm (3/32") Nozzle	Flow Rate (kg/h)		
Pa	Run 1	Run 2	Run 3
344738 (50 psi)	20.43	20.41	20.38
517107 (75 psi)	28.92	28.87	20.82
689476 (100 psi)	36.98	36.91	36.99

Flow Meter Valve 1 (4-inch Coil) COLD RUN 3			
Cold Run 3.1750 mm (1/8") Nozzle	Flow Rate (kg/h)		
Pa	Run 1	Run 2	Run 3
344738 (50 psi)	21.84	22.66	22.62
517107 (75 psi)	31.04	31	30.98
689476 (100 psi)	39.2	39.19	39.27

The goal was to observe which nozzle achieved a Mach number of 1 or above at all 3 discharge pressures using choked flow isentropic relations. Mass flow rates were also calculated to verify the accuracy of the flow meters.

Choked flow conditions are derived from the subject of Isentropic flow where constant entropy is present in a system. There are specific isentropic relationships that can be derived to determine mass flow of an ideal gas as mentioned previously. The Isentropic relationship used to determine Mach numbers for this thesis is shown in equation [18]:

$$M_e = \sqrt{\frac{2}{\gamma - 1} \left(\left(\frac{P_t}{P_e} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right)}$$

where M_e is the Mach number at nozzle exit, γ is the gamma constant (ratio of specific heats) of a given fluid, P_t is the inlet pressure of a given fluid, and P_e is the exit pressure of a given fluid [18]. The Isentropic relationship used to determine mass flow rate for a choked convergent nozzle is equation [18]:

$$\dot{m} = \sqrt{\frac{\gamma}{R}} \frac{P_t}{\sqrt{T_t}} \left(\frac{\gamma + 1}{2} \right)^{\frac{\gamma+1}{2(\gamma-1)}} A_e$$

where $\dot{m}$ represents the mass flow rate measured, γ is the gamma constant (ratio of specific heats) of a given fluid, R is the gas constant for a specific fluid, P_t is the inlet pressure of a given fluid, T_t is the inlet temperature of a given fluid, and A_e is the cross-sectional area of the nozzle exit [18]. Mach number and mass flow calculations for each nozzle during the Nitrogen cold test run are shown in Table 6.

Table 6. N₂ Mach Number and Mass Flow Calculation Cold Run Results

Actual Mass Flow Calculations at Nozzle Diameter = 1.5875 mm (1/16") (November 12th)						Constants	
Total Pressure (Pa)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Gamma Nitrogen (cp/cv)	1.4
344738 (50 psi)	1.539351604	Yes	0.00180775	6.507901359	12.13	R Constant Nitrogen (J/Kg-K)	296.8
517107 (75 psi)	1.730127447	Yes	0.002402333	8.648399642	15.85	Total Temp Tt (K)	295.372
689476 (100 psi)	1.90070153	Yes	0.003119362	11.22970208	20.13	Barometric Pressure (inHg)	30.00
						Atmospheric Pressure (Pa)	101591.7
Actual Mass Flow Calculations at Nozzle Diameter = 2.3813 mm (3/32") (November 12th)							
Total Pressure (Pa)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)		
344738 (50 psi)	1.017871538	Yes	0.002022575	7.281269726	20.43		
517107 (75 psi)	1.265481721	Yes	0.00276696	9.96105593	20.92		
689476 (100 psi)	1.433171627	Yes	0.003489688	12.56287562	36.99		
Actual Mass Flow Calculations at Nozzle Diameter = 3.1750 mm (1/8") (November 12th)							
Total Pressure (Pa)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	**NOT IN CHOKING CONDITION**	
344738 (50 psi)	0.585987254	No	0.002346932	8.448956355	22.84		
517107 (75 psi)	0.76727518	No	0.002746217	9.886382067	31.04		
689476 (100 psi)	0.926864236	No	0.00324001	11.66403604	39.27		

Calculations showed the only nozzle that did not produce choked flow conditions was the 3.1750 mm (1/8") diameter nozzle. Calculated Mach numbers did not achieve 1 or greater, therefore using Choked Flow Isentropic relations to calculate mass flow rates would not be valid. As a result, the 3.1750 mm (1/8") diameter nozzle had to be discarded for the remainder of the thesis project.

In both the 1.5875 mm (1/16”) and 2.3813 mm (3/32”) diameter nozzles, the calculated flow rates in comparison to the recorded flow rates by the flow meters all differ by roughly a factor of 2. This is mainly due to the flow meters being calibrated by OEM to read Carbon Dioxide vice Nitrogen, therefore mass flow readings recorded by the flow meters for Nitrogen were not completely accurate. Once the 1.5875 mm (1/16”) and 2.3813 mm (3/32”) nozzles were identified as the nozzles to be used for future calculations, cold run (engine off) and hot run (engine running) tests were conducted for each nozzle for both Nitrogen and Carbon Dioxide. This involved running the MATLAB script mentioned in the previous chapter for remote temperature and pressure readings, as well as manually tracking flow meter readings simultaneously during test runs.

2. Carbon Dioxide Hot Run Mass Flow Calculations

As mentioned previously, only the 4-inch diameter coil was able to be monitored and analyzed due to the delay in arrival of the MODBUS device upon order. The MODBUS enabled the ability to monitor the temperatures, pressures, and mass flow rates of all 4 coils remotely via MATLAB. Unfortunately, due to the delivery delay improvisation prevailed as a camera was used to track and time stamp mass flow readings from the 4-inch coil flow meter. This setup is shown in Figure 33.

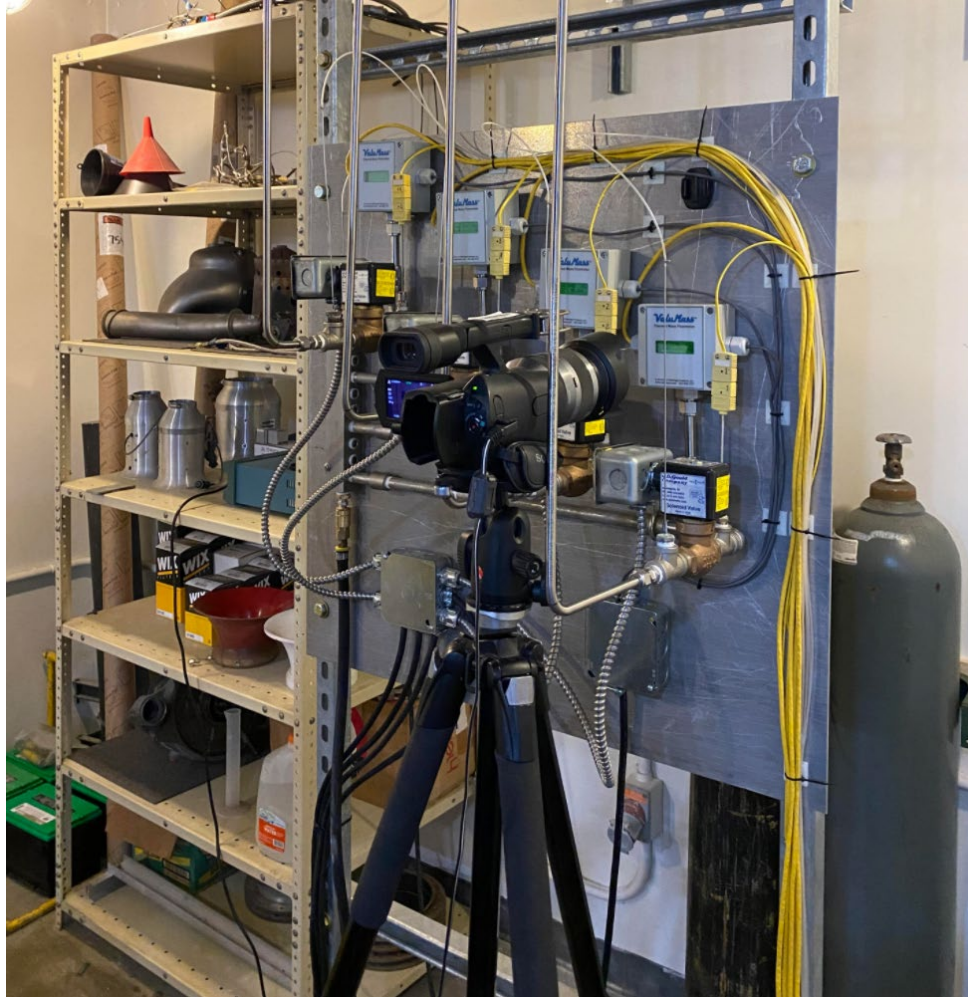


Figure 33. Camera Setup for 4-inch Coil Flow Meter Monitoring

The goal of these hot and cold test runs was to analyze heat exchanger effectiveness, calculate coil mass flow rates, and determine heat transfer rates at preset discharge pressures of Carbon Dioxide at 344,738 Pa (50 psi), 517,107 Pa (75 psi) and 689,476 Pa (100 psi). Nitrogen tests were run first as an experiment to work out nuances, then Carbon Dioxide tests were conducted following. Results of the Nitrogen hot and cold runs can be found in Appendix C. Engine speeds remained constant for all tests for consistency where ND was held at 48,000, and N1 was maintained at 4,800. Results of the Carbon Dioxide hot and cold runs are shown in Tables 7–10.

Table 7. Carbon Dioxide Cold Run, Nozzle Diameter 1.5875 mm (1/16")

Actual COLD Carbon Dioxide Mass Flow Calculations at Nozzle Diameter = 1.5875 mm (1/16") (December 1st)								
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Effectiveness (%)
344738 (50 psi)	308863.23	411199.895	1.59	Yes	0.002310218	8.316783539	8.684	N/A
517107 (75 psi)	457201.18	559537.845	1.79	Yes	0.003143615	11.31701441	12.25	N/A
689476 (100 psi)	620158.59	722495.255	1.95	Yes	0.004059148	14.61293331	15.91	N/A

Table 8. Carbon Dioxide Hot Run, Nozzle Diameter 1.5875 mm (1/16")

Actual HOT Carbon Dioxide Mass Flow Calculations at Nozzle Diameter = 1.5875 mm (1/16") (December 4th)								
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Effectiveness (%)
344738 (50 psi)	321705.7	424008.5016	1.61	Yes	0.001874083	6.746697304	6.875	54.1762155
517107 (75 psi)	489009.07	591311.8716	1.83	Yes	0.002503681	9.013250351	9.513	74.83126044
689476 (100 psi)	655860.31	758163.1116	1.98	Yes	0.003121212	11.23636228	12.26	94.20319915

Table 9. Carbon Dioxide Cold Run, Nozzle Diameter 2.3813 mm (3/32")

Actual COLD Carbon Dioxide Mass Flow Calculations at Nozzle Diameter = 2.3813 mm (3/32") (December 1st)								
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Effectiveness (%)
344738 (50 psi)	97190.36	199323.8422	1.06	Yes	0.002522262	9.080142588	15.99	N/A
517107 (75 psi)	167791.35	269924.8322	1.30	Yes	0.003415653	12.29635119	20.8	N/A
689476 (100 psi)	287059.2	389192.6822	1.56	Yes	0.004924879	17.72956516	31.6	N/A

Table 10. Carbon Dioxide Hot Run, Nozzle Diameter 2.3813 mm (3/32")

Actual HOT Carbon Dioxide Mass Flow Calculations at Nozzle Diameter = 2.3813 mm (3/32") (December 2nd)								
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Effectiveness (%)
344738 (50 psi)	161784.22	263579.06	1.28	Yes	0.002741941	9.870988405	14.46	37.60610391
517107 (75 psi)	279939.64	381734.48	1.55	Yes	0.003725439	13.41157947	20.81	61.61624927
689476 (100 psi)	408786.64	510581.48	1.74	Yes	0.004850575	17.46207019	28.22	74.18851127

As mentioned previously, the calculated mass flow rates for Nitrogen compared to the recorded meter mass flow rates differ by roughly a factor of 2 due to the OEM calibration of the flow meters for Carbon Dioxide. The Carbon Dioxide calculated and recorded mass flow rates for the 1.5875 mm (1/16") nozzle in both hot and cold runs were comparable with the max difference being 1.3 kg/h between both sets of data. The 2.3813 mm (3/32") nozzle flow rates for Carbon Dioxide hot and cold runs reflected more disparity as the max difference between both sets of data was 13.87 kg/h. The same trend was shown respectively for the Nitrogen data. Pressure maps comparing mass flow rates to pressure for each scenario can be found in Appendix D.

Analyzing the data in its entirety, one can conclude by observing the Mach numbers calculated that the higher the Mach number, the more isentropic the flow, therefore the more accurate the calculated mass flow rates would be in comparison to the recorded flow rates. In both Nitrogen and Carbon Dioxide data, the highest Mach numbers calculated were produced from the 1.5875 mm (1/16”) nozzle, thus will be the data represented for future comparisons.

Additionally, cold test runs with Nitrogen were also conducted to test differences in mass flow rates and pressures as the gasses are distributed past the manifold into the four flow meters on the inlet side of the heat exchanger in preparation for future thesis projects. These results can be found in Appendix E.

3. Carbon Dioxide Hot Run Effectiveness Calculations

In Tables 7–14, heat exchanger effectiveness was also calculated. Effectiveness, in relation to heat exchangers, is the ratio of the actual heat transfer rate to the maximum possible heat transfer rate, and is calculated using the equation [18]:

$$\varepsilon = \frac{(T_{c,o} - T_{c,i})}{(T_{h,i} - T_{c,i})}$$

where ε is measured heat exchanger effectiveness, $T_{c,o}$ is the Carbon Dioxide gas temperature exiting the heat exchanger, $T_{c,i}$ is the Carbon Dioxide gas temperature entering the heat exchanger, and $T_{h,i}$ is the engine exhaust inlet temperature [18]. More simply put, the higher the effectiveness value, the more efficient that heat exchanger is in its ability to transfer heat. For both Nitrogen and Carbon Dioxide, the higher the discharge pressure into the heat exchanger coils, the better the effectiveness values for the 1.5875 mm (1/16”) nozzle while the engine was running. At 689476 Pa (100 psi) discharge pressure, Carbon Dioxide reached an astounding effectiveness value of 94% using the 1.5875 mm (1/16”) nozzle. Heat exchanger Effectiveness vs. Pressure comparison between Nitrogen and Carbon Dioxide is graphically represented in Figure 34.

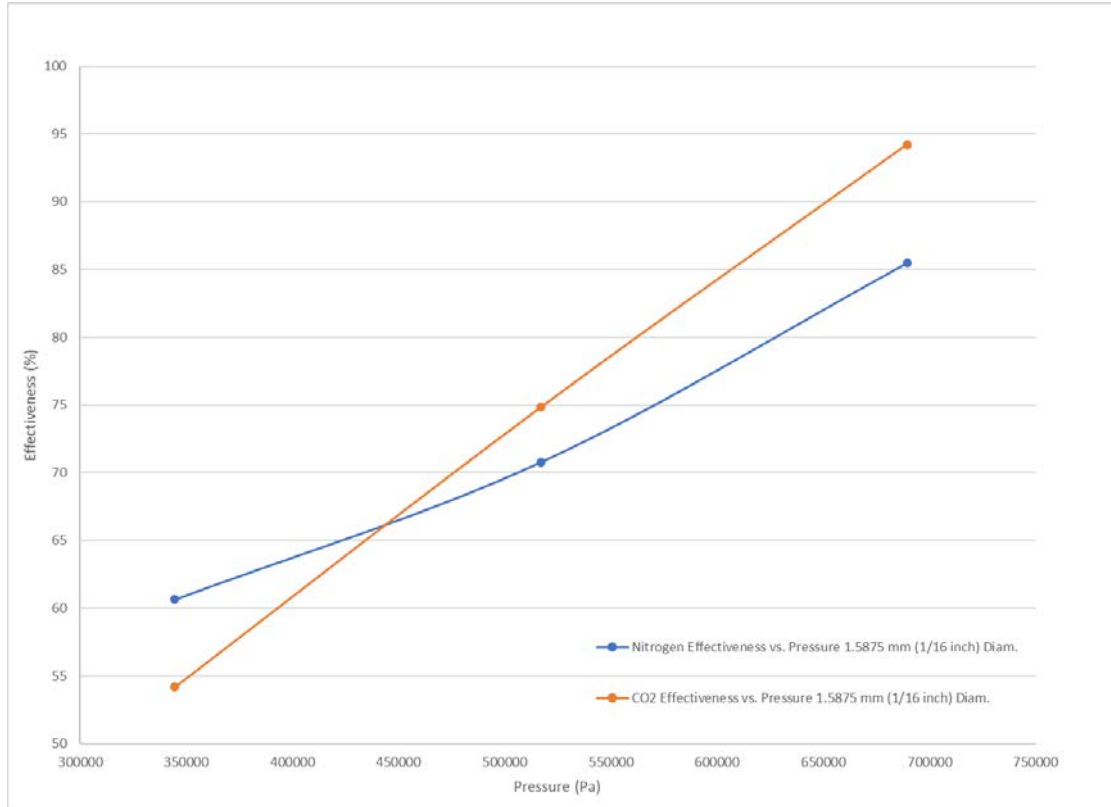


Figure 34. Heat Exchanger Effectiveness vs. Pressure Nitrogen and Carbon Dioxide Comparison for 1.5875 mm (1/16”) Nozzle

Once mass flow rate and heat exchanger effectiveness calculations were complete, the final calculation that had to be conducted was determining the heat transfer rate within the heat exchanger. There were two heat transfer rates to be calculated. The first was calculating the heat transfer of the Carbon Dioxide gas flowing through the coils of the heat exchanger while being heated up by engine exhaust (*heat absorbed by CO₂*). The second was calculating the overall heat transfer from the engine exhaust to the tube wall of the coil (*heat given off by engine exhaust*). The goal behind calculating these two heat transfer rates was to compare and verify the previous effectiveness calculations by using a secondary method of calculating effectiveness. Effectiveness can also be calculated using the more general form of the equation [18]:

$$\varepsilon = \frac{q}{q_{max}}$$

where ε is measured effectiveness, q is the actual heat transfer rate, and q_{max} is the maximum possible transfer rate [18].

Before heat transfer rates could be calculated, laminar and turbulent flow had to be determined, as it may had been a factor in the amount of heat transferred within the heat exchanger. To verify whether gas flow within the coils was laminar or turbulent, Reynolds number calculations were conducted. A Reynolds number is a dimensionless number that characterizes a ratio between inertial forces and viscous forces [18]. Depending on the value it will determine whether the flow of a fluid is laminar or turbulent based off its flow geometry. Reynolds numbers in this thesis was calculated using equation [18]:

$$Re_D = \frac{\rho u_m D}{\mu}$$

where Re_D represents the calculated Reynolds number for a circular tube, ρ is the fluid density, D represents the diameter of the tube, u_m is the mean velocity of the fluid, and μ is the dynamic viscosity of the fluid [18]. This Reynolds equation is designed for straight piped flow. The coils inside the heat exchanger have a helical design, therefore there is a known margin of error as these calculations were conducted with an assumption of a straight flow geometry. For straight piped flow with circular geometry, flow is laminar when $Re_D < 2300$, in transition when $2300 < Re_D < 10000$, and fully developed turbulent when $Re_D > 10000$ [19]. Results of Carbon Dioxide Reynolds calculations are shown in Tables 11 and 12.

Table 11. CO₂ Hot Run Reynolds Calculations, 1.5875 mm (1/16”) Nozzle Diameter

Pressure (Pa)	Mass Flow Rate (kg/s)	4in Coil Tube Diameter (m) (3/8 inch diam. tubing)	Area (m ²)	CO2 Outlet Temp. (K)	Calculated Velocity (m/s)	Dynamic Viscosity (N-s/m ²)	Calculated Reynolds No. (-)	Turbulent Condition? (Re > 10000)
344738 (50 psi)	0.001874083	0.009525	7.13E-05	469.8572	0.056	2.27E-05	11031	YES
517107 (75 psi)	0.002503681	0.009525	7.13E-05	511.9995	0.074	2.45E-05	13655	YES
689476 (100 psi)	0.003121212	0.009525	7.13E-05	541.593	0.093	2.57E-05	16215	YES

Table 12. CO₂ Hot Run Reynolds Calculations, 2.3813 mm (3/32”) Nozzle Diameter

Pressure (Pa)	Mass Flow Rate (kg/s)	4in Coil Tube Diameter (m) (3/8 inch diam. tubing)	Area (m ²)	CO ₂ Outlet Temp. (K)	Calculated Velocity (m/s)	Dynamic Viscosity (N·s/m ²)	Calculated Reynolds No. (-)	Turbulent Condition? (Re > 10000)
344738 (50 psi)	0.002741941	0.009525	7.13E-05	429.4027	0.082	2.10E-05	17470	YES
517107 (75 psi)	0.003725439	0.009525	7.13E-05	487.8959	0.111	2.35E-05	21218	YES
689476 (100 psi)	0.004850575	0.009525	7.13E-05	514.8763	0.144	2.46E-05	26325	YES

Calculations show that Carbon Dioxide gas in all scenarios were fully developed turbulent flows. Turbulent flow within the coil signifies that there will be some loss in the amount of heat transferred from the exhaust to the Carbon Dioxide gas, so differences in the amount of heat absorbed by the gases to the amount of heat given off by engine exhaust within the heat exchanger is to be expected.

4. Heat Transfer Rate Calculations and Dittus-Boelter Theory

Since Reynolds calculations verified turbulent flow, heat transfer rates could then be determined. For turbulent flows within a pipe, calculating heat transfer rates become more involved, for which there are more specific equations. To calculate the heat transfer within the coil (heat absorbed) as the Carbon Dioxide gas passes through the heat exchanger, the Dittus-Boelter equation was used. The Dittus-Boelter equation is specifically for “...fully developed (hydrodynamically and thermally) turbulent flow in a smooth, circular tube...” where a Nusselt number can be derived to calculate a heat coefficient [18]. This heat coefficient can then be plugged into a heat transfer rate equation specific to a respective application or flow geometry.

There are two forms of the Dittus-Boelter equation, (one for heating, and one for cooling). For the Dittus-Boelter equation to be applicable, conditions must meet the parameters for fully developed turbulent flow ($Re_D > 10000$). Again, like the Reynolds number used previously, the Dittus-Boelter equation is designed for straight piped flow, therefore there is a known margin of error in these calculations due to the helical shape of the coils. The heated form of the Dittus-Boelter equation was utilized to calculate the heat transfer rate within the heat exchanger coil.

The Dittus-Boelter equation (heated) used was [18]:

$$Nu_D = 0.023Re_D^{4/5}Pr^{0.4}$$

where Nu_D is the calculated Nusselt number for a circular tube, Re_D is the calculated Reynolds number for a circular tube, and Pr is the calculated Prandtl number of a particular fluid [18]. Once the Dittus-Boelter Nusselt number was calculated, it was used to find the heat coefficient by using the general Nusselt equation for a circular tube [18]:

$$Nu_D = \frac{hD}{k}$$

then rearranging it to:

$$h = \frac{Nu_D k}{D}$$

to solve for the specific heat coefficient for each scenario. Nu_D represents the calculated Nusselt number for a circular tube as stated before, h is the calculated heat coefficient, k is the thermal conductivity of a fluid, and D is the diameter of the tube (coil) [18]. Once the heat coefficient, h , was found for each scenario, it was then plugged into a heat transfer rate equation specific to counterflow heat exchangers to calculate the absorbed heat from the exhaust to the CO₂/N₂ gas. The equation is [18]:

$$q = hA\Delta T_{lm}$$

where q is the calculated heat transfer rate, h is the previously calculated heat coefficient, A is the coil surface area, and ΔT_{lm} is the log mean temperature [18]. Log Mean Temperature accounts for temperature changes of the fluid throughout the heat exchanger, as it cannot be assumed that temperature changes uniformly from inlet to outlet. The log mean temperature specific for a counterflow heat exchanger is defined as [18]:

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln (\Delta T_2 / \Delta T_1)}$$

such that ΔT_1 and ΔT_2 is defined as [18]:

$$\Delta T_1 \equiv T_{h,i} - T_{c,o}$$

$$\Delta T_2 \equiv T_{h,o} - T_{c,i}$$

where $T_{h,o}$ represents engine exhaust outlet temperature [18]. Refer to the definition of effectiveness mentioned earlier in this chapter for variables $T_{c,i}$, $T_{c,o}$ and $T_{h,i}$. Heat transfer calculations for heat absorbed by the Carbon Dioxide gas from engine exhaust are shown in Tables 13 and 14.

Table 13. Heat Transfer Rate Calculations for Carbon Dioxide, 1.5875 mm (1/16”) Diameter (Heat Absorbed by Carbon Dioxide)

Pressure (Pa)	4in Coil Tube Diameter (m) (3/8 inch diam. tubing)	4in Coil Tube Surface Area (m ²)	Calculated Heat Xfer Coefficient [W/(m ² -K)]	Delta T1 (K)	Delta T2 (K)	Mean Log Temp (K) (Counterflow Heat Exchangers)	Calculated Q (W) (flow through the tube)
344738 (50 psi)	0.009525	0.071779778	97.97	327.14	483.4427	400.22	2814.49
517107 (75 psi)	0.009525	0.071779778	126.67	290.00	486.3461	379.75	3452.79
689476 (100 psi)	0.009525	0.071779778	158.45	257.41	479.392	356.97	4059.90

Table 14. Heat Transfer Rate Calculations for Carbon Dioxide, 2.3813 mm (3/32”) Diameter (Heat Absorbed by Carbon Dioxide)

Pressure (Pa)	4in Coil Tube Diameter (m) (3/8 inch diam. tubing)	4in Coil Tube Surface Area (m ²)	Calculated Heat Xfer Coefficient [W/(m ² -K)]	Delta T1 (K)	Delta T2 (K)	Mean Log Temp (K) (Counterflow Heat Exchangers)	Calculated Q (W) (flow through the tube)
344738 (50 psi)	0.009525	0.071779778	136.03	364.60	479.8049	419.57	4096.79
517107 (75 psi)	0.009525	0.071779778	176.06	312.10	482.5192	391.14	4943.22
689476 (100 psi)	0.009525	0.071779778	227.70	290.12	482.7282	378.29	6182.77

The second heat transfer rate calculation that had to be conducted was the heat transfer from the engine exhaust to the tube wall of the coil and was calculated using the general heat transfer rate equation [18]:

$$q = hA(T_s - T_m)$$

where q is the heat transfer rate, h is the previously calculated heat coefficient, A is the surface area, T_s is the tube wall surface temperature, and T_m is the mean temperature of the Carbon Dioxide gas as it flows through the heat exchanger. These calculations are shown in Tables 15 and 16.

Table 15. Heat Transfer Rate Calculations for Carbon Dioxide, 1.5875 mm (1/16”) Diameter (Heat Radiated by Engine Exhaust)

Pressure (Pa)	Calculated Heat Xfer Coefficient [W/(m ² -K)]	4in Coil Tube Surface Area (m ²)	Exhaust Inlet Temp (K)	CO2 Mean Temp. (K)	Calculated Q (W) (flow Through Tube Wall)
344738 (50 psi)	97.97139969	0.071779778	797	381.21	2924.01
517107 (75 psi)	126.6688086	0.071779778	802	403.33	3624.84
689476 (100 psi)	158.446383	0.071779778	799	420.10	4309.32

Table 16. Heat Transfer Rate Calculations for Carbon Dioxide, 2.3813 mm (3/32”) Diameter (Heat Radiated by Engine Exhaust)

Pressure (Pa)	Calculated Heat Xfer Coefficient [W/(m ² -K)]	4in Coil Tube Surface Area (m ²)	Exhaust Inlet Temp (K)	CO2 Mean Temp. (K)	Calculated Q (W) (flow Through Tube Wall)
344738 (50 psi)	136.0314844	0.071779778	794	360.80	4229.91
517107 (75 psi)	176.0641868	0.071779778	800	391.69	5160.18
689476 (100 psi)	227.6967769	0.071779778	805	407.07	6503.71

Among heat transfer rates calculated between tables 13–14 and 15–16, results show that there is a slight loss of heat transferred from engine exhaust to the Carbon Dioxide gas as its discharged through the heat exchanger. This is to be expected, as heat must first transfer through the tube walls before it heats the pressurized gas inside the coils. The delta between the two heat transfer rates per scenario is shown in Tables 17 and 18.

Table 17. Carbon Dioxide Delta Q's, 1.5875 mm (1/16”) Diameter Nozzle

Pressure (Pa)	Calculated Q (W) (flow Through Tube Wall)	Calculated Q (W) (flow through the tube)	Delta Q (W) (Heat Lost Through Tube Wall)
344738 (50 psi)	2924.01	2814.49	109.52
517107 (75 psi)	3624.84	3452.79	172.05
689476 (100 psi)	4309.32	4059.90	249.42

Table 18. Carbon Dioxide Delta Q's, 2.3813 mm (3/32”) Diameter Nozzle

Pressure (Pa)	Calculated Q (W) (flow Through Tube Wall)	Calculated Q (W) (flow through the tube)	Delta Q (W) (Heat Lost Through Tube Wall)
344738 (50 psi)	4229.91	4096.79	133.12
517107 (75 psi)	5160.18	4943.22	216.96
689476 (100 psi)	6503.71	6182.77	320.95

The comparison of heat exchanger effectiveness using heat transfer rates to the previously calculated effectiveness using temperatures is shown for Carbon Dioxide in Tables 17 and 18 for the 1.5875 mm (1/16”) and 2.3813 mm (3/32”) nozzles. The heat effectiveness calculation using the heat transfer rates prove to be very unrealistic, with the lowest heat effectiveness percentage calculated being 95.07%. This could be due to the method of how the heat transfer rates were calculated. As mentioned previously, heat transfer rate calculations were made under the assumption of straight piped flow. Therefore, the Reynolds and Nusselt numbers found using the Dittus-Boelter method have marginal error due to the helical geometry of the coils inside the heat exchanger. The heat effectiveness calculations using the exhaust inlet temperature, as well as the Carbon Dioxide inlet and outlet temperatures, are more accurate and shall be the data to be relied upon in future thesis projects.

Table 19. Carbon Dioxide Heat Effectiveness Comparisons, 1.5875 mm (1/16”) Nozzle

Pressure (Pa)	Heat Effectiveness Using Temperature (K)	Heat Effectiveness Using Heat Transfer Rates (W)
344738 (50 psi)	54.18	96.85
517107 (75 psi)	74.83	95.80
689476 (100 psi)	94.20	95.07

5. Dittus-Boelter Analysis

Further analyzation was conducted to verify the accuracy of the previously calculated Carbon Dioxide heat transfer rates. There was uncertainty in the large heat transfer rates calculated, so another calculation was conducted for the 1.5875 mm (1/16”) nozzle data using heat transfer rate equation [18]:

$$q = \dot{m}_c c_{p,c} (T_{c,o} - T_{c,i})$$

where q is the heat transfer rate, $\dot{m}_c$ is the mass flow rate of the Carbon Dioxide gas, $c_{p,c}$ is the specific heat coefficient for Carbon Dioxide at its respective temperature, $T_{c,o}$ is the

outlet temperature of Carbon Dioxide from the heat exchanger, and $T_{c,i}$ is the inlet temperature of Carbon Dioxide as it enters the heat exchanger [18]. Revised heat transfer calculation results for the 1.5875 mm (1/16”) nozzle data are shown in Table 20.

Table 20. Revised Carbon Dioxide Heat Transfer Rate Calculations for the 1.5875 mm (1/16”) nozzle data

Pressure (Pa)	Mass Flow Rate (kg/s)	Specific Heat (J/kg-K)	CO2 Inlet Temp. (K)	CO2 Outlet Temp. (K)	CO2 Delta T (K)	Calculated Q (W) (Heat absorbed by CO2)
344738 (50 psi)	0.001874083	918	292.56	469.86	177.30	305.03
517107 (75 psi)	0.002503681	939	294.65	512.00	217.35	510.97
689476 (100 psi)	0.003121212	959	298.61	541.59	242.99	727.31

After further literature review, these revised heat transfer rates proved to be a more realistic representation of the heat transfer occurring inside the heat exchanger. Because the Dittus-Boelter equation used previously was not designed for a helical flow geometry, it was decided that it should be modified specifically for the heat exchanger to predict future performance. This was done through an iterative process where the coefficient and exponent of the Reynolds number within the Dittus-Boelter equation was manipulated to where graphically the slopes of the revised heat transfer rates and calculated Reynolds numbers aligned on a logarithmic plot. This is shown in Figure 35.

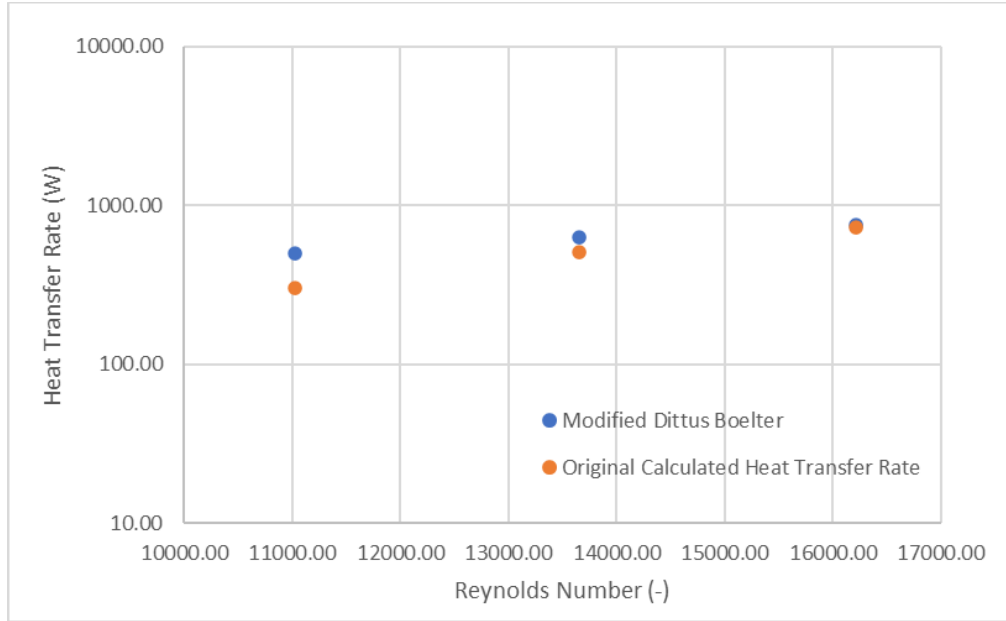


Figure 35. Logarithmic Plot of Dittus-Boelter and Heat Transfer Rate Relationship

The new Dittus-Boelter relationship found specific to the heat exchanger using this method was:

$$Nu_{HX} = 0.0017Re_D^{0.9}Pr^{0.4}$$

Using the new modified Dittus-Boelter relationship, the heat transfer coefficient, the heat transfer rate, as well as the performance of Kaim's modified heat exchanger design can potentially be predicted. The new relationship is only valid for Reynolds numbers between 11,000 and 27,000 until further testing is conducted. This will be verified for all four coils in following thesis projects.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

A. CONCLUSIONS

The work outlined in this thesis included a full analyzation of a waste heat recovery system already installed on Training Ship, Golden Bear, where efficiency and heat transfer rates were calculated. There were lessons learned from the analyzation of Golden Bear's system that enabled more fine tune calculations and detail for heat transfer rates calculated within this thesis.

