



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**IMPLEMENTATION OF AN INDUSTRIAL CONTROL
SYSTEM FOR THE GENERATION, COMPRESSION, AND
STORAGE OF HYDROGEN FROM RENEWABLE SOURCES**

by

Joshua D. Lewis

June 2021

Thesis Advisor:
Co-Advisor:

Anthony J. Gannon
Walter Smith

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 June 2021	3. REPORT TYPE AND DATES COVERED Master's thesis	
4. TITLE AND SUBTITLE IMPLEMENTATION OF AN INDUSTRIAL CONTROL SYSTEM FOR THE GENERATION, COMPRESSION, AND STORAGE OF HYDROGEN FROM RENEWABLE SOURCES			5. FUNDING NUMBERS RMNPB	
6. AUTHOR(S) Joshua D. Lewis				
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) Office of Naval Research One Liberty Center 875 N. Randolph Street, Suite 1425 Arlington, VA 22203-1995			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) This thesis implemented a control system to integrate the generation and compression of hydrogen gas to enable its production from renewable sources at remote locations. To mimic renewable power commercial-off-the-shelf power supplies were used to power the system. For the control system, programmable logic controllers were used to monitor and operate the overall system's various components. The harvesting of water from the atmosphere, via Peltier dehumidifiers, was found to be intermittent and is the limiting factor for hydrogen yield in the existing system. Hydrogen gas was generated by an electrolyzer at an average mass flow rate of 5.52×10^{-7} kg/s. The membrane dehumidifier installed to dry the saturated hydrogen gas was found to be ineffective. An electrochemical hydrogen compressor was used to compress hydrogen gas to the steady state maximum outlet pressure of 7492 kPa at an average mass flow rate of 4.3773×10^{-10} kg/s. This research demonstrated it is possible to autonomously produce compressed hydrogen gas from renewable sources. Additionally, improvements have been identified for implementation in future system designs.				
14. SUBJECT TERMS hydrogen, hydrogen generation, hydrogen storage, hydrogen compression, EHC compressor, renewable energy, energy security, energy resiliency, PLC, industrial control			15. NUMBER OF PAGES 177	
			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.

**IMPLEMENTATION OF AN INDUSTRIAL CONTROL SYSTEM FOR THE
GENERATION, COMPRESSION, AND STORAGE OF HYDROGEN
FROM RENEWABLE SOURCES**

Joshua D. Lewis
Lieutenant, United States Navy
BS, North Carolina State University, 2011

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

**NAVAL POSTGRADUATE SCHOOL
June 2021**

Approved by: Anthony J. Gannon
Advisor

Walter Smith
Co-Advisor

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

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This thesis implemented a control system to integrate the generation and compression of hydrogen gas to enable its production from renewable sources at remote locations. To mimic renewable power commercial-off-the-shelf power supplies were used to power the system. For the control system, programmable logic controllers were used to monitor and operate the overall system's various components. The harvesting of water from the atmosphere, via Peltier dehumidifiers, was found to be intermittent and is the limiting factor for hydrogen yield in the existing system. Hydrogen gas was generated by an electrolyzer at an average mass flow rate of $5.52\text{e-}7$ kg/s. The membrane dehumidifier installed to dry the saturated hydrogen gas was found to be ineffective. An electrochemical hydrogen compressor was used to compress hydrogen gas to the steady state maximum outlet pressure of 7492 kPa at an average mass flow rate of $4.3773\text{e-}10$ kg/s. This research demonstrated it is possible to autonomously produce compressed hydrogen gas from renewable sources. Additionally, improvements have been identified for implementation in future system designs.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	MOTIVATION	1
B.	HYDROGEN AS A MEANS TO ENERGY STORAGE.	2
C.	APPLICATIONS	8
D.	RESEARCH OVERVIEW.....	9
1.	Objective	9
2.	Outline.....	10
II.	SYSTEM OVERVIEW	13
A.	PHYSICAL COMPONENTS	16
B.	CONTROL COMPONENTS.....	22
C.	SENSOR COMPONENTS.....	27
1.	Electrical Sensors	27
2.	Physical Sensors	29
D.	SYSTEM OPERATION	31
1.	Safety Considerations	31
2.	Control Strategy.....	35
III.	SYSTEM PERFORMANCE	39
A.	WATER PRODUCTION	39
B.	HYDROGEN GAS PRODUCTION	40
C.	DRYER PERFORMANCE.....	43
D.	COMPRESSOR PERFORMANCE.....	49
IV.	DISCUSSION	57
A.	HANDLING OF SATURATED HYDROGEN GAS.....	57
B.	WATER GENERATION	59
C.	SIZING OF COMPONENTS	60
D.	ELECTRICAL STABILITY	61
E.	SYSTEM ISOLATION AND ADDITIONAL SAFETY	62
F.	IMPROVED SENSORS	63
G.	SUPPLY CHAIN MANAGEMENT	64
H.	SECURITY	64
V.	CONCLUSION	65
VI.	RECOMMENDATIONS.....	67

APPENDIX A. MICRO 850 CONTROLLER LAYOUT	69
A. GENERATION	69
B. COMPRESSION AND STORAGE.....	70
APPENDIX B. WATER REQUIRED TO FILL ONE DOT-3AA2265 CYLINDER WITH HYDROGEN GAS	71
APPENDIX C. GENERATION SIDE PURGING TIME CALCULATIONS.....	73
APPENDIX D. CALCULATIONS FOR THE REQUIRED CROSS- SECTIONAL AREA AND CORRESPONDING DIAMETER FOR RELATIVE HUMIDITY TESTING DEVICE	75
APPENDIX E. RELATIVE HUMIDITY SAMPLE CALCULATION	77
APPENDIX F. REQUIRED PRESSURE FOR DRY HYDROGEN RELATIVE HUMIDITY TEST	81
APPENDIX G. REQUIRED TIME TO FILL ONE DOT-3AA2265 CYLINDER BASED ON COMPRESSOR PERFORMANCE	83
APPENDIX H. VACUUM/PRESSURE PURGING CALCULATIONS	85
APPENDIX I. CALIBRATION CURVE HONEYWELL PRESSURE TRANSDUCER, MLH500PSL01A	87
APPENDIX J. CALIBRATION CURVE HONEYWELL PRESSURE TRANSDUCER, MLH03KPSB01A	89
APPENDIX K. RELATIVE HUMIDITY TESTING DEVICE INSERT DIMENSIONS.....	91
APPENDIX L. PIPING AND IDENTIFICATION (P&ID) DIAGRAM	93
APPENDIX M. HIGH PRESSURE SIDE PURGING PROCEDURE.....	99
APPENDIX N. HYDROGEN SYSTEM START UP PROCEDURE	105
APPENDIX O. CONNECTED COMPONENTS WORKBENCH CODE FOR HYDROGEN GENERATION.....	109
A. MAIN PROGRAM	109

B.	MAIN PROGRAM LOCAL VARIABLES.....	113
C.	USER DEFINED FUNCTION PID_CONTROLLED_VALVE	113
D.	USER-DEFINED FUNCTION PID_CONTROLLED_VALVE LOCAL VARIABLES	114
E.	USER-DEFINED FUNCTION MY_LIMIT	114
F.	USER-DEFINED FUNCTION MY_LIMIT LOCAL VARIABLES	114
G.	USER-DEFINED FUNCTION PID_CONVERTER.....	114
H.	USER-DEFINED FUNCTION PID_CONVERTER LOCAL VARIABLES	115
APPENDIX P. CONNECTED COMPONENTS WORKBENCH CODE FOR HYDROGEN COMPRESSION		117
A.	MAIN PROGRAM	117
B.	MAIN PROGRAM LOCAL VARIABLES.....	120
C.	USER DEFINED FUNCTION IP1.....	120
D.	USER DEFINED FUNCTION IP1 LOCAL VARIABLES	122
E.	USER DEFINED FUNCTION OP2	122
F.	USER DEFINED FUNCTION OP2 LOCAL VARIABLES	123
APPENDIX Q. MATLAB CODE FOR DATA ACQUISITION ON GENERATION SIDE		125
APPENDIX R. MATLAB CODE FOR DATA ACQUISITION ON COMPRESSION SIDE		129
APPENDIX S. MATLAB CODE FOR STOP BUTTON FUNCTION		133
APPENDIX T. MATLAB CODE FOR COMPRESSION DATA ANALYSIS		135
APPENDIX V. XIPERM DEHUMIDIFIER OPERATION MANUAL.....		145
APPENDIX W. X-CELL ELECTROCHEMICAL HYDROGEN COMPRESSOR, XC-HP1500D USER MANUAL		147
LIST OF REFERENCES		151
INITIAL DISTRIBUTION LIST		155

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

Figure 1.	Comparison of Key-Type Energy Storage Technologies in Sense of Storage Capacity and Discharge Power Duration. Source: [8].....	3
Figure 2.	Electrolysis. Source: [11].....	5
Figure 3.	Methods for Hydrogen Storage. Source: [13].....	6
Figure 4.	Overview of Compressed Hydrogen Gas Generation System Powered from Renewable Sources	9
Figure 5.	System Overview	15
Figure 6.	Kikusui PWX1500ML DC Power Supply	16
Figure 7.	GW Instek, GPS 1850D, DC Power Supply.....	17
Figure 8.	Ivation Dehumidifier.....	18
Figure 9.	Electrolyzer	19
Figure 10.	Xergy Membrane Dehumidifier,.....	19
Figure 11.	Marathon Electric Vacuum Pump.....	20
Figure 12.	Xergy Electrochemical Hydrogen Compressor	21
Figure 13.	Operation of an Electrochemical Hydrogen Compressor. Adapted from [25].	22
Figure 14.	Micro 850 Controller, 2080-LC50-24QBB, with Micro 800 Power Supply, 2080-PS120-240VAC.....	23
Figure 15.	2080-IF4 Plug-In Module	24
Figure 16.	2080-OF2 Plug-In Module.....	25
Figure 17.	2085-OF4 Expansion Module.....	25
Figure 18.	2085-IF8 Expansion Module	26
Figure 19.	Phoenix DC Transducer.....	27
Figure 20.	Eaton, EDC2420SP DC Current Sensor	28
Figure 21.	Eaton, EDC1420SC DC Current Sensor.....	28

Figure 22.	Alicat M-5SLPM-D/5M Hydrogen Gas Flow Meter.....	29
Figure 23.	KUS SSS7 Tank Level Indicator	30
Figure 24.	Honeywell Pressure Transducer Model #MLH500PSL01A	30
Figure 25.	Honeywell Pressure Transducer Model #MLH03KPSB01A	31
Figure 26.	Purging Process Depicted on Triangular Composition Diagram for Hydrogen/Oxygen/Nitrogen. Source: [14].....	32
Figure 27.	Swagelok Relief Valve, SS-RL3S4-MO.....	34
Figure 28.	Swagelok PRVN2F-02-2-VV-Q Relief Valve.....	34
Figure 29.	Swagelok Rupture Disk	35
Figure 30.	Theory of Constraints Cycle. Source: [45].	36
Figure 31.	Control Logic Flow Chart.....	37
Figure 32.	Electrolyzer Performance, Sampling 0.033 Hz.....	41
Figure 33.	Electrolyzer Performance, Sampling 1 Hz.....	41
Figure 34.	The Adiabatic Saturation Process. Source: [46].	43
Figure 35.	Relative Humidity Testing Device.....	44
Figure 36.	Dry Hydrogen Gas Relative Humidity Testing, Configuration #1	45
Figure 37.	Saturated Hydrogen Gas Relative Humidity Testing, Configuration #2.....	46
Figure 38.	Hydrogen Gas Produced by Electrolyzer Relative Humidity Testing, Configuration #3	46
Figure 39.	Hydrogen Gas after Membrane Dehumidifier Relative Humidity Testing, Configuration #4	46
Figure 40.	Schematic of Compressor Performance Testing Configuration	49
Figure 41.	Compressor Testing Configuration.....	50
Figure 42.	Compressor Voltage vs. Runtime	51
Figure 43.	Compressor Output Pressure vs. Runtime; Including Best Fit Curve	52

Figure 44.	Compressor Output Pressure vs. Runtime; Including Areas of Interest.....	52
Figure 45.	Mass Flow Rate (kg/s) through Compressor Over Various Pressure Ranges.....	54
Figure 46.	Proposed Desiccant Dryer Configuration	58
Figure 47.	Generation Micro850 Controller Layout	69
Figure 48.	Compression Micro850 Controller Layout.....	70
Figure 49.	The Adiabatic Saturation Process. Source: [46].	75
Figure 50.	Free Body Diagram of Relative Humidity Testing Device	81
Figure 51.	Honeywell Pressure Transducer, MLH500PSL01A.....	87
Figure 52.	Honeywell Pressure Transducer, M LH03KPSB01A.....	89

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 1.	Gravimetric Energy Densities of Common Energy Sources and Storage Mediums. Adapted from [14].	7
Table 2.	Volumetric Energy Densities of Common Energy Sources and Storage Mediums. Adapted from [14].	8
Table 3.	Physical Components	13
Table 4.	Control Components	14
Table 5.	Sensor Components	14
Table 6.	Results Water Production Test	39
Table 7.	Relative Humidity of Hydrogen Gas	48
Table 8.	Mass Flow Rate (kg/s) through Compressor over Various Pressure Ranges	55
Table 9.	Saturation Properties for Water—Temperature Increments. Adapted from [53].	77
Table 10.	Thermodynamic Properties of Water—Saturated Water. Adapted from [46].	77
Table 11.	Pressure vs. Output Voltage MLH500PSL01A	87
Table 12.	Pressure vs. Output Voltage, MLH03KPSB01A	89

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

A	cross sectional area, m ²
AMMPS	Advanced Medium Mobile Power Source
ASME	American Society of Mechanical Engineers
AC	alternating current
Btu	British thermal unit
COTS	commercial-off-the-shelf
CGA	Compressed Gas Association
C _{pH₂}	hydrogen gas specific heat at constant pressure, 14209 J/kg*K
DC	direct current
DOD	Department of Defense
DOT	Department of Transportation
EHC	electrochemical hydrogen compressor
H ₂	hydrogen gas
H ₂ O	water
Hz	Hertz
I	Electrical current, Amps
J	joules
kPa	kiloPascals
K	Kelvin
lbm	pounds mass
LPM	liters per minute
$\dot{m}$	mass flow rate, kg/s
m_{H_2}	mass of hydrogen, kg
M _{H₂}	hydrogen molar mass, 0.002016 kg/mol
NFPA	National Fire Protection Association
O ₂	oxygen Gas
P_h	high pressure, Pa
P_l	low pressure, Pa
P _{max}	Maximum system pressure, 13789.51 kPa (2000 psig)

P_{total}	total pressure, 101325 Pa
P_v	partial pressure of a vapor
P_g	saturation pressure of a vapor
Pa	Pascals
PEM	proton exchange membrane
PLC	programmable logic controller
psia	pounds per square inch absolute
psig	pounds per square inch gauge
PWM	pulse width modulator
Q	volumetric flow rate, m^3/s
R	electrical resistance, Ohms
R_{H_2}	hydrogen gas constant, $4124.3 \frac{\text{J}}{\text{kg} \cdot \text{K}}$
R_{vapor}	water vapor gas constant, $461.5 \frac{\text{J}}{\text{kg} \cdot \text{K}}$
ρ_{H_2}	density of hydrogen, $0.0813 \text{ kg}/\text{m}^3$
ρ_{water}	density of water at 15°C , $999.06 \text{ kg}/\text{m}^3$
SLPM	standard liter per minute
T_{dry}	temperature at dry bulb thermometer
TLI	tank level indicator
T_{st}	standard Temperature, 288.15 K
T_{wet}	temperature at wet bulb thermometer
V	volume, m^3
V_{ct}	compress testing volume, m^3
VDC	voltage direct current
V_{DOT}	volume of DOT storage cylinder, 0.0433 m^3
V_e	volts
U	velocity, m/s
$\dot{W}$	power, Watts
ω_1	humidity ratio at T_{dry}
ω_2	humidity ratio at T_{wet}

ACKNOWLEDGMENTS

First, I want to thank my wife, Dulce Lewis, for her unwavering support. Day in and day out she was the backbone of our family, ensuring that our children, Carleigh and Wyatt, were cared for, allowing me to focus on my research. She did all of this while also navigating the uncertainty associated with the Covid 19 pandemic. Without her, none of my accomplishments would have been possible.

I would also like to thank Dr. Anthony Gannon and Dr. Walter Smith for their support. Their knowledge and assistance were paramount to my success. It was a pleasure to work with both, and I learned a great deal from each one of them. Additionally, I would like to thank Mr. John Gibson, Aerospace Engineering Technician, for his assistance throughout this research. His level of craftsmanship and attention to detail made the most difficult of tasks easy to accomplish. Thank you all.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. MOTIVATION

In FY2017, the U. S. Energy Information Administration reported that the United States of America consumed over 102 quintillion joules (97 quadrillion British thermal units) of energy. Roughly 80 percent of all energy consumed was produced from fossil fuels [1]. The Department of Defense (DOD), in FY2017, consumed 746 quadrillion joules (707.9 trillion Btu) of energy, which is less than 1% of the total energy consumed by the United States. However, the DOD spent roughly \$11.9 billion on energy, which was roughly 2% of its FY2017 budget [2].

The DOD categorizes energy use into two categories: operational or installation. Operational energy is defined as the energy required for training, moving, and sustaining military forces and weapons platforms for military operations and training. Installation energy is defined as the energy needed to power fixed installations and enduring locations as well as non-tactical vehicles. Historically, operational energy, such as jet fuel and generators, make up 70% of the DOD's energy use, while installation comprises the remaining 30% [2].

Most recently, due to wars in Iraq and Afghanistan, the increased price of oil, and the impact of climate change, the DOD has taken greater action to address the department's energy consumption. These actions are evidenced by the deployment in 2016 of the Great Green Fleet, which used over 48 million gallons of F-76, marine diesel, blended with 10% biofuels [3]. Additional actions include the development, by the United States Army, of the Advanced Medium Mobile Power Source (AMMPS) microgrid. The AMMPS microgrid uses an Advanced Digital Control System to optimize generator efficiency and can incorporate renewable sources of energy into the microgrid [4]. With regards to installation energy, 42 U.S.C §8253 directs efficiency requirements for federal buildings, Energy Policy Act of 2005 directs the utilization of renewable energy sources, and the Energy Independence and Security Act of 2007 directed a reduction of oil consumption by federal non-tactical vehicles [2].

As the DOD has pushed for more use of renewable sources of energy, such as solar and wind, progress has been hindered by a lack of effective energy storage methods. Without an effective energy storage method incorporated into a renewable energy source, energy produced during periods of low demand and high supply energy is lost. Conversely, during periods of high demand and low supply, the system cannot meet the energy requirements of the user. The AMMPS microgrid is an operational example of this limitation of renewable sources of energy. Renewable energy can be a supplement to the AMMPS microgrid, but the primary means of energy production remains based on fossil fuels to ensure the user has energy available when needed. The limitations of renewable energy are not only constrained to operational energy they also affect installation energy. DOD installations with renewable sources of energy are still integrated into the commercial power grid. So, as was the case with the AMMPS microgrid, during periods of high demand and low supply, the DOD installations are dependent upon commercial sources of energy, which produces roughly 77% of its energy from fossil fuels [1, 2]. This dependence on the commercial power grid has also been noted as a threat to national security due to the grid being susceptible to extended outages [5]. Additionally, the introduction of renewable energy sources and energy storage will not only help to improve the DOD's energy security but the DOD's energy resiliency as well [6].

Improvements in effective energy storage methods will enhance the utilization of renewable energy, such as solar and wind, in order to meet both operational and installation energy requirements. At the same time, the use of renewable energy will decrease the DOD's dependence on oil, relax budgetary constraints due to fluctuations in oil prices, and reduce the emission of greenhouse gases.

B. HYDROGEN AS A MEANS TO ENERGY STORAGE.

Energy can be stored via various methods including mechanical, thermal, electro-chemical, and chemical. Mechanical energy storage is accomplished by harnessing the potential energy of either pumped-hydro or compressed air system, while chemical energy storage is represented by fossil fuels. Batteries and supercapacitors are forms of electro-chemical and electrostatic energy storage respectively. Each energy storage method has its

own set of disadvantages; mechanical energy is dependent upon geography, while chemical energy is dependent upon fossil fuels. Currently, electro-chemical storage methods, such as batteries and super capacitors, are the primary means for storing energy produced from renewable sources. Unfortunately, batteries present their own disadvantages summarized below.

Batteries produce electricity through a chemical reaction between an anode and a cathode, and in many cases are rechargeable by reversing the chemical reaction [7]. Batteries, however, do have several disadvantages. Those disadvantages include extended recharge times, system power limitations, and disposal of toxic materials [7].

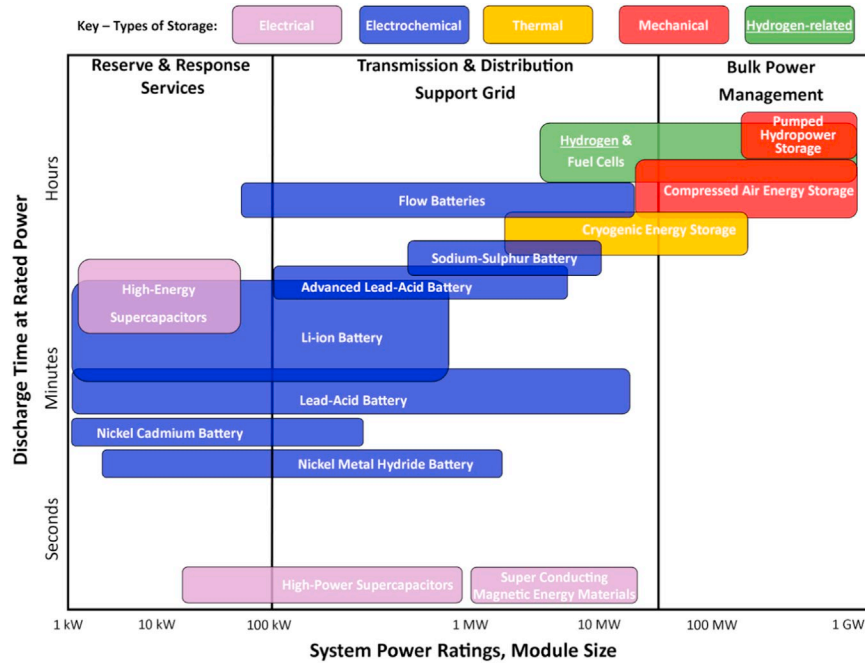
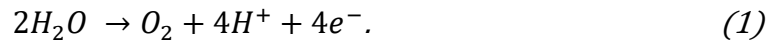


Figure 1. Comparison of Key-Type Energy Storage Technologies in Sense of Storage Capacity and Discharge Power Duration. Source: [8].

As demonstrated in Figure 1, hydrogen has the capability of providing stable energy at higher power ratings for extended periods of time compared to batteries. Hydrogen can be produced by either extraction from another fuel source, fermentation, or by electrolysis [9, 10]. The process of extracting hydrogen from another fuel source is accomplished by

reacting high temperature steam with either natural gas or renewable liquids. Natural gas reforming is currently the most common method for hydrogen production. Unfortunately, natural gas reforming is not a renewable source of hydrogen, because of its dependence upon fossil fuels. Unlike natural gas reforming, reforming bio-fuels is a renewable source for hydrogen production; however, it is more expensive and inefficient when compared to natural gas reforming. Fermentation for hydrogen production utilizes microorganisms that release hydrogen while digesting biomass. Similar to reforming renewable liquids the fermentation of bio-mass is a renewable means for hydrogen production. The one disadvantage of hydrogen production by extracting from another fuel source or fermentation is the immobility of these facilities. Another disadvantage is that these facilities are dependent upon resources being supplied to the facility for hydrogen production.

Electrolysis produces hydrogen by passing an electrical current through water. The anode reaction when an electric current is applied to water is



The electrons produced from this reaction pass through an electrical circuit to the cathode side of the electrolyzer. On the cathode the reaction,



combines the electrons [11].

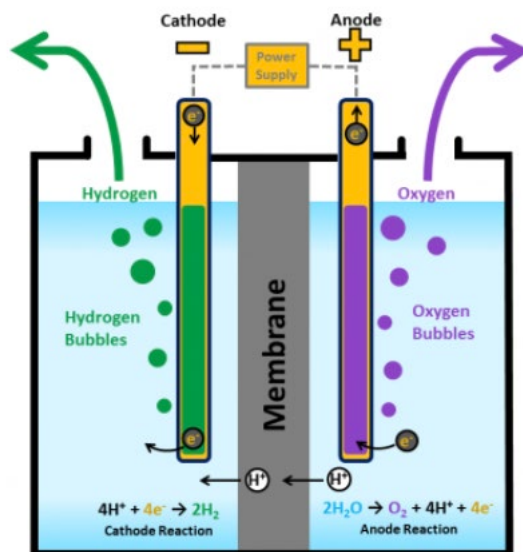


Figure 2. Electrolysis. Source: [11].

Figure 2 illustrates the production of hydrogen gas via electrolysis. Hydrogen production via electrolysis can overcome the disadvantages of producing hydrogen via extraction or fermentation. Water can be harnessed from local liquid sources or harvested from the ambient moisture in the atmosphere. According to the U. S. Geological Survey the Earth's atmosphere contains 12900 cubic kilometers (3,095 cubic miles) of water [12]. Also, when the electric current utilized during electrolysis is produced from renewable sources, such as solar or wind, the hydrogen gas is considered renewable as well. In the case of DOD requirements, this would reduce the need for fuel convoys in order to maintain power at forward operating bases, where bases could produce hydrogen on site.

Once the hydrogen gas has been produced, there are several methods for storing the hydrogen in either a physical- or material-based system. Material-based solutions are dependent upon certain metal and alloy's ability to absorb and release hydrogen. While hydrogen storage via metal hydrides has produced encouraging results, some metal hydrides are toxic, and all require heat addition in order to release the hydrogen from the material [13]. In contrast, the physical-based storage methods include compressed gas or liquid hydrogen. Because hydrogen's boiling point is -252.8°C (-423.1°F) hydrogen is

more easily stored as a compressed gas than as a liquid. Figure 3 shows various methods of hydrogen storage [13].

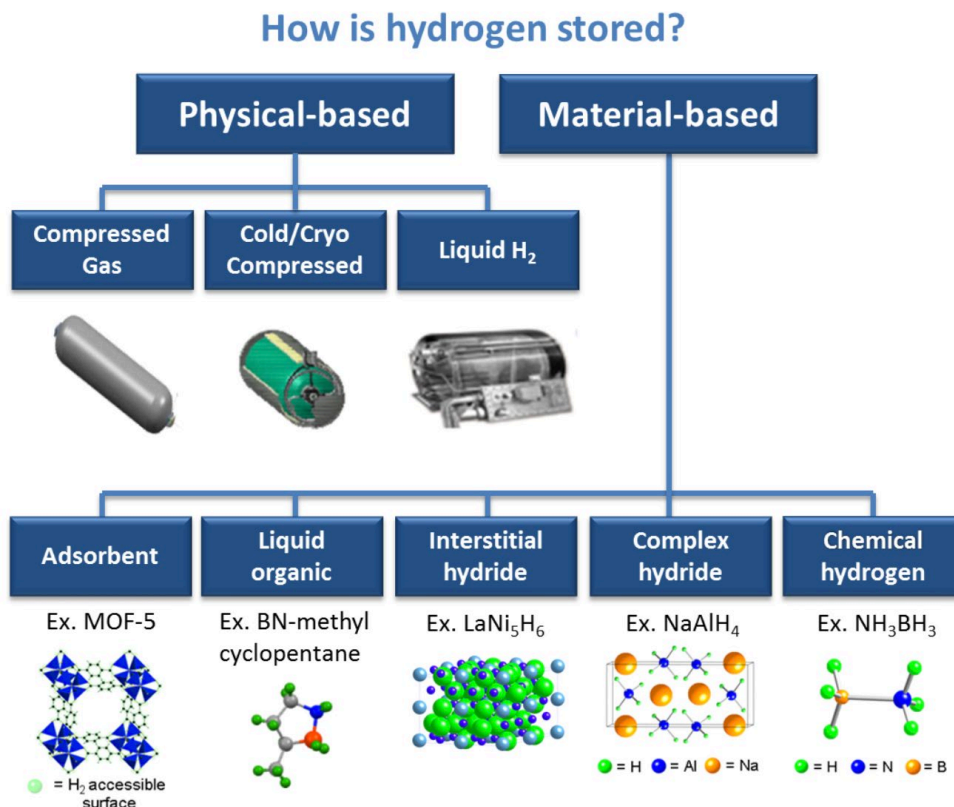


Figure 3. Methods for Hydrogen Storage. Source: [13].

The various methods of compressing the hydrogen gas for storage are necessary because of the energy density properties of hydrogen. Although hydrogen has the highest energy per mass gravimetric energy density compared to any fuel, its energy per volume, or volumetric energy density, is very low. Compression allows the increase of hydrogen's volumetric energy density. Table 1 and Table 2 list the gravimetric energy density and volumetric energy density, respectively, of several energy sources and storage devices.

Table 1. Gravimetric Energy Densities of Common Energy Sources and Storage Mediums. Adapted from [14].

Energy Source / Storage Medium	Gravimetric Energy Density [MJ/kg]
Gaseous H ₂ (g) 1atm	120-142
Liquid H ₂ (l)	120-142
Compressed Gaseous H ₂ (g) 700 Bar	120-142
Compressed Gaseous H ₂ (g) 350 Bar	120-142
Methane (g)	50.0-55.5
LNG (l)	49.4-55.2
LPG Propane (l)	46.0-50.0
CNG (g)	46.9-49.4
LPG Butane (l)	45.3-49.13
Crude Oil (l)	43.1-48.3
Gasoline (l)	44.5-48.2
Jet Fuel (l)	42.8-45.7
Diesel (l)	42.9-45.7
Biogas Fuel Oil (l)	24.4-41.9
Commercial by-products (used tires)	38.2
Coal (s)	16.3-33.5
Ethanol (l)	26.8-29.7
Commercial by-products (coffee grounds)	23.8
Biomass (wood)	19.9-21.3
Biomass (peat)	8.61-18.6
Commercial by-products (cow manure)	17.2
Fuel Cells (2015 Actual)	2.37
Fuel Cells (2020 Target)	2.34
Fuel Cells (Ultimate Target)	2.34
Primary Batteries	0.20-2.12
Secondary Batteries	0.11-0.72
Supercapacitors	0.007-0.036

Table 2. Volumetric Energy Densities of Common Energy Sources and Storage Mediums. Adapted from [14].

Energy Source / Storage Medium	Volumetric Energy Density [MJ/L]
Crude Oil (l)	34.4–47.6
Jet Fuel (l)	36.0–38.4
Diesel (l)	36.0–38.4
Gasoline (l)	33.4–36.2
Biogas Fuel Oil (l)	17.3–31.4
Coal (s)	11.0–31.1
LPG Propane (l)	23.5–25.5
LPG Butane (l)	23.1–25.1
Ethanol (l)	23.5
LNG (l)	22.2
Biomass (wood)	7.97–21.3
Commercial by-products (used tires)	14.7–20.2
Commercial by-products (cow manure)	17.1–17.9
Biomass (peat)	2.07–17.9
Liquid H ₂ (l)	8.5–9
CNG (g)	8.44–8.9
Commercial by-products (coffee grounds)	7.45
Primary Batteries	0.5–4.86
Compressed Gaseous H ₂ (g) 700 Bar	4.7
Fuel Cells (Ultimate Target)	3.06
Compressed Gaseous H ₂ (g) 350 Bar	2.7
Fuel Cells (2020 Target)	2.34
Fuel Cells (2015 Actual)	2.304
Secondary Batteries	0.20–2.05
Supercapacitors	0.005–0.05
Methane (g)	0.03–0.04
Gaseous H ₂ (g) 1 atm	0.0098–0.0115

As a result, the compression of renewably generated hydrogen can replace batteries and supercapacitors as the primary means for storing energy generated by renewable sources.

C. APPLICATIONS

Due to the high gravimetric energy density, hydrogen is especially attractive for flight applications. Unmanned aerial vehicles are increasing being applied to both commercial and military applications. And the use of hydrogen has the capability of increasing flight time for those systems. Additionally, other research is currently being conducted for the development of hydrogen powered vehicles and passenger aircraft [15].

Advances in technology, such as fuel cells and hydrogen powered gas turbines, can enable hydrogen gas to replace fossil fuels as the primary energy storage method [16].

