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

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Monterey, CA; Naval Postgraduate School

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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: Anthony J. Gannon
Co-Advisor: Walter Smith

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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 5.52e-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 4.3773e-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.
IMPLEMENTATION OF AN INDUSTRIAL CONTROL SYSTEM FOR THE GENERATION, COMPRESSION, AND STORAGE OF HYDROGEN FROM RENEWABLE SOURCES

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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 5.52e-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 4.3773e-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.
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# 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
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.</td>
<td>MAIN PROGRAM LOCAL VARIABLES</td>
<td>113</td>
</tr>
<tr>
<td>C.</td>
<td>USER DEFINED FUNCTION PID_CONTROLLED_VALVE</td>
<td>113</td>
</tr>
<tr>
<td>D.</td>
<td>USER-DEFINED FUNCTION PID_CONTROLLED_VALVE LOCAL VARIABLES</td>
<td>114</td>
</tr>
<tr>
<td>E.</td>
<td>USER-DEFINED FUNCTION MY_LIMIT</td>
<td>114</td>
</tr>
<tr>
<td>F.</td>
<td>USER-DEFINED FUNCTION MY_LIMIT LOCAL VARIABLES</td>
<td>114</td>
</tr>
<tr>
<td>G.</td>
<td>USER-DEFINED FUNCTION PID_CONVERTER</td>
<td>114</td>
</tr>
<tr>
<td>H.</td>
<td>USER-DEFINED FUNCTION PID_CONVERTER LOCAL VARIABLES</td>
<td>115</td>
</tr>
</tbody>
</table>