To fix the exhaust leakage mentioned in Kaim's thesis, the heat exchangers were disassembled to install fabricated gaskets in between each meshing point of the heat exchanger clamshell design. The heat exchangers were then tested for integrity to ensure that there was no leakage of exhaust by running the engine within the test cell. The tests were successful with no exhaust leakage present.

Additionally, the heat exchangers themselves were tested and analyzed for the first time with Carbon Dioxide to determine the effectiveness and heat transfer rate within the heat exchangers while the engine is in operation. With engine speeds set constant with a gas generator value of 48,000 rpm and output shaft speed of 4,800 rpm, the highest heat exchanger effectiveness calculated was 94.20% with Carbon Dioxide discharge pressure at 689,486 Pa (100 psi). The correlating mass flow rate and heat transfer rate calculated was 11.24 kg/h and 727.31 W respectively. This data was further analyzed to tailor the Dittus-Boelter equation specifically to predict future performance of the heat exchanger for all 4 coil diameters by method of iteration. The modified Dittus-Boelter equation formulated was:

$$Nu_{HX} = 0.0017Re_D^{0.9}Pr^{0.4}$$

Finally, as an addition to the project, another way of heat extraction was explored using Peltier Devices that turn heat into electricity using the heat radiated from the exhaust ducts. This concept is further explained in Appendix A.

B. FUTURE WORK

The original goal of this thesis was to create a pressure map of different flow types across all 4 flow meters to gauge heat exchanger performance. Unfortunately, without the MODBUS device being delivered, the available resources restricted data retrieval from only one flow meter. Retrieving mass flow data from the 4in diameter coil flow meter proved quite cumbersome as the readings had to be recorded by a camera and manually time stamped to be cross-referenced with MATLABs pressure and temperature readouts. The installation of the MODBUS protocol device, along with coding the device into MATLAB will ensure remote recording of all data taken, as well as provide more timely-accurate data.

Once the MODBUS is installed and coded into MATLAB as part of the DAQ system, a map of heat exchanger performance with different flow types should be established as a baseline to identify compressor performance requirements. After the baseline data for all coils is established, then further analyzation can occur to verify the new Dittus-Boelter relationship for the remaining coil diameters.

Lastly, the fabrication and installation of the Peltier Design on the engine exhaust duct should occur to further investigate the total amount of power that could be generated using the TEGpro Peltier devices.

APPENDIX A. PELTIER COOLER DESIGN CONCEPT

A. BACKGROUND: THE PELTIER EFFECT

While the Closed Loop CO₂ Brayton cycle heat exchange and energy extraction through convection using a heat exchanger, the Peltier Effect mainly uses conduction as a means of energy extraction [20]. The Peltier Effect is a thermoelectric process that converts high temperature heat sources directly into electricity using a specifically designed element or device. By definition, the Peltier effect “is a phenomenon that a potential difference applied across a thermocouple causes a temperature difference between the junctions of the different materials in thermocouple” [21]. Simply put, Peltier devices are simple tools that have no internal moving parts, and can be utilized to generate heat, cool down a specific area, or generate electricity [22]. These devices operate by “sandwiching” alumina ceramic substrates between two pads of electrically conductive material (metal), and the temperature difference across these two metal pads create enough potential to generate electricity [23]. One metal pad is considered the “Hot Side,” while the other metal pad is considered the “Cold Side” respective to the ceramic material sandwiched between the metal pads [23].

Figure 40 depicts generally how a real Peltier element is arranged showing the Hot and Cold Sides of the element with the ceramic material sandwiched in between, and Figure 41 shows the TEGpro Peltier device used for this thesis in the Peltier design concept.

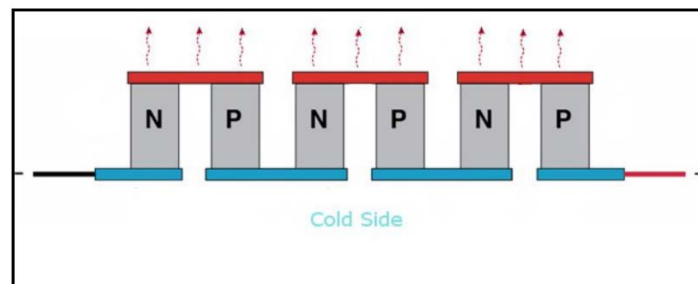


Figure 36. General Peltier Element Arrangement. Source: [22].



Figure 37. TEGpro Peltier Device. Source: [20].

In relation to this thesis project, the goal was to take this idea and place Peltier devices along the gas turbine exhaust duct to experimentally measure the amount of electricity that could be generated in addition to the Closed Loop CO₂ Brayton Cycle. Though experiments were not able to be conducted due to time constraints with fabrication time, a conceptual design was developed via Solidworks for follow-on experimentation in later thesis projects.

B. THE PELTIER DESIGN CONCEPT

The biggest challenge in the Peltier design concept was to determine how many Peltier devices could reasonably fit onto the gas turbine exhaust duct, and what was going to be used to create a heat sink for the “Cold Side” of the Peltier device. A heat sink is needed in order to form a temperature difference across the device to generate the electric potential needed for experimentation while the engine is running. The “Hot Side” of the Peltier device would somehow directly, or indirectly be attached to the gas turbine exhaust duct. The size of these Peltier devices were 56 mm (2.20”) in square dimension

with a height of roughly 5 mm (0.20”) as shown in Figure 42, so designing something that was small enough to fit around the exhaust duct, yet big enough to house multiple Peltier devices was paramount. The next challenge was to determine the material for the design. The material had to have relatively strong conductive properties yet be light enough to be bolted around the exhaust duct without compromising the ducts’ structural integrity. With the amount of material available on campus, aluminum was ultimately chosen to be the best option for the design.

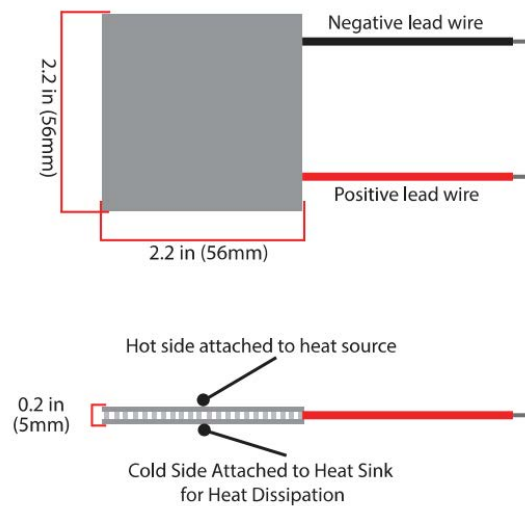


Figure 38. TEGpro Peltier Device Dimensions. Source: [20].

After much discussion and mock-up drawings, a clamshell encasing design model was decided upon and designed in Solidworks conceptually. The finished clamshell model would encase 8 Peltier devices per exhaust and be directly bolted around the exhaust duct itself. This would ensure maximum physical contact to the ducting. The goal was to create a design that would allow for maximum heat transfer from the exhaust duct to the design model itself. Therefore, the more surface area that is in contact with the ducting while the engine is running, the better chance for optimal heat transfer. Only half of the design model per duct was created in Solidworks with the assumption that parts could be easily duplicated in the fabrication process.

The model was composed of 3 key components, which totaled to 9 separate parts that had to be designed. Dimensions and sizes for each component will be shown in Solidworks drawings in Appendix E. The first component was the clamshell piece itself shown in Figures 44–46. This is the component of the design that would be in direct contact with the exhaust duct and sit “first in line” in transferring heat to the Peltier devices with relation to the other design components while the engine is in operation. Two of these clamshell pieces will bolt together around the exhaust duct with the circular surface of each piece being in direct contact with the exhaust. Thermal paste would be applied to the surfaces to ensure optimal heat transfer.

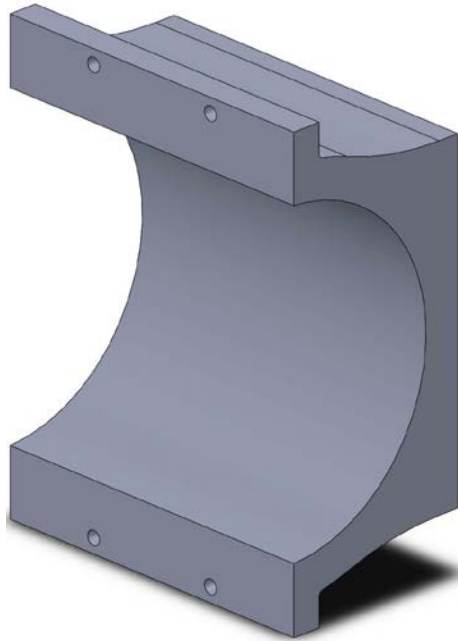


Figure 39. Design Component 1, Clamshell Piece Isometric View



Figure 40. Design Component 1, Clamshell Piece Side View

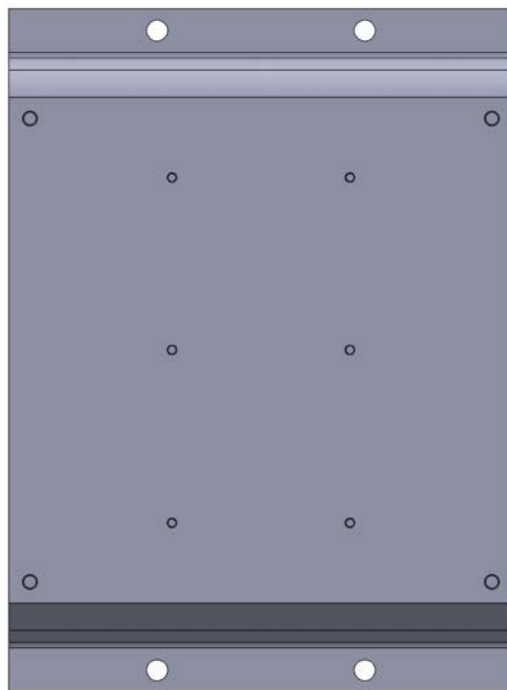


Figure 41. Design Component 1, Clamshell Piece Back View

The second component of the design was the TEG Block shown in Figures 47–51. This TEG Block would be “second in line” in transferring heat to the Peltier devices via conduction as it will be directly attached to the clamshell piece and the Cooling Block Cavity using hi-temp fasteners. The Cooling Block Cavity will be introduced later in the chapter and serves as the third and final component of the design. Its sole purpose is to house the Peltier devices and be the direct means of heat transfer to and from the devices themselves. The TEG Block would be composed of two separate parts (top and bottom pieces) and will house 4 Peltier Devices.

As mentioned before, the TEG Block will be directly bolted to the clamshell piece, as well as the Cooling Block Cavity. The idea is that the top and bottom pieces of the TEG Block would sandwich and be in direct contact with both sides of the 4 Peltier Devices. The devices would be placed into the square notches shown in Figure 32 (TEG Block Bottom), as the TEG Block Top, Figures 50 and 51, would be fastened down to create the sandwiching effect. This relationship is shown in Figure 52. Figure 53 depicts how the TEG Block “fits up” to the clamshell once fastened down.

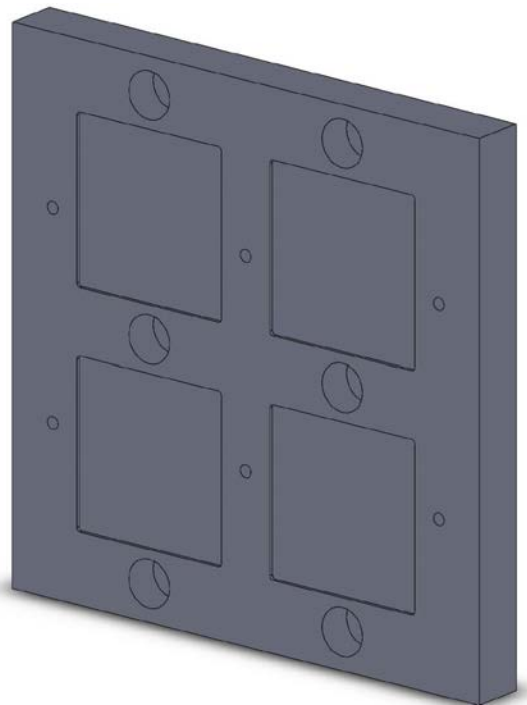


Figure 42. Design Component 2 Part 1, TEG Block Bottom Isometric View

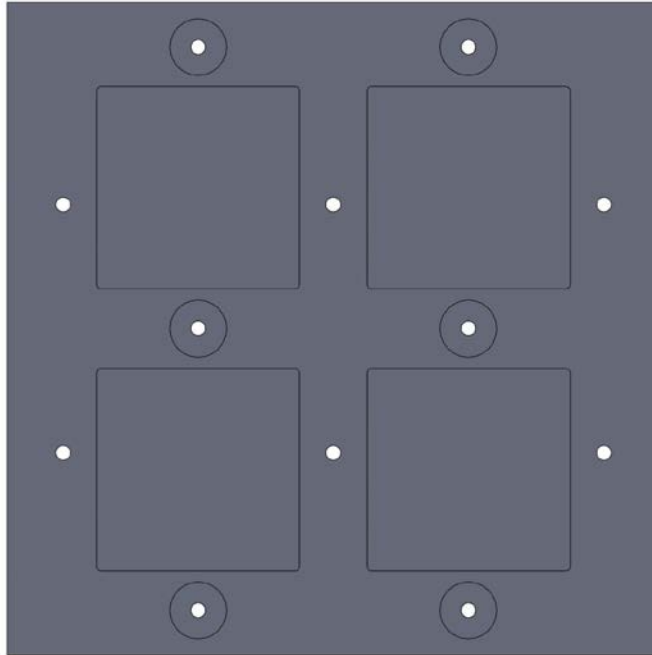


Figure 43. Design Component 2 Part 1, TEG Block Bottom Front View



Figure 44. Design Component 2 Part 1, TEG Block Bottom Back View

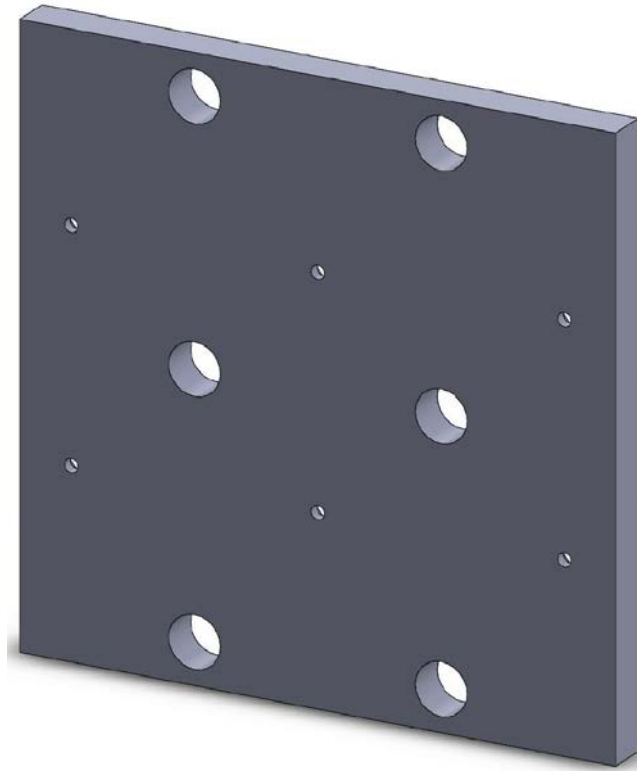


Figure 45. Design Component 2 Part 2, TEG Block Top Isometric View

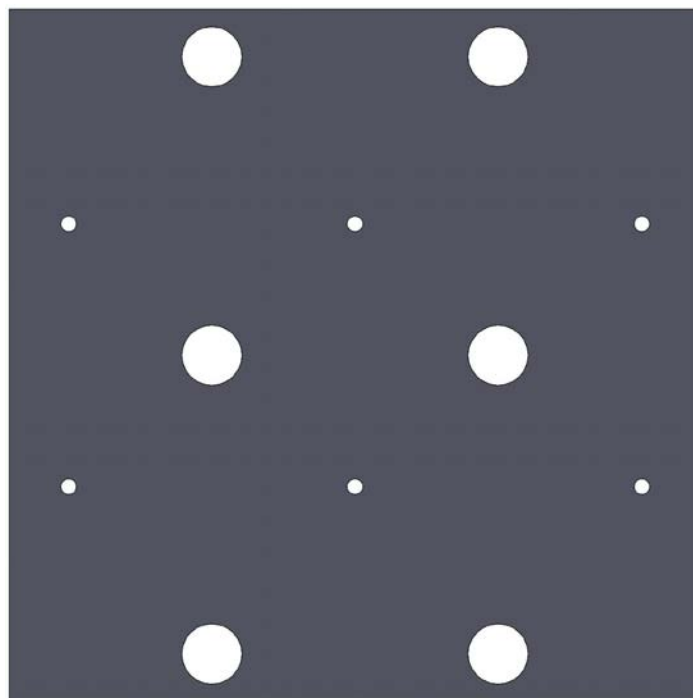


Figure 46. Design Component 2 Part 2, TEG Block Top Front View

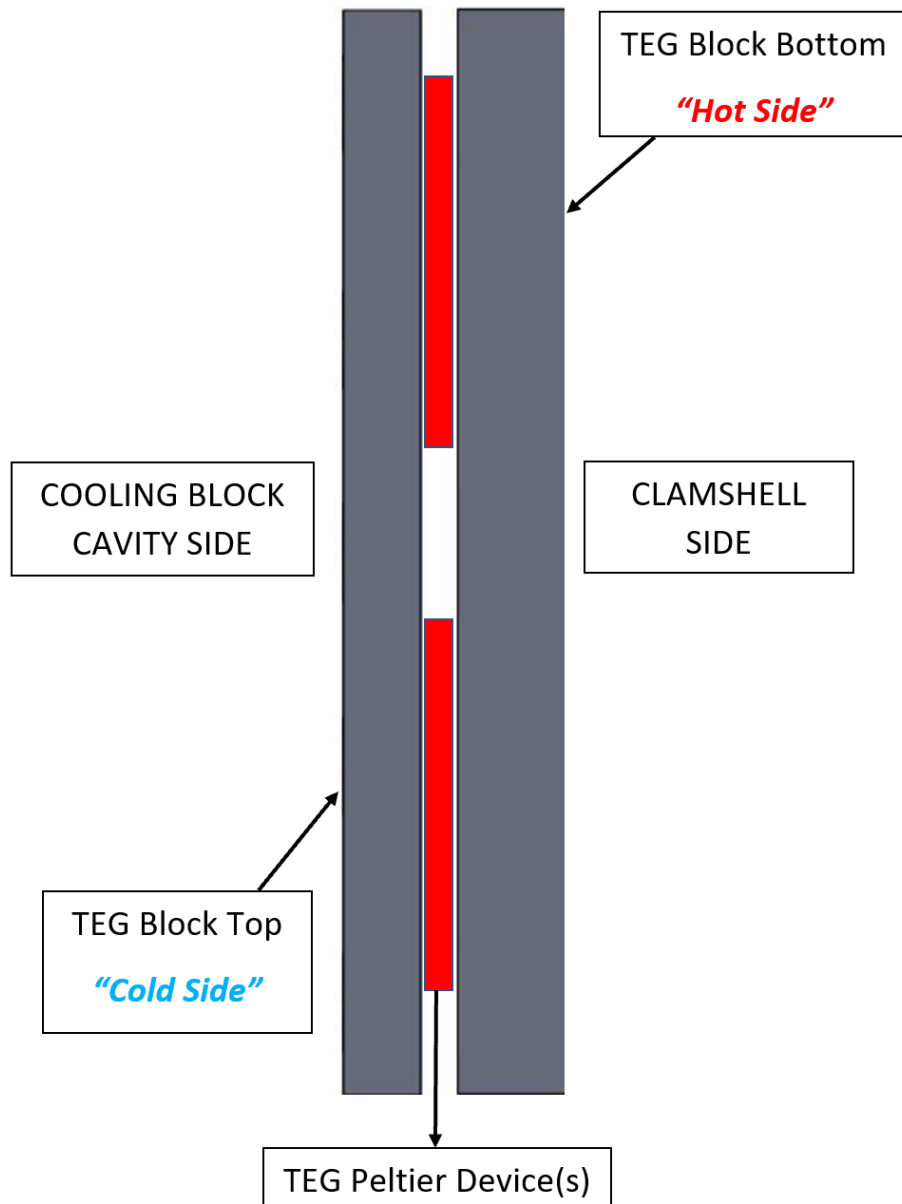


Figure 47. TEG Block Top and Bottom Assembly with Installed Peltier Devices Side View

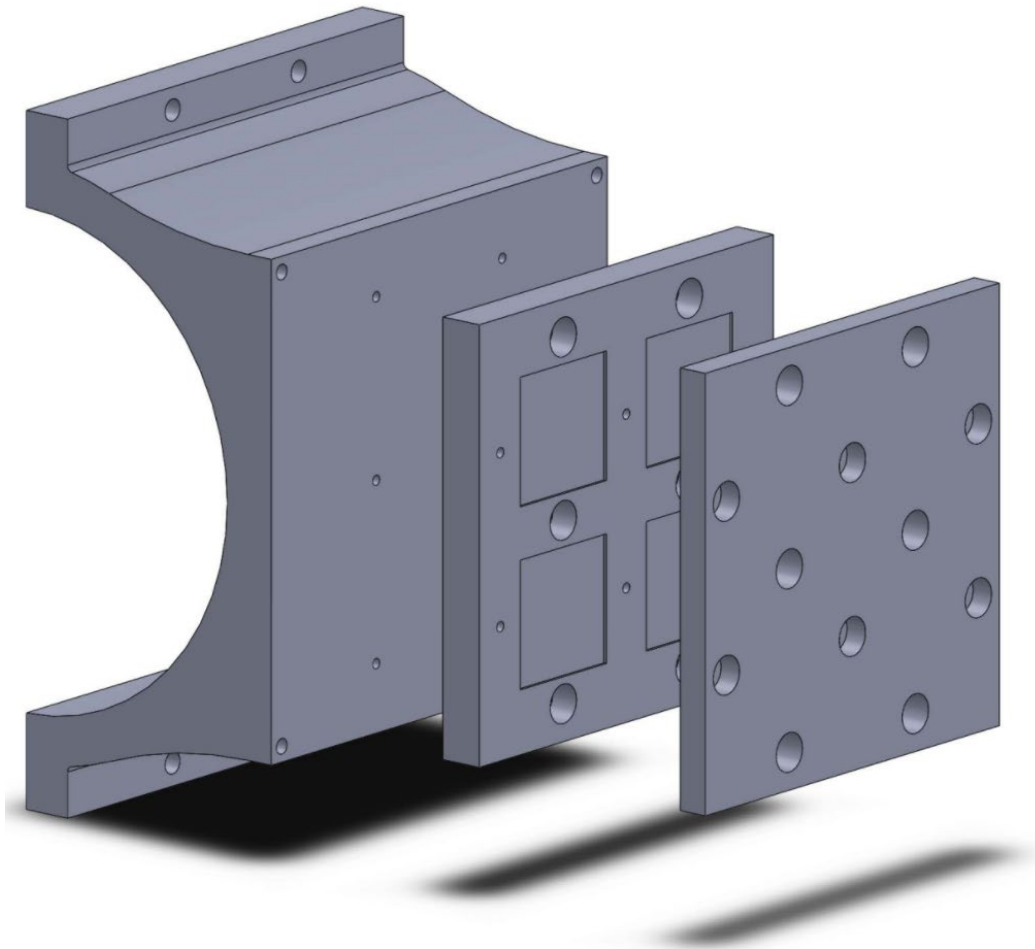


Figure 48. TEG Block and Clamshell “Fit-up”

The third and final component of the Peltier design model is the Cooling Block Cavity shown in Figure 54 and 55. The Cooling Block Cavity is “third in line” in the heat transfer from the exhaust duct to the Peltier devices. The sole purpose of the Cooling Block Cavity is to serve as the heat sink (Cold Side) needed for the Peltier devices to generate electricity while the engine is in operation. The Cooling Block Cavity is composed of two parts, the cooling cavity itself, and the cooling cavity cover, which is fastened to the top of the cavity using hi-temp fasteners. The idea behind the Cooling Block Cavity is that it would be filled with garden hose water through $\frac{1}{4}$ inch NPT fittings shown in Figure 56. This water would have continuous flow in and out of the cavity as there are 2 NPT fittings designed in the cooling cavity; one for inlet waterflow and one for outlet waterflow.

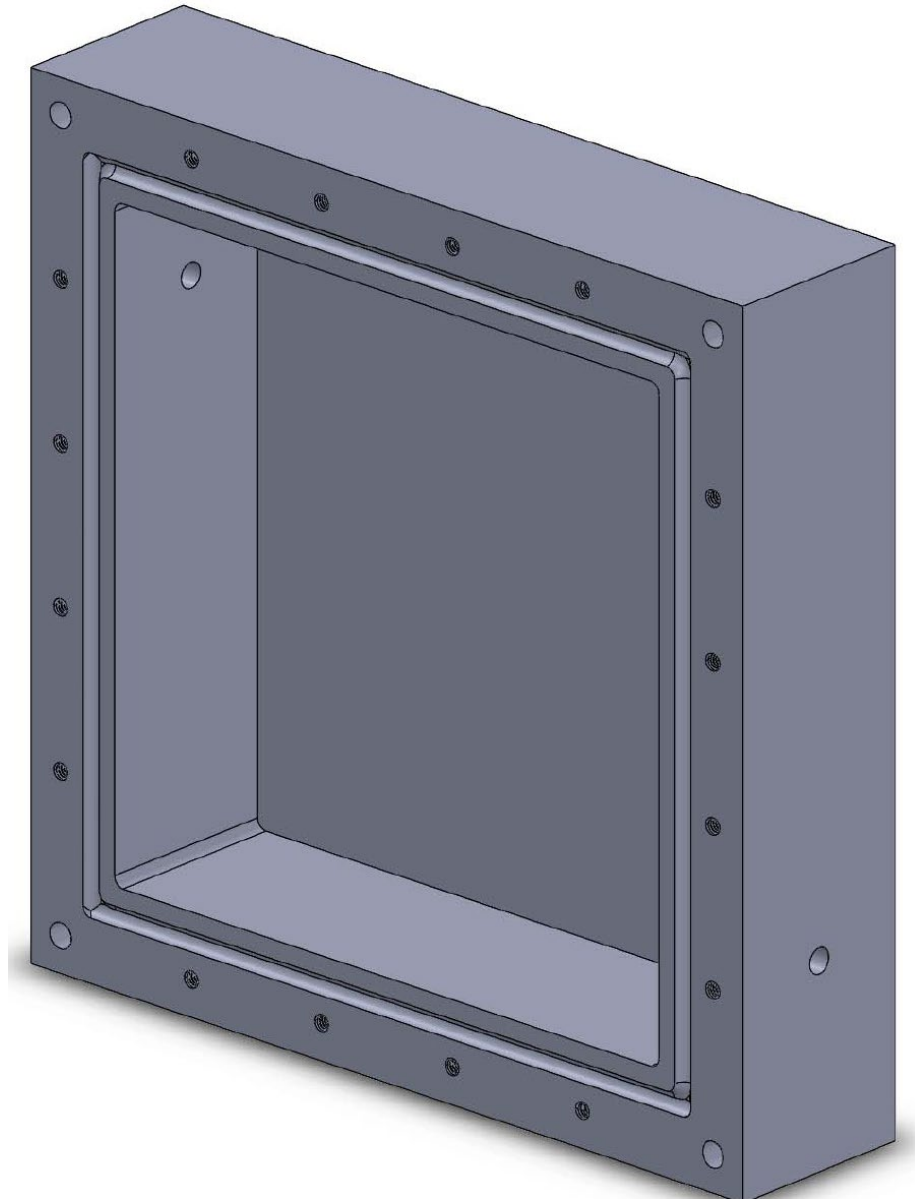


Figure 49. Design Component 3, Cooling Block Cavity Front Isometric View

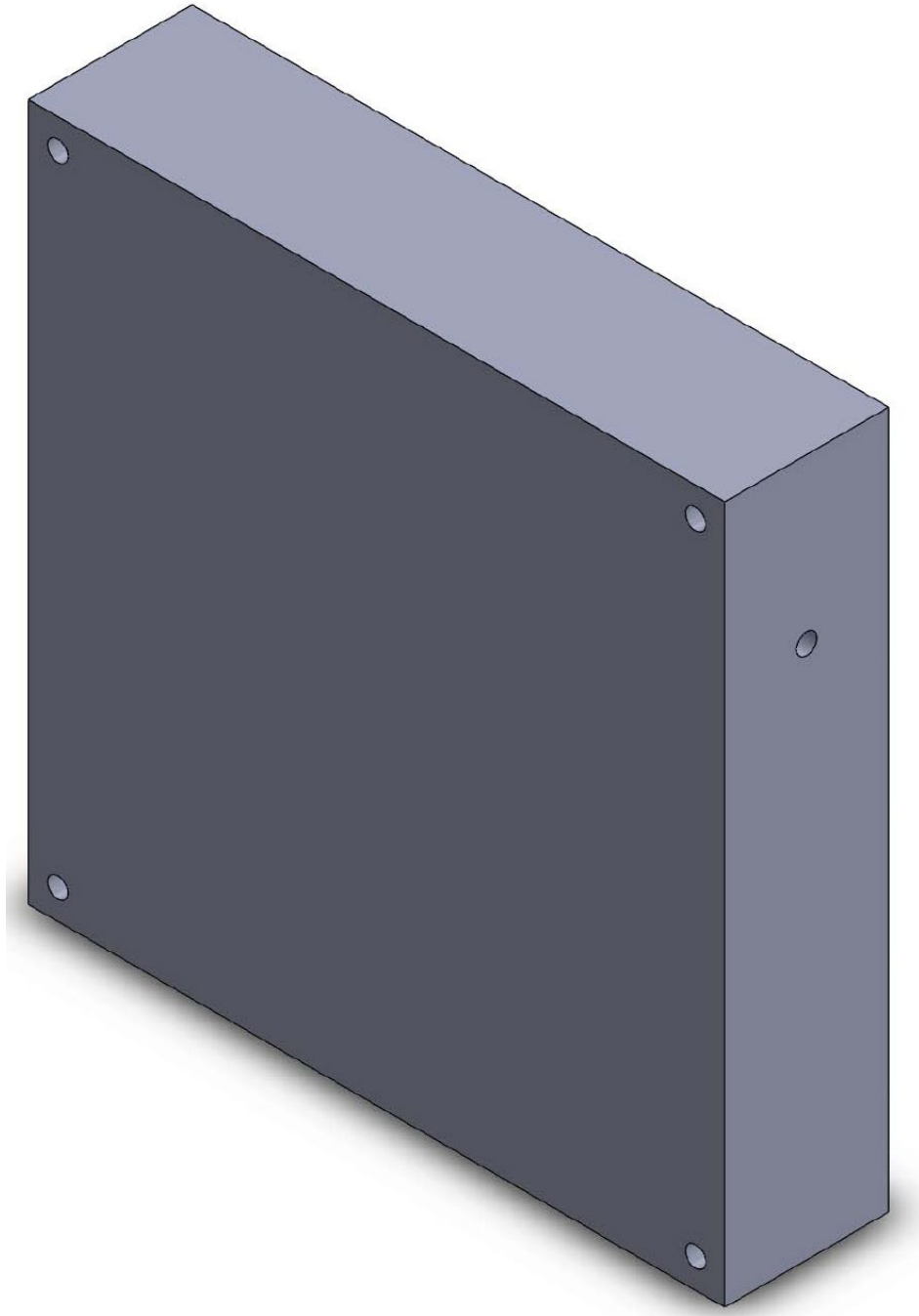


Figure 50. Design Component 3, Cooling Block Cavity Back Isometric View

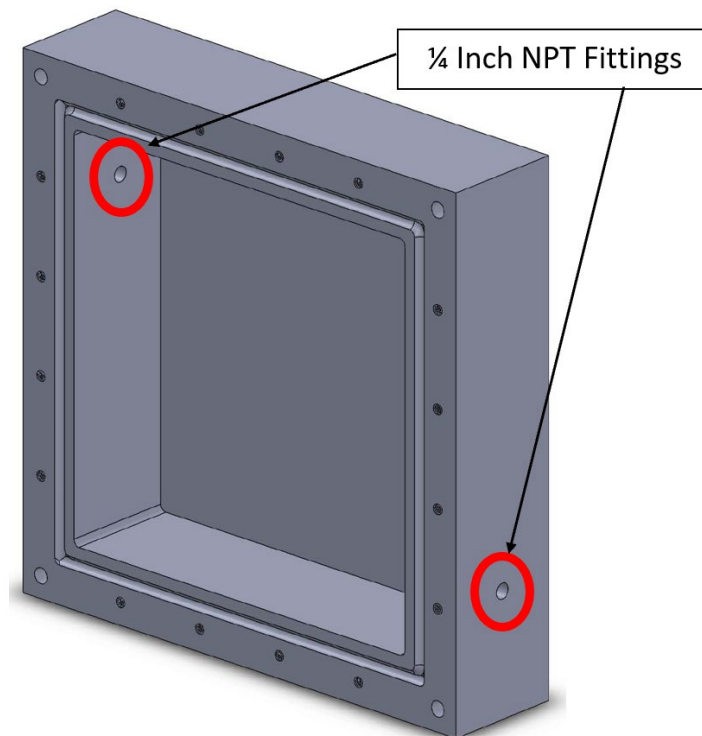


Figure 51. Cooling Block Cavity NPT Fitting Locations

Typical temperature for garden hose water is roughly 280 Kelvin (45° Fahrenheit). Exhaust temperatures from the gas turbine in full operation hover around 800 Kelvin (980° Fahrenheit). Therefore, in terms of Kelvin, there is a temperature difference of just over 500 Kelvin between the cooling cavity and the clamshell piece directly bolted around the exhaust duct. 500 Kelvin is more than sufficient to reach the temperature difference needed for the Peltier devices to generate electricity. This is assuming the aluminum material transfers the heat to and from the Peltier devices perfectly, which is known to be physically impossible, but gives ballpark estimates on what to expect when the design is ready for experimentation.

To prevent leakage, the water will be sealed in by small rubber gaskets that will fit into the semi-circular grooves that border the cavity shown in Figures 54 and 56. Once fastened down, the Cooling Block Cover and rubber gasket material should provide enough seal to uphold water integrity throughout the cavity. The Cooling Block Cover is shown in Figures 57 and 58.