Beneficially, the development of a mobile hydrogen generation, compression, and storage system removes the supply chain element. No longer would hydrogen gas produced have to be transported to the end user: the user would be able to produce hydrogen gas onsite. This aspect is attractive for the production of hydrogen gas at forward operating bases. For civilian applications for the local production of hydrogen gas at refueling stations for hydrogen powered vehicles.

D. RESEARCH OVERVIEW

1. Objective

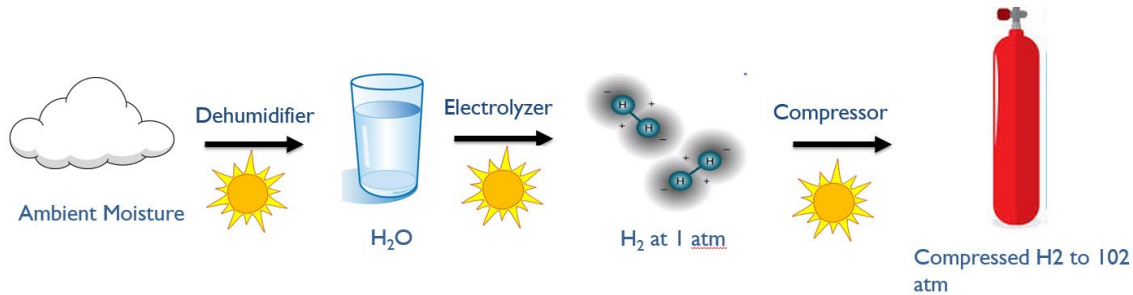


Figure 4. Overview of Compressed Hydrogen Gas Generation System Powered from Renewable Sources

The objective of this research was to integrate a control system into an existing small-scale plant for the generation and compression of hydrogen gas and evaluate its performance. The overall plant design was to be robust, mobile, and require little to no user interface to produce compressed hydrogen gas from renewable sources utilizing commercial-off-the-shelf (COTS) components. This research advances the development of hydrogen production from renewable sources in order to decrease the DOD's and United States' dependency on fossil fuels for energy and improve energy resiliency. Figure 4 provides a conceptual overview of the hydrogen of the hydrogen production system.

2. Outline

The subsequent chapters lay out the approach for achieving the objective, and for testing and evaluating those approaches. Chapter II provides an overview of the components that make up the overall hydrogen system. The components are organized into three sub-systems, physical, control, and sensors, which interact in order for the overall system to function. Furthermore, safety considerations and the control strategy utilized in the hydrogen system are addressed. Chapter III outlines system performance, details the methods for testing and evaluating the performance of the four major functions of the hydrogen system listed below.

1. Water generation from the atmosphere.
2. Hydrogen gas production.
3. Removal of water vapor from hydrogen gas.
4. Electrochemical hydrogen compressor (EHC) performance.

Additionally, the chapter expresses the results from the various testing methods. The key observations and results from testing are:

1. Water production is intermittent and the constraining process.
2. Electrolyzer averages a hydrogen gas mass flow rate of 5.52e^{-7} kg/s (1.22e^{-6} lbm/s).
3. Membrane dehumidifier is ineffective at drying saturated hydrogen gas.
4. EHC maximum outlet pressure when receiving input hydrogen gas at relatively atmospheric pressure is 7492.53 kPa (1071.99 psig).
5. EHC averages a mass flow rate of 4.37e^{-10} kg/s (9.63e^{-10} lbm/s).

Chapter IV, discussion, lays out several key observations and areas for improvement of the hydrogen system based upon the results from performance testing. Key areas discuss techniques for handling saturated hydrogen gas produced by the electrolyzer, improving the generation of water from the atmosphere, and properly size components to reduce constraints on the system. Additional observations from system performance testing

discussed include improving the electrical stability, safety considerations, and sensors for the system. Two areas outside the scope of this research, supply chain management and cyber security, are addressed as well because of their future impacts on future research and development.

The conclusion and recommendations chapters, Chapters V and VI, respectively, lay out advantages and limitations of the current hydrogen system and the necessary further on research to optimize the generation, compression, and storage of hydrogen system from renewable sources.

THIS PAGE INTENTIONALLY LEFT BLANK

II. SYSTEM OVERVIEW

There are several components utilized in order to create a hydrogen gas generation, compression and storage system. The system components have been divided into three sub-systems.

- Physical components
- Control components
- Sensor components

The system's physical components are the main drivers of the system and perform the actual operations key to producing and compressing hydrogen gas. The sensor components are utilized to monitor system characteristics during operation. Characteristics monitored include but are not limited to voltage, current, pressure, and volumetric flow rate. Finally, the system's control components are the interface between the physical and sensor components. The control components receive data from the sensor components and uses that data to regulate the physical components. A schematic featuring the three sub-systems and how the sub-systems interface is included in Figure 5. Tables 3–5 list the individual components of each sub-system and will be covered in detailed in the following paragraphs.

Table 3. Physical Components

Number	Description	Component
1	DC power supply	Kikusui PWL1500ML
2	DC power supply	GW Instek GPS 1850D
3	Dehumidifier	Ivation dehumidifier
4	Electrolyzer	Electrolyzer
5	Hydrogen dryer	Xergy membrane dehumidifier
6	Vacuum Pump	Marathon Electric Vacuum pump
7	Compressor	Xergy electrochemical hydrogen compressor

Table 4. Control Components

Number	Description	Component
1	Micro 850 Controller	2080-LC50-24QBB
2	Micro 800 power supply	2080-PS120-240VAC
3	Plug-in module	2080-IF4
4	Plug-in module	2080-OF4
5	Expansion module	2085-OF4
6	Expansion module	2085-IF8

Table 5. Sensor Components

Number	Description	Component
1	DC voltage transducer	Phoenix DC Transducer
2	Eaton current transducer	EDC 2420SP
3	Eaton current transducer	EDC1420SC
4	Alicat Flowmeter	M-5SLPM-D/5M
5	Tank level indicator	KUS SSS7
6	Honeywell pressure transducer	MLH500PSL01A
7	Honeywell pressure transducer	MLH03KPSB01A

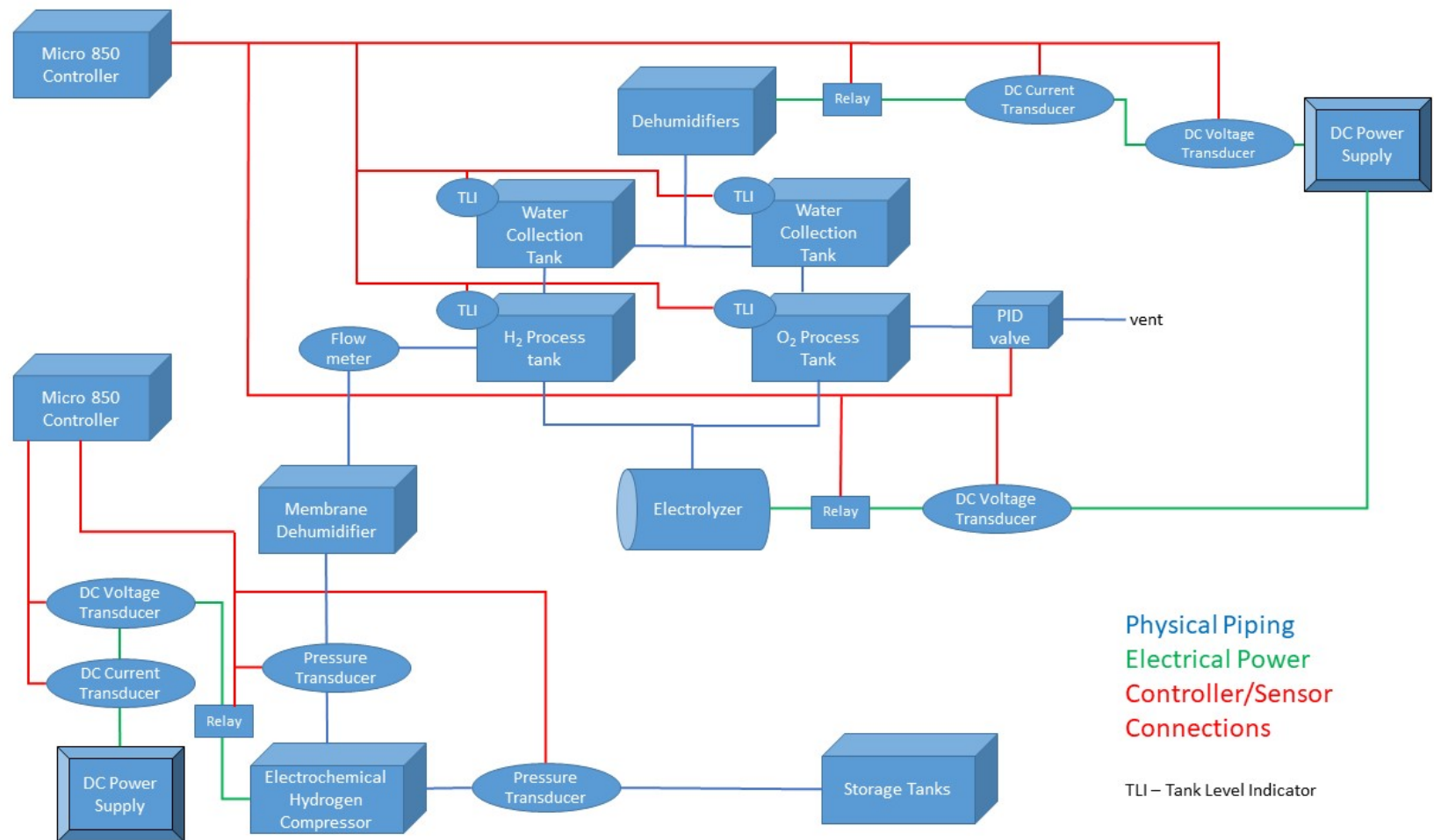


Figure 5. System Overview

A. PHYSICAL COMPONENTS

There are five major components of the overall system that are required for the generation and compression of hydrogen. Those five components included the direct current (DC) power supplies, dehumidifiers, electrolyzer, hydrogen gas dryer, and the compressor. Birkemeier has previously demonstrated the capability to generate hydrogen gas from solar power, however the solar panels were removed from the system and replaced with the DC power supply with the new concept being to use a solar powered battery-inverter system to drive it [17]. The DC power supply was added to the system to provide steady stable power during the implementation of the control strategy for the combined system. It became readily apparent during the initial implementation of a control strategy that the stable power provide by the DC power supplies were crucial to the autonomy of the hydrogen system. Future adaptations of the hydrogen system would require the use of a battery storage system to enable the continued monitoring of the system by the Mirco850 controller when operating from renewable power.



Figure 6. Kikusui PWX1500ML DC Power Supply

The DC power supply utilized was a Kikusui PWX1500ML, shown in the Figure 6, which powers the dehumidifiers, and electrolyzer. The DC power supply was limited to

providing a constant voltage of 13 volts and 20 amps, in order to simulate the output from a solar charge controller [18].

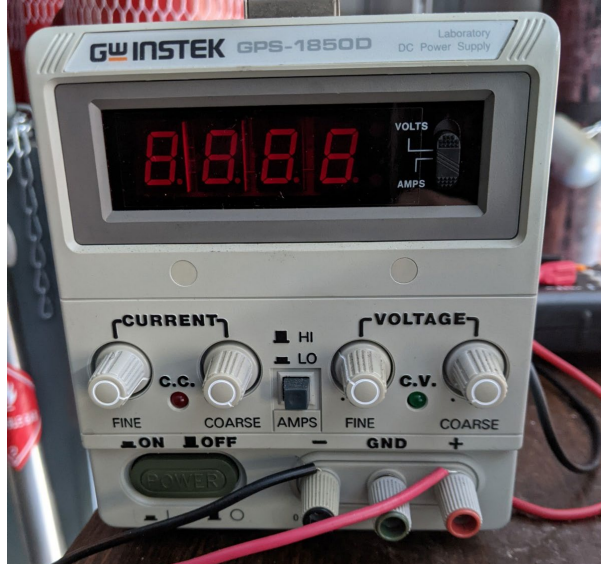


Figure 7. GW Instek, GPS 1850D, DC Power Supply

Due to the low required operating voltage of the EHC, a separate DC power supply was utilized. A GPS1850D DC power supply, Figure 7, was used. The GPS1850D power supply is capable of providing an output voltage ranging from 0 to 18 volts DC, and an output current from 0 to 5 Amps [19].



Figure 8. Ivation Dehumidifier

The dehumidifiers, shown in Figure 8, utilized in the system were four Ivation IVADM35 dehumidifiers. The dehumidifiers require a DC voltage of 13 volts and 4.6 amps each, in order to operate [20]. The dehumidifiers are thermo-electric dehumidifiers that operate based off the Peltier Effect. The Peltier Effect is when an electrical current is applied to a thermocouple a temperature difference is created [21]. Heat rejection from the hot side of the Peltier Effect for the dehumidifiers is aided by a small fan, which is the only moving part of the dehumidifier. The cold side of the Peltier cooler causes condensation of the ambient moisture by dropping below the dew point, which is collected in tanks for use by the electrolyzer.

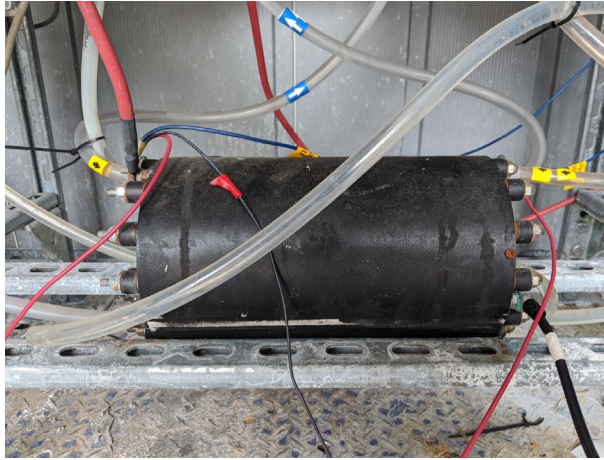


Figure 9. Electrolyzer

The electrolyzer, Figure 9, from Hybrid HydroTech, model HT5, is utilized to produce hydrogen gas from water through the process of electrolysis described previously. To operate, the electrolyzer requires a DC voltage ranging from 0 to 14 volts. A pulse width modulator (PWM) and remote control are included in the electrolyzer's wiring configuration. The PWM with the remote control allows the user to manually control the amount of power consumed by the electrolyzer. As previously demonstrated by Yu, the rate of hydrogen production by the electrolyzer is related to the power consumption. As the power applied to the electrolyzer increased the rate of hydrogen production increased. However, it was also demonstrated that as power applied increased the efficiency of the electrolyzer decreased [22].



Figure 10. Xergy Membrane Dehumidifier,

In order to dry the hydrogen gas being produced by the electrolyzer a Xergy membrane dehumidifier, Figure 10, was utilized. During operation saturated hydrogen gas is passed through the blue membrane tube, and a vacuum is established on the outside of the membrane. The purpose is to produce hydrogen gas with a relative humidity of less than 30%. The membrane dehumidifier is rated for a maximum inlet pressure of 1137 Pa (150 psig) [23].

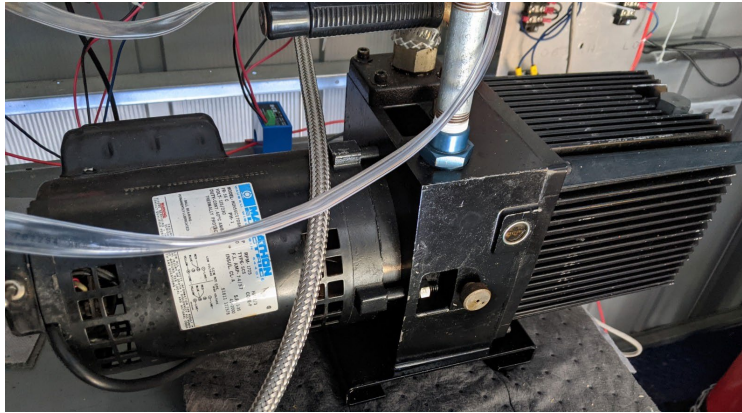


Figure 11. Marathon Electric Vacuum Pump

In order to achieve a vacuum inside the membrane dehumidifier a Marathon Electric vacuum pump, Figure 11, was utilized. The vacuum pump required 110 AC volts during operation and would achieve a vacuum pressure of 3392 Pa (.492 psia).



Figure 12. Xergy Electrochemical Hydrogen Compressor

The hydrogen compressor is an electrochemical hydrogen compressor, Figure 12, and manufactured by Xergy, X-Cell model [24]. The compressor utilizes a low relative humidity proton exchange membrane (PEM), less than 30%, located between an anode and cathode electrode in order to compress the hydrogen gas. The compression is accomplished by applying electrical power to the electrodes in order to oxidize the hydrogen gas. In the case of the X-Cell EHC, it is limited to a maximum voltage of 400 mV applied to the electrodes. During operation the positively charged hydrogen ions migrate through the PEM to produce hydrogen at the cathode. Equations (3) and (4) represent the electrochemical reactions at the anode oxidizing the hydrogen and the hydrogen evolution reaction at the cathode, respectively [25, 26].



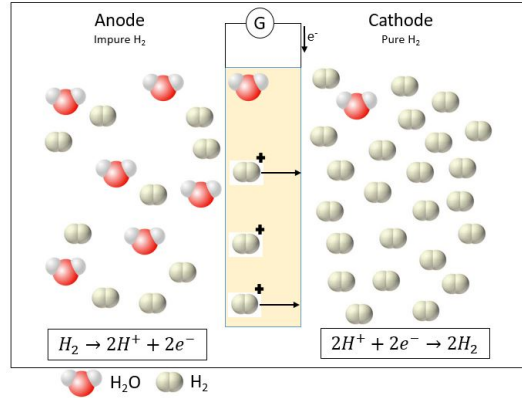


Figure 13. Operation of an Electrochemical Hydrogen Compressor.
Adapted from [25].

To summarize Fosson, an EHC has multiple advantages as opposed to more traditional mechanical methods for hydrogen compression. Those advantages include no moving parts, requiring less energy compared to mechanical compressors, and hydrogen purification [14]. The hydrogen purification, shown in Figure 13, is a result of the PEM which impedes the flow of any impurities, such as water vapor, from reaching the cathode side of the reaction [25, 26]. Additionally, a low relative humidity, dry, proton exchange membrane was chosen due to the tendency of a high relative humidity, wet, proton exchange membrane to degrade when not in operation.

B. CONTROL COMPONENTS

The control system used for the hydrogen system were Allen Bradley Micro 850 Programmable Logic Controllers (PLC). The Micro 850 controller used for both hydrogen generation and compression are a model 2080-LC50-24QBB.

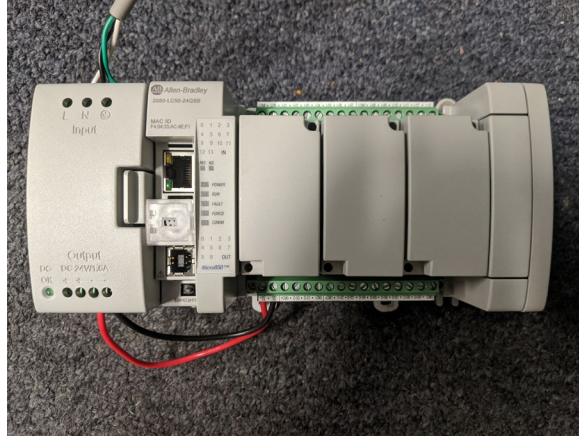


Figure 14. Micro 850 Controller, 2080-LC50-24QBB, with Micro 800 Power Supply, 2080-PS120-240VAC

The Micro 850 controller, Figure 14, is a fully customizable brick style controller with 14 embedded input pins and 10 embedded output pins. The embedded output pins are utilized to provide an output signal to various solid state relays for system operation. The embedded input pins can only determine if an input is present and are unable to assign a value to the input, thus additional plug-in and expansion modules are required in order to control the hydrogen system. The Micro 850 controllers can also support up to three plug-in modules and four expansion modules [27]. The optional Micro 800 power supply, 2080-PS120-240VAC, shown in Figure 14, was utilized to supply 24 VDC to the controller [28]. A detailed physical layout of the 2080-LC50-24QBB controllers used in the generation and compression side the hydrogen system can be found in Appendix A.

The Micro 850 controllers can support a wide array of plug-in and expansion modules; however, only a few were necessary for automation of the hydrogen system. The plu-in modules used were 2080-IF4 and 2080-OF2.

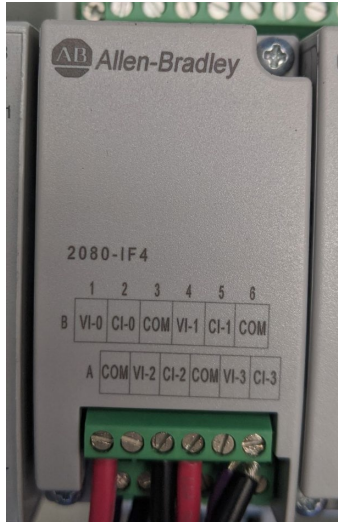


Figure 15. 2080-IF4 Plug-In Module

The 2080-IF4, shown in Figure 15 is a four channel, analog input plug-in module with a 16-bit data range. The plug-in module has three pins associated with each channel, which enables the user to receive either a voltage or current signal. The plug-in module is capable of handling an input voltage ranging from 0 to 10 VDC, while the input range for current is 4 to 20 mA. An input signal greater than 10 volts or 20 mA can result in damage to the plug-in module and controller [29]. The 2080-IF4 plug-in modules are used in the controller system to receive inputs from various instrumentation.



Figure 16. 2080-OF2 Plug-In Module

The 2080-OF2, shown in Figure 16, is a two-channel voltage/current analog output plug in module with 16 bit data range. Similar to the 2080-IF4, the 2080-OF2 is capable of an output voltage range from 0 to 10 VDC, or 0 to 20 mA [29]. The 2080-OF2 is used to output signals from the controller to a proportional-integral-derivative (PID) controlled valve employed to regulate the water level in the oxygen process tank.



Figure 17. 2085-OF4 Expansion Module

As previously stated, the Allen Bradley Micro 850 controllers can support expansion modules. The 2085-OF4 expansion module, Figure 17, is a four-channel analog

voltage/current output module. The 2085-OF4 operates at the same voltage and current output ranges as the 2080-OF2 and is utilized to provide a steady 4.5 DC voltage to the system's four tank level indicators (TLIs), which will be described in later sections [30].

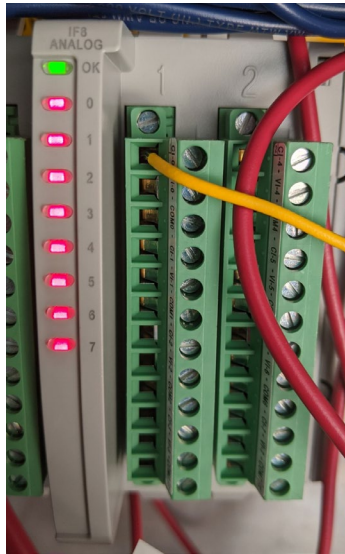


Figure 18. 2085-IF8 Expansion Module

The 2085-IF8 expansion module, shown in Figure 18 is an 8-channel analog voltage/current input expansion module. Similar to the 2080-IF4 plug-in module, the 2085-IF8 is capable of handling an input voltage ranging from 0 to 10 VDC, while the input range for current is 4 to 20 mA [30].

The backbone of the Micro 850 controllers is the PLC software, 'Connected Components Workbench,' (CCW). CCW enables the user to create and integrate programs and user defined functions in three different programming formats. The formats are ladder, function block, and structured text. Structured text made up the majority of the programming language used by the controller in the current application. The ladder format is not used in the program and the function block format is only used in relation to the PID controlled valve. The program and user defined functions can be found in Appendices O and P. Additionally, the Micro850 Controllers support MODBUS mapping, which is utilized in conjunction with MATLAB to provide data acquisition [27].

C. SENSOR COMPONENTS

There are several components as part of the hydrogen generation, compression and storage system that enable data collection and provide inputs to the Micro 850 controller. The sensor components were separated into two categories, electrical and physical, based on the parameter being monitored.

1. Electrical Sensors

The electrical sensors utilized in the system were installed in order to monitor voltage and current throughout the system.



Figure 19. Phoenix DC Transducer

The Phoenix-DC Transducers, Figure 19, are used to monitor the voltage being supplied by the DC power supply and the electrolyzer voltage, transducer #1 and transducer #2 respectively. Each Phoenix DC Transducer requires a supply voltage of 24VDC in order to operate. The purpose of each transducer is to read the voltage being received via pins 5.3 and 5.4 and convert to a standardized analog signal. The output analog signal is provided via pins 3.1 and 3.2, which ranges from 4 mA to 20 mA, and can be received by the 2080-IF4 plug in module [31]. Due to the low operating voltage of the EHC, the voltage applied to the compressor was read directly by the Micro850 Controller.



Figure 20. Eaton, EDC2420SP DC Current Sensor

In order to measure the current being supplied by the Kikusui DC power supply an Eaton DC Current sensor, model EDC2420SP, was utilized. The EDC2420SP, Figure 20, was powered by a 24 VDC supply, and was configured to read a DC current ranging from 0 to 50 Amps. The EDC2420SP would output a current signal ranging from 4 to 20 mA, which was read by the Micro850 controller [32].

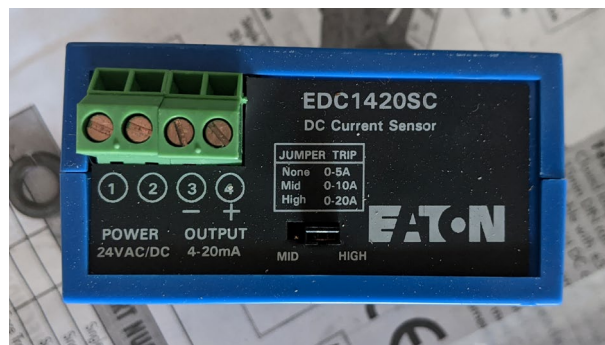


Figure 21. Eaton, EDC1420SC DC Current Sensor

The current being applied by the GW Instek DC power supply to the EHC was measured by an Eaton, model EDC1420SC, DC current sensor. The EDC1420SC, Figure 21, was powered by a 24VDC supply and was configured to read a DC current ranging from 0 to 5 Amps. The EDC1420SC would output a current signal ranging from 4 to 20 mA [33].

2. Physical Sensors

The physical sensors in the system were utilized to monitor various operating conditions such as volumetric flow rates, tank levels, and pressure.



Figure 22. Alicat M-5SLPM-D/5M Hydrogen Gas Flow Meter

There is an Alicat M-5SLPM-D/5M flow meter, Figure 22, located in the system on the outlet of the electrolyzer. There are no flow meters located on the high-pressure side of the system. The Alicat flow meter can read the volumetric flow rate of hydrogen gas from -5 to 5 Standard Liters per Minute (SLPM) [34].

Additionally, the flow meter is used to record the pressure, temperature, and liters per minute (LPM) of the hydrogen gas. MATLAB and an Alicat BB9 multi drop breakout box are used to receive the output data from the flow meter during system performance testing. The digital display on the flow meter is utilized by the operator during system purge process and startup.

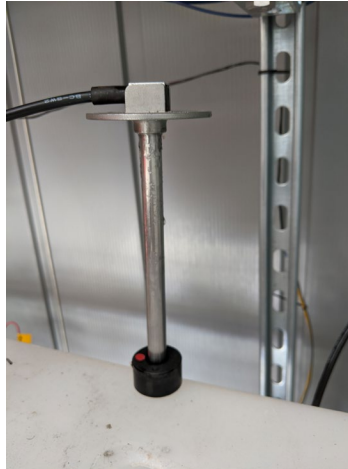


Figure 23. KUS SSS7 Tank Level Indicator

The Micro 850 Controller is able to monitor and record the water levels of the four tanks through the incorporation of tank level indicators (TLIs). There is one SSS7 TLI, Figure 23, for each tank. The TLIs are manufactured by KUS with the only moving part being the floater. As previously stated, the TLIs receive a steady supply voltage from the 2085-OF4 expansion module. As the position of the floater changes, the internal resistance of the TLI changes resulting in a change of the output voltage. The output voltage from the TLI is applied back to the controller, and the difference between the supplied input voltage and received output voltage is used to determine the level of liquid in each tank. The TLIs have a resolution of $\pm 2.1\text{mm}$ and mounted 25.4 mm (1 inch) above the bottom of each tank [35].



Figure 24. Honeywell Pressure Transducer Model #MLH500PSL01A



Figure 25. Honeywell Pressure Transducer Model #MLH03KPSB01A

There are two Honeywell pressure transducers utilized by the system to monitor pressure during operation. Each Honeywell pressure transducer outputs a signal ranging from 0.5VDC to 4.5VDC corresponding to its rated pressure range. The output signal from the Honeywell pressure transducer is capable of being read by the 2080-IF4 plug in module. The first pressure transducer, model #MLH500PSL01A, shown in Figure 24, is located on the low-pressure side of the compressor. The other pressure transducer, model #MLH03KPSB01A, shown in Figure 25, is used on the high-pressure side of the compressor. The model MLH500PSL01A has a rated pressure range from 101325 to 3548703 Pa (0 to 500 psig). While the model #MLK03KPSB01A has a rated pressure range from 101325 to 20785596 Pa (0 to 3000 psig) [36].

D. SYSTEM OPERATION

1. Safety Considerations

While hydrogen gas is a colorless, odorless, tasteless, and non-toxic gas there are certain characteristics of the hydrogen system of that require safety considerations [37]. These characteristics include the displacement of oxygen, the flammability of hydrogen, and the system operating pressure.

Atmospheric air is comprised of mostly nitrogen and only 20.9% oxygen, however, oxygen levels that drop below 19.5% can be hazardous to people [38]. As a result, all vents for the hydrogen system are positioned outside the buildings housing the system. The

position of these vents ensures that hydrogen gas does not accumulate inside the building where the displacement of oxygen is possible [39].

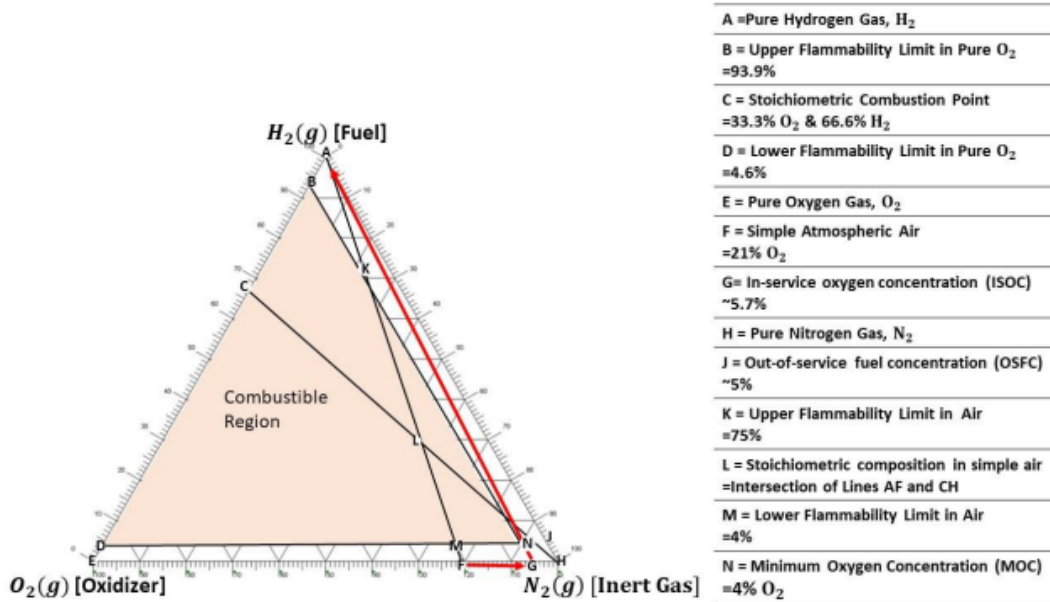


Figure 26. Purging Process Depicted on Triangular Composition Diagram for Hydrogen/Oxygen/Nitrogen. Source: [14].