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 |
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# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.</td>
<td>Comparison of Key-Type Energy Storage Technologies in Sense of Storage Capacity and Discharge Power Duration. Source: [8]</td>
<td>3</td>
</tr>
<tr>
<td>Figure 2.</td>
<td>Electrolysis. Source: [11]</td>
<td>5</td>
</tr>
<tr>
<td>Figure 3.</td>
<td>Methods for Hydrogen Storage. Source: [13]</td>
<td>6</td>
</tr>
<tr>
<td>Figure 4.</td>
<td>Overview of Compressed Hydrogen Gas Generation System Powered from Renewable Sources</td>
<td>9</td>
</tr>
<tr>
<td>Figure 5.</td>
<td>System Overview</td>
<td>15</td>
</tr>
<tr>
<td>Figure 6.</td>
<td>Kikusui PWX1500ML DC Power Supply</td>
<td>16</td>
</tr>
<tr>
<td>Figure 7.</td>
<td>GW Instek, GPS 1850D, DC Power Supply</td>
<td>17</td>
</tr>
<tr>
<td>Figure 8.</td>
<td>Ivation Dehumidifier</td>
<td>18</td>
</tr>
<tr>
<td>Figure 9.</td>
<td>Electrolyzer</td>
<td>19</td>
</tr>
<tr>
<td>Figure 10.</td>
<td>Xergy Membrane Dehumidifier,</td>
<td>19</td>
</tr>
<tr>
<td>Figure 11.</td>
<td>Marathon Electric Vacuum Pump</td>
<td>20</td>
</tr>
<tr>
<td>Figure 12.</td>
<td>Xergy Electrochemical Hydrogen Compressor</td>
<td>21</td>
</tr>
<tr>
<td>Figure 13.</td>
<td>Operation of an Electrochemical Hydrogen Compressor. Adapted from [25].</td>
<td>22</td>
</tr>
<tr>
<td>Figure 14.</td>
<td>Micro 850 Controller, 2080-LC50-24QBB, with Micro 800 Power Supply, 2080-PS120-240VAC</td>
<td>23</td>
</tr>
<tr>
<td>Figure 15.</td>
<td>2080-IF4 Plug-In Module</td>
<td>24</td>
</tr>
<tr>
<td>Figure 16.</td>
<td>2080-OF2 Plug-In Module</td>
<td>25</td>
</tr>
<tr>
<td>Figure 17.</td>
<td>2085-OF4 Expansion Module</td>
<td>25</td>
</tr>
<tr>
<td>Figure 18.</td>
<td>2085-IF8 Expansion Module</td>
<td>26</td>
</tr>
<tr>
<td>Figure 19.</td>
<td>Phoenix DC Transducer</td>
<td>27</td>
</tr>
<tr>
<td>Figure 20.</td>
<td>Eaton, EDC2420SP DC Current Sensor</td>
<td>28</td>
</tr>
<tr>
<td>Figure 21.</td>
<td>Eaton, EDC1420SC DC Current Sensor</td>
<td>28</td>
</tr>
</tbody>
</table>
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
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
<table>
<thead>
<tr>
<th>A</th>
<th>cross sectional area, m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMMPS</td>
<td>Advanced Medium Mobile Power Source</td>
</tr>
<tr>
<td>ASME</td>
<td>American Society of Mechanical Engineers</td>
</tr>
<tr>
<td>AC</td>
<td>alternating current</td>
</tr>
<tr>
<td>Btu</td>
<td>British thermal unit</td>
</tr>
<tr>
<td>COTS</td>
<td>commercial-off-the-shelf</td>
</tr>
<tr>
<td>CGA</td>
<td>Compressed Gas Association</td>
</tr>
<tr>
<td>CP₇₂</td>
<td>hydrogen gas specific heat at constant pressure, 14209 J/kg*K</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>DOD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>DOT</td>
<td>Department of Transportation</td>
</tr>
<tr>
<td>EHC</td>
<td>electrochemical hydrogen compressor</td>
</tr>
<tr>
<td>H₂</td>
<td>hydrogen gas</td>
</tr>
<tr>
<td>H₂O</td>
<td>water</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>I</td>
<td>Electrical current, Amps</td>
</tr>
<tr>
<td>J</td>
<td>joules</td>
</tr>
<tr>
<td>kPa</td>
<td>kiloPascals</td>
</tr>
<tr>
<td>K</td>
<td>Kelvin</td>
</tr>
<tr>
<td>lbm</td>
<td>pounds mass</td>
</tr>
<tr>
<td>LPM</td>
<td>liters per minute</td>
</tr>
<tr>
<td>̇m</td>
<td>mass flow rate, kg/s</td>
</tr>
<tr>
<td>̇m₇₂</td>
<td>mass of hydrogen, kg</td>
</tr>
<tr>
<td>M₁₁₂</td>
<td>hydrogen molar mass, 0.002016 kg/mol</td>
</tr>
<tr>
<td>NFPA</td>
<td>National Fire Protection Association</td>
</tr>
<tr>
<td>O₂</td>
<td>oxygen Gas</td>
</tr>
<tr>
<td>Pₗ</td>
<td>high pressure, Pa</td>
</tr>
<tr>
<td>Pₗ</td>
<td>low pressure, Pa</td>
</tr>
<tr>
<td>Pₘ₃₅</td>
<td>Maximum system pressure, 13789.51 kPa (2000 psig)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>$P_{\text{total}}$</td>
<td>total pressure, 101325 Pa</td>
</tr>
<tr>
<td>$P_v$</td>
<td>partial pressure of a vapor</td>
</tr>
<tr>
<td>$P_g$</td>
<td>saturation pressure of a vapor</td>
</tr>
<tr>
<td>Pa</td>
<td>Pascals</td>
</tr>
<tr>
<td>PEM</td>
<td>proton exchange membrane</td>
</tr>
<tr>
<td>PLC</td>
<td>programmable logic controller</td>
</tr>
<tr>
<td>psia</td>
<td>pounds per square inch absolute</td>
</tr>
<tr>
<td>psig</td>
<td>pounds per square inch gauge</td>
</tr>
<tr>
<td>PWM</td>
<td>pulse width modulator</td>
</tr>
<tr>
<td>Q</td>
<td>volumetric flow rate, m$^3$/s</td>
</tr>
<tr>
<td>R</td>
<td>electrical resistance, Ohms</td>
</tr>
<tr>
<td>$R_{\text{H}_2}$</td>
<td>hydrogen gas constant, 4124.3 $\frac{J}{\text{kg} \cdot \text{K}}$</td>
</tr>
<tr>
<td>$R_{\text{vapor}}$</td>
<td>water vapor gas constant, 461.5 $\frac{J}{\text{kg} \cdot \text{K}}$</td>
</tr>
<tr>
<td>$\rho_{\text{H}_2}$</td>
<td>density of hydrogen, 0.0813 kg/m$^3$</td>
</tr>
<tr>
<td>$\rho_{\text{water}}$</td>
<td>density of water at 15°C, 999.06 kg/m$^3$</td>
</tr>
<tr>
<td>SLPm</td>
<td>standard liter per minute</td>
</tr>
<tr>
<td>$T_{\text{dry}}$</td>
<td>temperature at dry bulb thermometer</td>
</tr>
<tr>
<td>TLI</td>
<td>tank level indicator</td>
</tr>
<tr>
<td>$T_{\text{st}}$</td>
<td>standard Temperature, 288.15 K</td>
</tr>
<tr>
<td>$T_{\text{wet}}$</td>
<td>temperature at wet bulb thermometer</td>
</tr>
<tr>
<td>V</td>
<td>volume, m$^3$</td>
</tr>
<tr>
<td>$V_{\text{et}}$</td>
<td>compress testing volume, m$^3$</td>
</tr>
<tr>
<td>VDC</td>
<td>voltage direct current</td>
</tr>
<tr>
<td>$V_{\text{dot}}$</td>
<td>volume of DOT storage cylinder, 0.0433 m$^3$</td>
</tr>
<tr>
<td>Ve</td>
<td>volts</td>
</tr>
<tr>
<td>U</td>
<td>velocity, m/s</td>
</tr>
<tr>
<td>$\dot{W}$</td>
<td>power, Watts</td>
</tr>
<tr>
<td>$\omega_1$</td>
<td>humidity ratio at $T_{\text{dry}}$</td>
</tr>
<tr>
<td>$\omega_2$</td>
<td>humidity ratio at $T_{\text{wet}}$</td>
</tr>
</tbody>
</table>
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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, electrochemical, 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 electrochemical 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].

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

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

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-. \quad (1)$$

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

$$4H^+ + 4e^- \rightarrow 2H_2 \quad (2)$$

combines the electrons [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].

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].