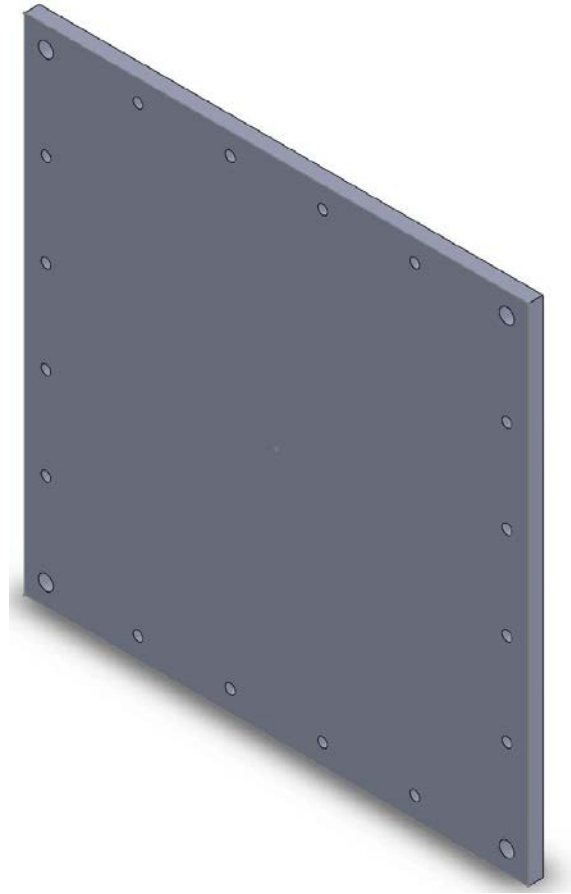


Figure 52. Design Component 3, Cooling Block Cover Isometric View

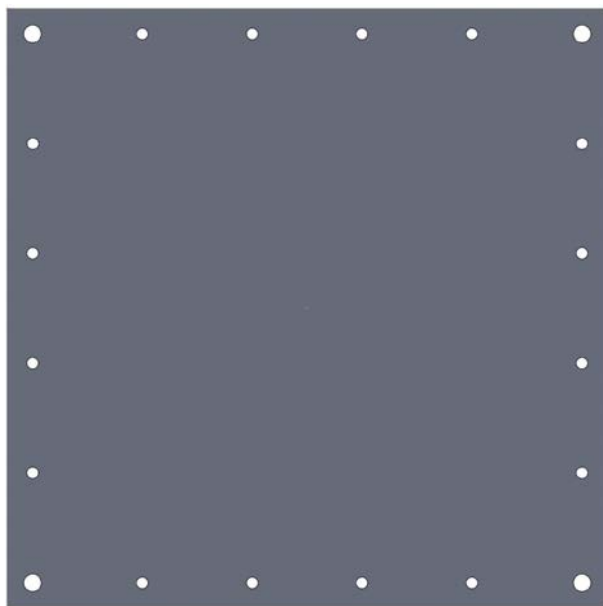


Figure 53. Design Component 3, Cooling Block Cover Back View

Figures 59–61 show all 3 design components together in a full assembly as it would be if it were installed on the exhaust duct. All three components would be fastened together by fabricated screw supports that would screw into the front face of the clamshell piece. These screw supports are depicted in Figures 62 and 63.

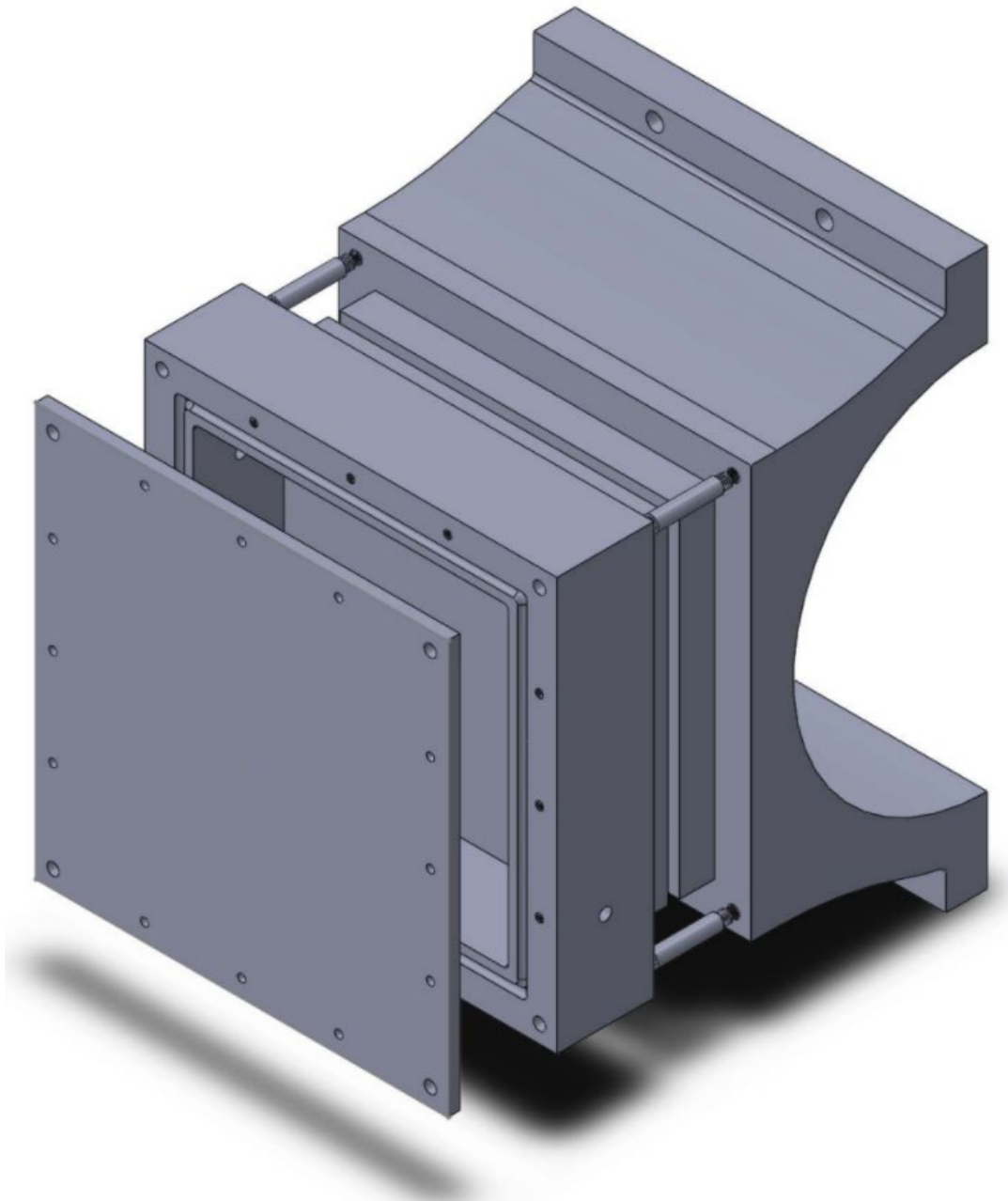


Figure 54. Peltier Design Full Assembly Isometric Front View

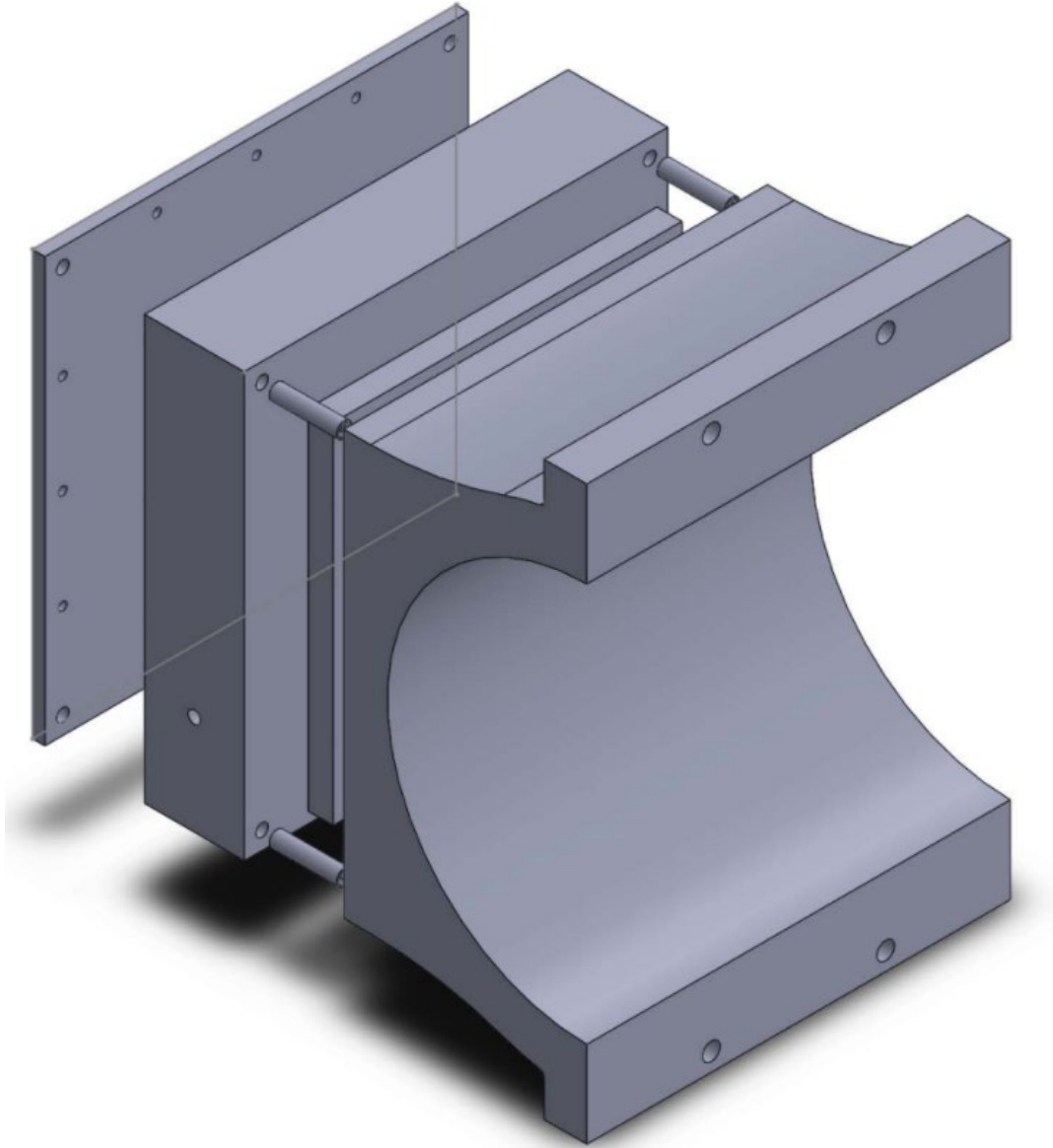


Figure 55. Peltier Design Full Assembly Isometric Back View



Figure 56. Peltier Design Full Assembly Side View



Figure 57. Peltier Design Screw Support Isometric View



Figure 58. Peltier Design Screw Support Side View

APPENDIX B. MATLAB DATA ACQUISITION SCRIPT

A. CURRENT MATLAB SCRIPT

Data Acquisition Script

Table of Contents

Code Description (SECTION 1).....	1
Pressure Brick Initialization (SECTION 2).....	1
Txt File Initialization (SECTION 3).....	2
User Inputs (SECTION 4).....	3
System Set-Up (SECTION 5).....	3
Data Gathering (SECTION 6).....	6
Output Data (SECTION 7).....	7
Functions (SECTION 8).....	8

Code Description (SECTION 1)

This code utilizes listeners to read temperature data in the background while gathering pressure data in the foreground. All data is stamped with a date stamp, and each data point is given a timestamp to identify it with data that was taken at the same time. All data is output via tab-delimited text files. This code was developed using work done by Belna as laid out in his thesis. This code was developed by LTJG Michael Kaim and Modified by LT Denzel Reina

Pressure Brick Initialization (SECTION 2)

Before running this script, ensure you calibrate all four pressure bricks (146, 147, 148 and 149) using the DSALink4v1.00 app on this computer's desktop. Once you open the app, type in the IP address for the pressure brick you are trying to calibrate (should only need to change the last grouping in the IP address for the desired pressure brick) and click the "Enter DSA IP Address, then CLICK here" button below. Then proceed to the following steps:

```
% 1. Click on "Command line" in the above task bar
% 2. Type command "list scan" in the Command Entry Window and ensure a
list
%   of 14 parameters populates in the dark gray box under "DSA"
% 3. Then type "SET BIN 1" (type list scan in again to ensure BIN
changed
%   to 1)
% 4. Then type "SET FPS 0" and check the change using "list scan"
again
% 5. Then click on "List I" tab on the left side of the window and
ensure
%"SET HOST" reads "0 0 T" if not, type "SET HOST 0 0 T" in the
Command
%   Entry Window
% 6. Click "Save" to save all parameter changes and close out the
window
% 7. Then click "CALZ" in the above task bar to perform a zero
calibration
%   on the desired pressure brick
```

```

% 8. Once Zero Calibration is complete, click on "Start Data File" in
the
%above task bar (Once you do it the first time in a day, there's
no
% need to start a new data file...just move on to step 10)
% 9. Click "ok" to save the scan in the current working directory.
% 10. Then Click Scan to verify all ports are reading correctly
% 11. You'll know if you have properly calibrated the pressure brick
if
% blue bars indicating pressure readings across the 16 different
%channels display somewhat irratically with correlating values
on the
% left hand side of the window.
% 12. Click "Stop" to stop scan
% 13. Click "Disconnect"
% 14. Then Click "Connect" and follow steps 1-13 for the next pressure
% brick until all four pressure bricks have been calibrated
% 15. Once all four pressure bricks have been calibrated, this code
will be
% ready to run.

```

Txt File Initalization (SECTION 3)

This part of the code prepares the text file output. Before running the engine, ensure the PressureBrick_Initialization.m script has been executed in order to zero the pressure bricks to the current ambient pressure.

```

% 'clearvars' is used instead of 'clear' because 's' and 'lh' are
associated
% with the NI Max data acquisition system and are designed to be
persistent
% variables to reduce the time it takes to start taking readings
clearvars -except s lh,clc,format compact,close all

% These Global variables allow temperature data to be recorded in the
b
% background and indexed with their appropriate time stamp
global k
global NIdata
global time
global tch
global vch

% The 'timestampfun' embeded at the end of this script uses the number
% input to determine what to do with the data. A '1' input means the
engine
% is not running and you wish to test the code. Leaving the field
empty
% will record the data as if the engine is running.
[datastamp,filestamp] = timestampfun(1); %a '1' input designates test
run

% The filenamer function simply checks to see if timestamped files
exist,

```

```
% and if not, creates them. The outputs are the FID codes for each
file.
[filenames] = filenamer(filestamp);
```

User Inputs (SECTION 4)

The "duration" input will determine how many data points the system will take during any particular speed setting. N1 and ND are set here as well to be printed on the output file. Manual input is easy, but dialogue boxes can be used as well.

```
duration = 10;

N1 = "46000"
% N1 = "idle"
% N1 = string(38340)
% N1 = string(43450)
% N1 = string(48560)
% N1 = string(51120)
% N1 = string(40890)
% N1 = string(46000)
% N1 = string(51000)

ND = "4800"
% ND = "idle"
% ND = string(3600)
% ND = string(4200)
% ND = string(4800)
% ND = string(5400)
% ND = string(6000)

% N1=string(inputdlg('Enter N1'))
% ND=string(inputdlg('Enter ND'))

N1 =
    "46000"
ND =
    "4800"
```

System Set-Up (SECTION 5)

This cell initializes all data acquisition devices. The temperature code was made using the Data Acquisition Toolbox in Matlab. The IP configuration was set up in the NI Max software. The pressure code was extracted from Matlab's Instrument Control Toolbox.

```
% NI System
% TChannels = 15; %1 module
TChannels = 30; %2 modules
tch = 1:TChannels;
VChannels = 4; %Voltage module
channels = TChannels+VChannels;
vch = TChannels+1:channels;

% Locates DAQ Devices
devices = daq.getDevices;
```

```

% Create DAQ Session. If a session 's' already exists, this line of
code is
% skipped in order to save time. At the beginning of the day, 'clear'
% should be run to ensure there are no variables left over from the
% previous day.
if exist('s','var')== 0
    s = daq.createSession('ni');
    % Set whether to gather data continuously or to scan a certain
amount
    s.IsContinuous = true;
    % Optional code to set a specific number of scans
    % s.NumberOfScans= 20;
    % Set the data acquisition rate
    s.Rate = 1;
    % Add Thermocouple Modules to measure temperature. Modules can
read 15
    % channels, and are set to read 15 thermocouples by default. Empty
channels
    % and bad connections will display approximately 2500 degrees
    chT1 =
addAnalogInputChannel(s,'cDAQ9188XT-1CCC957Mod1',1:15, 'Thermocouple')
    if TChannels > 15
        chT2 =
addAnalogInputChannel(s,'cDAQ9188XT-1CCC957Mod2',1:15, 'Thermocouple')
    end
    % Module 3 is for reading voltages from the Mass Flow gauges. At
the time
    % of writing this code, this voltage data requires a voltage
constant to
    % convert to mass flow during processing.
    chV =
addAnalogInputChannel(s,'cDAQ9188XT-1CCC957Mod4',1:4, 'Voltage');
    % Set up temperature units (Required to run script)
    % s.Channels(1).ADCTimingMode = 'HighResolution';
    for i=1:TChannels
        s.Channels(i).ThermocoupleType = 'K';
        s.Channels(i).Units = 'Kelvin';
    end
    % Create the listener which will run the input function whenever
the
    % 'DataAvailable' event runs
end

% This checks for the existence of a listener variable, 'lh', and
skips the
% code if it exists in order to save time.
if exist('lh','var') == 0
    lh=addlistener(s,'DataAvailable', @NI_Data);
end

% Pressure System (Code generated using Instrument Control Toolbox)
% See Belna's Thesis for more details
% Find a tcpip object.
tic

```

```

obj1 =
    instrfind('Type', 'tcpip', 'RemoteHost', '191.30.5.147', 'RemotePort',
    23, 'Tag', '');
obj2 =
    instrfind('Type', 'tcpip', 'RemoteHost', '191.30.5.146', 'RemotePort',
    23, 'Tag', '');
obj3 =
    instrfind('Type', 'tcpip', 'RemoteHost', '191.30.5.148', 'RemotePort',
    23, 'Tag', '');
obj4 =
    instrfind('Type', 'tcpip', 'RemoteHost', '191.30.5.149', 'RemotePort',
    23, 'Tag', '');
% Create the tcpip object if it does not exist, otherwise use the
% object that was found.
if isempty(obj1)
    obj1 = tcpip('191.30.5.147', 23);
else
    fclose(obj1); obj1 = obj1(1);
end
if isempty(obj2)
    obj2 = tcpip('191.30.5.146', 23);
else
    fclose(obj2); obj2 = obj2(1);
end
if isempty(obj3)
    obj3 = tcpip('191.30.5.148', 23);
else
    fclose(obj3); obj3 = obj3(1);
end
if isempty(obj4) %%%%
    obj4 = tcpip('191.30.5.149', 23); %%%%
else
    fclose(obj4); obj4 = obj4(1); %%%%
end
% Opens the previously specified objects and sets the parameters for
% each
% pressure brick
objects = [obj1;obj2;obj3;obj4]; %%%%
for ii=1:4 %%%%
    fopen(objects(ii));
    % Communicating with instrument object.
    fprintf(objects(ii), 'SET PERIOD 500');
    fprintf(objects(ii), 'SET AVG 32');
    % Set Frames Per Scan
    fprintf(objects(ii), 'SET FPS 1');
    % Set units to Pascals
    fprintf(objects(ii), 'SET UNITSCAN PA');
    % Set Engineering Units format
    fprintf(objects(ii), 'SET EU 1');
    % Set to ASCII data format
    fprintf(objects(ii), 'SET BIN 0');
    % Other Parameters
    fprintf(objects(ii), 'SET PERIOD 500');
    fprintf(objects(ii), 'SET AVG 32');

```

```

fprintf(objects(ii), 'SET FORMAT 0');
fprintf(objects(ii), 'SET TIME 0');
% Set Buffer to clear when full and continue sending data
fprintf(objects(ii), 'SET QPKTS 0');
end

```

Error using Data_Acquisition_Script_listeners_Reina_Modified_P4 (line 125)

Vendor 'ni' not recognized. Use 'daq.getVendors()' for a list of vendors.

Caused by:

Hardware 'ni' not operational using the Data Acquisition Toolbox.
Use 'daq.getVendors()' for a list of supported vendors.

Support for the vendor may require installation of the driver via the [Support Package Installer](matlab:daq.internal.supportPackageInstaller)

Data Gathering (SECTION 6)

The Temperature gathering code runs in the background after the `s.startBackground()` code is executed. From there, the pressure readings start within the for loop. The code is designed to take the specified number of readings from the pressure bricks while continuously gathering real-time temperature data at the specified rate. Once the pressure data is collected, the Temperature process is stopped so that the readings are taken during the same interval.

```

pdata1 = zeros(duration,16);
pdata2 = pdata1;
pdata3 = pdata1;
pdata4 = pdata1; %%%%
NIdata = zeros(1,channels);
time = 0;
k = 0;
s.startBackground();
% Takes the requested number of data points from the pressure bricks
while
% running the thermocouple readings in the background
timer=0;
for i=1:duration
%     if i>1
        pause(1-timer)
%     end
    tic
    % Sends Scan Command to DSA Pressure Brick
    fprintf(obj1, 'SCAN');
    fprintf(obj2, 'SCAN');
    fprintf(obj3, 'SCAN');
    fprintf(obj4, 'SCAN'); %%%%
    % Discards first variable from packet which lists frame number,
    % if set to FPS = 1 all frames will be 0
    frame = fscanf(obj1);
    frame = fscanf(obj2);
    frame = fscanf(obj3);
    frame = fscanf(obj4); %%%%
    for n=1:16

```

```

        % Extracts Pressure and Temperature readings in order # 1 to
16 ports
        tmp1 = fscanf(obj1);
        tmp2 = fscanf(obj2);
        tmp3 = fscanf(obj3);
        tmp4 = fscanf(obj4); %%%%
        data1 = str2num(tmp1);
        data2 = str2num(tmp2);
        data3 = str2num(tmp3);
        data4 = str2num(tmp4); %%%%
        % Takes Pressure readings and discards DSA temperature
readings
        pdata1(i,n)=data1(2);
        pdata2(i,n)=data2(2);
        pdata3(i,n)=data3(2);
        pdata4(i,n)=data4(2); %%%%
    end
    fprintf(1,'%1.0f\n',i)
%     fprintf(1,'%2.0f\n',k);
    timer = toc;
end
pause(1)
s.stop

for ii=1:4 %%%%
    % If FPS is set to 0 (infinite) this will stop pressure brick in a
secure manner
    fprintf(objects(ii), 'STOP');
    % Clear input buffer
    flushinput(objects(ii));
    % Clear output buffer
    flushoutput(objects(ii));
end

```

Output Data (SECTION 7)

This is where the data gets processed. The code is designed to take a specified number of readings and average them together for a single data point at the specified engine speeds. The data is then output into separate text files with the engine speed information, the unique time stamp for the data run, and the data output in a single line within their respective text files. This makes copying and pasting into excel easy with the tab delimiter specified. The first line of the text file may not line up with the data in excel since it is designed to look correct for the Matlab text reader, and therefore may need to be modified

```

% Split NI Data
tdata = NIdata(:,tch);
vdata = NIdata(:,vch);

% Consolidate pressure data into one variable
brick_ports = 1:16;
pdata = zeros(duration,48);
pdata(:,brick_ports)=pdata1;
pdata(:,brick_ports+16)=pdata2;

```

```

pdata(:,brick_ports+16*2)=pdata3;
pdata(:,brick_ports+16*3)=pdata4; %%%
[pm,pn] = size(pdata);

% Allocate space for average variables
pave = zeros(pm,1);pstd = pave;
tave = zeros(TChannels,1);tstd = tave;
vave = zeros(VChannels,1);vstd = vave;
% Calculates the average value for each port across all runs
for i = 1:pn
    pave(i,:) = mean(pdata(:,i));
    pstd(i,:) = std(pdata(:,i))./pave(i,:);
end
% Calculates the average value for each thermocouple across all runs
for i=1:TChannels
    tave(i,:) = mean(tdata(:,i));
    tstd(i,:) = std(tdata(:,i))./tave(i,:);
end
%Calculates the average value for each voltage across all runs
for i=1:VChannels
    vave(i,:) = mean(vdata(:,i));
    vstd(i,:) = std(vdata(:,i))./vave(i,:);
end Text_Output_Generator(filenamees,datastamp,N1,ND,time,pave,tave,vave,
pstd,tstd,vstd disp('Run Complete');

```

Functions (SECTION 8)

This part of the code is reserved for the local functions. Local Functions must be specified at the end of the code after everything else.

```

function [datastamp,filestamp] = timestampfun(test)
% This function creates a time and date stamp for the data output
files. If
% a script test run is designated, the filestamp variable is replaced
with
% 'test' to output the data to a continuous testing data file. For
actual
% data acquisition runs, the filestamp is the current date in YYYYMMDD
% format. The datastamp variable is the date but also includes the
time at
% which the run was initiated.
% [datastamp,filestamp] = timestampfun(test)
%where 'test' is a 1 for a script test run. Leave this field
empty
% for actual data acquisition.
if nargin == 0
    test=0;
end
% Calculate current date and time for timestamp
now = datetime('now');
y = num2str(year(now));
m = month(now);

```

```

if m<10
    m = (['0' num2str(m)]);
else
    m = num2str(m);
end
d = day(now);
if d<10
    d = (['0' num2str(d)]);
else
    d = num2str(d);
end
hr = hour(now);
if hr<10
    hr = (['0' num2str(hr)]);
else
    hr = num2str(hr);
end
min = minute(now);
if min<10
    min = (['0' num2str(min)]);
else
    min = num2str(min);
end
sec = round(second(now));
if sec<10
    sec = (['0' num2str(sec)]);
else
    sec = num2str(sec);
end

datastamp = [y m d '_' hr min '_' sec]
if test == 1
    filestamp = 'test'
else
    filestamp = [y m d]
end
end
function [filenames] = filenamer(filestamp)
% Description
% This function generates the filenames for each of the output text
% files.
% It uses the filestamp from the previous function to ensure each file
% is
% dated with the YYYYMMDD date format. The output 'filenames' is a
% cell
% array which is an input to the text file output function. No user
% input
% is necessary

% File Name Generator
mkdir(['Test Data\' filestamp])
Pfile = ['Test Data\' filestamp '\' filestamp '_PressureData' '.txt'];
Tfile = ['Test Data\' filestamp '\'
    filestamp ' TemperatureData' '.txt'];

```

```

Vfile = ['Test Data\' filestamp '\\' filestamp '_VoltageData' '.txt'];
NIdatfile = ['Test Data\' filestamp '\\' filestamp '_NIdata' '.txt'];
Pdatafile = ['Test Data\' filestamp '\\' filestamp '_pdata' '.txt'];
Pstd = ['Test Data\' filestamp '\\'
    filestamp '_PressureStdDev' '.txt'];
Tstd = ['Test Data\' filestamp '\\'
    filestamp '_TemperatureStdDev' '.txt'];
Vstd = ['Test Data\' filestamp '\\' filestamp '_VoltageStdDev' '.txt'];
filenames = {Pfile; Tfile; Vfile; NIdatfile; Pdatafile; Pstd; Tstd;
    Vstd};

save('names.mat','Pfile','Tfile','Vfile','NIdatfile','Pdatafile',
    'Pstd','Tstd','V

% File Generator
% If the file exists, this portion of the code is skipped. This would
% indicate a file with today's date is already created, and will
    simple by
% ammended.

% Pressure File
if exist(Pfile,'file') == 0
    P_atm = string(inputdlg('Enter Atmospheric Pressure (with
        units)'));
%     P atm = "29.90 inHg"
    PFID = fopen(Pfile,'w'); % Creates a file with Pfile name.
        % If file exists, this line is skipped.
    fprintf(PFID,'Atmospheric Pressure:\t%s\r',P_atm);
    fprintf(PFID,'Timestamp\t\tN1\tND\t');
%     fprintf(PFID,'%8.2f\t',
[1.01:.01:1.16,2.01:.01:2.16,3.01:.01:3.16]);
    fprintf(PFID,'1_%.2f\t',1:16);
    fprintf(PFID,'2_%.2f\t',1:16);
    fprintf(PFID,'3_%.2f\t',1:16);
    fprintf(PFID,'4_%.2f\t',1:16);%%%%
    fprintf(PFID,'\r\n');
    fclose(PFID);
end

% Temperature File
if exist(Tfile,'file') == 0
    TFID = fopen(Tfile,'w'); % Creates a file with Tfile name.
        % If file exists, this line is skipped.
    fprintf(TFID,'Timestamp\t\tN1\tND\t');
    fprintf(TFID,'%8.0f\t',1:32);
    fprintf(TFID,'\r\n');
    fclose(TFID);
end

% Voltage File
if exist(Vfile,'file') == 0
    VFID = fopen(Vfile,'w'); % Creates a file with Vfile name.
        % If file exists, this line is skipped.
    fprintf(VFID,'Timestamp\t\tN1\tND\t');
    fprintf(VFID,'%8.0f\t',1:10);

```

```

        fprintf(VFID, '\r\n');
        fclose(VFID);
    end

    % Raw NI Max Data File
    if exist(NIDatafile, 'file') == 0
        TFID = fopen(NIDatafile, 'w'); % Creates a file with Tdatafile
        name.
        % If file exists, this line is skipped.
        fclose(TFID);
    end

    % Raw Pressure Data File
    if exist(Pdatafile, 'file') == 0
        PFID = fopen(Pdatafile, 'w'); % Creates a file with Pdatafile name.
        % If file exists, this line is skipped.
        fclose(PFID);
    end

    % Pressure Standard Deviation File
    if exist(Pstd, 'file') == 0
        PFID2 = fopen(Pstd, 'w'); % Creates a file with Pstd name.
        % If file exists, this line is skipped.
        fprintf(PFID2, 'Timestamp\t\tN1\tND\t');
        fprintf(PFID2, '1_%.02f\t', 1:16);
        fprintf(PFID2, '2_%.02f\t', 1:16);
        fprintf(PFID2, '3_%.02f\t', 1:16);
        fprintf(PFID2, '4_%.02f\t', 1:16); %%%%
        fprintf(PFID2, '\r\n');
        fclose(PFID2);
    end

    % Temperature Standard Deviation File
    if exist(Tstd, 'file') == 0
        TFID2 = fopen(Tstd, 'w'); % Creates a file with Tstd name.
        % If file exists, this line is skipped.
        fprintf(TFID2, 'Timestamp\t\tN1\tND\t');
        fprintf(TFID2, '%-6.0f\t', 1:30);
        fprintf(TFID2, '\r\n');
        fclose(TFID2);
    end

    % Voltage Standard Deviation File
    if exist(Vstd, 'file') == 0
        VFID = fopen(Vstd, 'w'); % Creates a file with Vstd name.
        % If file exists, this line is skipped.
        fprintf(VFID, 'Timestamp\t\tN1\tND\t');
        fprintf(VFID, '%-6.0f\t', 1:10);
        fprintf(VFID, '\r\n');
        fclose(VFID);
    end
end

function Text_Output_Generator(filenamees, datastamp, N1, ND, time, pave,
tave, vave, pstd, tstd, vst

```

```

% Write Data to Text File
% This function takes the data as well as each time and date stamp and
% outputs them in separate text files for processing. The text files
% are
% tab-delimited and formatted to be viewed in MATLAB. For MATLAB data
% processing, the files need to be formatted further by removing
% excess
% tab delimiters. For excel, the data needs to be imported with the
% import
% function or can be copied and pasted directly into excel.

% Pressure Data
Pname = (['Pdata_' datastamp]);
PFID = fopen(string(filename(1)), 'a');
fprintf(PFID, '%s\t', Pname);
fprintf(PFID, '%s\t%s\t', [N1 ND]);
fprintf(PFID, '%08.2f\t', pave);
fprintf(PFID, '\r\n');
fclose(PFID);

% Temperature Data
Tname = (['Tdata_' datastamp]);
TFID = fopen(string(filename(2)), 'a');
fprintf(TFID, '%s\t', Tname);
fprintf(TFID, '%s\t%s\t', [N1 ND]);
fprintf(TFID, '%-010.4f\t', tave);
fprintf(TFID, '\r\n');
fclose(TFID);

% Voltage Data
Vname = (['Vdata_' datastamp]);
VFID = fopen(string(filename(3)), 'a');
fprintf(VFID, '%s\t', Vname);
fprintf(VFID, '%s\t%s\t', [N1 ND]);
fprintf(VFID, '%-010.4f\t', vave);
fprintf(VFID, '\r\n');
fclose(VFID);

% Raw NI Values
Tname = (['Trawdata_' datastamp]);
[m,n] = size(NIdata);
TFID = fopen(string(filename(4)), 'a');
fprintf(TFID, '%s\t', Tname);
fprintf(TFID, 'N1: %s\tND: %s\t\ntime\t', [N1 ND]);
fprintf(TFID, '%-10.0f\t', 1:n);
fprintf(TFID, '\n');
for i=1:m
    fprintf(TFID, '%2.2f\t', time(i));
    fprintf(TFID, '%-06.4f\t', NIdata(i,1:n));
    fprintf(TFID, '\r');
end
fprintf(TFID, '\n');
fclose(TFID);

% Raw Pressure Values
Pname = (['Prawdata_' datastamp]);
[m,n] = size(pdata);

```

```

PFID = fopen(string(filenames(5)), 'a');
fprintf(PFID, '%s\t', Pname);
fprintf(PFID, 'N1: %s\tND: %s\t\n', [N1 ND]);
%      fprintf(PFID, '%-6.4f\t',
[1.01:.01:1.16, 2.01:.01:2.16, 3.01:.01:3.16]);
fprintf(PFID, '1_%02.0f      \t', 1:16);
fprintf(PFID, '2_%02.0f      \t', 1:16);
fprintf(PFID, '3_%02.0f      \t', 1:16);
fprintf(PFID, '4_%02.0f      \t', 1:16); %%%%
fprintf(PFID, '\n');
for i=1:m
    fprintf(PFID, '%010.2f\t', pdata(i, 1:n));
    fprintf(PFID, '\r');
end
fprintf(PFID, '\n');
fclose(PFID);

% Pressure Standard Deviation
Pname = (['Pstd_' datastamp]);
PFID = fopen(string(filenames(6)), 'a');
fprintf(PFID, '%s\t', Pname);
fprintf(PFID, '%s\t%s\t', [N1 ND]);
fprintf(PFID, '%08.4G%%\t', pstd.*100);
fprintf(PFID, '\r\n');
fclose(PFID);

% Temperature Standard Deviation
Tname = (['Tstd_' datastamp]);
TFID = fopen(string(filenames(7)), 'a');
fprintf(TFID, '%s\t', Tname);
fprintf(TFID, '%s\t%s\t', [N1 ND]);
fprintf(TFID, '%-2.4f%%\t', tstd.*100);
fprintf(TFID, '\r\n');
fclose(TFID);

% Voltage Standard Deviation
Vname = (['Vstd_' datastamp]);
VFID = fopen(string(filenames(8)), 'a');
fprintf(VFID, '%s\t', Vname);
fprintf(VFID, '%s\t%s\t', [N1 ND]);
fprintf(VFID, '%-2.2f%%\t', vstd.*100);
fprintf(VFID, '\r\n');
fclose(VFID);
end

datastamp =
    '20210310_1521_21'
filestamp =
    'test'
Warning: Directory already exists.