In order to ensure that the system is operating outside the flammability limits, 4.6 to 93.9%, for hydrogen gas, Figure 26, a purge process is required [39, 40]. To paraphrase Fosson, there are three traditional methods for purging a hydrogen system. These methods include sweep purging, evacuation (vacuum), and pressurizing and venting cycles. The purging method employed on the compression side of the hydrogen system is a combination of evacuation and pressurizing with an inert gas, nitrogen. This combination purging method ensures oxygen levels inside the compression side of the system are below 1%, well outside of the flammability limits for hydrogen gas. Fosson's purging calculations and tabulated results are found in Appendix H [14]. Appendix M contains the procedure for accomplishing the vacuum/pressure purge of the compression side of the hydrogen system. Additionally, the EHC assists in hydrogen purification as a part of its operation.

The photon membrane employed in the EHC inhibits the flow of other gases thus farther contributing to the purity of the high-pressure hydrogen [25].

Unfortunately, due to the design of the system neither of the above purging methods can be employed to purge the system on the generation side. In order to achieve appropriate hydrogen purity a combination of system runtime and venting is utilized to remove oxygen from the system. Appendix C shows the calculated necessary runtime and venting in order to remove residual oxygen from the generation side of the system.

Lastly, that final major safety considerations for the hydrogen system is the system operating pressure. Fosson designed the system in accordance with codes and standards from the American Society of Mechanical Engineers (ASME), the National Fire Protection Association (NFPA), and Compressed Gas Association (CGA) [14]. The codes and standards utilized during initial system design remain valid during this research. The hydrogen system was designed for a maximum rated pressure of 20.64 MPa (3000 psi) with an operating pressure up to 13.78 MPa (2000 psi) [14]. The pressure limiting component for the system are the hydrogen storage cylinders. The cylinders utilized are Department of Transportation, DOT-3AA2265, approved storage cylinders with a volume of 43.3 liters (11.43 gallons). The DOT cylinders have a test pressure of 26.02 MPa (3775 psi) and rated service pressure of 15.61 MPa (2265 psi) [41]. In order to ensure system safety in the event of a control system failure there are relief valves and a rupture disk installed in the system.



Figure 27. Swagelok Relief Valve, SS-RL3S4-MO

The first relief valve in the system is a Swagelok SS-RL3S4-MO, Figure 27. The SS-RL3S4-MO is located on the generation side and set to a relief pressure of 68.94 kPa (10 psig) with an accuracy of ± 3 psig. The purpose of the generation side relief valve is to ensure no excess buildup of pressure that could occur due to backflow through the compressor when no power is applied [42].



Figure 28. Swagelok PRVN2F-02-2-VV-Q Relief Valve



Figure 29. Swagelok Rupture Disk

The second relief valve and rupture disk are located on the high-pressure side of the system. The relief valve is a Swagelok PRVN2F-02-2-VV-Q, Figure 28, is rated for 41.63 MPa (6000 psi) with a set relief pressure of 18.61 MPa (2700 psi) [43]. This relief valve is designed to ensure that the DOT storage cylinders do not exceed their rated burst pressure of 23.26 MPa (3375 psig). Finally, the rupture disk, Figure 29, located on the high-pressure side of the system is designed for 20.68 MPa (3000 psi) which is below the burst pressure of the DOT storage cylinders [14].

2. Control Strategy

The principal theory for implementation of a control strategy for the hydrogen system was the, ‘Theory of Constraints.’ The Theory of Constraints was first published by Eliyahu M. Goldratt and Jeff Cox in 1984, as a process for increasing throughput for manufacturing organizations [44]. According to the Theory of Constraints, a constraint is defined as anything that prevents the organization from achieving its goal. Regarding the hydrogen system, the goal is the production of high-pressure hydrogen gas.

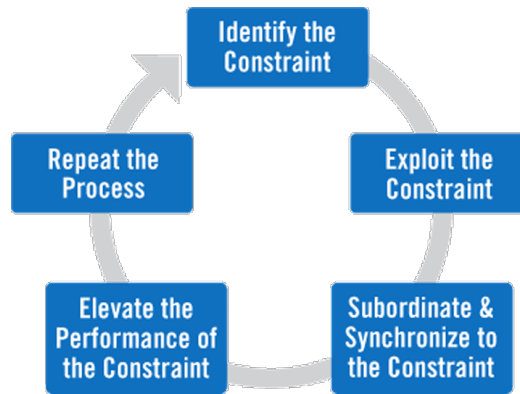


Figure 30. Theory of Constraints Cycle. Source: [45].

Figure 30 demonstrates the five steps to the Theory of Constraints. By accomplishing the first step, identify the constraints, it was discovered that water generation was the process in the system with limited the rate of production of high-pressure hydrogen. The metrics for that determination are described later in the system performance chapter. With the understanding that water generation is the limiting factor, the next step is to exploit the constraint. Exploiting the constraint means to maximize the constraint with existing resources. In the case of the hydrogen system this was accomplished by maximizing the operating time of the dehumidifiers. The control system would automatically provide power to the dehumidifiers as long as power and water storage was available. The next step was to subordinate the other components to water generation. This was accomplished by making the operation of the electrolyzer and compressor dependent upon the available water in the process tanks. The final two steps of the Theory of Constraints, elevate the constraints and repeat the process, were not accomplished during this research. However, the final two steps are addressed in the recommendation chapter for follow on research. Figure 31 is a control logic flow chart of the control strategy, and the CCW code for the generation and compression side can be found in Appendix O and P, respectively.

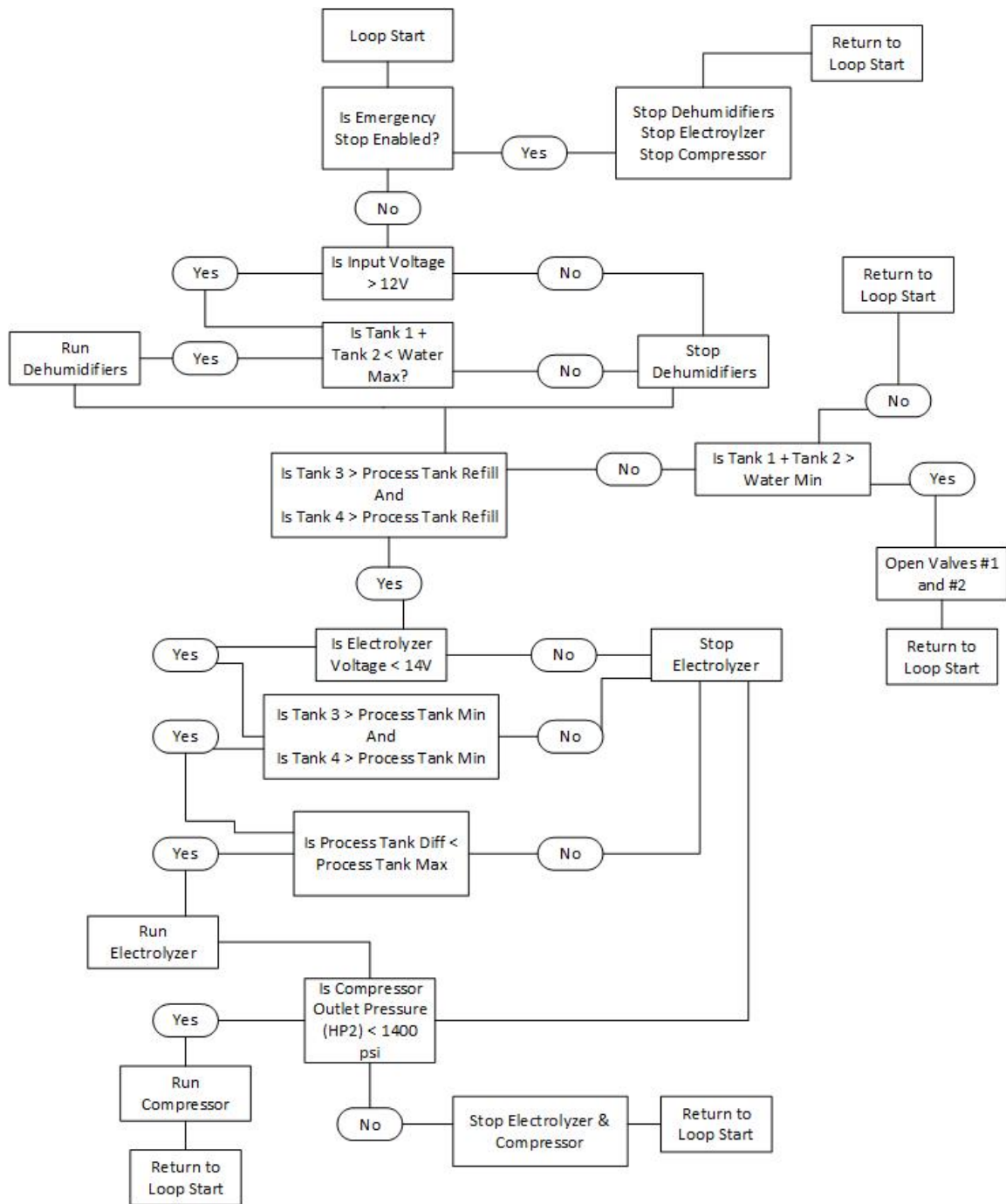


Figure 31. Control Logic Flow Chart

THIS PAGE INTENTIONALLY LEFT BLANK

III. SYSTEM PERFORMANCE

Several tests were conducted to evaluate system performance. The tests were designed to concentrate on four areas: rate of water generation, production of hydrogen gas, humidity levels of hydrogen gas, and the compressor efficiency.

A. WATER PRODUCTION

In order to evaluate the rate of water production by the dehumidifiers, the four units were ran continuously over set time intervals. At the end of each time intervals the total amount of water collected was measured and divided by the number of hours of production to provide a rate of production. Additionally, the power required to operate the four dehumidifiers was recorded. Table 6 shows the results of those test.

Table 6. Results Water Production Test

Test #	Date	Average Ambient Temperature (K)	Average Ambient Relative Humidity	Hours	Total Water Produced (kg)	Rate of production (kg/hr)	Time to fill one DOT-3AA2265 cylinder (days)	Power (Watts)	Kg/J
1	13Aug20	298.70	68.43%	8	0.1701	0.0212625	13.19	104	5.6797e-8
2	17Aug20	299.18	66.63%	8	0	0	∞	104	0
3	18Aug20	298.8	67.25%	8	0	0	∞	104	0
4	19Aug20-20Aug20	292.52	64.29%	17	0.4797	0.0282176	9.94	104	7.5367e-8
5	20Aug20	292.53	66.44%	8	0.1962	0.024525	11.44	104	6.5504e-8
6	20Aug20-21Aug20	292.09	73.65%	16	0.8691	0.054318	5.16	104	1.4508e-7
7	03Nov20	287.84	80.11%	8	.0787	0.0098375	28.52	104	2.627e-8

From Table 6 it can be determined that the performance of the dehumidifiers improved as the ambient temperature decreased and ambient relative humidity increased.

These conditions of low ambient temperature and high relative humidity occurred during overnight test, again highlighting the need for a battery buffer to allow operation during times of intermittent availability of direct solar energy.

Conversely, periods of high ambient temperature and low relative humidity yielded little or no water production. The lack of production is a result of the nature of the dehumidifiers themselves. As previously explained the dehumidifiers utilize the Peltier Effect and a fan to condensate water vapor. During these times of unfavorable conditions, the hot side of the Peltier element and internal fan were unable to sufficiently reject heat, thus resulting in the failure of the cold side of the element to achieve the necessary temperature to reach the saturation line for the amount of water vapor in the atmosphere. Test #2 and #3 demonstrate the lack of water production during unfavorable conditions and the overall intermittent production of the dehumidifiers.

Additionally, the effect of evaporation on water production by the dehumidifiers was analyzed. Four containers position next to each dehumidifier were used to model the water collection reservoir of the dehumidifiers. The surface area of water exposed to the atmosphere was 0.0102 m^2 (0.1098 ft^2) for each container. It was found that the amount of water lost due to evaporation was negligible for the current system operating environment.

B. HYDROGEN GAS PRODUCTION

In order to evaluate the rate of hydrogen production by the electrolyzer, the unit was operated with hydrogen gas vented straight to the atmosphere. This configuration serves as a baseline for the electrolyzer, because no other components are in the system to restrict or minimize the outlet flow from the electrolyzer.

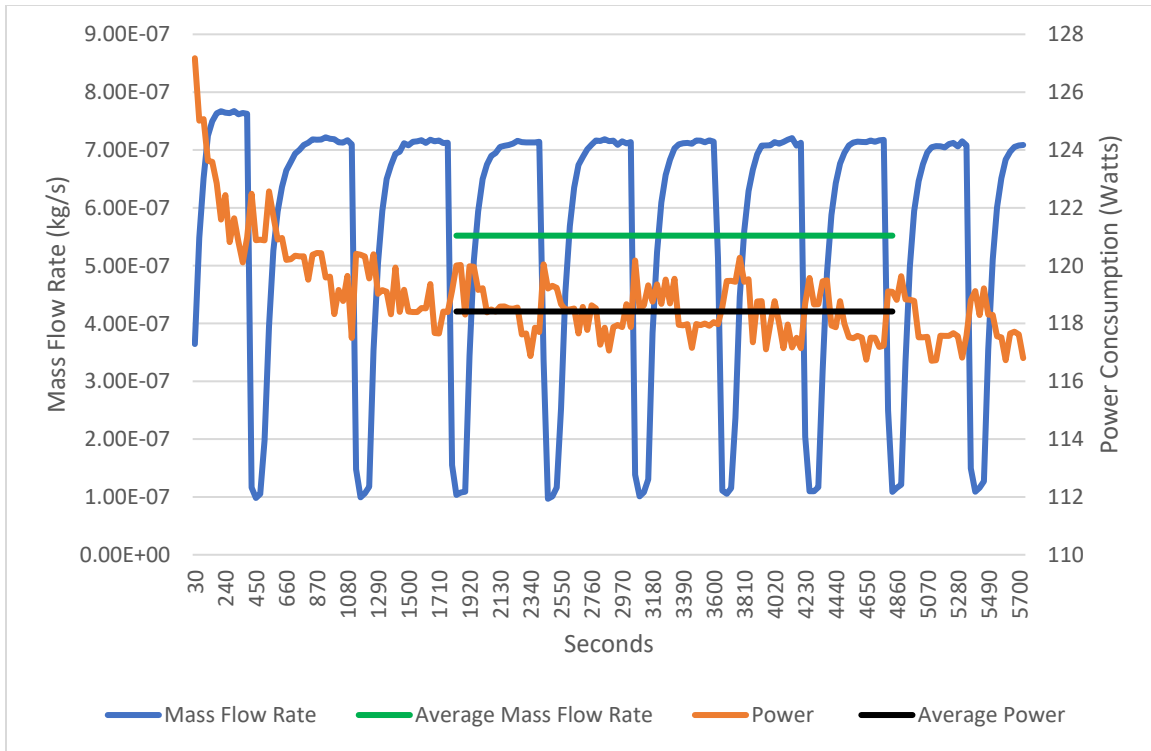


Figure 32. Electrolyzer Performance, Sampling 0.033 Hz

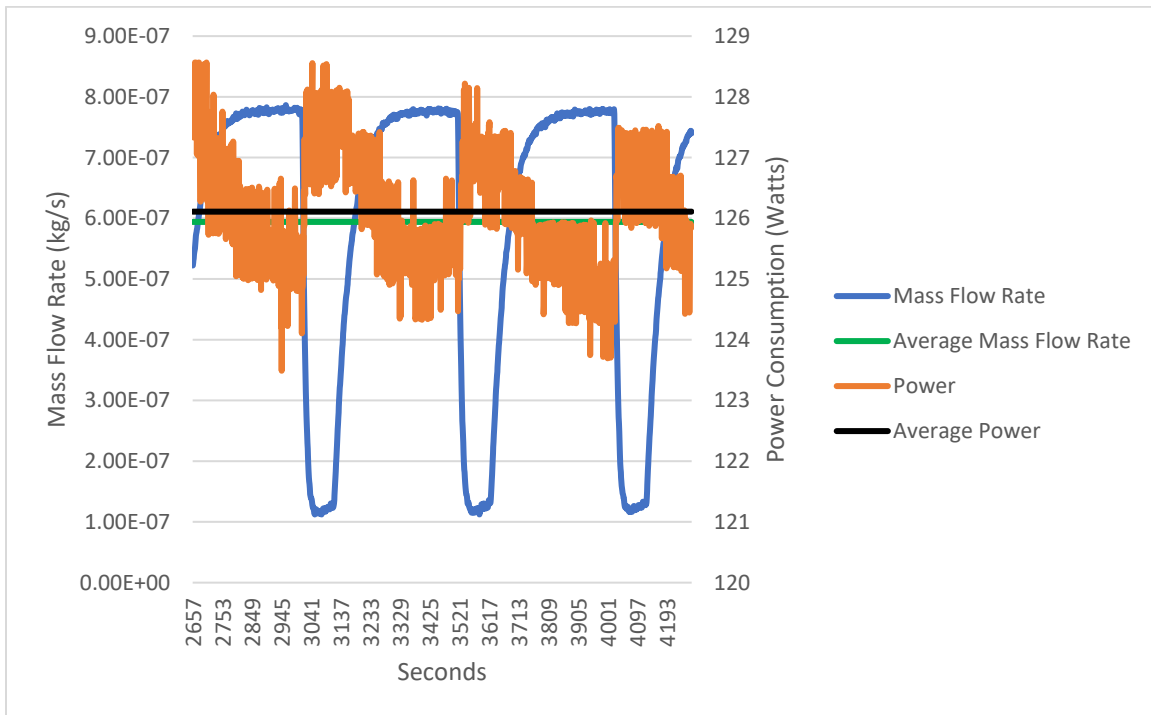


Figure 33. Electrolyzer Performance, Sampling 1 Hz

Figures 32 and 33 illustrate the electrolyzer performance at various sampling frequencies. The first test at a sampling frequency of 0.033 Hz showed that the mass flow rate, and the power consumed by the electrolyzer is not steady during operation. The mass flow rate of hydrogen gas from the electrolyzer oscillates from an approximate minimum of 1.04e^{-7} kg/s (2.29e^{-7} lbm/s) to an approximate maximum of 7.18e^{-7} kg/s (1.58e^{-6} lbm/s). This oscillation occurs at a period of 660 seconds (11 minutes). The average mass flow rate produced by the electrolyzer was 5.52e^{-7} kg/s (1.22e^{-6} lbm/s).

It is also of note that the power consumed by the electrolyzer oscillates in the same manner as the mass flow rate of hydrogen gas produced. In order to better capture this phenomenon, the test was repeated with a sampling frequency of 1 Hz.

Both test of the electrolyzer at different sampling frequencies exhibit the same characteristics with regards to oscillating mass flow rate and power consumption during operation. In order to examine this phenomenon, one must reference the definition of electrical power, Equation 5, and Ohm's Law, Equation 6.

$$\dot{W} = V_e I \quad (5)$$

$$V_e = IR \quad (6)$$

During operation, the electrolyzer is supplied a constant 13 volts; thus during periods of low power consumption the current applied to the electrolyzer is at its minimum. Applying this relationship of power and current to Ohm's Law it is determined that low power consumption, and low current correlates to a high internal resistance for the electrolyzer. This increase in internal resistance also corresponds to decreases in the mass flow rate of hydrogen gas produced. This phenomenon was noted by Birkemeier; however, at the time the electrolyzer was being supplied power directly from PV panels. Birkemeier attributed the oscillation in mass flow rate and power consumption as a characteristic of the PV panels and not the electrolyzer [17].

C. DRYER PERFORMANCE

As previously stated, the EHC installed in the hydrogen system requires the presence of dry hydrogen gas in order to operate. For the purpose of the EHC, dry hydrogen gas is defined as hydrogen gas with a relative humidity of less than 30 percent [24]. To ensure the EHC only received dry hydrogen, a membrane dehumidifier was installed in the system, and a provision to test the performance of the membrane dehumidifier was part of the experiment design.

The first step to evaluate dryer performance was to establish a baseline relative humidity for the hydrogen gas produced by the electrolyzer. The relative humidity is defined as the ratio of the mole fraction of the vapor in the mixture to the mole fraction of vapor in a saturated mixture at the same temperature and total pressure. Assuming the vapor as an ideal gas relative humidity can be expressed in terms of partial pressure and saturation pressure of the vapor, described by Equation 7 [46].

$$\phi = \frac{P_v}{P_g} \quad (7)$$

Normally the relative humidity of a mixture is determined by the wet and dry bulb temperatures from a psychrometer through an adiabatic saturation process.

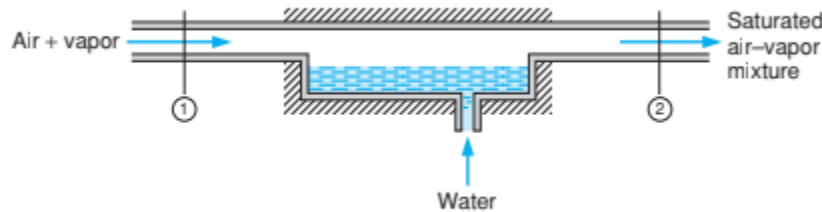


Figure 34. The Adiabatic Saturation Process. Source: [46].

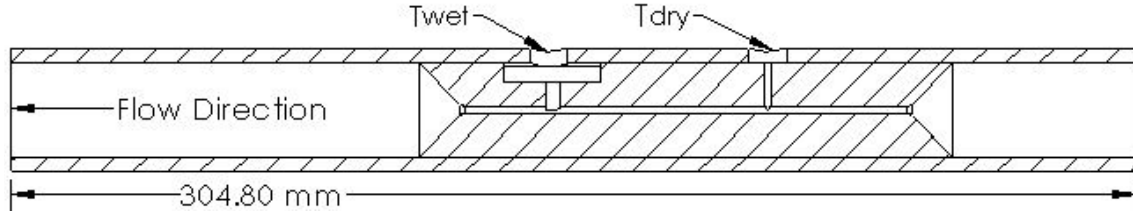


Figure 35. Relative Humidity Testing Device

During an adiabatic saturation process, if the relative humidity is less than 100% evaporation will occur on the wet bulb, thus resulting in a decrease in temperature. However, the slow velocity of the hydrogen gas posed a challenge for determining the relative humidity in this manner. During normal operating conditions the velocity of the hydrogen gas was insufficient to support evaporation on the wet bulb thermometer. In order to enable evaporation a testing device, Figure 35, was constructed out of a 3D printed insert and 25.4 mm (1 inch) polyvinyl chloride (PVC) pipe. The insert's purpose is to increase the velocity of hydrogen gas as the mixture passed by the wet and dry bulb thermometers.

When designing the insert the primary design requirement was achieving the required velocity ranging between 3 m/s (9.84 ft/s) and 10 m/s (32.80 ft/s) to support evaporation [47]. In order to determine the design characteristic to support this velocity the conservation of mass law was applied to the control volume, relative humidity testing device. Conservation of mass law states that mass can be neither created nor destroyed for a control volume. Equation 8 is the continuity equation used to express the conservation of mass law

$$\frac{dm_{C.V.}}{dt} = \Sigma \dot{m}_i - \Sigma \dot{m}_e = 0, \quad (8)$$

where

$\Sigma \dot{m}_i$ = Sum of mass flow into control volume

$\Sigma \dot{m}_e$ = Sum of mass flow exiting control volume

With the equation for determining mass flow rate, Equation 9, the appropriate cross-sectional area for flow through the testing device insert was determined. Appendix D contains the calculations for required cross sectional area and corresponding diameter.

$$\dot{m} = \rho AU \quad (9)$$

Due to additive manufacturing constraints the final diameter for the insert was increased from the calculated value of 1.6 mm (0.063 in) to 2mm (0.079 in). Access points were designed into the insert in order to position J type thermocouples to record the temperatures. Additionally, a square cut out was also removed around the wet bulb access point in order for saturated cotton material to be positioned around the thermocouple. The final dimensions for the insert are found in Appendix K. The insert was housed inside a 25.4 mm (1 inch) polyvinyl chloride (PVC) pipe.

In order to validate the operation of the relative humidity testing device commercially produced dry hydrogen gas was passed through the device and the wet and dry bulb temperatures were recorded. Once the relative humidity testing device was validated it was used to determine the relative humidity of the hydrogen gas produced by the electrolyzer and relative humidity of hydrogen gas once passing through the membrane dehumidifier.

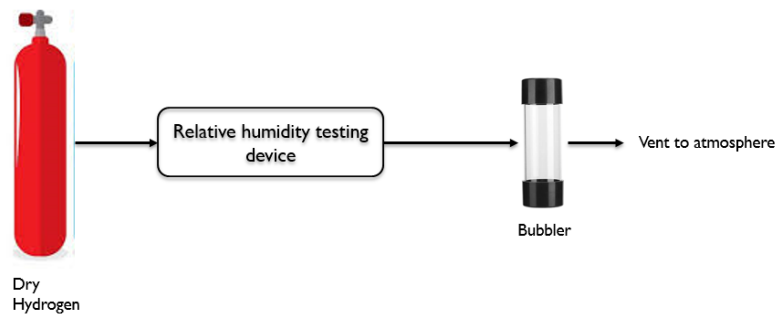


Figure 36. Dry Hydrogen Gas Relative Humidity Testing, Configuration #1

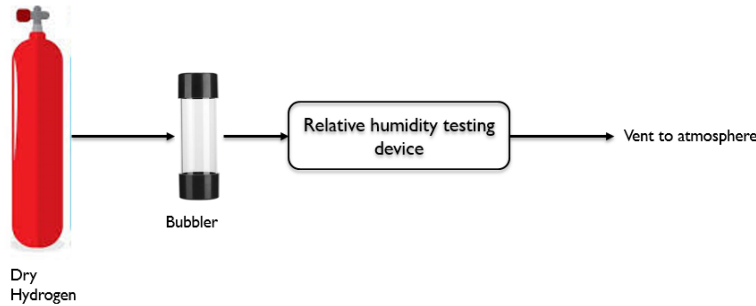


Figure 37. Saturated Hydrogen Gas Relative Humidity Testing, Configuration #2

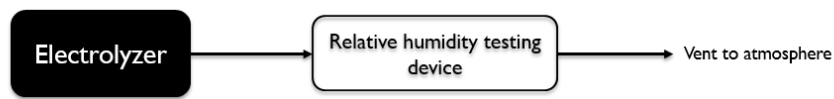


Figure 38. Hydrogen Gas Produced by Electrolyzer Relative Humidity Testing, Configuration #3

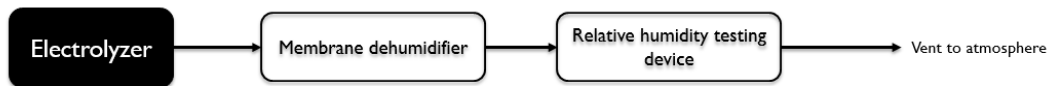


Figure 39. Hydrogen Gas after Membrane Dehumidifier Relative Humidity Testing, Configuration #4

Figure 36 shows the system configuration for recording wet and dry bulb temperatures of commercially produced dry hydrogen. In order for the velocity of hydrogen gas through the relative humidity testing device to be inside the required range of 3 m/s to 10m/s the pressure from the bottle had to be regulated down to 101.3 kPa (0.0005 psig). Appendix F shows calculations for how the required pressure was determined. The relative humidity of the dry hydrogen was determined to be 76%, which is higher than expected, which is a result of the lack of sensitivity of the testing.

There are multiple reasons for why the relative humidity of the commercially produced dry hydrogen is higher than expected, which include:

- Relative humidity testing device is not perfectly insulated, resulting in the web bulb thermometer receiving ambient heat from the environment preventing achieving lower web bulb temperatures.
- Velocity of hydrogen gas through device is greater than 10 m/s.
- Relative humidity testing device not perfectly sealed resulting in leaks of hydrogen gas.

The requirement to evaluate the relative humidity of the hydrogen gas was necessary to ensure safe operation of the EHC. While the relative humidity testing device exhibit shortcomings, this research is confident that the relative humidity testing device will register a temperature difference between the wet and dry bulbs when presented with hydrogen gas with a relative humidity less than 100%. Thus providing confirmation whether or not the membrane humidifier is capable of drying saturated hydrogen gas.

The second test, Figure 37, conducted was to pass dry hydrogen through a bubbler in order to saturate the hydrogen gas and record the wet and dry bulb temperatures. This test verified the operation of the relative humidity testing device with saturated hydrogen gas. The relative humidity of the saturated hydrogen gas was found to be 98%. With the relative humidity testing device validated the relative humidity of the hydrogen gas produced by the electrolyzer and hydrogen gas after passing through the membrane dehumidifier was recorded.

The third test, Figure 38, shows the testing configuration for the recording wet and dry bulb temperatures of hydrogen gas produced by the electrolyzer. The electrolyzer was located inside of the generation shed and the relative humidity testing device was located approximately 5 m from the electrolyzer and outside the generation shed. Wet and dry bulb temperatures were recorded after the electrolyzer had been allowed to operate for 4 min and 25 sec to ensure the generation side had been sufficiently purged. The relative humidity of the hydrogen gas produced by the electrolyzer was found to be 83.61%, which was less than the relative humidity of saturated hydrogen gas from testing configuration #2. It is hypothesized that this difference in relative humidity between testing configurations is the

result of heat addition to the hydrogen gas from the atmosphere. Ultimately, testing configuration #3 validated that the relative humidity testing device was capable of recording wet and dry bulb temperatures of hydrogen gas at the relatively slow mass flow rates produced by the electrolyzer.

The final test, Figure 39, shows the testing configuration for recording the wet and dry bulb temperatures of hydrogen gas that was been dried by the membrane dehumidifier. The electrolyzer, as with testing configuration #3, was operated for 4 minutes and 25 seconds to ensure system was sufficiently purged. As previously stated, the membrane dehumidifier required a vacuum in order to operate, thus a vacuum of 3392 Pa (.492 psia) was established and maintained during testing.

Table 7. Relative Humidity of Hydrogen Gas

Test	Ambient Temp, T_{∞}	Dry Bulb Temp, T_1	Wet Bulb Temp, T_2	% Relative Humidity
Dry Hydrogen	18.8 °C	21.6 °C	10.5 °C	76%
Saturated Hydrogen	12 °C	11.6 °C	10.5 °C	98%
Hydrogen produced by Electrolyzer	23 °C	31.1 °C	26.6 °C	83.1%
Hydrogen after membrane dehumidifier	12 °C	54 °C	52 °C	98%

Based on the testing results in Table 7, this research is confident to state that the membrane dehumidifier was ineffective at drying the saturated hydrogen gas.

D. COMPRESSOR PERFORMANCE

As previously stated, the electrochemical hydrogen compressor required inlet hydrogen gas with a relative humidity less than 30%. Due to the inability of the membrane dehumidifier to dry saturated hydrogen gas, the compressor test was limited to being supplied commercially produced hydrogen gas.

