DOT/FAA/TC-19/55

Aircraft Fuel Cell System

Federal Aviation Administration
William J. Hughes Technical
Center Aviation Research Division
Atlantic City International Airport
New Jersey 08405

May 2019

Final Report

This document is available to the U.S. public through the National Technical Information Services (NTIS), Springfield, Virginia 22161.

This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

U.S. Department of Transportation

Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/TC-19/55	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Aircraft Fuel Cell System		5. Report Date May 2019
		6. Performing Organization Code
7. Author(s) Robert Byron, William Smith		8. Performing Organization Report No. IFC RPT-1901
9. Performing Organization Name and Address Infinity Fuel Cell and Hydrogen, Inc. 431A Hayden Station Road Windsor, CT 06095		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTFACT-16-C-00038
12. Sponsoring Agency Name and Address Federal Aviation Administration WM J Hughes Technical Center Atlantic City International Airport, NJ 08485		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code
15. Supplementary Notes The Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division COR was Michael Walz		

16. Abstract

Current baseline power and energy sources for both fixed wing and Vertical Take-Off electric aircraft are batteries. While batteries meet the need for basic operation their lower specific energy translates to limitations on range and performance. Fuel cells, either alone or hybridized with batteries project to extend range and improve performance by providing higher overall specific energy. Similarly, manned transport aircraft project to benefit from increased specific energy provided by fuel cell systems as well as the ability to distributed these power sources within an aircraft. Unmanned aircraft do not need to meet the regulatory requirements of manned transport aircraft however they are exposed to similar or even more severe environmental and operational demands. The approach of the current program has been to design, build and test a fuel cell system specifically designed to meet the needs of these near term UAS applications, then use this as a baseline to compare to meeting the requirements for manned transport.

17. Key Words Fuel cell, hydrogen, oxygen, power, electric propulsion, oxygen, drone, UAS, Unmanned, battery, hybrid,		18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

Federal Aviation Administration

- Michael Walz
- Karen Mercer

Infinity Fuel Cell and Hydrogen

- Patrik Landor
- Chris Chestnut
- Bob Byron
- John Fayer

Western New England University

- Dr. Anthony Santamaria

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AFRL	Air Force Research Laboratory
ANL	Argonne National Laboratory
APU	Auxiliary Power Unit
ARC	Aviation Rulemaking Committee
ASL	Above Sea Level
ASTM	American Society for Testing and Materials
BEV	Battery Electric Vehicle
BNL	Brookhaven National Laboratory
BOL	Beginning of Life
BOS	Balance of System
BPP	Bi Polar Plate
cfm	Cubic Feet per Minute
ConOps	Concept of Operations
COPV	Carbon Fiber Overwrap Pressure Vessel
COTS	Commercial Off-The-Shelf
CRADA	Cooperative Research and Development Agreement
DEA	Dead Ended Anode
DOD	Department of Defense
DOE	Department of Energy
DC	Direct Current
EOL	End of Life
ESD	Energy Supply Device
EVM	Earned Value Management
FAA	Federal Aviation Administration
FIP	Form In Place
FMEA	Failure Modes and Effects Analysis
GCS	Ground Control Station
GDE	Gas Diffusion Electrode

GDL	Gas Diffusion Layer
GOX	Gaseous Oxygen
GPS	Global Positioning System
GUI	Graphical User Interface
HALE	High Altitude Long Endurance
I/O	Input and Output (software and controls)
ICE	Internal Combustion Engine
IP	Ingress Protection
IRAD	Internal Research and Development
LiPo	Lithium Polymer
LOX	Liquid Oxygen
MEA	Membrane and Electrode Assembly
MMC	Mobile Manufacturing Cart
MTBO	Mean Time Between Overhaul
MTOW	Maximum Take Off Weight
NASA	National Aeronautics and Space Administration
NDA	Non Disclosure Agreement
NOAA	National Oceanic and Atmospheric Administration
NWUAV	Northwest UAV (private company)
OEM	Original Equipment Manufacturer
P&ID	Piping and Instrumentation Diagram
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PMAD	Power Management and Distribution
PWM	Pulse Width Modulation
SRNL	Savannah River National Laboratory
SUAS	Small Unmanned Aircraft Systems
SWAP	Size Weight and Power
TCO	Total Cost of Ownership
UAS	Unmanned Aircraft Systems
UAV	Unmanned Aerial Vehicle
UML	Unified Modeling Language (software development)
WNEU	Western New England Universit

Executive Summary

Modern aircraft are becoming increasingly electrified with electrical power loads from personal entertainment, controls and propulsion increasing demand, while global requirements to decrease carbon dioxide and other harmful emissions are growing. Primary fuel cells, that can generate electrical power from various sources, and Regenerative Fuel Cells, that can store energy, are receiving increasing attention as candidates for next generation aircraft electrical power. Fuel cells have the potential to reduce or eliminate pollutants while providing clean, quiet, vibration-free power.

Early candidates for the application of fuel-cell power include Unmanned Aerial Systems, UAS, or drone aircraft, especially in smaller Class I or II sizes. These aircraft, whether designed for vertical or horizontal takeoff and landing, project to benefit from electrical power and propulsion systems. Fixed-wing drones benefit from electrical propulsion by reduced vibration and maintenance. Multi-rotor aircraft benefit from increased range, power and energy. For multi-rotor vehicles, electrical propulsion is essential since basic operation depends on real-time control and response of multiple propulsion motors. Conventional combustion propulsion engines simply cannot perform these functions.

Current baseline power and energy sources for both fixed wing and Vertical TakeOff, (VTO) electric aircraft are batteries. While batteries meet the need for basic operation, their lower specific energy translates to limitations on range and performance. Fuel cells, either alone or hybridized with batteries, project to extend range and improve performance by providing higher overall specific energy. Manned transport aircraft project to benefit similarly from the increased specific energy provided by fuel cell systems as well as from the ability to distributed these power sources within an aircraft.

Program Approach

UAS fuel cells as a target system:

Unmanned aircraft do not need to meet the regulatory requirements of manned transport aircraft; however, they are exposed to similar or even more severe environmental and operational demands. The approach of the current program has been to design, build and test a fuel-cell system specifically designed to meet the needs of these near-term UAS applications, then use this as a baseline for comparison in meeting the requirements for manned transport. The scope of the current program does not require flight test of such systems but does provide a pathway to flight test.

This project's approach is to develop a system based upon an open/closed cathode Proton Exchange Membrane (PEM) fuel-cell concept in which the cathode reactant and coolant delivery systems are shared. The simplicity of the air-cooled stack and its reduced balance of plant make it attractive for smaller UAS applications in general, while the closed cathode (oxygen-using) component of the design is beneficial for dense air and high-altitude applications.

The new system focuses on reducing volume and weight while still meeting the performance and cost targets of a UAS application.

Program Objectives and Prioritization

- Energy system design and development
- Prototype system manufacture
- System bench top testing
- In-airframe system testing (program goal)
- In-flight testing (long term objective outside the scope of this program)

Results / Accomplishments

- Designed, fabricated and tested new fuel cell stack and controls
- Implemented reduced weight and cost design approaches
- Conducted review of relation to Part 25 manned transport regulations
- Conducted review of environmental and other tests required by DO-160 if the system were to be qualified to meet manned transport applications

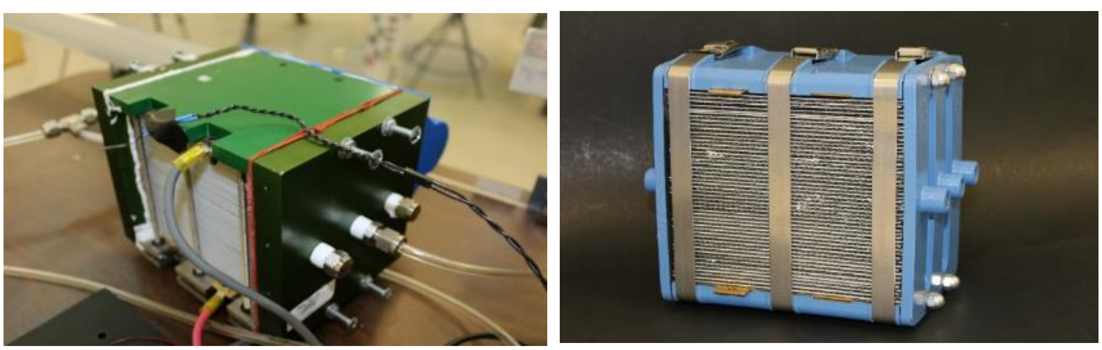


Figure 1 50-Cell Test Article (left) and 50-Cell Fully Packaged Stack Mockup (right)

1.0 Program Description and Background

Fuel cell systems are power-producing devices with separate energy storage systems necessary for proper operation. This effective separation of power and energy is not unlike more traditional power and energy systems, e.g., the internal combustion engine in a car provides the power to move the vehicle; the energy necessary to fuel the engine is stored in the fuel tank. It is exactly this separation of power and energy that makes fuel cell systems the “go-to” power source for many extreme applications. Unlike batteries, which provide power and store energy within the same package, a fuel cell power and energy system is a combination of mutually exclusive sub systems than can be better tailored to provide power at levels independent from the chosen form of energy storage. The hydrogen (and possibly oxygen) storage simply drives the endurance of the craft being powered by the fuel cell.

Within the fuel cell each cell converts hydrogen and oxygen to electrical power, water, and waste heat, and then passively removes the resulting water. This is achieved by introducing oxygen into a chamber on one side of a proton-conducting polymer membrane (the cathode chamber) and hydrogen into the other side (the anode chamber). At the anode, the hydrogen is ionized into electrons (providing power) and protons in a catalyzed chemical reaction. The protons are conducted through the proton-conducting membrane, drawn by the potential of the oxygen, where they combine with the oxygen molecules.

Infinity Fuel Cell and Hydrogen, Inc. (Infinity) has been developing both air dependent and air independent PEM fuel cell systems, as well as high pressure electrolyzers producing both hydrogen and oxygen, for the past fourteen years. This work has been predominantly funded through NASA and DOD efforts and is presently ongoing. The purpose for this work has primarily been the provision of power within spacecraft and UUVs, i.e., market segments without the available air usually associated with the use of fuel cell-based power systems.

1.1 Goal

The goal of this program is to advance understanding of the development and integration issues related to the use of fuels aboard transport aircraft by focusing on smaller scale systems in defined applications such as UAVs. Designing and testing of a fuel cell stack and balance of system that demonstrates the ability of a fuel cell power plant to power an Unmanned Aircraft System (UAS) with little vibration impacting payloads, little to no noise imparted to the local environment, and increased endurance over traditional technologies. These are all issues pertinent to adoption of UAS in many commercial markets.

Fuel cell integration onboard transport aircraft may begin to fit a variety of needs as the aircraft community, with Federal Aviation Administration (FAA) guidance, begins to understand and implement the technology. Among the many uses of this type of power system is its possible incorporation in the passenger area in the form of additional galley power, Auxiliary Power Unit (APU) for electronics, emergency power, etc. When operating in the passenger area the use of air versus stored oxygen is of critical importance, as the consumption of air necessary for passenger breathing cannot be impacted due to the operation of a fuel cell. In this scenario the ability of a fuel cell-based power system to consume stored oxygen during all or part of a flight may become a necessity. The adaptation of the fuel cell system developed as part of this program is being assessed in the future for potential application to transport aircraft and other oxygen-breathing fuel cell environments.

In the UAS market there is presently a need for the type of fuel cell system such as Infinity is developing that is the subject of this report. The use of a fuel cell system inherently brings benefits that Internal Combustion Engine (ICE) and battery-based power systems cannot. Many applications in this market require longer endurance than battery systems alone can provide, e.g., Facebook's Aquila[1] drone that was being developed to provide Internet access in remote locations underserved or not served at all. At these high altitudes the need for oxygen breathing fuel cell power systems is clear: low partial pressure of oxygen at 50,000 feet and above, the typical altitude for High Altitude Long Endurance (HALE) aircraft, precludes the use of air breathing fuel cell systems without the addition of compressors designed to increase oxygen concentration, but which also decrease system reliability and increase Mean Time Between Overhaul (MTBO).

At lower altitudes the issue of flight endurance is more critical. Present battery technology typically provides a 20-minute flight time for lower Maximum Take Off Weight (MTOW) vehicles, e.g., quad copters carrying cameras for still and video imagery, to approximately 90-minute flight times for military fixed wing aircraft performing overwatch and surveillance functions. These latter functions, performed by Group 1 (20 lb. MTOW) and Group 2 (21-55 lb. MTOW) UAS, are typically powered by either 2- or 4-stroke ICEs. These ICE powered aircraft have the ability to fly much longer than battery powered platforms, having achieved, in some cases, over 2 days flight time[2].

There is enormous interest in both military and commercial markets for noiseless and vibrationless flight. Vibration from ICE power plants impact the cameras mounted in the

[1] https://www.facebook.com/notes/mark-zuckerberg/the-technology-behind-aquila/10153916136506634/
[2] UAV Factory Penguin B (Infinity owns an electric version of this aircraft for future testing of fuel cell power systems). https://www.suasnews.com/2012/07/fifty-four-hour-flight-for-uav-factory-penguin-b/

payload bays[3]. This issue impacts both military and commercial customers. Likewise, noise level in airborne platforms for both military and commercial markets is a concern. In the military the acoustic signature affects the stealth of a mission. For most airframes of the Group 1 and 2 varieties the largest contributor to noise level is the propeller and not the ICE powering it[4], however, a fuel cell power plant driving a low-noise propeller[5] provides a complete solution to the problem. For commercial markets of the future a noise-free environment below the flight paths of airborne delivery platforms may be a requirement. A fuel cell system can satisfy both vibration and noise issues. As a solid-state device, the technology is inherently quiet in operation, with only balance of system components adding to noise levels. Infinity's traditional oxygen-breathing fuel cell design, with a reduced balance of system, provides a reduced noise level over competing fuel cell technologies. Incorporating the fundamental elements of this design to an air-breathing fuel cell platform, while not the subject of this activity, is certainly the direction Infinity would like to move in the future. The objective for this activity is the development of a lightweight fuel cell stack and minimized balance of system.

For several other government and commercial activities, the ability to fly in environments devoid of air or in debris-strewn air is critical. Several federal agencies find a use for the operation of UAS in these environments: National Aeronautics and Space Administration (NASA) Earth Sciences Directorate studying volcanic plumes; National Oceanic and Atmospheric Administration (NOAA) gathering data inside hurricane systems; Department of Defense (DOD) battlefield environments with Small Unmanned Aerial Systems (SUAS) operating in low altitude overwatch capacity. Oxygen acting as the oxidant for a fuel cell power system provides a closed cathode solution versus the open cathode design of most air-breathing fuel cells, or the air intake of an ICE system. Additionally, many of these markets would benefit from the ability to be able to fly into a compromised environment using ambient air, switchover to oxygen within the compromised environment, and then back to air to get home. This air-oxygen-air switchover capability would enable the UAS to operate at a much lower MTOW, since the oxygen storage requirement is minimized. A dual oxidant fuel cell architecture is a focus of this effort, but initial implementation of this architecture has bene focused on the H2/Air operation.

[3] Conversation with Unmanned Aerial Surveillance, a Temecula, California based company providing surveillance solutions to commercial markets, e.g., pipeline inspections, etc.
[4] Conversation with Chris Harris, President, Northwest UAV.
[5] http://www.nwuav.com/uav-products/low-noise-propellers.html

2.0 Description of Target Aircraft and Subsystems

The aircraft targeted by Infinity for initial testing of a fuel cell system is a UAV Factory Penguin BE. This is an electric version of UAV Factory's popular 50 lb. MTOW airframe sold around the globe. Infinity acquired a stripped-down version of the Penguin BE in 2016 for the purposes of integrating and testing fuel cell systems for long endurance flight.

2.1 State of The Art Airframes and Engines

The power and energy system for an Unmanned Aerial Vehicle (UAV) capable of satisfying the requirements for fixed wing airframes requires a reassessment of the manner in which power is provided to the standard UAV today. A traditional UAV platform in the 50 lb. MTOW class utilizes a gasoline-fueled ICE and a generator driven by the ICE for power supply to onboard equipment and payloads. Figure 2 illustrates a typical UAV platform in the 50 lb. MTOW class utilizing a pusher type propeller. A version of this particular airframe, the Penguin B, set an endurance record of 54.4 hours of non-stop flight in 2012[6], powered by a fuel injected ICE. This flight time is most likely achieved in the particular airframe under controlled conditions without a payload

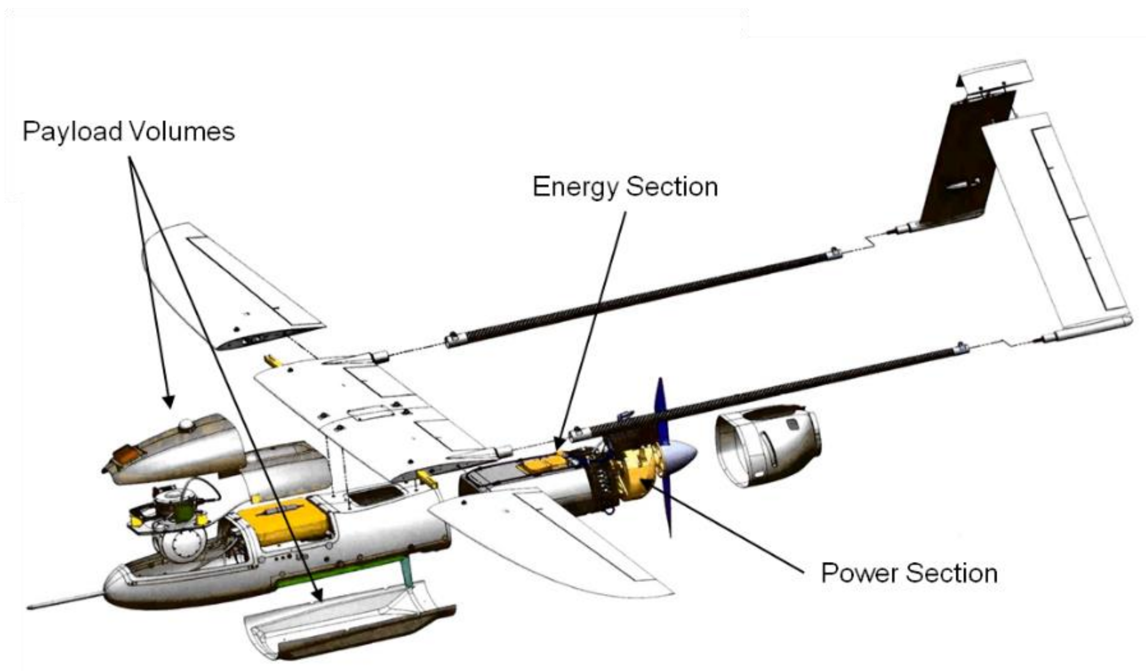


Figure 2 Exploded View of Penguin C

[6] Dossier: UAV Factory Penguin C, Unmanned Systems Technology, November 2014.

2.2 Traditional UAV Propulsion

The ICE-based energy system (engine and fuel storage), seen in Figure 3, is the UAV Factory's fuel injected ICE deployed in their Penguin product line[7]. This fully integrated energy system contains the prime mover, fuel storage, controls, and generator required for powering avionics and onboard customer payloads. The prime mover in this case is a single cylinder, two-stroke, air cooled 28 cc engine. This 2.1 kW engine turns the belt-driven generator that provides either 80 or 100 W, depending on the instrumentation located in the payload bay. This example is illustrated for two reasons: 1) it is the most detailed presentation found on state-of-the-art UAV power systems; 2) it shows some of the components contained in these state-of-the-art systems that may be duplicative, or not needed, with the implementation of a fuel cell power and energy system.

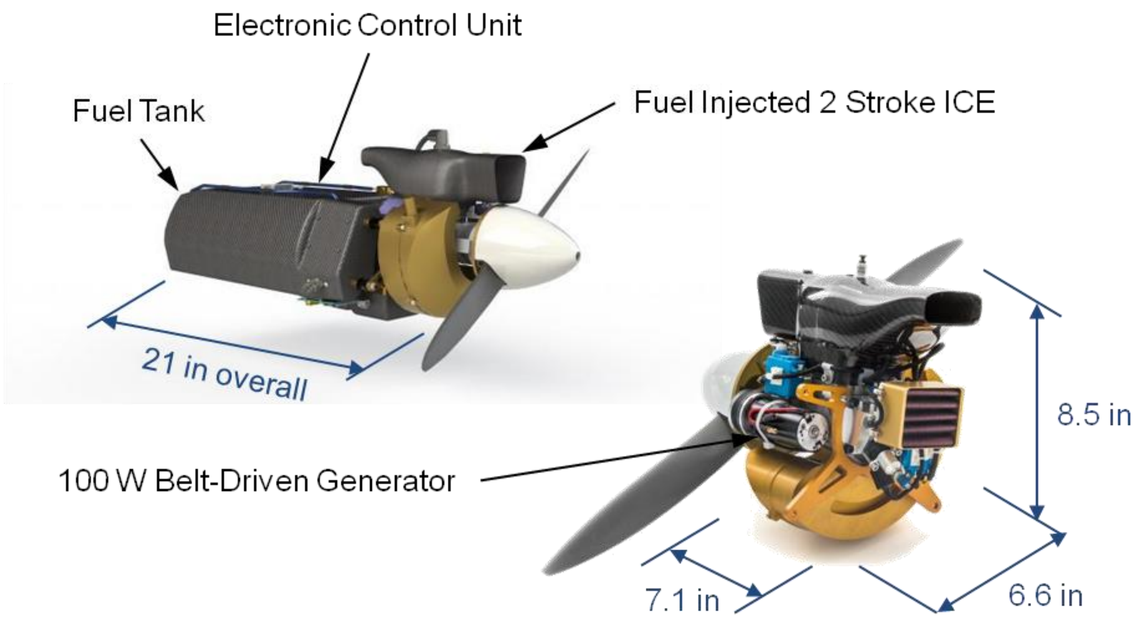


Figure 3 UAV Factory Fuel Injected ICE Energy System (Approx. Dims)

The 28-cc engine used in UAV Factory's airframes consumes approximately 400 g/kWh in cruise mode[8] and uses automotive grade gasoline at 98 octane. For the listed 20-hour flight time at an estimated cruise power of 1.5 kW (71% of peak power output), the total fuel storage requirement would be 12 kg. Adding this value to the rest of the energy system yields the total mass listed in Table 1, or 30.29 lb. The engine mass includes an 80-100 W generator, cooling, servo, and air filter. The engine control unit requires 10-24 VDC at less than 15 kW (max RPM). The fuel consumption noted

[7] UAV28-EFI Turnkey Fuel Injected Engine, http://www.uavfactory.com/product/77.
[8] Ibid.

accounts for an approximate fuel use of 400 g/kWh (max power output)[9]. The typical rule of thumb for estimating the mass of a complete energy system for a 50 lb. MTOW class UAV is approximately 40-50% of total mass, or between 20-25 lb. (max).[10] These data provide a reasonable starting point for the development of a UAV fuel cell power and energy system.

Table 1 UAV Factory ICE System Main Component Mass & Life Characteristics

Gas Engine						
Item	**Qty**	**lb**	**g**	**lb total**	**g total**	**Hours**
Engine	1	3.31	1,500	3.31	1,500	500
Fuel Pump	1	0.15	70	0.15	70	2,000
Engine Control Unit	1	0.37	170	0.37	170	N/A
Fuel	1	26.46	12,000	26.46	12,000	20
Total				***30.29***	***13,740***	

UAV Factory's ICE energy system is a well-integrated power plant utilizing advanced manufacturing techniques and leveraging present control technologies to provide longer endurance than many other airframe manufacturers in the same class. Several other airframe makers, ICE manufacturers, and fuel cell providers have been working to improve endurance in this class of UAV as well.

2.3 Electric UAV Propulsion

Northwest UAV (NWUAV) is a well-known manufacturer and supplier of ICE-based power systems for UAVs, most notably supplying the engines for Insitu's ScanEagle and Integrator platforms. Along with superior design and development of small ICEs, NWUAV has also worked toward the development of electric propulsion systems for UAVs under Air Force Research Lab (AFRL) funding, see Figure 4. This propulsion development work may dovetail nicely with Infinity's lightweight fuel cell research and development. Infinity has a Non-Disclosure Agreement (NDA) in place with NWUAV to discuss integration opportunities for a fuel cell energy system to power fixed wing craft.

[9] Typical flights with a standard payload consisting of a fully gimbaled camera system consume a full tank of fuel. Based on conversations with Unmanned Aerial Surveillance, a Temecula, California based end user of the Penguin B.
[10] Conversation with Jeff Ratcliffe, CTO, NWUAV.

Figure 4 Electric Propulsion Systems Under Development At NWUAV

The UAV Factory produces an electric version of their Penguin product line. This version employs a motor made by Hacker, part number A60-5S V2[11]. The specifications of this motor are detailed in Table 2.

Table 2 Hacker A60-5S V2 Electric Motor Specifications

Mass	595	g
Service Rating	295	kV
Current-Idle	1.7	A
Current-Operating	60	A
Current-Peak	100	A
Power-Peak	3,000	W
Volume	202	cm^3

Boeing also produces a drone through its subsidiary, Insitu, primarily for military use known as the Scan Eagle. Preliminary estimates for the power required for the electric motor of this approximately 50 lb. MTOW airframe is in the range of 1 kW[12].

2.4 Targeted Airframe

The UAV Factory's Penguin BE, referenced earlier, is the targeted airframe for this program. Part of the front payload bay is consumed by a battery, as seen in Figure 5. This version of the airframe is based on the traditionally-powered craft but uses a Lithium Polymer (LiPo) battery instead. This electric propulsion arrangement still provides a large payload bay and also opens up free space toward the aft of the

[11] From UAV Factory Penguin BE manual and Hacker reseller, http://www.aj-aircraft.com/Hacker-A60-5S-V2_p_15.html.
[12] Author's estimate based on prior discussions and programs relating to the particular airframe.

airframe, around and behind the electric motor, indicating the additional room available in a typical airframe for fuel cell propulsion and reactant storage.

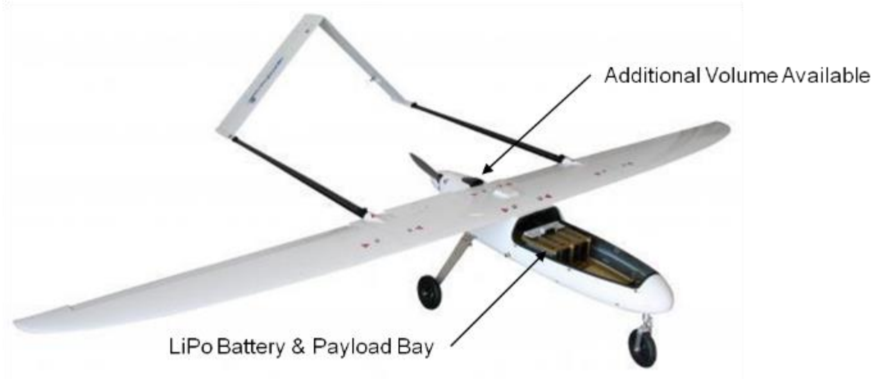


Figure 5 UAV Factory Penguin B Electric

The battery electric version of the aircraft has a limited flight time and reduced payload versus the ICE powered version of the aircraft. The product and performance specifications for the electric version[13] of the aircraft are shown in Table 3.

Table 3 UAV Factory Penguin BE Aircraft Specifications

PRODUCT SPECIFICATION

PARAMETER	VALUE
MTOW	21.5 kg
Empty Weight (excluding payload)[1]	14.9 kg
Wing Span	3.3 m
Length	2.27 m
Wing Area	0.79 m^2
Propulsion Type	Geared Brushless
Propulsion Power	2700 W
Battery Type	Lithium Polymer
Battery Cartridge Capacity	640 Wh
Onboard Voltage	6V, 12V
Onboard Continuous Power	100 Watts
Max Payload	6.6 kg
Takeoff Method	Catapult, Runway or car top launch
Environmental Protection	Sealed against rain, snow

PERFORMANCE

PARAMETER	VALUE
Endurance[2]	110 minutes with 2.8 kg payload
Cruise Speed	22 m/s
Stall Speed (with high lift system)[3]	13 m/s
Max Level Speed	36 m/s
Takeoff run[4]	30 m
CL max (45° flap deflection)	1.7
CL max (clean wing)	1.3
Ceiling	6000 m

[1] With standard landing gear, with battery cartridge
[2] In belly landing configuration
[3] Sea level altitude, 15 kg aircraft weight, 15 C°.
[4] Sea level altitude, 15 kg aircraft weight, 15 C°, concrete runway.

The battery being used presently in the UAV Factory Penguin B is a LiPo 48 cell module, seen in Figure 6, which provides both 6 and 12 VDC to the aircraft through an onboard DC-DC converter, as well as providing power to the electric motor via an

[13] http://www.uavfactory.com/product/69

electronic speed controller. This battery is capable of providing 640 Wh with a specific energy of 145 Wh/kg. Total weight is estimated to be approximately 4.4 kg. The electric motor turning the propeller can provide 2.7 kW output and total flight time is approximately 110 minutes.

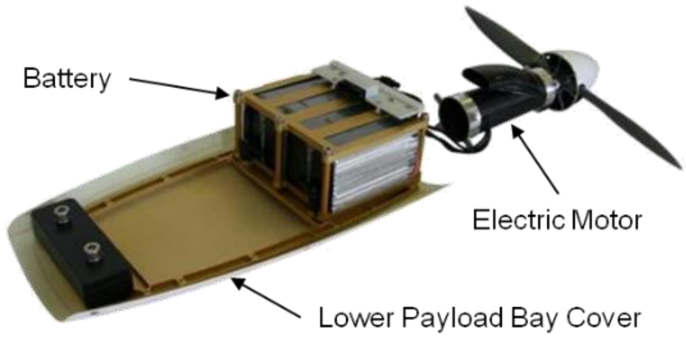


Figure 6 Penguin B Electric Propulsion System

Infinity has acquired a Penguin BE from UAV Factory using Internal Research and Development (IRAD) funding. After a thorough evaluation of several airframes available in the 50 lb. class, it was determined that UAV Factory has the most viable aircraft for fuel cell integration for this and other projects. Also, as a Group 2 aircraft, this platform with a fuel cell would ease early product introduction into both military and commercial surveillance markets.