```

Published with MATLAB® R2019a

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C. N₂ TESTING DATA AND CALCULATIONS

A. NITROGEN COLD RUN RESULTS

Actual COLD Nitrogen Mass Flow Calculations at Nozzle Diameter = 1/16" (November 12th)								
Total Pressure (psi)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Effectiveness (%)
50	293627.56	394927.56	1.54	Yes	0.00180775	6.507901359	12.13	N/A
75	423522.24	524822.24	1.73	Yes	0.002402333	8.648399642	15.85	N/A
100	580166.82	681466.82	1.90	Yes	0.003119362	11.22970208	20.13	N/A

Actual COLD Nitrogen Mass Flow Calculations at Nozzle Diameter = 3/32" (November 12th)								
Total Pressure (psi)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Effectiveness (%)
50	96044.95	197636.61	1.02	Yes	0.002035499	7.327797068	20.43	N/A
75	167357.73	268949.39	1.27	Yes	0.002769964	9.971869844	28.92	N/A
100	237530.91	339122.57	1.43	Yes	0.003492692	12.57368953	36.99	N/A

B. NITROGEN HOT RUN RESULTS

Actual HOT Nitrogen Mass Flow Calculations at Nozzle Diameter = 1/16" (November 20th)								
Total Pressure (psi)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Effectiveness (%)
50	308030.44	410028.4666	1.56	Yes	0.001457427	5.246738719	10.18	60.64648282
75	452261.85	554259.8766	1.76	Yes	0.001930774	6.95078767	13.1	70.72056893
100	614343.43	716341.4566	1.93	Yes	0.002434999	8.765998148	16.18	85.45524819

Actual HOT Nitrogen Mass Flow Calculations at Nozzle Diameter = 3/32" (November 25th)								
Total Pressure (psi)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Effectiveness (%)
50	140723.69	242857.1722	1.18	Yes	0.001995834	7.185003981	19.08	49.29711975
75	235904.55	338038.0322	1.43	Yes	0.002682832	9.658195591	26.27	64.05791224
100	327756.56	429890.0422	1.59	Yes	0.003371194	12.13629766	33.18	68.90991789

C. NITROGEN HOT RUN REYNOLDS CALCULATIONS

1. 1.5875 mm (1/16") Nozzle Diameter

Pressure (psi)	Mass Flow Rate (kg/s)	4in Coil Tube Diameter (m) (3/8 inch diam. tubing) (REF. 3)	Area (m ²)	CO2 Outlet Temp. (K)	Calculated Velocity (m/s)	Dynamic Viscosity (N-s/m ²) (REF. 2)	Calculated Reynolds No. (-)	Turbulent Condition? (Re > 10000)
50	0.00180775	0.009525	7.13E-05	489.8527	0.081	2.57E-05	9406	*NO*
75	0.002402333	0.009525	7.13E-05	510.0059	0.108	2.64E-05	12155	YES
100	0.003119362	0.009525	7.13E-05	535.6163	0.140	2.74E-05	15246	YES

*Not fully developed turbulent flow but is in transition.

2. 2.3813 mm (3/32") Nozzle Diameter

Pressure (psi)	Mass Flow Rate (kg/s)	4in Coil Tube Diameter (m) (3/8 inch diam. tubing) (REF. 3)	Area (m ²)	CO2 Outlet Temp. (K)	Calculated Velocity (m/s)	Dynamic Viscosity (N-s/m ²) (REF. 2)	Calculated Reynolds No. (-)	Turbulent Condition? (Re > 10000)
50	0.001995834	0.009525	7.13E-05	463.9052	0.090	2.47E-05	10792	YES
75	0.002682832	0.009525	7.13E-05	497.4169	0.120	2.60E-05	13820	YES
100	0.003371194	0.009525	7.13E-05	509.476	0.151	2.64E-05	17057	YES

D. NITROGEN HEAT TRANSFER CALCULATIONS

1. 1.5875 mm (1/16") Nozzle Diameter (Heat Absorbed by Nitrogen)

Pressure (Psi)	4in Coil Tube Diameter (m) (3/8 inch diam. tubing) (REF. 3)	4in Coil Tube Surface Area (m ²)	Calculated Heat Xfer Coefficient [W/(m ² -K)]	Delta T1 (K)	Delta T2 (K)	Mean Log Temp (K) (Counterflow Heat Exchangers) (REF. 1)	Calculated Q (W) (flow through the tube)
50	0.009525	0.071779778	115.51	319.15	505.7484	405.31	3360.58
75	0.009525	0.071779778	145.18	299.99	505.3848	393.80	4103.74
100	0.009525	0.071779778	179.69	273.38	501.5245	375.99	4849.46

*Cell highlighted in red represents Reynolds number from previous calculation did not meet Dittus-Boelter Conditions ($Re_D > 10000$) therefore data shall be disregarded.

2. 2.3813 mm (3/32") Nozzle Diameter (Heat Absorbed by Nitrogen)

Pressure (Psi)	4in Coil Tube Diameter (m) (3/8 inch diam. tubing) (REF. 3)	4in Coil Tube Surface Area (m ²)	Calculated Heat Xfer Coefficient [W/(m ² -K)]	Delta T1 (K)	Delta T2 (K)	Mean Log Temp (K) (Counterflow Heat Exchangers) (REF. 1)	Calculated Q (W) (flow through the tube)
50	0.009525	0.071779778	124.57	345.09	508.2304	421.41	3768.26
75	0.009525	0.071779778	158.42	313.58	507.4944	402.79	4580.24
100	0.009525	0.071779778	190.69	305.52	509.0684	398.67	5457.05

3. 1.5875 mm (1/16") Nozzle Diameter (Heat Radiated by Exhaust)

Pressure (Psi)	Calculated Heat Xfer Coefficient [W/(m ² -K)]	4in Coil Tube Surface Area (m ²)	Exhaust Inlet Temp (K)	N2 Mean Temp. (K)	Calculated Q (W) (flow Through Tube Wall)
50	115.5103283	0.071779778	809	393.05	3448.75
75	145.1775404	0.071779778	810	403.81	4232.82
100	179.6871637	0.071779778	809	418.55	5036.04

4. 2.3813 mm (3/32") Nozzle Diameter (Heat Radiated by Exhaust)

Pressure (Psi)	Calculated Heat Xfer Coefficient [W/(m ² -K)]	4in Coil Tube Surface Area (m ²)	Exhaust Inlet Temp (K)	N2 Mean Temp. (K)	Calculated Q (W) (flow Through Tube Wall)
50	124.5748405	0.071779778	809	378.84	3846.49
75	158.419283	0.071779778	811	396.96	4708.16
100	190.6945493	0.071779778	815	404.20	5622.98

E. NITROGEN HEAT TRANSFER RATE DELTA Q'S (W)

1. 1.5875 mm (1/16") Nozzle Diameter Heat Transfer Rate Delta's

Pressure (Psi)	Calculated Q (W) (flow Through Tube Wall)	Calculated Q (W) (flow through the tube)	Delta Q (W) (Heat Lost Through Tube Wall)
50	3448.75	3360.58	88.17
75	4232.82	4103.74	129.08
100	5036.04	4849.46	186.58

*Cells highlighted in red represents Reynolds number from previous calculation did not meet Dittus-Boelter Conditions ($Re_D > 10000$) therefore data shall be disregarded.

2. 2.3813 mm (3/32") Nozzle Diameter Heat Transfer Rate Delta's

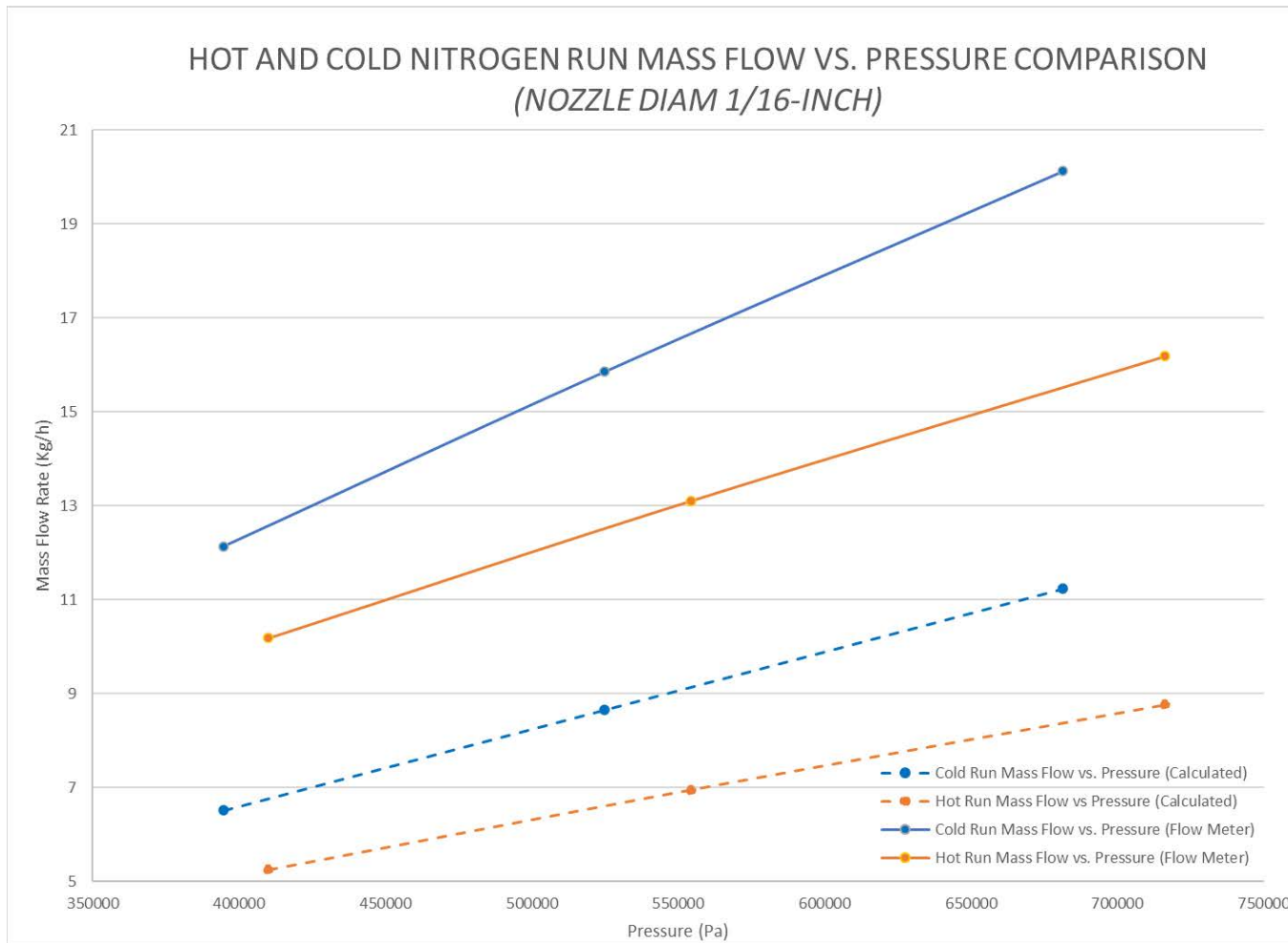
Pressure (Psi)	Calculated Q (W) (flow Through Tube Wall)	Calculated Q (W) (flow through the tube)	Delta Q (W) (Heat Lost Through Tube Wall)
50	3846.49	3768.26	78.24
75	4708.16	4580.24	127.92
100	5622.98	5457.05	165.93

F. NITROGEN HEAT EFFECTIVENESS COMPARISONS

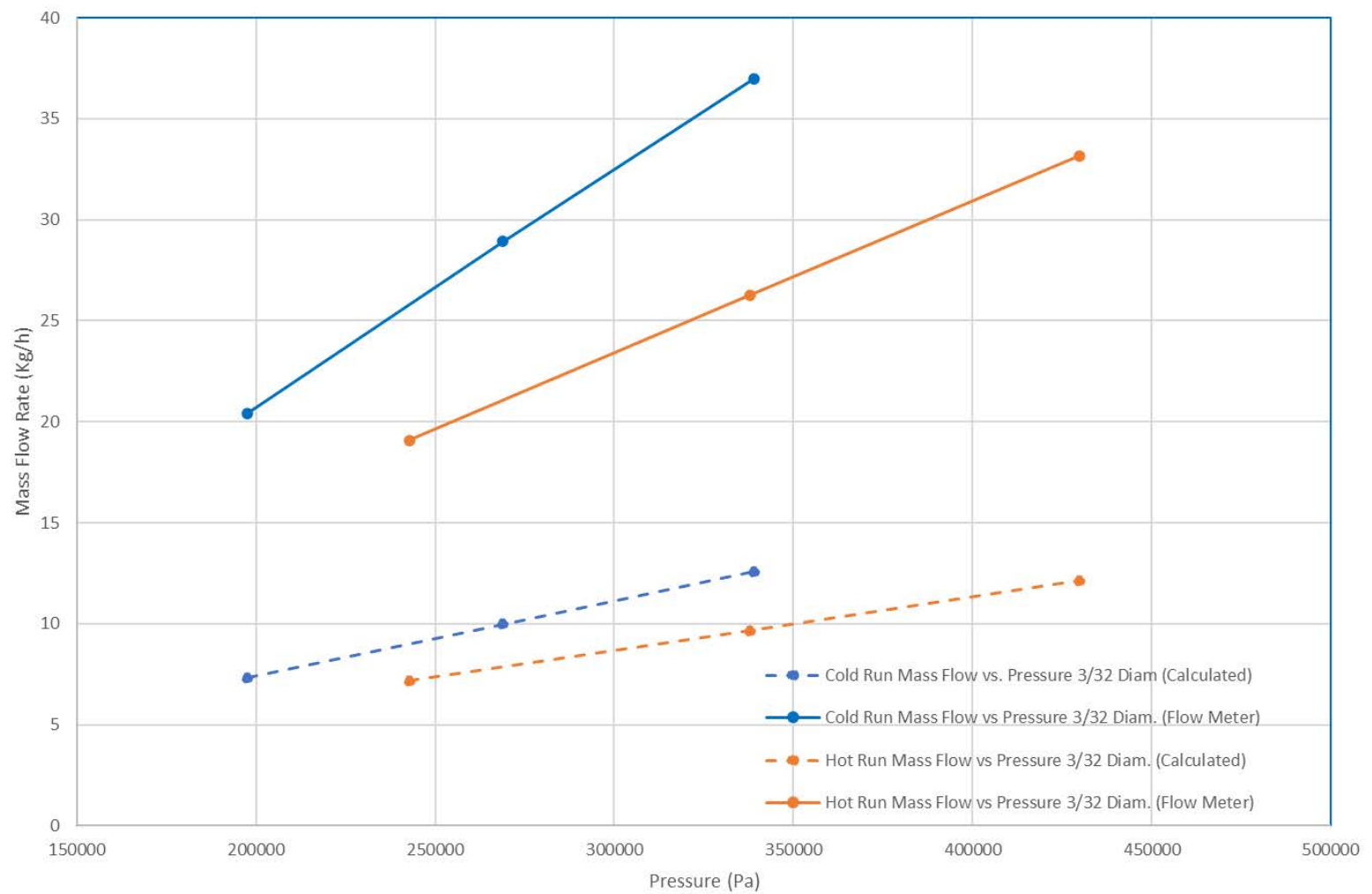
Pressure (Psi)	Heat Effectiveness Using Temperature (K)	Heat Effectiveness Using Heat Transfer Rates (W)
50	54.18	97.97
75	74.83	97.28
100	94.20	97.05

THIS PAGE INTENTIONALLY LEFT BLANK

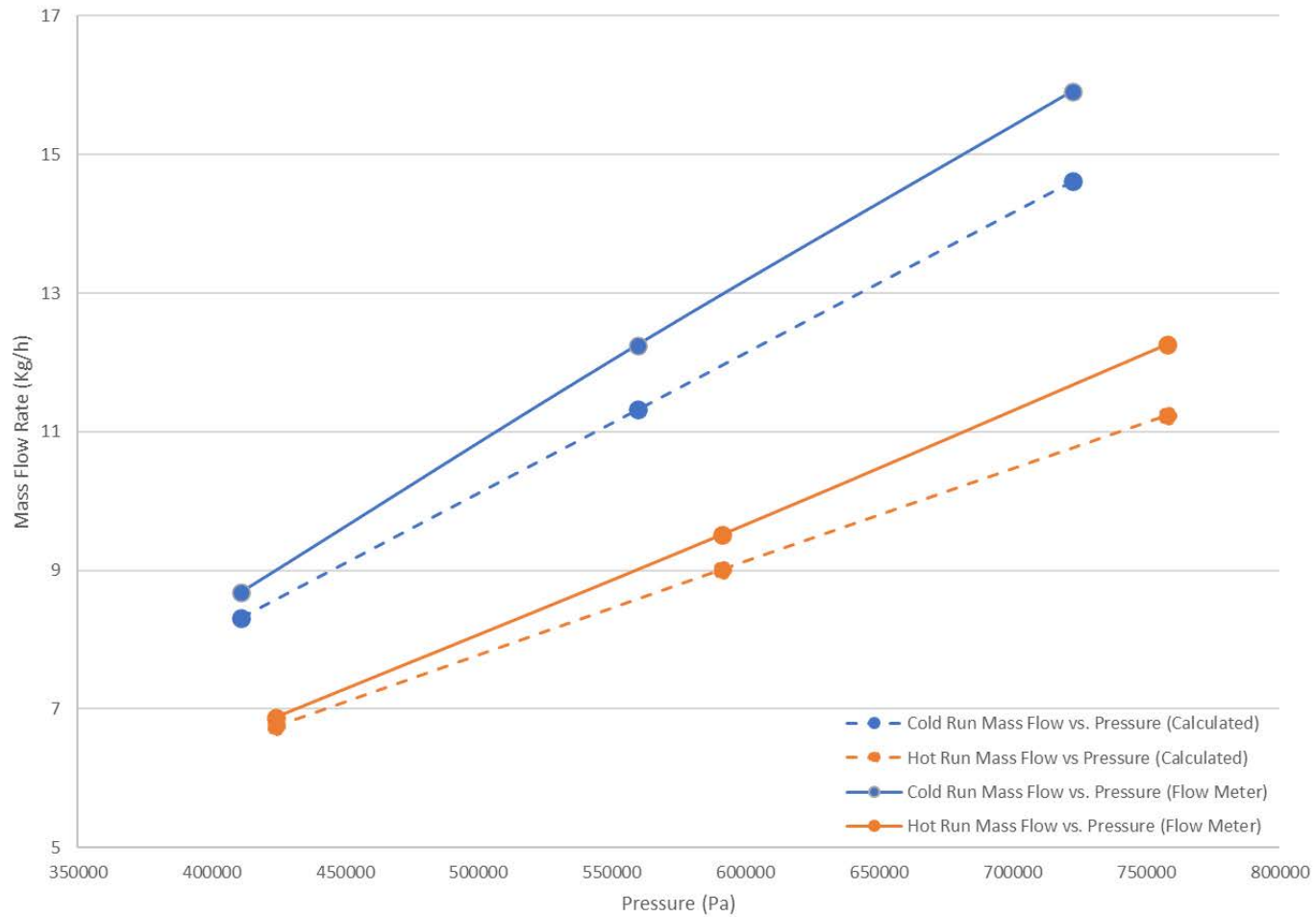
APPENDIX D. MASS FLOW RATE AND PRESSURE MAP TRENDS FOR N₂ AND CO₂ HOT RUNS



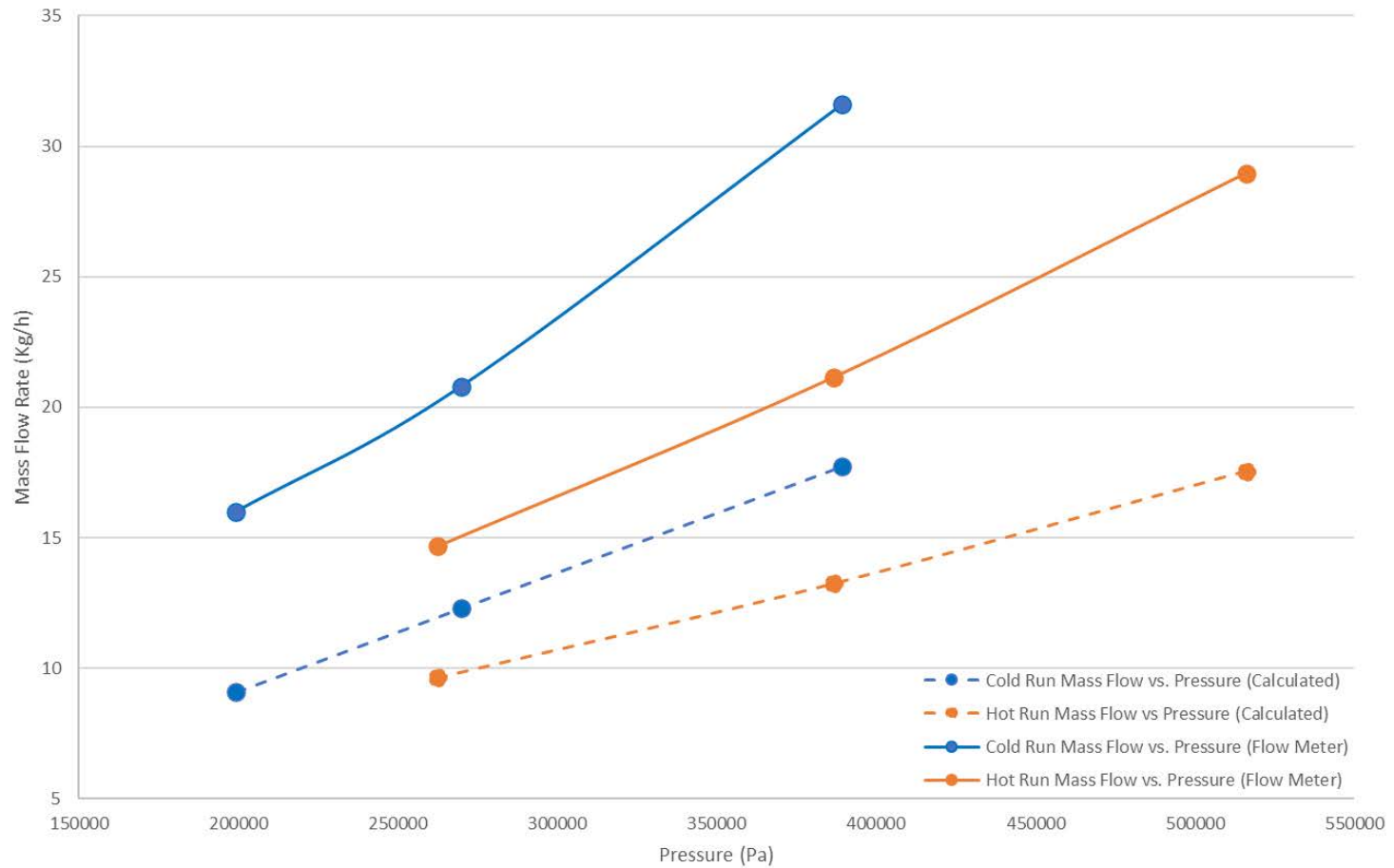
HOT AND COLD NITROGEN RUN MASS FLOW VS. PRESSURE COMPARISON
(NOZZLE DIAM 3/32-INCH)



HOT AND COLD CARBON DIOXIDE RUN MASS FLOW VS. PRESSURE COMPARISON
(NOZZLE DIAM 1/16-INCH)



HOT AND COLD CARBON DIOXIDE RUN MASS FLOW VS. PRESSURE COMPARISON
(NOZZLE DIAM 3/32-INCH)



APPENDIX E. FLOW METER MASS FLOW RATE DATA

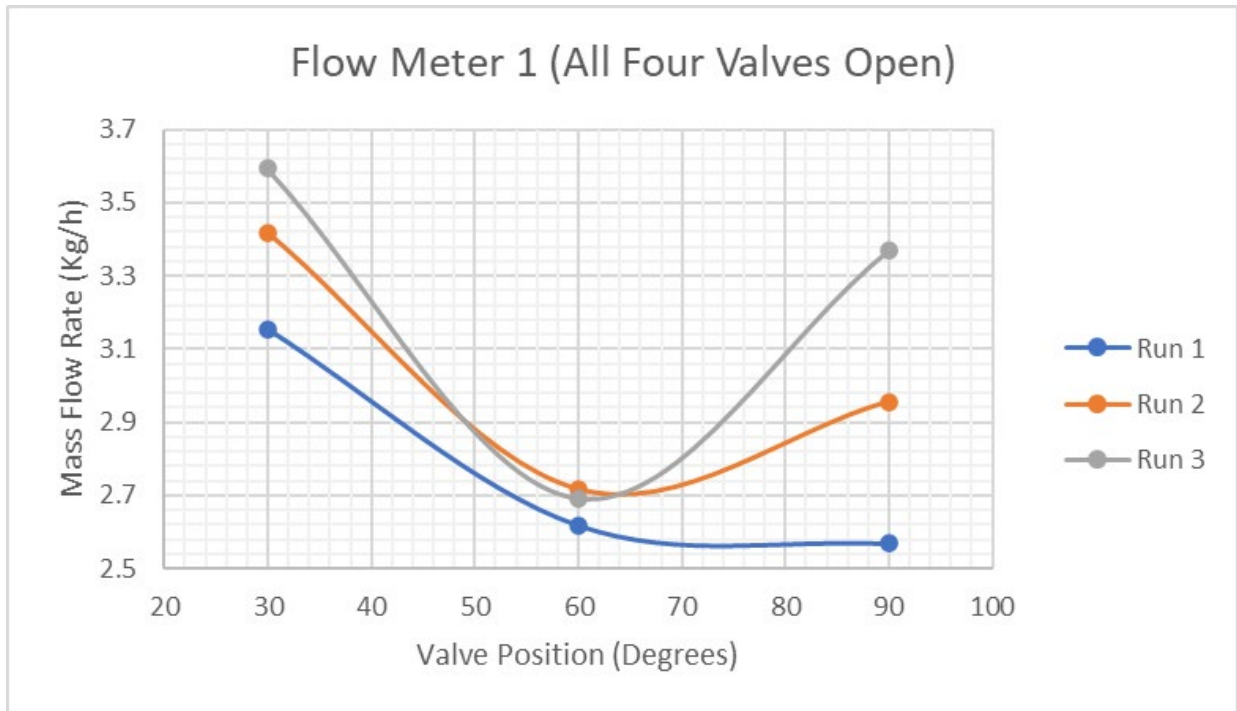
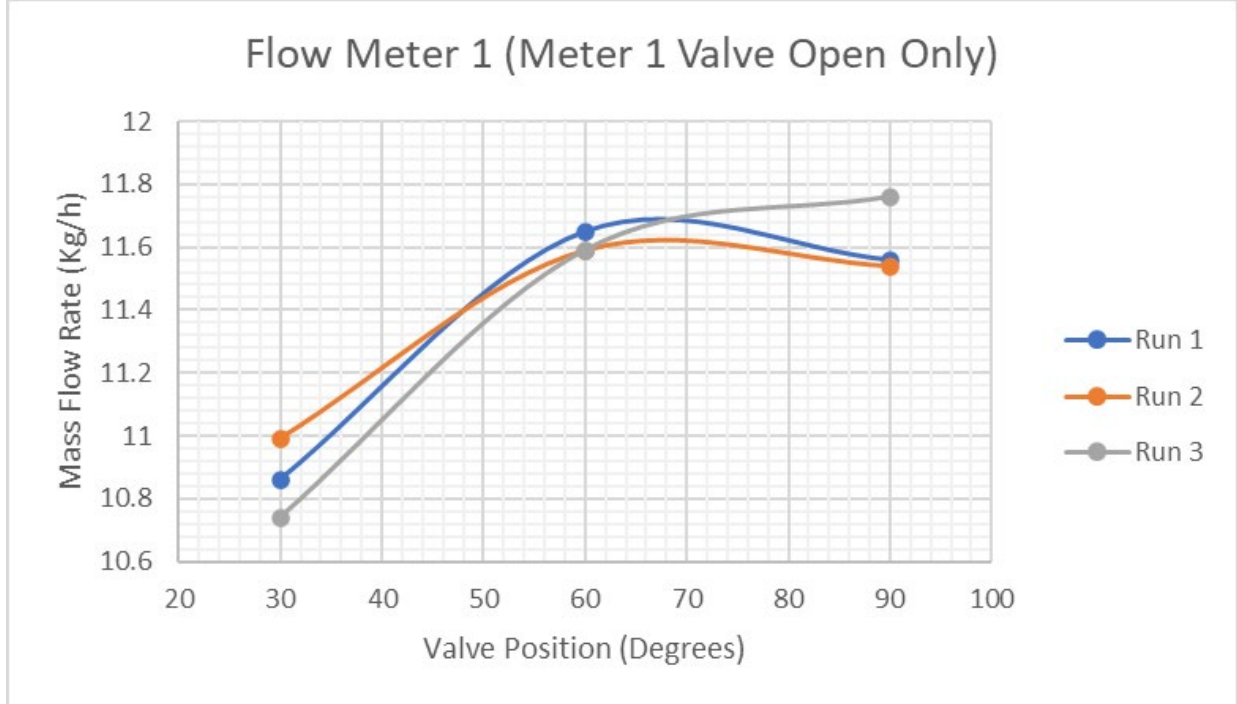
A. INDIVIDUAL FLOW METER ASSESSMENT DATA

FLOW METER ASSESSMENT RUN 1								
N2 COLD RUN	Flow Meters Assessed Individually (Kg/h)				All Four Flow Meters Simultaneously Assessed (Kg/h)			
Angles	Flow meter 1 (Kg/h)	Flow meter 2 (Kg/h)	Flow meter 3 (Kg/h)	Flow meter 4 (Kg/h)	Flow meter 1 (Kg/h)	Flow meter 2 (Kg/h)	Flow meter 3 (Kg/h)	Flow meter 4 (Kg/h)
30	10.86	10.25	9.978	9.685	3.155	3.312	1.777	2.98
60	11.65	11.4	10.98	10.66	2.619	2.966	4.444	2.29
90	11.56	11.51	11.05	10.74	2.568	3.095	4.579	2.086

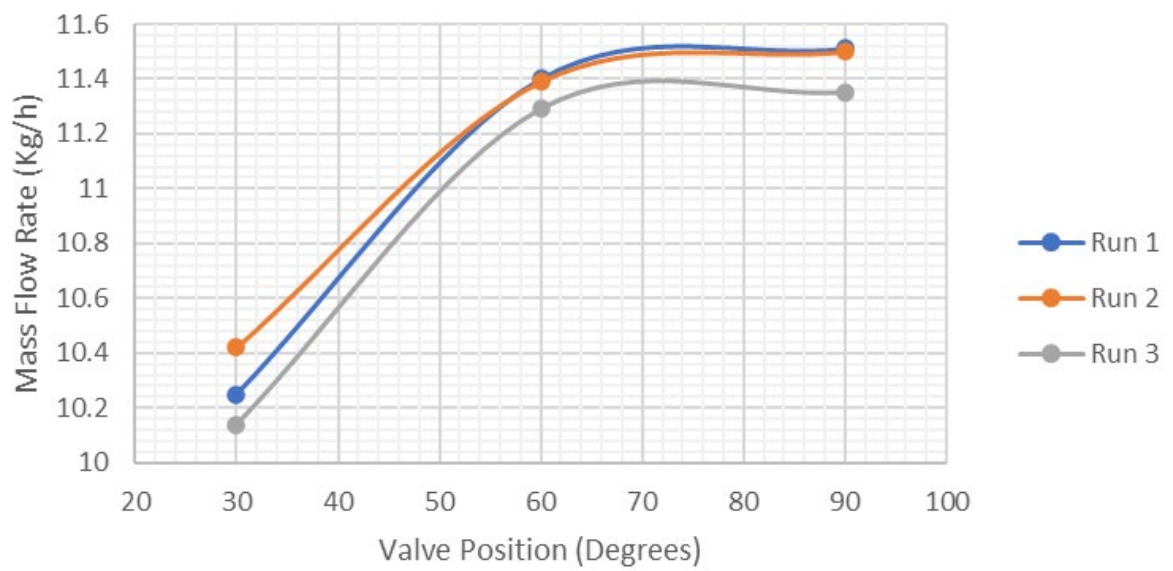
FLOW METER ASSESSMENT RUN 2								
N2 COLD RUN	Flow Meters Assessed Individually (Kg/h)				All Four Flow Meters Simultaneously Assessed (Kg/h)			
Angles	Flow meter 1 (Kg/h)	Flow meter 2 (Kg/h)	Flow meter 3 (Kg/h)	Flow meter 4 (Kg/h)	Flow meter 1 (Kg/h)	Flow meter 2 (Kg/h)	Flow meter 3 (Kg/h)	Flow meter 4 (Kg/h)
30	10.99	10.42	10.17	9.859	3.418	3.564	1.742	2.7667
60	11.59	11.39	11.07	10.68	2.717	2.865	4.687	2.054
90	11.54	11.5	11.06	10.72	2.956	3.141	4.131	2.074

FLOW METER ASSESSMENT RUN 3								
N2 COLD RUN	Flow Meters Assessed Individually (Kg/h)				All Four Flow Meters Simultaneously Assessed (Kg/h)			
Angles	Flow meter 1 (Kg/h)	Flow meter 2 (Kg/h)	Flow meter 3 (Kg/h)	Flow meter 4 (Kg/h)	Flow meter 1 (Kg/h)	Flow meter 2 (Kg/h)	Flow meter 3 (Kg/h)	Flow meter 4 (Kg/h)
30	10.74	10.14	9.881	9.554	3.593	3.004	1.829	2.648
60	11.59	11.29	11.08	10.71	2.691	2.882	4.891	1.93
90	11.76	11.35	11.11	10.72	3.368	2.959	4.044	2.056