<table>
<thead>
<tr>
<th>Energy Source / Storage Medium</th>
<th>Gravimetric Energy Density [MJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaseous H(_2) (g) 1atm</td>
<td>120-142</td>
</tr>
<tr>
<td>Liquid H(_2) (l)</td>
<td>120-142</td>
</tr>
<tr>
<td>Compressed Gaseous H(_2) (g) 700 Bar</td>
<td>120-142</td>
</tr>
<tr>
<td>Compressed Gaseous H(_2) (g) 350 Bar</td>
<td>120-142</td>
</tr>
<tr>
<td>Methane (g)</td>
<td>50.0-55.5</td>
</tr>
<tr>
<td>LNG (l)</td>
<td>49.4-55.2</td>
</tr>
<tr>
<td>LPG Propane (l)</td>
<td>46.0-50.0</td>
</tr>
<tr>
<td>CNG (g)</td>
<td>46.9-49.4</td>
</tr>
<tr>
<td>LPG Butane (l)</td>
<td>45.3-49.13</td>
</tr>
<tr>
<td>Crude Oil (l)</td>
<td>43.1-48.3</td>
</tr>
<tr>
<td>Gasoline (l)</td>
<td>44.5-48.2</td>
</tr>
<tr>
<td>Jet Fuel (l)</td>
<td>42.8-45.7</td>
</tr>
<tr>
<td>Diesel (l)</td>
<td>42.9-45.7</td>
</tr>
<tr>
<td>Biogas Fuel Oil (l)</td>
<td>24.4-41.9</td>
</tr>
<tr>
<td>Commercial by-products (used tires)</td>
<td>38.2</td>
</tr>
<tr>
<td>Coal (s)</td>
<td>16.3–33.5</td>
</tr>
<tr>
<td>Ethanol (l)</td>
<td>26.8–29.7</td>
</tr>
<tr>
<td>Commercial by-products (coffee grounds)</td>
<td>23.8</td>
</tr>
<tr>
<td>Biomass (wood)</td>
<td>19.9–21.3</td>
</tr>
<tr>
<td>Biomass (peat)</td>
<td>8.61–18.6</td>
</tr>
<tr>
<td>Commercial by-products (cow manure)</td>
<td>17.2</td>
</tr>
<tr>
<td>Fuel Cells (2015 Actual)</td>
<td>2.37</td>
</tr>
<tr>
<td>Fuel Cells (2020 Target)</td>
<td>2.34</td>
</tr>
<tr>
<td>Fuel Cells (Ultimate Target)</td>
<td>2.34</td>
</tr>
<tr>
<td>Primary Batteries</td>
<td>0.20–2.12</td>
</tr>
<tr>
<td>Secondary Batteries</td>
<td>0.11–0.72</td>
</tr>
<tr>
<td>Supercapacitors</td>
<td>0.007–0.036</td>
</tr>
</tbody>
</table>
Table 2. Volumetric Energy Densities of Common Energy Sources and Storage Mediums. Adapted from [14].

<table>
<thead>
<tr>
<th>Energy Source / Storage Medium</th>
<th>Volumetric Energy Density [MJ/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude Oil (l)</td>
<td>34.4–47.6</td>
</tr>
<tr>
<td>Jet Fuel (l)</td>
<td>36.0–38.4</td>
</tr>
<tr>
<td>Diesel (l)</td>
<td>36.0–38.4</td>
</tr>
<tr>
<td>Gasoline (l)</td>
<td>33.4–36.2</td>
</tr>
<tr>
<td>Biogas Fuel Oil (l)</td>
<td>17.3–31.4</td>
</tr>
<tr>
<td>Coal (s)</td>
<td>11.0–31.1</td>
</tr>
<tr>
<td>LPG Propane (l)</td>
<td>23.5–25.5</td>
</tr>
<tr>
<td>LPG Butane (l)</td>
<td>23.1–25.1</td>
</tr>
<tr>
<td>Ethanol (l)</td>
<td>23.5</td>
</tr>
<tr>
<td>LNG (l)</td>
<td>22.2</td>
</tr>
<tr>
<td>Biomass (wood)</td>
<td>7.97–21.3</td>
</tr>
<tr>
<td>Commercial by-products (used tires)</td>
<td>14.7–20.2</td>
</tr>
<tr>
<td>Commercial by-products (cow manure)</td>
<td>17.1–17.9</td>
</tr>
<tr>
<td>Biomass (peat)</td>
<td>2.07–17.9</td>
</tr>
<tr>
<td>Liquid H2 (l)</td>
<td>8.5–9</td>
</tr>
<tr>
<td>CNG (g)</td>
<td>8.44–8.9</td>
</tr>
<tr>
<td>Commercial by-products (coffee grounds)</td>
<td>7.45</td>
</tr>
<tr>
<td>Primary Batteries</td>
<td>0.5–4.86</td>
</tr>
<tr>
<td>Compressed Gaseous H2 (g) 700 Bar</td>
<td>4.7</td>
</tr>
<tr>
<td>Fuel Cells (Ultimate Target)</td>
<td>3.06</td>
</tr>
<tr>
<td>Compressed Gaseous H2 (g) 350 Bar</td>
<td>2.7</td>
</tr>
<tr>
<td>Fuel Cells (2020 Target)</td>
<td>2.34</td>
</tr>
<tr>
<td>Fuel Cells (2015 Actual)</td>
<td>2.304</td>
</tr>
<tr>
<td>Secondary Batteries</td>
<td>0.20–2.05</td>
</tr>
<tr>
<td>Supercapacitors</td>
<td>0.005–0.05</td>
</tr>
<tr>
<td>Methane (g)</td>
<td>0.03–0.04</td>
</tr>
<tr>
<td>Gaseous H2 (g) 1 atm</td>
<td>0.0098–0.0115</td>
</tr>
</tbody>
</table>

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

![Overview of Compressed Hydrogen Gas Generation System Powered from Renewable Sources](image)

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.