2.5 Targeted Aircraft Subsystems

The subsystems in Infinity's Penguin BE include the motor and motor controller, servos for all control surfaces, landing gear, and overall airframe. Additional subsystems required to fly the aircraft include, but are not limited to, the major components as listed in this section.

2.5.1 Autopilot

The autopilot system recommended for the UAV Factory Penguin B platform is either a Piccolo, made by Cloud Cap Technology[14], or a Kestrel, made by Procerus Technologies[15]. One of these autopilot systems would be integrated into the platform in the future should flight testing be performed. This integration would be done through a third-party team responsible for avionics integration, ground controls, and flight.

The fuel cell system onboard the platform will accommodate a range of potential autopilot solutions, as illustrated in Table 4; most importantly the voltage and power

---

[14] Cloud Cap Technology was acquired by Goodrich in 2009. Goodrich was acquired by UTC Aerospace Systems (UTAS) in 2012.
[15] Procerus Technologies was acquired by Lockheed Martin in January 2012.

requirements. These systems will also require antenna, GPS, radio, and other components as necessary for full implementation and flight.

Table 4 Autopilot Solutions for Penguin BE

			
	Piccolo SL	**Piccolo Nano**	**Kestrel V2.4**
Voltage Range	4.5 - 28	6 - 30	6 - 24
Power (W)	$4^{\dagger}$	$4^{\dagger}$	4.8
Mass (g)	$110^{\dagger}$	$51^{\dagger}$	17
Dimensions (mm)†	131 x 57 x 19	61 x 46 x 14	51 x 35 x 12

† Includes 900 MHz radio

2.5.2 Pitot tube

The baseline airframe acquired has no instrumentation included for determining vehicle speed. The provider of the Penguin BE, UAV Factory, offers a heated pitot tube option for this purpose.

Figure 7 illustrates this component with associated specifications.

Mass (g)	58
Length (mm)	238
Voltage	12
Power (Max) (W)	19
Fuse Current (A)	2

Figure 7 Heated Pitot Tube and Specifications

2.5.3 Ground control station

Controlling the Penguin BE airframe in flight requires a radio system to communicate with the onboard radio. The UAV Factory provides a ground control station as an optional package. Unmanned Aerial Surveillance in Temecula, California, or a similar company, would be engaged to provide the ground control station and flight expertise for any in-flight demonstrations in the future. This precludes the need for Infinity to acquire its own ground control station and leverages those already in the UAV surveillance market to perform specific testing to be defined by the Infinity team.

Figure 8 Ground Control Station for Penguin BE

3.0 Design Study

3.1 Concept of Operations

A full Concept of Operations (ConOps) has not been developed as a stand-alone document for this program; rather it is presented in this section in summarized form, drawing from other information in this report. It is not the intention of the Infinity team to fly the fuel cell system developed under this contract. It is helpful, however, to realize a potential ConOps strategy as an informative tool in the engineering process.

3.1.1 Introduction

The UAS community desires a noiseless and vibrationless power system with a long endurance energy system. Present state of the art for UAS is either a battery system or an ICE; the former proving power output and energy storage from the same module, the latter providing separated power and energy storage sub systems for longer flight times. The ICE systems tend to impart vibrations on sensitive payloads while batteries do not. Batteries simply cannot provide the flight endurance of ICE systems. No power and energy system for UAS can presently provide noiseless, vibrationless, long endurance flight.

In addition to the above-referenced issues is the ability of UAS to fly in and out of hazardous environments. A hazardous environment can be defined as hot air, dense air, debris-strewn air, high altitude low partial pressure oxygen, etc. These environments preclude the use of ICE systems, since the intake air required to operate the ICE can be compromised. Battery systems can operate in these environments, but at reduced flight times versus ICE systems.

Infinity has started the development of a unique air/oxygen fuel cell system that will allow not only for flight into and out of hazardous environments, but also provide extended flight time due to use of oxygen within the compromised flight environment while consuming air when outside of it. This latter point minimizes the quantity of oxygen to carry onboard, thereby minimizing overall UAS weight and contributing to extended flight time. Development of the lightweight, air-breathing fuel cell stack and system during this program is the first step toward realizing this dual oxidant approach to fuel cell systems.

3.1.2 Problem Statement

The initial problem statement requirement was to “Develop a lightweight Infinity fuel cell and hydrogen storage system for the purposes of integrating into a UAS airframe for benchtop testing. This preliminary testing will eventually lead to integration of oxygen-breathing capability (dual oxidant) and ultimately possible flight testing.”

3.1.3 System History

The air/oxygen fuel cell power system for UAS proposed by Infinity for this effort is not a system currently in use in the unmanned market. There is concern in the UAS community regarding flight time, power delivery to more payloads, and flying into and out of compromised airspace. A “compromised airspace” is defined by Infinity for the UAS market as one which lacks the quantity or quality of necessary air to feed an ICE powered craft. Battery powered craft can certainly provide UAV propulsion through these environments, but for a limited timeframe and sometimes resulting in loss of the UAS platform.

The loss of vehicle issue is best illustrated by NOAA’s present use of Raytheon’s Coyote UAV, seen in Figure 9. This system is tube launched from a manned aircraft flying above a hurricane. As the this particular UAS is released from the tube its wings unfold and it is remotely piloted down into the eye of the hurricane. After descending into the storm and gathering data for just over an hour the UAS battery is depleted and the vehicle is carried away by the storm. Each Coyote costs NOAA approximately $22,000.

Figure 9 NOAA scientist Paul Reasor holding a Raytheon Coyote UAV

Figure 10 NASA 2013 Volcanic Plume Measurement Program

As to limited time for data gathering, an example of a former NASA program run out of Ames Research Center utilized several AeroVironment Dragon Eye UAV platforms to study volcanic plumes[16]. Described as a “dense air” environment, a volcanic plume presents many challenges for a traditional ICE powered platform, whereas a fuel cell powered system, operating on oxygen inside the dense air environment, would allow for extended duration of data gathering versus current battery solutions providing one-hour flight endurance.

3.1.4 System Use

A flexible air/oxygen fuel cell system for UAS would be used in extreme environments where a compromised atmosphere precludes the use of ICE based power systems and

[16] https://www.nasa.gov/topics/earth/earthmonth/volcanic-plume-uavs.html

when flight times within these compromised environments necessitates longer duration flight.

Environments benefitting from the use of this system would include:

a) Hurricane and storm data gathering
b) Volcanic plume measurements
c) Forest fire overwatch and spotting
d) Military battlefield overwatch and surveillance
e) Oil and gas market offshore rig inspections

For these and other potential applications, the UAS incorporating an air/oxygen fuel cell power and energy system would fly into and out of the compromised airspace consuming ambient air to sustain fuel cell power generation. When entering the compromised airspace, the energy system switches from air to oxygen. While in the compromised environment the fuel cell will consume only the oxygen carried onboard the airframe. Upon exiting the compromised environment, the system will switch from oxygen to air to complete the mission. Hydrogen will be consumed by the fuel cell throughout the flight.

Hydrogen storage, therefore, is driven by the total length of the flight. Oxygen storage, on the other hand, is determined only by estimated flight duration within the compromised environment. This is advantageous from a Size, Weight, and Power (SWaP) perspective, since the physical mass of the oxygen per unit stored by volume is eight times that of the mass of the hydrogen per unit stored by volume.

3.1.5 Preliminary Flight Plan

This is a long-term objective of Infinity's broader development program regarding lightweight fuel cells for UAS applications.

Referencing Lockheed Martin's FlightService[17] for filing UAS operating in uncontrolled airspace, as well as the testing objectives of this program, the following is a very brief description of a preliminary flight plan.

Maximum Altitude:	2,000 ft
Operating Area:	Circular, 2 nm radius, center point TBD
Operating Time:	2-hour total with several intermittent switchovers between air and oxygen subsystems (total oxygen operation time not to exceed 30 minutes)

[17] https://www.1800wxbrief.com/Website/#!/

The operation of the aircraft would be performed by a partner of Infinity, since no Infinity employees are skilled in flying, or licensed to fly, the target aircraft.

3.2 System Requirements

3.2.1 System Boundaries

The interface control volume of the air/oxygen fuel cell energy system is defined as a combination of modules. The system is comprised of a power module and an energy module. Each of these modules for this particular program is planned to be capable of being installed into the airframe as separate components. The power module is comprised of the fuel cell stack, DC-DC converter, battery, instrumentation and controls. The energy module is comprised of hydrogen and oxygen storage tanks with controls for each. Communication, both fluid and electric, between the two modules is planned to be accomplished via quick connections where possible when fully implemented.

The system is designed to be a self-starting system requiring no external equipment to power up the UAS platform. A battery provides power to the control system when the start command is sent. This operation will also open the reactant valves to begin fuel cell power generation. Once reactant is flowing to the fuel cell the system will load follow, i.e., provide power on demand to airframe control system, motor, and payloads.

3.2.2 System Environment

A fuel cell power and energy system for use in a Class 2 aircraft should be able to withstand the demands of startup at sea level to 10,000 ft ASL, with the ability to reach maximum altitudes of 15,000 to 20,000 ft ASL. These requirements drive ambient operating conditions for temperature, pressure, relative humidity, and partial pressure of oxygen in the air.

The operator of the UAS will be stationed on the ground and flying the vehicle through a Ground Control Station (GCS); a typical system for the target airframe is illustrated in Figure 8.

Maintenance of the fuel cell power module shall be performed on the ground and will ideally consume no more than part of one day for overhaul. It is estimated that the fuel cell power system will last, under nominal operating conditions, between 2,000 and 5,000 operating hours. The energy storage module, consisting of lightweight Type III or IV hydrogen and oxygen tanks, filling mechanisms, and associated controls, shall be accessible at the time of power module removal. Ideally, the power module and energy module will reach End of Life (EOL) at approximately the same time, but this is not a hard requirement.

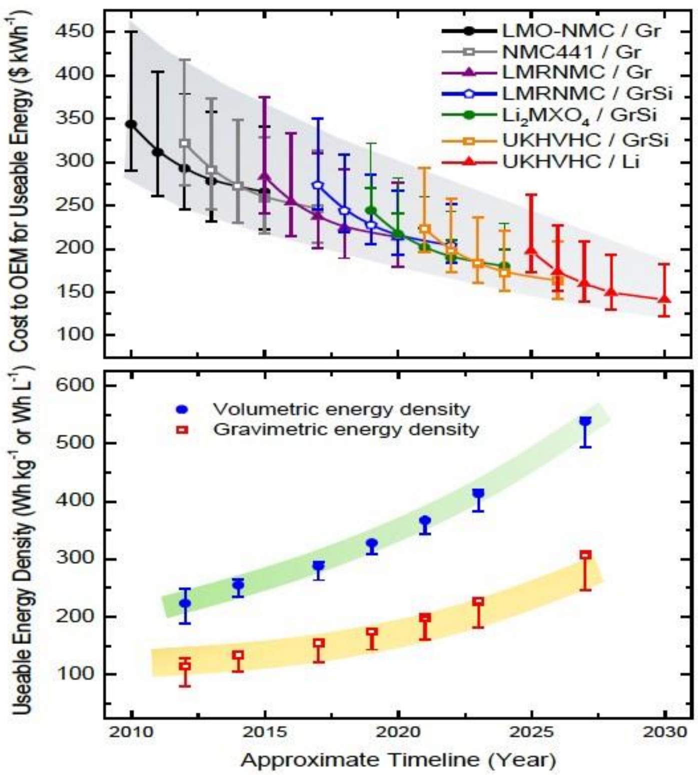
3.2.3 Requirements

The fuel cell power and energy system design requirements are based on meeting the market objectives of both military and commercial UAS applications. A description of each major requirement is listed below with a summary at the end of this section in Table 6.

3.2.3.1 Cost

A major driver for a fuel cell system is cost. Battery pricing for conventional LiPo and Li-ion packs typically used to power smaller UAS platforms have dropped significantly over the past several years and are projected to decrease further in the future. Much of the progress in battery chemistries has been an outgrowth of the electric vehicle market, see Figure 11, with gravimetric and volumetric energy densities projected to increase in the out years while costs continue to drop[18].

The cost targets for a fuel cell based UAS power system can be correlated to this Battery Electric Vehicle (BEV) development as well as to present ICE costs in the UAS market. Furthermore, the Total Cost of Ownership (TCO) when fuel cells are compared to ICE power solutions should be favorable since the MTBO for the fuel cell-based



Projections of battery energy density and cost in the following decades. In the cost plot, several cell chemistries are presented. LMO-NMC: a physical blend of Li1.1Mn1.9-xMxO4 with Li1+x(Ni1/3Mn1/3Co1/3)1-xO2; NMC441: (Li1+x(Ni4/9Mn4/9Co1/9)1-xO2); LMR-NMC: xLi2MnO3(1-x)LiMO2 with a capacity of 250 mAh/g @ 3.7 V; Li2MSiO4 – M = Mn or Ni with an assumed capacity of 250 mAh/g @ 4.2 V; UKHVHC – unknown high-voltage, high-capacity cathode with an assumed capacity of 250 mAh/g @ 4.7 V; Gr: graphite; GrSi: graphite silicon composite with a capacity of 1000 mAh/g @ 0.4 V.
Source: Kevin Gallagher, Argonne National Laboratory

Figure 11 Battery Performance Improvements vs Cost

system will be much longer than the present 400 to 500-hour ICE overhaul. The full

[18] https://arpa-e.energy.gov/?q=publications/long-range-low-cost-electric-vehicles-enabled-robust-energy-storage

TCO, accounting for acquisition costs, operating expenses, overhaul expenses, cost of overhaul downtime, rates of return, etc. will need to be examined more closely in the future for development of a complete business case.

For the purposes of this exercise, the cost of a fully commercialized fuel cell power and energy system should fall within the bounds of a battery system for short and medium endurance flights into and out of compromised airspace. See Table 5 for a comparison of projected battery costs for the year 2020.

Table 5 Battery Cost Comparison Across Power Range

ARPA-E Battery Data			
Year	**Low**	**High**	**Units**
2020	175	300	$/kWh
Projected System Comparison			
	Low	**High**	**Units**
Power	1	3	kW
Endurance	12	12	hours
Energy	12	36	kWh
Battery Cost	2,100	10,800	$per unit
ICE Cost	20,000	25,000	$per unit

3.2.3.2 Weight

As noted, the overall ICE mass for the targeted aircraft is 13.74 kg (reference Table 1). This figure is inclusive of the fuel required to fly approximately 20 hours. A fuel cell system capable of replacing the ICE system will need to be similar to this total mass or lighter than it to meet the 10 kg payload objectives of the aircraft.

3.2.3.3 Performance

With an output of approximately 2.1 kW peak, the ICE for the targeted airframe is a very capable small engine with a small footprint. The electric version of the same aircraft is provided with a 3-kW motor and a LiPo battery to drive it. Based on prior discussions and research, this motor may be a bit large for the airframe; other companies leverage smaller electric drives for similar applications. Therefore, the output power from the fuel cell system under development is in the 1 kW to 3 kW range; most likely at the lower end of this range.

3.2.3.4 Life Expectancy

The fuel cell systems designed and built by Infinity for NASA and DOD missions are capable of providing reliable power output for 20,000 hours or more. In UAS applications the service life requirement is far less. To meet the needs of this market, while providing better service life than traditional power technologies, the desire is to build a fuel cell system capable of at least 2,000 hours and perhaps up to 5,000 hours. Life of the product beyond the 5,000-hour mark may drive additional costs in the product's design, yielding less benefit to the UAS consumer.

3.2.4 Summary

3.2.4.1 System Operating Requirements

The system specifications in Table 6 have been developed based upon market assessment and technical airframe needs. This table represents an overall design target only for the energy system.

Table 6 Fuel Cell Energy System Top Level Requirements

Power	1	kW (peak)
Voltage	24 to 32	VDC
Flight Time (air)	120	min
Flight Time (oxygen)	30	min
Altitude	0 to 6,000	m
Temperature (ambient)	-25 to 120	°C
Pressure (ambient)	45 to 101	kPa

3.3 Design Analysis

A goal of this program is the development of a design architecture of a fuel cell-based power and energy system capable of powering a UAS platform. In the course of doing so, the fuel cell system should be able to effectively switch between oxidants feeding the fuel cell, i.e., air and oxygen. The ability to effectively demonstrate this technique may open further market potential in the UAS community. More importantly, however, it may further demonstrate the capability of a fuel cell system to provide dual oxidant operation that may one day lead to the technology’s acceptance onboard passenger aircraft.

While the dual oxidant design remains a goal, catalyst differences between air- and oxygen-breathing fuel cells is a cost and development issue. Therefore, a standard air-breathing platform was chosen as the initial implementation of the system architecture with provision in the design to accommodate the active switchover capability as resources permit.

The following design analysis details our approach to achieving this goal and describes design-tradeoffs.

3.3.1 System Analysis

The fuel cell itself will provide power to the aircraft and is decoupled from the energy storage system, i.e., hydrogen. Power generation, therefore, can be scaled appropriately to meet aircraft power needs; the volume of energy storage is driven only by flight time requirements. This section reviews the power, energy and environmental demands.

3.3.1.1 Power Demands

The peak power requirement for the Infinity owned Penguin BE aircraft, as received from the vendor is approximately 3 kW, primarily due to the due to the A60-5SV2 Hacker electric motor in the aircraft with a peak power rating of 2,600 watts. The Infinity team believes, after conversations with users of the same aircraft, that this motor may be oversized for the application. Other electric motors are available for Class 2 UAS that may have a much lower input power requirement on the order of approximately 1 kW. Therefore, the nominal power for fuel cell stack, in a fuel cell only configuration, was set as a 1 kW output with potential for a peak output power at 1.5 kW. As referenced earlier, other Class 2 aircraft operate with similarly sized motors. Also, in a hybrid battery-fuel cell configuration the existing motor may be suitable with the battery able to provide the peak power and the fuel cell provide the majority of cruise power.

3.3.1.2 Energy Storage

Infinity has explored several options for the storage of hydrogen, comparing market introduction, economics, availability, etc. The Department of Energy (DOE) has done an enormous amount of analysis and provided funding for research of storage technologies and this report leverages that work.

Infinity continues to be in discussions with several manufacturers of hydrogen storage technologies and has an NDA in place with Ardica Technologies to discuss forward options for the materials-based storage of hydrogen beyond the near-term.

3.3.1.2.1 Hydrogen Storage Technologies

The storage of hydrogen onboard the UAS platform can make or break the overall efficiency and cost of the fuel cell system. There are several storage methodologies being employed across multiple market segments today and each can be effective. The significant challenges in storing hydrogen onboard UAS are mass and volume. There is a broad range of technologies available for the storage of hydrogen, however, the focus of this effort was two-fold: near-term applicability and long-term effectiveness.

The hydrogen storage technologies landscape can be seen in Figure 12 on a volumetric versus gravimetric capacity basis[19]. Current hydrogen storage technologies are focused

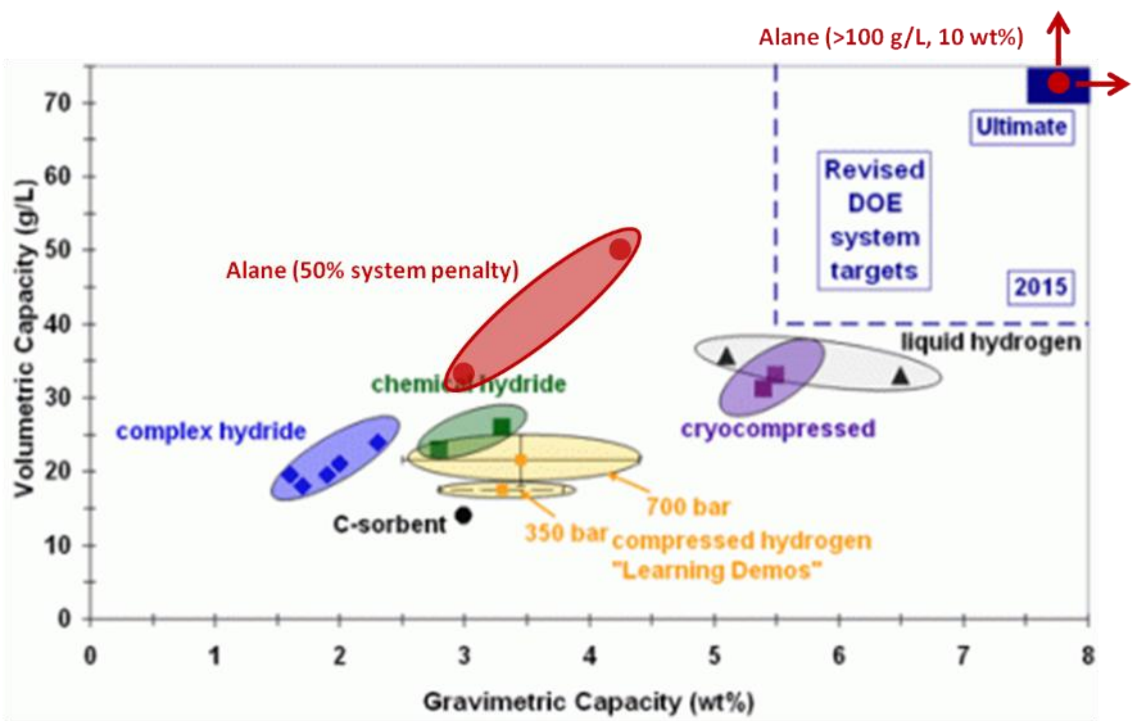


Figure 12 State of The Art Hydrogen Storage (DOE, ANL, BNL)

[19] http://energy.gov/eere/fuelcells/status-hydrogen-storage-technologies.

on maximizing storage potential while minimizing product cost long-term. The base chart is a current snapshot of storage technologies maintained by the DOE primarily for the automotive markets and includes gaseous, chemical, cryocompressed, and liquid hydrogen storage comparisons. Argonne National Laboratory (ANL) analysis indicates the present range of alane performance to be between 3 to 4.5 wt% hydrogen storage[20] on the chart, and Brookhaven National Laboratory (BNL) analysis indicates the maximum expected performance of alane-based storage systems at 10 wt% or greater[21].

The upper section of Figure 13 illustrates technology comparisons for the DOE automotive hydrogen storage effort, focusing on a longer-term production view of 500,000 units per year[22]. The lower portion of Figure 13 represents a technology, α-alane, developed by Savannah River National Laboratory (SRNL) and manufactured under a cooperative research and development agreement (CRADA) by Ardica Technologies. This latter material may provide a sea change in hydrogen storage

Projected H_2 Storage System Performance (5.6 kg H_2 usable)	Gravimetric kWh/kg (kg H_2/kg system)	Volumetric kWh/L (kg H_2/L system)	Costs* \$/kWh (\$/kg H_2)
700 bar compressed (Type IV, Single Tank)	1.4 (0.044)	0.8 (0.024)	\$15 (\$500)
Metal Hydride ($NaAlH_4$/Ti)	0.4 (0.012)	0.4 (0.012)	\$43 (\$1,432)
Sorbent (MOF-5, 100 bar, MATI, LN2 cooling)	1.3 (0.04)	0.7 (0.020)	\$16 (\$533)
Chemical Hydrogen Storage (AB-50 wt.%)	1.4 (0.043)	1.3 (0.040)	\$17 (\$566)
Ardica Technologies α-alane hydrogen storage cartride†	1.03 (TBD)	1.32 (TBD)	TBD (\$136)‡

- 700 bar compressed H_2 system projections from ANL / SA
- Materials-based system projections from Hydrogen Storage Engineering Center of Excellence (5/2015)

* Projected at 500,000 units / year

†Ardica technical information
‡Regression analysis of Ardica data

Figure 13 Hydrogen Storage Technologies Comparison

capability if the costs of manufacturing and recharging the aluminum-based material can be brought down to commercial levels. BNL indicates a near-term storage potential of 5.5 wt% and a long-term potential of ~10 wt%. Current compressed gas storage can provide approximately 4.5 wt%. Table 7 illustrates a recent survey of available composite storage tanks across a variety of fluids and certifications. These types of tanks can be made or acquired near-term.

[20] http://www3.aiche.org/proceedings/Abstract.aspx?PaperID=204705.
[21] Brookhaven National Laboratory, Alane for Hydrogen Storage and Delivery, June 2012.
[22] Stetson, Ned. Hydrogen Storage Program Area, DOE Fuel Cell Technologies Office, Annual Merit Review, 6-10 June 2016.

The near-term approach for Infinity's UAS fuel cell system employs compressed gas in a Type III tank while exploring longer-term and cost-effective solutions that can minimize mass and volume of a complete system. To this end, Infinity is actively working with HyperComp Engineering as a source for a type IV tank similar to the ones employed in the Toyota Mirai. This solution could supply ample hydrogen for long duration flights while leveraging very mature refueling technologies that, while not ubiquitous presently, could be implemented quite easily in the near term.

Table 7 Survey of Available Composite Tanks by Application and Certification

Fluid	Diameter (in)	Length (in)	Volume (in3)	Mass (lb)	Service (psi)	Liner	Cert	Proof/Service	Mass/Volume
Air	4.27	8.55	68	2.4	4,500	metallic	DOT CFFC	1.7	3.53%
Breathing Air	6.8	19	549	10.7	4,350	plastic	ISO 11119-3	1.5	1.95%
Breathing Air	6.02	21.52	415	9.02	4,351	metallic	EN12245	1.5	2.17%
Breathing Air	6.7	22	488	11	4,351	aluminum	EN12245	1.5	2.25%
Breathing Air	2	9	16	0.68	4,500	aluminum	ISO11119-2 / DOT	1.7	4.25%
Hydrogen	6.5	11.3	232	2.6	4,500	metallic	Aerospace		1.12%
Hydrogen	4.28	11.5	116	1.66	4,500	metallic	Aerospace		1.43%
Hydrogen	10.9	32.7	1995	43.9	5,076	aluminum	JARI 5001	1.5	2.20%
Hydrogen	4.5	42	439	14.3	10,000	aluminum	Aerospace	1.3	3.26%
Hydrogen	11.8	40.8	1965	66.1	10,150	aluminum	Hydrogen	1.5	3.36%
Hydrogen	4.6	98	13910	524	15,000	aluminum	Hydrogen	1.2	3.77%
Hydrogen	16.5	32.9	2007	84.7	5,076	aluminum	Aerospace	1.5	4.22%
Hydrogen	11.8	32.8	549	66.1	10,150	aluminum	Hydrogen	1.5	12.04%
Oxygen	6.93	21.65	549	11.68	4,351	metallic	EN12245	1.5	2.13%
Oxygen	5.7	14.5	259	6.4	1,850	stainless steel	ISO11119-2 / DOT	1.7	2.47%
Oxygen	2	9	16	1	4,500	steel	ISO11119-2	1.5	6.25%

Alternative storage technologies outside of those listed in this report are also being explored by Infinity as part of an ongoing effort to maximize both gravimetric and volumetric densities for UAS power and energy systems.

3.3.1.2.2 Oxidant Storage Technologies

The storage and refilling of oxygen require special care. There are two ways to store oxygen: gaseous oxygen (GOX) and liquid oxygen (LOX). Each can be delivered through typical commercial channels; however, safety requirements must be adhered to during transport, filling, and storage. Furthermore, the material selection of the storage tanks is of critical importance, with several materials, e.g., titanium, being ill-advised for use[23].

The storage of oxygen as LOX yields the greatest volumetric efficiency, but introduces a heavier storage device. For the UAV market it becomes challenging to accommodate the complexities of commercial refilling in the field. GOX storage is much more amenable to smaller UAVs but comes with the penalty of reduced energy density, therefore requiring greater volume within the airframe. GOX for the respiratory care market is ubiquitous and well-established. Standard storage cylinders have moved from

[23] Safety Standard for Oxygen and Oxygen Systems, NASA, NSS 1740.15, January 1996.

steel to aluminum and now plastic composites for weight reduction, with fill pressures to 2,000 psi[24].

A third option is the use of stored air. While compatible with air-breathing fuel cell catalyst, stored air requires far more volume than oxygen. This can be a limiting factor in its implementation on smaller UAVs.

3.3.2 Dual Oxidant Switchover

The prime goal of this effort is the development of a fuel cell system to be tested within a UAV platform and use this design as a basis for reviewing and evaluating upgrades/changes required to meet FAA operational and safety standards, e.g. 14 CFR Part 25 (transport aircraft), Part 107 (SUAS).

Introducing oxygen onto the cathode side of a Membrane and Electrode Assembly (MEA), which has been cost-reduced and optimized for air rather than oxygen, will serve to increase the degradation of the cathode catalyst unless the catalysis support structure is designed for O2 operation. Typical commercial H2/air MEAs utilize a carbon supported design which provides excellent performance with air as the oxidant.

In pure oxygen and/or at higher (electrolysis) voltages, these carbon supports can be attacked and degrade. For example, during fuel starvation and start-stop events high potentials can occur leading to rapid carbon support oxidation and loss as CO_2.This can be mitigated by adding a cell reversal tolerant catalyst able to catalyze oxygen evolution from water to provide an alternate oxidation reaction to CO_2 formation.[25]

Infinity utilizes H2/O2 designed MEAs in air independent fuel cell designs however these are typically considerably more costly than H2/Air MEAs. For the purposes of this initial design and fabrication cycle we decided to use lower cost conventional catalyst structures that can be readily upgraded in the future for dual oxidant use.

The ultimate system for the UAS market will be a dual oxidant platform utilizing compressed air storage. Although much less energy dense, this method would require the least modification to the catalyst layers within the fuel cell and therefore represents the least resource intensive approach to a minimum viable product. For this program, the development of the fuel cell stack hardware consumed most of the available resources and the dual oxidant approach as part of the current package was abandoned. This allowed the development team to focus on the lightweight, cost-effective fuel cell stack design.

---

[24] Options for Home Oxygen Therapy Equipment, Respiratory Care, Vol. 58, No. 1, January 2013.
[25] Non-Carbon Supports for Fuel Cell and Electrolyser Applications, Enrico Petrucco, Geoffrey H Spikes*, Ed A Wright, Johnson Matthey Technology Centre, Blount's Court Road, Sonning Common, Reading, RG4 9NH, UK

3.4 Power System Design and Modeling

Infinity's present fuel cell architecture is well-suited for air independent operation, i.e., utilizing pure hydrogen and oxygen as reactants. The introduction of air into the present platform requires design changes to several internal components, including bi polar plates (BPPs), advanced water removal, MEA, etc. Furthermore, the reduction of BPP and MEA costs is critical to the development of a low-cost fuel cell platform capable of serving the UAS and transport aircraft markets. Given these required changes, the Infinity team began a fuel cell stack design effort to meet the demands of an air-breathing architecture as a primary goal, while possibly maintaining the potential for inclusion of oxygen or stored air to provide dense air environment operation in the future.