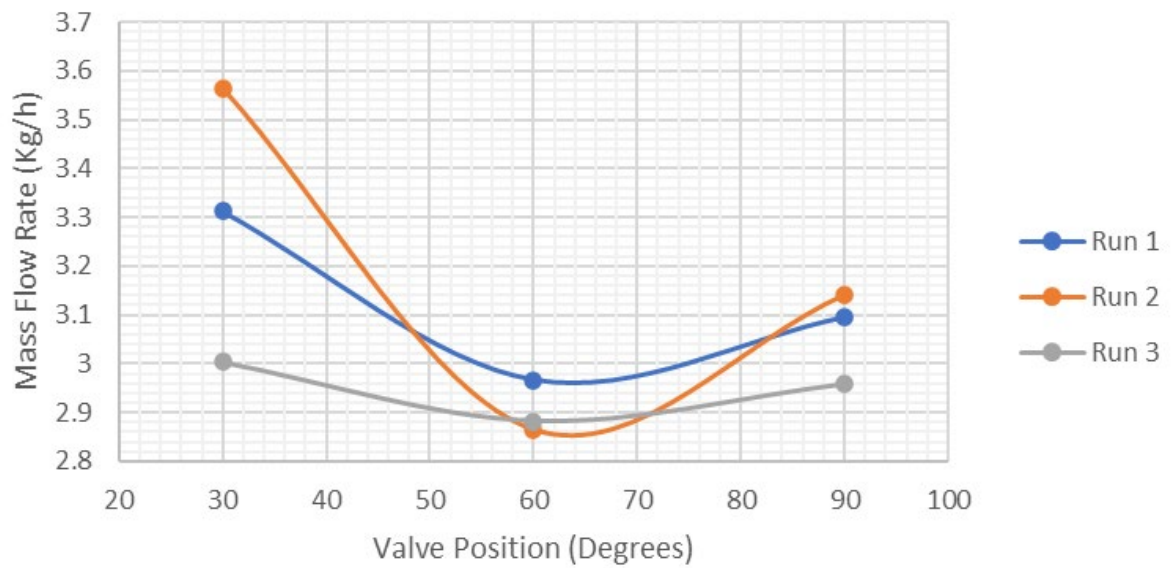
B. INDIVIDUAL FLOW METER CHARTED DATA

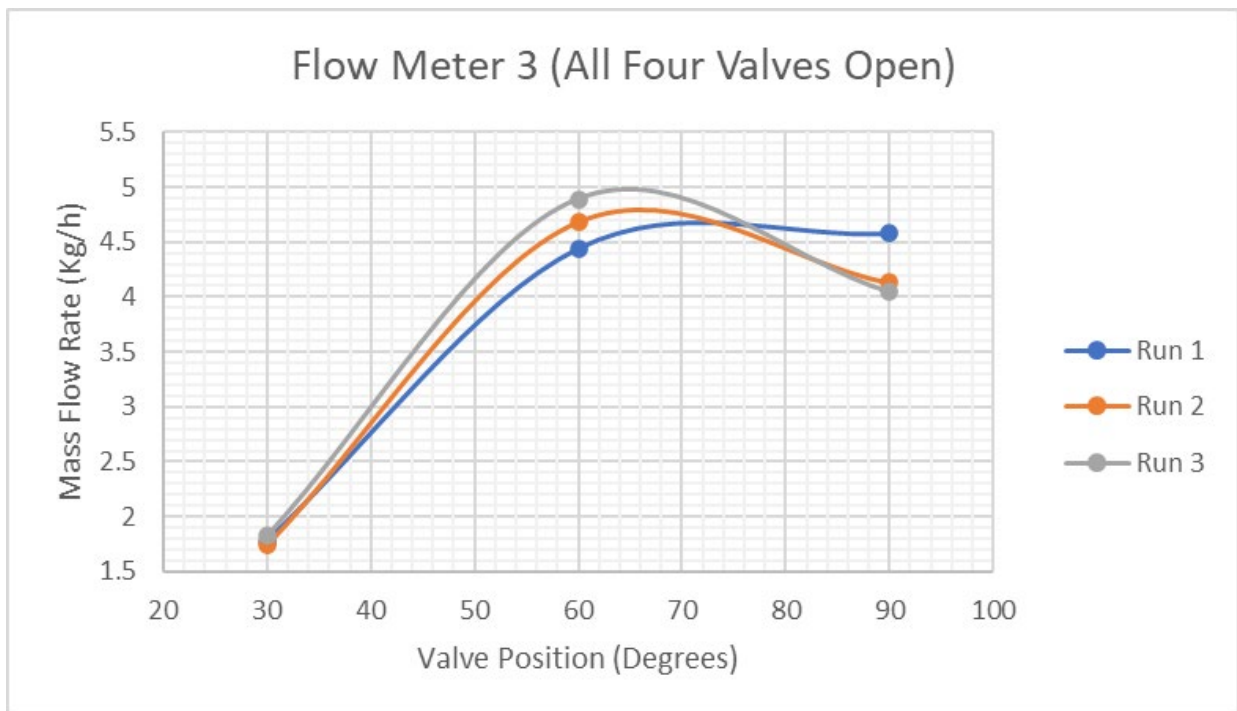
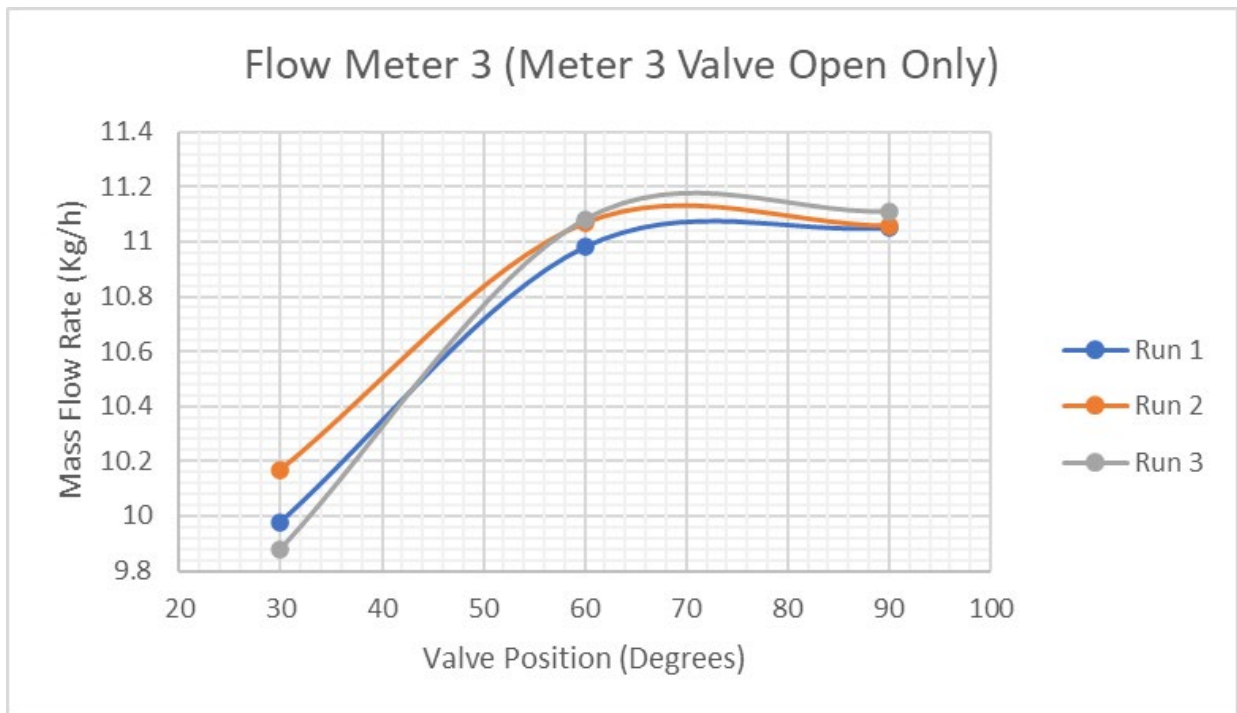


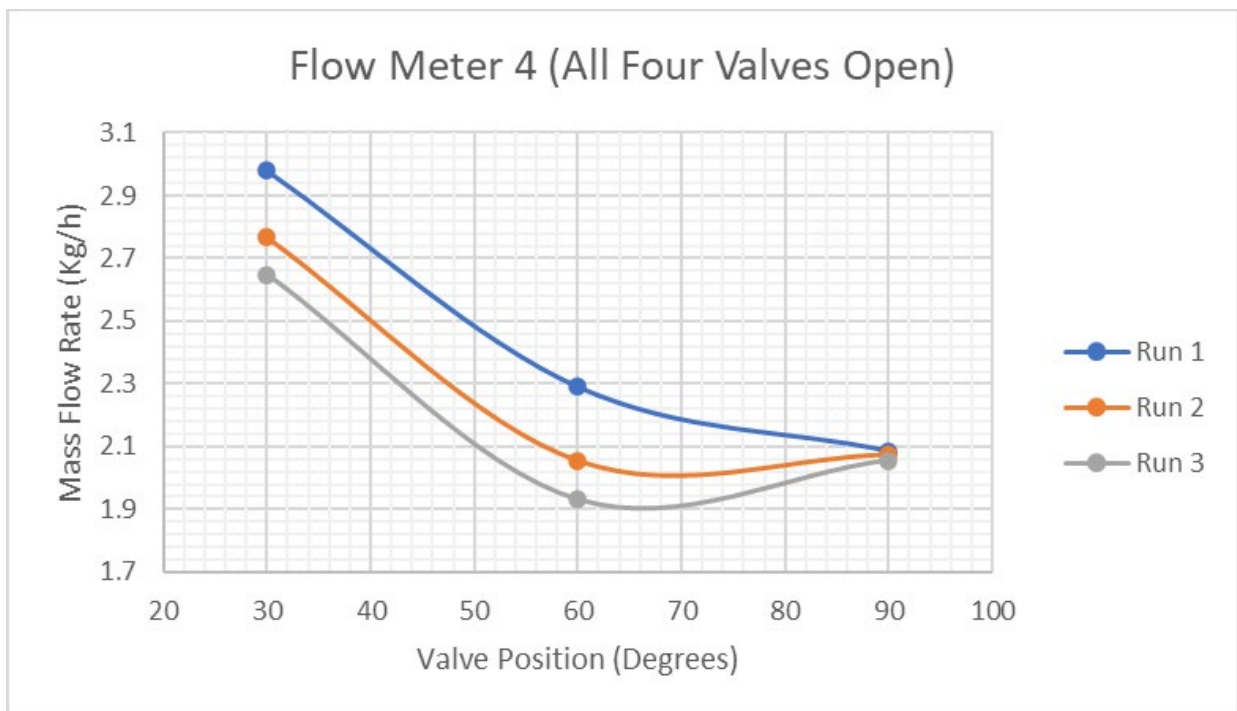
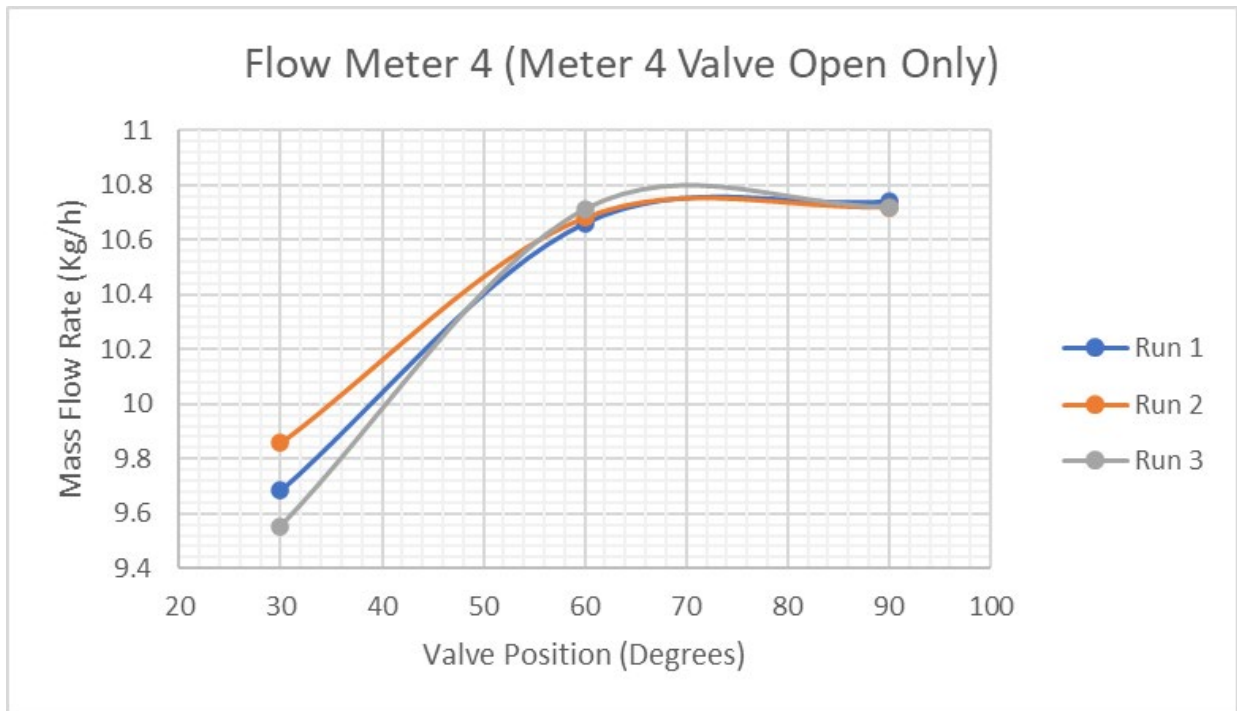
Flow Meter 2 (Meter 2 Valve Open Only)



Flow Meter 2 (All Four Valves Open)

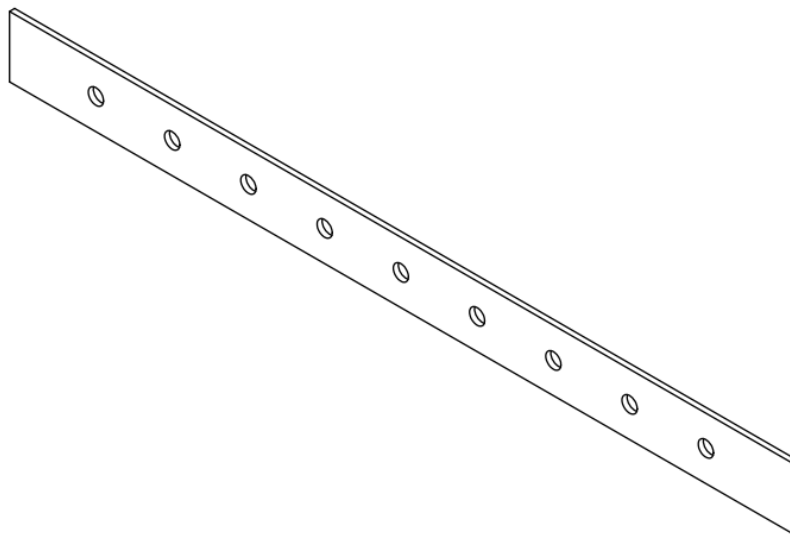
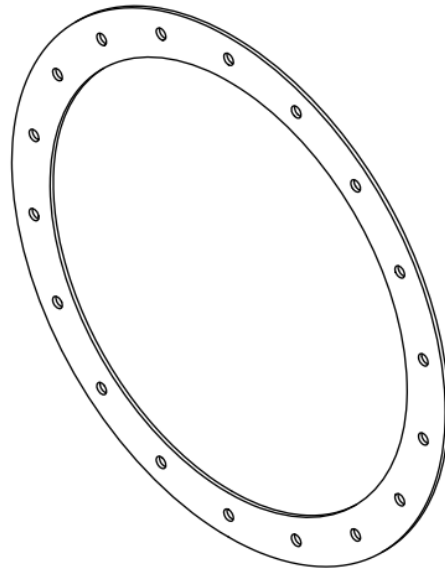






THIS PAGE INTENTIONALLY LEFT BLANK

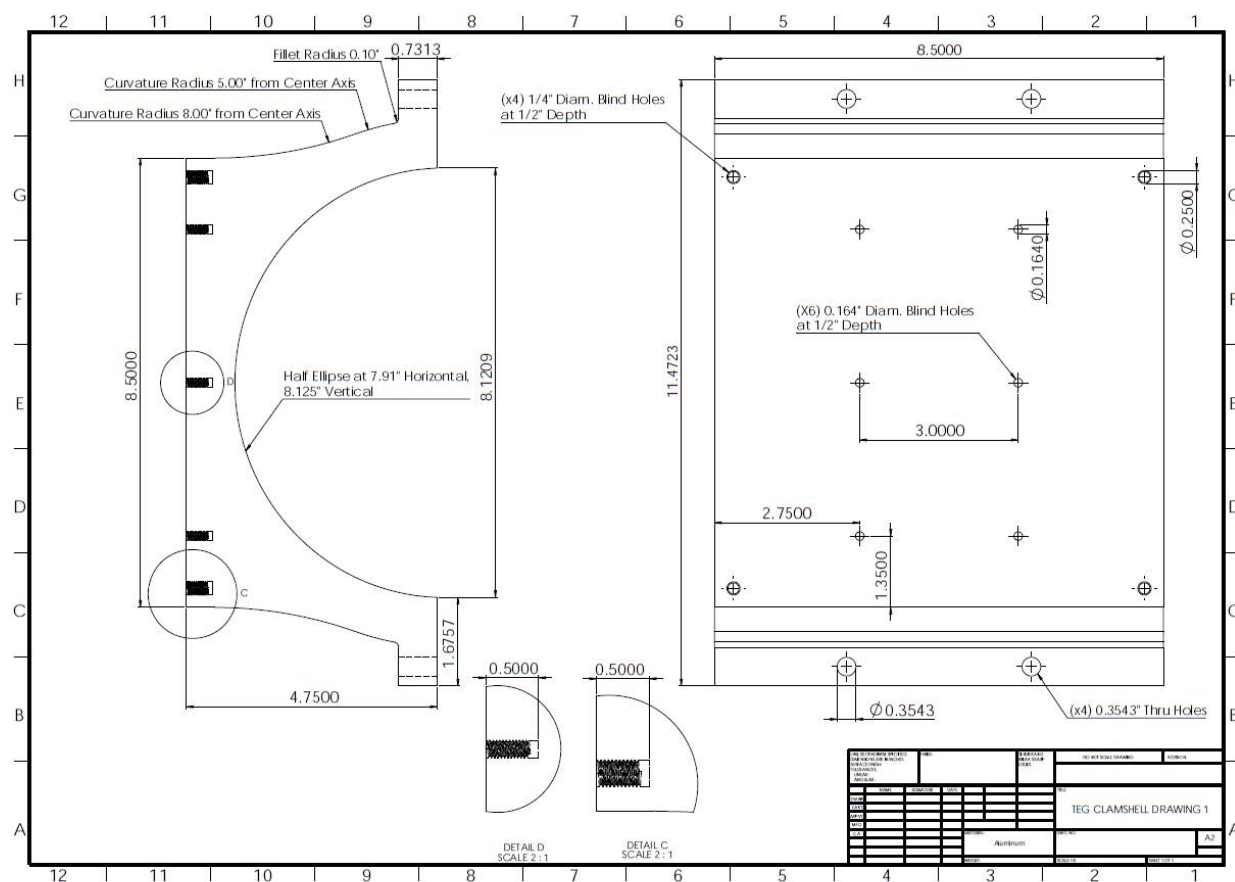
APPENDIX F. HEAT EXCHANGER GASKET SOLIDWORKS DRAWINGS



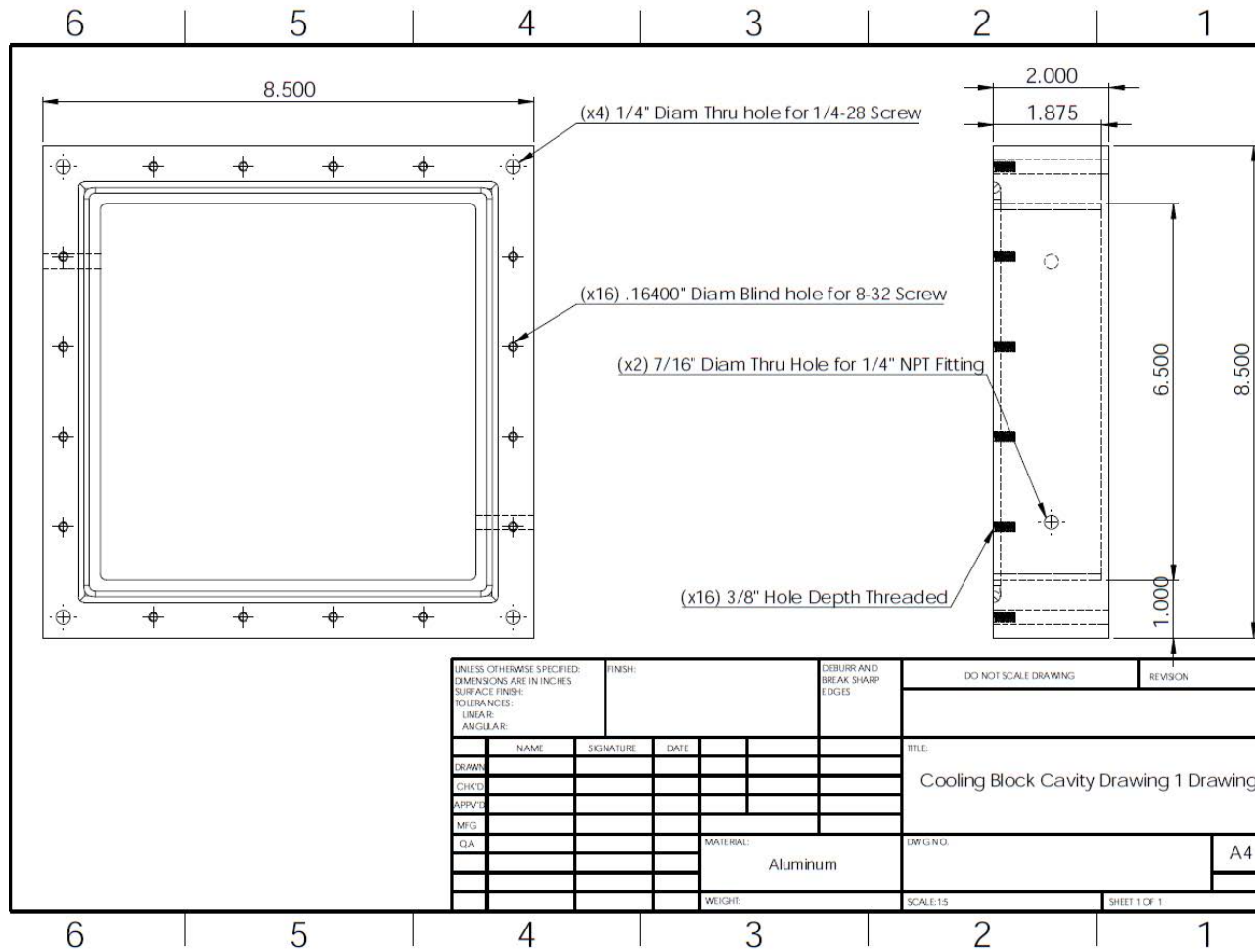
THIS PAGE INTENTIONALLY LEFT BLANK

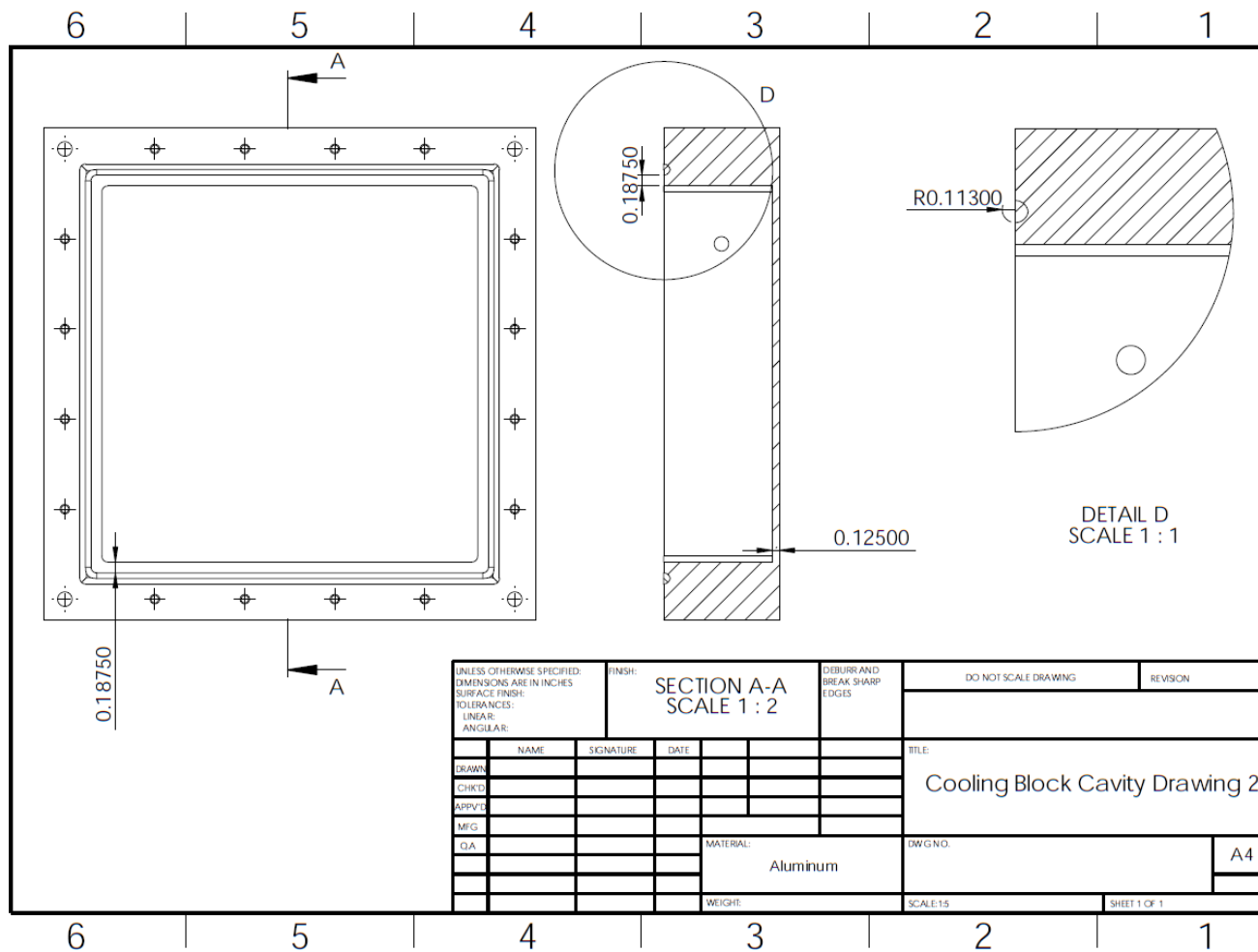
APPENDIX G. PELTIER DESIGN SOLIDWORKS DRAWINGS

A. TEG CLAMSHELL DRAWING

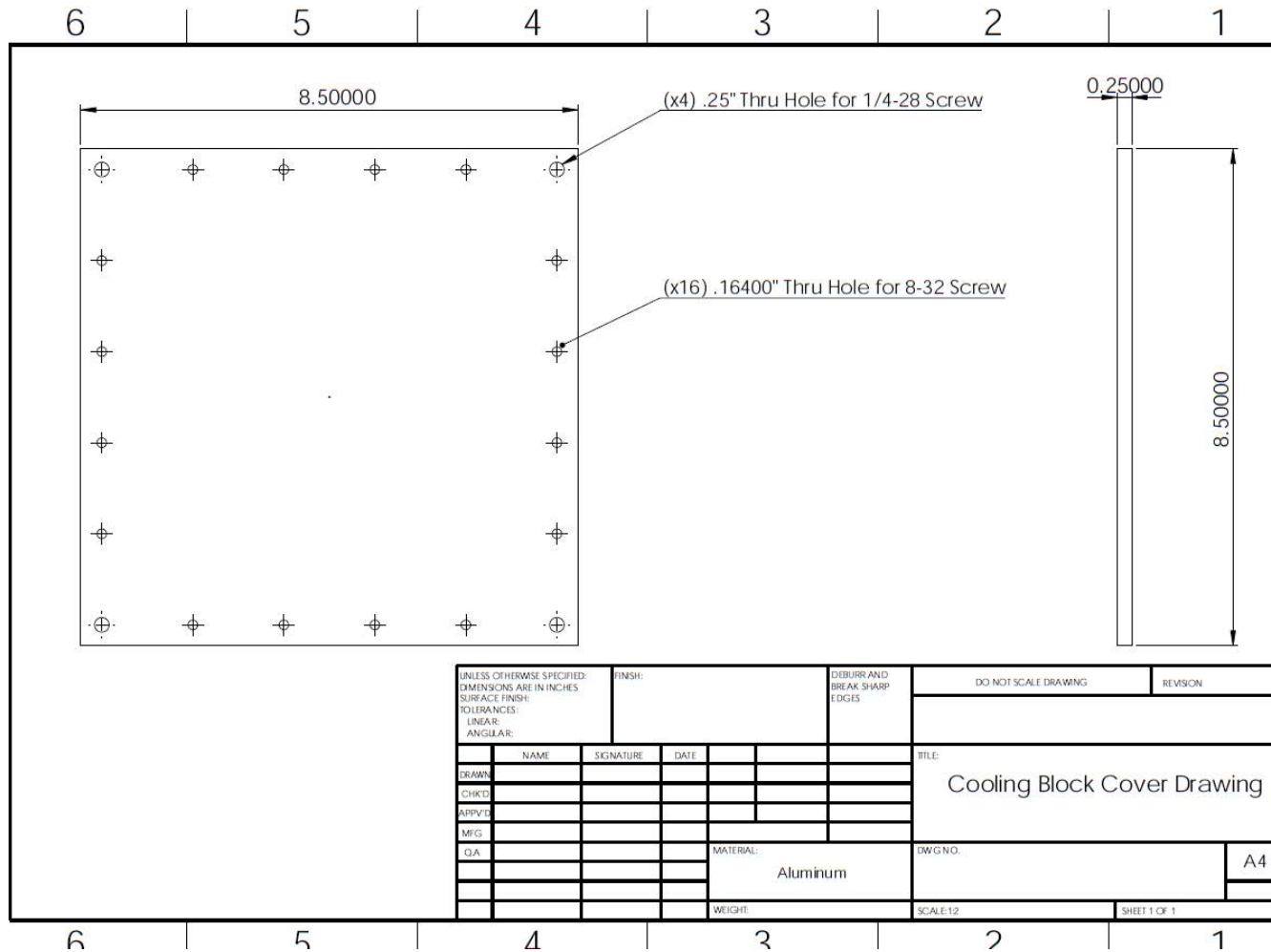


B. COOLING BLOCK CAVITY DRAWING





C. COOLING BLOCK COVER DRAWING



0.5000

7.2500

$\phi 0.6300$

$\phi 0.1640$

0.3670

7.2500

(x6) .164" Diam Thru Holes

(x6) .6300 Diam Blind Holes

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

TITLE:

TEG Block Top Drawing

DWG NO.

MATERIAL:

Aluminum

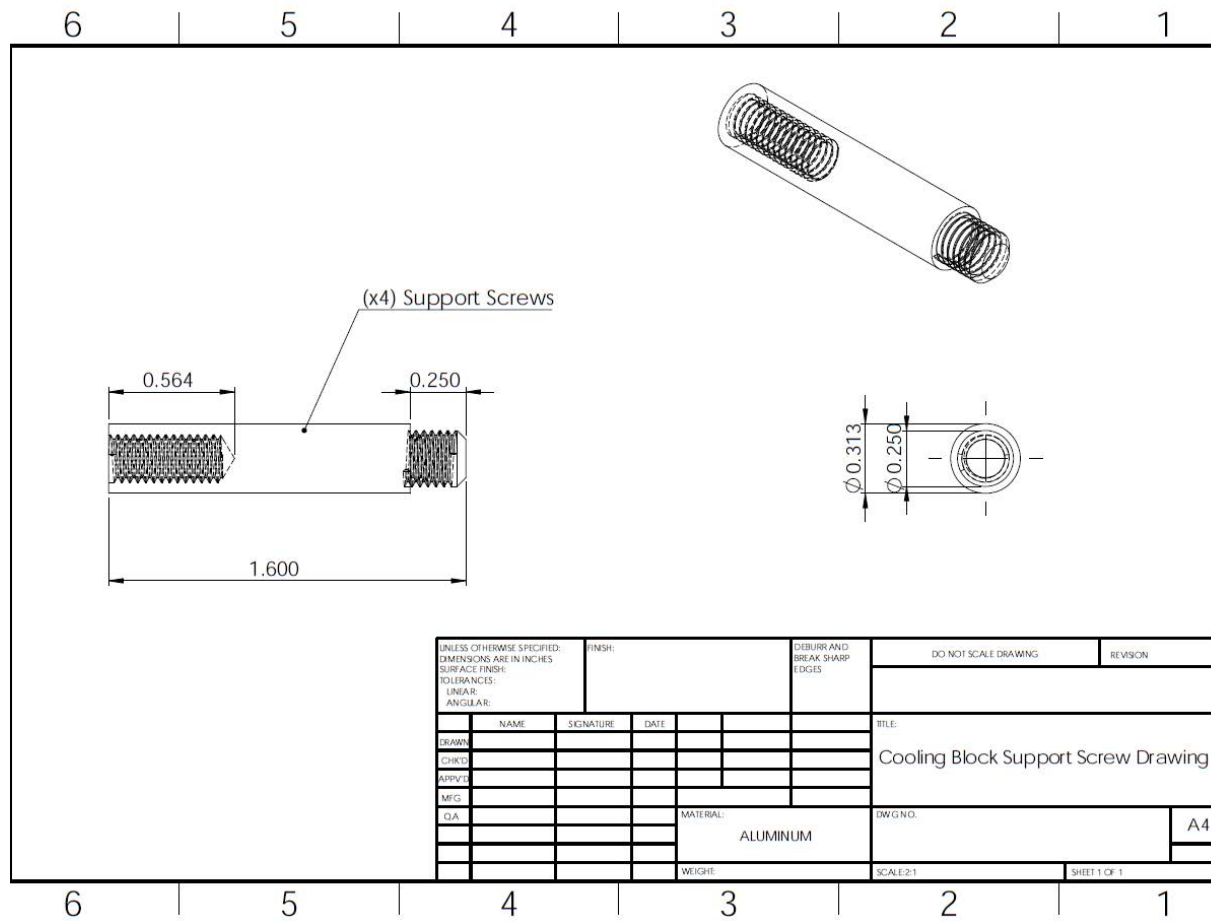
WEIGHT:

SCALE: 1:2

SHEET 1 OF 1

A4

F. COOLING BLOCK SUPPORT SCREW DRAWING



APPENDIX H. THERMOCOUPLE AND PRESSURE BRICK PORT LOCATIONS

A. THERMOCOUPLE INSTRUMENTATION

Thermocouple No.	Location
1	Compressor Inlet 1
2	Compressor Inlet 2
3	Compressor Outlet Left
4	Compressor Outlet Right
5	T5
6	Left Stack 1
7	Left Stack 2
8	Right Stack 1
9	Left Stack 3
11	<i>Not Assigned</i>
12	<i>Not Assigned</i>
13	Right Stack 3
14	HX Hot (IN)
15	HX Hot (OUT)
16	4" Coil (IN)
17	6" Coil (IN)
18	8" Coil (IN)
19	10" Coil (IN)
20	4" Coil (OUT)
21	6" Coil (OUT)
22	8" Coil (OUT)
23	10" Coil (OUT)

B. PRESSURE BRICK INSTRUMENTATION

Port	(Pressure Brick 1) 10" H ₂ O	(Pressure Brick 2) 2.5 PSID	(Pressure Brick 3) 100 PSID
1	Compressor Inlet Static	Compressor Inlet Static	Compressor Inlet Static
2	Compressor Inlet Total	Compressor Inlet Total	Compressor Inlet Total
3	<i>Not Assigned</i>	<i>Not Assigned</i>	Compressor Outlet Left
4	<i>Not Assigned</i>	<i>Not Assigned</i>	Compressor Outlet Right
5	<i>Not Assigned</i>	<i>Not Assigned</i>	Gas (CO ₂ /N ₂) Manifold Inlet Pressure
6	<i>Not Assigned</i>	<i>Not Assigned</i>	Gas (CO ₂ /N ₂) Manifold Outlet Pressure
7	Left Stack 1	Left Stack 1	Left Stack 1
8	Right Stack 1	Right Stack 1	Right Stack 1
9	Left Stack 0	Left Stack 0	Left Stack 0
10	Right Stack 0	Right Stack 0	Right Stack 0
11	Left Stack 2	Left Stack 2	Left Stack 2
12	Right Stack 2	Right Stack 2	Right Stack 2
13	Left Stack 3	Left Stack 3	Left Stack 3
14	Right Stack 3	Right Stack 3	Right Stack 3
15	Left Stack 4	Left Stack 4	Left Stack 4
16	Right Stack 4	Right Stack 4	Right Stack 4