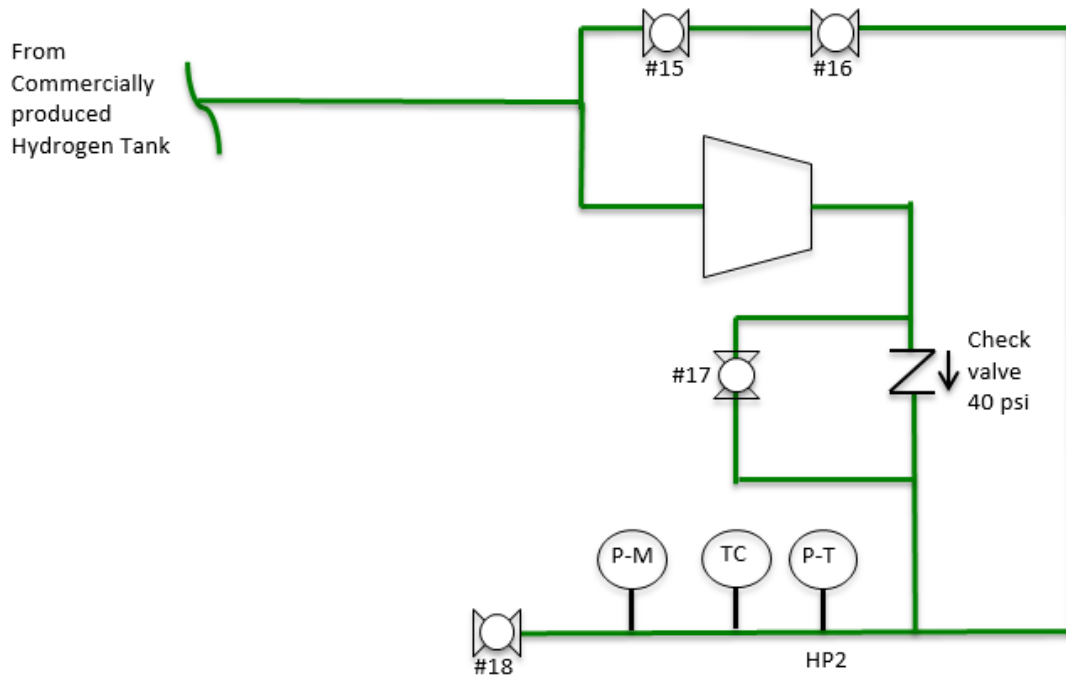


Figure 40. Schematic of Compressor Performance Testing Configuration

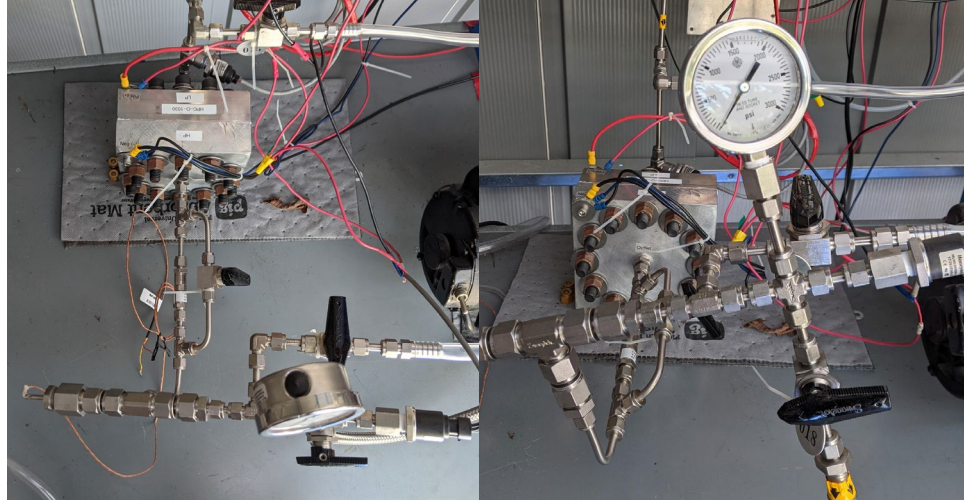


Figure 41. Compressor Testing Configuration

Figures 40 and 41 show the system alignment for the compressor testing. Valves #15, #16, and #17 were used during the purge process prior to testing and were in the closed position during testing. Valve #18 was also in the close position during testing in order to limit the volume of hydrogen gas being compressed. The check valve installed in the system was present in order to limit the back flow of hydrogen gas through the compressor should power be lost during operation. The compressor was supplied hydrogen gas at a constant inlet pressure of 135799.14 Pa (5 psig). Compressor output pressure was monitored by the Micro850 Controller via the Honeywell Pressure Transducer Model #MLK03KPSB01A indicated by HP2 in Figure 40. Additionally, output pressure from the Honeywell pressure transducer was verified by a mechanical pressure gauge installed in the system. The DC power supply was set to supply a constant voltage of 0.4 volts to the compressor for duration of the test. Samples were taken at a frequency of 0.033 Hz.

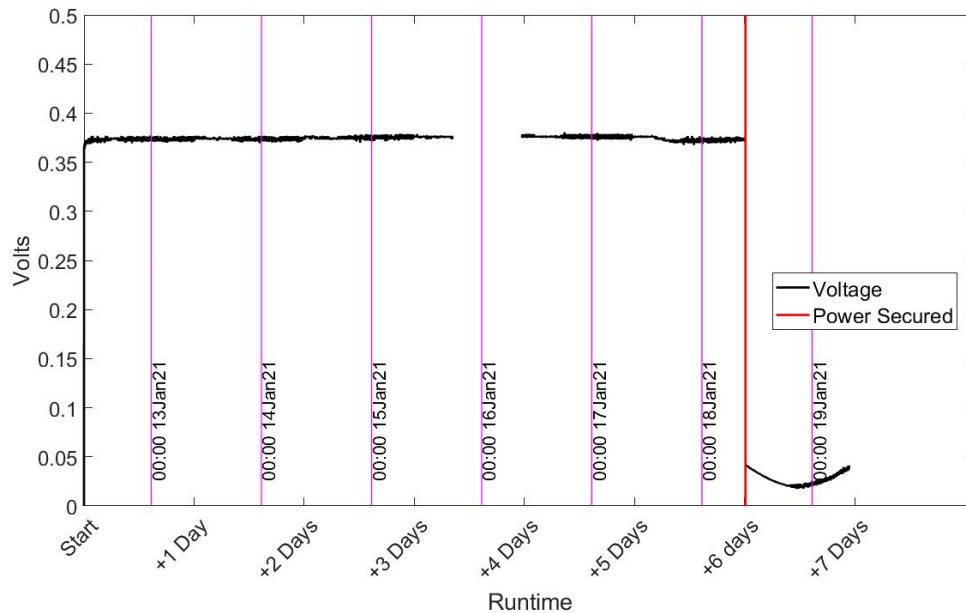


Figure 42. Compressor Voltage vs. Runtime

Figure 42 shows the voltage applied to the compressor for the duration of the test. The voltage remained relatively constant at approximately 0.375 volts. The difference in the DC supplied voltage of 0.4 volts and the compressor voltage of 0.375 volts can be contributed to internal resistance of the wiring configuration. Also, there is a break in recorded data beginning in the evening of 15 January 2021, because connectivity between the Micro850 controller and Dell laptop, used for data storage, was lost. Connectivity between the controller and laptop was reestablished on the morning of 16 January 2021. The current applied to the compressor could not be acquired with the Eaton, model EDC1460SP, DC current sensor due to the low operating current of the compressor. The current applied to the compressor ranged from 0.7 A at the start of testing to 0.032 A once max outlet pressure was achieved. The current applied to the compressor exhibited the characteristics of exponential decay during testing, however replacement of the Eaton, model EDC1460SP, DC current sensor would be required for further testing.

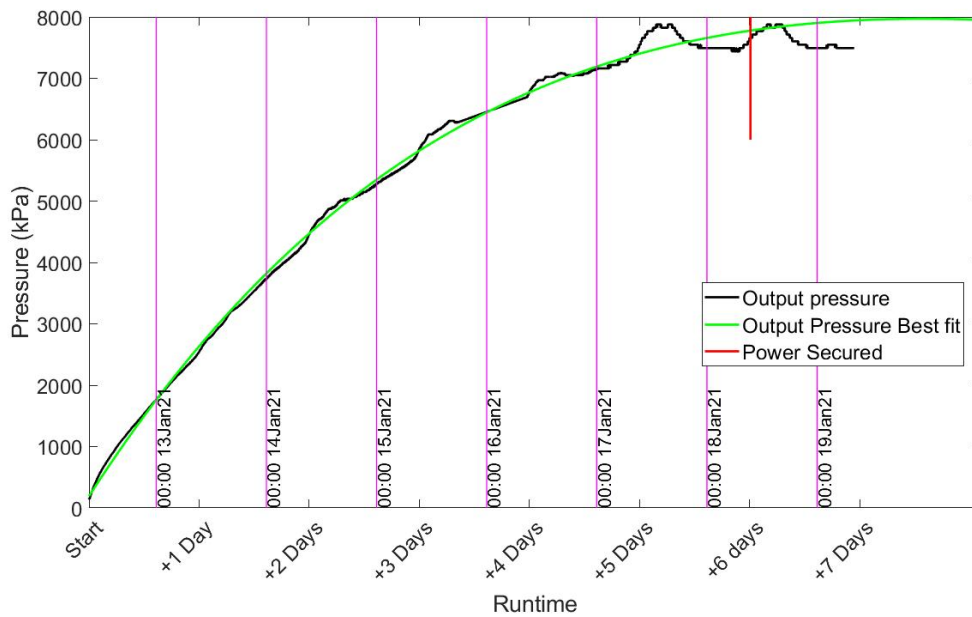


Figure 43. Compressor Output Pressure vs. Runtime; Including Best Fit Curve

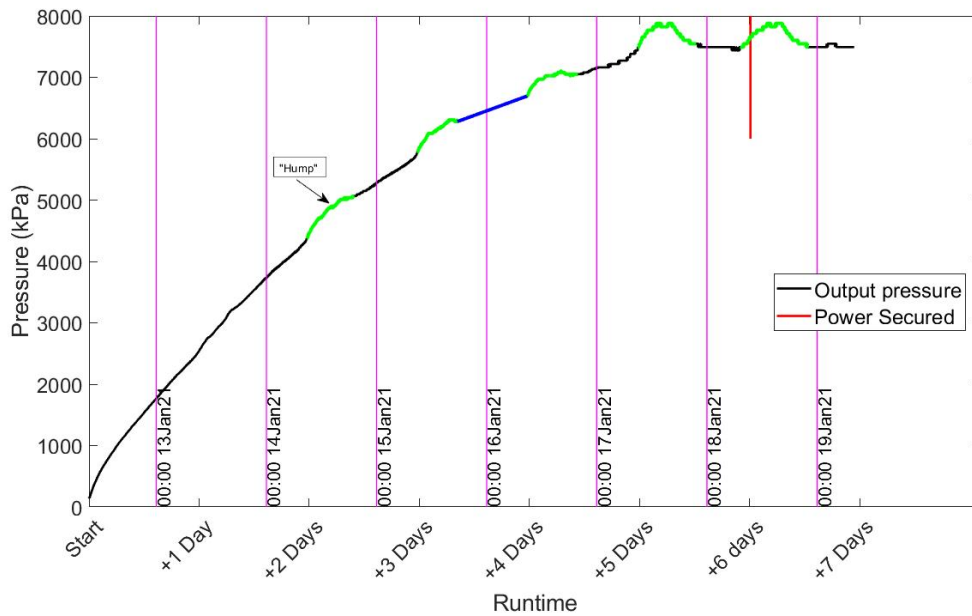


Figure 44. Compressor Output Pressure vs. Runtime; Including Areas of Interest

Figure 43 shows the outlet pressure from the compressor during testing. As depicted in Figure 43 the compressor operated constantly for approximately 6 days and reached a maximum outlet pressure of 7878.64 kPa (1128 psig). Over the course of the compressor test the ambient temperature average a daily high temperature of 295 K and an average daily low temperature of 282 K. Figure 44 highlights particular areas of interest when examining the compressor outlet pressure during testing. Portions of the compressor outlet pressure in Figure 44 that are highlighted in green corresponded to the middle of the day, corresponding to when the ambient temperature was at its highest. The system does not currently have a means for monitoring temperature on the outlet of the compressor, it is possible that the “hump” in the compressor outlet pressure is a result of heat addition. It is also reasonable to hypothesize that the steady state maximum outlet pressure of the compressor is 7492.53 kPa (1071.99 psig), which occurred around 00:00 PST on 18 January 2021. Thus, the maximum recorded outlet pressure of 7878.64 kPa (1128 psig) was a result of heating the hydrogen gas inside the control volume and not directly a result of the EHC. The blue highlighted portion of the outlet pressure in Figure 44 corresponds to the time in which connectivity with the Micro850 controller.

Another characteristic of the EHC to examine is the mass flow rate of hydrogen gas through the compressor. In order to conduct this analysis, the outlet hydrogen gas was treated as an ideal gas and assumed to have a constant temperature of 288.15 K. Based on the average daily high low ambient temperature use of a standard temperature is a reasonable approximation. Additionally, the outlet volume of the compressor was held constant for the duration of testing. Based on the assumptions, applying the ideal gas law yields Equation 9 for the amount of mass required to increase the pressure from a low pressure to higher pressure.

$$m = \frac{(P_h - P_l)V_{ct}}{R_{H_2}T_{st}} \quad (9)$$

Using Equation 9 and a standard increment of 300 kPa, yields a required mass increase of 8.588×10^{-6} kg (1.89×10^{-5} lbm) in order to rise the outlet pressure of the compressor. From the data collected during the compressor operational testing the time required to

increase the outlet pressure by 300 kPa was determined. Equation 10 shows that the time required was calculated as

$$\Delta t = t(@P_h) - t(@P_l), \quad (10)$$

where

$t(@P_h)$ = Compressor runtime at high pressure, in seconds

$t(@P_l)$ = Compressor runtime at low pressure, in seconds

With the amount of mass required to increase the pressure of hydrogen gas at the outlet of the compressor and the amount of time required by the compressor to do so an estimated mass flow rate through the compressor was calculated. Equation 11 is the equation used to determine the mass flow rate.

$$\dot{m} = \frac{m}{\Delta t} \quad (11)$$

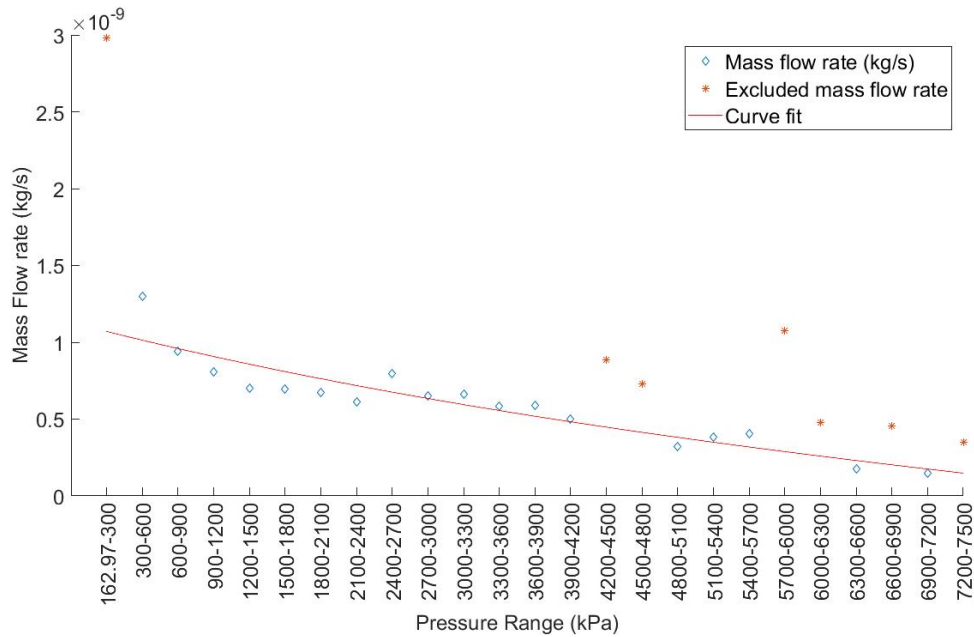


Figure 45. Mass Flow Rate (kg/s) through Compressor Over Various Pressure Ranges

Table 8. Mass Flow Rate (kg/s) through Compressor over Various Pressure Ranges

Sample #	Pressure Range (kPa)	Mass Flow Rate (kg/s)	Sample #	Pressure Range (kPa)	Mass Flow Rate (kg/s)	Sample #	Pressure Range (kPa)	Mass Flow Rate (kg/s)
1	162.97–300	2.9821e ⁻⁹	11	3000–3300	6.6269e ⁻¹⁰	21	6000–6300	4.7555e ⁻¹⁰
2	300–600	1.3012e ⁻⁹	12	3300–3600	5.8425e ⁻¹⁰	22	6300–6600	1.7424e ⁻¹⁰
3	600–900	9.3863e ⁻¹⁰	13	3600–3900	5.8906e ⁻¹⁰	23	6600–6900	4.5805e ⁻¹⁰
4	900–1200	8.0643e ⁻¹⁰	14	3900–4200	5.0049e ⁻¹⁰	24	6900–7200	1.5035e ⁻¹⁰
5	1200–1500	6.996e ⁻¹⁰	15	4200–4500	8.8632e ⁻¹⁰	25	7200 - 7500	3.5170e ⁻¹⁰
6	1500–1800	6.9655e ⁻¹⁰	16	4500–4800	7.2660e ⁻¹⁰			
7	1800–2100	6.7202e ⁻¹⁰	17	4800–5100	3.2275e ⁻¹⁰			
8	2100–2400	6.1171e ⁻¹⁰	18	5100–5400	3.8019e ⁻¹⁰			
9	2400–2700	7.9744e ⁻¹⁰	19	5400–5700	4.0607e ⁻¹⁰			
10	2700 - 3000	6.4917e ⁻¹⁰	20	5700–6000	1.0762e ⁻⁹			

Figure 45 and Table 8 shows the estimated mass flow rates through the compressor across various pressure ranges. As illustrated in Figure 45 the mass flow rate decreases as the compressor outlet pressure increase, which is to be expected based on the Figure 43 and 44. The mass flow rate at samples 1, 15, 16, 20, 21, 23, and 25 were excluded because the pressure rise across those pressure ranges were affected by ambient temperature. Sample 1 was excluded because the pressure range, P2–P1, was not the standard 300 kPa used to calculate the mass flow rate. The average mass flow rate of hydrogen gas through the compressor was approximately 4.37e-10 kg/s (9.65e⁻¹⁰ lbm/s). Based on the average mass flow rate through the compressor it would take approximately 19.7 years in order to fill one DOT-3AA2265 to a pressure of 7492.53 kPa (1071.99 psig); calculations can be found in Appendix G.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. DISCUSSION

The system performance testing yielded five key takeaways.

- Water production is intermittent and the constraining process.
- Electrolyzer averages a hydrogen gas mass flow rate of 5.52e^{-7} kg/s (1.22e^{-6} lbm/s).
- Membrane dehumidifier is ineffective at drying saturated hydrogen gas.
- EHC maximum outlet pressure when receiving hydrogen gas at relatively atmospheric pressure is 7492.53 kPa (1071.99 psig).
- EHC averages a mass flow rate of 4.37e^{-10} kg/s (9.65e^{-10} lbm/s).

In addition to the five key takeaways, several subtle characteristics of the hydrogen system were noted during its operation and testing that would require consideration in future design decisions.

A. HANDLING OF SATURATED HYDROGEN GAS

The first area that the system is deficient is in the operation of the membrane dehumidifier and the requirement to dry the hydrogen gas prior to reaching the EHC. The membrane dehumidifier exhibited an inability to dry saturated hydrogen gas when presented with gas at atmospheric pressure. Additionally, the vacuum pump required by the membrane dehumidifier exhibits a major power demand on the system. The vacuum pump also unlike the other major components in the system is not a solid state part making the pump more prone to failure, thus reducing the reliability of the overall system. In order to have a fully operational system a different method handling the saturated hydrogen gas would be required. There are two possible avenues for replacing the membrane dehumidifier; a desiccant based drying system or utilizing a wet proton exchange membrane in the EHC.

The major benefit of utilizing a desiccant drying system over the use of the membrane dehumidifier is the removal of the requirement for a vacuum pump. By removing the vacuum pump from the hydrogen system would reduce the power requirements and increase the overall reliability of the overall system. The only remaining requirement for use of a vacuum pump would be relegated to initial startup of the hydrogen system during the purging process. The other benefit of a desiccant drying system would be the production of dry hydrogen gas, allowing the hydrogen system to continue the use of the EHC with a dry proton exchange membrane. However, a desiccant drying system does have drawbacks that would need to be considered.

The major drawback of using a desiccant drying system is after extended operation the desiccant material would become saturated and no longer be effective at drying the saturated hydrogen gas being produced by the electrolyzer. Thus a means for periodically drying the desiccant material would be required.

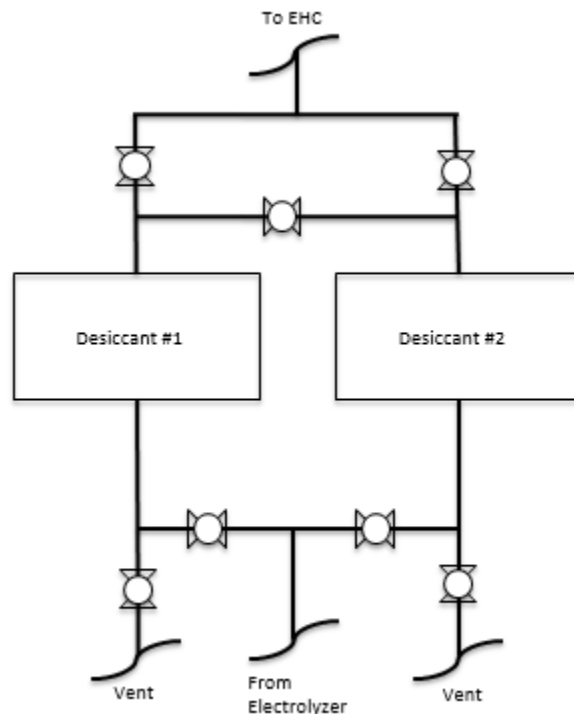


Figure 46. Proposed Desiccant Dryer Configuration

Unfortunately, using the proposed drying configuration, Figure 46, for a desiccant system has negative attributes. The first negative attribute is that a portion of the dry hydrogen gas has to be returned to the second desiccant tank to dry the desiccant and vented to the atmosphere. The other negative attributes are periodic operation of the system's valves. In order to operate the valves, either operator input, or a control system will be required. Obviously, the requirement of operator input in order to operate the drying system would reduce the autonomy of the overall hydrogen system. The challenges to using controllable valves is covered in a later discussion.

The simplest option for handling the saturated hydrogen gas produced by the electrolyzer would be to use a wet proton exchanged membrane inside of the EHC. The use of a wet proton exchange membrane could remove the requirement to dry the hydrogen gas from the electrolyzer. However, as previously stated wet proton exchange membrane are prone to degrade due to drying out if not in use frequent use, which poses a challenge for shipping the overall modular system. It would be possible for the PEM to degrade while the system is being transported to its location to begin hydrogen gas production. Additionally, there are purity concerns associated with using the wet PEM. Should water vapor be allowed to cross the PEM from the low to high-pressure side and thus into the hydrogen storage tanks the integrity of the system could be compromised. Further research is necessary to fully understand how a wet PEM in an EHC holds up to extended continuous operations, and the development of mitigation methods to ensure overall system safety.

B. WATER GENERATION

In the context of the Theory of Constraints, while the mass flow rate of the EHC is very slow the constraint on the system remains the generation of water from the atmosphere [44]. It is the intermittent nature of water generation that makes the process of generating water the limiting factor for the system. There are two options for handling the water generation constraint for the hydrogen system. First, option would be to remove the water generation from the ambient atmosphere from the system. Changing the system configuration in order to support receiving water from a municipal water supply would alleviate the issues with water generation. However, this approach is not desirable for the

overall hydrogen system. Relying on an already established water supply would limit the operating areas for the hydrogen system. Additionally, impurities in a municipal water supply could affect electrolyzer performance, and result in the creation of chlorine gas [48].

The preferred approach would be for the integration of a new robust water generation method in the overall hydrogen system. A robust water generation system would be required to produce water at rate to meet the supply demands of the electrolyzer and EHC. One such technology to investigate the metal-organic framework (MOF) by Yaghi at the University of California, Berkeley [49]. The MOF system utilizes a porous material to collect water vapor from the atmosphere. The initial MOF system was passive and would absorb water at night. The latest MOF system is uses fans and heater powered by solar energy in order to promote the continuous capture of water vapor from the atmosphere [50, 51]. The use of a water generation system already designed to operate off of solar energy would be aligned with the overall purpose of this research, production of compressed hydrogen gas from renewable sources.

C. SIZING OF COMPONENTS

Another deficiency of the current hydrogen system is the slow mass flow rates of the EHC. In accordance with the Theory of Constraints, in order to improve the overall system the EHC needs to be optimized. There are multiple options for the improving the performance of the EHC. Increasing the number of compression stages can increase the compressor's mass flow rate; however tends to have a negative effect on the maximum possible outlet pressure. Also to be considered is the possibility of placing multiple EHC in parallel to increase the overall mass flow through the system. Unfortunately, placing multiple EHCs in parallel will not increase the overall maximum pressure of the system. The overall system will be limited the lowest maximum pressure rating of the EHC in use. As the overall system is refined, especially the performance of the EHCs, it is important to perform continuous performance testing and analysis on all of the system's components. The proper sizing of various components, especially the electrolyzer and EHC, is vital to ensure the interoperability of the system.

Another characteristic for consideration when sizing components for the hydrogen system is the required electrical power for each component. Additional components or components with higher throughput might require the additional PV panels or batteries to meet the power demands of the system.

D. ELECTRICAL STABILITY

As previously stated, the hydrogen system was removed from the PV panels for the integration of the hydrogen compression system with the hydrogen generation system. Birkemeier demonstrated that it was possible to operate the hydrogen generation system directly from PV panels, however the system was prone to extended periods of down time due to clouds and nighttime [17]. As a result, it is this research's opinion that a more stable energy supply system is needed. The PV panels, and charge controller would remain a part of the system with the implementation of a battery buffer to provide a stable DC supply for the system. Additionally, the use of an inverter could be used to provide power to the solenoid valves, #1 and #2, and the PID controlled valve, #3, which require AC power. The implementation of a battery bank into the overall system design would be advantageous for the overall system.

One advantage of installing a battery buffer into the system would be the capability to handle fluctuations in power from PV panels. The overall system would be able to continue operation during periods of cloud cover, which previously would have left the system as inoperable. A properly sized battery buffer would also allow the system to continue operating during nighttime. As previously stated, the dehumidifier's inefficiency at rejecting heat from the Peltier element is a major hindrance to the generation of water. Nighttime operation would assist in water generation due to the lower ambient temperatures at night. Another advantage of a battery buffer is the continuous operation of the EHC, day and night, would aid in maximizing the potential of the EHC, thus exploiting the constraint. Lastly as previously stated a battery buffer would enable the continued monitoring of the system by the Mirco850 controller. With the current configuration the Mirco850 controller would be unable to recover from a temporary loss of power, resulting in loss of control of the system.

E. SYSTEM ISOLATION AND ADDITIONAL SAFETY

Currently installed in the system is a check valve located immediately after the EHC. The purpose of the check valve is, in the event of a loss of power to the EHC, to prevent the back flow of hydrogen gas across the PEM. Excessive backflow across the PEM could lead to a buildup of pressure on the generation side of the system resulting in possible damage to equipment or personnel. This research recognizes that the use of a check valve is not an appropriate manner for system isolation, and further improvements in system design are necessary. Additionally, the majority of the valves located in the system are manually operated ball and gate valves. While these manual valves and check valve aid in the simplicity of the overall system, they limit the autonomy and safety of the overall system.

In an ideal system the use of controllable valves would allow for the automatic switching between storage tanks and isolation of components in the event of a loss of power. An electro-pneumatic actuated ball valve in the normally closed position could be utilized in the system to increase autonomy. These valves could be integrated into the overall control system utilizing an electrical signal from the Micro850 controller to control the valves operation, and should power be lost to the controller automatically close, thus isolating the system. The issue with the electro-pneumatic actuator is the requirement for a compressed air system in order to supply the valves' actuator with air at 515 kPa (60 psig) air. The compressed air is used to perform the physical action of opening and maintaining the position of the valve. Normally in an industrial setting the availability of compressed air would not be a problem, however the hydrogen system is intended to be self-sufficient, and mobile. Thus in order to install controllable valves into the system a compressed air system would be required to be designed and installed in the system.

Lastly, it was observed during initial pressure and system integrity testing that the electrical current supplied to the EHC would slowly decay as the pressure gradient across the PEM increased. However, sharp increases in current were observed correlating to hydrogen leaks from the system. It is hypothesized that given established performance curves for the EHC deviations in electrical current could be used as an operating parameter for the indication of a hydrogen leak. With the inclusion of controllable valves and

established electrical current metrics the hydrogen system would be able to autonomously identify and isolate leaks.

F. IMPROVED SENSORS

Performance testing for the hydrogen system also highlighted deficiencies with some of the current sensors installed in the system. The areas where improved sensor is needed to better control and monitor the system are the following:

1. Improved tank level indicators
2. Replacement of Honeywell pressure transducers
3. Replacement of Eaton, model EDC1406SP, DC current sensor for monitoring current to the EHC
4. Implementation of temperature monitoring into control system.

As previously mentioned, the main parameter utilized by the control system used to relate the operation of different components to one another is the amount of water available in the various tanks. Thus installing deeper water collection and process tanks with corresponding tank level indicators would aid in the controllability of the system.

Another improvement for the hydrogen system's sensors would be the replacement of the Honeywell pressure transducers. During performance testing the transducer, model #MLH500PSL01A, on the inlet side of the EHC was damaged, and requiring replacement. A future replacement of the inlet side of the EHC should have a smaller pressure range being that the inlet of the EHC in a fully operational configuration would operate approximately atmospheric conditions. Additionally, voltage signal from the Honeywell pressure transducers is affected by the internal resistance of the wire connecting the sensor to the Mirco850 controller. As a result, future pressure sensors should have a current output signal vice a voltage signal, in order to remove any possible signal distortion.

As previously mentioned, the operating current for the EHC ranged from 0.7 to 0.032 Amps, and the Eaton, model EDC1460SP, lacked the resolution in order to accurately monitor the EHC's current draw. Future sensor considerations should consider the low operating amperage for the EHC.

Lastly, future versions of the control system should be able to monitor the temperature of the hydrogen gas during operation. Monitoring the temperature would enable the controller to account for pressure rise due to temperature increase, as well as improve system safety.

G. SUPPLY CHAIN MANAGEMENT

It is outside the scope of this research, but supply chain concerns should be taken into account and further investigated. This researcher identified two supply chain concerns associated with the overall system that require attention when making future design decisions. The first supply concern is that the company that produced the electrolyzer, Hybrid Hydrotech, is no longer in business. Alternative vendors should be recognized early in order to alleviate the potential electrolyzer supply issues should the current electrolyzer become damaged and to support the production of additional systems. Lastly, in accordance with COMUSFLTFORCOMINST 4790.3 Volume 5 the hydrogen system will be required to meet Level One system requirements, because of the high-pressure hydrogen gas. It must be ensured that companies that supply EHC's are able to meet the Level One system requirements. Consideration by the appropriate DOD organization should begin to determine the requirements for certifying vendors for production of EHCs that meet military specifications. As with the electrolyzer, alternative vendors for the EHCs should be identified in order to verify that the vendor has the industrial capacity to meet the DOD's future requirements.

H. SECURITY

Also outside the scope of this research but should be taken into consideration as a design parameter going forward is the security features, both physical and cyber, of the hydrogen system. The final hydrogen system will require the implementation of physical security methods to ensure that during operation the hydrogen system is not either inadvertently or intentionally compromised by physical means. Moreover, PLCs have been shown to be vulnerable to cyber-attacks [52]. Future design decisions should consider the impacts on the physical and cyber security of the hydrogen system.

V. CONCLUSION

The purpose of this research was the implementation of a control system to integrate the generation and compression of hydrogen gas. To support the implementation of the control system the overall system was removed from PV panels and powered using commercially off the shelf DC power supplies. For the control system, programmable logic controllers were used to monitor and control the operation of the overall systems various components.

During system performance testing it was found that water generation by the dehumidifiers was intermittent. Hydrogen gas was generated by an electrolyzer, which averaged a mass flow rate of 5.52×10^{-7} kg/s (1.22×10^{-6} lbm/s). The membrane dehumidifier installed in order to dry the saturated hydrogen gas was found to be ineffective. Finally, an electrochemical hydrogen compressor was used to compress hydrogen gas to the steady state maximum outlet pressure of 7492.53 kPa (1071.99 psig) at an average mass flow rate of 4.37×10^{-10} kg/s (9.65×10^{-10} lbm/s).

In conclusion it is possible to autonomously produce compressed hydrogen gas from renewable sources. Additionally, improvements have been identified for implementation in future system designs.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. RECOMMENDATIONS

It is recommended that future research should focus on three main areas for improving the overall system. The three main areas of focus are handling of saturated hydrogen, electrical stability, and water generation.

The first area of focus is the handling of the saturated hydrogen gas from the electrolyzer. This research recommends that the EHC should operate utilizing a wet PEM, thus removing the requirement to dry the hydrogen gas. Further research should be conducted to test performance of an EHC with a wet PEM, especially in how the PEM holds up to extended operations and what purity the compressed hydrogen gas is.

Second, future design and research should concentrate on placing the system back on renewable sources of energy. The installation of PV panels with a battery bank would provide power to the system with an energy buffer in order to provide the control system electrical stability. Electrical stability in the form of batteries would allow for the system to continue operations during intermittent losses of solar energy.