Any fuel cell system utilized for UAS propulsion, as well as FAA testing as part of this effort, should at the very least address market requirements for the UAS community. The driving elements of a successful fuel cell power and energy system that can compete with ICE and battery-based systems will include the following: high gravimetric and volumetric efficiencies; lower TCO than ICE and battery systems. Embedded in the TCO calculation are first and operating costs.

3.4.1 Preliminary Stack Performance Design

The final prototype product is an air-breathing proton exchange membrane fuel cell (PEMFC) to be bench tested with appropriate hydrogen storage and ambient air feed. A baseline objective was established to address the need for, and the design potential of, a dual oxidant system. This type of fuel cell would consume ambient air drawn from a fan or compressor, but also be able to utilize stored air or oxygen from an onboard tank. Infinity's background in building hydrogen/oxygen fuel cell systems provided a natural starting point for oxygen storage over air.

Each fuel cell stack is comprised of individual repeat elements and capped at both ends with non-repeating end hardware. Much like a battery, these individual cells, when connected in series, produce a voltage equal to the individual cell voltage multiplied by the number of cells in series. This stack of cells, and therefore the power system itself, must be able to feed a standard electrical bus in a UAS with maximum efficiency. If a DC-DC converter is to be used as part of a power management and distribution (PMAD) device, then a fairly tight input voltage to the converter should be provided from the fuel cell stack. Figure 14 illustrates the price/efficiency of DC-DC converters versus input voltage for another Infinity application. The electrical bus voltage chosen for the drone system is a consistent 24 VDC or greater.

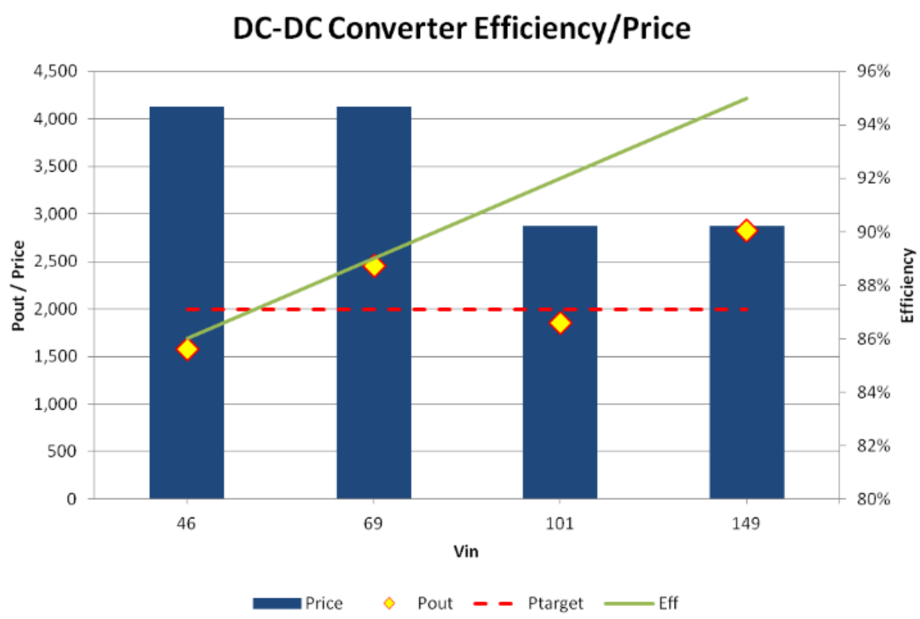


Figure 14 DC-DC Converter Example

To maintain a consistent voltage output level, the fuel cell stack must be designed with both beginning-of-life (BOL) and end-of-life (EOL) estimations to properly predict performance over a specified lifetime. Implicit to this design consideration are appropriate estimates of voltage degradation rates per hour, as well as degradation due to start/stop cycling of the fuel cell system. Leveraging Infinity's proprietary modeling tools, and assuming reasonable mission profiles over a period of time, appropriate product predications can be made. Figure 15 represents the estimated BOL performance of a complete fuel cell stack operating on air and hydrogen at reasonable stoichiometric rates of consumption. All the analyses presented assume hydrogen supplied at 99.99% purity. Hydrogen quality below this value, most notably at 99.95% may be evaluated and tested at a later date. This "4 nines" versus "3 nines" assessment of fuel quality delivered to the fuel cell stack can become critical during operation in the field and may limit lifetime of the stack as well as flight time.

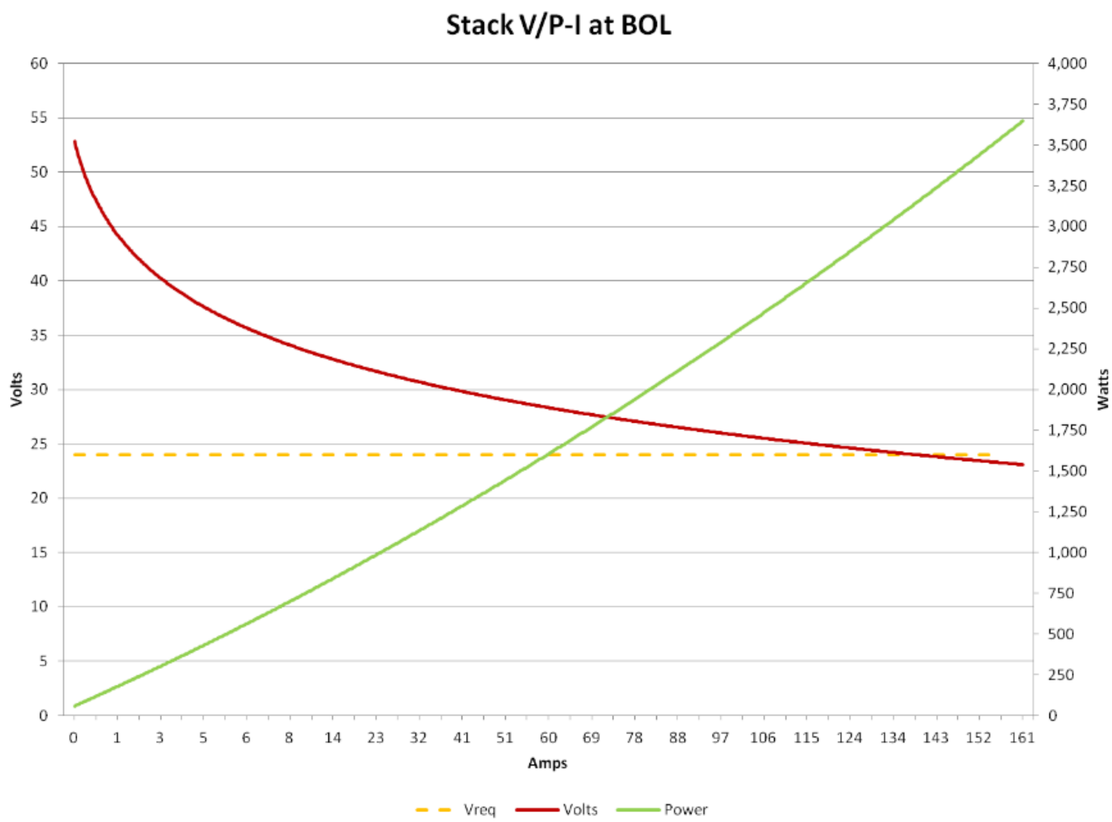


Figure 15 Fuel Cell Stack Voltage & Power vs Current

3.4.2 System Packaging and Modeling

Early modeling of a proposed fuel cell system contained within the targeted airframe focused on a 12-hour flight time. The system would be comprised of a power module

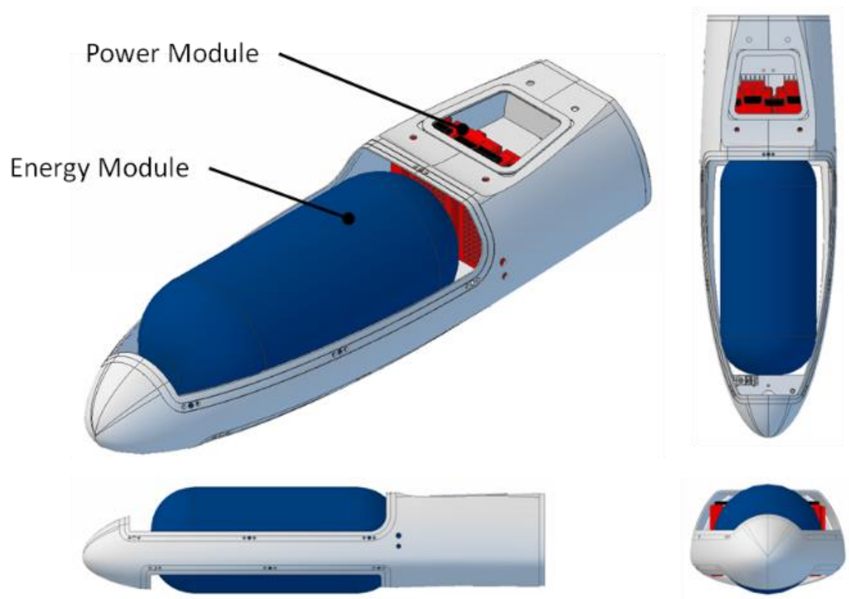


Figure 16 Fuel Cell Energy System in Acquired Airframe

and energy module, as seen in Figure 16, and would utilize available volume. This analysis yielded a 3-kW power module (to power the existing motor in the airframe) and a Type IV tank containing compressed hydrogen at 700 bar, providing 8 hours of flight time. Given that the electric motor supplied by the Original Equipment Manufacturer (OEM) is oversized for the application (and the goals of this project), a smaller electric motor may be acquired. This smaller motor will require less energy storage and will free some volume for a small oxygen tank. This power and energy system consume the entirety of the payload bay and is not intended to demonstrate payload-carrying capability. Rather, this program is intended to demonstrate the ability of a UAS to fly on a dual oxidant fuel cell power system, and not necessarily for the 8-hour flight time originally modeled by the Infinity team. The combination of reduced flight time and power requirements may ultimately yield a system with smaller tanks, lower pressure storage, and smaller fuel cell power module.

3.3.2.1 System Peripherals

The major required elements for potentially flying the targeted airframe are listed, inclusive of operation and maintenance issues. This list is dedicated to the completion of the outlined program, as well as a start to a more comprehensive UAS product list.

a. Licensed operator (the pilot)
b. Spotter for pilot
c. Ground control station
d. Airfield suitable for UAS flight
e. Hydrogen fuel for filling tank prior to flight
f. Hydrogen fueling mechanism
g. Oxygen for filling tank prior to flight
h. Oxygen filling mechanism

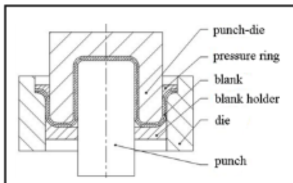
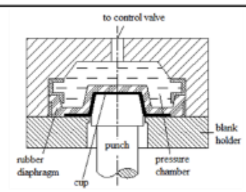
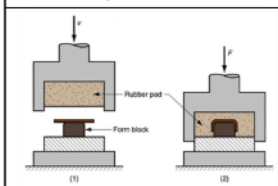
3.4.3 Fuel Cell Repeat Element Bi Polar Plate Design

The hydrogen and oxygen fuel cells developed by Infinity to date rely on a much different operating paradigm than that required for the drone market. Very robust and capable of removing product water in each individual cell, Infinity's present fuel cell hardware is simply too expensive for the more cost-competitive drone markets. The drone fuel cell must be easily manufactured and lightweight enough to satisfy the MTOW of targeted aircraft. The active area of the fuel cell – that area covered by the catalyzed membrane through which the electrochemical reaction producing power, heat, and water takes place – must be critically sized to maintain projected power levels.

A BPP serves two functions in a fuel cell: 1) the BPP directs reactants into each cell of the fuel cell stack; 2) the BPP provides a serialized electrical connection between cells in a fuel cell stack. For decades the material of choice for BPPs was graphite. It is easily machinable and provides good electrical conductivity through the fuel cell stack. Graphite, however, can be brittle and easily damaged in operation. Furthermore, it is generally a thicker material when employed as a BPP, with a higher mass than other materials. For these and other reasons many fuel cell manufacturers (Infinity included) have chosen to employ metallic BPPs. Metal plates can be significantly lighter than graphite while providing excellent electrical conductivity. The down sides of employing metal as a BPP lie in its corrosiveness in a fuel cell environment, necessity for bonding of several layers, and choosing a cost-effective method of forming thin sheets.

Many methods have been employed to form sheet metal. For the types of metal foil of interest in aerospace and fuel cell markets, three processes dominate: 1) Stamping; 2) Hydroforming; 3) Rubber Pad Forming, see Table 8. Each method has advantages and disadvantages.

Table 8 Metal Forming Processes

	STAMPING - Two tooling dies required - High pressure press - $$$ first cost - $ part cost
	HYDROFORMING - Single tooling die required - Water or oil as pressing fluid - $$ first cost -$$ part cost
	RUBBER PAD FORMING - Single tool die required - Low pressure press - $ first cost - $$ part cost

The stamping process requires both positive and negative tooling dies and fairly high pressures. The tooling is typically placed in a hydraulic press with the sheet metal to be formed in between the tooling. Alignment of the die set is critical. Since the tooling die set imparts significant impact forces to the sheet metal – a key parameter to proper stamping – the dies must be manufactured from hardened steel, which drives up the first cost, however the part cost is rather low.

The hydroforming process is an alternative to conventional matched die forming, e.g. metal stamping. Developed over the course of the 20th century, the process leverages water or oil as a working fluid while eliminating the impact forces associated with stamping. As a result, the process provides a lower first cost and reasonable part costs.

There are limitations associated with feature designs but the process is amenable to the fabrication of fuel cell BPPs.

The rubber pad process, also known as the Guerin process, generally utilizes a single tool and a rubber pad. The die is placed in a low-pressure press with the material to be formed located between the die and the rubber pad. The rubber pad – generally a urethane – is used as the pressing “fluid”, forcing the sheet metal into the features located on the tool die. This process is well established in the aerospace market where lower volumes of precise parts are typically required. The one die approach translates to lower first costs, while the greater time per press lends itself to lower volume production, i.e., higher part costs than conventional forming methods.

For the development of an air-breathing fuel cell for the UAS community, Infinity selected a hybrid rubber pad forming process. With low first costs this method fits budgetary and scheduling constraints. Furthermore, the potential for pulling the process in-house would provide part cost reductions through the beta phase of product development and into early commercial release. Figure 17 illustrates the concept for both male and female molding tools, along with a BPP between the two.

The stacking arrangement of repeat hardware in the fuel cell stack follows a non-

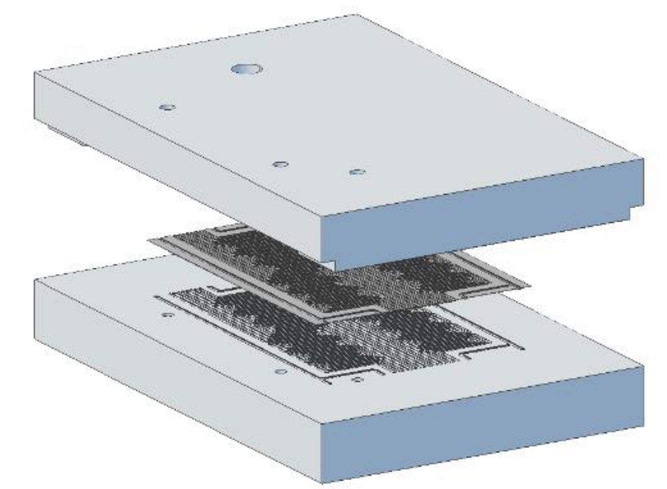


Figure 17 BiPolar Plate and Forming Tools

traditional A-B-C-A approach; A=anode flow field, B=MEA, C=cathode flow field, Figure 18. A traditional graphite BPP is relatively thick and allows for the pressing or machining of anode and cathode flow fields on either side of the plate. When using thin metal foils to form flow fields the BPP is actually two flow fields placed back-to-back in the stacking profile such that the back side of both the anode and the cathode plates are in contact providing the bipolar function and the electrically conductive path.

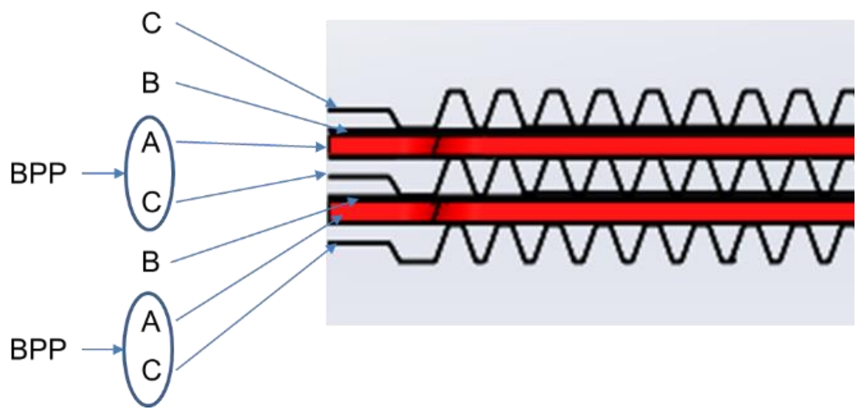


Figure 18 Fuel Cell Repeat Elements and Bi Polar Plates

The challenge in utilizing thin metal plates for flow fields lies in sealing the hardware when stacked such that the gaps created by the lack of thickness in the BPP are filled with a sealing material. If utilizing an adhesive approach for stack assembly then this gap area, seen in Figure 19, both seals and adheres the repeat elements together.

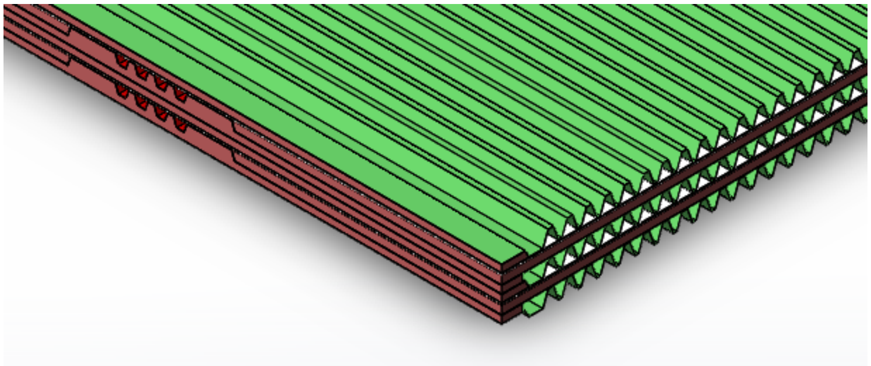


Figure 19 Fuel Cell Repeat Elements and Associated Sealing

The Infinity UAS fuel cell product development approach will be to minimize the number of part numbers required in building the fuel cell stack while also minimizing the total number of parts required. This is standard practice in high volume industries and one that will serve the UAS market pricing demands well.

3.4.3.1 Fuel Cell Bipolar Plate Sealing Approach

A goal of the UAS fuel cell is low cost in production. Per vendor quotes obtained during this project it became known that the joining of metal plate elements in forming BPPs represented up to a full third of the overall cost of fabrication. Generally, for metal BPPs the bonding method of choice is welding.

To reduce this cost, an approach was attempted to join the two-part bipolar plate by a different approach. Instead of welding, the metal plates comprising the BPP were planned to be compressed against one another during the assembly process, remaining in constant contact during operation. Historical fuel cell operating evidence suggests corrosion may be an issue in this configuration, however the expected lifetime of the current product being developed should be the limiting factor when fielded.

To make the compressed BPP concept viable, a sealing methodology was required to both contain reactants in the active area of each cell (internal to the stack) while preventing incoming reactants to the stack via external manifolds from entering the active areas. This seal must be of a low durometer to effect proper sealing and must also be integral to each part being assembled. Managing very thin O-rings during the assembly of multi-cell fuel cell stacks would be extremely cumbersome. These requirements have led to the development of Form-In-Place (FIP) gaskets for use in development of this product. The sealing material in this case is critical and must interact well with hydrogen and possibly pure oxygen.

There are several manufacturers of FIP gasket material. These materials span a fairly large durometer range, see Figure 20, however this development project will require materials at the lower end of the scale in the “Soft” range. This will allow for approximately 25% to 30% compression of the gasket material with little overall force required during assembly compared to the force requirement for the GDL.

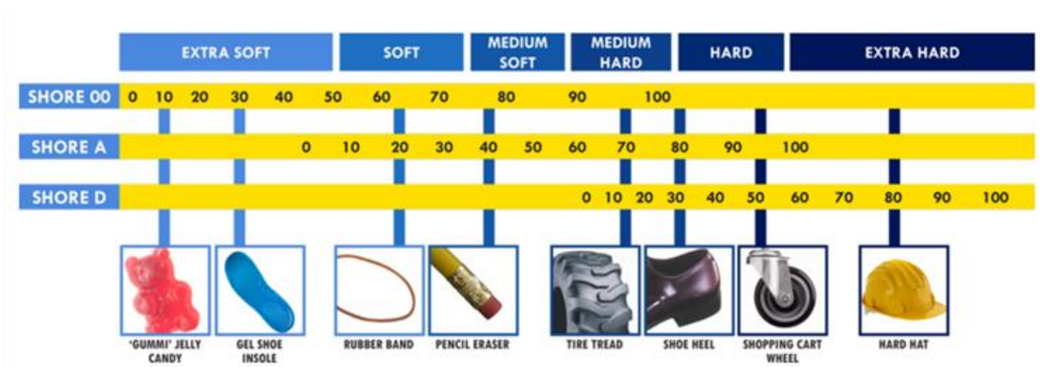


Figure 20 Shore Hardness Scales

3.4.4 Fuel Cell Stack Architecture

The overall design of the fuel cell stack incorporates cost effective approaches to manufacturing individual cell components for achieving a lightweight design. To meet the challenges of the drone environment the design team has attempted to minimize balance of system (BOS) components, allowing for multi-tasking components as appropriate. As seen in Figure 21, the original fuel cell stack concept allowed for a single fan to pull ambient coolant air through the active fuel cell stack hardware, thus providing a pre-heated coolant air outlet from which to draw reactant supply for fuel cell operation. This pre-heating is an advantage when operating at higher, and colder, altitudes as moisture in the very cold incoming air could condense within the stack, causing performance issues. The potential inclusion of this performance improvement has been postponed for now pending the outcome of testing without it.

Additionally, with major markets in mind for this fuel cell product flying at or below a 400 ft altitude, the inclusion of pre-heated reactant air is far less necessary. Therefore, the initial design was focused on a two-fan approach: one larger fan for thermal control and one smaller fan for reactant air delivery. The additional parasitic loss over a broad range of operating conditions is compensated by the increased simplicity in the overall system architecture.

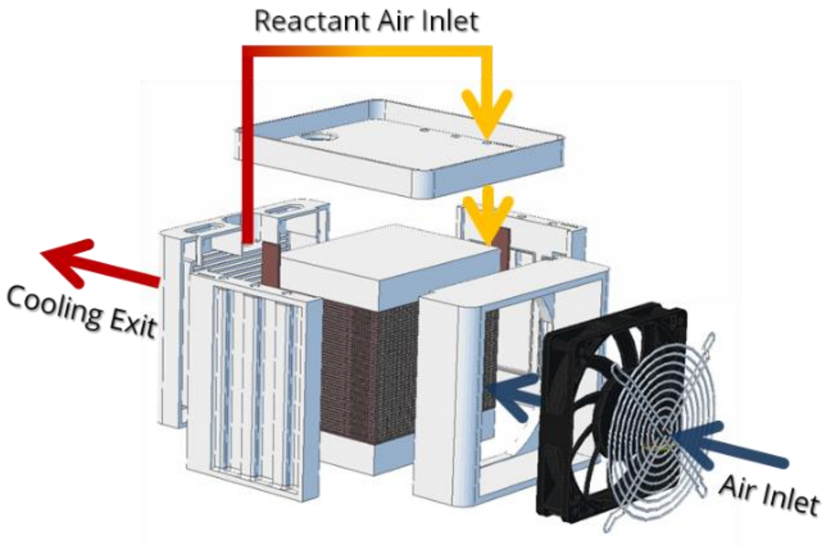


Figure 21 UAS Fuel Cell Stack Preliminary Air Flow Scheme

The externally manifolded approach not only provides a lower cost part, but it also allows for further integration into airframes in the future. Presently most airframes – fixed wing and multirotor – are designed independently of the power system. Power system components are certainly accounted for in terms of mounting and operation, but airframe design and power system design are mutually exclusive operations. Removing the external manifolds from the fuel cell stack and inserting directly into the fuselage, utilizing the fuselage as the external manifolds, could provide complete integration of airframe and power system, thereby further reducing the cost and increasing the efficiency of the entire drone platform. This opportunity may be explored further in the future.

3.4.5 Control System Approach

The complete control system adheres to the state diagram shown in Figure 22. The full fuel cell stack will be free of individual cell voltage taps to minimize I/O count. Stack voltage will be measured and assessed relative to theoretical values based upon measured current and calculated current density. Since this is a hybrid battery/fuel cell system, each energy producing subsystem will be monitored and assessed during startup, run, and shutdown. Shutdown and safing of the fuel cell will be done when input parameters demand it. Fuel cell air input will be driven through a control algorithm derived from the single cell testing already performed to determine variable airflow across the full breadth of the power band while not allowing an oversupply of air, as this would be detrimental to stack performance (causes membrane dryout).

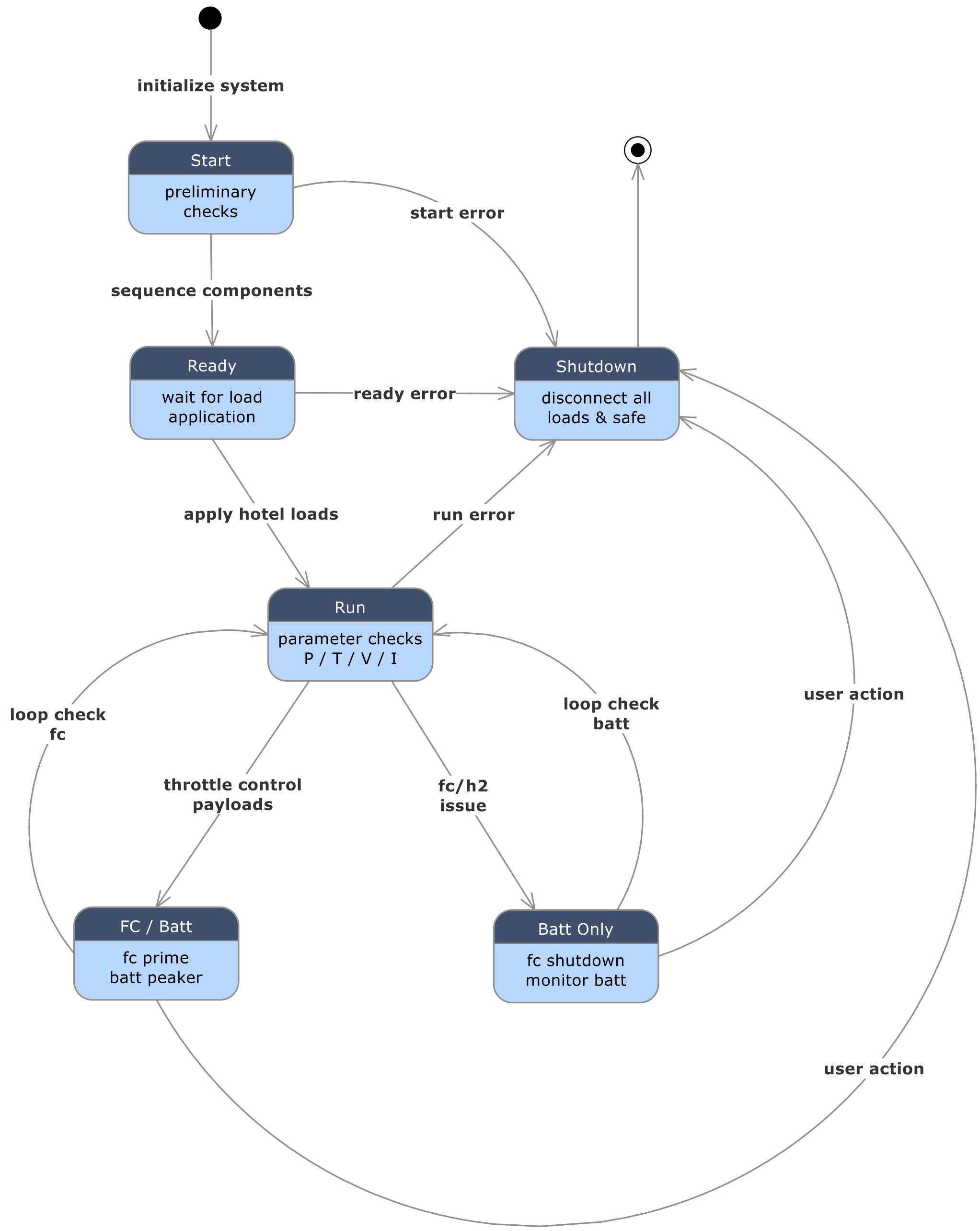


Figure 22 UML State Diagram

The states defined for the system, per Unified Modeling Language (UML), illustrate system status. Between each state several activities must take place and these will be defined per a system activity diagram. The controls algorithms are being developed per the state diagram, the activity diagram (still under development), and sub routines developed during single cell testing. An electrical schematic is in work and will be completed in parallel with control system development. A Graphical User Interface (GUI) will be employed for monitoring and control of the integrated benchtop testing. This will allow for greater ease in visual assessment of all I/O outside of more cumbersome code viewers.

Next steps will be ordering a full complement of fuel cell stack materials and preparing for a full stack build. A Failure Modes and Effects Analysis (FMEA) will be performed once the complete electrical schematic is finished and this will lead into the completion of the compliance matrix study. MEAs will be fabricated while waiting for final BPP tooling to arrive. Once tooling is received, the BPPs will be fabricated and the sealing solution applied. Stack containment in the form of 3D printed manifolds will be obtained prior to full stack build and the lightweight fuel cell will then be assembled, with system integration following shortly thereafter.