APPENDIX I. RAW DATA

A. N₂ NOZZLE COLD RUN TEST DATA

1. Temperature Data for All 3 Nozzle Dimensions

Timestamp	N1	ND	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Tdata_20201116_1528_01	51000	6000	294.6	294.57	295.73	295.37	295.66	296.79	296.74	297.26	297.2	2566	2566	2566	297.55	297.45	297.24	295.64
Tdata_20201116_1530_38	51000	6000	294.62	294.59	295.74	295.38	295.69	296.76	296.73	297.17	297.15	2566.1	2566.1	2566.1	297.48	297.39	297.17	295.75
Tdata_20201116_1532_60	51000	6000	294.64	294.6	295.73	295.39	295.72	296.67	296.67	297.07	297.04	2566.1	2566.1	2566.1	297.34	297.25	297.05	295.62
Tdata_20201116_1537_12	51000	6000	294.68	294.65	295.73	295.43	295.75	296.61	296.61	296.99	296.95	2566.3	2566.3	2566.3	297.19	297.13	296.95	295.78
Tdata_20201116_1539_12	51000	6000	294.69	294.66	295.72	295.43	295.76	296.61	296.61	296.98	296.95	2566.4	2566.4	2566.4	297.19	297.13	296.96	295.8
Tdata_20201116_1540_58	51000	6000	294.71	294.67	295.69	295.41	295.77	296.52	296.53	296.86	296.82	2566.4	2566.4	2566.4	296.96	296.97	296.8	295.84
Tdata_20201116_1542_59	51000	6000	294.72	294.69	295.66	295.41	295.77	296.44	296.46	296.78	296.74	2566.5	2566.5	2566.5	296.91	296.89	296.72	296.27
Tdata_20201116_1545_57	51000	6000	294.74	294.71	295.62	295.39	295.78	296.35	296.38	296.68	296.65	2566.6	2566.6	2566.6	296.84	296.79	296.63	295.66
Tdata_20201116_1550_08	51000	6000	294.76	294.73	295.57	295.38	295.78	296.24	296.27	296.55	296.51	2566.7	2566.7	2566.7	296.72	296.65	296.48	295.51
Tdata_20201116_1602_40	51000	6000	294.8	294.77	295.5	295.36	295.78	296.09	296.11	296.35	296.32	2566.8	2566.8	2566.8	296.44	296.42	296.27	294.64
Tdata_20201116_1604_52	51000	6000	294.8	294.77	295.46	295.34	295.78	296.03	296.06	296.29	296.26	2566.8	2566.8	2566.8	296.39	296.36	296.22	295.54
Tdata_20201116_1606_48	51000	6000	294.8	294.77	295.43	295.32	295.76	295.97	296	296.22	296.19	2566.9	2566.9	2566.9	296.31	296.28	296.14	295.71
Tdata_20201116_1609_01	51000	6000	294.8	294.76	295.38	295.29	295.75	295.89	295.93	296.13	296.1	2566.9	2566.9	2566.9	296.24	296.2	296.06	295.92
Tdata_20201116_1611_07	51000	6000	294.8	294.76	295.33	295.26	295.73	295.8	295.85	296.02	295.99	2566.9	2566.9	2566.9	296.13	296.09	295.94	295.71
Tdata_20201116_1613_13	51000	6000	294.8	294.76	295.29	295.23	295.71	295.57	295.66	295.71	295.66	2566.9	2566.9	2566.9	295.73	295.74	295.6	295.83
Tdata_20201116_1615_16	51000	6000	294.8	294.77	295.22	295.18	295.69	295.41	295.51	295.51	295.46	2566.9	2566.9	2566.9	295.45	295.51	295.39	296.08
Tdata_20201116_1617_10	51000	6000	294.78	294.75	295.15	295.12	295.65	295.25	295.36	295.31	295.26	2566.9	2566.9	2566.9	295.15	295.29	295.18	296.03
Tdata_20201116_1619_39	51000	6000	294.78	294.75	295.07	295.04	295.61	295.1	295.2	295.14	295.1	2567	2567	2567	295.04	295.1	295.01	296.04
Tdata_20201116_1624_37	51000	6000	294.75	294.73	294.95	294.94	295.52	294.82	294.94	294.82	294.77	2567	2567	2567	294.68	294.74	294.68	294.29
Tdata_20201116_1626_34	51000	6000	294.73	294.71	294.89	294.9	295.48	294.71	294.84	294.7	294.64	2566.9	2566.9	2566.9	294.55	294.61	294.53	295.37
Tdata_20201116_1628_27	51000	6000	294.72	294.7	294.82	294.85	295.44	294.57	294.71	294.52	294.47	2566.9	2566.9	2566.9	294.26	294.42	294.35	295.52
Tdata_20201116_1630_54	51000	6000	294.7	294.68	294.73	294.78	295.38	294.46	294.59	294.43	294.38	2566.9	2566.9	2566.9	294.24	294.32	294.27	295.52
Tdata_20201116_1632_56	51000	6000	294.68	294.67	294.68	294.74	295.34	294.4	294.53	294.37	294.32	2566.9	2566.9	2566.9	294.22	294.27	294.2	295.56
Tdata_20201116_1635_05	51000	6000	294.66	294.65	294.63	294.69	295.29	294.3	294.43	294.24	294.19	2566.8	2566.8	2566.8	294.07	294.14	294.08	295.59
Tdata_20201116_1638_14	51000	6000	294.63	294.61	294.56	294.61	295.22	294.11	294.26	294.01	293.95	2566.8	2566.8	2566.8	293.8	293.88	293.83	294.99
Tdata_20201116_1640_25	51000	6000	294.6	294.59	294.49	294.53	295.17	293.96	294.12	293.84	293.78	2566.8	2566.8	2566.8	293.61	293.7	293.64	295.28
Tdata_20201116_1642_07	51000	6000	294.57	294.57	294.43	294.47	295.12	293.84	294	293.68	293.63	2566.7	2566.7	2566.7	293.39	293.53	293.48	295.25

17	18	19	20	21	22	23	24	25	26	27	28	29	30
295.82	295.83	295.71	297.07	297.18	297.2	297.25	2567.5	2567.5	2567.5	2567.5	2567.5	2567.5	2567.5
295.97	295.97	295.22	297.2	297.26	297.39	297.27	2567.5	2567.6	2567.6	2567.6	2567.6	2567.6	2567.6
295.83	295.82	295.01	297.14	297.21	297.35	297.08	2567.6	2567.6	2567.6	2567.6	2567.6	2567.6	2567.6
295.97	296	295.07	297.41	297.4	297.58	297.21	2567.6	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7
295.99	296.01	294.68	297	297.07	297.29	296.9	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7
296.02	296.05	294.5	296.87	296.96	297.19	296.72	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7
296.5	296.51	294.36	296.95	297.05	297.32	296.66	2567.7	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8
295.86	295.87	294.12	296.91	296.97	297.27	296.54	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8
295.66	295.7	294.04	296.91	296.94	297.25	296.48	2567.8	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9
294.74	294.76	294.35	296.18	296.25	296.36	296.28	2568	2568	2568	2568	2568	2568	2568
295.69	295.69	294.04	296.09	296.15	296.26	295.87	2568	2568	2568	2568	2568	2568	2568
295.89	295.88	293.8	296.03	296.09	296.2	295.68	2568	2568	2568	2568	2568	2568	2568
296.11	296.1	293.61	296.11	296.17	296.31	295.52	2568	2568	2568	2568	2568	2568	2568
295.95	295.95	293.32	295.84	295.94	296.09	295.17	2568	2568	2568	2568	2568	2568	2568
296.05	296.08	293.19	295.58	295.73	295.89	294.81	2568	2568	2568	2568	2568	2568	2568
296.33	296.32	293.07	295.52	295.67	295.89	294.63	2568	2568	2568	2568	2568	2568	2568
296.28	296.32	292.61	295.05	295.23	295.46	294.25	2568	2568	2568	2568	2568	2568	2568
296.29	296.35	292.13	294.75	294.96	295.2	293.89	2568	2568	2568	2568	2568	2568	2568
294.43	294.41	292.47	294.67	294.74	294.94	294.03	2568	2568	2568	2568	2568	2568	2568
295.49	295.51	292.43	294.59	294.67	294.86	293.93	2567.9	2568	2568	2568	2568	2568	2568
295.68	295.68	292.36	294.51	294.56	294.75	293.82	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9
295.68	295.64	292.31	294.47	294.45	294.65	293.63	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9
295.8	295.7	292.11	294.19	294.24	294.43	293.35	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9
295.84	295.8	292.03	294.05	294.12	294.31	293.14	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8
295.18	295.08	292.03	294.1	294.09	294.29	293	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8
295.39	295.29	291.88	293.98	293.95	294.19	292.8	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8
295.34	295.24	291.82	293.89	293.84	294.08	292.68	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7

2. Pressure Data for All 3 Nozzle Dimensions

Atmospheric Pressure:			30															
Timestamp	N1	ND	1_01	1_02	1_03	1_04	1_05	1_06	1_07	1_08	1_09	1_10	1_11	1_12	1_13	1_14	1_15	1_16
Pdata_20201116_1528_01	51000	6000	-0.2	-0.24	-0.31	-0.03	-0.15	-0.1	-0.33	-0.12	-0.17	0.06	-0.15	-0.2	-0.2	-0.34	-0.32	-0.35
Pdata_20201116_1530_38	51000	6000	-0.23	-0.15	-0.23	-0.03	-0.15	0.02	-0.31	-0.24	-0.08	-0.02	-0.1	-0.18	-0.31	-0.42	-0.18	-0.22
Pdata_20201116_1532_60	51000	6000	-0.08	-0.15	-0.11	0.05	-0.03	-0.02	-0.2	-0.12	0	0.19	0	-0.07	-0.06	-0.19	-0.03	-0.3
Pdata_20201116_1537_12	51000	6000	-0.12	-0.21	-0.27	-0.1	-0.18	-0.08	-0.2	0	-0.12	0.15	-0.08	-0.07	-0.18	-0.29	-0.24	-0.15
Pdata_20201116_1539_12	51000	6000	-0.08	-0.07	0.05	-0.2	-0.09	-0.03	-0.16	0.1	-0.02	0.18	-0.05	-0.11	-0.15	-0.26	-0.15	-0.15
Pdata_20201116_1540_58	51000	6000	-0.37	-0.37	-0.39	-0.02	-0.38	-0.07	-0.36	-0.19	-0.27	0.02	-0.23	-0.33	-0.4	-0.51	-0.42	-0.63
Pdata_20201116_1542_59	51000	6000	-0.22	-0.21	0.16	-0.1	-0.14	0.15	-0.23	-0.19	-0.07	0.11	-0.18	-0.16	-0.29	-0.37	-0.3	-0.43
Pdata_20201116_1545_57	51000	6000	-0.23	-0.16	0.1	-0.1	-0.23	0.03	-0.21	-0.03	-0.05	0.11	-0.12	-0.21	-0.2	-0.3	-0.2	-0.33
Pdata_20201116_1550_08	51000	6000	-0.2	-0.16	-0.23	-0.26	-0.11	-0.33	-0.31	-0.02	-0.27	0.13	-0.21	-0.13	-0.35	-0.27	-0.29	-0.45
Pdata_20201116_1602_40	51000	6000	-0.23	-0.26	-0.26	-0.15	-0.11	-0.15	-0.15	0.02	-0.08	0.13	-0.07	-0.2	-0.29	-0.27	-0.25	-0.48
Pdata_20201116_1604_52	51000	6000	-0.28	-0.29	-0.29	-0.23	-0.29	-0.2	-0.21	0	-0.12	-0.05	0	-0.29	-0.35	-0.34	-0.29	-0.43
Pdata_20201116_1606_48	51000	6000	-0.23	-0.16	-0.18	-0.02	-0.02	-0.11	-0.21	-0.05	-0.25	0.08	-0.21	-0.28	-0.32	-0.37	-0.25	-0.43
Pdata_20201116_1609_01	51000	6000	-0.25	-0.21	-0.34	0.1	-0.12	0.07	-0.18	0	-0.13	0.05	-0.12	-0.28	-0.26	-0.32	-0.29	-0.53
Pdata_20201116_1611_07	51000	6000	-0.26	-0.26	-0.02	-0.13	-0.09	-0.03	-0.26	-0.05	-0.1	0.02	-0.08	-0.29	-0.37	-0.37	-0.27	-0.35
Pdata_20201116_1613_13	51000	6000	-0.2	-0.11	0.13	-0.02	-0.08	-0.2	-0.1	0.13	-0.07	0.18	-0.03	-0.15	-0.22	-0.26	-0.12	-0.38
Pdata_20201116_1615_16	51000	6000	-0.26	-0.15	-0.15	0.26	-0.17	0.05	-0.11	0.08	-0.05	0.29	-0.13	0	-0.2	-0.14	-0.08	-0.33
Pdata_20201116_1617_10	51000	6000	-0.08	-0.1	0.05	-0.31	0.02	0.02	-0.1	0.1	-0.05	0.34	0	-0.03	-0.09	-0.29	-0.12	-0.5
Pdata_20201116_1619_39	51000	6000	-0.19	-0.08	-0.31	-0.54	0.37	-0.55	-0.03	0.22	0.05	0.31	0.05	-0.07	-0.09	-0.4	-0.05	-0.3
Pdata_20201116_1624_37	51000	6000	-0.25	-0.15	-0.02	0.1	-0.06	-0.05	0	0.3	-0.05	0.26	0.03	-0.11	-0.14	-0.29	-0.05	-0.32
Pdata_20201116_1626_34	51000	6000	-0.25	-0.11	0	0.07	-0.06	-0.02	0.08	0.25	-0.03	0.32	-0.03	-0.15	-0.26	-0.27	-0.13	-0.42
Pdata_20201116_1628_27	51000	6000	-0.23	-0.07	-0.1	-0.05	-0.09	-0.02	0.02	0.25	-0.02	0.29	0.03	-0.03	-0.34	-0.27	-0.1	-0.48
Pdata_20201116_1630_54	51000	6000	-0.31	0	-0.1	0.08	0	0.08	-0.02	0.15	-0.02	0.26	-0.08	-0.02	-0.18	-0.22	-0.07	-0.38
Pdata_20201116_1632_56	51000	6000	-0.26	0.08	-0.03	-0.07	-0.03	0.15	-0.02	0.29	0.05	0.36	-0.02	0.05	-0.22	-0.21	0.07	-0.28
Pdata_20201116_1635_05	51000	6000	-0.28	0.02	-0.15	0.1	-0.05	0.05	-0.02	0.27	-0.03	0.26	-0.13	-0.11	-0.22	-0.26	-0.03	-0.28
Pdata_20201116_1638_14	51000	6000	-0.3	-0.1	-0.16	0	-0.11	-0.13	0.11	0.27	0.05	0.4	-0.16	0.02	-0.18	-0.11	-0.05	-0.42
Pdata_20201116_1640_25	51000	6000	-0.25	-0.15	0.02	0	0.11	0.1	0.15	0.29	0.13	0.39	-0.08	0.23	-0.08	-0.11	0.02	-0.15
Pdata_20201116_1642_07	51000	6000	-0.3	-0.02	-0.08	-0.13	-0.14	0.18	0.13	0.24	0.07	0.32	-0.16	-0.05	-0.22	-0.21	-0.02	-0.2

2_01	2_02	2_03	2_04	2_05	2_06	2_07	2_08	2_09	2_10	2_11	2_12	2_13	2_14	2_15	2_16
0.68	-0.34	0.65	-0.6	0.5	0.15	-0.31	-0.49	0	2.07	-1.89	-0.94	0.3	0.85	-2.22	0.32
0.68	-0.68	0.32	-0.45	0.17	-0.77	-0.47	-1.15	0	1.27	-0.95	-0.31	-0.15	1.18	-2.07	-0.16
0.41	-0.34	0.49	-0.3	0.99	-0.15	-1.24	-0.49	0.48	1.91	-1.08	-0.16	0.3	1.02	-1.78	0
0.68	-0.68	0.97	-0.6	1.16	-0.62	-0.62	-0.82	0.63	1.91	-1.62	0.16	0	1.52	-2.52	0.16
0.41	-0.17	0.97	-0.9	0.66	-0.62	-0.62	-0.49	0.48	1.43	-1.49	0.31	0.15	1.69	-1.63	-0.32
-0.14	-0.68	0.48	-1.35	0.17	-0.62	-0.47	-0.49	0.48	1.59	-1.35	0	0	1.18	-1.48	-0.32
0.27	-0.51	0.65	-0.9	0.5	-0.92	-0.78	-1.64	0.48	1.91	-2.16	-0.16	0	1.19	-1.78	0
0.27	-1.19	0.16	-0.6	0	-0.62	-0.62	-0.99	0.16	1.59	-1.49	-0.16	0.44	1.52	-1.93	-0.16
0.41	-0.68	0.81	-0.75	0.33	-1.39	-0.78	-1.15	0.16	0.96	-1.49	0.31	-0.15	1.69	-1.93	0.16
0.41	-1.36	0.16	-1.34	-0.17	-0.46	-0.31	-1.31	0.47	0.96	-1.35	0.16	-0.3	1.86	-1.63	0.16
0.41	-1.7	-0.16	-1.49	0.33	-0.62	-0.31	-1.31	0.79	0.8	-1.62	0.78	-0.74	1.35	-1.78	0.32
-0.41	-1.7	-0.16	-1.79	-0.33	-0.62	-0.93	-1.31	0	0.64	-1.76	0.16	-1.19	1.18	-1.93	0.48
-0.27	-1.19	-0.16	-1.49	-0.17	-0.46	-0.62	-0.99	1.11	0.48	-1.35	0.78	-0.3	1.86	-1.63	0.32
-0.14	-1.53	-0.32	-1.64	-0.33	-0.77	0	-1.15	0.32	1.59	-1.35	-0.16	-0.6	1.35	-1.63	0.49
0.27	-1.53	0.16	-1.34	-0.17	-0.77	0	-1.31	0	1.59	-1.35	-0.16	-0.6	1.86	-1.19	0.32
0.27	-1.53	0.16	-1.49	-0.66	-0.31	0	-0.66	0.63	1.27	-1.35	0.78	-0.74	2.37	-1.63	0.32
0.41	-0.85	-0.32	-1.49	0.17	-0.46	0.16	-0.99	0.16	1.91	-1.76	-0.16	-0.15	1.52	-1.63	0.32
0.41	-1.19	0.32	-1.49	0.66	-0.92	-0.31	-0.49	1.11	0.96	-1.76	1.41	0	1.35	-1.78	0.81
0.14	-1.19	-0.49	-0.9	0	-0.77	-0.47	-0.82	0.32	0.64	-1.89	0.31	0	0.85	-2.52	0
0.27	-1.53	0	-0.6	-0.17	-1.08	-0.78	-1.64	0.32	2.23	-1.62	0.16	-0.3	0.68	-2.22	-0.49
0.41	-0.34	0.65	-1.49	0.83	-0.62	-0.62	-1.48	0.48	2.23	-2.03	-0.16	0.15	0.85	-2.52	-0.49
0.27	-0.17	0.16	-0.9	-0.17	-0.77	-1.09	-0.66	0.32	2.07	-1.49	0	0	0.68	-3.11	-0.65
0.14	-1.02	-0.16	-0.75	0.33	-0.62	-1.09	-0.49	0.32	1.43	-1.89	0	-0.15	0.34	-2.52	-0.16
0.27	-1.02	-0.16	-1.2	0.17	-0.15	-0.78	-0.82	0.16	1.59	-1.62	-0.47	-0.15	0.34	-2.67	-0.33
-0.14	-1.36	-0.49	-1.49	-0.5	-0.31	-0.93	-0.99	0	1.11	-1.35	-0.79	-0.3	0.34	-2.52	-0.33
0.27	-1.02	-0.32	-1.94	0	0	-0.31	-1.48	-0.32	1.59	-1.35	-0.94	0.15	0.68	-2.07	-0.49
-0.14	-1.7	-0.49	-1.49	-0.33	-1.08	-0.47	-1.48	-0.48	0.96	-1.62	-0.47	-0.74	0.85	-1.78	0

4_01	4_02	4_03	4_04	4_05	4_06	4_07	4_08	4_09	4_10	4_11	4_12	4_13	4_14	4_15	4_16
3.69	0	0	18.45	18.37	-36.94	-3.74	-3.5	-3.57	0	-3.83	14.36	10.66	0	-12809	-10.32
7.37	6.84	0	22.14	29.4	-18.47	-3.74	3.5	-3.57	0	-3.83	21.54	10.66	0	-16342	-10.32
11.06	0	0	22.14	33.07	-14.77	0	0	-7.14	0	3.83	28.73	14.22	0	-18433	-3.44
3.69	3.42	-3.79	22.14	33.07	-11.08	-3.74	0	0	0	0	32.32	17.77	-3.75	-3273.6	-27.51
11.06	3.42	0	29.52	25.72	-22.16	0	3.5	0	0	7.67	25.14	21.33	0	-5390.1	-13.76
11.06	3.42	0	18.45	25.72	-22.16	7.47	7	-7.14	0	7.67	21.55	21.33	0	-6704.6	-20.63
3.69	3.42	3.79	18.45	33.07	-11.08	0	7	-7.14	0	0	28.73	21.33	0	-8879.7	-6.88
11.06	10.26	0	33.21	33.07	-18.47	0	0	0	3.63	7.67	28.73	24.88	7.51	-3848.5	0
0	3.42	3.79	18.45	29.4	-14.77	0	10.49	-7.14	7.25	0	32.32	21.33	7.51	-23373	-13.76
7.37	6.84	0	18.45	25.72	-22.16	0	0	0	0	42.16	61.03	21.33	15.01	-30759	-6.88
11.06	-3.42	3.79	11.07	29.4	-18.47	0	3.5	0	0	42.16	50.26	17.77	37.52	-29693	-10.32
11.06	6.84	3.79	7.38	11.02	-22.16	-3.74	7	28.57	7.25	38.33	50.26	46.2	45.03	-26584	-6.88
18.43	3.42	11.38	29.52	29.4	-14.77	0	7	32.14	0	38.33	53.85	56.85	41.27	-36764	-6.88
3.69	0	3.79	14.76	11.02	-25.85	0	0	32.14	36.26	45.99	50.26	49.75	41.27	-36808	-3.44
18.43	10.26	3.79	33.21	33.07	-18.47	-3.74	3.5	35.71	36.26	38.33	57.44	46.19	37.52	-32304	30.93
7.37	0	0	25.83	29.4	-25.85	-3.74	7	35.71	43.51	38.33	61.03	63.96	37.52	-30422	24.06
11.06	10.26	3.79	18.45	18.37	-22.16	0	0	35.71	39.88	45.99	57.44	56.85	41.27	-34860	27.49
18.43	3.42	11.38	22.14	25.72	-18.47	-3.74	10.49	35.71	36.26	38.33	64.61	49.75	33.77	-35991	24.06
7.37	3.42	15.18	7.38	25.72	-25.85	0	0	35.71	39.88	49.83	50.26	53.3	48.78	-27738	24.06
7.37	3.42	18.97	29.52	22.05	-29.55	-7.48	7	39.28	39.88	45.99	43.08	53.3	41.27	-35424	24.06
14.74	3.42	3.79	22.14	18.37	-18.47	-7.48	7	32.14	39.88	45.99	46.67	46.19	41.27	-35614	27.49
11.06	0	11.38	7.38	25.72	-14.77	-7.48	0	21.43	43.51	45.99	53.85	46.19	45.03	-38547	20.62
14.74	3.42	7.59	29.52	22.05	-18.47	-11.22	3.5	32.14	54.38	45.99	43.08	42.64	41.27	-37774	24.06
14.74	0	11.38	33.21	25.72	-22.16	-7.48	0	28.57	39.88	42.16	50.26	46.19	41.27	-44501	24.06
11.06	6.84	18.97	22.14	11.02	-36.94	0	7	28.57	36.26	38.33	61.03	60.41	41.27	-45665	24.06
18.43	3.42	11.38	14.76	29.4	-18.47	0	0	32.14	36.26	38.33	50.26	49.75	41.27	-43267	17.18
7.37	0	3.79	18.45	18.37	-29.55	-3.74	3.5	32.14	36.26	42.16	53.85	46.19	37.52	-42158	24.06

B. N₂ HOT RUN DATA

1. N₂ Hot Run Temperature Data for 1/16-Inch Nozzle

Timestamp	N1	ND	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tdata_20201120_1011_59	46000	4800	300.05	299.15	535.5	544.9	924.47	797.58	799.03	806.7	2563.7	788.02	2563.5	2563.5	798.94	2563.5	806.54
Tdata_20201120_1013_58	46000	4800	301.25	299.96	535.91	533.5	923.77	799.2	800.27	806.72	2563.8	789.33	2563.5	2563.5	799.11	2563.5	806.21
Tdata_20201120_1015_32	46000	4800	300.74	300.2	537.75	535.65	927.4	800.04	801.49	809.68	2563.8	789.94	2563.6	2563.6	802.14	2563.6	809.08
Tdata_20201120_1017_24	46000	4800	301.73	299.79	538.21	535.52	927.91	800.51	802.02	810.95	2563.8	790.2	2563.6	2563.6	803.6	2563.6	810.09
Tdata_20201120_1019_02	46000	4800	301.91	300.34	538.11	535.05	927.32	800.52	802.26	810.46	2563.8	790.25	2563.6	2563.6	803.05	2563.6	809.81
Tdata_20201120_1020_42	46000	4800	302.27	300.88	539.01	536.57	929.5	803.02	804.42	811.25	2563.9	792.16	2563.6	2563.6	804.09	2563.6	810.33
Tdata_20201120_1022_58	46000	4800	302.84	301.08	537.78	534.98	926.58	800.78	802.04	811.57	2564	789.96	2563.7	2563.7	803.99	2563.7	810.38
Tdata_20201120_1024_44	46000	4800	302.97	301.06	538.22	535.36	927.19	801.21	802.51	810.75	2564	790.32	2563.8	2563.8	803.37	2563.8	809.61
Tdata_20201120_1026_53	46000	4800	303.26	301.36	538.45	535.62	927.64	802.07	803.21	811.59	2564.1	790.87	2563.8	2563.8	804.07	2563.8	810.15

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
294.09	294.07	294.16	295.5	295.5	454.18	396.49	426.31	622.21	2564.5	2564.6	2564.6	2564.6	2564.6	2564.6	2564.6
295.29	295.18	295.21	296.65	296.65	477.3	418.59	447.38	639.24	2564.6	2564.7	2564.7	2564.7	2564.7	2564.7	2564.7
296.25	296.05	296.02	297.5	297.5	489.85	429.19	456.12	648.73	2564.6	2564.7	2564.7	2564.7	2564.7	2564.7	2564.7
297.62	297.32	297.15	298.26	298.26	510.01	441.94	464.58	667.94	2564.7	2564.7	2564.7	2564.7	2564.7	2564.7	2564.7
298.34	297.95	297.7	298.85	298.85	517.32	444.73	465.84	671.1	2564.7	2564.8	2564.8	2564.8	2564.8	2564.8	2564.8
299.15	298.66	298.34	299.42	299.42	521.92	447.65	466.73	672.77	2564.8	2564.8	2564.8	2564.8	2564.8	2564.8	2564.8
300.8	300.3	299.91	300	300	530.28	454.23	470	679.26	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9
301.48	300.94	300.49	300.29	300.29	535.62	455.92	469.42	682.57	2564.9	2565	2565	2565	2565	2565	2565
302.45	301.82	301.33	300.85	300.85	535.6	455.79	468.05	681.44	2565	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1

2. N₂ Hot Run Pressure Data for 1/16-Inch Nozzle

Atmospheric Pressure:		30.12																
Timestamp	N1	ND	1_01	1_02	1_03	1_04	1_05	1_06	1_07	1_08	1_09	1_10	1_11	1_12	1_13	1_14	1_15	1_16
Pdata_20201120_1011_59	46000	4800	-1E+06	-556.1	-9.85	-7.3	-7.02	-6.71	1635.7	1645.6	2068.6	1697	1556.9	1510	1781.9	-10.19	1731.5	-9.75
Pdata_20201120_1013_58	46000	4800	-1E+06	-553.6	-6.94	-7.74	-6.85	-6.12	1630.9	1619.8	2032.1	1725.6	1540	1489.3	1763.4	-10.92	1712.5	-10.1
Pdata_20201120_1015_32	46000	4800	-1E+06	-558.3	-8.73	-9.04	-7.31	-6.84	1660	1645.7	2091.2	1698.8	1577.7	1514.7	1801.5	-11.49	1755.4	-11.1
Pdata_20201120_1017_24	46000	4800	-1E+06	-558.2	-5.12	-8.22	-7.39	-8.97	1659.3	1650.3	2106.8	1740.2	1578.5	1514.5	1803.8	-11.45	1750.2	-10.81
Pdata_20201120_1019_02	46000	4800	-1E+06	-554.2	-7.96	-8.61	-7.71	-5.12	1642.5	1636.4	2026.8	1701.7	1546.8	1502.6	1776.4	-10.97	1723.3	-10.15
Pdata_20201120_1020_42	46000	4800	-1E+06	-555.7	-10.17	-10.52	-7.88	-8.91	1633.4	1636.7	2050.6	1738.6	1542.4	1499.8	1771.5	-12.56	1717.5	-12.13
Pdata_20201120_1022_58	46000	4800	-1E+06	-553.6	-9.12	-7.12	-8.67	-9.84	1616.3	1628.8	2036.9	1728.4	1528.7	1493.3	1753.4	-12.53	1698	-11.85
Pdata_20201120_1024_44	46000	4800	-1E+06	-550.4	-9.3	-9.81	-7.18	-7.25	1622.7	1618.2	2012.8	1714.6	1530.8	1487.6	1757	-12.65	1701.6	-11.93
Pdata_20201120_1026_53	46000	4800	-1E+06	-549.8	-10.12	-7.2	-5.11	-7.28	1596	1640.3	2005.2	1689.1	1507.3	1498.7	1725.9	-12.42	1677.9	-11.95

2_01	2_02	2_03	2_04	2_05	2_06	2_07	2_08	2_09	2_10	2_11	2_12	2_13	2_14	2_15	2_16
-8314	-556.1	-5.02	-4.49	-8.79	-9.71	1630.9	1642.7	2077.5	1703.6	1554.8	1507.3	1779	-13.42	1730.4	-6.98
-8182	-551.6	-4.21	-7.33	-6.64	-12.79	1628.7	1618.5	2037.2	1716	1538.2	1486.8	1760.4	-14.28	1711.9	-6.82
-8230	-558.3	-6.81	-7.63	-8.13	-11.56	1655.9	1644.3	2085.8	1710.5	1576.3	1513.6	1799.9	-13.43	1755.5	-8.12
-8188	-556.8	-3.24	-7.18	-8.46	-10.17	1656.4	1649.9	2106.9	1741.4	1577.6	1512.8	1801.5	-13.77	1749.2	-8.28
-8103	-551	-6.64	-6.88	-6.14	-9.4	1639.8	1635.1	2027	1700.3	1546.5	1502	1775	-13.25	1722.8	-7.47
-8067	-554.1	-4.05	-8.22	-9.45	-9.4	1630.4	1636.2	2052.3	1744.7	1542.8	1498.8	1770.3	-14.44	1717.5	-7.96
-8007	-550.4	-3.57	-6.88	-9.95	-9.86	1614.6	1629.7	2036.2	1725	1529.2	1494.3	1752.8	-13.59	1699.1	-6.98
-7976	-547.7	-3.4	-6.28	-5.31	-10.63	1621.7	1618.8	2023.6	1722.9	1532.6	1488.3	1757.1	-12.74	1703.2	-6.01
-7940	-546.3	-3.08	-4.34	-6.8	-9.71	1595.6	1641.8	2013.4	1697.6	1509	1500.6	1725.9	-12.06	1680.6	-6.49

3. N₂ Hot Run Temperature Data for 3/32-Inch Nozzle

Timestamp	N1	ND	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tdata_20201125_1220	46000	4800	298.22	296.9	533.46	531.2	920.67	793.1	794.6	802.83	2564.5	782.99	2564.3	2564.3	795.29	2564.3	802.73
Tdata_20201125_1221	46000	4800	298.51	296.73	533.42	530.34	919.37	793.91	795.24	802.18	2564.5	783.66	2564.3	2564.3	795.12	2564.3	802.06
Tdata_20201125_1224	46000	4800	298.36	297.04	540.16	537.2	931.8	800.33	801.98	808.44	2564.6	790.97	2564.4	2564.4	802.08	2564.4	809.03
Tdata_20201125_1226	46000	4800	301	298.78	541.07	537.45	933.71	804.54	806.63	811.14	2564.6	794.88	2564.4	2564.4	804.29	2564.4	810.96
Tdata_20201125_1227	46000	4800	300.93	299.22	541.75	538.72	935.36	805.02	806.75	812.5	2564.7	795.04	2564.5	2564.5	805.56	2564.5	812.27
Tdata_20201125_1229	46000	4800	301.24	298.89	541.25	537.84	932.99	804.81	806.58	811.37	2564.7	794.01	2564.5	2564.5	804.49	2564.5	811.06
Tdata_20201125_1231	46000	4800	302.78	299.99	542.51	538.98	935.55	807.19	808.33	814.93	2564.7	795.74	2564.6	2564.6	807.48	2564.6	814.26
Tdata_20201125_1232	46000	4800	302.99	300.58	543.42	540.26	937.13	808.11	809.61	815.67	2564.8	797.2	2564.6	2564.6	808.22	2564.6	815
Tdata_20201125_1234	46000	4800	304.05	301.1	543.7	540.15	937.64	809.69	811.03	815.79	2564.9	798.22	2564.7	2564.7	808.28	2564.7	815.01

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
291.44	291.49	291.55	292.75	416.88	380.45	404.26	646.7	2565.4	2565.4	2565.5	2565.5	2565.5	2565.5	2565.5	2565.5
292.73	292.73	292.74	293.73	448.73	409.26	434.68	663.54	2565.4	2565.4	2565.5	2565.5	2565.5	2565.5	2565.5	2565.5
293.77	293.69	293.62	294.39	463.91	423.34	447.47	674.7	2565.5	2565.5	2565.5	2565.5	2565.5	2565.5	2565.5	2565.5
295.13	295.04	294.86	294.85	486.34	438.36	459.77	683.85	2565.5	2565.5	2565.6	2565.6	2565.6	2565.6	2565.6	2565.6
295.79	295.65	295.38	295.28	492.61	438.36	462.79	686.55	2565.6	2565.6	2565.7	2565.7	2565.7	2565.7	2565.7	2565.7
296.51	296.3	296.04	295.73	497.42	447.14	464.48	687.14	2565.6	2565.6	2565.7	2565.7	2565.7	2565.7	2565.7	2565.7
297.7	297.49	297.2	295.97	507.66	452.97	467.75	684.2	2565.7	2565.7	2565.8	2565.8	2565.8	2565.8	2565.8	2565.8
298.27	298.02	297.7	296.25	508.54	453.72	466.7	684.27	2565.7	2565.7	2565.8	2565.8	2565.8	2565.8	2565.8	2565.8
298.93	298.64	298.31	296.54	509.48	453.43	465.25	685.03	2565.8	2565.8	2565.9	2565.9	2565.9	2565.9	2565.9	2565.9