Lastly, this research recommends that a metal-organic framework water harvesting system be obtained and integrated into the overall system. The performance of the metal-organic framework system should be evaluated to determine the feasibility of this component for the generation of water.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A. MICRO 850 CONTROLLER LAYOUT

A. GENERATION

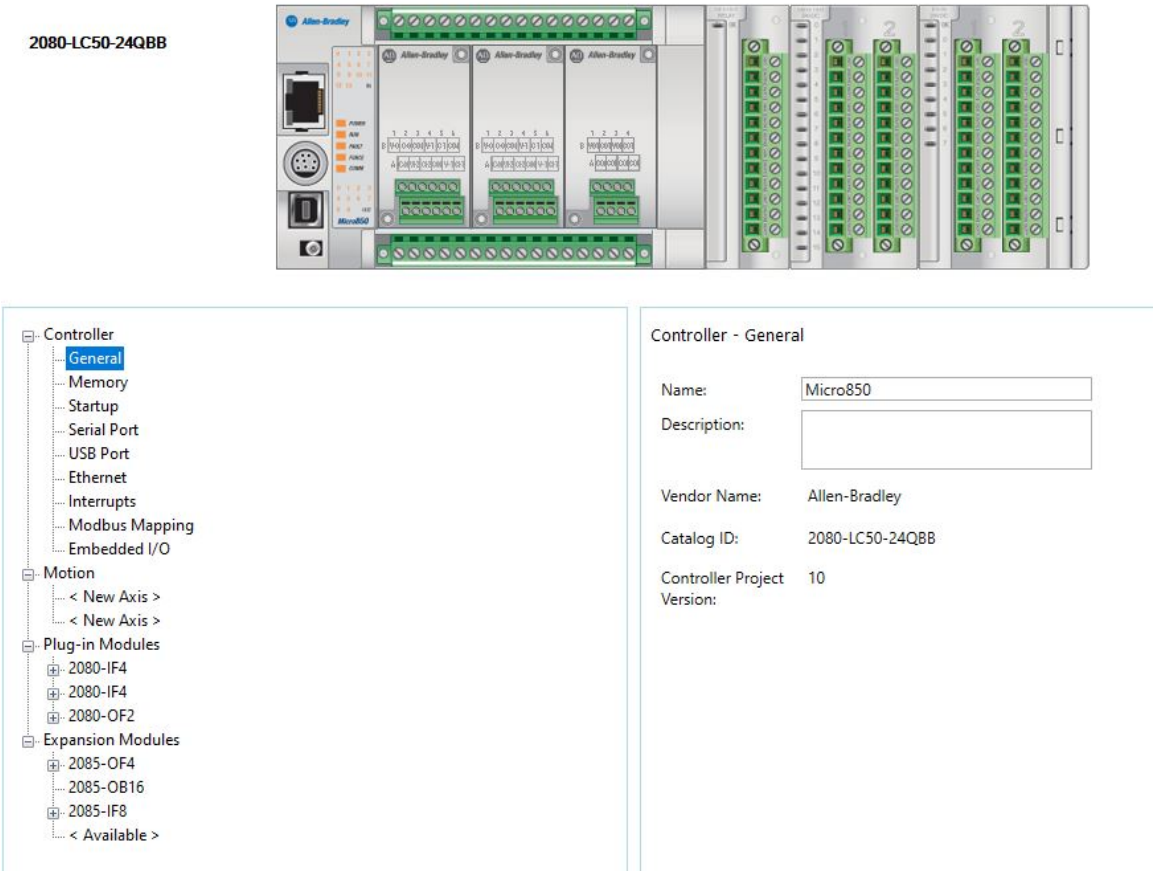


Figure 47. Generation Micro850 Controller Layout

B. COMPRESSION AND STORAGE

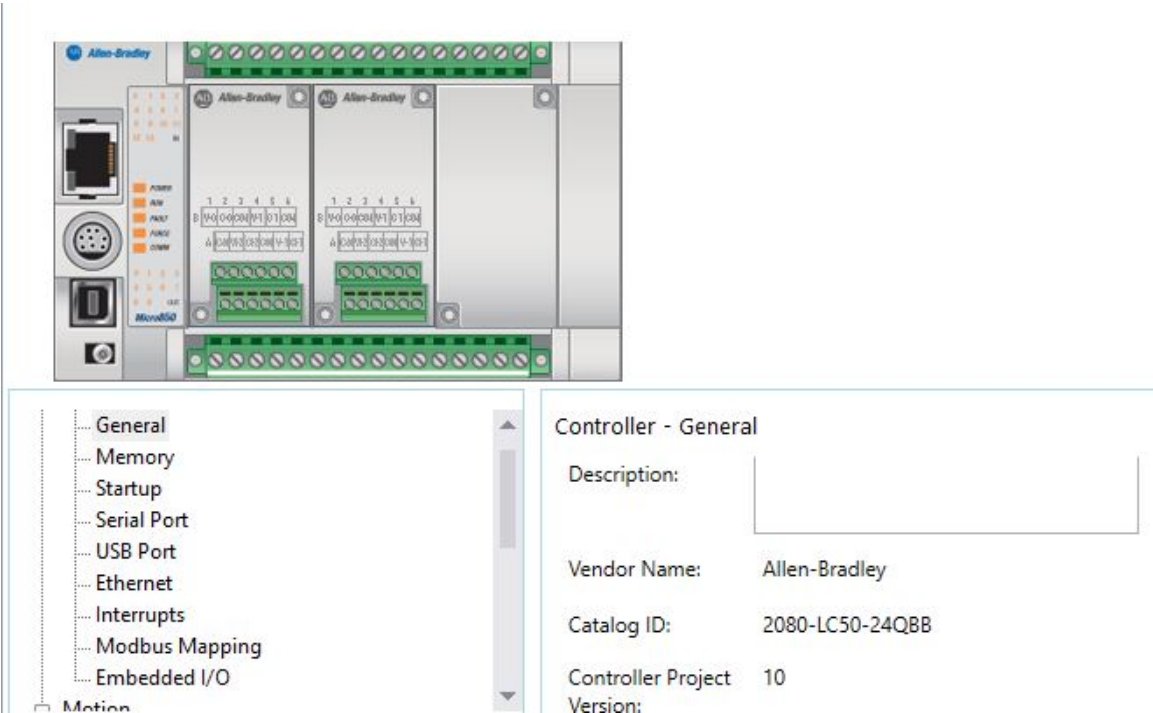


Figure 48. Compression Micro850 Controller Layout

APPENDIX B. WATER REQUIRED TO FILL ONE DOT-3AA2265 CYLINDER WITH HYDROGEN GAS

In order to determine the specific volume of hydrogen inside one pressurized DOT-3AA2265 cylinder, the ideal gas law is applied as

$$P_{max}(v_{H2}) = R_{H2} (T_{st}), \quad (B.1)$$

where

$$v_{H2} = \text{specific volume of hydrogen} .$$

Rearranging the ideal gas law to solve for the specific volume of hydrogen gas

$$v_{H2} = \frac{R_{H2} (T_{st})}{P_{max}} = \frac{(4124.3)(288.15)}{13.78951e^6} \quad (B.2)$$

yields

$$v_{H2} = 0.08618 \frac{m^3}{kg} .$$

Next is to determine the mass of hydrogen gas in the storage cylinder,

$$m_{H2} = \frac{V_{DOT}}{v_{H2}}, \quad (B.3)$$

where

$$m_{H2} = \frac{0.0433}{0.08618}$$

$$m_{H2} = 0.50242 \text{ kg} .$$

In order to relate amount of hydrogen to water, the mass of hydrogen is converted into moles of hydrogen

$$mol_{H2} = \frac{m_{H2}}{M_{H2}}, \quad (B.4)$$

which yields

$$mol_{H2} = 249.21681 \text{ moles} .$$

The chemical composition of water, H₂O, provides a mole fraction of hydrogen in water of 2/3. With this mole fraction it can be determined how many of moles of water is necessary to produce the required moles of hydrogen. Equation B.5 demonstrates this relationship

$$mol_{water} = \frac{mol_{H_2}}{X}, \quad (B.5)$$

where

$$X = \text{mole fraction } H_2 \text{ in } H_2O = \frac{2}{3}$$

yields

$$mol_{water} = 373.82521 \text{ moles.}$$

Now that the number of moles of water has been determined, a mass of water can be determined to be

$$m_{water} = (mol_{water})M_{water}, \quad (B.6)$$

where

$$M_{water} = 0.018015 \frac{kg}{mol}$$

yields

$$m_{water} = 6.73446 \text{ kg} .$$

Assuming density of water at a standard temperature of 15°C (288.15 K), the volume of water require can be determined as

$$Vol_{water} = \frac{m_{water}}{\rho_{water}}, \quad (B.7)$$

where

$$\rho_{water} = \text{Density of water at } 15^\circ\text{C} = 999.06 \frac{kg}{m^3}$$

yields

$$Vol_{water} = 0.00674 \text{ m}^3 = 6.740 \text{ liters (1.78 gallons)} .$$

APPENDIX C. GENERATION SIDE PURGING TIME CALCULATIONS

All calculations were conducted with an assumed mass flow rate of $5.52e^{-7}$ kg/s, which based upon hydrogen gas production testing. Assuming standard density for hydrogen of 0.0813 kg/m^3 , the volumetric flow rate of hydrogen gas is determined.

$$\dot{m} = \rho_{H_2}AU = 5.52e^{-7} \frac{\text{kg}}{\text{s}}$$

thus,

$$Q = AU = 6.789e^{-6} \frac{\text{m}^3}{\text{s}}$$

Because of the conservation of mass law and continuity equation the slowest velocity of hydrogen gas will occur where the cross-sectional area is the largest. The largest diameter of the piping on the generation side is 10 mm. Thus,

$$A = \frac{\pi}{4}d^2 \tag{C.1}$$

$$A = 7.854e^{-5} \text{ m}^2$$

Yields,

$$U = \frac{Q}{A} = 0.08645 \frac{\text{m}}{\text{s}} \tag{C.2}$$

A time, t , for hydrogen to travel from the electrolyzer outlet to the vent is determined knowing that the length of piping from the outlet to the vent is 10.6 m.

$$t = \frac{L}{U} = \frac{10.6 \text{ m}}{0.08645 \frac{\text{m}}{\text{s}}} = 122.6 \text{ seconds} \tag{C.3}$$

Assuming a Factor of Safety, FS, of 2, the final required purge time, t_{purge} , is determined.

$$t_{\text{purge}} = FS * t = 2 * (122.6) = 245.23 \text{ seconds} \sim 4 \text{ min } 5 \text{ seconds} \tag{C.4}$$

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX D. CALCULATIONS FOR THE REQUIRED CROSS-SECTIONAL AREA AND CORRESPONDING DIAMETER FOR RELATIVE HUMIDITY TESTING DEVICE

All calculations were conducted with an assumed mass flow rate of $5.52e^{-7}$ kg/s, which based upon hydrogen gas production testing. Assuming standard density for hydrogen of 0.0813 kg/m³, the volumetric flow rate of hydrogen gas is determined.

$$\dot{m} = \rho_{H_2}AU = 5.52e^{-7} \frac{kg}{s}$$

thus,

$$Q = AU = 6.789e^{-6} \frac{m^3}{s}$$

In order to determine the required cross-sectional area and corresponding for the testing device the continuity equation, Equation D.1, was applied.

$$\frac{dm_{c.v.}}{dt} = \Sigma \dot{m}_i - \Sigma \dot{m}_e = 0 \quad (D.1)$$

From Figure 49, the adiabatic saturation process, that depicts the operation of the relative testing device, the continuity equation can be simplified.

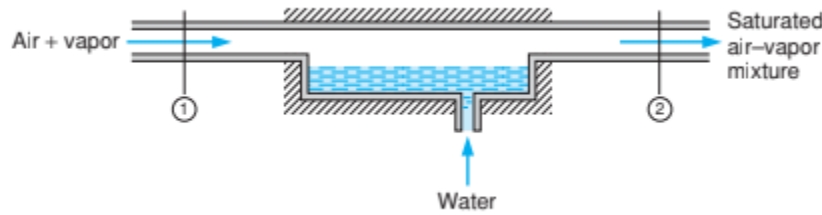


Figure 49. The Adiabatic Saturation Process. Source: [46].

Simplified continuity equation,

$$\dot{m}_1 = \dot{m}_2$$

Thus,

$$\rho_1 A_1 U_1 = \rho_2 A_2 U_2 \quad (D.2)$$

Assuming constant density, $\rho_1 = \rho_2$, yields,

$$A_1 U_1 = A_2 U_2 = Q = 6.789e^{-6} \frac{m^3}{s}$$

With a required velocity of 4 m/s at the exit, yields,

$$A_2 = \frac{Q}{U_2} = 1.697e^{-6} m^2 \quad (D.3)$$

Thus, the required diameter is,

$$d = \sqrt{\frac{4 \cdot A}{\pi}} \quad (D.4)$$

$$d = 0.00147 m = 1.47 mm$$

APPENDIX E. RELATIVE HUMIDITY SAMPLE CALCULATION

Table 9. Saturation Properties for Water—Temperature Increments.
Adapted from [53].

Temperature (K)	Pressure (MPa)	Density (kg/m ³)	Volume (m ³ /kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)
299.5	0.00343418	996.649	0.00100336	110.471	110.474	0.386115
299.6	0.00345449	996.622	0.00100339	110.889	110.892	0.387511
299.7	0.00347491	996.595	0.00100342	111.307	111.311	0.388906
299.8	0.00349544	996.568	0.00100344	111.725	111.729	0.390301
299.9	0.00351607	996.54	0.00100347	112.143	112.147	0.391695
300	0.00353681	996.513	0.0010035	112.561	112.565	0.393089
⋮	⋮	⋮	⋮	⋮	⋮	⋮
303	0.00421054	995.651	0.00100437	125.103	125.107	0.434686
303.1	0.0042348	995.621	0.0010044	125.521	125.525	0.436065
303.2	0.00425918	995.591	0.00100443	125.939	125.943	0.437444
303.3	0.00428368	995.561	0.00100446	126.357	126.361	0.438823
303.4	0.0043083	995.53	0.00100449	126.775	126.779	0.440201
303.5	0.00433305	995.5	0.00100452	127.193	127.197	0.441578
303.6	0.00435792	995.469	0.00100455	127.611	127.615	0.442955
303.7	0.00438291	995.439	0.00100458	128.029	128.033	0.444332
303.8	0.00440803	995.408	0.00100461	128.447	128.451	0.445708
303.9	0.00443327	995.377	0.00100464	128.865	128.869	0.447083
304	0.00445864	995.346	0.00100468	129.283	129.287	0.448459
304.1	0.00448414	995.316	0.00100471	129.701	129.705	0.449833
304.2	0.00450976	995.284	0.00100474	130.119	130.123	0.451208
304.3	0.00453551	995.253	0.00100477	130.537	130.541	0.452582
304.4	0.00456138	995.222	0.0010048	130.955	130.959	0.453955
304.5	0.00458739	995.191	0.00100483	131.373	131.377	0.455328

Table 10. Thermodynamic Properties of Water—Saturated Water.
Adapted from [46].

Temp (°C)	Pressure (kPa)	Enthalpy, kJ/kg		
		Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g
25	3.169	104.87	2442.30	2547.17
30	4.246	127.77	2430.48	2556.25
35	5.628	146.66	2418.62	2565.28

With the measured wet and dry bulb temperatures from the relative humidity testing device the relative humidity of the hydrogen gas can be determined.

$$T_{dry} = 31.11\text{ }^{\circ}\text{C} = 304.26\text{ K}$$

$$T_{wet} = 26.66\text{ }^{\circ}\text{C} = 299.81\text{ K}$$

Using a linear interpolation and Table 9 the saturation pressure of water vapor at T_{wet} is determined.

$$P_{vapor,2} = P_{high} - \left(\frac{P_{high} - P_{low}}{T_{high} - T_{low}} \right) * (T_{high} - T_{wet}) \quad (E.1)$$

$$P_{vapor,2} = 4333.04669 - \left(\frac{4333.04669 - 3434.176377}{303.5 - 299.5} \right) * (303.5 - 299.81)$$

$$P_{vapor,2} = 3505.33694\text{ Pa}$$

With saturation pressure of water vapor at T_{wet} , the mass ratio of water vapor to dry hydrogen, ω_2 is determined.

$$\omega_2 = \left(\frac{R_{H_2}}{R_{vapor}} \right) * \left(\frac{P_{vapor,2}}{P_{total} - P_{vapor,2}} \right) \quad (E.2)$$

$$\omega_2 = \left(\frac{4123.4}{461.5} \right) * \left(\frac{3505.33694}{101325 - 3505.33694} \right)$$

$$\omega_2 = 0.32024485$$

Assuming a steady state process and neglecting kinetic and potential energy, the first law of thermodynamics is applied to formulate an equation for the mass ratio of water vapor to dry hydrogen, ω_1 , at T_{dry} .

$$\omega_1 = \frac{C_{p_{H_2}}(T_{dry} - T_{wet}) + \omega_2 * h_{fg,2}}{(h_{v,1} - h_{f,2})} \quad (E.3)$$

The enthalpy values required for Equation E.3, were found using Table 10 and a linear interpolation, which yielded:

$$h_{fg,2} = \text{Evap}, h_{fg}, \text{Enthalpy at } T_{wet} = 2438360 \frac{J}{kg * K}$$

$$h_{v,1} = \text{Enthalpy of sat vapor at } T_{dry} = 2558256.67 \frac{J}{kg * K}$$

$$h_{f,2} = \text{Enthalpy of sat liquid at } T_{wet} = 111836.667 \frac{J}{kg * K}$$

Thus,

$$\omega_1 = \frac{14209(304.26 - 299.81) + 0.32024485 * 2438360}{(2558256.67 - 111836.667)}$$

$$\omega_1 = 0.34500345$$

With the mass ratio of water vapor to dry hydrogen the relative humidity, ω_1 , at T_{dry} , Equation E.4 is used to calculate the relative humidity, ϕ_1 , of the hydrogen gas.

$$\phi_1 = \left(\frac{\omega_1}{\left(\left(\frac{R_{H2}}{R_{vapor}} \right) + \omega_1 \right)} * \left(\frac{P_{total}}{P_{vapor,1}} \right) \right) * 100 \quad (E.4)$$

A linear interpolation of Table 8 yields a $P_{vapor,1}$ of 4532.29202 Pa. Thus,

$$\phi_1 = \left(\frac{0.34500345}{\left(\left(\frac{4124.3}{461.5} \right) + 0.34500345 \right)} * \left(\frac{101325}{4532.29202} \right) \right) * 100$$

$$\phi_1 = 83.1\%$$

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX F. REQUIRED PRESSURE FOR DRY HYDROGEN RELATIVE HUMIDITY TEST

Bernoulli's equation, Equation F.1, was applied, in order to determine the required regulated pressure of dry hydrogen from the commercial hydrogen tank to achieve a velocity of 10 m/s through the relative humidity testing device.

$$P_{in} + \left(\frac{1}{2}\rho U_{in}^2\right) + \rho g z_{in} = P_{out} + \left(\frac{1}{2}\rho U_{out}^2\right) + \rho g z_{out} \quad (F.1)$$

For this analysis the following assumptions were made:

- Incompressible fluid
- Difference in potential energy, $\rho g z$, is negligible.
- Pressure at the outlet is atmospheric pressure.
- Density, ρ , of hydrogen gas is 0.0813 kg/m³
- Velocity at the inlet is 0 m/s

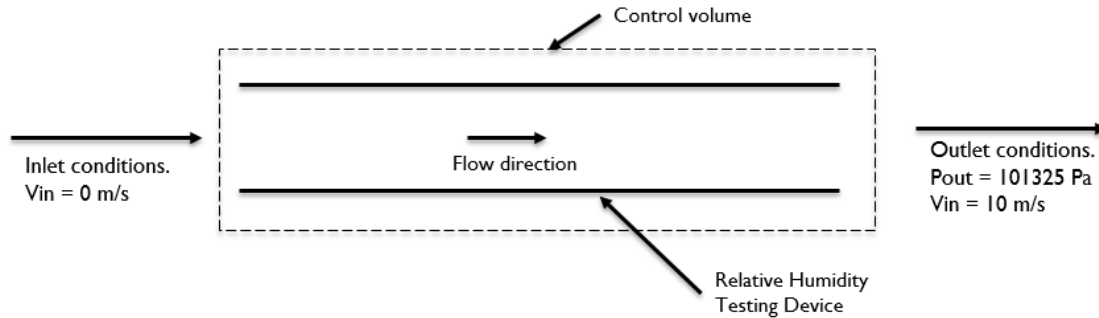


Figure 50. Free Body Diagram of Relative Humidity Testing Device

The resulting Bernoulli's equation based upon the assumptions is Equation F.2.

$$P_{in} = P_{out} + \left(\frac{1}{2}\rho U_{out}^2\right) \quad (F.2)$$

which yields;

$$P_{in} = 101325 + \left(\frac{1}{2} * (0.0813) * 10^2\right)$$

$$P_{in} = 101329.0691 \text{ Pa} = 0.000589 \text{ psig}$$

APPENDIX G. REQUIRED TIME TO FILL ONE DOT-3AA2265 CYLINDER BASED ON COMPRESSOR PERFORMANCE

All calculations were conducted based on the average compressor mass flow rate of 4.3773×10^{-10} kg/s and maximum compressor outlet pressure of 7492.53 kPa. Assuming an Ideal Gas and a standard temperature the time required to fill on DOT-3AA2265 is determined.

$$m_{DOT} = \frac{P \cdot V_{DOT}}{R_{H_2} \cdot T_{st}} \quad (G.1)$$

Yields,

$$m_{DOT} = 0.27299 \text{ kg}$$

Thus,

$$\Delta t = \frac{m_{DOT}}{\dot{m}} \quad (G.2)$$

Where,

$\Delta t = \text{Required time to fill one DOT – 3AA2265 cylinder, seconds}$

$\dot{m} = \text{Average mass flow rate of compressor}$

Yields,

$$\Delta t \approx 6.2 \times 10^8 \text{ seconds} \approx 19.7 \text{ years}$$

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX H. VACUUM/PRESSURE PURGING CALCULATIONS

The following is excerpted from [14] and provided as background information to help future researchers. This research has built upon Fosson's vacuum/pressure purging calculations to develop a purging procedure for the hydrogen system.

The purge station was designed to deliver at least 34 atm (500 psi) nitrogen using a commercial-off-the-shelf gas cylinder header and regulator. The vacuum pump available for use by the laboratory was capable of delivering a maximum of 711 mm (28 in) Hg (gauge) vacuum (0.064 atm).

The number of vacuum/pressure purge cycles required is calculated according to the formula found in [27] as follows:

$$N \geq \frac{\ln\left(\frac{C_{safe}}{C_{air}}\right)}{\ln\left(\frac{P_{Low}}{P_{High}}\right)} = \frac{\ln\left(\frac{0.01}{0.21}\right)}{\ln\left(\frac{P_{Low}}{P_{High}}\right)}, \quad (17)$$

$N = 1, 2, 3, \dots$

where,

C_{safe} = Safe concentration of residual oxygen, 1% per CGA G-5.4

C_{air} = Initial concentration of oxygen in air, 21%

P_{Low} = Absolute pressure after vacuum

and,

P_{High} = Purging pressure of inert gas, 34 atm N_2 (500 psi) maximum.

The total mass of N_2 required for the vacuum/pressure purge process is calculated as follows:

$$m = n \times M = \frac{(P_{High} - P_{Low}) \cdot V}{R \cdot T} \times \frac{M}{1000(g/kg)}, \quad (18)$$

where,

n = Moles of purge gas added to the station, mol

M = Molar Mass of Nitrogen, $28.0134 \frac{g}{mol}$

V = Total Volume of vessels, 0.2592 m³

R = Universal Gas Constant, $8.314 \frac{J}{mol \cdot K}$

T = normal temperature, 298.15 K (25 °C).

Table 11 provides list of optimum vacuum/pressure combinations to conserve purge gas.

Table 11. Optimum Vacuum/Pressure Purge Regimes

P _{Low} , atm	P _{High} , atm	N	Total Mass of N ₂ Required, kg
0.064	1.7	1	0.5
0.332	1.7	2	0.8
0.064	1.3	2	0.8
0.332	1.3	3	0.9
0.666	2.0	3	1.2
0.666	3.4	2	1.6
1.0	3.0	3	1.8
0.332	7.1	1	2.0
1.0	4.7	2	2.2
0.666	14.3	1	4.0
1.0	21.0	1	6.0

APPENDIX I. CALIBRATION CURVE HONEYWELL PRESSURE TRANSDUCER, MLH500PSL01A

The output voltage was recorded at 20 psig increments from 0 to 500 psig, in order to establish a calibration curve for the Honeywell pressure transducer, MLH500PSL01A. Nitrogen gas was used to pressurize the system for the calibration.

Table 11. Pressure vs. Output Voltage MLH500PSL01A

Pressure (psi)	Output voltage (Volts)	Pressure (psi)	Output voltage (Volts)
0	0.505	260	2.6071
20	0.6712	280	2.8003
40	0.8368	300	2.9724
60	1.017	320	3.1462
80	1.155	340	3.2826
100	1.32	360	3.4467
120	1.4805	380	3.5967
140	1.6368	400	3.7746
160	1.7804	420	3.9435
180	1.9645	440	4.1129
200	2.127	460	4.2638
220	2.2958	480	4.4304
240	2.4481	500	4.5429

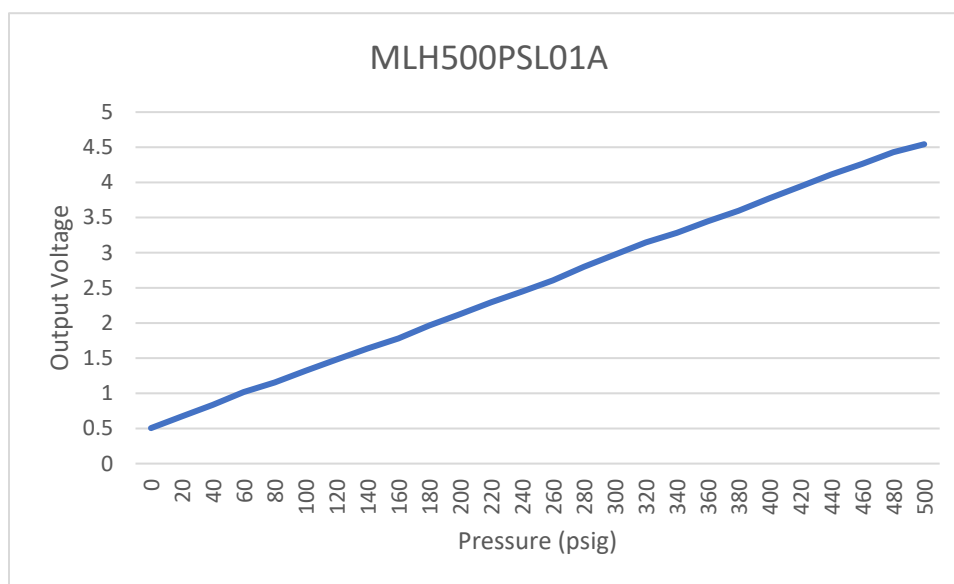


Figure 51. Honeywell Pressure Transducer, MLH500PSL01A

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX J. CALIBRATION CURVE HONEYWELL PRESSURE TRANSDUCER, MLH03KPSB01A

The output voltage was recorded at 20 psig increments from 0 to 500 psig, in order to establish a calibration curve for the Honeywell pressure transducer, MLH03KPSB01A. Nitrogen gas was used to pressurize the system for the calibration.

Table 12. Pressure vs. Output Voltage, MLH03KPSB01A

Pressure (psi)	Output voltage (Volts)	Pressure (psi)	Output voltage (Volts)
0	0.51	260	0.8619
20	0.54	280	0.8949
40	0.565	300	0.9188
60	0.59	320	0.9474
80	0.6187	340	0.9755
100	0.646	360	1.001
120	0.6727	380	1.026
140	0.6997	400	1.0559
160	0.724	420	1.0847
180	0.7545	440	1.1113
200	0.7842	460	1.1378
220	0.8096	480	1.1645
240	0.8349	500	1.185

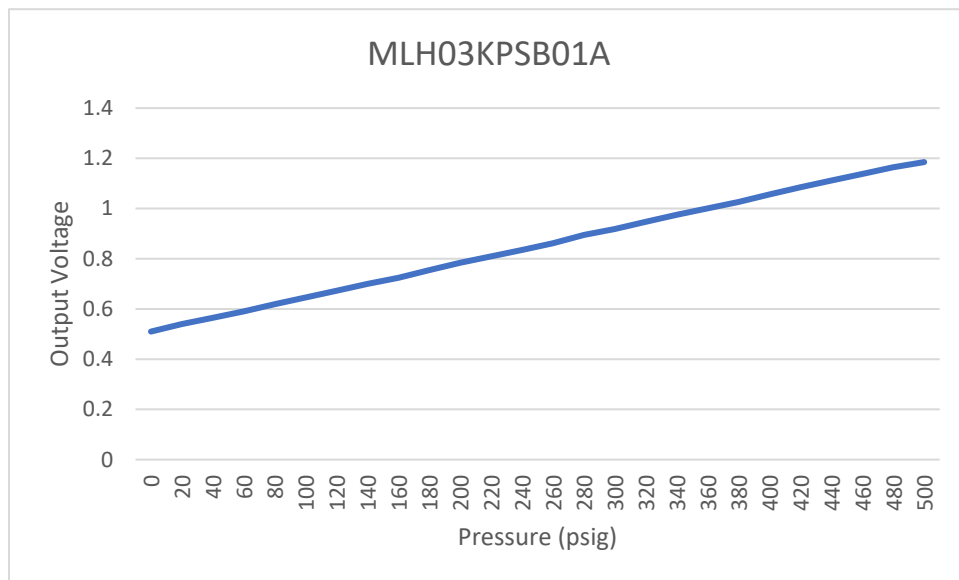
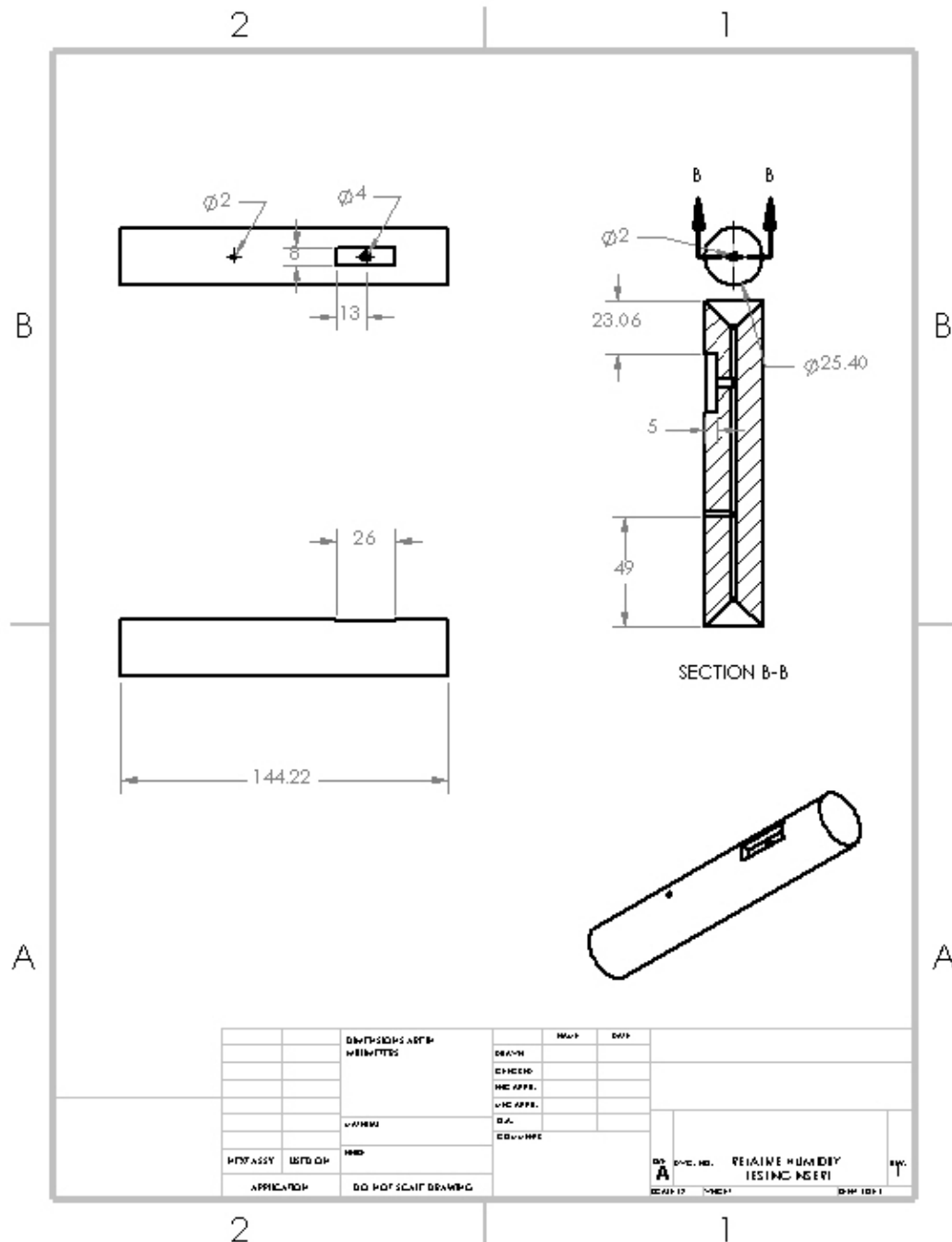