3.4.6 Balance of System Architecture

System hardware has been kept to a minimum part count to reduce both mass and volume while maintaining all necessary controls and I/O for safe operation, see Figure 23. Much of the inlet hardware indicated in the P&ID is included in the regulator Infinity will be acquiring, including the fill port, burst disc, pressure transducer, and pressure gauge. Leveraging this purpose-built regulator has reduced the mass of these individual components significantly. This version of the P&ID includes both the reactant air blower and the cooling fan (attached to the fuel cell stack).

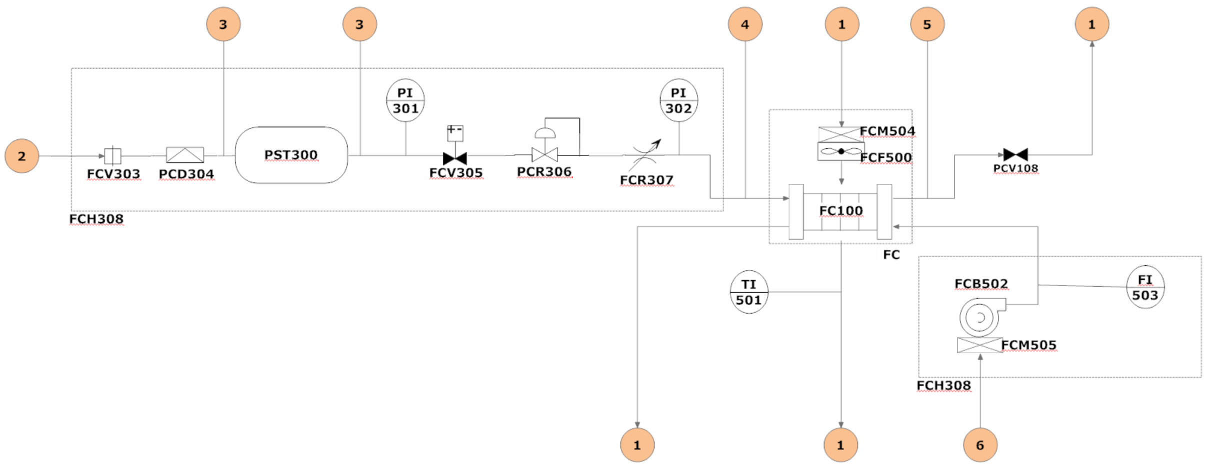


Figure 23 Piping & Instrumentation Diagram

Minimal instrumentation is utilized in this system to maximum potential within the control system. The yellow numbered circles represent states along the flow paths; the associated state table is indicated in Table 9.

Table 9 Preliminary Fuel Cell System State Table

--- STATE TABLE ---								
State	Fluid	Tmin	Tmax	Pmin	Pmax	Vmin	Vmax	RHmax
		°C	°C	bar (a/g)	bar (a/g)	lpm	lpm	%
1	Air (Ambient)	-20	50	TBD (a)	1 (a)	-	-	100
2	Hydrogen (Fill)	-20	50	5 (g)	350 (g)	TBD	TBD	5
3	Hydrogen (Stored)	-20	50	5 (g)	350 (g)	-	-	1
4	Hydrogen (FC Inlet)	-20	50	0.2 (g)	0.5 (g)	0	25	5
5	Hydrogen (FC Outlet, Nom)	65	80	0.2 (g)	0.5 (g)	0	25	100
6	Air (FC Inlet)	-20	50	TBD (a)	1 (a)	0	200	100
7	Air (FC Outlet)	65	80	TBD (a)	TBD (a)	0	200	100
8	Air (Cooling Inlet)	-20	50	TBD (a)	1 (a)	0	200	100
9	Air (Cooling Outlet, Nom)	65	80	TBD (a)	1 (a)	0	200	100

3.5 Certification Compliance Review: Part 25 Regulations

Building on the work of the Energy Supply Device Aviation Rulemaking Committee (ESD ARC) Infinity is mapping the ARC recommendations for applicable parts of the regulations as they apply both to a generic fuel cell system and to the UAV fuel cell system currently under development. The goal of the document under development is to provide a detailed framework for qualification of a generic fuel cell system for a Part 25 application. To do this the document will summarize a review of the UAV fuel cell as if it were to be qualified under Part 25. This will highlight which Part 25 regulations can practically be met by the UAV design and which require substantial additions or modifications. The basis for this is the current draft ARC document. The UAV fuel cell design is being reviewed with respect to each subpart regulation identified in the ARC draft along with relevant Advisory Circulars. Each subpart will be addressed with a separate analysis that considers both manned transport and unmanned applications and details how compliance with the regulation may be achieved.

4.0 Fabrication Report

This section details results of the manufacturing stage of the program including:

- 4.1 Subsystem and component development and test
- 4.2 Single cell manufacture and test
- 4.3 Prototype manufacture and test

One major issue related to the fabrication of the bipolar pate that required a change to the initial implementation of the design architecture from a closed cathode with two-fan to an open cathode with one blower. This in-turn affects…

4.1 Subsystem and component development and test

The following section details results of testing of components and subsystems and of the development of manufacturing processes. These include:

- Air flow subsystem
- Bipolar Plate
- Sealing
- MEA
- Fuel Cell Stack
- Controls
- Hydrogen Storage

4.1.1 Air Flow Testing

As outlined above, a primary goal of developing the targeted UAS fuel cell power system is to meet application requirements with a cost-effective product. Optimization of the air flow scheme is an important consideration in achieving that objective. Opportunity exists to leverage the incoming air flow to the UAS fuel cell power system for both cooling and reactant air, while also preheating the reactant air. Managing the split air flow stream, however, can become challenging. The cooling air requirement must be maintained at varying power levels while the reactant air stoichiometry must be sufficient for efficient power generation.

In order to test the single air flow concept, test hardware was acquired and a representative chamber was constructed, see Figure 24, to duplicate a manifolded fuel cell concept. The chamber dimensions seen in the figure are not critical; the measurement of air flow through each of two exiting paths via a singular control is representative of the multi-chamber concept. The chamber itself was constructed from plasticized corrugated board. Hot wire anemometer wind speed sensors (Modern Devices) were placed at locations 3 and 4 (see diagram). A 200-cfm fan was positioned at location 1 and a louvered sliding door was positioned between locations 2 and 4 (represented by bold dashed line in diagram).

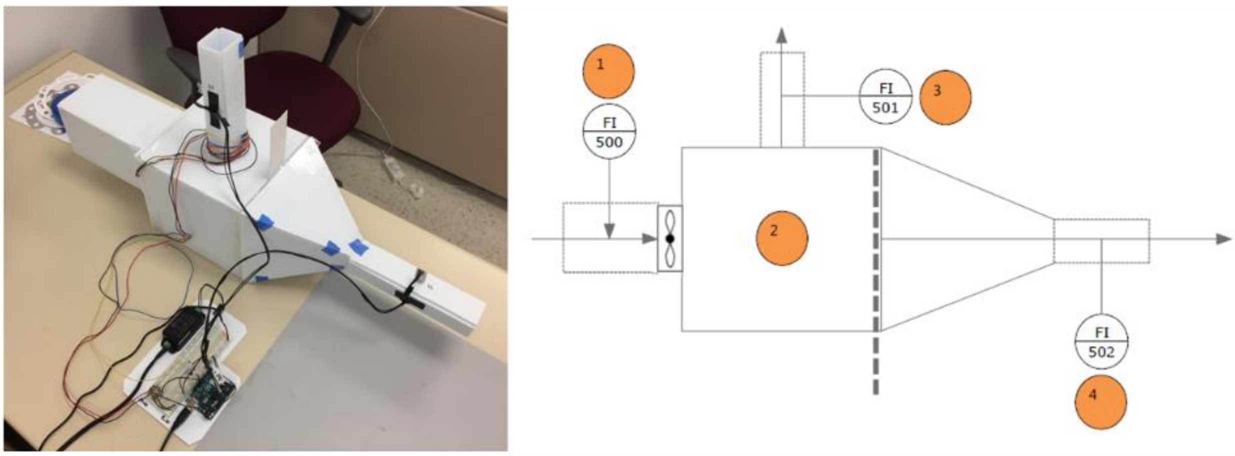


Figure 24 Airflow Testing Setup

During operation in the completed product it was planned that the required fan would be pulse width modulation (PWM) controlled. To begin the development of this type of system, a control board (Arduino) was acquired and programmed to operate the fan based on a feedback control loop from the wind speed sensors. A series of air flow measurements were taken and converted to cfm ratings at locations 3 and 4. The resulting data for varying combinations of open and closed conditions at locations 3 and 4 can be seen in Figure 25. Although the fan rating was 200 cfm, the maximum attainable flow from the test article was approximately 72 cfm (leftmost chart in figure), assuming original formulas provided by vendor. The wind sensors were also tested in a wind tunnel at Western New England University (WNEU) and the formulas developed through the course of that testing yielded a potential 121 cfm combined flow rate from both AFS 3 and 4. This 121 cfm rate would correspond to a pressure in the chamber of approximately 10 mm H_2O (0.014 psig)[26], see Figure 26. The lower flow rate through the test article was due to the large pressure differential within the test article and the inability of the test fan to overcome it.

[26] From Delta Model EFB1324SHE-EP Specification, Rev. 01, dated 6 Aug 2012

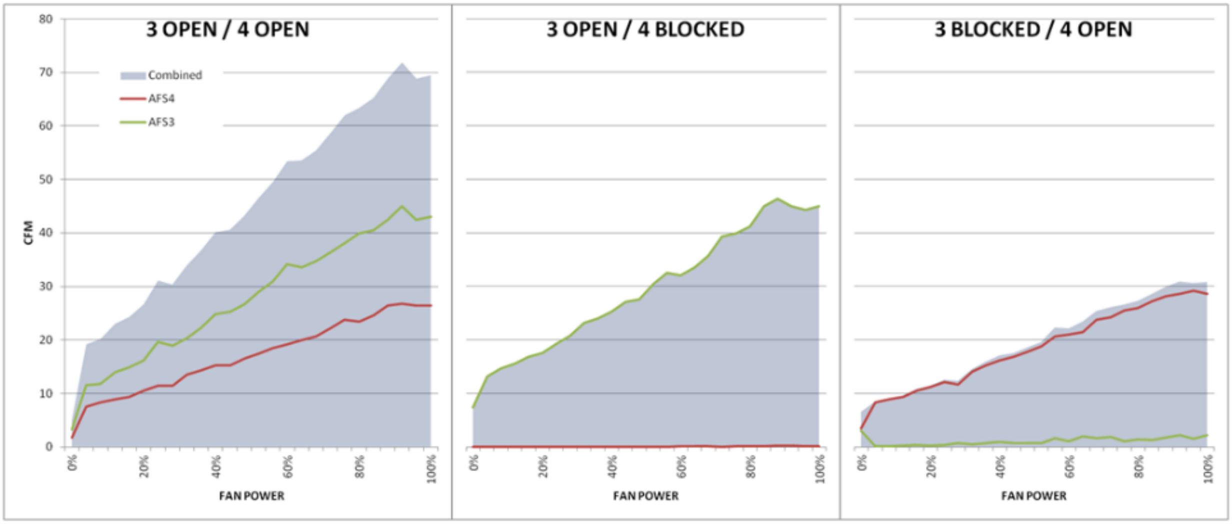


Figure 25 Air Flow Test Results

The concept system would ideally be configured such that air flow sensors would provide feedback to either a one or two fan system to establish more efficient control of air flow to the stack. One of the key takeaways from this testing is the wide gap in reduction formulas necessary to implement an economical hot wire anemometer for this purpose. Further literature and internet reviews of other experimentation with similarly priced hot wire anemometers revealed similar difficulties in both calibration and end results as that experienced by the Infinity team. The challenge of choosing the appropriate fan is exacerbated by the imposed requirement of powering the fan from the 24 VDC output of the fuel cell stack with little or no modification through buck/boost conversion.

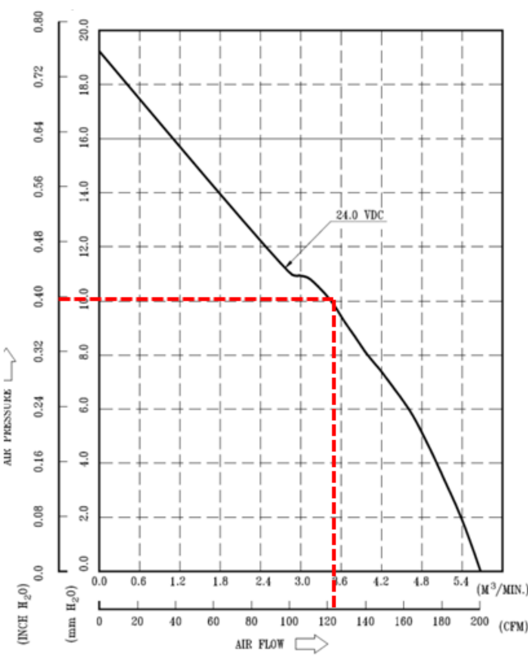


Figure 26 Air Flow vs Pressure

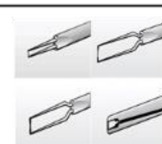
Given the restrictive manifold environment of the edge feed fuel cell it was determined that it would be necessary to specify a fan with much greater flow capacity at pressure. Utilizing a compressor or blower would suffice as well, however these components are often higher cost. A quick comparison of other fan offerings, Figure 27, illustrates the difference in fan blade designs which may improve overall performance and provide proper airflow for either cooling or reactant air. Based on test results and further evaluation, a two-fan approach was initially selected, with one fan providing coolant air and a second fan providing reactant air. Although adding more parts to the final product, the resultant efficiency in air delivery in both modes was determined to be a benefit. Further developments in the overall stack and system, as detailed below required redesign of this airflow concept for the initial implementation of the architecture, but it remains highly attractive for selected applications.

Figure 27 Fan Comparison: Test Article (L), High Static Pressure (M), High Flow (R)

4.1.1.1 Air Flow Measurement

To provide ultimate efficiency in the delivery of air in the two-fan approach, the implementation of a feedback loop via air flow sensors would be desirable. Further investigation into air flow sensing reveals several options and price points, Table 10. Inexpensive devices, like the one tested, require more correction than devices with significantly higher price points. The higher price usually puts the device out of reach for commercial product development. A cost benefit analysis is underway to determine the

Table 10 Comparison of Various Air Flow Sensing Devices

		
Modern Devices	**Honeywell**	**Exotic Hot Wire**
Accuracy ±5 m/s laminar	Up to 7 cfm	High accuracy
12 VDC supply	10 VDC @ 60 mW	Good signal sensitivity
Internal temp. corr.	1.2 inH_2O ΔP @ full scale	Very delicate
$	$$	$$$

efficacy of applying air flow measurement versus simple correlation of fan speed to static pressure and required air flow. A simple correlation made for stoichiometric condition versus fan speed and PWM control via Arduino or Raspberry Pi controller for reactant air flow and coolant air required would suffice.

4.1.1.2 Air Flow Temperature Measurement

The temperature of the air stream was inherently measured during air flow testing as part of utilizing a hot wire anemometer. In practice it would be beneficial to monitor the outgoing, and possibly incoming, reactant and cooling air streams. Since the final design of this product will employ a two-fan system; one for reactant air and one for coolant air, the ability to control PWM settings for the particular fan employed for that stream. This operating paradigm may provide benefit in reducing parasitic power draw from the drone's power and energy system, thus increasing available energy for longer flight times.

Table 11 Temperature Sensor Comparison

		
Thermistor	**Thermocouple**	**RTD**
Small operating range	Durable	High accuracy
Self heating	Fast response	Better repeatability
No signal amplification	Output amplification	Easier calibration
$	$$	$$$

A general review of available temperature sensing technologies yields the standard cast of characters typically used in the fuel cell community, see Table 11. Generally, thermocouples are convenient for use in lab testing given their fast response times; cost is typically an issue. For the development of this low-cost fuel cell-based power product, the Infinity team will be assessing the cost of temperature sensing to trade against the need for such measurement and control.

4.1.1.3 Airflow: IP Rating of Air Infiltration System

Since the drone being powered by the fuel cell system will eventually navigate airspace with inclement weather, it is desirous that any incoming air be free of water and debris. An oxygen or bottled air supply to the fuel cell would certainly preclude any introduction of debris into the fuel cell system, however, utilizing the air intake function through various altitudes will invariably draw water into the system. Furthermore, with the fuel cell stack being air cooled, the necessity to power the separate cooling fan will always be an issue when considering water infiltration. Filter media will play a role in managing debris and water infiltration. Proper Ingress Protection (IP). ratings of electrical components will prevent component failure in operation.

Many Commercial Off-The-Shelf (COTS) components are available in a variety of IP ratings. Fans, blowers, etc. can be acquired to meet most environmental situations. Figure 28 illustrates the range of IP ratings for electrical components to be operated in the field. Providing dust and water protection to all electrical components of the fuel cell power system is critical in flight. The targeted minimum IP rating for fuel cell electrical components is IP54: Dust protected; Protected against water splashing from any angle.

Figure 28 IP Ratings Chart

4.1.1.4 Cathode Blower Evaluation

Three blowers were acquired that will meet the cathode airflow requirements of the fuel cell stack under development and evaluated with respect to airflow, vibration, cost, control requirements, and voltage requirements. These were primarily qualitative tests and meant to properly define the correct option for inclusion in the final product. Table 12 illustrates the overall findings.

The ultimate cathode feed blower for the fuel cell product will be the Nidec model given its broad airflow and pressure capabilities. Further, the lifetime of the blower is significant compared to others in the same market. The manufacturer claims to have one of these blowers on life test (at zero back pressure) for the past 11 years.

Table 12 Cathode Feed Options

		
Nidec	San Ace	San Ace
Blower	Blower	Dual Fan
24 VDC	12/24 VDC	12 VDC
100 LPM	1,850 LPM	930 LPM
4.0 kPa	1.95 kPa	1.7 kPa
90 g	200 g	110 g
$$$	$	$

Both San Ace blowers may satisfy cooling fan/blower requirements for the fuel cell, however, the 200 g unit was determined to be too heavy to meet performance specifications. The dual fan may meet both pressure and flow for cooling requirements.

4.1.2 Bi Polar Plate Fabrication

To better understand the rubber pad forming process, and assess its viability for the current development program, a 3-D printed plastic version of the tooling die was made and used in conjunction with varying durometer urethane pads. This go/no-go testing yielded partial pressings of the metal foil, but also proved the concept for further evaluation. Figure 29 shows the original pressing test setup and one of the resultant metal sheet pressings. Note the feature detail in the image. Although specified depth was not attained during the press operation, the feature development alone provided reason enough to move forward with additional testing.

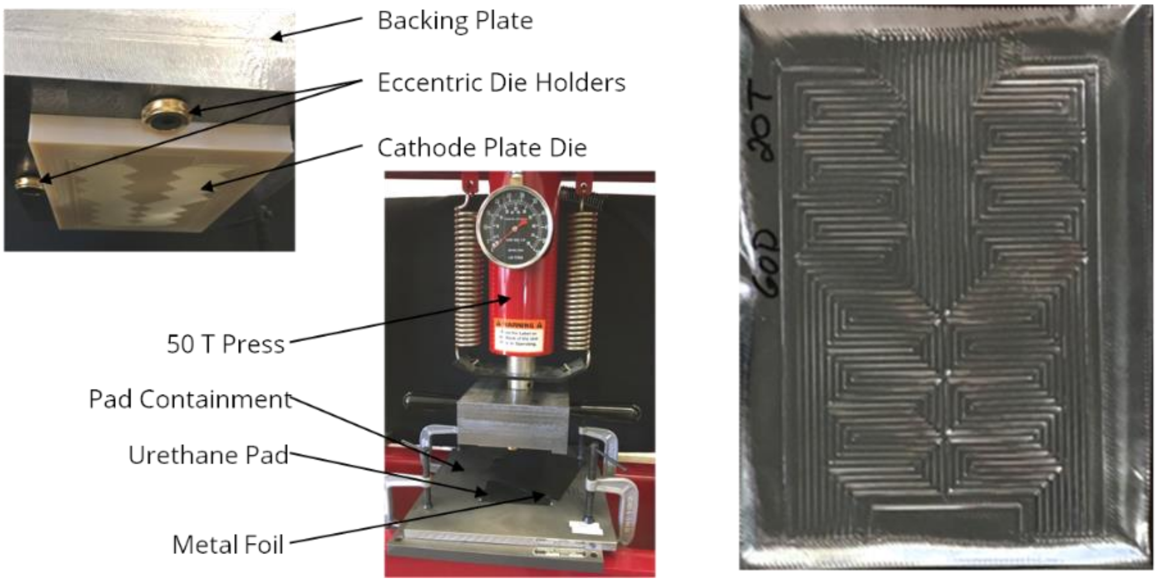


Figure 29 Go/No-Go Rubber Pad Press Test and Associated Formed Part

The next step in evaluating this forming process was the acquisition of a harder tool. In this case, although considered soft tooling, a forming tool was fabricated from aluminum and combined with pad containment and a press plate, see Figure 30. The pressing operation was limited by the available 50-ton hydraulic press located at Infinity's facility. Several press runs over several weeks were performed, including both contained and uncontained, known as "free pad", compressions. In contained mode, the urethane pads used as the press "fluid" must be houses within a depression in the tooling to prevent lateral movement. Literature suggests this will provide more pressing force per unit area into the part being formed. Testing proved it is rather difficult to contain the pad's lateral forces with built-up tooling; rather, a dedicated female tool is required, and in practice this will increase first costs of acquiring tooling. Free pad presses were also performed on the 50-ton press (rightmost image in Figure 30).

Figure 30 Soft Tooling for Rubber Pad Press Testing

The results from this in-house press testing (Figure 31) illustrate several unique challenges to the operation and during the course of testing many variations to the pressing operation were attempted, including pad durometer, press force, and free/fixed pad. The images represent early to later pressings and demonstrate increasing feature fidelity. The specified dimensions of the part, however, were never fully achieved. After exhausting all options for in-house pressing, the Infinity team approached an outside supplier to solicit advice and produce test samples of the formed flow field on their hydraulic presses. The general consensus among the Infinity team was that the in-house press was simply not large enough to provide the force required. The rightmost image in Figure 31 is a sample pressed at rather low press force but utilizing a very thick urethane pad at the vendor's facility. This pressing was the best yet, but still did not meet depth specifications. Pressing attempts at up to 400 tons did not solve the depth issue. Interestingly, the rightmost press image was performed at only 50 tons and yielded the greatest feature fidelity.

Figure 31 Rubber Pad Formed Flow Field Part Testing

After further discussions with the forming vendor it was suggested that the forming of such a complex part may require the use of both a positive and a negative tool, similar to the stamping process but a soft tool rather than a hard tool, with rubber pad place on top of the two-die set when forming the part. This hybrid process is the method of choice when performing rubber pad pressing of metal parts at the vendor's facility.

4.1.2.1 Open vs. Closed Cathode

Overall control of the fuel within the system is highly dependent on how the fuel cell is being fed reactant. The hydrogen feed to the fuel cell is well established and is controlled through the regulator. The air into the fuel cell can be fed through either an open or closed cathode flow field design. An open cathode fuel cell utilizes a flow-through air flow field, allowing for low resistance, high velocity air to flow into the fuel cell and react quickly with the catalyzed membrane. These flow fields are characterized by low pressure drops and typically shorter flow field channels.

Conversely, a closed cathode serpentine flow channel provides longer channel lengths, and therefore larger back pressures across the channels, allowing for better water removal, Figure 33. The increased backpressure, however, requires more powerful air-moving equipment, which typically increases overall mass and volume of the complete fuel cell system. Both flow field arrangements were evaluated during final full-scale single cell testing to determine effects on both fuel cell and system performance.

Through several iterations of test hardware and operating parameters it was determined that an open cathode design would be employed for the initial prototype due to better performance when combined with the MEA Infinity is presently assembling for this program. The open cathode, or straight-through flow field, will be coupled with the serpentine flow field for anode (hydrogen) flow. This arrangement tested well during trial runs of full-scale single cell hardware.

Figure 32 Open Flow-Through Cathode

Figure 33 Multiple Serpentine Cathode

Open Cathode Performance Impact Summary

While the open cathode provides benefits of simplicity, lower, cost and weight these benefits tradeoff against potential benefits of closed cathode air or O2 systems. These include:

- Performance: O2 partial pressure
- Altitude limitations
- Dry out/wet up operational envelope design

Performance:

The hydrogen-oxygen reaction is positively correlated to oxygen partial pressure meaning performance in terms of watts/cell also increases as O2 partial pressure increases. The open cathode H2-air system inherently limits the ability to increase O2 partial pressure since it essentially operates at ambient or near ambient pressure. A closed cathode H2-air system provides the ability to pressurize the cathode, increasing the O2 partial pressure thereby increasing performance. A closed cathode H2-O2 system provides the highest performance per cell area. However, each of these increases in performance must in-turn be traded off against potential increases in system complexity, weight and cost.

Altitude

One key factor in selection of an open or close cathode is the required altitude of intended application. Since O2 partial pressure decreases with altitude performance also decreases with altitude. Designers must trade off altitude capability against closed cathode system factors. At very low altitudes an open cathode may be an excellent choice. As altitude increases, closed cathode-pressurized systems start to provide better overall tradeoffs. As altitude increases to the point where O2 partial pressure is near or at zero, oxygen systems are required

Dry-out, Wet-up and Cooling Design Issues

Other factors related to open vs. closed cathode decisions include maintenance of proper water balance and proper cooling. The open cathode air flow typically provides both oxygen reactant and cooling air flow. The H2-O2 reaction produces water in addition to power. The product water that is produced must be removed but not all of it. Enough of the water produced by the reaction is required to be retained in the MEA internal structure to allow the reaction to proceed. Also, since cooling in an open cathode is usually is accomplished via air flow enough air must be provided to maintain thermal balance, as well as O2 supply and water removal. However if too much air flow is provided the cell may dry out reducing performance. The design must balance and control these factors to provide required performance.

4.1.3 Bipolar Plate Process

Thin metallic plates being formed onsite for use as fuel cell flow fields has been the goal of this program from the beginning. Mass savings experienced due to small, thin, foil-based plates is required for integration into UAS airframes and further market adoption. Several challenges were encountered during early prototyping phases, leading to material upgrades and process changes to better form the required plates. Figure 34 illustrates an updated metal BPP forming process developed over the course of this project and is now being implemented at Infinity's facility.

Figure 34 Flow Field Fabrication Process

All flow fields required for one complete fuel cell stack build have been through first press, annealing, and second press. Four samples (2 anode, 2 cathode) have been plated and sealed, see Figure 35 for example of each. The plating process is nickel-based and designed for stainless steel components in commercial markets where price-sensitivity is of prime concern. Initial conductivity measurements, prior to single cell testing, indicate that this plating process may not be appropriate for fuel cell use. These nickel-plated flow fields will be used in functional single cell testing to determine efficacy of the plating. Other plating options have been explored and are currently being assessed further in parallel with single cell testing of finalized fuel cell components.

Figure 35 Nickel Plated Flow Fields - Anode (L) - Cathode (R)

4.1.4 Sealing Material Testing

Utilizing materials in the Shore 00-65 to A-35, Infinity performed preliminary testing of possible stack sealing materials in association with a local manufacturer. This FIP material was deposited on sample 316 stainless steel strips using a pneumatic applicator and then cured using a UV-A light across varying application widths and cure times. Figure 36 is a representative example of test samples of gasket material that was deposited, cured, and pressed to varying thicknesses, some of which were brought to failure.

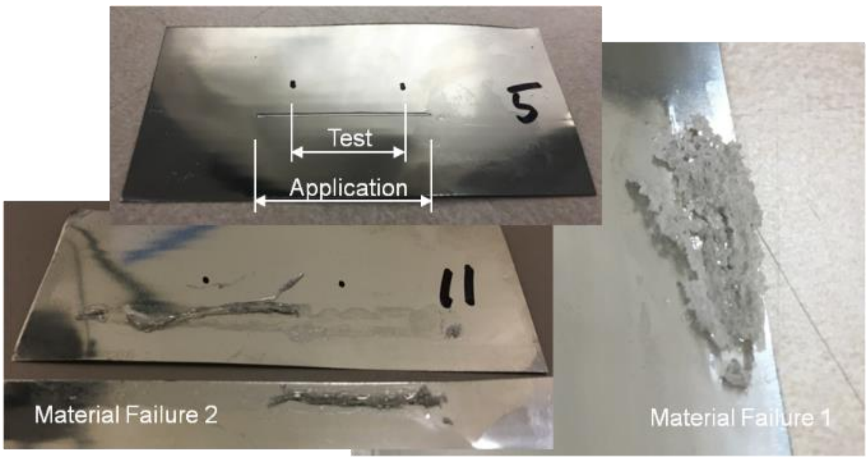


Figure 36 FIP Gasket Material Test Samples

All testing was performed with knowledge of, and use of, the formulas derived for such products per the American Society for Testing and Materials (ASTM) D395, Test Method B. See figure 37 for formula definitions.

Compression set (ASTM D395, Test Method B)

$$C_B = \frac{(t_0 - t_i)}{(t_0 - t_n)}$$

$t_0 = \text{specimen initial thickness}$

$t_i = \text{specimen final thickness}$

$t_n = \text{spacer thickness}$

Deflection (IFC test definition)

$$D = \frac{(t_0 - t_n)}{t_0}$$

Recovery (IFC test definition)

$$R = 1 - \frac{(t_0 - t_i)}{t_0}$$

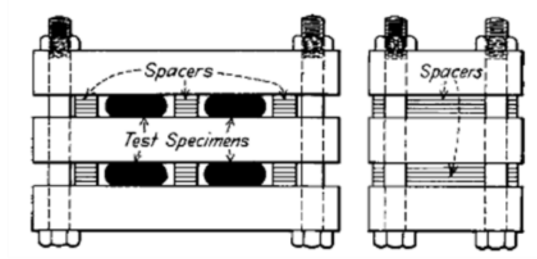


figure 37 Seal Material Testing Definitions

Figure 38 represents a cross sectional view of the applied gasket with respect to an embedded gasket groove on a fully formed BPP.