N₂ Hot Run Pressure Data for 3/32-Inch Nozzle

Atmospheric Pressure:		30.16																	
Timestamp		N1	ND	1_01	1_02	1_03	1_04	1_05	1_06	1_07	1_08	1_09	1_10	1_11	1_12	1_13	1_14	1_15	1_16
Pdata	20201125_1220_34	46000	4800	-999999	-570.57	-12.46	-11.24	-10.86	-12.95	1655	1667.9	2084.9	1732.7	1563.6	1529.7	1792.1	-13.59	1745.7	-13.17
Pdata	20201125_1222_36	46000	4800	-999999	-565.71	-9.02	-11.1	-14.55	-11.92	1659	1663.2	2097.4	1756.4	1567.8	1521.8	1796	-14.62	1745.9	-13.87
Pdata	20201125_1224_12	46000	4800	-999999	-590.55	-11.81	-10.38	-12.45	-11.92	1812.4	1715.9	2403.8	1833	1725.2	1567.7	1977.1	-14.41	1922.4	-13.75
Pdata	20201125_1226_06	46000	4800	-999999	-584.82	-10.13	-13.96	-14.13	-12.2	1773	1714.5	2321.5	1831	1678.3	1558.3	1925.1	-15.57	1871.3	-14.95
Pdata	20201125_1227_39	46000	4800	-999999	-584.07	-11.41	-12.5	-11.64	-9.96	1770.8	1709.2	2321	1836.1	1686.9	1555.1	1923.2	-14.94	1874.6	-14.43
Pdata	20201125_1229_16	46000	4800	-999999	-585.02	-11.23	-12.04	-13.99	-13.31	1786.1	1689.1	2300.7	1847.9	1686.1	1544.2	1929.7	-15.98	1877.2	-15.43
Pdata	20201125_1231_09	46000	4800	-999999	-581.82	-12.35	-11.67	-11.76	-11.97	1734.1	1704.7	2239.4	1811	1644.6	1551.6	1875.1	-15.55	1832.3	-15.17
Pdata	20201125_1232_48	46000	4800	-999999	-580.33	-13.98	-14.62	-12.44	-15.15	1739.2	1664.1	2275.7	1758.8	1646.4	1522.8	1888.2	-17.17	1834.3	-16.3
Pdata	20201125_1234_28	46000	4800	-999999	-575.77	-14.19	-11.94	-8.93	-12.56	1716.7	1676.1	2228.1	1762.7	1626.6	1529.1	1863.4	-16.99	1815.4	-16.12

2_01	2_02	2_03	2_04	2_05	2_06	2_07	2_08	2_09	2_10	2_11	2_12	2_13	2_14	2_15	2_16
-8633.8	-567.91	-10.54	-8.53	-10.95	-10.17	1654.8	1669.7	2097	1736.7	1562.2	1530.3	1791.5	-11.39	1746.1	-11.53
-8492.5	-563.63	-11.51	-9.87	-9.62	-8.94	1659	1665.6	2100	1766.4	1567.1	1523.7	1794.9	-13.09	1746.6	-12.18
-8795.5	-589.02	-10.7	-8.68	-11.12	-8.47	1812.3	1718.4	2398	1832.4	1724.2	1568.2	1976.1	-12.41	1922.6	-12.66
-8623.4	-583.74	-10.38	-11.36	-10.45	-11.86	1773.8	1715.5	2322.7	1836.7	1677.4	1559.3	1924.4	-13.6	1871.5	-13.31
-8564.9	-583.36	-11.67	-10.92	-9.95	-8.94	1770.5	1710.4	2322.6	1836.4	1685.7	1555.1	1922.6	-13.09	1873.9	-14.29
-8510.1	-585.1	-10.22	-12.57	-13.27	-10.63	1785.3	1690.2	2303.3	1851.7	1684.9	1544.7	1928.9	-16.14	1875.6	-15.75
-8429.7	-581.7	-12.96	-10.47	-11.44	-11.71	1733.7	1704.9	2244.2	1807.1	1642	1551.6	1873.6	-14.78	1831.6	-15.59
-8359.8	-581.63	-12.81	-11.81	-10.79	-11.4	1739.1	1665	2274.7	1758.2	1644.3	1523	1886.4	-15.98	1833.7	-16.07
-8310.3	-576.77	-12.48	-9.12	-8.79	-11.86	1717.7	1677.2	2227.2	1769.1	1623.8	1528.9	1862.6	-14.79	1815.3	-14.45

3_01	3_02	3_03	3_04	HX IN		3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
				3_05	3_06										
-8619.4	-525.17	426508	413596	189690	132610	1646.7	1682.8	2125.5	1773.6	1592.3	1561.2	160246	132600	132655	132269
-8475.8	-513.5	425288	412426	194148	137493	1643.1	1690.5	2117.8	1799.6	1600.5	1557.8	164357	137526	137546	137177
-8774.3	-556.29	442689	430073	197400	140724	1788.6	1751	2398.9	1858.9	1757	1605.6	167277	140729	140782	140370
-8619.4	-564.07	437474	424762	298656	232851	1746.8	1735.9	2321.9	1859.3	1706.1	1583.5	265808	232898	232897	232467
-8534.1	-564.07	437901	425145	299908	234937	1735.6	1736.4	2318	1862.6	1706.1	1579.9	267622	235000	235016	234530
-8487.1	-552.53	436636	423957	300969	235905	1773.3	1691.1	2318.2	1866.3	1710.7	1554.1	268388	235950	235973	235491
-8430.4	-540.84	433888	421099	399666	327536	1712.7	1698.6	2268	1807.6	1651.9	1565.1	365972	327630	327621	327104
-8334.1	-552.4	433076	420443	399394	327687	1708.8	1698.5	2298.8	1777.5	1682.7	1557.3	366011	327755	327791	327225
-8284.1	-548.51	431216	418474	399425	327757	1670.5	1694.9	2222.5	1767	1655.3	1561.2	366059	327834	327845	327319

4_01	4_02	4_03	4_04	4_05	4_06	4_07	4_08	4_09	4_10	4_11	4_12	4_13	4_14	4_15	4_16
40.51	0	37.93	-7.38	-22.05	33.23	3.73	7	-7.14	32.64	0	7.18	3.55	22.5	-15949	0
40.51	3.42	45.52	-14.76	-29.4	33.23	0	3.5	24.99	54.39	0	50.25	35.53	33.76	-15978	30.92
33.14	3.42	45.52	-22.14	-25.73	0	-3.74	0	17.85	47.14	-3.84	43.07	35.53	11.25	-6663.5	34.36
36.84	34.2	45.52	7.38	-36.75	55.39	0	34.98	14.28	43.51	-3.84	35.89	35.53	15.01	-11569	30.92
33.16	34.2	49.31	0	-36.75	36.93	-3.74	34.98	10.71	36.26	22.99	35.89	35.53	11.25	-1706.7	27.49
25.79	23.94	49.31	0	-36.75	36.93	-7.47	34.98	35.7	72.5	22.99	71.78	63.95	48.75	-10339	51.54
33.16	27.36	45.52	0	-11.03	25.85	-14.95	24.48	32.13	72.5	22.99	68.19	49.74	41.25	-10230	34.36
66.29	44.45	53.1	33.2	-3.68	62.77	22.41	62.96	35.7	72.5	22.99	64.6	53.29	41.25	-11317	37.79
47.87	44.45	56.9	29.51	-14.7	59.08	18.67	52.46	35.7	68.87	19.16	53.83	46.18	45	-14773	34.36

C. CO₂ COLD RUN DATA

1. CO₂ Cold Run Temperature Data for 1/16-Inch Nozzle

Timestamp	N1	ND	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Tdata_20201203_1201_55	46000	4800	290.36	290.39	290.1	290.07	289.4	289.46	289.62	289.37	289.31	289.49	2563.7	2563.7	289.22	289.14	289.06	290.72
Tdata_20201203_1203_20	46000	4800	290.36	290.39	290.11	290.08	289.41	289.53	289.68	289.45	289.4	289.55	2563.7	2563.7	289.32	289.23	289.15	290.6
Tdata_20201203_1205_07	46000	4800	290.35	290.38	290.15	290.1	289.42	289.59	289.74	289.53	289.48	289.62	2563.7	2563.7	289.39	289.32	289.22	290.57
Tdata_20201203_1206_41	46000	4800	290.35	290.38	290.18	290.12	289.44	289.65	289.81	289.63	289.58	289.69	2563.7	2563.7	289.48	289.39	289.36	290.87
Tdata_20201203_1208_03	46000	4800	290.35	290.39	290.21	290.14	289.45	289.71	289.87	289.73	289.67	289.79	2563.8	2563.8	289.58	289.45	289.41	290.75
Tdata_20201203_1209_11	46000	4800	290.35	290.39	290.24	290.16	289.46	289.77	289.91	289.82	289.75	289.85	2563.8	2563.8	289.69	289.5	289.46	290.74
Tdata_20201203_1210_45	46000	4800	290.36	290.39	290.3	290.2	289.49	289.84	289.99	289.91	289.84	289.94	2563.9	2563.9	289.8	289.58	289.54	290.98
Tdata_20201203_1212_05	46000	4800	290.34	290.39	290.33	290.22	289.5	289.89	290.05	289.98	289.92	290.02	2563.9	2563.9	289.93	289.65	289.61	290.95
Tdata_20201203_1213_31	46000	4800	290.37	290.4	290.38	290.24	289.52	289.95	290.11	290.06	290	290.1	2564	2564	290.06	289.7	289.68	291.14

17	18	19	20	21	22	23	24	25	26	27	28	29	30
290.74	290.65	290.19	289.12	288.99	289.12	289.38	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9
290.61	290.52	290.19	289.14	288.99	289.14	289.5	2565	2565	2565	2565	2565	2565	2565
290.56	290.47	290.24	289.23	289.05	289.22	289.63	2565	2565	2565	2565	2565	2565	2565
290.92	290.82	290.33	289.4	289.19	289.4	289.91	2565	2565	2565	2565	2565	2565	2565
290.78	290.7	290.36	289.44	289.19	289.41	289.97	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1
290.78	290.72	290.39	289.47	289.21	289.46	290.02	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1
291.07	291	290.43	289.69	289.35	289.64	290.25	2565.2	2565.2	2565.2	2565.2	2565.2	2565.2	2565.2
291.04	290.99	290.34	289.75	289.37	289.69	290.36	2565.2	2565.2	2565.2	2565.2	2565.2	2565.2	2565.2
291.24	291.22	290.15	289.85	289.42	289.78	290.44	2565.2	2565.2	2565.2	2565.2	2565.2	2565.2	2565.2

2. CO₂ Cold Run Pressure Data for 1/16-Inch Nozzle

Atmospheric Pressure:		30.22																
Timestamp	N1	ND	1_01	1_02	1_03	1_04	1_05	1_06	1_07	1_08	1_09	1_10	1_11	1_12	1_13	1_14	1_15	1_16
Pdata_20201203_1201_55	46000	4800	0.12	0	-0.15	-0.08	-0.03	0.08	-0.07	0.24	0.03	-0.37	0.05	0.1	0.14	0.1	-0.08	0.2
Pdata_20201203_1203_20	46000	4800	0.08	0	-0.26	-0.11	-0.15	0.02	-0.03	-0.07	0.05	-0.37	0.07	0	0.15	0.06	0.07	0.05
Pdata_20201203_1205_07	46000	4800	0.16	-0.1	-0.16	0	0.02	0.02	-0.2	0.19	0.13	-0.37	0.12	-0.05	0.14	0.1	-0.1	0.2
Pdata_20201203_1206_41	46000	4800	0.09	0.1	-0.11	0.18	-0.23	0.2	-0.16	0.12	-0.02	-0.39	0.02	0.03	0.09	0.14	-0.05	0.13
Pdata_20201203_1208_03	46000	4800	0.08	0	-0.26	0.03	-0.05	-0.1	-0.18	-0.03	0.03	-0.35	0	-0.11	0.03	0.03	0.03	0.02
Pdata_20201203_1209_11	46000	4800	0.03	0.05	-0.16	0.05	0.11	0.1	-0.2	0.12	0.05	-0.37	0	-0.05	0.08	0.19	-0.03	0.23
Pdata_20201203_1210_45	46000	4800	0	-0.03	-0.1	-0.28	0	-0.02	-0.31	0.13	-0.05	-0.58	-0.07	-0.26	-0.08	0.02	-0.18	0.12
Pdata_20201203_1212_05	46000	4800	0.12	0.05	-0.16	-0.15	0	-0.05	-0.26	0.02	0.02	-0.5	-0.05	-0.13	0.05	0.11	-0.07	0.1
Pdata_20201203_1213_31	46000	4800	0.14	0.08	-0.16	0	-0.02	-0.02	-0.16	0.35	0.13	-0.52	0.07	-0.05	0.11	0.1	-0.03	0.08

2_01	2_02	2_03	2_04	2_05	2_06	2_07	2_08	2_09	2_10	2_11	2_12	2_13	2_14	2_15	2_16
-0.14	-0.51	0.49	1.04	0.99	-0.15	-0.78	-1.48	-0.64	0.64	0.27	0.16	-0.89	0.17	0.74	-0.49
-0.55	-0.51	0.49	1.34	0.16	-0.31	-0.47	-0.99	-0.16	0.48	0	0.31	-0.3	0.68	0.29	-0.97
-0.82	-1.02	-0.16	0.6	0.66	-0.31	-0.31	-1.81	-0.16	0.8	0.27	0.31	-1.49	-0.51	0.59	-0.81
-0.14	-0.34	0.16	0.9	-0.17	-0.15	-0.62	-0.49	-0.48	-0.64	0	1.25	-0.6	0.51	-0.3	-1.14
-0.27	-0.51	1.13	1.04	-0.17	-0.15	-0.78	-0.99	-0.48	-0.32	-0.41	0.63	-0.45	1.35	0.15	-1.3
-0.55	-0.34	0.32	0.9	0.16	0.15	-0.31	-1.48	-1.43	0	0	0.47	-0.89	0	0.3	-0.49
-0.27	-0.51	0.16	0.9	0.16	-0.15	-0.16	-1.48	-1.27	-0.48	0.13	0.78	-0.74	-0.34	-0.3	-0.33
-0.96	-0.51	0.32	0.75	-0.83	-0.77	-0.62	-1.81	-0.79	-0.32	0.27	0.63	-0.89	0.34	0	-0.49
-0.41	-0.68	0.16	0.75	-0.33	-0.31	-0.62	-1.81	-0.95	0.32	0.27	0.16	-1.49	0.17	-0.15	-0.49

3. CO₂ Cold Run Temperature Data for 3/32-Inch Nozzle

Timestamp	N1	ND	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tdata_20201201_1220_18	46000	4800	290.55	290.65	290.34	290.32	289.78	290.13	290.24	290.24	290.18	290.11	2563.7	2563.7	2563.7	2563.7	290.16
Tdata_20201201_1222_35	46000	4800	290.54	290.64	290.34	290.32	289.78	290.1	290.22	290.29	290.24	290.12	2563.7	2563.7	2563.7	2563.7	290.17
Tdata_20201201_1224_02	46000	4800	290.53	290.64	290.36	290.33	289.8	290.12	290.23	290.31	290.26	290.12	2563.7	2563.7	2563.7	2563.7	290.17
Tdata_20201201_1227_06	46000	4800	290.53	290.63	290.37	290.33	289.81	290.15	290.26	290.3	290.24	290.15	2563.7	2563.7	2563.7	2563.7	290.17
Tdata_20201201_1228_19	46000	4800	290.53	290.62	290.36	290.33	289.83	290.15	290.26	290.31	290.25	290.16	2563.8	2563.8	2563.8	2563.8	290.17
Tdata_20201201_1229_33	46000	4800	290.53	290.62	290.34	290.33	289.83	290.14	290.25	290.32	290.27	290.15	2563.8	2563.8	2563.8	2563.8	290.16
Tdata_20201201_1231_45	46000	4800	290.52	290.62	290.31	290.31	289.83	290.13	290.23	290.29	290.24	290.13	2563.9	2563.9	2563.9	2563.9	290.12
Tdata_20201201_1247_24	46000	4800	290.46	290.55	290.19	290.23	289.84	289.97	290.07	290.04	290	289.94	2564.1	2564.1	2564.1	2564.1	289.93
Tdata_20201201_1249_16	46000	4800	290.45	290.55	290.17	290.22	289.85	289.95	290.05	290	289.96	289.94	2564.1	2564.1	2564.1	2564.1	289.88

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
290.12	290.15	290.2	290.24	290.25	290.22	290.22	290.31	290.08	2564.6	2564.7	2564.7	2564.7	2564.7	2564.7	2564.7
290.37	290.46	290.49	290.31	290.23	290.19	290.29	290.29	290.02	2564.7	2564.7	2564.7	2564.7	2564.7	2564.7	2564.7
290.56	290.68	290.72	290.33	290.2	290.17	290.26	290.26	290.05	2564.7	2564.8	2564.8	2564.8	2564.8	2564.8	2564.8
290.67	290.84	290.87	290.14	290.22	290.18	290.31	290.31	290.03	2564.8	2564.8	2564.8	2564.8	2564.8	2564.8	2564.8
290.85	291.02	291.05	289.82	290.15	290.11	290.24	289.95	2564.8	2564.8	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9
290.9	291.08	291.12	289.26	290.13	290.09	290.23	289.81	2564.8	2564.8	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9
291.1	291.33	291.34	285.53	289.99	290.11	290.32	288.81	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9
290.98	291.2	291.22	287.17	289.67	289.76	290.07	288.68	2565	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1
290.85	291.06	291.06	285.71	289.4	289.69	290.02	287.8	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1

4. CO₂ Cold Run Pressure Data for 3/32-Inch Nozzle

Atmospheric Pressure:		30.16																
Timestamp	N1	ND	1_01	1_02	1_03	1_04	1_05	1_06	1_07	1_08	1_09	1_10	1_11	1_12	1_13	1_14	1_15	1_16
Pdata_20201201_1220_18	46000	4800	-0.33	-0.13	-0.18	-0.05	-0.05	-0.24	0.13	0.15	0.3	-0.02	0.12	0.13	0.15	-0.05	0.13	-0.17
Pdata_20201201_1222_35	46000	4800	-0.3	-0.11	0.02	-0.03	-0.02	-0.1	0.03	0.03	0.12	-0.06	-0.03	0.07	-0.05	-0.24	0.02	-0.12
Pdata_20201201_1224_02	46000	4800	-0.39	0	-0.05	0.03	0.03	-0.13	0.16	0.15	0.2	0.02	0.02	0.13	-0.02	-0.22	0.08	-0.08
Pdata_20201201_1227_06	46000	4800	-0.47	-0.02	-0.13	0.07	0	-0.23	-0.02	0.42	0.12	-0.05	0.03	0	-0.05	-0.11	-0.03	-0.23
Pdata_20201201_1228_19	46000	4800	-0.39	0.03	0.06	0.12	0	0.05	0.21	0.35	0.33	0.15	0.08	0.16	0	-0.06	0.07	-0.17
Pdata_20201201_1229_33	46000	4800	-0.47	-0.08	-0.1	0.1	-0.14	-0.08	0.16	0.34	0.3	0.03	0.07	0.08	0.08	-0.16	0.1	-0.13
Pdata_20201201_1231_45	46000	4800	-0.45	-0.1	0.13	-0.11	0.09	0.03	0.18	0.4	0.23	-0.06	0.02	0.08	0.02	-0.08	0.02	-0.1
Pdata_20201201_1247_24	46000	4800	-0.76	-0.02	0.19	0.1	0.32	-0.31	0.31	0.35	0.32	0.08	0.08	0.11	0	0.02	0.24	-0.1
Pdata_20201201_1249_16	46000	4800	-0.73	0.02	-0.13	0.13	-0.01	0.25	0.38	0.49	0.37	0.1	0.15	0.15	0.11	-0.05	0.18	-0.18

2_01	2_02	2_03	2_04	2_05	2_06	2_07	2_08	2_09	2_10	2_11	2_12	2_13	2_14	2_15	2_16
-0.55	1.36	-0.32	0.15	0.16	0.31	0.62	0.33	-1.11	0.16	-0.95	0.47	-0.45	-0.51	-0.59	-0.32
0	1.53	-0.32	0.15	0.5	0.61	1.24	0.49	-1.27	0.32	-1.22	0.63	-0.75	-0.34	-1.04	-0.16
0.27	1.7	-0.16	0.3	0.66	1.23	1.24	0.98	-0.79	0.32	-1.08	0.94	-0.3	-1.19	-1.48	0.32
0.41	2.03	0	0.9	0.66	0.61	1.71	1.48	-0.64	-0.64	-1.22	0.63	-0.15	-0.85	-1.33	-0.16
0.68	2.2	0.48	0.6	1.65	1.38	1.71	1.64	-0.32	0	-0.81	0.47	-0.3	-1.36	-1.48	-0.33
0.55	2.37	0.16	0.9	0.99	1.23	2.18	1.64	-0.32	-0.16	-1.49	0	-0.6	-1.7	-1.04	-0.65
0.82	2.71	0.97	1.19	1.65	1.38	1.87	1.64	-0.95	-0.64	-1.08	0.16	-0.15	-1.36	-1.04	-1.14
0.82	1.87	0	1.49	1.32	1.54	1.55	0.82	-1.75	-0.96	-1.89	-0.31	-0.6	-2.38	-1.93	-0.32
0.55	1.7	0.16	0.45	1.16	0.77	1.55	0.98	-1.59	-1.6	-1.49	-0.79	-0.6	-1.19	-1.48	-1.14

D. CO₂ HOT RUN DATA

1. CO₂ Hot Run Temperature Data for 1/16-Inch Nozzle

Timestamp	N1	ND	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tdata_20201204_1018_46	46000	4800	298.26	297.42	534.96	532.46	923.72	794.83	796.81	805.32	2564	785.3	2563.7	2563.7	805.21	796.9	775.3
Tdata_20201204_1020_30	46000	4800	298.99	297.41	535.29	532.79	924.15	796.81	798.51	805.07	2564	786.86	2563.8	2563.8	804.99	797.12	776.75
Tdata_20201204_1022_06	46000	4800	300.13	297.88	535.32	532.75	923.59	798.39	799.77	805.8	2564	787.51	2563.8	2563.8	805.19	798.02	778.03
Tdata_20201204_1024_01	46000	4800	300.5	298.23	537.96	534.96	928.2	801.09	802.72	810.31	2564.1	790.82	2563.9	2563.9	809.66	802.45	781.79
Tdata_20201204_1025_31	46000	4800	300.05	298.42	537.72	534.84	925.32	800.08	800.91	806.69	2564.2	788.96	2564	2564	805.85	799.04	778.71
Tdata_20201204_1027_01	46000	4800	300.48	298.36	537.54	534.54	924.74	800.1	800.89	806.97	2564.3	788.52	2564	2564	806.26	799.49	779.41
Tdata_20201204_1028_50	46000	4800	301.49	299.23	537.61	534.67	925.31	800.94	1023	807.6	2564.3	788.85	2564.1	2097.9	806.5	799.66	778.48
Tdata_20201204_1030_30	46000	4800	300.91	298.74	537.25	534.25	924.65	800.84	1185	806.82	2564.4	789.27	2564.2	1679	805.57	798.96	778.34
Tdata_20201204_1032_10	46000	4800	302.11	299.48	538.64	535.16	925.53	802.24	876.71	806.95	2564.5	790.11	2564.2	1483.6	805.85	799.53	778.68

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
291.59	291.62	291.67	292.84	438.55	372.64	404.11	633.08	2564.6	2564.7	2564.7	2564.7	2564.7	2564.7	2564.7	2564.7
292.56	292.57	292.58	293.78	469.86	403.59	432.82	652.71	2564.7	2564.8	2564.8	2564.8	2564.8	2564.8	2564.8	2564.8
293.39	293.36	293.33	294.63	486.4	421.12	447.24	660.59	2564.8	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9
294.65	294.62	294.49	295.42	512	440.6	460.61	679.4	2564.8	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9	2564.9
295.22	295.07	294.9	295.98	519.51	446.75	464.6	679.18	2564.9	2565	2565	2565	2565	2565	2565	2565
295.92	295.67	295.45	296.49	524.06	449.52	466	680.15	2564.9	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1
297	296.73	296.42	296.82	534.7	455.98	468.67	685.05	2565	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1	2565.1
297.85	297.54	297.23	297.11	538.75	459.38	470.47	686.79	2565.1	2565.2	2565.2	2565.2	2565.2	2565.2	2565.2	2565.2
298.61	298.18	297.86	297.37	541.59	460.88	471.24	686.94	2565.2	2565.3	2565.3	2565.3	2565.3	2565.3	2565.3	2565.3

2.

CO₂ Hot Run Pressure Data for 1/16-Inch Nozzle

Atmospheric Pressure:		30.21																
Timestamp	N1	ND	1_01	1_02	1_03	1_04	1_05	1_06	1_07	1_08	1_09	1_10	1_11	1_12	1_13	1_14	1_15	1_16
PData_20201204_1018_46	46000	4800	-999999	-568.05	-9.38	-8.68	-11.18	-11.36	1702.5	1704.5	2164.8	1769.9	1618.4	1562.4	1838.4	-13.03	1794.7	-13.08
PData_20201204_1020_30	46000	4800	-999999	-562.58	-11.47	-10.55	-10.3	-10.08	1705.1	1685.6	2124	1782.9	1609.8	1551.6	1838.8	-13.83	1786.2	-14
PData_20201204_1022_06	46000	4800	-999999	-559.73	-14.14	-13.17	-9.76	-10.39	1685.1	1670.8	2089	1766.6	1588.4	1541.1	1811.5	-14.17	1762	-14.7
PData_20201204_1024_01	46000	4800	-999999	-565.38	-14.07	-11.74	-12.64	-12.69	1699	1709.6	2170	1807.4	1610.9	1564.8	1839.3	-15.52	1792.4	-15.78
PData_20201204_1025_31	46000	4800	-999999	-564.35	-11.38	-10.25	-10.95	-14.02	1751.1	1670.4	2180.8	1808.6	1645	1534.2	1869.2	-14.97	1821.5	-15.01
PData_20201204_1027_01	46000	4800	-999999	-563.54	-12.72	-12.76	-13.54	-11.19	1735.1	1673	2141.9	1803.5	1630	1536.3	1856.4	-15.87	1805	-15.8
PData_20201204_1028_50	46000	4800	-999999	-560.15	-10.8	-11.04	-11.97	-11.58	1704.9	1680	2128.6	1769.5	1602.6	1536.5	1825.7	-16.09	1778.9	-16.18
PData_20201204_1030_30	46000	4800	-999999	-559.78	-11.49	-12.26	-11.7	-11.5	1704.5	1673.2	2132.8	1793.8	1601.6	1540.5	1827.6	-15.36	1778.2	-15.6
PData_20201204_1032_10	46000	4800	-999999	-560.09	-12.82	-12.39	-12.48	-13.55	1697.6	1676.2	2139.2	1737.5	1594.2	1540.8	1820.9	-16.92	1771.9	-16.93

	2_01	2_02	2_03	2_04	2_05	2_06	2_07	2_08	2_09	2_10	2_11	2_12	2_13	2_14	2_15	2_16
	-8873.1	-564.35	-6.81	-8.83	-9.46	-8.47	1706.6	1706.7	2168.5	1778.3	1617.8	1565.3	1839.5	-10.88	1797.8	-10.88
	-8734	-559.92	-6.65	-5.24	-6.8	-7.55	1703.5	1687.8	2129.7	1783.2	1608.2	1555.4	1839.6	-10.54	1790.1	-12.34
	-8598.9	-555.68	-12.97	-9.87	-7.47	-9.24	1687.5	1674.5	2103	1785	1587.2	1544.1	1811.4	-14.96	1765.1	-12.34
	-8611.3	-563.66	-8.27	-8.68	-6.8	-8.78	1699.8	1711.6	2184.8	1800.7	1608.7	1567.7	1840.5	-12.41	1795.2	-14.94
	-8548.6	-562.13	-8.27	-8.68	-6.8	-7.4	1752.8	1672.5	2187	1803.4	1642.4	1536.9	1869.3	-13.09	1824.2	-13.48
	-8478.1	-561.89	-8.92	-10.17	-10.61	-10.17	1734.6	1675.4	2151.5	1805	1627.7	1539.1	1857	-14.62	1808	-14.61
	-8387.9	-557.88	-8.43	-7.93	-9.79	-10.63	1705.1	1681.6	2127.3	1765.9	1598.5	1538.5	1826.4	-14.28	1780.8	-15.75
	-8359.3	-559.05	-9.72	-10.77	-10.62	-8.63	1704.4	1675	2133.6	1786.2	1599.7	1541.9	1827.7	-14.79	1779.4	-16.07
	-8328.2	-559.41	-10.54	-11.07	-9.62	-12.33	1697.9	1677.7	2138.8	1749.1	1592	1542.6	1821.2	-16.99	1773.4	-17.37

3. CO₂ Hot Run Temperature Data for 3/32-Inch Nozzle

Timestamp	N1	ND	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tdata_20201202_1219_53	46000	4800	299.74	297.49	534.65	531.88	920.82	795.29	796.24	802.51	2564.4	784.76	2564.1	2564.1	802.26	794.26	772.66
Tdata_20201202_1221_38	46000	4800	299.75	298.18	536.38	533.56	924.11	798.16	799.44	805.51	2564.5	787.45	2564.2	2564.2	805.17	797.72	775.98
Tdata_20201202_1223_15	46000	4800	300.09	297.91	536.14	533.38	923.25	797.5	798.78	805.5	2564.6	786.62	2564.3	1670.4	804.92	797.92	776.85
Tdata_20201202_1225_13	46000	4800	302.45	299.78	537.81	534.44	925.22	800.87	801.88	808.34	2564.6	789.33	2564.3	1401.9	807.53	800.18	778.12
Tdata_20201202_1226_49	46000	4800	302.17	299.42	537.35	533.93	924.61	801.01	801.51	806.49	2564.7	789.47	2564.4	637.91	805.74	798.71	777.54
Tdata_20201202_1228_21	46000	4800	302.63	300.15	542.23	538.91	933.65	807.08	808.24	812.43	2564.8	795.82	2564.5	418.63	811.89	804.9	781.99
Tdata_20201202_1230_13	46000	4800	303.54	300.93	543.03	539.79	934.56	808.24	809.21	814.6	2564.9	796.68	2564.6	-433.41	813.96	806.67	783.22
Tdata_20201202_1232_03	46000	4800	303.69	301.22	542.72	539.36	934.32	807.43	808.76	814.8	2564.9	795.74	2564.6	-32673	814.12	807.09	783.16
Tdata_20201202_1233_40	46000	4800	303.35	301.24	542.82	539.18	933.86	808.64	809.56	813.76	2565	796.81	2564.7	-7E+06	812.9	805.49	782.8

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
292.2	292.27	292.45	293.57	429.4	389.09	416.92	658.54	2565.2	2565.2	2565.2	2565.2	2565.2	2565.2	2565.2	2565.2
293.25	293.29	293.44	294.12	453.49	411.29	438.38	675.67	2565.3	2565.3	2565.3	2565.3	2565.3	2565.3	2565.3	2565.3
294.21	294.23	294.3	294.65	467.11	424.13	449.27	681.84	2565.4	2565.4	2565.4	2565.4	2565.4	2565.4	2565.4	2565.4
295.48	295.52	295.47	294.75	487.9	438.42	459.4	675.45	2565.4	2565.5	2565.5	2565.5	2565.5	2565.5	2565.5	2565.5
296.05	296.02	295.93	294.74	493.29	442.35	460.86	675.98	2565.5	2565.5	2565.5	2565.5	2565.5	2565.5	2565.5	2565.5
296.67	296.61	296.48	294.62	498.5	445.45	462.59	680.96	2565.5	2565.6	2565.6	2565.6	2565.6	2565.6	2565.6	2565.6
297.93	297.87	297.7	293.27	511	453.61	466.99	664.34	2565.6	2565.7	2565.7	2565.7	2565.7	2565.7	2565.7	2565.7
298.64	298.58	298.42	292.08	513.03	453.41	464.77	663.83	2565.7	2565.7	2565.7	2565.7	2565.7	2565.7	2565.7	2565.7
299.27	299.21	299.06	290.85	514.88	455.1	465.76	663.83	2565.7	2565.7	2565.7	2565.7	2565.7	2565.7	2565.7	2565.7

CO₂ Hot Run Pressure Data for 3/32-Inch Nozzle

Atmospheric Pressure:		30.06																	
Timestamp		N1	ND	1_01	1_02	1_03	1_04	1_05	1_06	1_07	1_08	1_09	1_10	1_11	1_12	1_13	1_14	1_15	1_16
Pdata	20201202_1219_53	46000	4800	-999999	-557.31	-12.21	-10.3	-10.7	-12.36	1681.6	1660.7	2095.1	1766.3	1580.9	1525.8	1804.6	-14.04	1755.6	-14.18
Pdata	20201202_1221_38	46000	4800	-999999	-562.49	-10.41	-10.3	-11.63	-11.49	1692.4	1667.6	2142.7	1756	1597.6	1531.8	1830.8	-14.85	1775.8	-14.93
Pdata	20201202_1223_15	46000	4800	-999999	-560.16	-12.17	-12.77	-14.43	-14.58	1702.7	1667.9	2113.8	1769.8	1601.3	1526.6	1822.8	-15.94	1773.1	-16.23
Pdata	20201202_1225_13	46000	4800	-999999	-556.43	-11.88	-12.83	-12.12	-11.28	1673.4	1639.1	2091.2	1760.5	1569.1	1503.3	1797.5	-16.01	1747.6	-16.28
Pdata	20201202_1226_49	46000	4800	-999999	-555.14	-10.66	-13.52	-11.33	-11.9	1657.4	1641.6	2063.7	1761.3	1560.2	1513.3	1782	-15.88	1730.6	-15.89
Pdata	20201202_1228_21	46000	4800	-999999	-570.38	-13.22	-11.7	-9.66	-12.31	1743.2	1689.6	2239.5	1771.1	1645.5	1542.9	1882.4	-15.91	1826.5	-16.04
Pdata	20201202_1230_13	46000	4800	-999999	-566.06	-11.9	-12.76	-12.6	-10.59	1735.6	1668.7	2211	1783.7	1640.3	1524.5	1871.5	-15.38	1822.9	-15.86
Pdata	20201202_1232_03	46000	4800	-999999	-566.4	-13.85	-11.39	-11.72	-13.92	1717.5	1656.3	2174.3	1771.2	1621.1	1514.9	1847.7	-16.42	1799	-16.71
Pdata	20201202_1233_40	46000	4800	-999999	-566.48	-12.45	-13.11	-11.97	-12.75	1728.1	1640.7	2192.2	1775	1629.9	1509.9	1858.6	-16.6	1806	-16.78