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 $5.52 \times 10^7$ 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.
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>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DC power supply</td>
<td>Kikusui PWL1500ML</td>
</tr>
<tr>
<td>2</td>
<td>DC power supply</td>
<td>GW Instek GPS 1850D</td>
</tr>
<tr>
<td>3</td>
<td>Dehumidifier</td>
<td>Ivation dehumidifier</td>
</tr>
<tr>
<td>4</td>
<td>Electrolyzer</td>
<td>Electrolyzer</td>
</tr>
<tr>
<td>5</td>
<td>Hydrogen dryer</td>
<td>Xergy membrane dehumidifier</td>
</tr>
<tr>
<td>6</td>
<td>Vacuum Pump</td>
<td>Marathon Electric Vacuum pump</td>
</tr>
<tr>
<td>7</td>
<td>Compressor</td>
<td>Xergy electrochemical hydrogen compressor</td>
</tr>
</tbody>
</table>
### Table 4. Control Components

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Micro 850 Controller</td>
<td>2080-LC50-24QBB</td>
</tr>
<tr>
<td>2</td>
<td>Micro 800 power supply</td>
<td>2080-PS120-240VAC</td>
</tr>
<tr>
<td>3</td>
<td>Plug-in module</td>
<td>2080-IF4</td>
</tr>
<tr>
<td>4</td>
<td>Plug-in module</td>
<td>2080-OF4</td>
</tr>
<tr>
<td>5</td>
<td>Expansion module</td>
<td>2085-OF4</td>
</tr>
<tr>
<td>6</td>
<td>Expansion module</td>
<td>2085-IF8</td>
</tr>
</tbody>
</table>

### Table 5. Sensor Components

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DC voltage transducer</td>
<td>Phoenix DC Transducer</td>
</tr>
<tr>
<td>2</td>
<td>Eaton current transducer</td>
<td>EDC 2420SP</td>
</tr>
<tr>
<td>3</td>
<td>Eaton current transducer</td>
<td>EDC1420SC</td>
</tr>
<tr>
<td>4</td>
<td>Alicat Flowmeter</td>
<td>M-5SLPM-D/5M</td>
</tr>
<tr>
<td>5</td>
<td>Tank level indicator</td>
<td>KUS SSS7</td>
</tr>
<tr>
<td>6</td>
<td>Honeywell pressure transducer</td>
<td>MLH500PSL01A</td>
</tr>
<tr>
<td>7</td>
<td>Honeywell pressure transducer</td>
<td>MLH03KPSB01A</td>
</tr>
</tbody>
</table>
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 adaptions 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.

![Kikusui PWX1500ML DC Power Supply](image)

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](image)

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].
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.
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 9. Electrolyzer

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).
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].

\[
H_2 \rightarrow 2H^+ + 2e^- \quad (3)
\]

\[
2H^+ + 2e^- \rightarrow 2H_2 \quad (4)
\]
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.
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 plug-in modules used were 2080-IF4 and 2080-OF2.
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.
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.

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].

![2085-IF8 Expansion Module](image)

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.

![Phoenix DC Transducer]

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.

![Alicat M-5SLPM-D/5M Hydrogen Gas Flow Meter](image)

**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.
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 ±2.1mm and mounted 25.4 mm (1 inch) above the bottom of each tank [35].

Figure 23. KUS SSS7 Tank Level Indicator

Figure 24. Honeywell Pressure Transducer Model #MLH500PSL01A
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 354870 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].

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 litters (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.
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].
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 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
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>
<thead>
<tr>
<th>Test #</th>
<th>Date</th>
<th>Average Ambient Temperature (K)</th>
<th>Average Ambient Relative Humidity</th>
<th>Hours</th>
<th>Total Water Produced (kg)</th>
<th>Rate of production (kg/hr)</th>
<th>Time to fill one DOT-3AA2265 cylinder (days)</th>
<th>Power (Watts)</th>
<th>Kg/J</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13Aug20</td>
<td>298.70</td>
<td>68.43%</td>
<td>8</td>
<td>0.1701</td>
<td>0.0212625</td>
<td>13.19</td>
<td>104</td>
<td>5.6797e-8</td>
</tr>
<tr>
<td>2</td>
<td>17Aug20</td>
<td>299.18</td>
<td>66.63%</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>∞</td>
<td>104</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>18Aug20</td>
<td>298.8</td>
<td>67.25%</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>∞</td>
<td>104</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>19Aug20-20Aug20</td>
<td>292.52</td>
<td>64.29%</td>
<td>17</td>
<td>0.4797</td>
<td>0.0282176</td>
<td>9.94</td>
<td>104</td>
<td>7.5367e-8</td>
</tr>
<tr>
<td>5</td>
<td>20Aug20</td>
<td>292.53</td>
<td>66.44%</td>
<td>8</td>
<td>0.1962</td>
<td>0.024525</td>
<td>11.44</td>
<td>104</td>
<td>6.5504e-8</td>
</tr>
<tr>
<td>6</td>
<td>20Aug20-21Aug20</td>
<td>292.09</td>
<td>73.65%</td>
<td>16</td>
<td>0.8691</td>
<td>0.054318</td>
<td>5.16</td>
<td>104</td>
<td>1.4508e-7</td>
</tr>
<tr>
<td>7</td>
<td>03Nov20</td>
<td>287.84</td>
<td>80.11%</td>
<td>8</td>
<td>0.0787</td>
<td>0.0098375</td>
<td>28.52</td>
<td>104</td>
<td>2.627e-8</td>
</tr>
</tbody>
</table>

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 was 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 the 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 Ohms 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].

\[ \phi = \frac{P_v}{P_g} \]  

(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].
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

\[
\frac{dm_{CV}}{dt} = \Sigma \dot{m}_i - \Sigma \dot{m}_e = 0, \quad (8)
\]

where

\[
\Sigma \dot{m}_i = \text{Sum of mass flow into control volume}
\]

\[
\Sigma \dot{m}_e = \text{Sum of mass flow exiting control volume}
\]

44
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.