Modulus of Elasticity

$$E = \frac{\sigma}{\varepsilon}$$

$\sigma = Stress$
$\varepsilon = Strain$
$E = Young' Modulus$

Strain

$$\varepsilon = \frac{\Delta l}{l_0}$$

$\Delta l = Change\ in\ length$
$l_0 = Initial\ length$

Stress

$$\sigma = \frac{F_n}{A}$$

$F_n = Normal\ force$
$A = Area\ of\ sealing\ surface$

Normal force required for compression

$$F_n = \frac{E \cdot A \cdot \Delta l}{l_0}$$

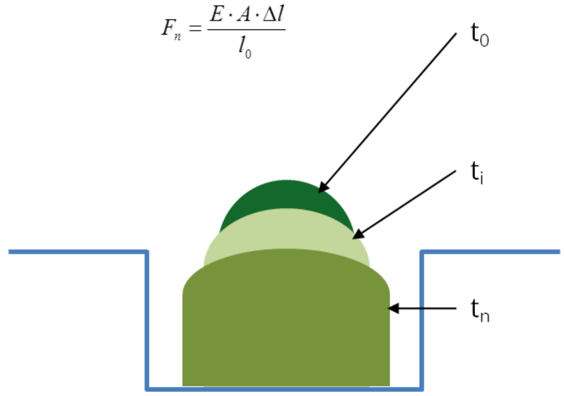


Figure 38 Mechanical Property Definitions for Seal Material in Sealing Groove

The test effort on the sealing material confirmed data as suggested on data sheets of each material. Compression set, as seen in Table 13, closely approximates theoretical. Furthermore, it was learned that these results could be obtained over a fairly wide range of application variables.

Table 13 FIP Gasket Material Sample Testing

DATE	Sample No.	CURE (s)	TIP (Ga)	RUN (press)	POSITION	t_o	t_i	t_n	C_B	Def	Rec
9/14/2017	10	2.0	18	7	1	0.016	0.015	0.006	10.0%	45.5%	95.5%
9/14/2017	10	2.0	18	7	2	0.016	0.016	0.006	0.0%	45.5%	100.0%
9/14/2017	10	2.0	18	7	3	0.016	0.016	0.006	0.0%	45.5%	100.0%
9/14/2017	10	2.0	18	7	4	0.019	0.018	0.006	7.7%	52.0%	96.0%
9/14/2017	11	2.0	18	8	1	0.013	0.012	0.006	14.3%	36.8%	94.7%
9/14/2017	11	2.0	18	8	2	0.015	0.014	0.006	11.1%	42.9%	95.2%
9/14/2017	11	2.0	18	8	3	0.015	0.014	0.006	11.1%	42.9%	95.2%
9/14/2017	11	2.0	18	8	4	0.016	0.015	0.006	10.0%	45.5%	95.5%

Once all flow fields are plated, they are returned to Infinity for deposition of sealing material. Infinity has invested in an FIP gasket machine, see Figure 39, outside of this program for use in applying sealing material across all of its fuel cell stack components.

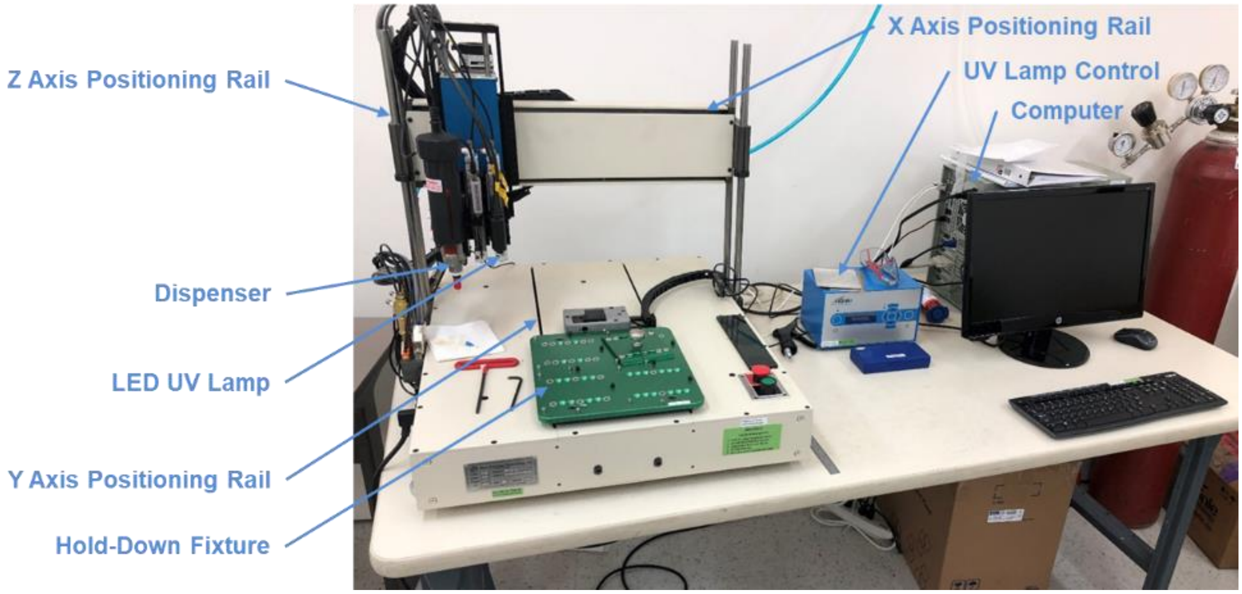


Figure 39 Robotic Dispensing System for Seal Application

Each flow field in this design configuration requires sealing on at least one surface once the part is plated. The anode flow field is sealed on two sides; the cathode flow field is sealed on one side only. In addition to sealing the flow fields, each manifold is sealed on one side, providing a gasket between the manifold and the side of the fuel cell stack. The process for applying seals to one side of a flow field is shown in Figure 40. The flow field sealing process is as follows: 1) Prepare fixture to receive flow field; 2) Align flow field plate; 3) Apply magnetic hold-down to secure plate to fixture; 4) Dispense sealing material; 5) An additional step after seal application is the UV cure, which follows the same path as the applied sealing material.

Figure 40 Robotic Dispensing of Sealing Material on Flow Field

Seal placement on the formed plates has been designed to achieve proper gasketing to contain reactant and prevent leakage into the opposite flow field during operation. The critical locations for gasketing are the H2 inlet and outlet regions. These gasket regions are crucial to keep the hydrogen contained within the anode flow field and sealed against the appropriate manifold sections. Establishing the dispensing path both at the edge of the plate and inboard, forming a parallel run of sealing material, is critical in providing stable compression and leak-free operation.

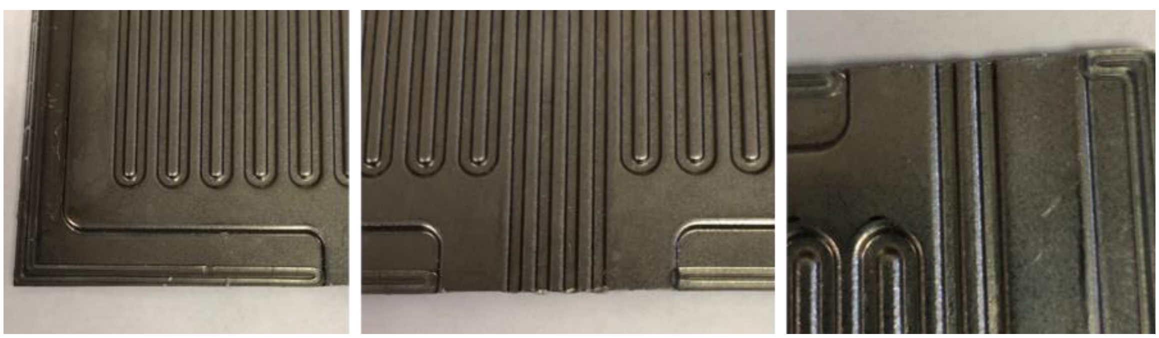


Figure 41 Anode Flow Field Channel and Sealing Detail

Once sealed, flow fields are stacked to form BPPs and combined with MEAs to form repeat elements within a complete fuel cell stack embodiment.

4.1.4 MEA Fabrication and Test

In order to achieve a low-cost factor in the current fuel cell stack design, the exploration of in-house manufacturing of MEAs is required. The first step to locking in a final encapsulated MEA design is to finalize parameters for the hot-pressing of the Gas Diffusion Electrode (GDE) to the raw Nafion® membrane. This 5-layer MEA will then be placed within a laminated plastic frame, providing both a sealing surface and hard stop for assembly.

4.1.4.1 Coupon Samples – Initial Fabrication and Testing

To determine optimal parameters for hot-pressing the GDE and Nafion®, multiple tests and press iterations were conducted using a 12 cm^2 single cell stack developed at WNEU, Figure 42. Due to its small size, it allowed for quick turn-around times in terms of hardware setups, builds, disassembles, etc. and kept material cost to a minimum. The serpentine flow channels for the stack are machined into graphite plates, with a 1 mm^2 square channel geometry for the cathode and 1 mm x 0.8 mm channel geometry on the anode side.

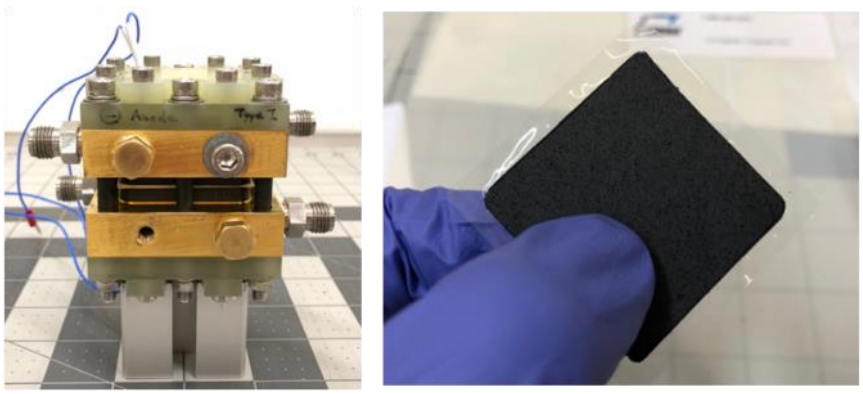


Figure 42 WNEU 12 cm^2 Single Cell and Hot Pressed MEA

The experimental setup used in the hot press procedure for MEAs consisted of an in-house hydraulic press, machined hot press platens, and heater control boxes to regulate platen temperature. Figure 43 shows this experimental setup, with hot press platens mounted to the hydraulic press and heater cartridge control boxes to the right. All of the 12 cm^2 MEAs for testing were assembled on this setup, as well as future MEAs to be used in the final 90 cm^2 stack.

Figure 43 MEA Hot Press

Parameters such as temperature and pressure were adjusted for each MEA build and test, and a baseline of 2 minutes per press was followed. Tests were conducted on both papers based and cloth-based GDE. Multiple hot-press temperatures and pressures were tested by running each hot-pressed MEA through a number of polarization curves. Table 14 provides an overview of hot press parameters for each test.

Figure 44 shows the fuel cell lab testing station (on loan from Infinity Fuel Cell) at

Table 14 Hot Pressing Parameters by Test ID

ID	Date	Material	Ttop Meas	Tbot Meas	Pressure	Press Time
			C	C	psi	mm:ss.ss
A-1	12/6/2017	GDL-CT	100	103	1,240	02:00.90
A-2B	12/12/2017	29BC	80	80	500	02:00.79
A-3	12/13/2017	29BC	57	60	660	02:02.83
A-4	12/19/2017	29BC	97	97	550	02:01.42
A-5	12/20/2017	GDL-CT	100	100	495	02:01.91

WNEU. This test setup was used to conduct break-in procedures on newly assembled MEAs along with collecting performance data from polarization curves for comparison and characterization. A heater control box-maintained fuel cell temperature at 70°C and the Scribner 850C test stand pre-heated the reactant gasses to that same 70°C. Hydrogen and air were used as reactant gasses in order to mimic conditions that the full-scale fuel cell will be subject to. The 12 cm^2 stack was brought online with a preliminary nitrogen purge for 20 minutes, followed by either wet or dry reactant gas. A dry startup was performed for MEA test A-3 and every subsequent test thereafter in order to once again mimic real-world operating conditions.

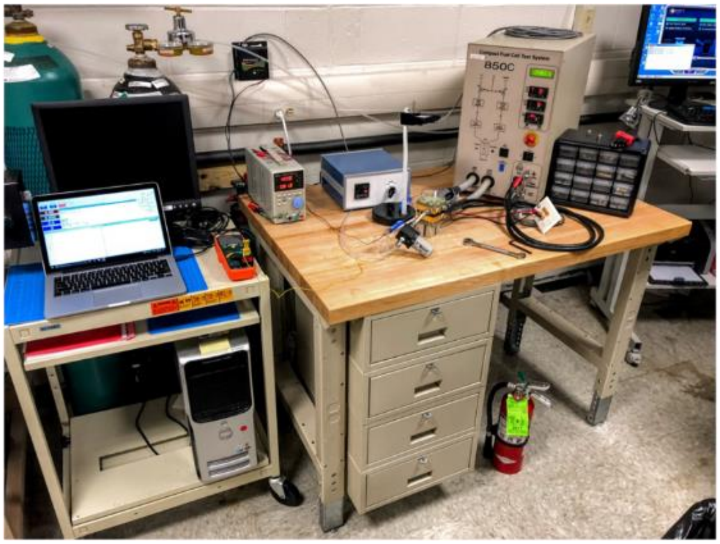


Figure 44 WNEU Fuel Cell Lab Testing Station

The data in Figure 45 illustrates the results of the MEA testing. Based on these polarization curves, it can be seen that as pressing temperature increased, so did the performance of the cell. It was concluded that the temperature has a stronger role in good adhesion and bonding between the membrane and GDE rather than pressure. The far extremes for pressure and temperature were not explored in this testing matrix, as schedule limitations are a controlling factor; however further testing and research will be conducted as an internal research and development activity to determine the points of diminishing return for each parameter. The 2-minute press time also remained unchanged throughout the tests, and is another variable that will need to be explored in further research.

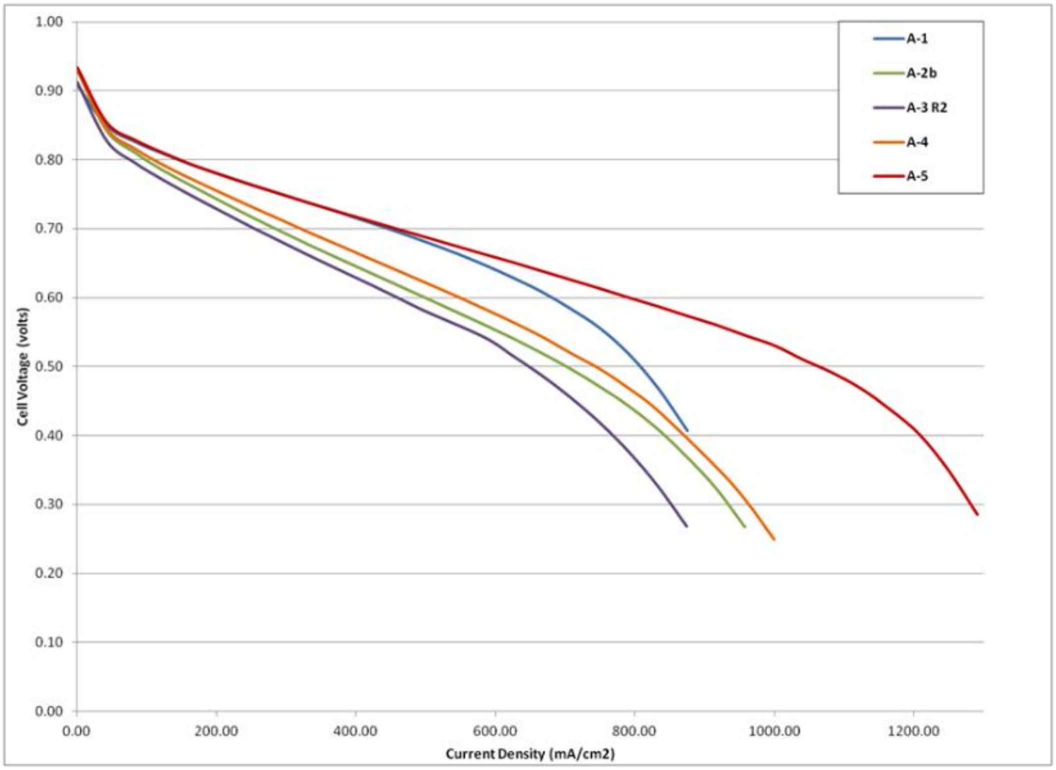


Figure 45 Polarization Curves for Each Hot Pressed MEA Test

From the data presented, A-1 and A-5 provided the most favorable performance characteristics, most likely due to the properties of the GDL material employed. The early onset of the concentration loss region of the POL curve for A-1 were likely due to over-compression in the GDL, leading to reactant gas flow restriction. By reducing the compressive pressure used during the hot press, much higher performance was achieved as seen in the A-5 test data. Further testing is planned to find the maximum performance curve with respect to hot-press pressure, however for the purposes of current product development, scaled up estimates using A-5 data show adequate performance while still maintaining performance margin.

4.1.4.2 Full Scale MEA Prototyping & Manufacturing Preparation

In parallel with MEA coupon testing, preliminary plastic frame material testing was performed. Matching material thickness to GDL thickness is of prime importance when developing an air-breathing MEA. Early testing involved proper lamination of plastic and adhesive layers to form the appropriate lamination around the Nafion® and GDL materials.

MEA assembly steps have been established and prototype manufacturing tooling files and drawings have been created. As seen in Figure 46, the assembly process for a fully configured MEA includes layup of soft materials, hot pressing of these soft goods, layup of hot pressed soft goods within a layup of hard frame materials, and rolling of all layers. This is a generally well-established process within the fuel cell community. However, the unique aspect for Infinity, and all companies employing it, is in the particular material and process recipes developed. For Infinity, the goal in processing MEAs onsite was cost reduction. The performance of these MEAs, discussed elsewhere in this report, was acceptable for further development of fuel cell power systems for drones.

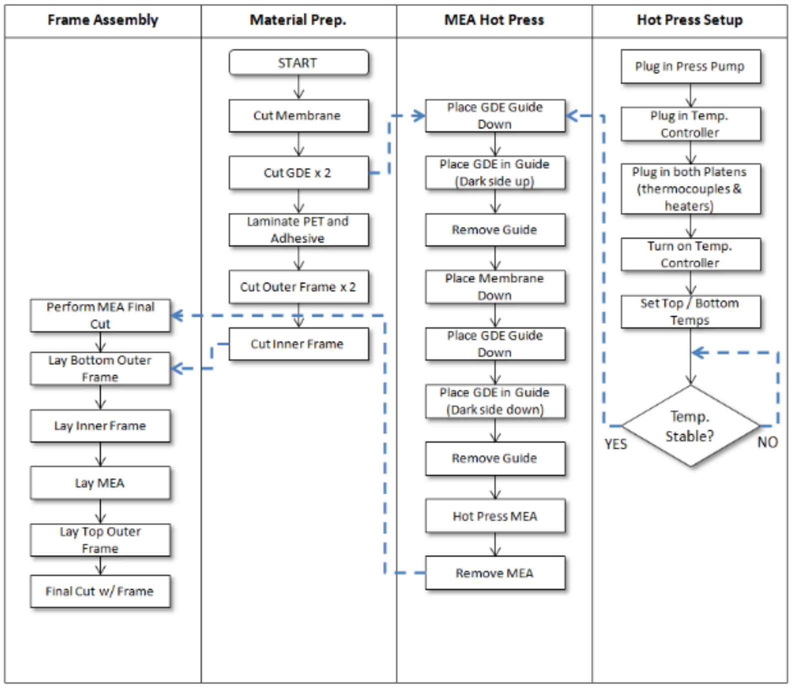


Figure 46 PEMFC MEA Manufacturing Process

Initial full scale MEA fabrication was completed utilizing in-house hot press, die cutting press, and steel rule dies, Figure 47, for cutting various soft and hard goods. While this

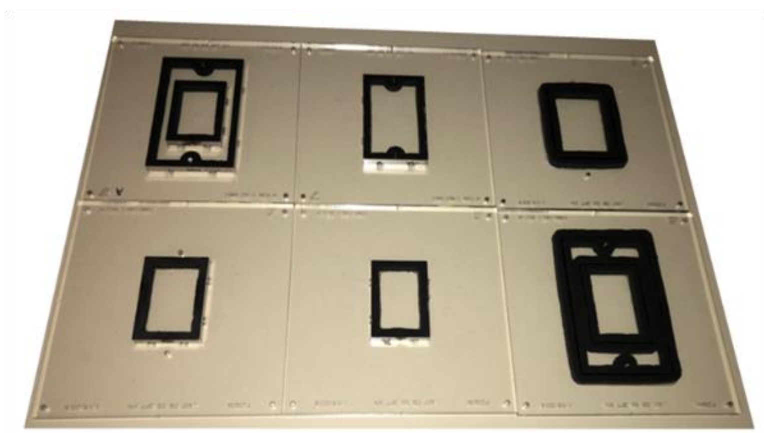


Figure 47 Steel Rule Dies for MEA Fabrication

early processing suffices for the initial development, a midterm solution is necessary for full scale low volume production. To this end, a Mobile Manufacturing Cart (MMC) concept has been envisioned by the Infinity team, Figure 48. This assembly cart is designed to hold all materials and tools used in the assembly of MEAs in roll form, while providing the convenience of navigating between pressing and cutting stations within the Infinity facility. This may provide a convenient intermediate platform for future production needs.

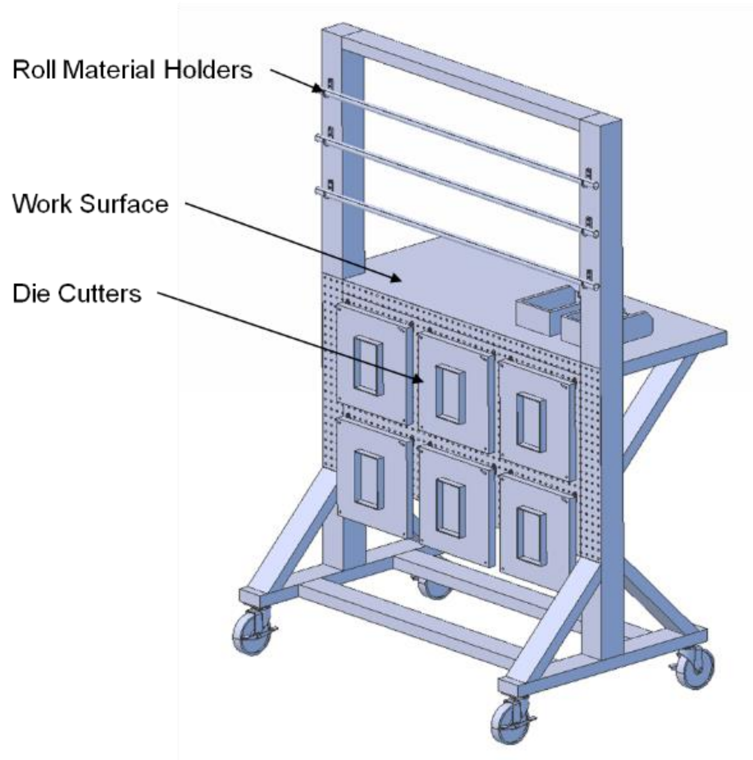


Figure 48 Mobile PEMFC MEA Manufacturing Cart

First assembly of full scale MEAs proved to be challenging. The first full scale MEA (FS1) was assembled entirely according to the process developed prior. The soft goods comprised of the Nafion® membrane and the Gas Diffusion Electrode (GDE) were hot pressed separately and then place within hard plastic framing materials during assembly. The GDE is comprised of GDL material with a catalyst applied to one side ready for hot pressing. Unfortunately, during the assembly process the hot-pressed soft goods moved underneath elements of the hard-plastic framing material, producing ridges at the GDL/frame interface, see Figure 49. This ridge prevents complete contact between the flow field and the GDL which will reduce electrical conductivity in the cell, resulting in poor performance; some of these ridges can be seen on the left side of the image. The black area in the center of the MEA is the active area comprised of the membrane, GDLs, and catalyst layers. The outer white colored perimeter is the hard-plastic frame comprised of multiple layers of thin plastic and adhesive. The overall size of the frame is much larger than the final product and is designed to fit within the two stainless steel halves of the single cell test article.

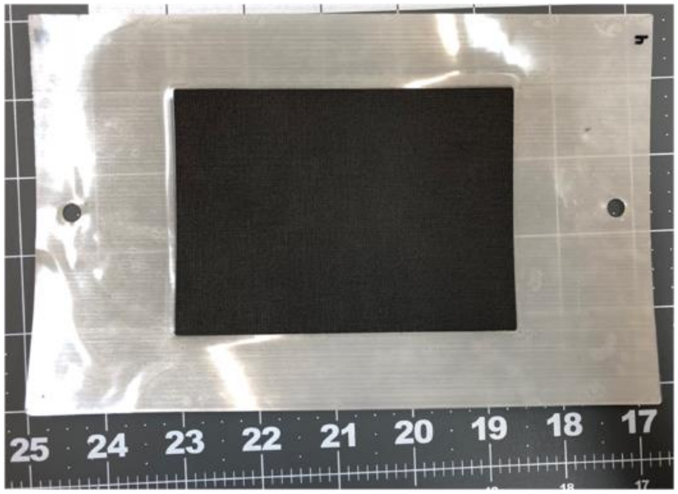


Figure 49 Full Scale MEA First Fab (FS1)

An additional full-scale hot press attempt was made after FS1. The process for manufacturing FS2 was changed slightly in that the soft goods were dry fit along with the hard goods and hot pressed as an entire assembly. This was done to accommodate a simpler assembly process at the expense of providing a lower pressure and temperature to all the components during the hot press. The resultant MEA is shown in Figure 50 and represents a much better press, with no overlapping and ridges.

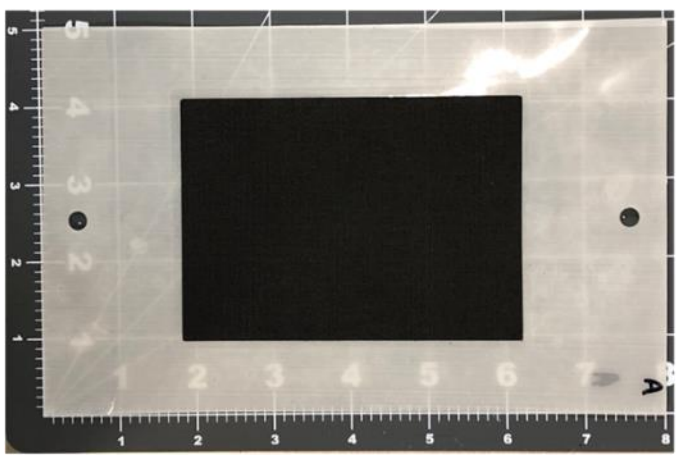


Figure 50 Full Scale MEA Second Fab (FS2)

These full scale MEAs have undergone testing in single cell hardware to prove out performance of the MEA itself, as well as the flow field design chosen for this application.

Full Scale Testing - Initial

Prior to ordering tooling and material for a complete fuel cell stack, a full scale, 90 cm2, single cell has been tested under the same conditions as the coupon tests. To minimize variables during this testing, and maximize obtained test data, robust 316 stainless steel flow field plates have been acquired which have reactant flow channels machined in place to Infinity's specifications, see Figure 51. Testing will be iterative, as necessary, to prove out the flow field design, which will then be incorporated into the ultimate metal foil BPP design and tooling.

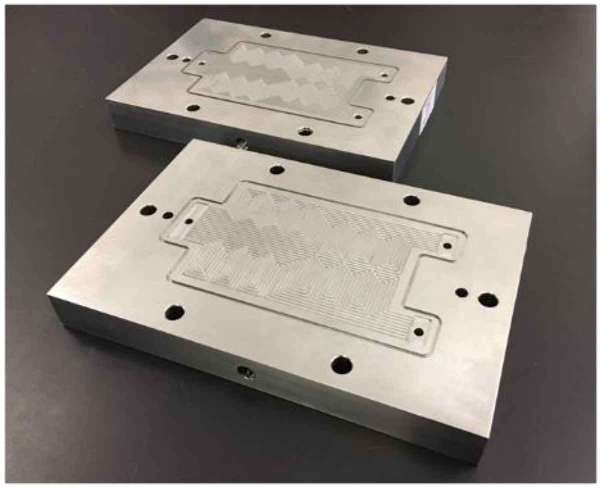


Figure 51 Full Scale Single Cell Flow Field Plates

Initial testing of the full scale MEAs discussed earlier was not successful. Since both MEAs (FS1, FS2) were compromised, good results were not expected across the entirety of a polarization curve. Also, flow rates were not well established for this particular design, leading to what is believed to have been dry out of the membrane. There were no failures of components during testing, however, startup of the fuel cells was never fully achieved due to lack of wet up across the MEA. Wetting up the membrane is critical to fuel cell performance, as water is necessary to achieve the electrochemical process.

Coupon Testing – Final

Through the course of initial coupon tests flow schemes and rates were established for each cell and compared to initial design analyses. The final set of coupon tests were utilized for startup evaluation of the MEA, as well as comparison to competitor's products. Figure 52 indicates performance of various coupon tests run both with and without humidification of the MEA during initial startup. The A5 version of the coupon test dominates over performance of similar membranes hot pressed at various pressures. A5 also performs above competitor A (listed in the figure as COMP A), yielding sufficient voltage and current density to satisfy the power objectives of this program.