	2_01	2_02	2_03	2_04	2_05	2_06	2_07	2_08	2_09	2_10	2_11	2_12	2_13	2_14	2_15	2_16
	-8611.7	-558.03	-11.99	-13.01	-11.44	-14.02	1680.6	1660.1	2087.8	1770.7	1578.6	1525	1804.2	-15.63	1754.7	-15.91
	-8594.4	-562.69	-11.34	-14.65	-12.77	-13.4	1692.3	1667.3	2129.6	1758.2	1596.3	1530.5	1830.2	-16.82	1775	-17.21
	-8502.5	-560.48	-11.99	-14.95	-12.43	-13.1	1699.8	1666.8	2116.2	1763.5	1598.4	1525.6	1822.2	-17.33	1772.4	-18.02
	-8357.7	-557.68	-12.47	-15.25	-10.78	-14.33	1672.5	1638.5	2086.4	1762.5	1566.5	1502.3	1796.4	-16.99	1746.5	-18.19
	-8289.1	-555.63	-15.06	-15.54	-11.93	-12.17	1656.9	1640.2	2054.1	1749.6	1557.1	1512.3	1780.9	-17.67	1729.6	-18.02
	-8462.2	-571.07	-14.58	-13.46	-10.11	-16.17	1743.1	1688.6	2233.8	1785.3	1643.2	1541.6	1881.1	-16.99	1825.7	-17.86
	-8377.9	-567.33	-14.42	-17.19	-9.78	-7.24	1734.5	1668	2208.3	1780.5	1637.1	1523.3	1871.1	-16.99	1821.8	-18.35
	-8313.2	-567.72	-14.58	-17.04	-10.94	-14.17	1714.8	1654.6	2182.7	1766.2	1616.6	1513.7	1847.6	-18.18	1797	-19.81
	-8307.5	-567.37	-14.9	-14.05	-12.43	-15.1	1725.5	1639.5	2193.7	1771.8	1625.8	1508.5	1858	-17.5	1804.1	-19

E. N₂ INDIVIDUAL FLOW METER ASSESSMENT DATA

1. N₂ Temperature Data for All 4 Flow Meters

Timestamp	N1	ND	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tdata_20201116_152	51000	6000	294.6	294.57	295.73	295.37	295.66	296.79	296.74	297.26	297.2	2566	2566	2566	297.55	297.45	297.24
Tdata_20201116_153	51000	6000	294.62	294.59	295.74	295.38	295.69	296.76	296.73	297.17	297.15	2566.1	2566.1	2566.1	297.48	297.39	297.17
Tdata_20201116_153	51000	6000	294.64	294.6	295.73	295.39	295.72	296.67	296.67	297.07	297.04	2566.1	2566.1	2566.1	297.34	297.25	297.05
Tdata_20201116_153	51000	6000	294.68	294.65	295.73	295.43	295.75	296.61	296.61	296.99	296.95	2566.3	2566.3	2566.3	297.19	297.13	296.95
Tdata_20201116_153	51000	6000	294.69	294.66	295.72	295.43	295.76	296.61	296.6	296.98	296.95	2566.4	2566.4	2566.4	297.19	297.13	296.96
Tdata_20201116_154	51000	6000	294.71	294.67	295.69	295.43	295.77	296.52	296.53	296.86	296.82	2566.4	2566.4	2566.4	296.96	296.97	296.8
Tdata_20201116_154	51000	6000	294.72	294.69	295.66	295.41	295.77	296.44	296.46	296.78	296.74	2566.5	2566.5	2566.5	296.91	296.89	296.72
Tdata_20201116_154	51000	6000	294.74	294.71	295.62	295.39	295.78	296.35	296.38	296.68	296.65	2566.6	2566.6	2566.6	296.84	296.79	296.63
Tdata_20201116_155	51000	6000	294.76	294.73	295.57	295.38	295.78	296.24	296.27	296.55	296.51	2566.7	2566.7	2566.7	296.72	296.65	296.48
Tdata_20201116_160	51000	6000	294.8	294.77	295.5	295.36	295.78	296.09	296.11	296.35	296.32	2566.8	2566.8	2566.8	296.44	296.42	296.27
Tdata_20201116_160	51000	6000	294.8	294.77	295.46	295.34	295.78	296.03	296.06	296.29	296.26	2566.8	2566.8	2566.8	296.39	296.36	296.22
Tdata_20201116_160	51000	6000	294.8	294.77	295.43	295.32	295.76	295.97	296	296.22	296.19	2566.9	2566.9	2566.9	296.31	296.28	296.14
Tdata_20201116_160	51000	6000	294.8	294.76	295.38	295.29	295.75	295.89	295.93	296.13	296.1	2566.9	2566.9	2566.9	296.24	296.2	296.06
Tdata_20201116_161	51000	6000	294.8	294.76	295.33	295.26	295.73	295.8	295.85	296.02	295.99	2566.9	2566.9	2566.9	296.13	296.09	295.94
Tdata_20201116_161	51000	6000	294.8	294.76	295.29	295.23	295.71	295.57	295.66	295.71	295.66	2566.9	2566.9	2566.9	295.73	295.74	295.6
Tdata_20201116_161	51000	6000	294.8	294.77	295.22	295.18	295.69	295.41	295.51	295.51	295.46	2566.9	2566.9	2566.9	295.45	295.51	295.39
Tdata_20201116_161	51000	6000	294.78	294.75	295.15	295.12	295.65	295.25	295.36	295.31	295.26	2566.9	2566.9	2566.9	295.15	295.29	295.18
Tdata_20201116_161	51000	6000	294.78	294.75	295.07	295.04	295.61	295.1	295.2	295.14	295.1	2567	2567	2567	295.04	295.1	295.01
Tdata_20201116_162	51000	6000	294.75	294.73	294.95	294.94	295.52	294.82	294.94	294.82	294.77	2567	2567	2567	294.68	294.74	294.68
Tdata_20201116_162	51000	6000	294.73	294.71	294.89	294.9	295.48	294.71	294.84	294.7	294.64	2566.9	2566.9	2566.9	294.55	294.61	294.53
Tdata_20201116_162	51000	6000	294.72	294.7	294.82	294.85	295.44	294.57	294.71	294.52	294.47	2566.9	2566.9	2566.9	294.26	294.42	294.35
Tdata_20201116_163	51000	6000	294.7	294.68	294.73	294.78	295.38	294.46	294.59	294.43	294.38	2566.9	2566.9	2566.9	294.24	294.32	294.27
Tdata_20201116_163	51000	6000	294.68	294.67	294.68	294.74	295.34	294.4	294.53	294.37	294.32	2566.9	2566.9	2566.9	294.22	294.27	294.2
Tdata_20201116_163	51000	6000	294.66	294.65	294.63	294.69	295.29	294.3	294.43	294.24	294.19	2566.8	2566.8	2566.8	294.07	294.14	294.08
Tdata_20201116_163	51000	6000	294.63	294.61	294.56	294.61	295.22	294.11	294.26	294.01	293.95	2566.8	2566.8	2566.8	293.8	293.88	293.83
Tdata_20201116_164	51000	6000	294.6	294.59	294.49	294.53	295.17	293.96	294.12	293.84	293.78	2566.8	2566.8	2566.8	293.61	293.7	293.64
Tdata_20201116_164	51000	6000	294.57	294.57	294.43	294.47	295.12	293.84	294	293.68	293.63	2566.7	2566.7	2566.7	293.39	293.53	293.48

16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
295.64	295.82	295.83	295.71	297.07	297.18	297.2	297.25	2567.5	2567.5	2567.5	2567.5	2567.5	2567.5	2567.5
295.75	295.97	295.97	295.22	297.2	297.26	297.39	297.27	2567.5	2567.6	2567.6	2567.6	2567.6	2567.6	2567.6
295.62	295.83	295.82	295.01	297.14	297.21	297.35	297.08	2567.6	2567.6	2567.6	2567.6	2567.6	2567.6	2567.6
295.78	295.97	296	295.07	297.41	297.4	297.58	297.21	2567.6	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7
295.8	295.99	296.01	294.68	297	297.07	297.29	296.9	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7
295.84	296.02	296.05	294.5	296.87	296.96	297.19	296.72	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7
296.27	296.5	296.51	294.36	296.95	297.05	297.32	296.66	2567.7	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8
295.66	295.86	295.87	294.12	296.91	296.97	297.27	296.54	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8
295.51	295.66	295.7	294.04	296.91	296.94	297.25	296.48	2567.8	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9
294.64	294.74	294.76	294.35	296.18	296.25	296.36	296.28	2568	2568	2568	2568	2568	2568	2568
295.54	295.69	295.69	294.04	296.09	296.15	296.26	295.87	2568	2568	2568	2568	2568	2568	2568
295.71	295.89	295.88	293.8	296.03	296.09	296.2	295.68	2568	2568	2568	2568	2568	2568	2568
295.92	296.11	296.1	293.61	296.11	296.17	296.31	295.52	2568	2568	2568	2568	2568	2568	2568
295.71	295.95	295.95	293.32	295.84	295.94	296.09	295.17	2568	2568	2568	2568	2568	2568	2568
295.83	296.05	296.08	293.19	295.58	295.73	295.89	294.81	2568	2568	2568	2568	2568	2568	2568
296.08	296.33	296.32	293.07	295.52	295.67	295.89	294.63	2568	2568	2568	2568	2568	2568	2568
296.03	296.28	296.32	292.61	295.05	295.23	295.46	294.25	2568	2568	2568	2568	2568	2568	2568
296.04	296.29	296.35	292.13	294.75	294.96	295.2	293.89	2568	2568	2568	2568	2568	2568	2568
294.29	294.43	294.41	292.47	294.67	294.74	294.94	294.03	2568	2568	2568	2568	2568	2568	2568
295.37	295.49	295.51	292.43	294.59	294.67	294.86	293.93	2567.9	2568	2568	2568	2568	2568	2568
295.52	295.68	295.68	292.36	294.51	294.56	294.75	293.82	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9
295.52	295.68	295.64	292.31	294.47	294.45	294.65	293.63	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9
295.56	295.8	295.7	292.11	294.19	294.24	294.43	293.35	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9	2567.9
295.59	295.84	295.8	292.03	294.05	294.12	294.31	293.14	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8
294.99	295.18	295.08	292.03	294.1	294.09	294.29	293	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8
295.28	295.39	295.29	291.88	293.98	293.95	294.19	292.8	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8	2567.8
295.25	295.34	295.24	291.82	293.89	293.84	294.08	292.68	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7	2567.7

2. N₂ Pressure Data for All Four Flow Meters

Atmospheric Pressure:			30																	
Timestamp	N1	ND	1_01	1_02	1_03	1_04	1_05	1_06	1_07	1_08	1_09	1_10	1_11	1_12	1_13	1_14	1_15	1_16		
PData_20201116_1528_01	51000	6000	-0.2	-0.24	-0.31	-0.03	-0.15	-0.1	-0.33	-0.12	-0.17	0.06	-0.15	-0.2	-0.2	-0.34	-0.32	-0.35		
PData_20201116_1530_38	51000	6000	-0.23	-0.15	-0.23	-0.03	-0.15	0.02	-0.31	-0.24	-0.08	-0.02	-0.1	-0.18	-0.31	-0.42	-0.18	-0.22		
PData_20201116_1532_60	51000	6000	-0.08	-0.15	-0.11	0.05	-0.03	-0.02	-0.2	-0.12	0	0.19	0	-0.07	-0.06	-0.19	-0.03	-0.3		
PData_20201116_1537_12	51000	6000	-0.12	-0.21	-0.27	-0.1	-0.18	-0.08	-0.2	0	-0.12	0.15	-0.08	-0.07	-0.18	-0.29	-0.24	-0.15		
PData_20201116_1539_12	51000	6000	-0.08	-0.07	0.05	-0.2	-0.09	-0.03	-0.16	0.1	-0.02	0.18	-0.05	-0.11	-0.15	-0.26	-0.15	-0.15		
PData_20201116_1540_58	51000	6000	-0.37	-0.37	-0.39	-0.02	-0.38	-0.07	-0.36	-0.19	-0.27	0.02	-0.23	-0.33	-0.4	-0.51	-0.42	-0.63		
PData_20201116_1542_59	51000	6000	-0.22	-0.21	0.16	-0.1	-0.14	0.15	-0.23	-0.19	-0.07	0.11	-0.18	-0.16	-0.29	-0.37	-0.3	-0.43		
PData_20201116_1545_57	51000	6000	-0.23	-0.16	0.1	-0.1	-0.23	0.03	-0.21	-0.03	-0.05	0.11	-0.12	-0.21	-0.2	-0.3	-0.2	-0.33		
PData_20201116_1550_08	51000	6000	-0.2	-0.16	-0.23	-0.26	-0.11	-0.33	-0.31	-0.02	-0.27	0.13	-0.21	-0.13	-0.35	-0.27	-0.29	-0.45		
PData_20201116_1602_40	51000	6000	-0.23	-0.26	-0.26	-0.15	-0.11	-0.15	-0.15	0.02	-0.08	0.13	-0.07	-0.2	-0.29	-0.27	-0.25	-0.48		
PData_20201116_1604_52	51000	6000	-0.28	-0.29	-0.29	-0.23	-0.29	-0.2	-0.21	0	-0.12	-0.05	0	-0.29	-0.35	-0.34	-0.29	-0.43		
PData_20201116_1606_48	51000	6000	-0.23	-0.16	-0.18	-0.02	-0.02	-0.11	-0.21	-0.05	-0.25	0.08	-0.21	-0.28	-0.32	-0.37	-0.25	-0.43		
PData_20201116_1609_01	51000	6000	-0.25	-0.21	-0.34	0.1	-0.12	0.07	-0.18	0	-0.13	0.05	-0.12	-0.28	-0.26	-0.32	-0.29	-0.53		
PData_20201116_1611_07	51000	6000	-0.26	-0.26	-0.02	-0.13	-0.09	-0.03	-0.26	-0.05	-0.1	0.02	-0.08	-0.29	-0.37	-0.37	-0.27	-0.35		
PData_20201116_1613_13	51000	6000	-0.2	-0.11	0.13	-0.02	-0.08	-0.2	-0.1	0.13	-0.07	0.18	-0.03	-0.15	-0.22	-0.26	-0.12	-0.38		
PData_20201116_1615_16	51000	6000	-0.26	-0.15	-0.15	0.26	-0.17	0.05	-0.11	0.08	-0.05	0.29	-0.13	0	-0.2	-0.14	-0.08	-0.33		
PData_20201116_1617_10	51000	6000	-0.08	-0.1	0.05	-0.31	0.02	0.02	-0.1	0.1	-0.05	0.34	0	-0.03	-0.09	-0.29	-0.12	-0.5		
PData_20201116_1619_39	51000	6000	-0.19	-0.08	-0.31	-0.54	0.37	-0.55	-0.03	0.22	0.05	0.31	0.05	-0.07	-0.09	-0.4	-0.05	-0.3		
PData_20201116_1624_37	51000	6000	-0.25	-0.15	-0.02	0.1	-0.06	-0.05	0	0.3	-0.05	0.26	0.03	-0.11	-0.14	-0.29	-0.05	-0.32		
PData_20201116_1626_34	51000	6000	-0.25	-0.11	0	0.07	-0.06	-0.02	0.08	0.25	-0.03	0.32	-0.03	-0.15	-0.26	-0.27	-0.13	-0.42		
PData_20201116_1628_27	51000	6000	-0.23	-0.07	-0.1	-0.05	-0.09	-0.02	0.02	0.25	-0.02	0.29	0.03	-0.03	-0.34	-0.27	-0.1	-0.48		
PData_20201116_1630_54	51000	6000	-0.31	0	-0.1	0.08	0	0.08	-0.02	0.15	-0.02	0.26	-0.08	-0.02	-0.18	-0.22	-0.07	-0.38		
PData_20201116_1632_56	51000	6000	-0.26	0.08	-0.03	-0.07	-0.03	0.15	-0.02	0.29	0.05	0.36	-0.02	0.05	-0.22	-0.21	0.07	-0.28		
PData_20201116_1635_05	51000	6000	-0.28	0.02	-0.15	0.1	-0.05	0.05	-0.02	0.27	-0.03	0.26	-0.13	-0.11	-0.22	-0.26	-0.03	-0.28		
PData_20201116_1638_14	51000	6000	-0.3	-0.1	-0.16	0	-0.11	-0.13	0.11	0.27	0.05	0.4	-0.16	0.02	-0.18	-0.11	-0.05	-0.42		
PData_20201116_1640_25	51000	6000	-0.25	-0.15	0.02	0	0.11	0.1	0.15	0.29	0.13	0.39	-0.08	0.23	-0.08	-0.11	0.02	-0.15		
PData_20201116_1642_07	51000	6000	-0.3	-0.02	-0.08	-0.13	-0.14	0.18	0.13	0.24	0.07	0.32	-0.16	-0.05	-0.22	-0.21	-0.02	-0.2		

	2 01	2 02	2 03	2 04	2 05	2 06	2 07	2 08	2 09	2 10	2 11	2 12	2 13	2 14	2 15	2 16
	0.68	-0.34	0.65	-0.6	0.5	0.15	-0.31	-0.49	0	2.07	-1.89	-0.94	0.3	0.85	-2.22	0.32
	0.68	-0.68	0.32	-0.45	0.17	-0.77	-0.47	-1.15	0	1.27	-0.95	-0.31	-0.15	1.18	-2.07	-0.16
	0.41	-0.34	0.49	-0.3	0.99	-0.15	-1.24	-0.49	0.48	1.91	-1.08	-0.16	0.3	1.02	-1.78	0
	0.68	-0.68	0.97	-0.6	1.16	-0.62	-0.62	-0.82	0.63	1.91	-1.62	0.16	0	1.52	-2.52	0.16
	0.41	-0.17	0.97	-0.9	0.66	-0.62	-0.62	-0.49	0.48	1.43	-1.49	0.31	0.15	1.69	-1.63	-0.32
	-0.14	-0.68	0.48	-1.35	0.17	-0.62	-0.47	-0.49	0.48	1.59	-1.35	0	0	1.18	-1.48	-0.32
	0.27	-0.51	0.65	-0.9	0.5	-0.92	-0.78	-1.64	0.48	1.91	-2.16	-0.16	0	1.19	-1.78	0
	0.27	-1.19	0.16	-0.6	0	-0.62	-0.62	-0.99	0.16	1.59	-1.49	-0.16	0.44	1.52	-1.93	-0.16
	0.41	-0.68	0.81	-0.75	0.33	-1.39	-0.78	-1.15	0.16	0.96	-1.49	0.31	-0.15	1.69	-1.93	0.16
	0.41	-1.36	0.16	-1.34	-0.17	-0.46	-0.31	-1.31	0.47	0.96	-1.35	0.16	-0.3	1.86	-1.63	0.16
	0.41	-1.7	-0.16	-1.49	0.33	-0.62	-0.31	-1.31	0.79	0.8	-1.62	0.78	-0.74	1.35	-1.78	0.32
	-0.41	-1.7	-0.16	-1.79	-0.33	-0.62	-0.93	-1.31	0	0.64	-1.76	0.16	-1.19	1.18	-1.93	0.48
	-0.27	-1.19	-0.16	-1.49	-0.17	-0.46	-0.62	-0.99	1.11	0.48	-1.35	0.78	-0.3	1.86	-1.63	0.32
	-0.14	-1.53	-0.32	-1.64	-0.33	-0.77	0	-1.15	0.32	1.59	-1.35	-0.16	-0.6	1.35	-1.63	0.49
	0.27	-1.53	0.16	-1.34	-0.17	-0.77	0	-1.31	0	1.59	-1.35	-0.16	-0.6	1.86	-1.19	0.32
	0.27	-1.53	0.16	-1.49	-0.66	-0.31	0	-0.66	0.63	1.27	-1.35	0.78	-0.74	2.37	-1.63	0.32
	0.41	-0.85	-0.32	-1.49	0.17	-0.46	0.16	-0.99	0.16	1.91	-1.76	-0.16	-0.15	1.52	-1.63	0.32
	0.41	-1.19	0.32	-1.49	0.66	-0.92	-0.31	-0.49	1.11	0.96	-1.76	1.41	0	1.35	-1.78	0.81
	0.14	-1.19	-0.49	-0.9	0	-0.77	-0.47	-0.82	0.32	0.64	-1.89	0.31	0	0.85	-2.52	0
	0.27	-1.53	0	-0.6	-0.17	-1.08	-0.78	-1.64	0.32	2.23	-1.62	0.16	-0.3	0.68	-2.22	-0.49
	0.41	-0.34	0.65	-1.49	0.83	-0.62	-0.62	-1.48	0.48	2.23	-2.03	-0.16	0.15	0.85	-2.52	-0.49
	0.27	-0.17	0.16	-0.9	-0.17	-0.77	-1.09	-0.66	0.32	2.07	-1.49	0	0	0.68	-3.11	-0.65
	0.14	-1.02	-0.16	-0.75	0.33	-0.62	-1.09	-0.49	0.32	1.43	-1.89	0	-0.15	0.34	-2.52	-0.16
	0.27	-1.02	-0.16	-1.2	0.17	-0.15	-0.78	-0.82	0.16	1.59	-1.62	-0.47	-0.15	0.34	-2.67	-0.33
	-0.14	-1.36	-0.49	-1.49	-0.5	-0.31	-0.93	-0.99	0	1.11	-1.35	-0.79	-0.3	0.34	-2.52	-0.33
	0.27	-1.02	-0.32	-1.94	0	0	-0.31	-1.48	-0.32	1.59	-1.35	-0.94	0.15	0.68	-2.07	-0.49
	-0.14	-1.7	-0.49	-1.49	-0.33	-1.08	-0.47	-1.48	-0.48	0.96	-1.62	-0.47	-0.74	0.85	-1.78	0

3_01	3_02	3_03	3_04	HX IN		HX OUT		3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
				3_05	3_06	3_06	3_07										
-22.67	-11.67	-11.44	0.01	64007	47404	11.5	-22.69	-11.54	-22.2	15.68	0.01	50365	46901	46854	46730		
15.13	19.48	-15.26	-23.03	321110	293628	0.01	3.79	34.67	18.54	15.69	-18.34	297896	293621	293660	293421		
-18.9	27.26	19.11	15.39	319277	290919	-7.65	-30.26	0.02	29.65	43.1	11.03	295252	290906	290911	290673		
-22.67	-3.88	11.46	11.53	436636	407297	7.68	-34.04	-11.54	-3.69	11.79	7.35	412935	407248	407252	406954		
3.79	0.01	-30.53	-23.03	451989	423522	34.5	-3.77	11.57	-7.39	-11.69	-29.34	428905	423499	423520	423242		
15.15	-58.33	-91.61	-95.95	452158	423228	99.69	41.65	30.86	-62.88	-101.54	-80.68	428601	423223	423272	422978		
3.81	74	61.12	19.26	609796	580167	-30.63	-34.02	19.31	74.13	78.42	22.07	586756	580213	580205	579917		
-7.54	19.5	7.67	7.72	598065	569329	11.53	-22.69	-3.82	14.87	19.72	0.03	576046	569333	569340	569044		
136.11	183	95.48	-65.22	597398	568662	-11.46	45.45	154.1	192.7	94.08	-58.65	575419	568681	568739	568518		
-3.77	7.8	15.27	-11.51	152039	95276	42.17	-15.12	19.27	11.14	3.96	-11	116792	95299	95293	95152		
45.4	120.72	99.28	3.91	147589	96045	-19.12	-26.44	50.11	126.02	98.04	11.07	117516	96110	96100	96024		
-3.76	-27.23	-7.63	-26.87	148302	95082	61.33	-3.77	19.27	-7.38	-19.52	-36.68	116448	95142	95110	94985		
-11.32	-7.77	0.01	-23.02	231109	165200	49.85	-3.77	3.87	-7.38	-11.68	-18.33	193893	165241	165230	165038		
-41.55	-23.34	15.28	3.88	230045	167358	34.51	-30.25	-23.08	-22.19	11.82	0.03	195848	167440	167406	167212		
-18.89	11.69	34.36	3.85	228242	165736	26.84	-22.69	3.86	11.14	19.61	3.68	194240	165810	165793	165621		
-7.55	-11.67	15.27	-15.35	310337	235917	49.83	-3.77	7.72	0.02	0.02	-11	271049	235966	235990	235785		
-15.11	3.9	38.18	7.69	306917	237531	26.83	-30.26	-3.85	14.83	23.53	7.35	272476	237601	237603	237386		
-68.02	-42.8	38.18	53.8	305635	237504	30.67	-49.17	-65.44	-44.41	31.35	44.06	272421	237564	237541	237310		
-11.33	23.37	30.55	19.22	95245	26588	-3.82	-34.04	-3.84	29.64	43.09	14.69	62242	26620	26631	26563		
11.35	19.47	7.66	-11.5	94276	26301	3.85	-7.56	23.12	25.94	23.53	-14.66	61581	26329	26344	26287		
0	38.94	22.92	3.85	94187	26231	-22.98	-18.91	15.42	25.94	43.09	11.02	61484	26233	26266	26233		
3.78	0.01	-11.44	-7.68	141410	48395	3.84	-15.13	3.86	-14.8	3.95	-14.67	101037	48409	48446	48357		
-3.78	-46.7	-72.5	-46.06	135628	48256	46.01	15.15	11.56	-44.41	-54.72	-44.02	100647	48263	48302	48212		
-11.34	3.9	-11.45	-7.67	135781	48093	3.83	-7.56	-11.54	3.71	11.75	-7.33	100481	48101	48151	48083		
0	11.69	-7.63	0.01	184650	74657	0.01	0	-15.39	-7.39	15.68	-7.33	143152	74705	74736	74669		
-11.34	3.9	-15.26	0.01	184022	74506	0.01	-18.91	-23.09	-14.81	7.85	-11	142948	74550	74577	74521		
-11.34	15.58	-3.81	11.54	185459	75364	-3.82	-15.13	-38.48	-11.09	19.6	0.01	144286	75385	75431	75347		

4_01	4_02	4_03	4_04	4_05	4_06	4_07	4_08	4_09	4_10	4_11	4_12	4_13	4_14	4_15	4_16
3.69	0	0	18.45	18.37	-36.94	-3.74	-3.5	-3.57	0	-3.83	14.36	10.66	0	-12809	-10.32
7.37	6.84	0	22.14	29.4	-18.47	-3.74	3.5	-3.57	0	-3.83	21.54	10.66	0	-16342	-10.32
11.06	0	0	22.14	33.07	-14.77	0	0	-7.14	0	3.83	28.73	14.22	0	-18433	-3.44
3.69	3.42	-3.79	22.14	33.07	-11.08	-3.74	0	0	0	0	32.32	17.77	-3.75	-32736	-27.51
11.06	3.42	0	29.52	25.72	-22.16	0	3.5	0	0	7.67	25.14	21.33	0	-5390.1	-13.76
11.06	3.42	0	18.45	25.72	-22.16	7.47	7	-7.14	0	7.67	21.55	21.33	0	-6704.6	-20.63
3.69	3.42	3.79	18.45	33.07	-11.08	0	7	-7.14	0	0	28.73	21.33	0	-8879.7	-6.88
11.06	10.26	0	33.21	33.07	-18.47	0	0	0	3.63	7.67	28.73	24.88	7.51	-3848.5	0
0	3.42	3.79	18.45	29.4	-14.77	0	10.49	-7.14	7.25	0	32.32	21.33	7.51	-23373	-13.76
7.37	6.84	0	18.45	25.72	-22.16	0	0	0	0	42.16	61.03	21.33	15.01	-30759	-6.88
11.06	-3.42	3.79	11.07	29.4	-18.47	0	3.5	0	0	42.16	50.26	17.77	37.52	-29693	-10.32
11.06	6.84	3.79	7.38	11.02	-22.16	-3.74	7	28.57	7.25	38.33	50.26	46.2	45.03	-26584	-6.88
18.43	3.42	11.38	29.52	29.4	-14.77	0	7	32.14	0	38.33	53.85	56.85	41.27	-36764	-6.88
3.69	0	3.79	14.76	11.02	-25.85	0	0	32.14	36.26	45.99	50.26	49.75	41.27	-36808	-3.44
18.43	10.26	3.79	33.21	33.07	-18.47	-3.74	3.5	35.71	36.26	38.33	57.44	46.19	37.52	-32304	30.93
7.37	0	0	25.83	29.4	-25.85	-3.74	7	35.71	43.51	38.33	61.03	63.96	37.52	-30422	24.06
11.06	10.26	3.79	18.45	18.37	-22.16	0	0	35.71	39.88	45.99	57.44	56.85	41.27	-34860	27.49
18.43	3.42	11.38	22.14	25.72	-18.47	-3.74	10.49	35.71	36.26	38.33	64.61	49.75	33.77	-35991	24.06
7.37	3.42	15.18	7.38	25.72	-25.85	0	0	35.71	39.88	49.83	50.26	53.3	48.78	-27738	24.06
7.37	3.42	18.97	29.52	22.05	-29.55	-7.48	7	39.28	39.88	45.99	43.08	53.3	41.27	-35424	24.06
14.74	3.42	3.79	22.14	18.37	-18.47	-7.48	7	32.14	39.88	45.99	46.67	46.19	41.27	-35614	27.49
11.06	0	11.38	7.38	25.72	-14.77	-7.48	0	21.43	43.51	45.99	53.85	46.19	45.03	-38547	20.62
14.74	3.42	7.59	29.52	22.05	-18.47	-11.22	3.5	32.14	54.38	45.99	43.08	42.64	41.27	-37774	24.06
14.74	0	11.38	33.21	25.72	-22.16	-7.48	0	28.57	39.88	42.16	50.26	46.19	41.27	-44501	24.06
11.06	6.84	18.97	22.14	11.02	-36.94	0	7	28.57	36.26	38.33	61.03	60.41	41.27	-45665	24.06
18.43	3.42	11.38	14.76	29.4	-18.47	0	0	32.14	36.26	38.33	50.26	49.75	41.27	-43267	17.18
7.37	0	3.79	18.45	18.37	-29.55	-3.74	3.5	32.14	36.26	42.16	53.85	46.19	37.52	-42158	24.06

LIST OF REFERENCES

- [1] H. L. Greenley, "Department of Defense Energy Management Background and Issues for Congress," Congressional Research Service, Washington, DC, 2019.
- [2] Department of the Navy, "Marines," October 2010. [Online]. Available: <https://www.hqmc.marines.mil/Portals/160/Docs/Navy-Energy-Vision-Oct-2010.pdf>. [Accessed August 2020].
- [3] P. Mark S. Spector, "Advanced Research Projects Agency-Energy (ARPA-E)," 19 October 2017. [Online]. Available: <https://arpa-e.energy.gov/sites/default/files/2d%20-%20Spector%20%28final%29.pdf>. [Accessed September 2020].
- [4] PAL-CON, Ltd, *Gas Turbine Recuperator Heat Exchanger (Regenerative Cycle)*, Stephenville, Texas: PAL-CON, 2011.
- [5] R. S. Carleton and E. P. Weinert, "The American Society of Mechanical Engineers" 4 June 1989. [Online]. Available: https://watermark.silverchair.com/v002t03a006-89-gt-230.pdf?token=AQECAHi208BE49Ooan9kkhW_Ercy7Dm3ZL_9Cf3qfKAc485ysgAAAYwggPiBgkqhkiG9w0BBwagggPTMIIDzwIBADCCA8gGCSqGSIb3DQEHATAeBglghkgBZQMEAS4wEQQMTb0Wv7CzYVVgHgVEAgEQgIIDmZSygqdfJNWOQdbZhMnfYNLRB9GhzWkm2. [Accessed August 2020].
- [6] M. Kaim, "waste heat recovery from a Gas Turbine Engine Using a Heat Exchanger and Associated Centrifugal Compressor Volure Design and Simulation," Naval Postgraduate School , Monterey, California, 2019.
- [7] C. Buck, "Waste Heat Recovery System For a Gas Turbine Engine and Carbon Dioxide Compression," Naval Postgraduate School, Monterey, CA, 2018.
- [8] S. J. Polsinelli, "Waste Heat Recovery Carbon Dioxide Heat Exchanger For Gas Turbine Engines," Naval Postgraduate School, Monterey, California, 2018.
- [9] Energy Efficient Singapore, "Energy Efficient Singapore," [Online]. Available: https://www.e2singapore.gov.sg/DATA/0/docs/NewsFiles/More%20power%20with%20Organic%20Rankine%20Cycle_v3.pdf. [Accessed August 2020].
- [10] A. Singh, "Slidehare," 15 January 2014. [Online]. Available: <https://www.slideshare.net/shorokhaibam/organic-rankine-cycle-macro-power-plant>. [Accessed August 2020].
- [11] World Cement, "World Cement," World Cement, 1 August 2013. [Online]. Available: https://www.worldcement.com/europe-cis/01082013/whr_cement_industry_organic_rankine_cycle_77/. [Accessed September 2020].

- [12] J. Grace, W. Abrams and M. Mastergeorge, "TS Golden Bear Demonstration of the Thermal Energy Harvesting and Conversion System," Naval Surface Warfare Center Carderock, Bethesda, Maryland, 2019.
- [13] Navy BMR, "Navy BMR," Department of the Navy, [Online]. Available: https://www.navybmr.com/study%20material/14265a/14265A_ch12.pdf%20%5b5. [Accessed September 2020].
- [14] S. Patel, "Power," Power, 1 April 2019. [Online]. Available: <https://www.powermag.com/what-are-supercritical-co2-power-cycles/>. [Accessed September 2020].
- [15] T. D. Belna, "Upgrade Transonic Compressor Test Rig Data Acquisition System," Naval Postgraduate School, Monterey, CA, 2018.
- [16] Perle, "IOLAN SDS Rack Terminal Servers," Perle, 2021. [Online]. Available: <https://www.perle.com/products/iolan-sds-rack-terminal-server.shtml>. [Accessed 15 February 2021].
- [17] P. Garth Hobson, *Marine Propulsion Gas Turbine Lab*, Monterey, California: Naval Postgraduate School, 2016.
- [18] T. L. Bergman, A. S. Lavine, F. P. Incropera and D. P. Dewitt, *Fundamentals of Heat and Mass Transfer Seventh Edition*, Hoboken, NJ: John Wiley and Sons, 2011.
- [19] B. R. Munson, T. H. Okiis, W. W. Huebsch and A. P. Rothmayer, *Fundamentals of Fluid Mechanics*, 7th Edition, Madison Park, Kentucky: John Wiley & Sons, Inc, 2013.
- [20] TEGpro, *TE-MOD-22W7V-56*, Randolph, Vermont: TEGpro, 2104.
- [21] S. H. Price, "The Physics of Cooling Techniques," Physics 212 Web Project, 26 March 2007. [Online]. Available: http://ffden-2.phys.uaf.edu/212_spring2007.web.dir/sedona_price/phys_212_webproj_home.html. [Accessed 28 January 2021].
- [22] Survival-Manual, "Peltier Elements Make Heat Cold Or Electricity," Survival Manual, 2014. [Online]. Available: <https://www.survival-manual.com/electricity/peltier-elements.php>. [Accessed 28 January 2021].
- [23] Advanced Thermoelectric, "How a Thermoelectric Cooler Works," Pollock Industries, Inc., 2021. [Online]. Available: <https://www.electracool.com/moduleworking.htm>. [Accessed 28 January 2021].

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California