\[ m = \rho AU \]  \hspace{1cm} (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 10 m/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**

<table>
<thead>
<tr>
<th>Test</th>
<th>Ambient Temp, $T_\infty$</th>
<th>Dry Bulb Temp, $T_1$</th>
<th>Wet Bulb Temp, $T_2$</th>
<th>% Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Hydrogen</td>
<td>18.8 °C</td>
<td>21.6 °C</td>
<td>10.5 °C</td>
<td>76%</td>
</tr>
<tr>
<td>Saturated Hydrogen</td>
<td>12 °C</td>
<td>11.6 °C</td>
<td>10.5 °C</td>
<td>98%</td>
</tr>
<tr>
<td>Hydrogen produced by Electrolyzer</td>
<td>23 °C</td>
<td>31.1 °C</td>
<td>26.6 °C</td>
<td>83.1%</td>
</tr>
<tr>
<td>Hydrogen after membrane dehumidifier</td>
<td>12 °C</td>
<td>54 °C</td>
<td>52 °C</td>
<td>98%</td>
</tr>
</tbody>
</table>

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
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 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.

\[
m = \frac{(P_h - P_l)\nu_c}{R_{H_2}T_{st}}
\]

(9)

Using Equation 9 and a standard increment of 300 kPa, yields a required mass increase of 8.588e-6 kg (1.89e-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

\[ t(@P_h) = \text{Compressor runtime at high pressure, in seconds} \]

\[ t(@P_l) = \text{Compressor runtime at low pressure, in seconds} \]

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

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

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.
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 $5.52 \times 10^{-7}$ 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 consider.

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 able to 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\texttimes{}10^{-7} \text{ kg/s} (1.22\texttimes{}10^{-6} \text{ 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 \text{ kPa} (1071.99 \text{ psig}) at an average mass flow rate of 4.37\texttimes{}10^{-10} \text{ kg/s} (9.65\texttimes{}10^{-10} \text{ 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.
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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 recommendations 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 loses of solar energy.

Lastly, this research recommendations 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.
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

$$v_{H2} = \frac{R_{H2} \ (T_{st})}{P_{max}} = \frac{(4124.3)(288.15)}{13.7951e6} \quad (B.2)$$

yields

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

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

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

where

$$m_{H2} = 0.0433 \quad 0.08618 \quad m_{H2} = 0.50242 \ \text{kg}.$$ 

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

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

where

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

yields

\[
mol_{\text{water}} = 373.82521 \text{ moles}.
\]

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

\[
m_{\text{water}} = (mol_{\text{water}})M_{\text{water}}, \quad (B.6)
\]

where

\[
M_{\text{water}} = 0.018015 \frac{kg}{mol}
\]

yields

\[
m_{\text{water}} = 6.73446 \text{ kg}.
\]

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

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

where

\[
\rho_{\text{water}} = \text{Density of water at 15°C} = 999.06 \frac{kg}{m^3}
\]

yields

\[
Vol_{\text{water}} = 0.00674 m^3 = 6.740 \text{ liters (1.78 gallons)}.
\]
APPENDIX C. GENERATION SIDE PURGING TIME CALCULATIONS

All calculations were conducted with an assumed mass flow rate of $5.52 \times 10^{-7}$ 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.

$$\dot{m} = \rho_{H_2}AU = 5.52 \times 10^{-7} \frac{kg}{s}$$

thus,

$$Q = AU = 6.789 \times 10^{-6} \frac{m^3}{s}$$

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,

$$A = \frac{\pi}{4}d^2$$  \hspace{1cm} (C.1)

$$A = 7.854 \times 10^{-5} m^2$$

Yields,

$$U = \frac{Q}{A} = 0.08645 \frac{m}{s}$$  \hspace{1cm} (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.

$$t = \frac{L}{U} = \frac{10.6 \frac{m}{s}}{0.08645 \frac{m}{s}} = 122.6 \text{ seconds}$$  \hspace{1cm} (C.3)

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

$$t_{\text{purge}} = FS \times t = 2 \times (122.6) = 245.23 \text{ seconds} \sim 4 \text{ min 5 seconds}$$  \hspace{1cm} (C.4)
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 $5.52 \times 10^{-7}$ 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.

$$\dot{m} = \rho_{H_2} A U = 5.52 \times 10^{-7} \text{ kg/s}$$

thus,

$$Q = AU = 6.789 \times 10^{-6} \text{ m}^3/\text{s}$$

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

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

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].](image)

75
Simplified continuity equation,

\[ m_1 = \dot{m}_2 \]

Thus,

\[ \rho_1 A_1 U_1 = \rho_2 A_2 U_2 \]  \hspace{1cm} (D.2)

Assuming constant density, \( \rho_1 = \rho_2 \), yields,

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

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

\[ A_2 = \frac{Q}{U_2} = 1.697 e^{-6} \text{ m}^2 \]  \hspace{1cm} (D.3)

Thus, the required diameter is,

\[ d = \sqrt{\frac{4\pi A}{\pi}} \]  \hspace{1cm} (D.4)

\[ d = 0.00147 \text{ m} = 1.47 \text{ mm} \]
APPENDIX E. RELATIVE HUMIDITY SAMPLE CALCULATION