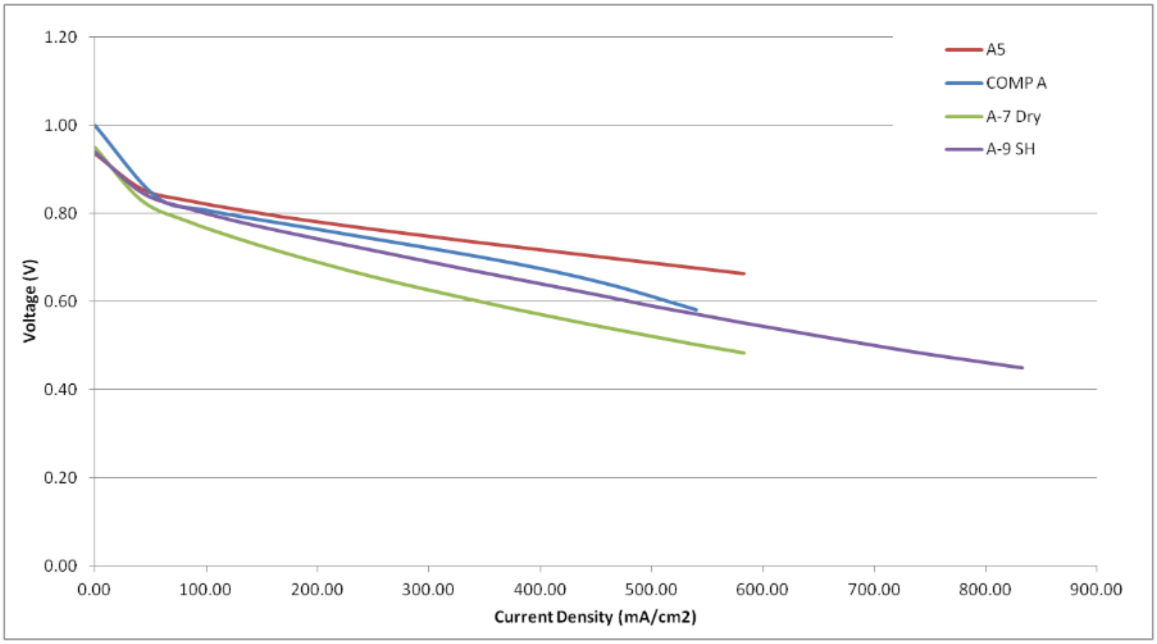


Figure 52 Second Round of Coupon Testing

All of the coupon testing was done using a Scribner fuel cell test station with electronic load and mass flow controllers. Humidification of the reactants was eventually turned off over the course of testing to simulate a dry start of the fuel cell (as would be the case for fuel cells produced in volume). One issue with the test station, however, was the introduction of water vapor through the test station plumbing, thus yielding slightly humidified reactant when the non-humidified reactant option was selected. Since testing of the ultimate fuel cell product will require dry reactant inlet conditions, dead ended anode (DEA), and blower supplied air, we began weaning the small-scale testing from direct test station reactant feed during this second round of testing.

DEA operation of the fuel cell in the field is the norm for other hydrogen/air PEMFCs, as this allows for hydrogen to be available at the catalyzed membrane for immediate uptake of load. DEA operation, however, requires periodic purging of the anode during operation, particularly when running on ambient air as nitrogen will diffuse across the MEA and accumulate in the anode. This purging serves to remove anodic contaminants, thus increasing performance of the fuel cell. Purging also increases hydrogen consumption slightly, driving the stoichiometric rate above 1.

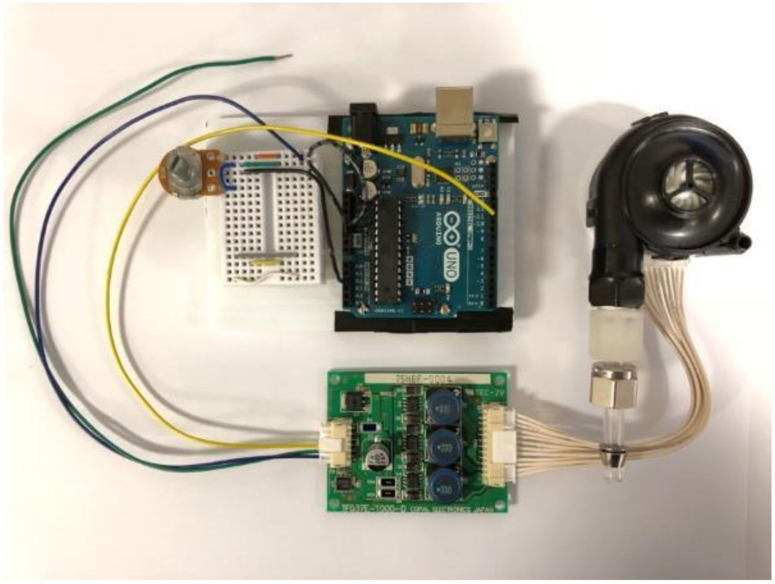


Figure 53 Miniature Cathode Feed Blower with Arduino PWM Control

Cathode side air supplied by a small blower in the ultimate fuel cell product will need to conform to predetermined stoichiometric rates during startup and variable load operation. Further, the supply of ambient air can vary depending on altitude and local quality. To better duplicate the operation of the fuel cell in the field, the Nidec blower discussed earlier was employed during lab testing. PWM control of the blower during early testing was performed manually given the very low flow rates we were running on the 12cm^2 test article. For larger active area testing, a control algorithm was employed for PWM control via an Arduino based controller to establish proper stoichiometry over a broad range of operation, see Figure 53.

The chart in Figure 54 illustrates one of our last tests, A9, for which we utilized the fuel cell station for its electronic load capability only; relying on hydrogen fed directly from a tank to satisfy DEA, and blower supplied cathode air. The figure indicates reasonable performance over a standard polarization curve under the listed conditions. Also shown are respectable cathode stoichiometric rates. Based on previous testing, the parasitic losses associated with higher cathode flow rates provided by the blower are negligible.

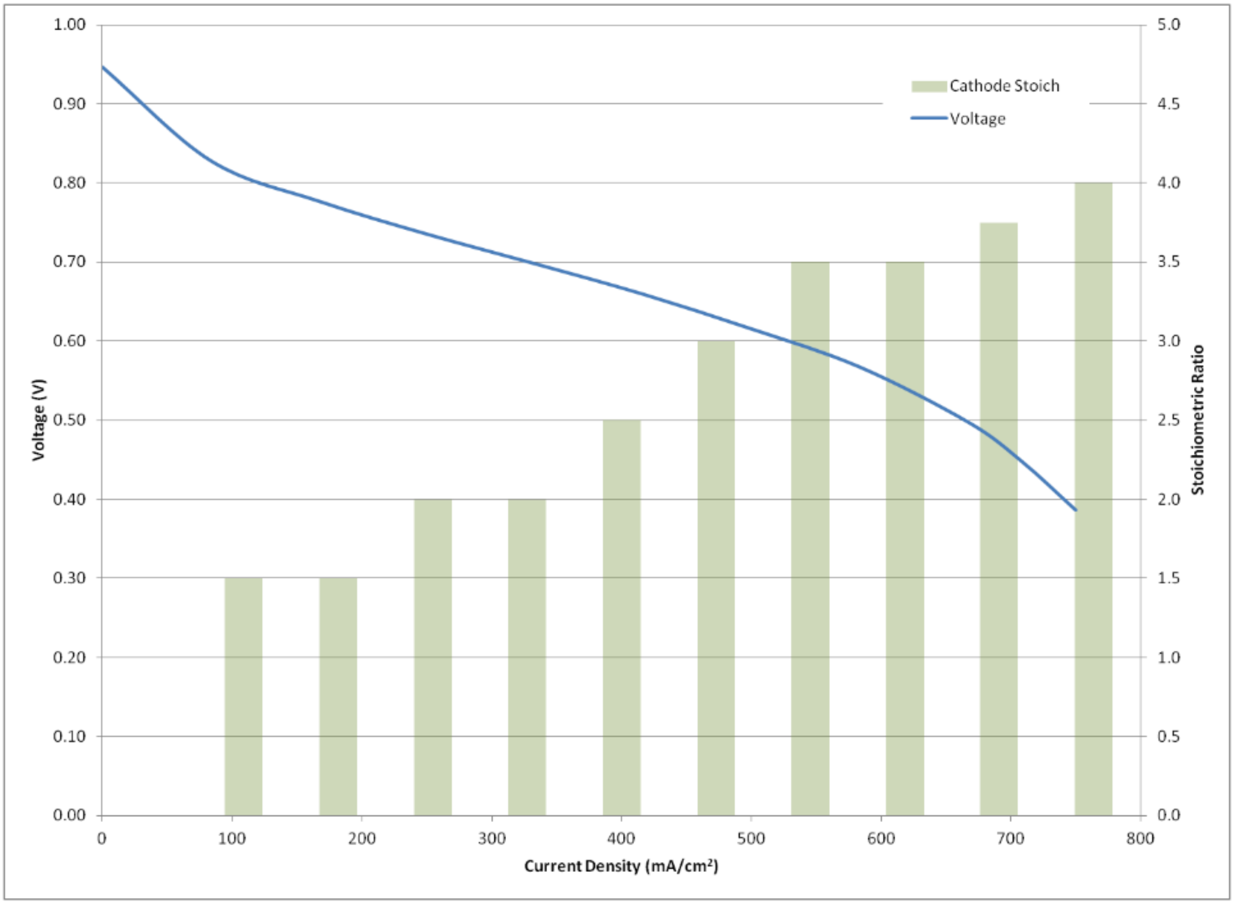


Figure 54 Coupon Test of Dry Anode Feed and Blower Supplied Cathode Air

After completion of this final round of coupon testing, a full scale MEA was hot pressed and assembled in the single cell hardware for performance testing. As with the first round of full-scale testing, this next phase helped the team determine the performance of the flow field design prior to placement of the order for BPP forming dies.

4.1.5 Fuel Cell Short Stack Development Manufacturing and Test

The fuel cell stack combines all of the elements discussed above:

- MEA
- Bipolar Plate
- Sealing
- Coating
- Reactant Flow

Into one functional unit able to receive reactants and generate power. The pathway to development of this stack is to design and build single cell/and or short stack hardware then increase the number of cells to the required full prototype design once short stack testing confirms proper operation.

The integration of these individual components into an operating stack is often the most challenging stage of a new fuel cell system. The stack brings together electrical, chemical, mechanical, fluidic, thermal and other factors into one functional subsystem.

This section details the initial design approach and results of short stack fabrication and test and modifications required to support full scale prototype manufacturing and test.

4.1.5.1 Initial Stack design and manufacture approach

The nominal fuel cell stack voltage was established by the requirements as a 28 VDC average output over its lifecycle. Lifetime of the stack itself was estimated to be between 1,500 and 2,000 hours. To meet these requirements the fuel cell stack, see Figure 55, is configured as an edge-fed, 50 cell, 90 cm^2 active area, product with a design maximum output power rating of 1.5 kW. While single cell testing to date had been performed with actual MEA configurations using machined plates, fully formed thin metallic foil flow fields were planned to be tested together with the final MEA configuration as part of the stack development testing. Modifications to materials and processing would be made as necessary based on these tests.

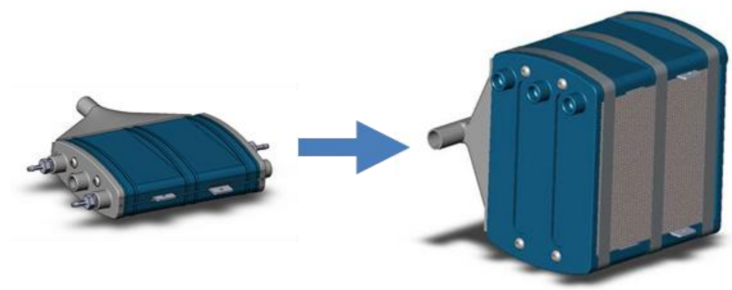


Figure 55 Single Cell Test Platform Leading to Full Scale Stack

The initial design stack was to have all stackable hardware held together with 2-3 metal bands running around the outer surface of all components. This is a proven, cost-effective method for securing all components in a stacked configuration while also providing adequate internal compression for the Gas Diffusion Layers and providing proper electrical conductivity through the fuel cell stack. A similar configuration is used by various other fuel cell stack manufacturers.

A simple fixture (left side of Figure 56) was developed to allow the components to self-align in a corner while being placed on the stack. This fixture allows the straps to be applied and tensioned while the stack components are in the stacking fixture.

The compression strapping of the fuel cell is an easily reproduced assembly method that lends itself to larger volume production. The strap is made of stainless steel, cut to length, and held tight with a clip. The strap has approximately 1 inch folded back over onto itself. It is passed through the clip, allowing the bent-over portion to lay outside the clip on its bottom face. The strap is then passed around the stack and passed back through the clip (middle of Figure 56). The tensioning tool (right side of Figure 56) is then attached and the handle is screwed down, applying tension to the strap. When full tension is achieved, the tensioning tool is moved to fold the strap back over the clip.

The hydrogen inlet and outlet manifolds can be seen in Figure 56 (M) as the plastic

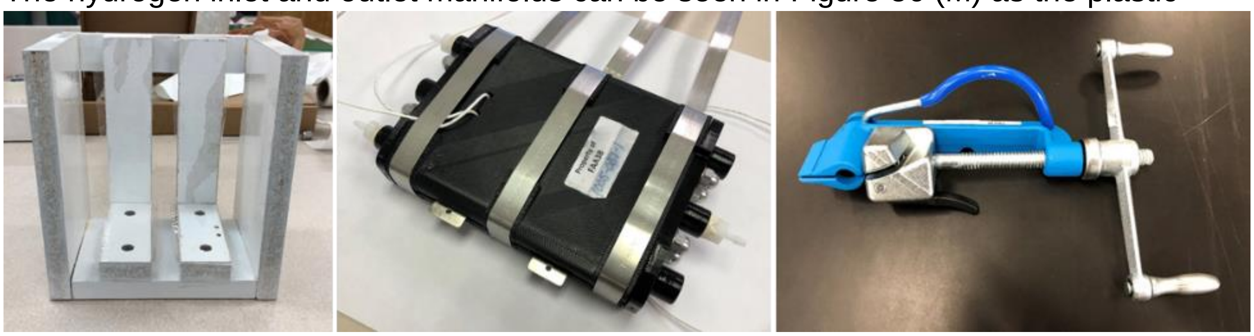


Figure 56 Stack Assembly Fixture, Assembled Single Cell, and Tensioning Tool (R)

components containing three bosses each. All the plastic hardware – 2 end plates and 2 manifolds – were 3D printed in ABS plastic. While the end plates are held in place by the aforementioned metal straps, the manifolds are held in place with small diameter threaded rod running the length of each side of both end plates and acorn nuts.

4.1.5.2 Results of short stack testing

A full scale MEA was manufactured to the design previously tested with the machined flow field. Seals were applied to the bipolar plates and the manifolds and the short stack was assembled using the metal strapping configuration shown above. Several issues became evident:

1) First, the ABS 3-D printed H_2 manifolds were found to be both permeable to H_2 gas diffusion and difficult to seal to the edge of the single cell stack.

Corrective action: To address this issue metallic manifolds were manufactured that would not allow diffusion of the H_2 and facilitate edge sealing.

2) After the new H_2 manifolds were installed single cell testing commenced using the Scribner test system and the single cell Arduino controller. Operational testing indicated performance substantially below expectations. Further testing indicated the possibility of inadequate internal cell compression. To determine if this was the cause, the single

cell was disassembled, the MEA was removed and pressure sensitive measurement paper was placed in the MEA location and the cell was reassembled using the strapping method. After assembly and compression, the measurement paper was removed and inspected. Inspection indicated poor internal compression leading to high interfacial contract resistance.

Corrective Action: An assessment of the load train indicated that the 3D printed endplate and the strapping mechanism were not able to provide adequate in-cell compression. A revised load train was designed and fabricated using conventional metallic endplates, ties rods and compression Belleville washers. Versions were manufactured suitable for both the single cell and 50 cell stacks.

While the strapping mechanism is widely used in fuel cell manufacture further review of the implementation on this stack indicated more detailed design analysis and development was required than available within remaining program resources. Also, since the primary purpose of this stage of testing was verification of fundamental operation of the cell and stack, use of a conventional load train minimized development variables.

3) Testing of the single cell resumed using the revised manifolds, endplates and tie rod configuration. Internal compression was as planned and testing at lower power levels replicated single cell testing of coupons and in machined plates. However, testing at higher power levels indicated dry out in the MEA. A humidification device was added to provide at least partial humidification of the inlet cathode air. With this is in place, testing resumed and achieved successful operation of the single cell using the formed bipolar plates, figure 55.

Corrective Action-Dry Air Operation: While operation was successful the design is based on operation with dry air with self-humidifying MEAs not an external humidifier. Further investigation of previous successful coupon testing indicated the Scribner test equipment may have had residual moisture present that provided a degree of humidification. After further review Infinity determined that the membrane was suitable for dry air operation but the GDLs could be further optimized to retain moisture within the cell. Moisture retentive GDLs used in similar applications were identified, selected and purchased however they were not able to be integrated into the test program within the available schedule. This is a planned future IRAD or other effort.

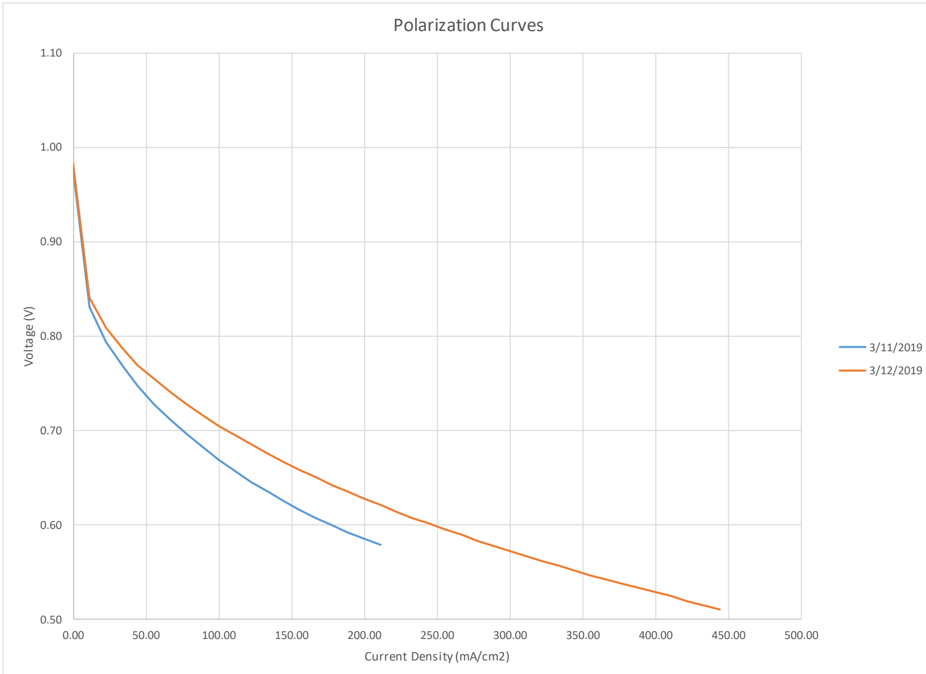


Figure 57 The Full Area Single Cell Met Initial Performance Goals

After achieving successful single cell testing the next step was to assemble and test the 50-cell prototype cell stack. Prototype stack manufacture is detailed in Section 4.2 and testing is detailed in Section 5.

4.1.6 Controls

The control of the fuel cell stack and safe operation of hydrogen delivery was accomplished via an Arduino control board. Several of the control algorithms to be employed in the overall control system architecture have already been developed over the course of single cell testing. Arduino was chosen as a developmental control's platform due to ease of use, quick-turn modification potential, and low cost. This controller has satisfied all testing to date and is projected to satisfy prototype system demonstration as well.

Once coupon testing was completed at WNEU, full scale testing commenced on Infinity's fuel cell test stand. Having a test capability of 500 W, this stand is capable of testing single to multiple full-scale cells, or short stacks, for further prove-out once all MEAs and BPPs are fabricated, and prior to assembling the complete fuel cell stack. Combinations of several flow field types were tested on both anode and cathode sides of Infinity's MEA to prove out analytical performance modeling. Flow field design is critical to the overall performance, as well as mass and volume reduction of the fuel cell stack.

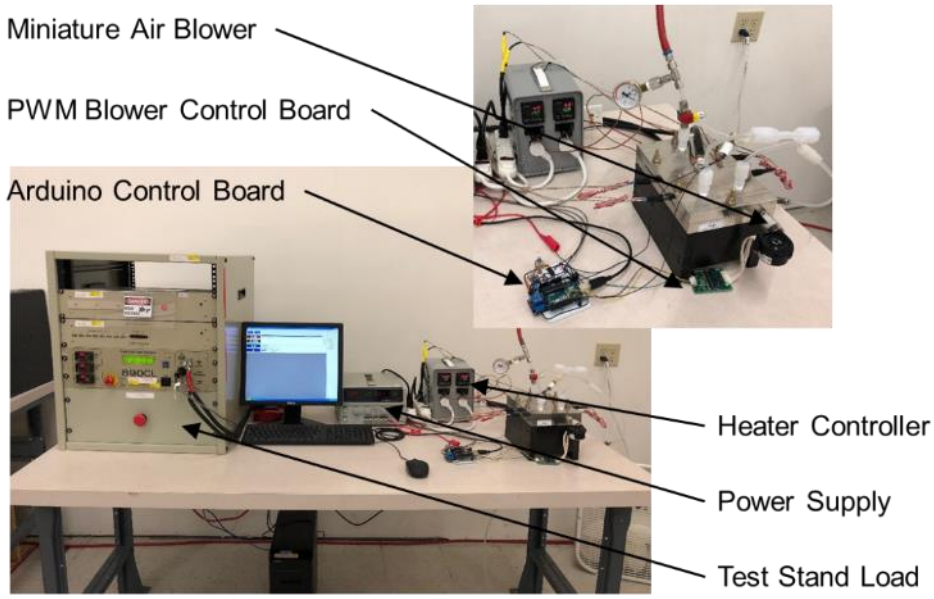


Figure 58 Infinity's 500 W Fuel Cell Test Station

The control system for the single cell testing has been finalized, assembled and tested. The single cell system consists of hydrogen supply and hydrogen vent valves, a Nidec blower for air supply, a relay module, current sensor, and load contactor. An Arduino-based CPU will be used to control and monitor all components and signals. Other signals to be received and monitored by the Arduino are cell stack voltage, battery voltage, and cell stack temperature. A complete system schematic can be seen in Figure 59. All of the signals and controls will be visible and accessible via a GUI.

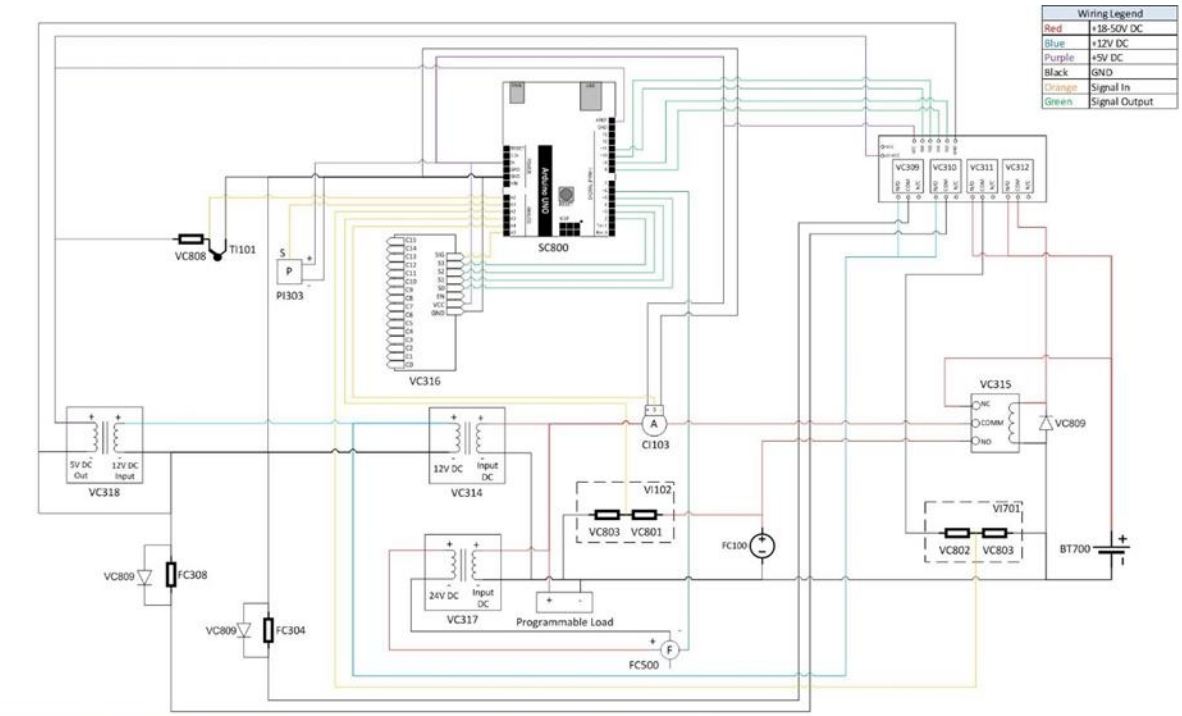


Figure 59 Electrical Schematic for Class II Drone Fuel Cell System

The valves chosen for the hydrogen supply and vent are simple 12-volt solenoid valves with very low power (1 W) consumption. These valves have barbed fittings integrated into the body to reduce weight of any additional required fittings and have a sealing capacity of 50 psi.

The blower to be used for single cell testing has been selected for its simplicity, durability, and air flow capacity. The blower only requires 24 V power and a 0-5 V signal (supplied from the Arduino via the control software) to regulate blower speed. The blower is also capable of air flows up to 100 L/min and thus can be used for much larger builds if necessary.

The relay module consists of 4 opto-isolated relays mounted to a single board. Powered by 5 V these relays are used to send power to the various devices (solenoid valves, contactor, etc.) on the control system. They were selected for their low power consumption (< 0.5 W), and their relay solenoid isolation from the rest of the system.

The power for all the devices in the single cell control system will come from 3 different power supplies: 5 V, 12 V, and 24 V power is required. On the full stack system, these will all be replaced by low power DC/DC convertors and will draw power directly from the battery or the fuel cell.

The GUI has also been updated, see Figure 60. Included now are warning lights to indicate to the operator that certain parameters have exceeded a predetermined warning and/or alarm limit. The system can record data, including fuel cell voltage, battery voltage, current, fuel cell temperature, and hydrogen supply pressure. A live plot of fuel cell and battery voltages provides real-time insight into power system health.

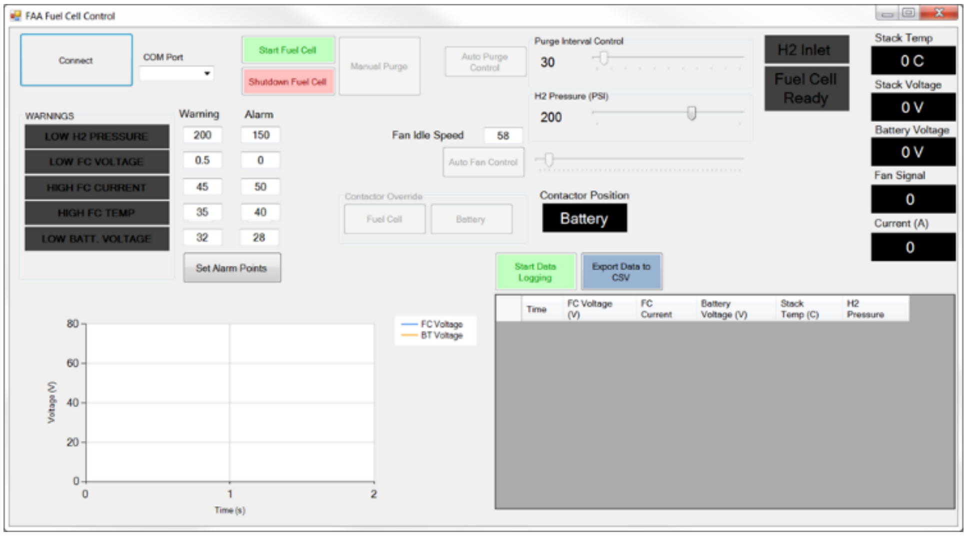


Figure 60 Updated Graphical User Interface (GUI)

For ease of operation, an automated start and shutdown have been pre-programmed into the control logic. Pressing the start button will initiate the blower to supply air to the fuel cell, open the hydrogen supply valve, and vent the stack to remove any air on the anode. Fuel cell stack health will be monitored via voltage sense and, when the stack is ready to accept a load, indicate to the user that the system is ready for operation. The automated shutdown operation initiates removal of power from the blower and hydrogen valves, while also switching back to battery potential via the contactor in the system.

The air blower speed will be controlled manually for single cell testing. Appropriate blower speed versus stoichiometric air reactant requirement will be determined during single cell testing. The data obtained will be used to develop tabular air flow versus PWM signal information which will then be incorporated into the full-scale control logic.

A duplicate control system is being built to use for software development and to have as a backup to the original control system. All of the required components have been ordered and are now in stock. Assembly of the second control system has begun and is expected to finish in early January.

4.1.7 Hydrogen Storage

The design and control of the overall fuel cell system within an aircraft – a drone in this case – requires management of hydrogen pressure, stack temperature, system voltage and current, along with necessary safety measures. The system under development for inclusion in Infinity's Class II drone has been designed to provide proper control and safety while minimizing overall size and weight.

To this end, a single hydrogen tank with attached regulator has been coupled with a small blower or fan to provide both hydrogen and air to the fuel cell stack, Figure 61. In this arrangement, the energy storage system is decoupled from the power system (the fuel cell), yielding opportunity for scalability and flexibility in future UAS and transport aircraft applications. The positioning of the system precludes the use of the payload bay of this particular aircraft, however, future airframe design with dedicated fuel cell integration would open up dedicated volumes for payload use.

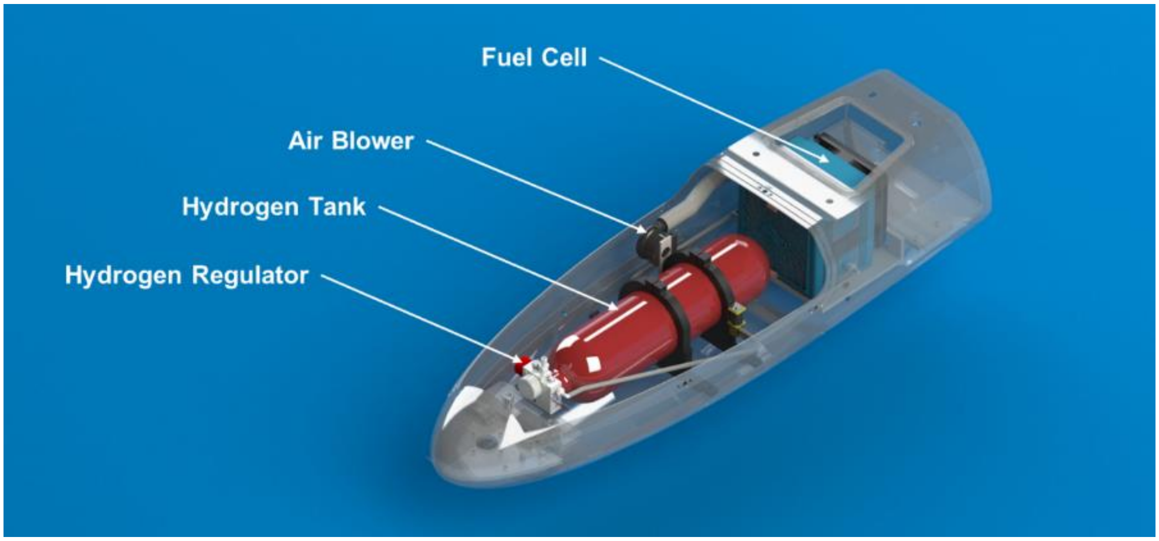


Figure 61 Prototype Fuel Cell System Integration

The housing around the fuel cell system in the image is the fuselage of the Penguin aircraft. This is a pusher prop design, so the electric motor and propeller reside off the flat face located to the rear of the fuel cell (shown in blue). The configuration of fuel cell stack is outfitted with a separate cooling fan and air blower; the configuration to be built may be a single air feed used for both reactant supply and cooling. The control board is not mounted within this image. The hydrogen tank is 4,500 psi capable with an internal volume of 1.6 liters. This hydrogen volume, along with Infinity's fuel cell stack, should provide an average flight time of approximately 1.2 hours, depending on mission profile and flight dynamics. This projected flight time will satisfy benchtop testing and preliminary flight testing. The regulator attached to the hydrogen tank has been designed specifically for the drone market by a supplier to Infinity and therefore has the low mass and volume required for the application

Hydrogen tanks and regulators have been ordered and will be integrated upon receipt. These components have been engineered by a leader in the compressed gas equipment market specifically for the size and weight efficiencies required in the drone market.