Figure 52. Honeywell Pressure Transducer, M LH03KPSB01A

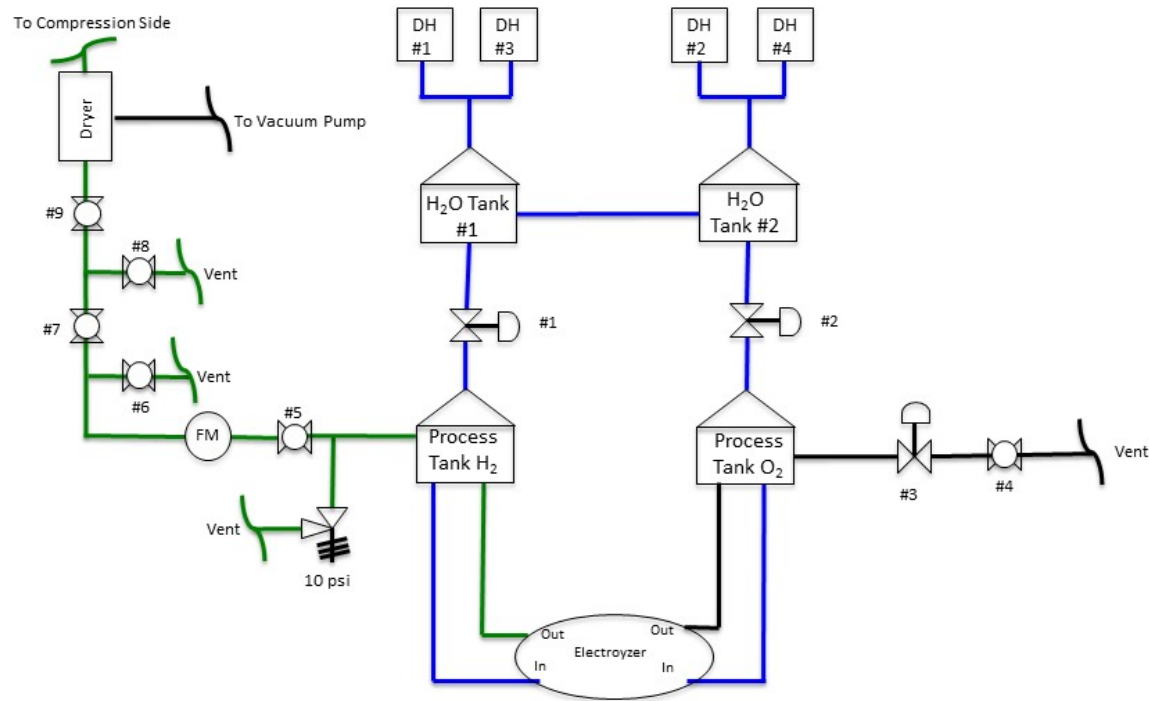
THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX K. RELATIVE HUMIDITY TESTING DEVICE INSERT DIMENSIONS

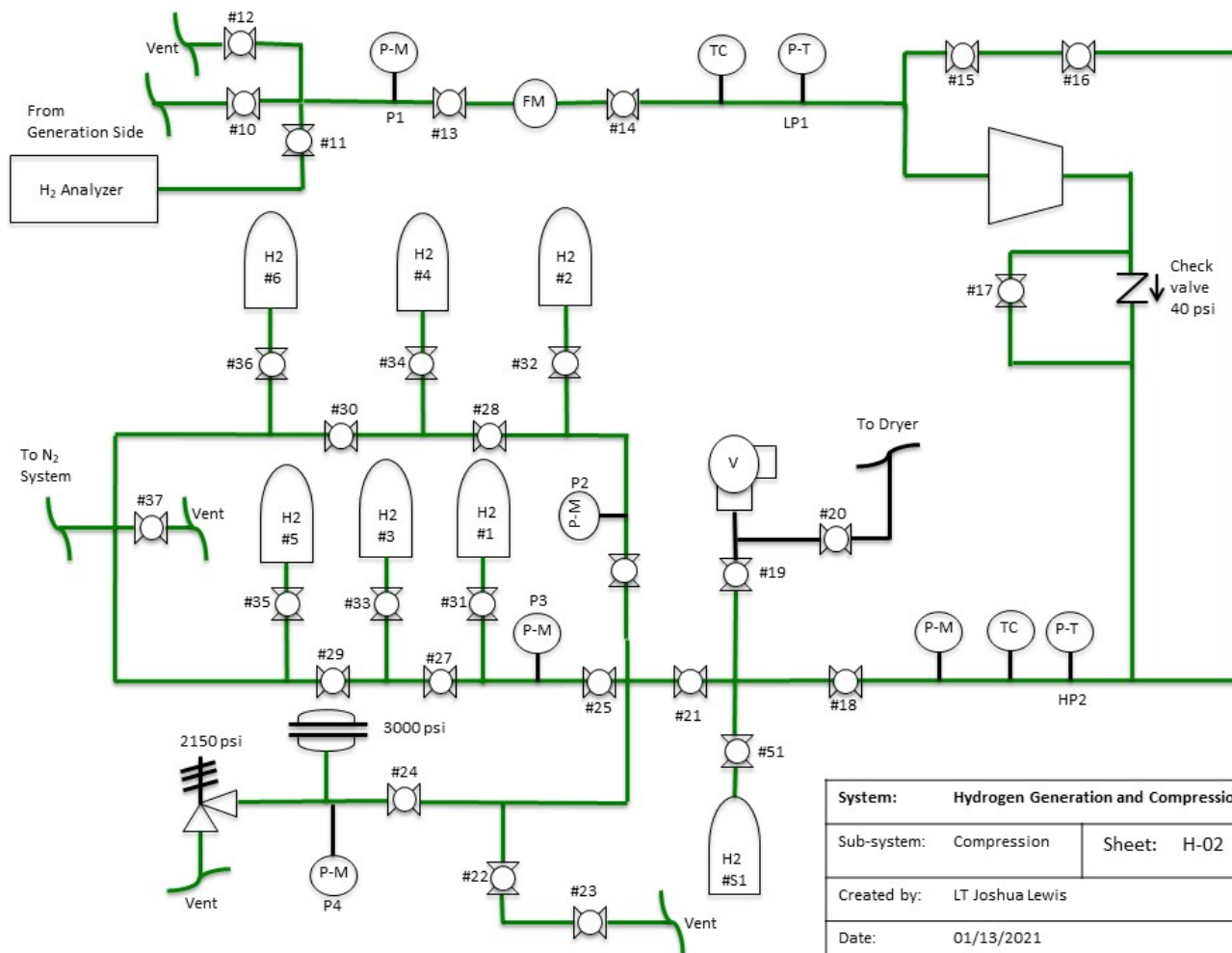


THIS PAGE INTENTIONALLY LEFT BLANK

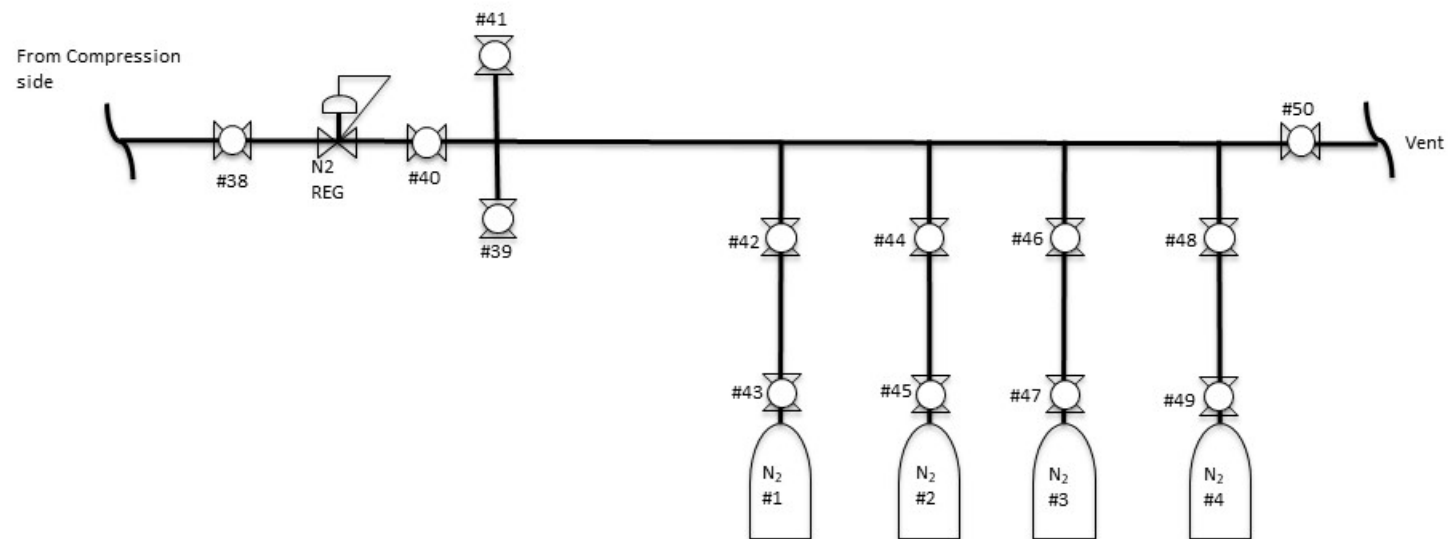
APPENDIX L. PIPING AND IDENTIFICATION (P&ID) DIAGRAM



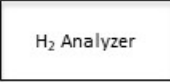
System:	Hydrogen Generation and Compression	
Sub-system:	Generation	Sheet: H-01
Created by:	LT Joshua Lewis	
Date:	01/13/2021	



System:	Hydrogen Generation and Compression	
Sub-system:	Compression	Sheet: H-02
Created by:	LT Joshua Lewis	
Date:	01/13/2021	



System:	Hydrogen Generation and Compression	
Sub-system:	Nitrogen	Sheet: H-03
Created by:	LT Joshua Lewis	
Date:	01/13/2021	

Symbols			
Check Valve		Dehumidifier	
Relief Valve		Pressure Gauge (Mechanical)	
Manual Valve		Pressure Transducer	
Compressor		Thermocouple	
Pressure Cylinder		Flow rate Measurement	
Tank		Hydrogen Gas Analyzer	
Electrolyzer		Water Piping (H ₂ O)	

System:	Hydrogen Generation and Compression	
Sub-system:	Legend	Sheet: H-04
Created by:	LT Joshua Lewis	
Date:	01/13/2021	

Symbols			
Regulator		Vacuum Pump	
Rupture Disk		Membrane Dehumidifier	
Hydrogen Gas (H ₂)			

System:	Hydrogen Generation and Compression	
Sub-system:	Legend	Sheet: H-05
Created by:	LT Joshua Lewis	
Date:	1/13/2021	

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX M. HIGH PRESSURE SIDE PURGING PROCEDURE

WARNING: FAILURE TO COMPLETE THIS PROCEDURE PRIOR TO SYSTEM START UP CAN LEAD TO FLAMMABLE HYDROGEN GAS. FLAMMABLE HYDROGEN GAS CAN LEAD TO SERIOUS BODILY HARM OR DEATH.

WARNING: THIS PROCEDURE IS WRITTEN TO ACCOMPANY THE P&ID DIAGRAM FOUND IN APPENDIX L. CHANGES IN SYSTEM DESIGN OR LAYOUT WILL VOID THIS PROCEDURE.

1. Verify no power applied to the electrochemical hydrogen compressor.
 - a. Compressor Off. ☐
2. Verify system in secure configuration.
 - a. Close all valves #13 through #51. ☐
3. Align relief valves
 - a. Open valve #24 ☐
4. Align system for purge.
 - a. Open valve #14. ☐
 - b. Open valve #15 ☐
 - c. Open valve #16 ☐
 - d. Open valve #17 ☐
 - e. Open valve #18 ☐
 - f. Open valve #21 ☐
 - g. Open valve #25 ☐
 - h. Open valve #27 ☐
 - i. Open valve #29 ☐

5. Align Hydrogen (H₂) Storage Tanks to be used.

a. Swagelok Sampling Bottle. ☐

i. Open valve #51. ☐

b. H₂ Storage Tank #1. ☐

i. Open valve #31. ☐

c. H₂ Storage Tank #2. ☐

i. Open valve #26. ☐

ii. Open valve #32. ☐

d. H₂ Storage Tank #3. ☐

i. Open valve #33. ☐

e. H₂ Storage Tank #4. ☐

i. Open valve #26. ☐

ii. Open valve #28. ☐

iii. Open valve #34. ☐

f. H₂ Storage Tank #5. ☐

i. Open valve #35. ☐

g. H₂ Storage Tank #6. ☐

i. Open valve #26. ☐

ii. Open valve #28. ☐

iii. Open valve #30. ☐

iv. Open valve #36. ☐

6. Align vacuum pump and vacuum system

a. Open valve #19. ☐

b. Power on vacuum pump. ☐

- c. Vacuum system until pump gauge reads 28 inHg. ☐
- d. Secure vacuum pump. ☐
- e. Close valve #19. ☐

CAUTION: ONLY ONE N₂ SUPPLY TANK IS REQUIRED FOR PURGING SYSTEM.

7. Align N₂ Supply Tank to be used.

- a. N₂ Supply Tank #1. ☐
 - i. Open valve #42. ☐
 - ii. Open valve #43. ☐
- b. N₂ Supply Tank #2. ☐
 - i. Open valve #44. ☐
 - ii. Open valve #45. ☐
- c. N₂ Supply Tank #3. ☐
 - i. Open valve #46. ☐
 - ii. Open valve #47. ☐
- d. N₂ Supply Tank #4. ☐
 - i. Open valve #48. ☐
 - ii. Open valve #49. ☐

CAUTION: FAILURE TO ENSURE N₂ REGULATOR IS SET TO LOWEST POSSIBLE PRESSURE PRIOR TO INTRODUCTION OF N₂ TO COMPRESSION SYSTEM CAN LEAD TO RAPID PRESSURE INCREASE IN THE SYSTEM RESULTING IN DAMAGE TO EQUIPMENT.

8. Align N₂ System.

- a. Open valve #19. ☐

9. Fill Compression system with N₂ gas.

- a. Open valve #38. ☐
- b. Slowly increase N₂ regulator until pressure gauge #2 (P2) reads 20 psi. ☐
- c. Close valve #38. ☐

10. Secure N₂ Supply Tanks in use.

- a. N₂ Supply Tank #1. ☐
 - i. Close valve #42. ☐
 - ii. Close valve #43. ☐
- b. N₂ Supply Tank #2. ☐
 - i. Close valve #44. ☐
 - ii. Close valve #45. ☐
- c. N₂ Supply Tank #3. ☐
 - i. Close valve #46. ☐
 - ii. Close valve #47. ☐
- d. N₂ Supply Tank #4. ☐
 - i. Close valve #48. ☐
 - ii. Close valve #49. ☐

11. Align vacuum pump and vacuum system

- a. Open valve #19. ☐
- b. Power on vacuum pump. ☐
- c. Vacuum system until pump gauge reads 28 inHg. ☐
- d. Secure vacuum pump. ☐
- e. Close valve #19. ☐

NOTES: UPON COMPLETION OF THIS PROCEDURE COMPRESSION SIDE IS READY FOR DRY HYDROGEN FROM THE GENERATION SIDE TO BE INTRODUCED TO THE SYSTEM.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX N. HYDROGEN SYSTEM START UP PROCEDURE

WARNING: COMPLETE THE HIGH PRESSURE SIDE PURGING PROCEDURE, APPENDIX M, PRIOR TO SYSTEM START UP. FAILURE TO COMPLETE HIGH PRESSURE SIDE PURGE CAN LEAD TO FLAMMABLE HYDROGEN GAS, WHICH CAN RESULT IN SERIOUS BODILY HARM OR DEATH.

WARNING: THIS PROCEDURE IS WRITTEN TO ACCOMPANY THE P&ID DIAGRAM FOUND IN APPENDIX L. CHANGES IN SYSTEM DESIGN OR LAYOUT WILL VOID THIS PROCEDURE.

1. Verify system in secure configuration.
 - a. Close all valves #4 through #12. ☐

NOTES: VALVES #1 AND #2 ARE SOLENOID VALVES CONTROLLED BY THE MICRO850 CONTROLLER AND ARE NORMALLY CLOSED. VALVE #3 IS A PROPORTIONAL CONTROLLED VALVE USED TO REGULATE THE SAFE RELEASE OF OXYGEN GAS TO THE ATMOSPHERE.

2. Align Oxygen (O₂) gas ventilation
 - a. Open valve #4. ☐
3. Align system for generation side purge.
 - a. Open valve #3. ☐
 - b. Open valve #5. ☐
 - c. Open valve #7. ☐
 - d. Open valve #9. ☐
 - e. Open valve #10. ☐
 - f. Open valve #12. ☐

CAUTION: ELECTROLYZER IS RATED FOR A MAXIMUM APPLIED VOLTAGE OF 14 VOLTS. VOLTAGES GREATER THAN 14 VOLTS CAN DAMAGE THE ELECTROLYZER.

4. Provide power to generation system.
 - a. Turn on PWX1500ML DC Power Supply. ☐
 - b. Set output voltage to 13 volts. ☐
 - c. Set output current to 20 Amps. ☐
 - d. Press output. ☐

CAUTION: ONCE THE OUTPUT BUTTON HAS BEEN PRESSED ELECTRICAL ENERGY IS APPLIED TO THE GENERATION SYSTEM, AND THERE IS A RISK OF ELECTRICAL SHOCK.

5. Provide power to the electrolyzer.
 - a. Verify remote control turn dial is to the lowest possible setting. ☐
 - b. Toggle switch on electro remote control to the ON position. ☐
 - c. Verify electro remote displays roughly 10 ± 2 . ☐

NOTES: IF ELECTRO REMOTE IS OUTSIDE OF AN ACCEPTABLE RANGE, ADJUST THE ELECTRO PWM UNTIL ELECTRO REMOTE IS IN THE PROPER RANGE.

NOTES: ONCE ELECTRO REMOTE IS ON THE ELECTROLYZER WILL START PRODUCING HYDROGEN GAS.

6. Start membrane dehumidifier.
 - a. Open valve #20. ☐
 - b. Turn on vacuum pump. ☐

WARNING: FAILURE TO ALLOW THE GENERATION SYSTEM THE REQUIRED OPERATING TIME TO PURGE CAN RESULT IN FLAMMABLE

HYDROGEN GAS. FLAMMABLE HYDROGEN GAS CAN CAUSE SERIOUS BODILY HARM OR DEATH.

7. Conduct generation system purge.
 - a. Using flowmeter #1 verify flow rate greater than 0.40734 LPM ($6.789 \times 10^{-6} \text{ m}^3/\text{s}$). ☐
 - b. Allow system to operate for 4 minutes and 5 seconds. ☐
 - c. Close valve #13.
8. Fill compression system with hydrogen gas.
 - a. Open valve #13. ☐
 - b. Allow hydrogen gas to fill compression system. ☐
 - c. Close valve #15. ☐
 - d. Close valve #16. ☐
 - e. Close valve #17. ☐

CAUTION: ELECTROCHEMICAL HYDROGEN COMPRESSOR IS RATED FOR A MAXIMUM VOLTAGE OF 0.4 VOLTS. VOLTAGE GREATER THAN 0.4 VOLTS WILL DAMAGE THE COMPRESSOR.

9. Start electrochemical hydrogen compressor.
 - a. Turn on DC Power supply. ☐
 - b. Set voltage to 0.04 volts.
 - c. Set current to 5 Amps.

NOTES: UPON COMPLETION OF THIS PROCEDURE THE SYSTEM IS COMPRESSING HYDROGEN GAS BEING PRODUCED BY THE ELECTROLYZER.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX O. CONNECTED COMPONENTS WORKBENCH CODE FOR HYDROGEN GENERATION

A. MAIN PROGRAM

```
(* This is the control program for the hydrogen generation side. The purpose of this program is to capture ambient moisture and using the hydrotube produce hydrogen and oxygen gas.*)
```

```
(*First step is to establish the emergency stop button. The emergency stop button is normally closed. Power is routed from the controllers 24v power supply through the emergency stop button and back to the Input pin _IO_EM_DI_01. The embedded input board can only tell if a signal is present or not, it can not determine amplitude. Any_TO_INT converts the incoming signal into either a one (1) or a zero (0). One (1) means that a signal is present and the emergency stop button is not engaged. Zero (0) means that there is no signal present and the emergency stop button is engaged. The ENABLE parameter is used later in the program as a requirement to turn on dehumidifiers and hydrotube.*)
```

```
ENABLE:= ANY_TO_INT(_IO_EM_DI_01);
```

```
(*Next step is determine voltage being supplied by the DC power supply and voltage applied to the hydrotube.*)
```

```
(*InputVoltage is determining the amount of voltage being supplied by the DC power supply. This is accomplished by using the DC transducer #2.*)
```

```
InputVoltage(ANY_TO_REAL(_IO_P2_AI_00),InputVoltage.InputMin,InputVoltage.InputMax,InputVoltage.OutputMin,InputVoltage.OutputMax);  
Voltage:=InputVoltage.Output - VOLTAGE_OFFSET;
```

```
(*INPUT_VOLTAGE_2 is determining the voltage being supplied to the hydrotube. This is accomplished by using the DC transducer #1.*)
```

```
INPUT_VOLTAGE_2(ANY_TO_REAL(_IO_P2_AI_01),INPUT_VOLTAGE_2.InputMin,INPUT_VOLTAGE_2.InputMax,INPUT_VOLTAGE_2.OutputMin,INPUT_VOLTAGE_2.OutputMax);  
ELECTRO_VOLTAGE:=INPUT_VOLTAGE_2.Output - ELECTRO_VOLTAGE_OFFSET;
```

```
(*Determine Power consumption*)
```

```
Input_current(ANY_TO_REAL(_IO_X3_AI_00),Input_current.InputMin,Input_current.InputMax,Input_current.OutputMin,Input_current.OutputMax);  
Current:=(Input_current.Output)-Current_Offset;
```

```
(* Next step is to determine the water level in the various tanks. Tank 1 and 2 are water from the dehumidifiers. Tank 3 and 4 are the process tanks connected to the hydrotube. Tank 3 is the hydrogen process tank, and Tank 4 is the oxygen process tank. The output is inches of water*)
```

```

LEVEL_1 (ANY_TO_REAL(_IO_P1_AI_01), LEVEL_1.InputMin, LEVEL_1.InputMax, LEVEL_1.OutputMin, LEVEL_1.OutputMax);
TANK_1:=LEVEL_1.Output;

LEVEL_2 (ANY_TO_REAL(_IO_P1_AI_02), LEVEL_2.InputMin, LEVEL_2.InputMax, LEVEL_2.OutputMin, LEVEL_2.OutputMax);
TANK_2:=LEVEL_2.Output;

LEVEL_3 (ANY_TO_REAL(_IO_P1_AI_00), LEVEL_3.InputMin, LEVEL_3.InputMax, LEVEL_3.OutputMin, LEVEL_3.OutputMax);
TANK_3:=LEVEL_3.Output;

LEVEL_4 (ANY_TO_REAL(_IO_P1_AI_03), LEVEL_4.InputMin, LEVEL_4.InputMax, LEVEL_4.OutputMin, LEVEL_4.OutputMax);
TANK_4:=LEVEL_4.Output;

(*The total amount of water available to fill the process tanks are WATER_TOTAL.*)

WATER_TOTAL:= TANK_1 + TANK_2;

(*PROCESS_TANK_DIFF is the difference in tank level between process tank 3 and process tank 4.*)

PROCESS_TANK_DIFF:= ABS(TANK_3 - TANK_4);

(*Now that the system inputs have been determined, the following is the control logic.*)

(*First set of control logic is for the dehumidifiers. Due to the relatively slow rate of water production from the dehumidifiers, if the water tanks are not full the dehumidifiers need to run a maximum output. Max output is for all four dehumidifiers to be on and collecting water.*)

IF VOLTAGE > VOLTAGE_MIN THEN
    IF ENABLE = ANY_TO_INT(1) THEN
        IF WATER_TOTAL < WATER_MAX THEN
            _IO_EM_DO_04:=TRUE;
            _IO_EM_DO_05:=TRUE;
            _IO_EM_DO_06:=TRUE;
            _IO_EM_DO_07:=TRUE;
        ELSE
            _IO_EM_DO_04:=FALSE;
            _IO_EM_DO_05:=FALSE;
            _IO_EM_DO_06:=FALSE;
            _IO_EM_DO_07:=FALSE;
        END_IF;
    ELSE
        _IO_EM_DO_04:=FALSE;
        _IO_EM_DO_05:=FALSE;
        _IO_EM_DO_06:=FALSE;
        _IO_EM_DO_07:=FALSE;
    END_IF;
ELSE
    _IO_EM_DO_04:=FALSE;

```

```

_IO_EM_DO_05:=FALSE;
_IO_EM_DO_06:=FALSE;
_IO_EM_DO_07:=FALSE;
END_IF;

```

(* Next set of control logic is for the hydrotube. Hydrotube has a maximum allowed voltage, which is 14 volts. Voltage greater than 14 volts can damage the hydrotube. Also the hydrotube has to have water in both process tank in order to function. Hydrotube will produce hydrogen gas at a faster rate than the compressor can process, so an increase in pressure due to build up of hydrogen gas will result in decrease of water level in process tank 3. Program will shut off power to the electrolyzer is the difference in water level between tank 3 and tank 4 is greater than Process_Tank_Max_Diff. Thus allowing the compressor to catch up and decrease hydrogen gas accumulation and pressure.*)

```

IF ELECTRO_VOLTAGE < ELECTRO_VOLTAGE_MAX THEN
  IF TANK_3 > PROCESS_TANK_MIN THEN
    IF TANK_4 > PROCESS_TANK_MIN THEN
      IF PROCESS_TANK_DIFF < PROCESS_TANK_MAX_DIFF THEN
        IF ENABLE = ANY_TO_INT(1) THEN
          _IO_EM_DO_08:=TRUE;
          _IO_EM_DO_09:=TRUE;
        ELSE
          _IO_EM_DO_08:=FALSE;
          _IO_EM_DO_09:=FALSE;
        END_IF;
      ELSE
        _IO_EM_DO_08:=FALSE;
        _IO_EM_DO_09:=FALSE;
      END_IF;
    ELSE
      _IO_EM_DO_08:=FALSE;
      _IO_EM_DO_09:=FALSE;
    END_IF;
  ELSE
    _IO_EM_DO_08:=FALSE;
    _IO_EM_DO_09:=FALSE;
  END_IF;
ELSE
  _IO_EM_DO_08:=FALSE;
  _IO_EM_DO_09:=FALSE;
END_IF;

```

(*Next set of control logic is for refilling the process tank with water as the hydrotube consumes water. If the Process tank is less than the process tank minimum and there is sufficient water in Tank 1 and 2, then valve will open allowing water from Tank 1 to Tank 3 and Tank 2 to Tank 4.*)

```

IF TANK_3 > PROCESS_TANK_MIN THEN
  _IO_EM_DO_02:=FALSE;
ELSE IF WATER_TOTAL > WATER_MIN THEN
  _IO_EM_DO_02:=TRUE;

```

```

ELSE
    _IO_EM_DO_02:=FALSE;
END_IF;
END_IF;

```

```

IF TANK_4 < PROCESS_TANK_MIN THEN
    IF WATER_TOTAL > WATER_MIN THEN
        _IO_EM_DO_03:= TRUE;
    ELSE
        _IO_EM_DO_03:=FALSE;
    END_IF;

```

```

ELSE
    _IO_EM_DO_03:= FALSE;
END_IF;

```

(*Next set of control logics is to regulate the building of oxygen gas in process tank 4. There is a controlled PID valve Which opens and closes based on the water level difference between process tank 3 and 4. Oxygen is currently vented to the atmosphere.*)

```

IF PROCESS_TANK_DIFF > PROCESS_TANK_SETPPOINT THEN
    (*PID used to monitor oxygen process tank. Returns value corresponding to
    how open the proportional valve needs to be to bring the water level
    difference
    to zero.*)

```

```

    LEVEL:=PID_controlledValve(PROCESS_TANK_DIFF);
    (*Output voltage value to proportional valve pin _IO_P3_AO_00*)
    _IO_P3_AO_00 := ANY_TO_UINT(abs(PID_Converter(LEVEL)));

```

```

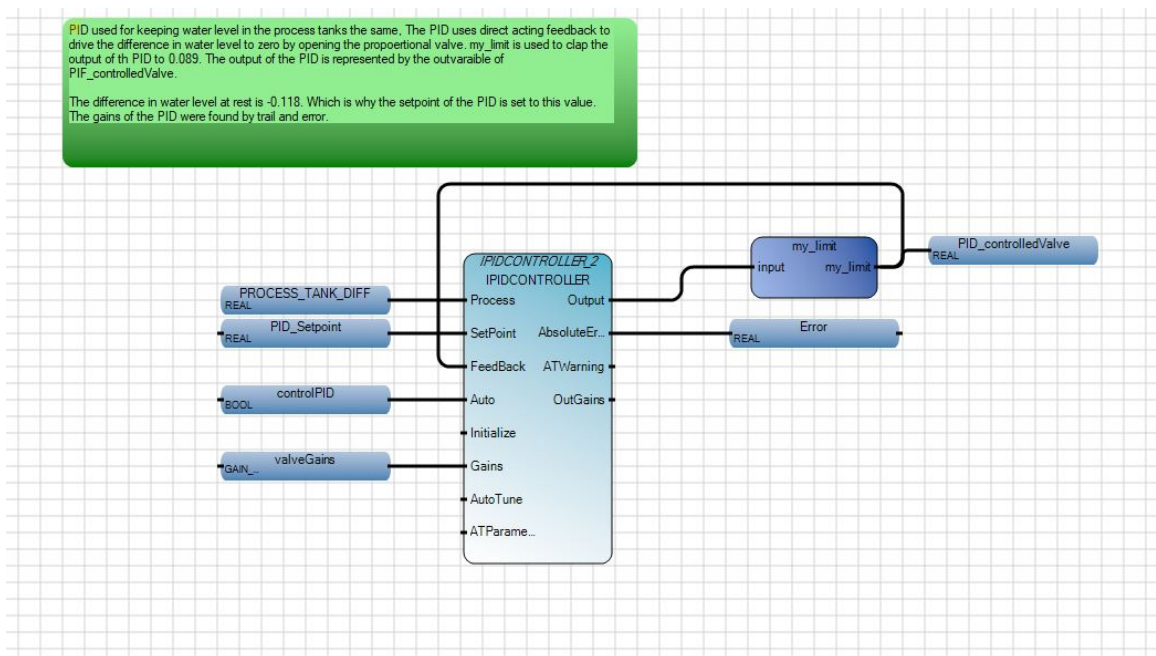
END_IF;

```

B. MAIN PROGRAM LOCAL VARIABLES

Name	Alias	Data Type	Dimension	Project Value	Initial Value	Comment	String Size
InputVoltage		SCALER		...	...		
VOLTAGE		REAL					
LEVEL_2		SCALER		...	...		
TANK_2		REAL					
VOLTAGE_MIN		REAL			12.0		
LEVEL_1		SCALER		...	...		
TANK_1		REAL					
LEVEL_3		SCALER		...	...		
TANK_3		REAL					
LEVEL_4		SCALER		...	...		
TANK_4		REAL					
VOLTAGE_OFFSET		REAL			2.3		
WATER_TOTAL		REAL					
WATER_MIN		REAL			2.0		
WATER_MAX		REAL			11.0		
WATER_SET		REAL			9.0		
INPUT_VOLTAGE_2		SCALER		...	...		
ELECTRO_VOLTAGE		REAL					
ENABLE		INT					
ELECTRO_VOLTAGE_OFFS		REAL			4.5		
ELECTRO_VOLTAGE_MAX		REAL			14.0		
PROCESS_TANK_MIN		REAL			1.5		
PROCESS_TANK_DIFF		REAL					
PROCESS_TANK_SETPOIN		REAL			0.0		
LEVEL		REAL					
Input_current		SCALER		...	...		
Current		REAL					
Current_Offset		REAL			2.55		
PROCESS_TANK_MAX_DIF		REAL			1.0		
*							