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

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Pressure (MPa)</th>
<th>Density (kg/m³)</th>
<th>Volume (m³/kg)</th>
<th>Internal Energy (kJ/kg)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy (J/g*K)</th>
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<td>0.00100471</td>
<td>129.701</td>
<td>129.705</td>
<td>0.449833</td>
</tr>
<tr>
<td>304.2</td>
<td>0.00450976</td>
<td>995.284</td>
<td>0.00100474</td>
<td>130.119</td>
<td>130.123</td>
<td>0.451208</td>
</tr>
<tr>
<td>304.3</td>
<td>0.00453551</td>
<td>995.253</td>
<td>0.00100477</td>
<td>130.537</td>
<td>130.541</td>
<td>0.452582</td>
</tr>
<tr>
<td>304.4</td>
<td>0.00456138</td>
<td>995.222</td>
<td>0.0010048</td>
<td>130.955</td>
<td>130.959</td>
<td>0.453955</td>
</tr>
<tr>
<td>304.5</td>
<td>0.00458739</td>
<td>995.191</td>
<td>0.00100483</td>
<td>131.373</td>
<td>131.377</td>
<td>0.455328</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Pressure (kPa)</th>
<th>Sat. Liquid h_f</th>
<th>Evap. h_fg</th>
<th>Sat. Vapor h_g</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>3.169</td>
<td>104.87</td>
<td>2442.30</td>
<td>2547.17</td>
</tr>
<tr>
<td>30</td>
<td>4.246</td>
<td>127.77</td>
<td>2430.48</td>
<td>2556.25</td>
</tr>
<tr>
<td>35</td>
<td>5.628</td>
<td>146.66</td>
<td>2418.62</td>
<td>2565.28</td>
</tr>
</tbody>
</table>


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

\[
T_{\text{dry}} = 31.11 \degree \text{C} = 304.26 \text{ K}
\]

\[
T_{\text{wet}} = 26.66 \degree \text{C} = 299.81 \text{ K}
\]

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

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

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

\[
P_{\text{vapor,2}} = 3505.33694 \text{ Pa}
\]

With saturation pressure of water vapor at \(T_{\text{wet}}\), the mass ratio of water vapor to dry hydrogen, \(\omega_2\) is determined.

\[
\omega_2 = \left(\frac{R_{\text{H2}}}{R_{\text{vapor}}}\right) * \left(\frac{P_{\text{vapor,2}}}{P_{\text{total}} - P_{\text{vapor,2}}}\right) \quad (E.2)
\]

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

\[
\omega_2 = 0.32024485
\]

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, \(\omega_1\), at \(T_{\text{dry}}\).

\[
\omega_1 = \frac{c_{p_{\text{H2}}}(T_{\text{dry}} - T_{\text{wet}}) + \omega_2 * h_{fg,2}}{(h_{v,1} - h_{fg,2})} \quad (E.3)
\]

The enthalpy values required for Equation E.3, were found using Table 10 and a linear interpolation, which yielded:
\[ h_{fg,2} = Evap, h_{fg}, Enthalpy \text{ at } T_{wet} = 2438360 \frac{J}{kg \cdot K} \]

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

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

Thus,

\[ \omega_1 = \frac{14209(304.26 - 299.81) + 0.32024485 \times 2438360}{(2558256.67 - 111836.667)} \]

\[ \omega_1 = 0.34500345 \]

With the mass ratio of water vapor to dry hydrogen the relative humidity, \( \omega_1 \), at \( T_{dry} \), Equation E.4 is used to calculate the relative humidity, \( \phi_1 \), of the hydrogen gas.

\[ \phi_1 = \left( \frac{\omega_1}{\left( \frac{R_{H_2}}{R_{\text{vapor}}} \right) + \omega_1} \right) \times \left( \frac{P_{\text{total}}}{P_{\text{vapor,1}}} \right) \times 100 \quad (E.4) \]

A linear interpolation of Table 8 yields a \( P_{\text{vapor,1}} \) of 4532.29202 Pa. Thus,

\[ \phi_1 = \left( \frac{0.34500345}{\left( \frac{4124.3}{461.5} \right) + 0.34500345} \right) \times \left( \frac{101325}{4532.29202} \right) \times 100 \]

\[ \phi_1 = 83.1\% \]
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, \( \rho gz \), is negligible.
- Pressure at the outlet is atmospheric pressure.
- Density, \( \rho \), of hydrogen gas is 0.0813 kg/m\(^3\)
- Velocity at the inlet is 0 m/s

![Free Body Diagram of Relative Humidity Testing Device](image)

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;
\[ P_{ln} = 101325 + \left( \frac{1}{2} \times (0.0813) \times 10^2 \right) \]

\[ P_{ln} = 101329.0691 \text{ Pa} = 0.000589 \text{ psig} \]
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 $4.3773 \times 10^{-10}$ 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.

\[
m_{\text{DOT}} = \frac{p_{\text{DOT}} V_{\text{DOT}}}{R_{\text{H}_2} T_{st}} \quad (G.1)
\]

Yields,

\[
m_{\text{DOT}} = 0.27299 \text{ kg}
\]

Thus,

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

Where,

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

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

Yields,

\[
\Delta t \approx 6.2e^8 \text{ seconds} \approx 19.7 \text{ years}
\]
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:

\[
N \geq \frac{\ln \left( \frac{C_{\text{meq}}}{C_{\text{air}}} \right)}{\ln \left( \frac{P_{\text{low}}}{P_{\text{high}}} \right)} = \ln \left( \frac{0.01}{0.21} \right).
\]

where,

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

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

P_{\text{low}} = \text{Absolute pressure after vacuum}

and,

P_{\text{high}} = \text{Purging pressure of inert gas, 34 atm N}_2 (500 \text{ psi}) \text{ maximum.}