The hydrogen storage tank is a Type III (metal liner) Carbon Fiber Overwrap Pressure Vessel (COPV), Figure 62. This particular tank was chosen due to it lightweight materials and pressure capability. The intent of this program is to store the hydrogen at lower pressure than the 310 bar (~4,500 psi) rated working pressure. This tank has a 1.5 L volume, capable of providing enough run time of the fuel cell system to prove out its operation for an extended period of time.

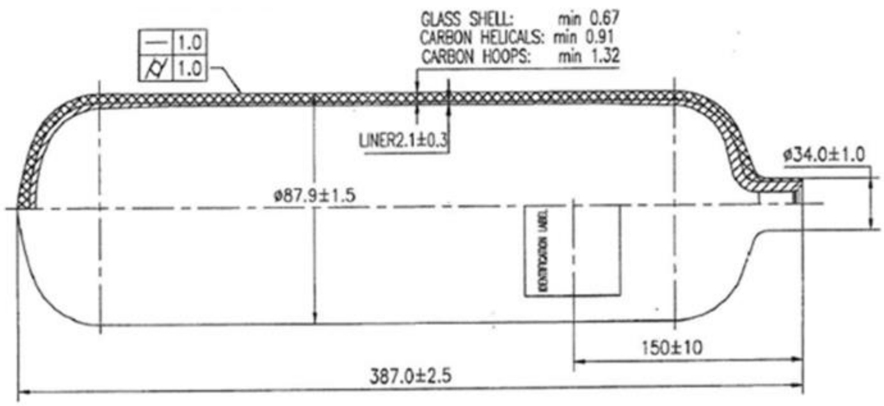


Figure 62 Lightweight Hydrogen Storage Tank

The hydrogen regulator, Figure 63, will be obtained from the same supplier as the tank. This tank/regulator combination was purposely designed and built for drone applications, with reduced mass and volume as a packaged component.

Update: An order was placed in October 2018 for the above equipment. After assurances that the production was on track but with significant delays the vendor informed Infinity in April 2019 they could not deliver. As a result, Infinity utilized in-house stored reactants for all hydrogen testing. The vendor claims that product will be available in the future. Infinity is also seeking alternative sources.

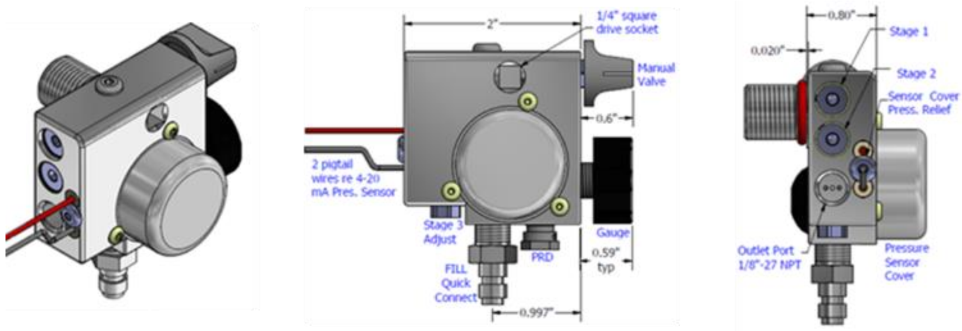


Figure 63 Lightweight Pressure Regulator for Drone Applications

4.2 Full Scale Prototype Manufacturing - Components

Based on the results of component and subsystem development and test as described above manufacturing of the final prototype manufacturing commenced.

4.2.1 Bipolar Plate Manufacturing

As noted in Section 4.1.2 above one set of bipolar plate hardware had been previously procured and several pieces had been nickel plated. Evaluation of this hardware indicated two issues:

1) The vendor that annealed the plates damaged them in process and had contaminated the surfaces

2) The nickel plating was very heavy and indicated lower than planned conductivity

For these two reasons Infinity decided to remanufacture the bipolar plates. A second heat treat vendor was selected and a company specializing in stainless steel fuel cell bipolar coatings was used for the conductive coating. This company had not been used earlier since they are located in Sweden and we preferred to attempt to develop a local source.

Manufacturing with these new vendors was successful. The plates were formed, heat treated and coated as required.

Sealing

As noted in the sealing section above the stack uses a framed MEA and elastomeric seals between that frame and the bipolar plates and edge feed manifolds for stack reactant feed. In this initial implementation of the design we elected to also use elastomeric seals within the two parts of the bipolar plate. In accordance with procedures previously developed elastomeric seals were applied as required onto all of the bipolar plate parts and on manifold assemblies as required.

4.2.2 Endplates tie rods and follow up materials

As previously described the endplate design was changed for this prototype to minimize variables in regard to in-cell loading and compression.

4.2.3 MEAs

MEAs sufficient to support the 50-cell build were manufactured at Infinity. These MEAs, Figure 64, for this build are based on the successful development testing. They are Nafion®-based and fully framed with PET at the outer perimeter. As noted above, the assembly of the MEA follows a GDE-based process and requires hot pressing to properly set catalytic zones.

Figure 64 Final Membrane and Electrode Assembly (MEA)

4.3 Fuel Cell Stack Assembly & System Hardware

4.3.1 Assembly Process

After all of the required components were prepared for assembly, the 50-cell prototype stack was assembled using the stacking fixture described earlier. In that process each cell was placed in the fixture and three sides were aligned to the fixture. In the revised endplate configuration, figure 63, the tie rods were tightened to compress the elastomeric seals to the required dimensions. During the compression process some excess seal material was observed as extruded to the edges of the cells and the force required to compress was higher than anticipated.

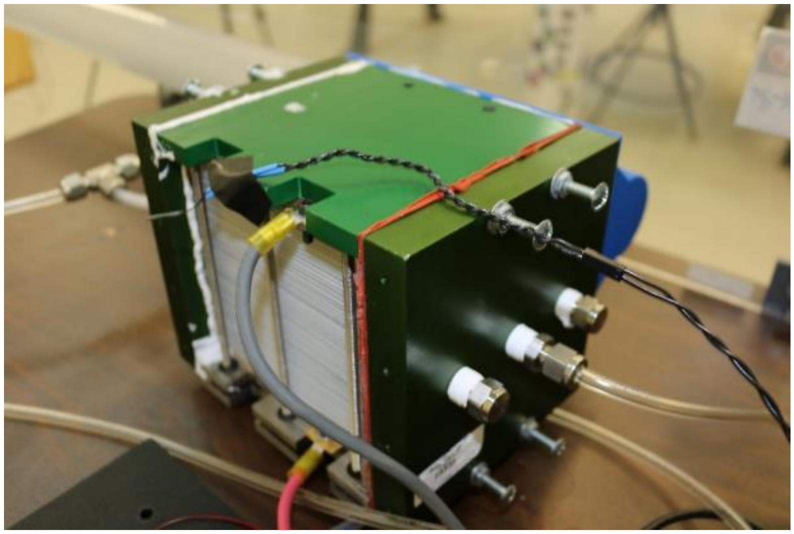


Figure 65 Fully Compressed Prototype Stack on Test

After the stack was compressed the manifold plates were mounted on each end pf the stack and attached to the endplates by machine screw fasteners.

4.3.2 Manufacturing Testing

Prior to operation testing static tests were done to confirm proper overall sealing and electrical impedance of the stack and of each cell. Dry impedances were somewhat higher than anticipated but appeared to be acceptable for initial operation. The excess seal material observed during compression appeared to be partially preventing internal cell loading distribution from reaching planned design levels.

The cells appeared to seal properly however, after this initial assembly some excess leakage was detected from the H2 manifolds. Additional seal material was applied to the manifolds and the rate reduced to acceptable levels for initial performance testing. Improvement of this manifold seal was identified as a future item to correct.

5.0 Performance Testing and Environmental Test Plans

5.1 Prototype Test setup and Plan

5.1.1 Setup

With a goal of 1.5 kW peak power, the prototype test required use of a higher power capable load and the prototype compatible Arduino controller. The following equipment was used, Figure 66, as the test setup for prototype testing.

- TDI Dynaload WCL488 4000-1000-12000 12 kW Programmable DC Load
- Infinity customized Thermatron 8 kW Custom Cooling Cart 935ET2B07
- 24/12 VDC Instek GPS-2303 power supply
- Infinity fabricated- Arduino based control system
- Dell Laptop running custom fuel cell control software
- SAN Ace B97 Model 9BMC24P2G001 Sanyo Denki Air Blower

Figure 66 Prototype Test Setup

5.1.2 Test Plan

This was the initial test of the first build of this prototype. Accordingly, the planned testing focused on fundamental operation:

- Start/stop operation
- Steady-state stability at low loads
- Performance characterization across varying current densities

The test was configured for staffed operation with operator input required to provide power to the control system, select airflow rates, and manually adjust various control parameters such as vent frequency depending on the observed operation. When fully characterized the control system should eb able to allow the system to run in a fully automated manner but our test protocol required staffing for this initial operation and characterization.

5.2 Performance test results

5.2.1 Test Conditions and Initial Performance:

The stack was mounted to the test system the week of May 6, 2019 and testing started.

Initial conditions were:

- H2 Pressure: approx. 16 psia
- Air Pressure to blower: lab ambient
- Stack starting temperature: 25 deg C

The control system was provided with required power and reactants were applied to the stack. The stack polarized as planned and exhibited an average OCV of approximately 900 mV. However, as load was applied the cell voltages exhibited a lower than required response. This had been observed previously in single cell testing however once humidity was added to the air the single cell would wet up and perform to acceptable levels.

The MEAs are fabricated and stored dry however the fuel cell reaction requires hydrated membranes to allow protonic conduction. The MEAs used in this build are designed for dry operation but do need a small amount of initial water production to hydrate and allow current to flow. To facilitate operation a humidifier device was added to the inlet air flow circuit and testing resumed.

5.2.2 Results

With humidified air the MEAs did improve operation but were still below expectations. Open Circuit Voltage, OCV was acceptable and operation up to approximately 100 watts stable however voltages were lower than modeled. The prototype stack was allowed to operate for several days with variations in humidification and increases in H2 supply pressure that did slightly improve performance

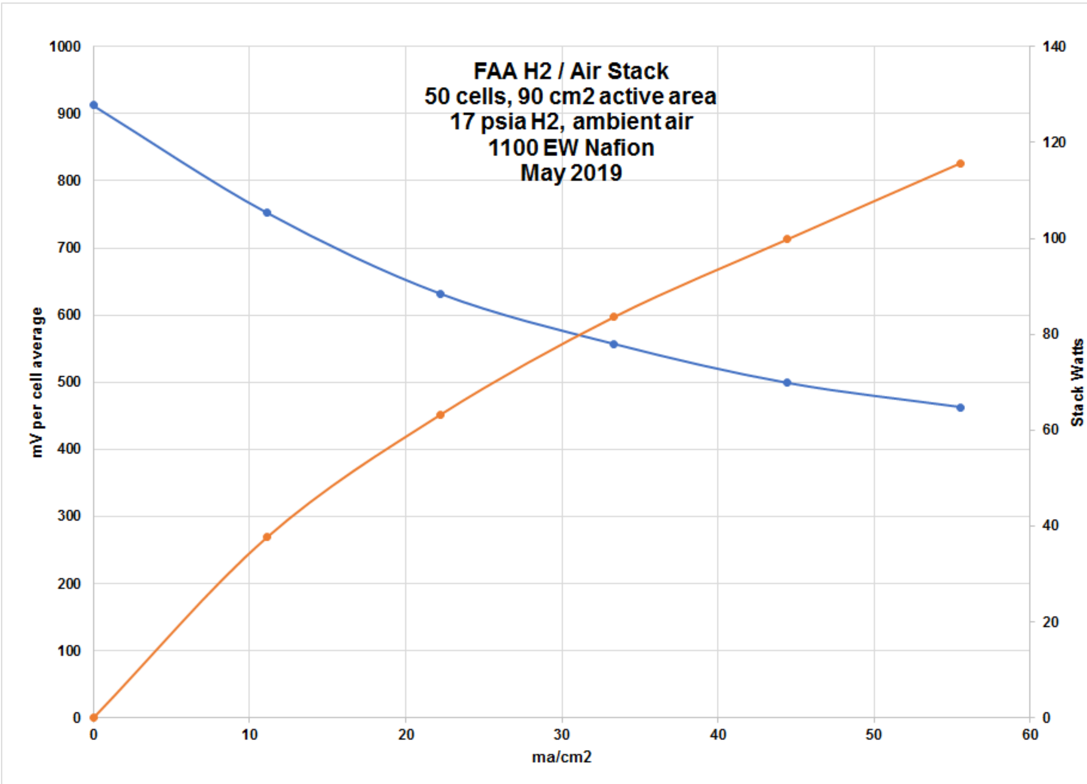


Figure 67 Initial Testing of 50 cell FAA Prototype Cell Stack

After further operation and humidification failed to increase performance the stack was dismounted and impedances were measured again. Cell average impedance was approximately 50 mohm as compared to the single cell that measured approximately 19.6 mohm after a similar initial break-in run. The conclusion was that cell impedances were higher than planned due to internal electrical conductivity being lower than planned due to excessive seal material that did not compress fully on stacking and assembly. No further testing was conducted pending further review however a plan was developed to modify the stack to correct excessive seal material issue to improve conductivity and overall performance. This plan is part of the recommended next actions discussed below.

While full power operation was not achieved the overall result was encouraging. The stack started and stopped as planned, operation was stable even if lower than planned, operation over the current range measured was linear and indicated a correctable stack impedance issue. The control system worked as planned and provided a basis for next generation hardware and software upgrades.

5.3 Aircraft Integration

The overall program has focused more on development of the prototype stack and system and less on integration into the planned airframe however this remains a goal of the overall product effort. To advance this Infinity is exploring continued stack and system development and test and additional aircraft integration under internal IRAD efforts.

5.4 Flight Design vs. Test Prototype

While the planned 3D printed materials had excessive permeation that prevented use in the final prototype the overall package remains a highly attractive approach for final implementation in suitable materials. Using the parts originally intended for the prototype, Infinity assembled a second stack to explore form and fit within the target aircraft. This mockup stack, figure 67 is comprised of 50 cells using actual anode and cathode flow fields and uses the endplates, manifolds and strapping approach from the baseline design. As an IRAD activity we plan to use this packaging mockup to explore placement on the aircraft and integration within the fuselage, figure 68.

Figure 68 Prototype Cell Stack Packaging Mockup

Figure 69 Prototype Mockup Placement Within Infinity – Penguin Airframe

5.5 Environmental Test Plan

See Exhibit 2

5.6 Hazard Analysis

See Exhibit 3

6.0 Conclusions and Recommendations

6.1 Conclusions

The goal of the program was to use development of a fuel cell system intended for use on a Class II drone to serve the dual purpose of technology development and provide a basis for review for compliance with transport aircraft requirements including: CFR Part 25 regulations, Safety Hazard analyses and DO-160 environmental test requirements.

Overall conclusion:

The system development process achieved partial success but more remains to done to reach complete system operability. However, the process did provide the design basis for the document development and evaluation regarding Part 25 requirements, Safety Hazard analyses and environmental test requirements. The stack and system have yet to achieved their overall design performance goals but did achieve partial success with next steps identified that are planned to be implemented under Infinity internal funding as resources permit.

The overall effort attempted to achieve a system embodying product, price and performance characteristics suitable for low cost implementation across multiple markets and vehicles. Achieving this low cost/high performance objective, especially within the scope of the effort, proved challenging. Lower cost design approaches impacted performance. Addressing resulting performance issues required modification of some of the lower cost design approaches and impacted overall cost and schedule.

However, the combined effect of this iterative process resulted in achievement of several lower cost stack and high-performance system elements, especially in the area of MEA manufacturing and flow-field design, that will carry forward into continuing development. It also highlighted other design approaches, such as edge feed plates, that are of questionable benefit and still others such as banded-stack retention that appear to be excellent cost-performance options but required additional engineering to mature.

The systems effort also provided valuable insight into aircraft integration and certification. The UAV Factory, the manufacturer of the Infinity owned-Penguin BE aircraft, makes this platform available to system integrators and even provides 4-day training sessions specifically to assist integrators in customizing the platform for their applications. As the fuel cell system advances in the next stage we intend to participate in such training working toward a system that can be retrofit to the Penguin BE as a package for operators that want to investigate a fuel cell system as a range extender for all- electric operations.

Table 15 below provides a detailed summary of the results and recommended next steps. The program achieved significant progress in several key design elements and identified areas where additional development is required.

Table 15 Results and Next Steps

Item	Objective and Approach	Results	Next Steps
Stack Elements			
Bipolar Plate			
- Flow field design	Objective: A flow field was designed to be common to multiple implementations of the bipolar plate - open cathode - closed cathode - O2 operation - air cooled - liquid cooled Approach: The bipolar plate is comprised of two elements: One contains the serpentine flow field formed into the metal foil the other is a linear flow field. The goal was one common serpentine formed element that could be used in different bipolar plate implementations by changing orientations	**Good:** Operation: The anode serpentine flow field operated as predicted in open cathode, air cooled implementation The flow-field has been designed for multiple orientations to permit closed cathode and O2 operation: Not tested yet	Define design/test program for the following new implementations: - Closed cathode- air cooled - closed cathode – liquid cooled - repeat both on O2
- Forming	- This goal was to have a lightweight, reduced-cost, forming process that could be done in-house	**Good but caused delays:** Forming achieved but process took longer than planned	Investigate tradeoffs of manufacturing formed plates in-house vs. at vendor using either hydro-forming or mass production stamping approaches Retain option of etching parts for development parts
- Coating	- The goal was to implement a low-cost high-performance coating	**Very Good:** Coating successful in performance and cost	Extended durability testing of coatings Investigate cost/ viability of investing to bring process in-house
- Joining Design	- Objective: Reduce cost of joining - Approach: Use elastomeric seals and join the two-part bipolar plate on assemble	**Did not perform as planned:** - Result: Joining the bipolar parts during the final stack assembly proved difficult and created sealing and interfacial contact issues that can be readily addressed by joining prior to assembly with a permanent bond/weld process	**Corrective Action:** 1) Join bipolar plates prior to stack assembly 2) Investigate cost/weight tradeoffs of one double sided etched part for open cathode-air cooled implementation
- Manifold design	- Objective: Simplify manifold implementation and provide flexible modular stack - Approach: Implement as edge-seal design with manifolds formed by 3-D printed structures applied to target bipolar plate edge sections	**Did not perform as planned** 1) Initial 3-D parts were porous and leaked 2) Initial implementation of elastomeric seals on bipolar plates intruded onto manifold	**Corrective action:** There are many challenges since you are trying to seal on an inherently imperfect surface. This may be possible with high precision parts but the combination of limited production-formed

Item	Objective and Approach	Results	Next Steps
		seal locations causing uneven seal surfaces	parts exacerbated an already challenging seal approach. 1) Retain initial bipolar plates-conventional manifold design
MEAs	Objective: Design MEA for H2/air operation and manufacture in house	**Results: Very Good** New framed MEA was designed, and manufactured in-house and met design performance requirements except for dry air operation in an open cathode configuration	**Next Steps:** Redesigned GDLs have been identified and procured that should allow operation on dry air in an open cathode configuration
Stack Assembly			
Manifolds	Objective: develop H2 manifolds that seal on edge feed cells	**Result: Incomplete** 3D printed manifolds were permeable and could not seal H2. These were replaced with aluminum manifolds that sealed H2 but edge seal in general was a challenge. It eventually was sealed but the design is not robust	**Corrective Action:** Modify bipolar plate design to return to allow implementation of a conventional manifold design
Endplates	Objective: Lightweight, low cost endplates that seals stack and provides designed level of internal contact	**Result: In Process** First try at 3D printed strapped endplates did not work. Load train was inadequate and no means of ensuring internal load train provided. Conventional revised endplate was implemented that sealed and could provide good interfacial contact resistance	**Corrective Action**: The shaped endplate-strapped design theoretically provides an excellent low-cost approach to stack assembly and has been implemented by others in the fuel cell industry. This implementation via 3D printed parts was inadequate. Design changes have been identified and will be implemented in future builds
Initial 50-cell build	Objective: Build and test initial 50-cell stack assembly and achieve required performance	**Result: Partial Success** The stack was assembled and tested but assembly was difficult. Excess elastomeric seal material unloaded active area increasing contact resistance and flowed external to bipolar plates making edge sealing difficult but eventually did seal. Internal impedances were high and explained limited performance. However, impedances were uniform. Ability to record individual cell voltages during test was limited	**Corrective** Actions: Longer term- Implement changes for stack components detailed above. Near Term: Disassemble, clean parts. Seal bipolar plates prior to assemble and reapply elastomeric seals to ensure no seal material flows external to plates when compressed. Reduce number of cells on test from 50 to 40/45to allow current test load equipment to monitor and record all cells

Item	Objective and Approach	Results	Next Steps
Control System	Objective: Design, fabricate and program a simplified control system that could be basis for flight design	**Result: Very Good** A simplified control system was developed and utilized for single cell and stack testing. Design and implementation provided basis for next step in development	**Next Step:** Current design is intended for lab user. Review controls design for end user and flight operations including environmental requirements. Design, fabricate and test.
Aircraft Integration			
Current Program	Objective: Integrate into Infinity-owned Penguin airframe and conduct ground test	**Result: Incomplete** Review of aircraft integration issues conducted but stack was not ready to allow even limited operational integration. Initial H2 tank vendor could not deliver, second source in process.	**Corrective Action:** Near Term: Continue integration and test with rebuilt Generation 1 stack external to aircraft using shop supplied gases
Ongoing Effort	Objective: Develop kit to retrofit Penguin BE with H2 fuel cell and tanks- current concept: - External wing tanks - Hybrid FC/battery architecture - upgraded with autopilot & camera **Threshold goal**: ground test **Objective goal 1**: Flight test at low altitude **Objective goal 2**: Flight test at high altitude on H2/air		Steps: - evaluate liquid vs/ air cooling for 20K ft operation - 4-day training course at UAV factory
Future Effort	Upgrade to O2/air switchover or other means to allow higher		
Other Future activities			
Benchmark Competition	Objective: Competition has evolved, goal is to understand current competition and define best practices		Other: As permitted by budget and other factors, acquire competing hardware and evaluate/

6.2 Recommendations

Based on the progress achieved it is recommended that additional development and test be pursued leading to flight test on the target Penguin airframe leading to a kit that could be retrofit to the Penguin BE airframe. To accomplish this the following near term and longer-term actions have identified.

Near term assembly and test

- Disassemble, and clean parts of the initial test stack, recover and reuse all MEAs
- Assemble/bond the bipolar plates prior to reassembly into the stack
- Apply reduced amounts of FIP gasket seal material to the bipolar plates prior to reassembly
- Reassemble the test stack with 40 to 45 cells to allow individual cell monitoring
- Retest with humidification to replicate single cell performance across the entire stack
- Fabricate and test single cell with improved water retentive MEA
- Assuming successful MEA test, fabricate 50 new MEAs with improved water retentive MEA and rebuild stack with new MEAs with improved reduced FIP gasket seal material
- Retest with dry supply air at ambient pressure air

Mid term

- Redesign the bipolar plate manifold to eliminate the edge feed seal
- Redesign the endplates to implement the banded retention approach
- Build two air cooled stacks: as open cathode/ air cooled and closed cathode/air cooled
- Build liquid cooled closed air/cathode version
- Build liquid cooled closed air-O2 cathode version
- Select at least one version, integrate into aircraft and conduct initial ground testing

Longer Term

Aircraft Environmental Integration and Flight

- Conduct environmental testing of integrated aircraft fuel cell system
- Upgrade aircraft for flight and fly with fuel cell/battery hybrid power system
- Qualify Develop “strap on” variant system that can be retrofit onto production aircraft

Exhibits

The following exhibits provide more detail regarding the Part 25 Review, the Environmental Test plan and the Hazard Analysis referenced in the body of this document.

Exhibit 1 CFR Part 25 Review

Exhibit 2 Environmental Test Plan

Exhibit 3 Hazard Analysis

Compliance Report

Aircraft Fuel Cell Power System

Contract No. DTFACT-16-C-00038

AJA-4A2
Federal Aviation Administration
WM J Hughes Technical Center
Atlantic City International Airport, NJ 08485

Distribution: COR: Michael Walz
CO: Karen Mercer

Infinity POC: William Smith
Quarterly Administrative Report

by:
Infinity Fuel Cell and Hydrogen, Inc.
431A Hayden Station Road
860-688-6500 tel
860-688-6511 fax
www.infinityfuel.com

October 10, 2018

Table of Contents

1.0 Summary

Purpose:

The purpose of this document is to serve both as a guide to meeting requirements for integration of a Fuel Cell into a Class II UAS and as a reference for subsequent integration of a similar Fuel Cell into a Code of Federal Regulations, Title 14 Part 25 (known as 14 CFR Part 25) regulated Transport Aircraft.

Tasks required under the Infinity-FAA Contract DTFACT-16-C-00038 include the design and analysis of the integration of a Proton Exchange Membrane Fuel Cell, PEMFC, into a Class II UAS, with the initial target aircraft being an Infinity-owned Fuel Cell Factory Penguin BE, Figure 1. While the initial focus is on the UAS integration, part of this effort is to assess the suitability, including compatibility, performance, Total Cost of Ownership (TCO), effectiveness, etc. of the design of the UAS fuel cell product to meet requirements of CFR Part 25 if installed for use aboard a passenger transport aircraft.

In 2015 the FAA chartered an Energy Supply Device Aircraft Rulemaking Committee, ESD ARC, with objectives to:

a. Develop a plan for determining appropriate airworthiness standards and guidance for energy supply device installations. with a primal)' focus on transport airplanes but also considering other types of aircraft.
b. Identify hazards associated with installations of hydrogen fuel cells, batteries, ultra-capacitors, and other energy supply devices on transport airplanes and other types of aircraft.
c. Identify the designs and operational principles that may be used to safeguard against these hazards.
d. Identify the current rules in Title 14, Code of Federal Aviation Regulations (14 CFR) part 25 that are applicable for addressing energy supply device installations.
e. Determine proposed revisions of, and any additions to, the applicable part 25 rules needed to provide an appropriate and adequate level of safety for energy supply device installations and operation.
f. Review the existing advisory circulars and FAA policy memorandums and statements that provide guidance relating to this subject and determine proposed revisions or additions to the guidance. As a part of this effort, determine proposed guidance on the assumptions and approach that should be used to perform a safety assessment of these energy supply device installations.
g. Recommend appropriate airworthiness standards and guidance for energy supply device installations.

One of the outputs of the ARC process was a detailed summary, by subpart, mapping the likely applicability of existing Part 25 regulations to various fuel cell related applications as well identifying proposed new regulations.

Building from this the ARC analysis, this current document maps ARC identified regulations to the UAS fuel cell, identifies compliance approaches and reviews additional effort that may be required for a Transport Aircraft to use that UAS fuel cell aboard a Part 25 regulated aircraft.

This assumes that integration into a currently certified Transport Aircraft would require approval of a Supplemental Type Certificate. To support that, another goal of this document is to assist in planning for a STC application, Figure 2, and in planning for development of familiarization materials to be used in developing a proposed Certification Basis.

While this document uses the UAS integration as the baseline project this document is also intended to serve as a reference document compiling relevant portions of the ARC, Part 25 and Air Circulars cited by the ARC related to fuel cells.