C. USER DEFINED FUNCTION PID_CONTROLLED_VALVE



D. USER-DEFINED FUNCTION PID_CONTROLLED_VALVE LOCAL VARIABLES

Name	Alias	Data Type	Direction	Dimension	Initial Value	Comment	String Size
Error		REAL	Var				
valveGains		GAIN_PID	Var		...		
PID_Setpoint		REAL	Var		0.118		
controlPID		BOOL	Var		TRUE		
IPIDCONTROLLER_2		IPIDCONTROLL	Var		...		
PROCESS_TANK_DIFF		REAL	VarInput				
PID_controlledValve		REAL	VarOutput				
*							

E. USER-DEFINED FUNCTION MY_LIMIT

(* This function is used within the PID function for clamping the output to 0.089. Limiting the output of the PID prevents the proportional valve from opening to much causing a steep drop in pressure in the hydrogen process tank. It will usually return a value of 0.089 when there is a difference due to the low resolution and slow reaction time of the water-level sensor. *)

```
IF lowerLimit <= input AND upperLimit >= input THEN
my_limit := input;
ELSIF input > upperLimit
THEN my_limit := upperLimit;
END_IF;
```

F. USER-DEFINED FUNCTION MY_LIMIT LOCAL VARIABLES

Name	Alias	Data Type	Direction	Dimension	Initial Value	Comment	String Size
lowerLimit		REAL	Var		0.0		
upperLimit		REAL	Var		0.089		
input		REAL	VarInput				
my_limit		REAL	VarOutput				
*							

G. USER-DEFINED FUNCTION PID_CONVERTER

```
PID_Converter:=(dataInput/(tank_diff_high-tank_diff_low))*(analog_high-
analog_low);
```

H. USER-DEFINED FUNCTION PID_CONVERTER LOCAL VARIABLES

	Name	Alias	Data Type	Direction	Dimension	Initial Value	Comment	String Size
	tank_diff_high		REAL	Var		1.0		
	tank_diff_low		REAL	Var		0.0		
	analog_high		REAL	Var		65535.0		
	analog_low		REAL	Var		0.0		
	dataInput		REAL	VarInput				
	PID_Converter		REAL	VarOutput				
*								

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX P. CONNECTED COMPONENTS WORKBENCH CODE FOR HYDROGEN COMPRESSION

A. MAIN PROGRAM

```
(*Main Program for automating Hydrogen compression*)
(*NOTES FOR FIRST TIME USER*)
(* #1 Understanding controller pin assignment and notation in the
connect components
software. Each physical pin location on the controller has an
associated variable in the
software program.

Example:
_IO_P1_AI_00 := _Input/Output_Plug in #1_Input Signal_Channel 0.
_IO_P2_AI_03 := _Input/Output_Plug in #2_Input Signal_Channel 3.
_IO_EM_DI_01 := _Input/Output_Embedded_Input Signal_Pin 01.
_IO_EM_DO_03 := _Input/Output_Embedded_Output_Signal_Pin 03.

#2 Understanding data type.
BOOL data type:= Only outputs is either TRUE or False. For a input
signal TRUE means
there is a signal present, while FALSE means there is not a signal
present. BOOL can not tell you anything about the signal just simply
that one is present. For an output signal TRUE means to supply a
voltage out from the controller, while FALSE means do not supply a
voltage. The embedded input and output pins are only capable of
operating as a BOOL data type. Scaler:= Used to convert the analog
signal received by the controller into a number that can be understood
by the user. The IF-04 plug ins used by the controller are a 14 bit
data system which means that the REAL data type ranges from 0 to 65535.
The plug in is also rated to receive either a voltage from 0 to 10
volts,
or current from 4 to 20 mA. REAL:= This data type was used because the
scaler function will only receive or output REAL values.*)

TEST := ANY_TO_INT(_IO_EM_DI_01);

(*First step is to determine the DC voltage from the power source. This
is done via
the scaler function.*)

Voltage(ANY_TO_REAL(_IO_P1_AI_00),Voltage.InputMin,Voltage.InputMax,Voltage.OutputMin,Voltage.OutputMax);

DC_SUPPLY_VOLTAGE := Voltage.Output;

(*Next Step is to determine the actual voltage at the compressor. This
is important
because there is voltage lost due to resistance in the cables from the
DC Power Source and the compressor. The compressor is only able to
handle a maximum voltage of .5V for the single cell compressor.
Second_Voltage is the voltage reading from the positive and negative
```

terminals of the compressor. However, because the compressor is not grounded as well as that controller and DC Power Source do not share a common ground there is interference. This interference is in the negative leads from the compressor negative terminal to the controller plug in. The variable Difference is calculating the interference in the line. With the Actual voltage at the compressor a function of Second_Voltage - Difference.*)

```
Second_Voltage (ANY_TO_REAL(_IO_P1_AI_01), Second_Voltage.InputMin, Second_Voltage.InputMax, Second_Voltage.OutputMin, Second_Voltage.OutputMax);
```

```
Difference (ANY_TO_REAL(_IO_P1_AI_02), Difference.Inputmin, Difference.InputMax, Difference.OutputMin, Difference.OutputMax);
```

```
Compressor_Voltage := Second_Voltage.Output - Difference.Output;
```

(*Next to record current to the compressor*)

```
Amp_input (ANY_TO_REAL(_IO_P1_AI_03), Amp_input.InputMin, Amp_input.InputMax, Amp_input.OutputMin, Amp_input.OutputMax);
```

```
Amp_scale:=Amp_input.Output;
```

```
Amp_convert (Amp_scale, Amp_convert.InputMin, Amp_convert.InputMax, Amp_convert.OutputMin, Amp_convert.OutputMax);
```

```
Current:= Amp_convert.Output - (Currentoffset);
```

(*Next to install safety/automatic cutoff to the compressor in the event

Compressor_Voltage is greater than .4 volts. This is done via an IF THEN statement. The variable C_V_Setpoint is established in the local variables list for the main program, and set at .4 which is the limit for the compressor.*)

```
IF Compressor_Voltage > C_V_Setpoint OR TEST = ANY_TO_INT(0) THEN
  _IO_EM_DO_00:= FALSE; (*Opens relay to compressor*)
ELSE
  _IO_EM_DO_00:= TRUE; (*Closes relay to compressor*)
END_IF;
```

(*Now that the compressor is operating now we need to determine the pressure on both the inlet and outlet sides of the compressor*)

(*Each transducer is labeled on the physical system with the same notation as the program.

LP_TRANS_1 - Low Pressure Transducer #1 (located on inlet side)

HP_TRANS_1 - High Pressure Transducer #1 (located on outlet side)*)

```
LP_TRANS_1 (ANY_TO_REAL(_IO_P2_AI_01), LP_TRANS_1.InputMin, LP_TRANS_1.InputMax, LP_TRANS_1.OutputMin, LP_TRANS_1.OutputMax);
```

```
Va_LP1:=LP_TRANS_1.Output;
```

```

HP_TRANS_1(ANY_TO_REAL(_IO_P2_AI_00),HP_TRANS_1.InputMin,HP_TRANS_1.InputMax,HP_TRANS_1.OutputMin,HP_TRANS_1.OutputMax);

Va_HP1:=HP_TRANS_1.Output;

LP1 := IP1(Va_LP1);

HP2 := OP2(Va_HP1);

(*Once we have reached our final desired pressure on the outlet side of
the
compressor we need to turn the compressor off as not to over pressurize
the system.*)

IF HP2 >= HP_Cutoff THEN
_IO_EM_DO_00:= FALSE;
ELSE
_IO_EM_DO_00:=TRUE;
END_IF;

```

B. MAIN PROGRAM LOCAL VARIABLES

	Name	Alias	Data Type	Dimension	Project Value	Initial Value
	Voltage		SCALER		...	...
	DC_SUPPLY_VOLTAGE		REAL			
	Second_Voltage		SCALER		...	...
	Compressor_Voltage		REAL			
	Difference		SCALER		...	...
	HP_TRANS_1		SCALER		...	...
	LP_TRANS_1		SCALER		...	...
	LP_TRANS_2		SCALER		...	...
	Va_LP1		REAL			
	C_V_Setpoint		REAL			.4
	Va_LP2		REAL			
	Va_HP1		REAL			
	HP_Cutoff		REAL			1400.0
	HP1		REAL			
	LP1		REAL			
	HP2		REAL			
	INTERRUPT		BOOL			
	ENABLE		INT			
	IRQType		UDINT			
	TEST		INT			
	Amp_input		SCALER		...	...
	Amp_convert		SCALER		...	...
	Current		REAL			
	Amp_scale		REAL			
	Currentoffset		REAL			.7
	HP_Cutoff_2		REAL			450.0
	LP_Cutoff		REAL			12.0
*						

C. USER DEFINED FUNCTION IP1

(* This Function is used to determine the pressure on the inlet side of the compressor*)

(*First step is to receive the input from the Low Pressure transducers. Receiving that input and converting it is accomplished in the main program. The Honeywell transducers produce a output signal that ranges from .5 volts to 4.5 volts. Using Nitrogen as the working fluid a calibration table was created to associate a pressure with the received output voltage.*)

(* Variable List:

Va_LP1 = Voltage Actual from Low Pressure Transducer 1

```

V1 = Voltage #1 from calibration table
V6 = Voltage #6 from calibration table
V11 = Voltage #11 from calibration table
V16 = Voltage #16 from calibration table
V21 = Voltage #21 from calibration table
V26 = Voltage #26 from calibration table
P1 = Pressure #1 from calibration table
P6 = Pressure #6 from calibration table
P11 = Pressure #11 from calibration table
P16 = Pressure #16 from calibration table
P21 = Pressure #21 from calibration table
P26 = Pressure #26 from calibration table.
IP1 = Inlet pressure #1. Pressure reading from Low Pressure Transducer
#1*)

(* A linear interpolation was used to determine the pressure associated
with the Actual voltage from the transducer. A linear interpolation was
used instead of the scaler function because I wanted to break the
interpolation up into small segments. Scaler function would create a
larger error (error = Pressure actual - LP1) than interpolating over a
smaller range of values.*)

IF Va_LP1 > V1 AND Va_LP1<=V6 THEN
IP1:= ANY_TO_REAL(P6 - ((P6-P1)/(V6-V1))*(V6 - Va_LP1));
END_IF;

IF Va_LP1 > V6 AND Va_LP1 <= V11 THEN
IP1:= ANY_TO_REAL(P11 - ((P11-P6)/(V11-V6))*(V11 - Va_LP1));
END_IF;

IF Va_LP1 > V11 AND Va_LP1 <= V16 THEN
IP1:= ANY_TO_REAL(P16 - ((P16-P11)/(V16-V11))*(V16 - Va_LP1));
END_IF;

IF Va_LP1 > V16 AND Va_LP1 <= V21 THEN
IP1:= ANY_TO_REAL(P21 - ((P21-P16)/(V21-V16))*(V21 - Va_LP1));
END_IF;

IF Va_LP1 > V21 AND Va_LP1 <= V26 THEN
IP1:= ANY_TO_REAL(P26 - ((P26-P21)/(V26-V21))*(V26 - Va_LP1));
END_IF;

```

D. USER DEFINED FUNCTION IP1 LOCAL VARIABLES

	Name	Alias	Data Type	Direction	Dimension	Initial Value
	P6		REAL	Var		100.0
	V6		REAL	Var		1.3226
	P1		REAL	Var		0.0
	P11		REAL	Var		200.0
	V1		REAL	Var		.505
	P16		REAL	Var		300.0
	V16		REAL	Var		2.9724
	P21		REAL	Var		400.0
	V21		REAL	Var		3.7746
	P26		REAL	Var		500.0
	V26		REAL	Var		4.5429
	V11		REAL	Var		2.127
	Va_LP1		REAL	VarInput		
	IP1		REAL	VarOutput		
*						

E. USER DEFINED FUNCTION OP2

(* This Function is used to determine the pressure from HP_TRANS_1 on the outlet side of the compressor*)

(*First step is to receive the input from the High Pressure transducers. Receiving that input and converting it is accomplished in the main program. The Honeywell transducers produce a output signal that ranges from .5 volts to 4.5 volts. Using Nitrogen as the working fluid a calibration table was created to associate a pressure with the received output voltage.*)

(* Variable List:

Va_HP1 = Voltage Actual from High Pressure Transducer 1

V1 = Voltage #1 from calibration table

V6 = Voltage #6 from calibration table

V11 = Voltage #11 from calibration table

V16 = Voltage #16 from calibration table

V21 = Voltage #21 from calibration table

V26 = Voltage #26 from calibration table

P1 = Pressure #1 from calibration table

P6 = Pressure #6 from calibration table

P11 = Pressure #11 from calibration table

P16 = Pressure #16 from calibration table

P21 = Pressure #21 from calibration table

P26 = Pressure #26 from calibration table.

OP2 = Outlet pressure 2. Pressure reading from High Pressure Transducer #1*)

(* A linear interpolation was used to determine the pressure associated with the Actual voltage from the transducer. A linear interpolation was

used instead of the scaler function because I wanted to break the interpolation up into small segments. Scaler function would create a larger error (error = Pressure actual - OP2) than interpolating over a smaller range of values.*)

```

IF Va_HP1 > V1 AND Va_HP1<=V6 THEN
OP2:= ANY_TO_REAL(P6 - ((P6-P1)/(V6-V1))*(V6 - Va_HP1));
END_IF;

IF Va_HP1 > V6 AND Va_HP1 <= V11 THEN
OP2:= ANY_TO_REAL(P11 - ((P11-P6)/(V11-V6))*(V11 - Va_HP1));
END_IF;

IF Va_HP1 > V11 AND Va_HP1 <= V16 THEN
OP2:= ANY_TO_REAL(P16 - ((P16-P11)/(V16-V11))*(V16 - Va_HP1));
END_IF;

IF Va_HP1 > V16 AND Va_HP1 <= V21 THEN
OP2:= ANY_TO_REAL(P21 - ((P21-P16)/(V21-V16))*(V21 - Va_HP1));
END_IF;

IF Va_HP1 > V21 AND Va_HP1 <= V26 THEN
OP2:= ANY_TO_REAL(P26 - ((P26-P21)/(V26-V21))*(V26 - Va_HP1));
END_IF;

IF Va_HP1 > V26 AND Va_HP1 <= V31 THEN
OP2:= ANY_TO_REAL(P31 - ((P31-P26)/(V31-V26))*(V31 - Va_HP1));
END_IF;

```

F. USER DEFINED FUNCTION OP2 LOCAL VARIABLES

	Name	Alias	Data Type	Direction	Dimension	Initial Value
	V1		REAL	Var		.510
	V31		REAL	Var		4.5
	P1		REAL	Var		0.0
	P31		REAL	Var		3000.0
	V6		REAL	Var		.646
	P6		REAL	Var		100.0
	V11		REAL	Var		.7842
	P11		REAL	Var		200.0
	V16		REAL	Var		.9188
	P16		REAL	Var		300.0
	V21		REAL	Var		1.0599
	P21		REAL	Var		400.0
	V26		REAL	Var		1.185
	P26		REAL	Var		500.0
	Va_HP1		REAL	VarInput		
	OP2		REAL	VarOutput		
*						

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX Q. MATLAB CODE FOR DATA ACQUISITION ON GENERATION SIDE

```
%% Hydrogen Gas Generation Data Collection

close all;
clear all;
clc;

% Matlab code for obtaining modbus data from Allen Bradley Micro850 PLC
% controller (PLC) and volumetric flow data from alicat flow meters,
% from
% the generation side of the hydrogen gas system.

% Set up Procedure.
% Steps for collecting data from PLC for Generation Side.
% Step 1: Ensure that computer settings are set so that computer never
% sleeps when plugged into power.
% Step 2: Physically connect computer to PLC via ethernet cable.
% Step 3: Physically connect computer to Alicat via USB and Alicat
Model
% BB9-232.
% Step 3: Open Connected Components Workbench (CCW) and corresponding
% program file.
% Step 4: Utilizing CCW connect to the PLC.
% Step 5: Obtain assigned IP Address for the PLC and input into Matlab.
ipaddress = '169.254.113.175'; % Input IP Address of PLC
% Step 5: Obtain Unit ID for Alicat flow meter.
UnitID = 'A'; % Input Unit ID for Alicat.
% Step 6: Enter Date of test, format YYYYMMDD.
Date = 20201217;
% Step 7: Enter start time of test, format HHMM, 24 hour clock.
Starttime = 1100;
% Step 8: Switch PLC into Run Mode to start executing the program.
% Step 9: Run Matlab code

% Below is the matlab code and explanation for each line.

% Verify no existing COM connections are open, and COM being used by
% Alicat.

out = instrfind
v =seriallist
% out should return an empty array and v should be COM6 for the Alicat.
%%
Date = num2str(Date); % Convert Date from a number to string.
Starttime = num2str(Starttime); %Convert start time from number to
string.

% Establish stop button.
```

```

mybutton = figure(1);
hui =
uicontrol(mybutton,'style','pushbutton','string','STOP','callback',@pus
hbutton,'tag','stopbutton','UserData',0,'position',[20 20 600 600]);
set(hui,'units','normalized');
set(hui,'position',[.1 .1 .8 .8]);
set(hui,'value');

% Connect to the PLC Modbus
m = modbus('tcpip',ipaddress)

% Connect to serial object which is the Alicat flow meter.
Flowmeter_1 =
serial('COM4','Timeout',2,'BaudRate',19200,'Terminator','CR');
fopen(Flowmeter_1);

% Establish file to write data to.
filename = [Date '_' Starttime '_Generation_RAW_Data.xls'];
fid = fopen(filename,'a'); % Assign properties to file. 'a' means to
write new data
% to file without deleting existing data.

% Write first line to data file which is the title for each column.
Title = {'Sample #' 'Run Time' 'DC Supply Voltage' 'Current'
'Electrolyzer Voltage' 'Tank 1 (inches)' 'Tank 2 (inches)' 'Tank 3
(inches)' 'Tank 4 (inches)' 'ID' 'Pressure (psia)' 'Temperature (C)'
'LPM' 'SLPM' 'Gas'};
for ii = 1:length(Title)
    fprintf(fid,'%s\t',Title{ii}); %Tells matlab to print each element of
the array to a single cell.
end
fprintf(fid,'\n'); %Skips to the next line

%Establish file to write converted data to.
filename2 = [Date '_' Starttime '_Data_SI_Units.xls'];
fid2 = fopen(filename2,'a');

Title2 = {'Sample #' 'Run Time' 'DC Supply Voltage' 'Current' 'Power
Consumption' 'Tank 1 (meters)' 'Tank 2 (meters)' 'Tank 3 (meters)'
'Tank 4(meters)' 'Water Volume Total' 'Volumetric flow (m^3/sec)'
'Velocity (m/s)' 'Flow meter Pressure (Pa)' 'Flow meter Temperature
(K)' 'Density (kg/m^3)' 'Mass Flow Rate (kg/s)' 'Mass per power
(kg/J)'};

for iiii = 1:length(Title2)
    fprintf(fid2,'%s\t',Title2{iiii}); %Tells matlab to print each element
of the array to a single cell.
end
fprintf(fid2,'\n'); %Skips to the next line

R = 4124.3; % Gas Constant for H2 (J/Kg-K)
Area = (12*0.0254)*(15*0.0254); %Establish area of water and process
tanks in m^2.

```

```

Area_pipe = (pi/4)*(0.01^2); % Cross Sectional area of plastic tubing
Time = 0; % Establish starting time
pauselen = 30; % Establish how often to take data.
Sample = 1;% Set Sample #
Runtime = 0; % Set Runtime

% Establish while loop for reading and printing data. Findobj is
looking at
% the stop button, if stop button is pressed value will change to 1 and
% cause while loop to stop. get(findobj function is depended upon
% pushbutton function that is saved in the same folder as this code.
Time
% ensures that the code will stop running after 24 hours regardless if
the
% stop button is pressed or not.
while get(findobj('tag','stopbutton'),'UserData')==0 & Time <=
(24*60*60)
    tic;
    get(findobj('tag','stopbutton'),'UserData');
    % Read data from the modbus.
    PLC = read(m,'holdingregs',400001,10,'single');

    % Read data from flow meter
    fprintf(Flowmeter_1,UnitID); %Send command to Flowmeter, Must match
UnitID
    IN = fscanf(Flowmeter_1); %Receive data from flowmeter
    IJ_US=find(IN==32); %Data received is in a string of characters
separated by spaces.
    % The number 32 is equal to a space. find(IN==32) is locating all
the
    % spaces in the string of data. Once you have the spaces located the
    % data is located between the spaces.
    ID = char(IN(1:IJ_US(1)-1)); %flowmeter ID
    RAW_Pressure = str2double(char(IN(IJ_US(1):(IJ_US(2)-1)))); %PSIA
    RAW_Temp = str2double(char(IN(IJ_US(2)+1:IJ_US(3)-1))); %Degrees C
    RAW_LPM = str2double(char(IN(IJ_US(3)+1:IJ_US(4)-1))); %Liters per
minute
    RAW_SLPM = str2double(char(IN(IJ_US(4)+1:IJ_US(5)-1))); %Standard
liters per minute
    RAW_Gas = char(IN(IJ_US(5)+1:end-1)); %Gas

    %Convert Raw data to SI units
    Power = (PLC(2))*(PLC(10));
    Tank1SI = PLC(4)*0.0254; %Convert inches to meters
    Tank2SI = PLC(5)*0.0254; %Convert inches to meters
    Tank3SI = PLC(6)*0.0254; %Convert inches to meters
    Tank4SI = PLC(7)*0.0254; %Convert inches to meters
    Vol_Tot = (Tank1SI + Tank2SI + Tank3SI + Tank4SI)*Area; %Total water
volume.
    flow = (RAW_LPM)*(.001/60); %m^3/sec
    velocity = flow/Area_pipe;
    Pressure = (RAW_Pressure)*6894.75728; %pascals
    Temperature = (RAW_Temp)+273.15; %Kelvin
    Density = Pressure/(R*Temperature);

```

```

MassFlow = flow*Density; %kg/s
Mass_per_power = MassFlow/Power; %kg/J

% Print Raw Data to file.
RAW = {num2str(Sample) num2str(Runtime) PLC(2) PLC(10) PLC(3) PLC(4)
PLC(5) PLC(6) PLC(7) ID num2str(RAW_Pressure) num2str(RAW_Temp)
num2str(RAW_LPM) num2str(RAW_SLPM) RAW_Gas};

for i = 1:length(RAW)
    fprintf(fid,'%s\t',RAW{i});
end
fprintf(fid,'\n'); %Printing data complete move to next line.

% Print Converted Data to File
Convert = {num2str(Sample) num2str(Runtime) PLC(2) PLC(10)
num2str(Power) num2str(Tank1SI) num2str(Tank2SI) num2str(Tank3SI)
num2str(Tank4SI) num2str(Vol_Tot) num2str(flow) num2str(velocity)
num2str(Pressure) num2str(Temperature) num2str(Density)
num2str(MassFlow) num2str(Mass_per_power)};
for iii= 1:length(Convert)
    fprintf(fid2,'%s\t',Convert{iii});
end
fprintf(fid2,'\n');
Sample = Sample +1; %Reset Sample
Runtime = Runtime + pauselen; %Reset Runtime
toc;
pause(pauselen-toc); %Pause loop for 30 seconds. Data collection
will only occur every 30 seconds
Time = Time + pauselen; %Reset Time

end

%%
fclose(fid);% Close the file.
fclose(fid2); %Close the file.
fclose(Flowmeter_1); %Close the serial object to flow meter
delete (Flowmeter_1); %Delete serial object.

```

APPENDIX R. MATLAB CODE FOR DATA ACQUISITION ON COMPRESSION SIDE

```
%% Hydrogen Gas Compression Data Collection

close all;
clear all;
clc;

% Matlab code for obtaining modbus data from Allen Bradley Micro850 PLC
% controller (PLC) from
% the Compression side of the hydrogen gas system.

% WARNING: Conduct High Pressure Side Purging Procedure prior
% to operating the compression system.

% Set up Procedure.
% Steps for collecting data from PLC for Compression Side.
% Step 1: Ensure that computer settings are set so that computer never
% sleeps when plugged into power.
% Step 2: Physically connect computer to PLC via ethernet cable.
% Step 3: Open Connected Components Workbench (CCW) and corresponding
% program file.
% Step 4: Utilizing CCW connect to the PLC.
% Step 5: Obtain assigned IP Address for the PLC and input into Matlab.
ipaddress = '169.254.105.98'; % Input IP Address of PLC
% Step 6: Enter Date of test, format YYYYMMDD.
Date = 20210116;
% Step 7: Enter start time of test, format HHMM, 24 hour clock.
Starttime = 0845;
% Step 8: Switch PLC into Run Mode to start executing the program.
% Step 9: Run Matlab code

% Below is the matlab code and explanation for each line.

Date = num2str(Date); % Convert Date from a number to string.
Starttime = num2str(Starttime); %Convert start time from number to
string.

% Establish stop button.
mybutton = figure(1);
hui =
uicontrol(mybutton,'style','pushbutton','string','STOP','callback',@pus
hbutton,'tag','stopbutton','UserData',0,'position',[20 20 600 600]);
set(hui,'units','normalized');
set(hui,'position',[.1 .1 .8 .8]);
set(hui,'value');
```

```

% Connect to the PLC Modbus

m = modbus('tcpip',ipaddress);

% Establish file to write data to.
filename = [Date '_' Starttime '_Compression_Data.xls'];
fid = fopen(filename,'a'); % Assign properties to file. 'a' means to
write new data to file without deleting existing data.

% Write first line to data file which is the title for each column.
Title = {'Sample #' 'Run Time' 'Compressor Voltage' 'Current' 'Power
Consumption' 'Input Pressure (psig)' 'Input Pressure (Pa)' 'Output
Pressure #2 (psig)' 'Output Pressure #2 (Pa)'};
for ii = 1:length(Title)
    fprintf(fid,'%s\t',Title{ii}); %Tells matlab to print each element of
the array to a single cell.
end
fprintf(fid,'\n'); %Skips to the next line

% Establish constants
R = 4124.3; % Gas Constant for H2 (J/Kg-K)
Area = (12*0.0254)*(15*0.0254); %Establish area of water and process
tanks in m^2.
Area_pipe = (pi/4)*(0.01^2); % Cross Sectional area of plastic tubing
Time = 0; % Establish starting time
pauselen = 30; % Establish how often to take data.
Sample = 1;% Set Sample #
Runtime = 0; % Set Runtime
%%
% Establish while loop for reading and printing data. Findobj is
looking at
% the stop button, if stop button is pressed value will change to 1 and
% cause while loop to stop. get(findobj function is depended upon
% pushbutton function that is saved in the same folder as this code.
Time
% ensures that the code will stop running after 24 hours regardless if
the
% stop button is pressed or not.
while get(findobj('tag','stopbutton'),'UserData')==0
    tic;
    get(findobj('tag','stopbutton'),'UserData');
    % Read data from the modbus.
    PLC = read(m,'holdingregs',400001,7,'single');

    %Convert Raw data to SI units
    Power = (PLC(2))*(PLC(3)); % Determne Compressor Power consumption
(watts)
    LP1 = (PLC(4)+14.7)*6894.75728; % Convert from Psia to Pa
    HP2 = (PLC(6)+14.7)*6894.75728; % Convert from Psia to Pa

```

```

    % Print Raw Data to file.
    RAW = {num2str(Sample) num2str(Runtime) PLC(2) PLC(3) num2str(Power)
    PLC(4) num2str(LP1) PLC(6) num2str(HP2)};

    for i = 1:length(RAW)
        fprintf(fid,'%s\t',RAW{i});
    end
    fprintf(fid,'\n'); %Printing data complete move to next line.

    Sample = Sample +1; %Reset Sample
    Runtime = Runtime + 30; %Reset Runtime
    toc;
    pause(pauselen-toc); %Pause loop for 30 seconds. Data collection
    will only occur every 30 seconds
    Time = Time + pauselen; %Reset Time

end

fclose(fid);% Close the file.