The total mass of N2 required for the vacuum/pressure purge process is calculated as follows:

\[
m = n \times M = \left( \frac{P_{\text{high}} - P_{\text{low}}}{R \cdot T} \right) V \times \frac{M}{1000 \text{ (g/kg)}},
\]

where,

n = \text{Moles of purge gas added to the station, mol}

M = \text{Molar Mass of Nitrogen, 28.0134 g/mol}
\[ V = \text{Total Volume of vessels, } 0.2592 \text{ m}^3 \]

\[ R = \text{Universal Gas Constant, } 8.314 \frac{J}{mol \cdot K} \]

\[ T = \text{normal temperature, } 298.15 \text{ K (25 °C).} \]

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

<table>
<thead>
<tr>
<th>( P_{\text{Low}}, \text{ atm} )</th>
<th>( P_{\text{High}}, \text{ atm} )</th>
<th>( N )</th>
<th>\text{Total Mass of } N_2 \text{ Required, kg}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.064</td>
<td>1.7</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>0.332</td>
<td>1.7</td>
<td>2</td>
<td>0.8</td>
</tr>
<tr>
<td>0.064</td>
<td>1.3</td>
<td>2</td>
<td>0.8</td>
</tr>
<tr>
<td>0.332</td>
<td>1.3</td>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>0.666</td>
<td>2.0</td>
<td>3</td>
<td>1.2</td>
</tr>
<tr>
<td>0.666</td>
<td>3.4</td>
<td>2</td>
<td>1.6</td>
</tr>
<tr>
<td>1.0</td>
<td>3.0</td>
<td>3</td>
<td>1.8</td>
</tr>
<tr>
<td>0.332</td>
<td>7.1</td>
<td>1</td>
<td>2.0</td>
</tr>
<tr>
<td>1.0</td>
<td>4.7</td>
<td>2</td>
<td>2.2</td>
</tr>
<tr>
<td>0.666</td>
<td>14.3</td>
<td>1</td>
<td>4.0</td>
</tr>
<tr>
<td>1.0</td>
<td>21.0</td>
<td>1</td>
<td>6.0</td>
</tr>
</tbody>
</table>
APPENDIX I. CALIBRATION CURVE HONEYWELL PRESSURE TRANSUDER, 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

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

Figure 51. Honeywell Pressure Transducer, MLH500PSL01A
APPENDIX J. CALIBRATION CURVE HONEYWELL PRESSURE TRANSUDER, 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

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

Figure 52. Honeywell Pressure Transducer, MLH03KPSB01A
APPENDIX K. RELATIVE HUMIDITY TESTING DEVICE INSERT

DIMENSIONS
APPENDIX L. PIPING AND IDENTIFICATION (P&ID) DIAGRAM
<table>
<thead>
<tr>
<th>Symbols</th>
<th>Check Valve</th>
<th>Dehumidifier</th>
<th>Relief Valve</th>
<th>Pressure Gauge (Mechanical)</th>
<th>Manual Valve</th>
<th>Pressure Transducer</th>
<th>Compressor</th>
<th>Thermocouple</th>
<th>Pressure Cylinder</th>
<th>Flow rate Measurement</th>
<th>Tank</th>
<th>Hydrogen Gas Analyzer</th>
<th>Electrolyzer</th>
<th>Water Piping (H₂O)</th>
</tr>
</thead>
</table>

System: Hydrogen Generation and Compression

Sub-system: Legend

Sheet: H-04

Created by: LT Joshua Lewis

Date: 01/15/2021

96
<table>
<thead>
<tr>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regulator</strong></td>
</tr>
<tr>
<td>![Regulator Icon]</td>
</tr>
<tr>
<td><strong>Vacuum Pump</strong></td>
</tr>
<tr>
<td>![Vacuum Pump Icon]</td>
</tr>
<tr>
<td><strong>Rupture Disk</strong></td>
</tr>
<tr>
<td>![Rupture Disk Icon]</td>
</tr>
<tr>
<td><strong>Membrane Dehumidifier</strong></td>
</tr>
<tr>
<td>![Membrane Dehumidifier Icon]</td>
</tr>
<tr>
<td><strong>Hydrogen Gas (H₂)</strong></td>
</tr>
<tr>
<td>![Hydrogen Gas Icon]</td>
</tr>
</tbody>
</table>

**System:** Hydrogen Generation and Compression

**Sub-system:** Legend

**Sheet:** H-05

**Created by:** LT Joshua Lewis

**Date:** 1/13/2021
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 N\text{\textsubscript{2}} SUPPLY TANK IS REQUIRED FOR PURGING SYSTEM.**

7. Align N\text{\textsubscript{2}} Supply Tank to be used.
   a. N\text{\textsubscript{2}} Supply Tank #1. □
      i. Open valve #42. □
      ii. Open valve #43. □
   b. N\text{\textsubscript{2}} Supply Tank #2. □
      i. Open valve #44. □
      ii. Open valve #45. □
   c. N\text{\textsubscript{2}} Supply Tank #3. □
      i. Open valve #46. □
      ii. Open valve #47. □
   d. N\text{\textsubscript{2}} Supply Tank #4. □
      i. Open valve #48. □
      ii. Open valve #49. □

**CAUTION: FAILURE TO ENSURE N\text{\textsubscript{2}} REGULATOR IS SET TO LOWEST POSSIBLE PRESSURE PRIOR TO INTRODUCTION OF N\text{\textsubscript{2}} TO COMPRESSION SYSTEM CAN LEAD TO RAPID PRESSURE INCREASE IN THE SYSTEM RESULTING IN DAMAGE TO EQUIPMENT.**

8. Align N\text{\textsubscript{2}} System.
   a. Open valve #19. □

9. Fill Compression system with N\text{\textsubscript{2}} gas.
a. Open valve #38.

b. Slowing increase N₂ regulator until pressure gauge #2 (P2) reads 20 psi.

c. Close valve #38.

10. Secure N₂ Supply Tanks in use.

   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.

   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.
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.

   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 (6.789e-6 m³/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.

   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.
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 dehumidifers 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 tranducer #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 dehumidifers. 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*)

109
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 dehumidifers. Due to the relatively slow rate of water production from the dehumidifers, if the water tanks are not full the dehumidifers need to run a maximum output. Max output is for all four dehumidifers 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;
  END_IF;
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
    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;

(*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 if 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.*)
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_SETPOINT 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

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C. USER DEFINED FUNCTION PID_CONTROLLED_VALVE

PID used for keeping water level in the process tank is the same. The PID uses direct acting feedback to drive the difference in water level between the set points by opening the proportional valve myLimit is used to clip the output of the PID to 0.000. The output of the PID is represented by the output variable of PID_ControlledValve.

The difference in water level at set is 0.118. Which is why the output of the PID is set to this value. The gains of the PID were tuned by trial and error.
D. USER-DEFINED FUNCTION PID_CONTROLLED_VALVE LOCAL VARIABLES

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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

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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

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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 date 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 recieve 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,Vol
tage.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

<table>
<thead>
<tr>
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<th>Alias</th>
<th>Data Type</th>
<th>Dimension</th>
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<th>Initial Value</th>
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</table>

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

<table>
<thead>
<tr>
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</table>

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

<table>
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<th>Name</th>
<th>Alias</th>
<th>Data Type</th>
<th>Direction</th>
<th>Dimension</th>
<th>Initial Value</th>
</tr>
</thead>
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</tbody>
</table>
APPENDIX Q. MATLAB CODE FOR DATA ACQUISITION ON GENERATION SIDE

%% Hydrogen Gas Generation Data Collection

close all;
clear all;
cic;

% 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',@pushbutton,'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	',Title{ii}); % Tells matlab to print each element of the array to a single cell.
end
fprintf(fid,'
'); % 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 iiiii = 1:length(Title2)
    fprintf(fid2,'%s	',Title2[iiiii]); % Tells matlab to print each element of the array to a single cell.
end
fprintf(fid2,'
'); % 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)+1:1Ij_US(3)-1))); %Degrees C
 RAW_LPM = str2double(char(IN(Ij_US(3)+1:1Ij_US(4)-1))); %Liters per
 minute
 RAW_SLPM = str2double(char(IN(Ij_US(4)+1:1Ij_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)*6894.57728; %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	',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	',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.
%% Hydrogen Gas Compression Data Collection

% 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);
hi =
uitable(mbutton, 'style', 'pushbutton', 'string', 'STOP', 'callback', @pus
htbutton, 'tag', 'stopbutton', 'UserData', 0, 'position', [20 20 600 600]);
set(hi, 'units', 'normalized');
set(hi, 'position', [.1 .1 .8 .8]);
set(hi, '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	',Title{ii}); %Tells matlab to print each element of
the array to a single cell.
end
fprintf(fid,'
'); %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)); % Determine 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	',RAW{i});
end
fprintf(fid,'
'); %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.
APPENDIX S. MATLAB CODE FOR STOP BUTTON FUNCTION

```matlab
function pushbutton(src,event)
set(findobj('tag','stopbutton'),'UserData',1);
get(findobj('tag','stopbutton'),'UserData');
end
```
APPENDIX T. MATLAB CODE FOR COMPRESSION DATA ANALYSIS

%% Joshua Lewis
% Compressor run 12-19Jan2021

clear all;
cic;
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;

135
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

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('Compressor Voltage (Volts)','fontsize',20) % Label Y axis and set font size
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

% % % 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.Disp = ‘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'
um2str(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 fitype and options.
ft = fitype( '{exp2}' );
excludedPoints = excludedata( xData, yData, 'Indices', [1 13 17 22] );
opts = fitoptions( 'Method', 'NonlinearLeastSquares' );
opts.Display = 'Off';
opts.StartPoint = [5.5563298632128e-10 -0.112083617892534
7.9690316138274e-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)
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 fitttype and options.
ft = fittype( 'exp2' );
excludedPoints = excludedata( xData, yData, 'Indices', [1 15 16 20 21 23 25] );
opts = fitoptions( 'Method', 'NonlinearLeastSquares' );
opts.Normalize = 'on';
opts.StartPoint = [-1.61688499978107e-10 0.241787395334357.4430085231241e-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)
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)
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.

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Xiperm™ Dehumidifier Operation Manual

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<table>
<thead>
<tr>
<th>Xiperm™ Dehumidifier Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation pressure (PSIG)</td>
<td>∼ 150</td>
</tr>
<tr>
<td>Inlet RH</td>
<td>0 - 100%</td>
</tr>
<tr>
<td>Vacuum (PSIG)</td>
<td>∼ -14.7</td>
</tr>
<tr>
<td>Tube fittings</td>
<td>1/8&quot; Swagelok® tube fittings</td>
</tr>
<tr>
<td>Vacuum fitting</td>
<td>37° flared JIC</td>
</tr>
</tbody>
</table>

COMPONENTS

OUTLET 1/8” Swagelok® tube fitting
Xiperm™ tube
37° flared JIC fitting for vacuum
175 PSIG Pressure relief
INLET 1/8” Swagelok® tube fitting

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.

![Diagram of Start-up Process]

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 COMPRRESSOR, 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 10652  
| (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 3/8” 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.
LIST OF REFERENCES


INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California