```

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX S. MATLAB CODE FOR STOP BUTTON FUNCTION

```
function pushbutton(src,event)
set(findobj('tag','stopbutton'),'UserData',1);
get(findobj('tag','stopbutton'),'UserData');
end
```

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX T. MATLAB CODE FOR COMPRESSION DATA ANALYSIS

```
%% Joshua Lewis
% Compressor run 12-19Jan2021

clear all;
clc;
close all;
format long
tic
% Read data file
filename = 'Complete Run.xlsx';
M = xlsread(filename,'A2:K20012');
Runtime = M(:,2); % Read runtime (seconds)
Pout_pa = M(:,11); % Read Output Pressure in Pascals,
Volt = xlsread(filename,'E2:E20012');

%% Establish variables
Pout_psia = (Pout_pa/(6894.75729)+14.7); %Pout_pa was based off of a
psig,so convert back to psig, then convert to psia
Pout_psig = Pout_psia - 14.7; % Convert to psig
Pout_pa = Pout_psia*6894.75729; %convert psia to Pascals
Pout_kpa = Pout_pa/1000; %Convert Pa to kPa
pressure_range_psi = [0 1200];
kpa_max_range = 8e3;
pressure_range_kpa = [0 kpa_max_range];
voltrange = [0 .5];
daysec = 86400
V = 3.402249e-5; %m^3
R = 4124.3; %J/kg-K
T = 288.15; %K
P_psig = (50)*6894.75729;
P_pa = 300000;
Max_kpa = max(Pout_kpa)

display('Finished establish variables')
%% Plot Voltage
fig = figure();
set(fig,'units','normalized');
set(fig,'position',[.2 .2 .7 .7]);

plot(Runtime,Volt,'k','LineWidth',2)
hold on

secure = find(Runtime >= 518900,1);
stoptime = [Runtime(secure) Runtime(secure)];
Runtime_curve = Runtime(1:secure);
kpa_curve = Pout_kpa(1:secure);
plot(stoptime,voltrange,'r','LineWidth',2)

start = 52800;
```

```

step = 86400;
for ii=2:8
    alldays.(genvarname(['Day' num2str(ii)])) = [start start];
    plot(alldays.(genvarname(['Day'
num2str(ii)])),voltrange,'m','LineWidth',1)
    start = start + step;
end
for II = 1:7
    alltextx.(genvarname(['textpoint_x' num2str(II)])) =
mean(alldays.(genvarname(['Day' num2str(II+1)])))+5000;
    alltexty.(genvarname(['textpoint_y' num2str(II)])) = .025;
end

text(alltextx.textpoint_x1,alltexty.textpoint_y1,'00:00
13Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x2,alltexty.textpoint_y2,'00:00
14Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x3,alltexty.textpoint_y3,'00:00
15Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x4,alltexty.textpoint_y4,'00:00
16Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x5,alltexty.textpoint_y5,'00:00
17Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x6,alltexty.textpoint_y6,'00:00
18Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x7,alltexty.textpoint_y7,'00:00
19Jan21','Rotation',90,'fontsize',16);

ax = gca; % Get current axes
set(ax,'FontSize',18) % Set axes font size to 18
xticks([0 step 2*step 3*step 4*step 5*step 6*step 7*step])
xticklabels({'Start','+1 Day','+2 Days','+3 Days','+4 Days','+5
Days','+6 days','+7 Days'})
xtickangle(45)
xlabel('Runtime','fontsize',20) % Label X axis and set font
sizeylabel('Compressor Voltage (Volts)','fontsize',20) % Label Y axis
and set font size
ylabel('Volts')
title('Compressor Voltage vs Runtime','fontsize',20) % Set figure title
and font size
lgd = legend('Voltage','Power Secured'); % Establish legend
lgd.FontSize = 18; % Set legend font size
lgd.Location = 'best'; % Set legend location to the bottom right corner
hold off

display('Plot voltage')

%% Establish Pressure Rise vs Runtime Curve (psig) with curve fit
fig = figure();
set(fig,'units','normalized');
set(fig,'position',[.2 .2 .7 .7]);

% [xData, yData] = prepareCurveData( Runtime, Pout_psig );

```

```

% ft = fittype( 'poly2' );% Set up fittype and options.
% [fitresult, gof] = fit( xData, yData, ft, 'Normalize', 'on' );% Fit
model to data.
% h = plot( fitresult, xData, yData,'k');
plot(Runtime,Pout_psig,'k')
hold on

start = 52800;
step = 86400;
for ii=2:8
    alldays.(genvarname(['Day' num2str(ii)])) = [start start];
    plot(alldays.(genvarname(['Day'
num2str(ii)])),pressure_range_psi,'m','LineWidth',1)
    start = start + step;
end

ax = gca; % Get current axes
set(ax,'FontSize',18) % Set axes font size to 18
xlabel('Runtime (seconds)','fontsize',20) % Label X axis and set font
size
ylabel('Pressure (psig)','fontsize',20) % Label Y axis and set font
size
title('Compressor Outlet Pressure vs Runtime','fontsize',20) % Set
figure title and font size
lgd = legend('Output pressure','Output Pressure Best fit','00:00
13Jan2021','00:00 14Jan2021','00:00 15Jan2021','00:00 16Jan2021','00:00
17Jan2021','00:00 18Jan2021','00:00 19Jan2021'); % Establish legend
lgd.FontSize = 18; % Set legend font size
lgd.Location = 'Southeast'; % Set legend location to the bottom right
corner
hold off

display('pressure rise psig')
%% Establish Pressure Rise vs Runtime (kPa) with curve fit.
fig = figure();
set(fig,'units','normalized');
set(fig,'position',[.2 .2 .7 .7]);

plot(Runtime,Pout_kpa,'k','LineWidth',2)
hold on

[xData, yData] = prepareCurveData( Runtime_curve, kpa_curve );
% Set up fittype and options.
ft = fittype( 'exp2' );
opts = fitoptions( 'Method', 'NonlinearLeastSquares' );
opts.Display = 'Off';
opts.Normalize = 'on';
opts.StartPoint = [4871.10060721252 -0.116647446929012 0 -
0.116647446928458];
% Fit model to data.
[fitresult_kpa, gof] = fit( xData, yData, ft, opts );
% Plot fit with data.
h = plot(fitresult_kpa,'g');
h.LineWidth = 2;

```

```

% a = -1.501e8;
% b = -0.2269;
% c = 1.501e8;
% d = -.2268;
% fun = @(x) (a*exp(b*x)+c*exp(d*x));
% g = normalize((Runtime_curve)');
% fplot(fun,[g(1) g(end)])

plot(stoptime,[6000 8000],'r','LineWidth',2)

start = 52800;
step = 86400;
for ii=2:8
    alldays.(genvarname(['Day' num2str(ii)])) = [start start];
    plot(alldays.(genvarname(['Day'
num2str(ii)])),pressure_range_kpa,'m','LineWidth',1)
    start = start + step;
end

for II = 1:7
    alltextx.(genvarname(['textpoint_x' num2str(II)])) =
mean(alldays.(genvarname(['Day' num2str(II+1)])))+5000;
    alltexty.(genvarname(['textpoint_y' num2str(II)])) = 1;
end

text(alltextx.textpoint_x1,alltexty.textpoint_y1,'00:00
13Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x2,alltexty.textpoint_y2,'00:00
14Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x3,alltexty.textpoint_y3,'00:00
15Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x4,alltexty.textpoint_y4,'00:00
16Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x5,alltexty.textpoint_y5,'00:00
17Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x6,alltexty.textpoint_y6,'00:00
18Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x7,alltexty.textpoint_y7,'00:00
19Jan21','Rotation',90,'fontsize',16);

ax = gca; % Get current axes
set(ax,'FontSize',18) % Set axes font size to 18

xticks([0 step 2*step 3*step 4*step 5*step 6*step 7*step])
xticklabels({'Start','+1 Day','+2 Days','+3 Days','+4 Days','+5
Days','+6 days','+7 Days'})
xtickangle(45)
xlabel('Runtime','fontsize',20) % Label X axis and set font size
ylabel('Pressure (kPa)','fontsize',20) % Label Y axis and set font size
title('Compressor Outlet Pressure vs Runtime','fontsize',20) % Set
figure title and font size

```

```

lgd = legend('Output pressure','Output Pressure Best fit','Power Secured'); % Establish legend
lgd.FontSize = 18; % Set legend font size
lgd.Location = 'best'; % Set legend location to the bottom right corner
hold off

display('pressure rise Kpa')

%% Establish pressure rise (kPa) with areas of interest
fig = figure();
set(fig,'units','normalized');
set(fig,'position',[.2 .2 .7 .7]);

plot(Runtime,Pout_kpa,'k','LineWidth',2)
hold on

plot(stoptime,[6000 8000],'r','LineWidth',2)

start = 52800;
step = 86400;
for ii=2:8
    alldays.(genvarname(['Day' num2str(ii)])) = [start start];
    plot(alldays.(genvarname(['Day' num2str(ii)])),pressure_range_kpa,'m','LineWidth',1)
    start = start + step;
end

for II = 1:7
    alltextx.(genvarname(['textpoint_x' num2str(II)])) =
    mean(alldays.(genvarname(['Day' num2str(II+1)])))+5000;
    alltexty.(genvarname(['textpoint_y' num2str(II)])) = 1;
end

text(alltextx.textpoint_x1,alltexty.textpoint_y1,'00:00
13Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x2,alltexty.textpoint_y2,'00:00
14Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x3,alltexty.textpoint_y3,'00:00
15Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x4,alltexty.textpoint_y4,'00:00
16Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x5,alltexty.textpoint_y5,'00:00
17Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x6,alltexty.textpoint_y6,'00:00
18Jan21','Rotation',90,'fontsize',16);
text(alltextx.textpoint_x7,alltexty.textpoint_y7,'00:00
19Jan21','Rotation',90,'fontsize',16);

II = find(Runtime >= 171100,1);
PP = find(Runtime >= 207900,1);
Temp_time1 = Runtime(II:PP);
Temp_kpa1 = Pout_kpa(II:PP);

II = find(Runtime >= 257600,1);

```

```

PP = find(Runtime >= 289800,1);
Temp_time2 = Runtime(II:PP);
Temp_kpa2 = Pout_kpa(II:PP);

II = find(Runtime >= 344000,1);
PP = find(Runtime >= 383600,1);
Temp_time3 = Runtime(II:PP);
Temp_kpa3 = Pout_kpa(II:PP);

II = find(Runtime >= 430500,1);
PP = find(Runtime >= 476400,1);
Temp_time4 = Runtime(II:PP);
Temp_kpa4 = Pout_kpa(II:PP);

II = find(Runtime >= 510700,1);
PP = find(Runtime >= 563500,1);
Temp_time5 = Runtime(II:PP);
Temp_kpa5 = Pout_kpa(II:PP);

Interpret_time = Runtime(9635:11450);
Interpret_kpa = Pout_kpa(9635:11450);

plot(Temp_time1,Temp_kpa1,'g','Linewidth',3);
plot(Temp_time2,Temp_kpa2,'g','Linewidth',3);
plot(Temp_time3,Temp_kpa3,'g','Linewidth',3);
plot(Temp_time4,Temp_kpa4,'g','Linewidth',3);
plot(Temp_time5,Temp_kpa5,'g','Linewidth',3);
plot(Interpret_time,Interpret_kpa,'b','Linewidth',3);

ax = gca; % Get current axes
set(ax,'FontSize',18) % Set axes font size to 18
xticks([0 step 2*step 3*step 4*step 5*step 6*step 7*step])
xticklabels({'Start','+1 Day','+2 Days','+3 Days','+4 Days','+5
Days','+6 days','+7 Days'})
xtickangle(45)
xlabel('Runtime','fontsize',20) % Label X axis and set font size
ylabel('Pressure (kPa)','fontsize',20) % Label Y axis and set font size
title('Compressor Outlet Pressure vs Runtime','fontsize',20) % Set
figure title and font size
lgd = legend('Output pressure','Power Secured'); % Establish legend
lgd.FontSize = 18; % Set legend font size
lgd.Location = 'best'; % Set legend location to the bottom right corner
hold off

display('highlight temp dependence')

%% Mass Flow rates for every 50PSIG increase
%Mass for increase 50 psig
mass_psi = (P_psig*V)/(R*T);
g = Pout_psig(1);
start = 50;
for ii=1:22
II = find(Pout_psig >= start,1,'first');

```

```

allpoints.(genvarname(['Point' num2str(ii)])) = Runtime(II);
start = start + 50;
end

allspan.(genvarname(['span' num2str(1)])) =
allpoints.(genvarname(['Point' num2str(1)]))-0;
for ii=2:22
    allspan.(genvarname(['span' num2str(ii)])) =
allpoints.(genvarname(['Point' num2str(ii)]))-
allpoints.(genvarname(['Point' num2str(ii-1)]));
end

for ii=1:22
    allmassflow.(genvarname(['Mass flow' num2str(ii)]))=
mass_psi/(allspan.(genvarname(['span' num2str(ii)])));
end

fig = figure();
set(fig,'units','normalized');
set(fig,'position',[.2 .2 .7 .7]);
hold on
Sample= [1:22];
% for ii=1:22
% plot(Sample(ii),allmassflow.(genvarname(['Mass Flow'
num2str(ii)])),'.')
% end

for ii=1:22
    Massflow_psi(ii) = allmassflow.(genvarname(['Mass Flow'
num2str(ii)]));
end
Sample = [Sample]';
Massflow_psi = [Massflow_psi]';
avgMassflow_psi = (sum(Massflow_psi))/(max(Sample))
K= table(Sample,Massflow_psi)
% [fitresult, gof] = massflowpolyfit(Sample, Massflow)
[xData, yData] = prepareCurveData( Sample, Massflow_psi );

% Set up fittype and options.
ft = fittype( 'exp2' );
excludedPoints = excludeddata( xData, yData, 'Indices', [1 13 17 22] );
opts = fitoptions( 'Method', 'NonlinearLeastSquares' );
opts.Display = 'Off';
opts.StartPoint = [5.55663298632128e-10 -0.112083617892534
7.96900316138274e-10 -0.0712816923771056];
opts.Exclude = excludedPoints;

% Fit model to data.
[fitresult, gof] = fit( xData, yData, ft, opts );
plot( fitresult, xData, yData, excludedPoints,'*' );

%Format plot
ax = gca; % Get current axes
set(ax,'FontSize',18) % Set axes font size to 18

```

```

xticks(1:22)
xticklabels({'8.93-50','50-100','100-150','150-200','200-250','250-300','300-350','350-400','400-450','450-500','500-550','550-600','600-650','650-700','700-750','750-800','800-850','850-900','900-950','950-1000','1000-1050','1050-1100'})
xtickangle(90)
ylabel('Mass Flow rate (kg/s)','FontSize',18)
xlabel('Pressure Range (psig)','FontSize',18)
title('Mass Flow Rate across Pressure Ranges','FontSize',18)
lgd = legend('Mass flow rate (kg/s)','Excluded mass flow rate','Curve fit'); % Establish legend
lgd.FontSize = 18; % Set legend font size
lgd.Location = 'Northeast'; % Set legend location to the bottom right corner
hold off
display('mass flow psi')
%%
% Mass for increase of 300kPa
mass_pa = (P_pa*V)/(R*T)

start = 300;
for ii=1:25
    II = find(Pout_kpa >=start,1,'first');
    allpoints.(genvarname(['Point' num2str(ii)])) = Runtime(II);
    start = start + 300;
end

allspan.(genvarname(['span' num2str(1)])) =
allpoints.(genvarname(['Point' num2str(1)]))-0;
for ii=2:25
    allspan.(genvarname(['span' num2str(ii)])) =
allpoints.(genvarname(['Point' num2str(ii)]))-
allpoints.(genvarname(['Point' num2str(ii-1)]));
end

for ii=1:25
    allmassflow.(genvarname(['Mass flow' num2str(ii)]))=
mass_pa/(allspan.(genvarname(['span' num2str(ii)])));
end
for ii=1:25
    Massflow_kpa(ii) = allmassflow.(genvarname(['Mass Flow'
num2str(ii)]));
end
Sample= [1:25];

fig = figure();
set(fig,'units','normalized');
set(fig,'position',[.2 .2 .7 .7]);
hold on

% for ii=1:25
% plot(Sample(ii),allmassflow.(genvarname(['Mass Flow'
num2str(ii)])),'.')

```

```

% end

% Fit: 'untitled fit 1'.
[xData, yData] = prepareCurveData( Sample, Massflow_kpa );

% Set up fittype and options.
ft = fittype( 'exp2' );
excludedPoints = excludeddata( xData, yData, 'Indices', [1 15 16 20 21
23 25] );
opts = fitoptions( 'Method', 'NonlinearLeastSquares' );
opts.Normalize = 'on';
opts.StartPoint = [-1.61688499978107e-10 0.24178739533435
7.44300852312412e-10 -0.303609150939664];
opts.Exclude = excludedPoints;

% Fit model to data.
[fitresult_mflow, gof] = fit( xData, yData, ft, opts );

% Plot fit with data.
plot(fitresult_mflow, xData, yData, 'd', excludedPoints, '**');

%Format plot
ax = gca; % Get current axes
set(ax, 'FontSize', 18) % Set axes font size to 18
xticks(1:25)
xticklabels({'162.97-300', '300-600', '600-900', '900-1200', '1200-
1500', '1500-1800', '1800-2100', '2100-2400', '2400-2700', '2700-
3000', '3000-3300', '3300-3600', '3600-3900', '3900-4200', '4200-
4500', '4500-4800', '4800-5100', '5100-5400', '5400-5700', '5700-
6000', '6000-6300', '6300-6600', '6600-6900', '6900-7200', '7200-
7500', '7500-7800'})
xtickangle(90)
ylabel('Mass Flow rate (kg/s)', 'FontSize', 18)
xlabel('Pressure Range (kPa)', 'FontSize', 18)
title('Mass Flow Rate across Pressure Ranges', 'FontSize', 18)
lgd = legend('Mass flow rate (kg/s)', 'Excluded mass flow rate', 'Curve
fit'); % Establish legend
lgd.FontSize = 18; % Set legend font size
lgd.Location = 'Northeast'; % Set legend location to the top right
corner
hold off

display('Finished Plot Mass flow per 300 Kpa')

Sample = [Sample]';
Massflow_kpa = [Massflow_kpa]';
avgMassflow_kpa = (sum(Massflow_kpa)-Massflow_kpa(1)-Massflow_kpa(15)-
Massflow_kpa(16)-Massflow_kpa(20)-Massflow_kpa(21)-Massflow_kpa(23)-
Massflow_kpa(25))/(max(Sample))
K = table(Sample, Massflow_kpa)

```

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX V. XIPERM DEHUMIDIFIER OPERATION MANUAL

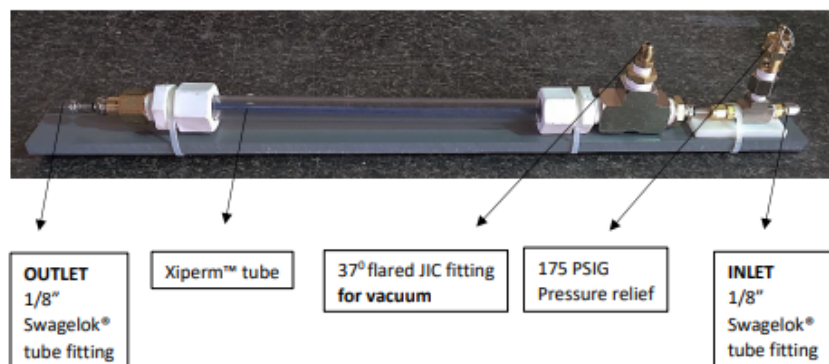
The operating manual reproduced in this appendix, are copyrighted by Xergy Inc., and used with permission from Xergy Inc.

Xiperm™ Dehumidifier Operation Manual

 Xergy Inc.
299 Cluckey Dr., Suite A
Harrington, DE 19952
(P): +1 302-629-5768
info@xergyinc.com
www.xergyinc.com

Xiperm™ Dehumidifier Specifications	
Operation pressure (PSIG)	~ 150
Inlet RH	0 - 100%
Vacuum (PSIG)	~ -14.7
Tube fittings	1/8" Swagelok® tube fittings
Vacuum fitting	37° flared JIC

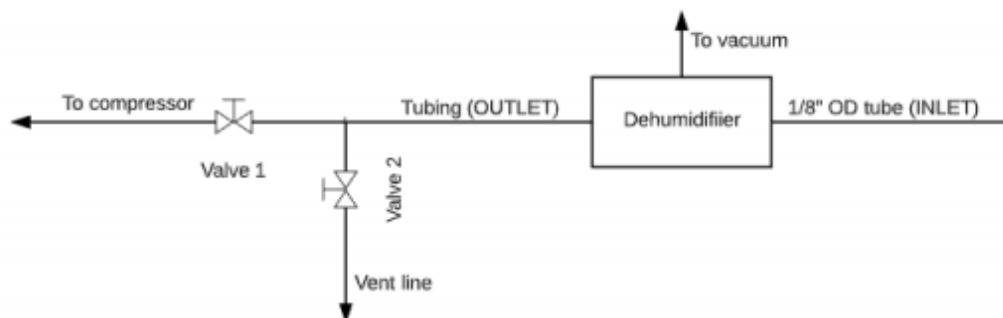
COMPONENTS



The figure above shows the important components of the dehumidifier. The wet gas flows through the tube and vacuum is pulled on the shell side. The tube is designed to operate at 150 PSIG, and the pressure relief valve protects the tube and is set to open at 175 PSIG.

Start-up:

1. Install 1/8" OD tubing into the 1/8" Swagelok® tube fitting provided on the inlet side to connect the gas line to the dehumidifier.
2. Using a suitable adapter, connect the 1/8" Swagelok® tube fitting on the outlet to the compressor and vent line as shown below.



3. Connect a hose to the 37° flared JIC fitting provided, to connect to the vacuum pump.
4. Open valve 2 and close valve 1 so that the gas flow through the dehumidifier initially vents through the vent line.
5. Start the flow of the gas through the tube and turn the vacuum pump ON.
6. The RH of the gas on the outlet side starts to drop immediately and reaches ~40% in about 5 minutes.
7. Open the valve 1 and close valve 2 so that the dehumidified is now fed to the compressor.

Shutdown:

1. Turn the vacuum pump OFF (if using a vacuum pump with oil, follow appropriate precautions so as not to get oil into the dehumidifier).
2. Turn off the gas flow and vent down the system through the vent line.

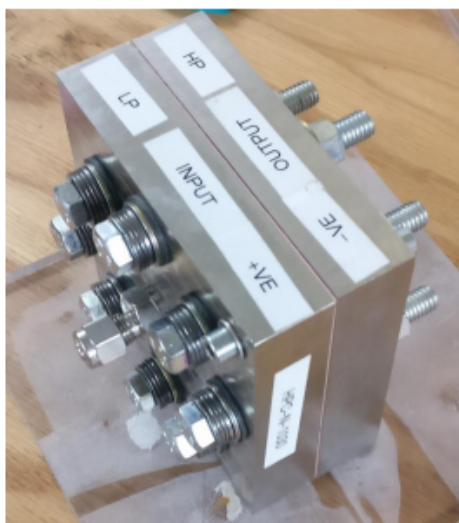
APPENDIX W. X-CELL ELECTROCHEMICAL HYDROGEN COMPRESSOR, XC-HP1500D USER MANUAL

The operating manual reproduced in this appendix, are copyrighted by Xergy Inc., and used with permission from Xergy Inc.

XCELL™ Electrochemical Hydrogen Compressor XC-HP1500D User Manual

 Xergy Inc.
299 Clukey Dr., Suite A
Harrington, DE 19952
(P): +1 302-629-5768
info@xergyinc.com
www.xergyinc.com

XC-HP1500D Specifications	
Operational Voltage (VDC)	<0.4
Humidity Range (%RH)	<50%, optimal <30%
Inlet Pressure (psi)	>150
Outlet Pressure (psi)	<1500
Gas Fittings	¼" Yor-Lok Tube Fittings
Electrical Terminal	¼" Bolt



Page 1 of 3

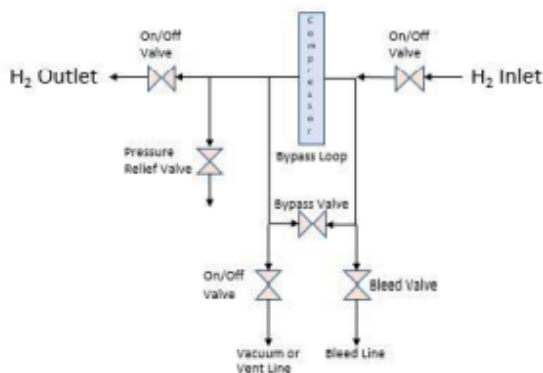
Precautionary Statements

- 1) There must be no gases other than hydrogen present in the system when voltage is being applied.
- 2) It is recommended to have a pressure relief valve on the high-pressure side to maintain system pressure below the maximum pressure of the system.
- 3) If using the membrane dehumidifier, it is recommended to have a pressure relief valve on the low-pressure side to maintain inlet system pressure below the maximum pressure of the membrane dehumidifier.

Operation

Set-up

- 1) Set compressor unit on its side on a stable surface
- 2) Attach Hydrogen Gas inlet and outlet lines to 1/4" Tube Yor-Lock Fittings.
 - a. Input connection: Low pressure (LP) side
 - b. Output connection: High pressure (HP) side
- 3) Attach electrical terminals to endplates by means of 1/4" bolt and washer firmly.
 - a. Positive (+ve) Terminal: Low Pressure (LP) Side
 - b. Negative (-ve) Terminal: High Pressure (HP) Side
- 4) See system schematic below for recommended setup of balance of plant including tubing and valves



Start-up

- 1) Close all valves in the system except for the bypass valve.
- 2) Open the vacuum valve and vacuum out the system for 1 min.
- 3) Close the vacuum valve.
- 4) Set the hydrogen tank to 20psi.
- 5) Open the hydrogen tank valve until the compressor pressure reaches 20psi and then open the bleed line valve for 1 min.
- 6) Close the bleed line valve and the hydrogen tank valve.

- 7) Repeat steps 2-6 ten times to ensure that only hydrogen is present in the system.
- 8) Close the bypass valve.
- 9) Open the hydrogen tank to the desired inlet pressure.
- 10) Apply operational voltage to begin hydrogen compression.
 - a. The system current will fluctuate on initial start-up before equilibrating.
 - b. The system current may decrease as the system begins to compress hydrogen.

Shutdown - Storage

- 1) Turn off the power supply and disconnect the electrical leads from the compressor.
- 2) Vent system pressure and store accordingly.

Shutdown – Continued Testing

- 1) Turn off the power supply and disconnect the electrical leads from the compressor.
- 2) Close all valves in the system.
- 3) Open the bypass valve and the bleed line valve to equilibrate pressure in the system to atmospheric.
- 4) Close the bleed line valve and open the hydrogen tank valve so that the internal pressure of the system is 150psi.
- 5) Close the hydrogen tank valve.
- 6) If the system has positive pressure before next test, bleed and pressurization on start-up needs to only be done once instead of ten times.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

- [1] “Annual Energy Outlook 2020 with Projections to 2050,” U.S. Energy Information Administration, January 29, 2020, <https://www.eia.gov/aeo>.
- [2] Greenley, H. L., 2005, “Department of Defense Energy Management: Background and Issues for Congress,” Congressional Research Service, Report R45832.
- [3] Closson, S., 2013, “The Military and Energy: Moving the United States Beyond Oil,” *Energy Policy* 61, pp. 306–316, <http://dx.doi.org/10.1016/j.enpol.2013.05.102>.
- [4] B. Wilson, “Tactical Microgrids: Mobile and Sustainable Power,” seminar presented at Naval Postgraduate School, Monterey, CA, January 14, 2020, <https://nps.edu/web/eag/january-14-2020>.
- [5] Williams, D., 2009, “Energy Security and National Security; Securing U.S. Energy Resources,” Strategy Research Project, U.S. Army War College, Carlisle Barracks, PA.
- [6] Reintjes, C. 2019, *Energy Resiliency: How DOD Can Become Energy Resilient and Still Meet Its Renewable Energy Goals*. Monterey California. Naval Postgraduate School.
- [7] Jha, A. R., 2012, “Next Generation Batteries and Fuel Cells for Commercial, Military, and Space Applications,” *Current Status of Rechargeable Batteries and Fuel Cells*, Taylor and Francis Group, pp. 1–43, <http://ebookcentral.proquest.com>.
- [8] Moller, K. T., Jensen, T. R., Akiba, E., Li, H., 2016, “Hydrogen—A Sustainable Energy Carrier,” *Progress in Natural Science: Materials International*, 27, pp. 34–40. <http://dx.doi.org/10.1016/j.pnsc.2016.12.014>.
- [9] U.S. Department of Energy, “Hydrogen Production and Distribution,” accessed February 09, 2021, https://afdc.energy.gov/fuels/hydrogen_production.html.
- [10] Dicks, A. L., Rand, D. A. J., 2018, “Fuel Cells Systems Explained,” *Hydrogen Storage*, John Wiley & Sons Ltd., Hoboken, NJ, pp 323–350.
- [11] U.S. Department of Energy, “Hydrogen Production: Electrolysis,” accessed July 24, 2020, <http://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis>.
- [12] U. S. Geological Survey, “How Much Water Is There on Earth?,” accessed February 10, 2021.

- [13] Department of Energy, “Hydrogen Storage,” accessed July 24, 2020, <https://www.energy.gov/eere/fuelcells/hydrogen-storage>.
- [14] Fosson, E., “Design and Analysis of a Hydrogen Compression and Storage Station,” M.S. thesis, Mech. Egr. Dept., Naval Postgraduate School, Monterey, CA, USA 2017.
- [15] “Why Interest in Hydrogen as an Aviation Fuel has Reignited,” last modified October 28, 2020, accessed February 10, 2021.
- [16] Langston, L., S., 2019, “Hydrogen Fueled Gas Turbines.” ASME. Mechanical Engineering. March 2019, 141 (03), pp. 52–54, <https://doi.org/10.1115/1.2019-MAR-6>.
- [17] Birkemeier, S., “Industrial Automation of Solar-Powered Hydrogen Generation Plant,” M.S. thesis, Mech. Egr. Dept., Naval Postgraduate School, Monterey, CA, USA, 2018.
- [18] Kikusui, “User’s Manual: Regulated DC Power Supply,” accessed February 10, 2021, https://manual.kikusui.co.jp/P/PWX_V6_E6.pdf.
- [19] “Linear DC Power Supply,” Good Will Instrument Co. accessed February 10, 2021, www.farnell.com/datasheets/2027954.pdf.
- [20] “Mid Size Dehumidifier Instruction Manual,” accessed February 10, 2021.
- [21] “The Peltier Effect and Thermoelectric Cooling,” University of Alaska Fairbanks, accessed July 24, 2020.
- [22] Yu, S. F., 2017, “Analysis of an Improved Solar-Powered Hydrogen Generation System for Sustained Renewable Energy Production,” M.S. thesis, Mech. Egr. Dept., Naval Postgraduate School, Monterey, CA, USA.
- [23] “Xiperm Dehumidifier Operation Manual,” Xergy, Inc. Harrington, DE, 19952
- [24] “XC-HP1500D User Manual,” Xergy Inc., Harrington, DE, 19952
- [25] Rhandi, M., Tregaro, M., Druart, F., Deseure, J., Chatenet, M., 2020, “Electrochemical Hydrogen Compression and Purification Versus Competing Technologies: Part 1. Pros and Cons,” *Chin. J. Catal.*, Vol 41, No. 5, pp 756–769.
- [26] Grigoriev, S. A., Shtatniy, I. G., Millet, P., Porembsky, V. I., 2010, “Description and Characterization of an Electrochemical Hydrogen Compressor/Concentrator Based on Solid Polymer Electrolyte Technology,” *International Journal of Hydrogen Energy*, Vol 36, pp 4148–4155, [dio:10.1016/j.ijhydene.20110.07.012](https://doi.org/10.1016/j.ijhydene.20110.07.012).

- [27] Rockwell Automation Inc., “Micro850 24 Point Programmable Controllers,” accessed February 10, 2021.
- [28] Rockwell Automation Inc., “Micro800 Programmable Controller External AC Power Supply,” accessed February 10, 2021.
- [29] Rockwell Automation Inc., “Micro800 Plug-in Modules,” accessed February 10, 2021.
- [30] Rockwell Automation Inc., “Micro800 Expansion I/O Modules,” accessed February 10, 2021.
- [31] Phoenix Contact, “Voltage Measuring Transducers,” accessed February 10, 2021.
- [32] Eaton, “CurrentWatch Current Sensors, EDC Series Current Sensors,” accessed February 10, 2021.
- [33] Eaton, “EDC1460SC,” Accessed February 10, 2021, <https://www.eaton.com/us/en-us/skuPage.EDC1420SC.html>.
- [34] Alicat Scientific, “Operating Manual,” accessed February 10, 2021, <https://documents.alicat.com/manuals/DOC-MANUAL-M.pdf>.
- [35] KUS, “SSS/SSL Sender,” accessed February 10, 2021, <https://kus-usa.com/product/sss-ssl-sender/>.
- [36] Honeywell, “MLH Series,” accessed February 10, 2021.
- [37] Compressed Gas Association Inc., 2017 “CGA G5-2017 Hydrogen,” Eighth Edition, Chantilly, VA. pp. 1.
- [38] Malesky, M., “Minimum Oxygen Concentration for Human Breathing,” last modified March 10, 2018, accessed October 26, 2020.
- [39] Compressed Gas Association Inc., 2013. “CGA G-5.6 Hydrogen Pipeline Systems-2005,” First Edition, Chantilly, VA. p. 21.
- [40] Compressed Gas Association Inc., 2012. “CGA G-5.4-2012 Standard for Hydrogen Piping Systems at User Locations,” Fifth Edition, Chantilly, VA. p. 11.
- [41] J & R Welding Supply Co., “High Pressure Gas Cylinders,” last modified May 8, 2013, accessed February 10, 2021.
- [42] Swagelok, “Proportional Relief Valves,” accessed February 11, 2021, <https://www.swagelok.com/downloads/webcatalogs/en/MS-01-141.pdf>.
- [43] Swagelok, “Proportional Safety Relief Valves,” accessed February 11, 2021. <https://www.swagelok.com/downloads/WebCatalogs/EN/MS-02-432.PDF>.

- [44] Rattner, S., 2006, "What is the Theory of Constraints, and How Does it Compare to LEAN Thinking?," Lean Enterprise Institute, last modified September 8, 2006, accessed October 26, 2020, <https://www.lean.org/common/display/?o=223>.
- [45] Vorne Industries Inc., "Theory of Constraints," accessed October 26, 2020, <https://www.leanproduction.com/theory-of-constraints.html>.
- [46] Borgnakke, C., Sonntag, R., 2009, "Fundamentals of Thermodynamics," Seventh Edition, John Wiley & Sons, Inc., Hoboken, NJ, pp. 523–548.
- [47] ASTM International, 2015, "Standard Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)," West Conshohocken, PA.
- [48] Aquarius Education and Public Outreach, "Electrolysis of Salt Water," NASA, accessed April 8, 2021, <https://aquarius.nasa.gov/pdfs/electrolysis.pdf>.
- [49] Sanders, R., 2019 "Water Harvester Makes it Easy to Quench your Thirst in the Desert." University of California Berkley, last modified August 27, 2019, accessed February 11, 2021, <https://news.berkeley.edu/2019/08/27/water-harvester-makes-it-easy-to-quench-your-thirst-in-the-desert/>.
- [50] Kim, H., Rao, S. R., Kapustin, E. A., Zhao, L., Yang, S., Yaghi, O. M., and Wang, E.N., 2018, "Adsorption-Based Atmospheric Water Harvesting Device for Arid Climates," *Nature Communications*, 9:1191, doi: 10.1038/s41467-018-03162-7.
- [51] Hanikel, N., Prevot, M. S., Fathieh, F. Kapustin, E. A., Lyu, H., Wang, H., Diercks, N. J., Glover, T. G., and Yaghi, O. M., 2019, "Rapid Cycling and Exceptional Yield in a Metal-Organic Framework Water Harvester," *ACS Cent. Sci.* 2019, 5, 1699–1706.
- [52] Yrlmaz, E. N., Sayan, H. H., Gonen, S., and Karacayilmaz, G., 2019, "Cyber Security Analysis of DoS and MitM Attacks Against PLCs Used in Smart Grids," 2019 7th International Istanbul Smart Grids and Cities Congress and Fair (*ICSG*), Istanbul, Turkey, 2019, pp. 36–40, doi: 10.1109/SGCF.2019.8782313.
- [53] Lemmon, E. W., McLinden, M. O., and Friend, D. G., "Thermophysical Properties of Fluid Systems," NIST Chemistry WebBook, NIST Standard Reference Database Number 96, National Institute of Standards and Technology, Gaithersburg, MD, 20899, accessed February 11, 2021, <https://doi.org/10.18434/T4D303>.

INITIAL DISTRIBUTION LIST

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