Figure 1 Infinity Owned Penguin BE Platform

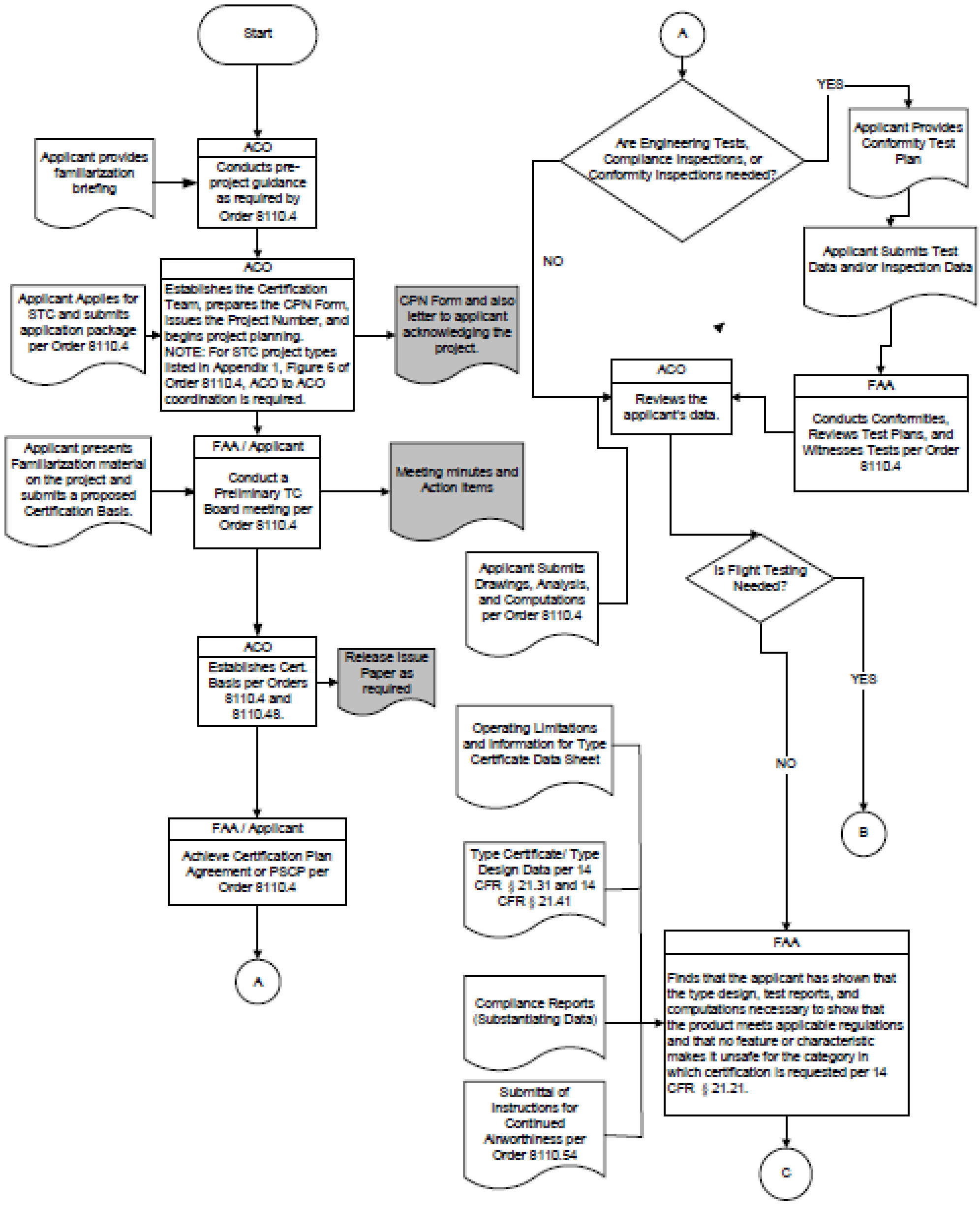


Figure 2 STC Application Process

The goal of this process is to design the system, whenever possible, in such a way so as to both satisfy UAS requirements and Part 25. In instances where the design does not align with the requirements of Part 25, a goal is to define how future designs may be met. In instances where the demands of the section are believed to be inapplicable to either the current or future design such designation is made in the relevant portion of the design study.

This document defines the codes and standards that are to be met and process to be followed to ensure the safety of the energy storage system. It also defines measures that have been taken to verify compliance with the appropriate codes and standards, deviations from the codes and standards that were found and how deviations have been addressed and resolved to ensure safety of the system being developed.

Background: Infinity Unmanned Aircraft System Fuel Cell, UAS-FC
As reference for the analysis he following summarizes the describes the Infinity Fuel Cell design.

Key Characteristics Summary

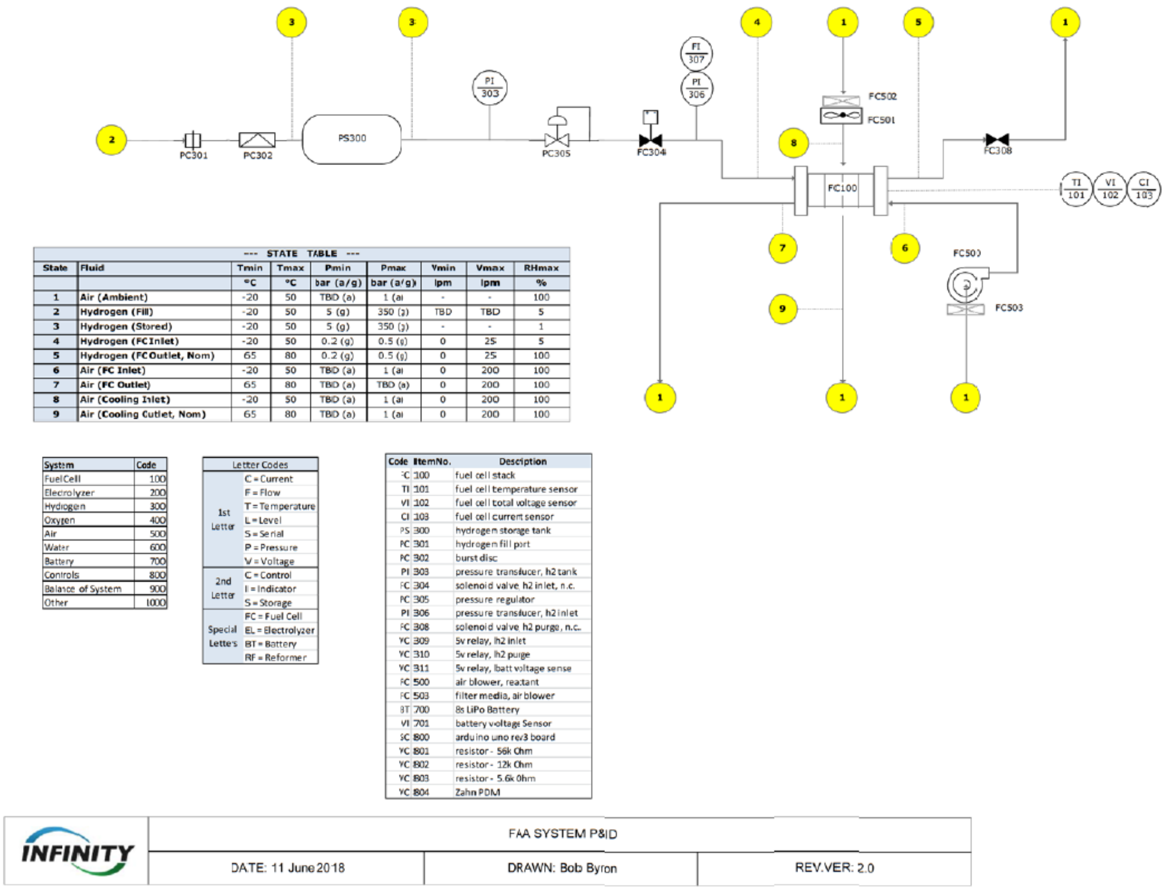
Characteristic	Units	Nominal
Power	Watts	1300
Stack Voltage	Volts	24 VDC
Life	Hours	1500
Dimensions	Inches	6.8 x 5.25 x 5.53
Cells	ea.	50
Cell area	Cm2	90
Operating Temp	Deg C	65

Fuel cell stack Technology description
The cell stack, Figure 3 is a 50 cell, stack of 90 cm2 H2-air cells operating at a nominal 65 deg C. The baseline design that will be tested first is an open cathode configuration where a common air source is used for both oxygen supply and cooling. The stack cell architecture is designed to allow reconfiguration to a close cathode if required.

Figure 3 Infinity 1.5 kW Cell Stack

<u>Fuel cell system P&ID description</u>

The system P&ID and control system shown in Figures 4 and 5. This P&ID is a simple control system that supplies hydrogen from one pressurized cylinder and oxygen from air supplied to the open cathode of the stack. Suitable pressure, temperature, voltage, current and other measurements and control devices ensure safe and reliable operation.



--- STATE TABLE ---								
State	Fluid	Tmin	Tmax	Pmin	Pmax	Vmin	Vmax	RHmax
		°C	°C	bar (a/g)	bar (a/g)	lpm	lpm	%
1	Air (Ambient)	-20	50	TBD (a)	1 (a)	-	-	100
2	Hydrogen (Fill)	-20	50	5 (g)	350 (g)	TBD	TBD	5
3	Hydrogen (Stored)	-20	50	5 (g)	350 (g)	-	-	1
4	Hydrogen (FC Inlet)	-20	50	0.2 (g)	0.5 (g)	0	25	5
5	Hydrogen (FC Outlet, Nom)	65	80	0.2 (g)	0.5 (g)	0	25	100
6	Air (FC Inlet)	-20	50	TBD (a)	1 (a)	0	200	100
7	Air (FC Outlet)	65	80	TBD (a)	TBD (a)	0	200	100
8	Air (Cooling Inlet)	-20	50	TBD (a)	1 (a)	0	200	100
9	Air (Cooling Outlet, Nom)	65	80	TBD (a)	1 (a)	0	200	100

System	Code
Fuel Cell	100
Electrolyzer	200
Hydrogen	300
Oxygen	400
Air	500
Water	600
Battery	700
Controls	800
Balance of System	900
Other	1000

Letter Codes	
1st Letter	C = Current
	F = Flow
	T = Temperature
	L = Level
	S = Serial
	P = Pressure
	V = Voltage
2nd Letter	C = Control
	I = Indicator
	S = Storage
Special Letters	FC = Fuel Cell
	EL = Electrolyzer
	BT = Battery
	RF = Reformer

Code	ItemNo.	Description
FC	100	fuel cell stack
TI	101	fuel cell temperature sensor
VI	102	fuel cell total voltage sensor
CI	103	fuel cell current sensor
PS	300	hydrogen storage tank
PC	301	hydrogen fill port
PC	302	burst disc
PI	303	pressure transducer, h2 tank
FC	304	solenoid valve, h2 inlet, n.c.
PC	305	pressure regulator
PI	306	pressure transducer, h2 inlet
FC	308	solenoid valve, h2 purge, n.c.
YC	309	5v relay, h2 inlet
YC	310	5v relay, h2 purge
YC	311	5v relay, batt voltage sense
FC	500	air blower, reactant
FC	503	filter media, air blower
BT	700	8s LiPo Battery
VI	701	battery voltage Sensor
SC	800	arduino uno rev3 board
YC	801	resistor - 56k Ohm
YC	802	resistor - 12k Ohm
YC	803	resistor - 5.6k Ohm
YC	804	Zahn PDM

Figure 4 Fuel Cell System P&ID

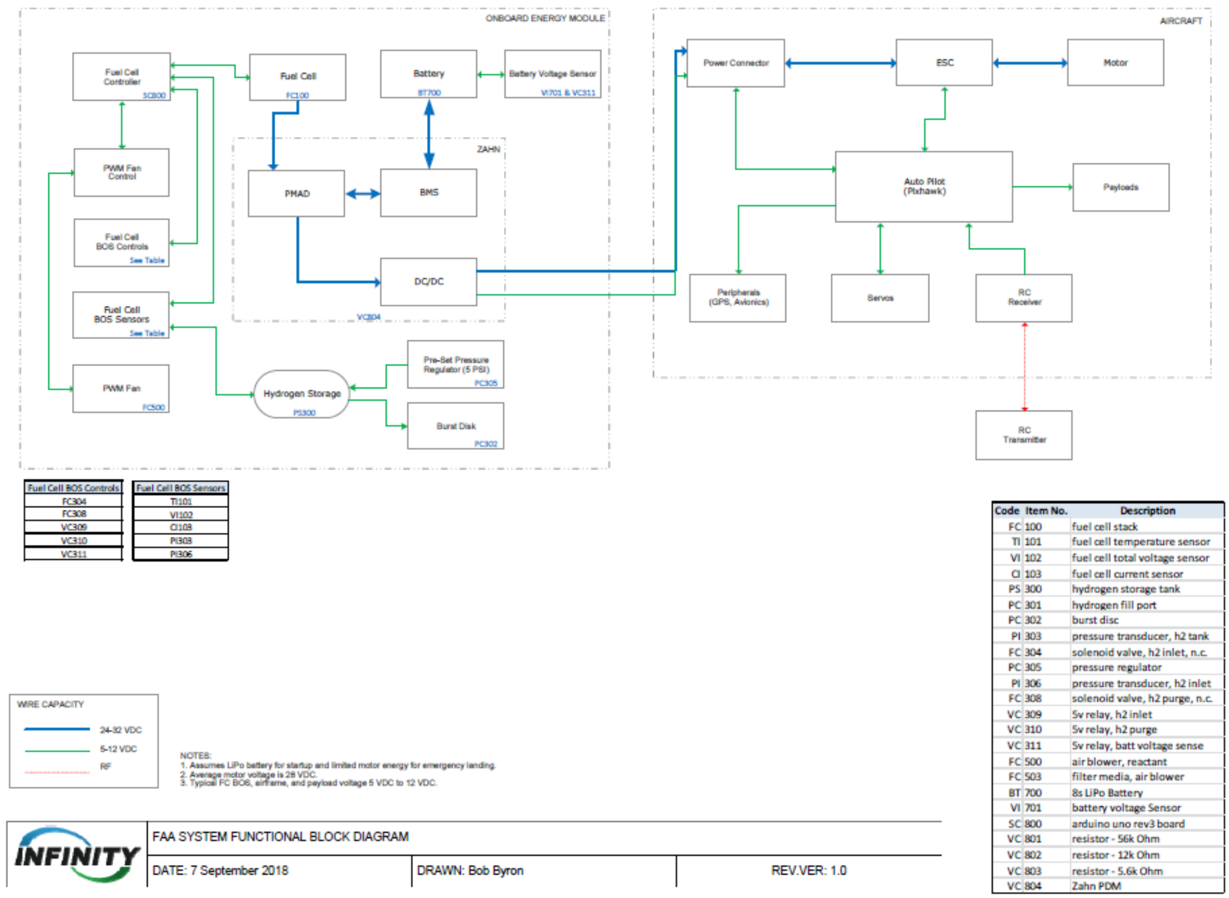


Figure 5 System Control Block Diagram

Packaging

The system under development for inclusion in Infinity's Class II drone has been designed to provide proper control and safety while minimizing overall size and weight. To this end, a single hydrogen tank with attached regulator has been coupled with a small blower or fan to provide both hydrogen and air to the fuel cell stack, Figure 6. In this arrangement, the energy storage system, the hydrogen, is decoupled from the power system (the fuel cell), yielding opportunity for scalability and flexibility in future UAS and transport aircraft applications. The positioning of the system precludes the use of the payload bay of this particular aircraft, however, future airframe design with dedicated fuel cell integration would open up dedicated volumes for payload use.

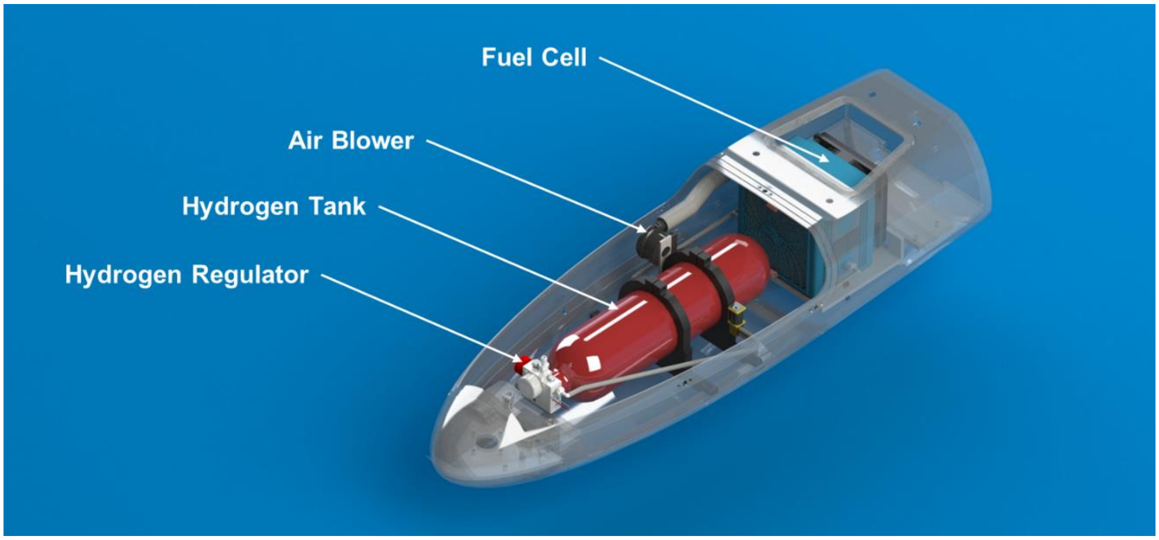


Figure 1 Prototype Fuel Cell System Integration

The housing around the fuel cell system in the image is the fuselage of the Penguin aircraft. This is a pusher prop design, so the electric motor and propeller reside off the flat face located to the rear of the fuel cell (shown in blue). The configuration of fuel cell stack is outfitted with a separate cooling fan and air blower; the configuration to be built may be a single air feed used for both reactant supply and cooling. The control board is not mounted within this image. The hydrogen tank is 4,500 psi capable with an internal water volume of 1.6 liters capable of storing approximately 35 to 40 grams of hydrogen. This hydrogen, along with Infinity's fuel cell stack, should provide an average flight time of approximately 1.2 hours, depending on mission profile and flight dynamics. This projected flight time will satisfy benchtop testing and preliminary flight testing. The regulator attached to the hydrogen tank has been designed specifically for the drone market by a supplier to Infinity and therefore has the low mass and volume required for the application

2.0 Applicable Documents and Contributing Personnel

2.1 Primary Codes and Standards

The following codes and standards have been the primary requirements for guiding the design and installation of the system on an operative UAS. Compliance with these documents is detailed in section 3.0

- Code of Federal Regulations, 25 (FAA) CFR 25.21-25/1733 Selections
- MIL-STD-704 Aircraft Electric Power Characteristics
- MIL-STD-461F - Department of Defense Interface Standard Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment
- MIL-STD-464C - Department of Defense Interfaces Standard Electromagnetic Environmental Effects Requirements for Systems

2.2 Supporting Codes and Standards: Air Circulars

These codes and standards have been reviewed for relevance and implemented as appropriate. Portions may apply to the installation as referenced from primary documents. The text of the referenced air circular reports has been included as an appendix to this document.

- AMC 25.831
- AC 20-32B
-AC 25-9A
-AC 25-16
-AC 25-795-3
-AC 25.869-1A
-AC 20-144
-AC 20-128A
-AC 25.981-1C
-AC 25-30
-AC 25-994-1
-AC 20-135
-AC 25.1435-1
-AC 25.1362-1
-AC 25-795-7
-AC 1353-1A
-AC 20-107
-AC 20-29B
-AC 20-175
-AC 25-795-3
-AC 25-795-9
-AC 120-80A
-AC 25.795-9
-AC 20-136B
-AC 20-155A
-AC 20-158A
-AC 1360-1
-AC 25.1455-1
-AC 25-27A
-AC 120-42B
-AC.1701-1

- NFPA 55--Standard for Storage, Use and Handling of Compressed Gases
- Code of Federal Regulations, 29 (Labor) CFR 1910.103 *Hydrogen*
- NEC/NFPA 70---Electrical Codes

2.3 Generated Documents

The following documents have been generated to support the safe design and installation.

Infinity Fuel Cell and Hydrogen, Inc.
FMEA Infinity System (Appendix A)
Design Analysis of FAA Part 25 Sections B-H (Appendix B)

2.4 Subsystem- Component Supplier Documents

These documents are supplied to support applicable requirements.

Major Component Cut Sheets (Appendix C)

2.5 Contributing Personnel

The following summarizes the background and roles of relevant project personnel followed by short resumes of each person:

Name	**Role**
Robert Byron	Program Lead / Primary Design Innovator
Christopher Chestnut	Lead Designer
John Fayer	Fuel Cell Design and Test
Kelvin Hecht	Systems Safety and Reliability Expert
Patrik Landor	Testing and Systems Analysis
William Smith	Infinity Fuel Cell Program Manager

Personnel

Robert Byron
Years of Experience: 20+
Position: Business Development
Education: BSME, University of Arizona

Mr. Byron acts as the Business Development lead and New Product Development consultant at Infinity Fuel Cell and Hydrogen, Inc., joining the company as a contractor in 2014. He has been involved in the design and development of electrochemical stacks and systems including fuel cell and hydrogen electrolyzer products for over 20 years.

Mr. Byron's prior experience includes: currently an independent consultant providing business development, product management, and new product development services;

Recent Experience:

United Technologies UTC Power Managing Space Shuttle fuel cell program, as well as business development and product management for stationary 400 kW fuel cell systems;

First Solar as the Director of Product Management for ground-based solar systems;

NASA Johnson Space Center focusing on Space Shuttle fuel cell system support and advanced fuel cell and solar energy systems for space applications;

Proton Energy Systems as a Product Engineer involved in the design and development of electrolyzer and fuel cell stacks and systems.

Mr. Byron holds 7 US patents.

Name: Christopher Chestnut
Years of Experience: 28
Position: Project Engineer II
Education: BS Mechanical Engineering, Northeastern University
BS Civil Engineering Technology, Central Conn. State University

Experience: Mr. Chestnut has worked for Infinity since 2016.

- Designing a small compact fuel cell for commercial applications
- Program manager on MDA program to build 80 cell Fuel Cell demonstrator

Prior experience includes:

- Several design, manufacturing, quality and project positions.
- Mechanical design using Solidworks and Pro-E [Creo].
- Holds patents in the area of Laser Imaging, Fiber Optic Sensors and Telecommunication.

Name: **John Fayer**
Years of Experience: **8**
Position: **Design & Test Engineer**
Education: **BS Mechanical Engineering, University of Connecticut**

Experience:

Infinity Fuel Cell and Hydrogen, Inc.

Mr. Fayer joined Infinity in 2009 and rapidly became a key contributor across all of our products. As a Design and Test Engineer he has been the lead engineer designing and testing fuel cell components, stacks, systems and test equipment. He has developed a strong background in fuel cell development and can independently lead challenging projects. His contributions include:

• Developing PEM fuel cell stacks and fuel cell systems for government agencies including NASA, NAVY and the MDA at power output levels ranging from 100 wats to over 20kW in size.
• Assembling and testing fuel cells
• Assembling and testing complete fuel cell systems
• Supporting testing in the field as required
• Developing automated inspection equipment for production parts

UTC Power 2008-2009
Drafting and Design for fuel cell systems and test fixtures.

Skills and experience include:

- PTC Creo and lntralink database, modeling, detail drawing and FEA
- Microsoft Office Suite experience
- Writing and maintain operating procedures
- Ability to work in a team environment
- Problem solving
- PEM electrolyzer testing

KELVIN HECHT
Consultant

Mr. Hecht provides consulting services to the US Department of Energy, UTC Fuel Cells and on occasion, to small fuel cell manufacturers.

Mr. Hecht is the recognized expert on fuel cell codes and standards. He chairs the CSA America committee that produced the US National Standard for Stationary Fuel Cell Power Plants. He also is the Technical Advisor to the United States Technical Advisory Group to IEC TC105, which writes international fuel cell standards, and chairs TC105's working groups on Terminology and Stationary Power Plants. He also is a 2005 recipient of IEC's "1906 Award" for his outstanding service to TC105.

Since 1979, Mr. Hecht has been active in almost all fuel cell standards committees including ANSI, AGA, ASME PTC 50, IEEE, NFPA 853, IEC, UL and CSA America.

Before retiring from United Technologies Corporation, Mr. Hecht was manager of Product Assurance at UTC's Fuel Cell Operation, responsible for produce safety, reliability and maintainability. He also had the additional responsibilities of Manager, Environmental Compliance and Manager, Industrial Health and Safety. During that 35-year period, Mr. Hecht was responsible for the reliability and safety of the fuel cells in the Apollo and Shuttle space missions as well as the third-party safety certification of commercial 200 kW power plants.

Mr. Hecht edits the website www.fuelcellstandards.com tracking the world-wide development of fuel cell and hydrogen infrastructure standards.

EDUCATION

Mr. Hecht has a degree in Physics from Tufts University and advanced courses from Trinity College, University of Washington, University of Wisconsin, Northeastern University and the U.S. Department of Labor's OSHA Training Center

Name: **Jay LaGrange**
Years of Experience: **37**
Position: **Engineering Manager**
Education: **BS Mechanical Engineering, Clarkson University**
MS Management, Rensselaer Polytechnic Institute Graduate Center in Hartford, CT
Licenses: **Professional Engineer in State of CT**

Experience: Mr. LaGrange joined Infinity in 2009 as a Development Engineer and now serves as our as Engineering Manager with Project emphasis.

- Manages the design and building of patented fuel cells for customers including NASA and the Navy.
- Developed a unique patent for high differential water removal, 150 cm^2 fuel cell for NASA.
- Manage configuration & documentation control via Pro-E Windchill 10.0 and Creo 1.0.
- Manage multiple projects including project planning along with direct customer interface.
- Supervise team members during design, building and testing. for

Previous Fuel Cell experience includes:

- UTC Power; Developing and maintaining critical Space Shuttle Orbiter balance of plant components.
- H Power; Supervising design personnel developing 500 W to 1 kW Fuel Cell Stacks and Systems.
- Parker Energy Systems; Heavy teaming with customers to design and develop tailored balance of plant systems. Complete systems were manufactured for small portable solid oxide and methanol fuel cell systems. Developed and sold sub-systems for PEM transportation and stationary applications.

Name:	**William Smith**
Years of Fuel Cell Experience:	**31**
Position:	**Founder and President**
Education:	**BA Physics, University of Connecticut, MBA University of Massachusetts**

2002-Present: Infinity Fuel Cell and Hydrogen, Inc. Windsor, CT
Mr. Smith is Founder and President of Infinity Fuel Cell and Hydrogen, Inc., starting the company in 2002 focused on the application of PEM technology to fuel cell and hydrogen systems. He has served as Program Manager and Principal Investigator for most major Infinity programs, including programs at NASA Glenn Research Center, DoD fuel cell projects for the Naval Air Warfare Center in China Lake, the Naval Underwater Weapons Center, the Defense Logistics Agency, and for the General Atomics' LDUUV program with the Office of Naval Research.

1996-2002: Proton Energy Systems, Inc. Wallingford, CT
Co-Founder and VP of Business Development at Proton Energy Systems, Inc. (now Proton Onsite Division of NEL) where he led Business Development as Proton grew from a startup company through an IPO on the NASDAQ in 2000.

1980-1996: United Technologies, Hamilton Standard Division, Windsor Locks, CT
Business Development Program Manager for United Technology's Hamilton Sundstrand Division focusing on electrochemical and aircraft systems for commercial, space and military markets

1978-1980: Perkin-Elmer Corporation, Wilton, CT
Optical Engineer and Business Development manager for Perkin Elmer focused on advanced optical and high energy laser systems.

Selected Publications and Presentations

1. Advances in Non-Flow-Through PEM Fuel Cells for Aerospace Applications, 6th European PEFC & Electrolyser Forum, KKL Lucerne, Switzerland, July 4-7, 2017
2. Advances in Fuel Cells Power Sources for Directed Energy Applications, William Smith, 2017 Annual Directed Energy Symposium, Huntsville, AL, February 13-17, 2017
3. Non-Flow Through PEM Fuel Cells for Air-Independent Applications, Jay LaGrange, William Smith, Unmanned Systems Conference, Association for Unmanned Vehicle Systems International (AUVSI), 2015 Atlanta, GA
4. Advances in Non Flow-Through PEM Fuel Cells for Air-Independent Applications, William Smith, 2012 Fuel Cell Seminar & Exposition, Mohegan Sun Uncasville, Connecticut USA, November 5-8, 2012
5. Advances in Non Flow-Through PEM Fuel Cell Development, William Smith & Alfred Meyer, 17th International Symposium on Unmanned Untethered Submersible Technology (UUST11), Portsmouth, NH, USA, August 21-24, 2011

Issued U.S. Patents

"Electrochemical Cell", (2015), U.S. Patent Number 9,118,040 B2, William F. Smith, James F. McElroy, and Jay W. LaGrange
"Electrochemical Cell", (2014), U.S. Patent Number 8,715,871 B2, Christopher Callahan, James F. McElroy, Alfred Meyer and William F. Smith

"Electrochemical Cell", (2013), U.S. Patent Number 8,506,787 B2, Christopher Callahan, James F. McElroy, Alfred Meyer and William F. Smith

"Modular Regenerative Fuel Cell System", (2011), U.S. Patent 8,003,268 B2, William F. Smith

"Hydrogen Generator Apparatus for Internal Combustion Engine and Method Thereof", (2003) U.S. Patent 6,659,049, J. Zagaja, T. Molter, L. Moulthrop, and W. Smith

"Electrochemical Gas Purifier," (2001) U.S. Patent 6,168,705 B1, Trent M. Molter and William F. Smith

"Ionizable Substance Detector," (1992) U.S. Patent 5,118,398. J. McElroy and W. Smith

"Fuel Cell Product Water Liquid Gas Stripper," (1992) U.S. Patent 5,122,239 J. McElroy and W. Smith

"Solid State High-Pressure Oxygen Generator," (1994) U.S. Patent 5.350,496, W. Smith and J. McElroy

"Atmosphere Membrane Humidifier and Method and System for Producing Humidified Air," (1994) U.S. Patent 5,348,691 J. McElroy, W. Smith, J.Genovese

3.0 Codes and Standards Compliance

3.1 Planned UAS Fuel Cell Review with Respect to 14 CFR Part 25

Compliance matrices have been developed and used to verify that the as-built installation meets required Codes and Standards. The compliance matrices are detailed in a separate Excel spreadsheet and map the UAS fuel cell design against relevant Part 25 requirements.

Item	Title
Appendix B	14 CFR 25 Airworthiness Standards, Transport Category Airplanes

Appendix A Failure Modes and Effects Analysis (FMEA)

Figure references and component callouts in section 1 above.

Infinity Fuel Cell and Hydrogen, Inc.

FAILURE MODE AND EFFECT / HAZARD ANALYSES
FAA Contract DTFACT-16-C-0038
Aircraft Fuel Cell Power System

TABLE OF CONTENTS

Frequency Code - F

1. Unlikely event during life of equipment
2. Possible event during life of equipment
3. Probable event during life of equipment

Severity Code - S

1. Negligible
2. Loss of efficiency; reduced mission time
3. System failure; mission abort, "controlled" landing
4. Major equipment damage, personnel hazard, fire

FAILURE MODE AND EFFECT / HAZARD ANALYSIS
Aircraft Fuel Cell Power System
FAA Contract DTFACT-16-C-0038

Component	Failure Mode	Failure Effect	F	S	Comments	Proposed Action
1.1 FC 100 Fuel Cell Stack	1. External leakage a. Hydrogen	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
	2. Internal failures a. crossover	**System failure.** Mission abort. Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warning for "controlled" landing on battery power.	2	3		Consider automatic shutdown for high temperature.
	b. Coolant blockage	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	3. Reaction degradation	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
2.1 FC 304 Hydrogen inlet solenoid valve Normally (unpowered) closed	1. Fails closed	**System failure.** Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warns for "controlled" landing on battery power.	2	3		
	2. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
2.2 PC 305 Pressure regulator Maintain H2 pressure to stack, FC 100.	1. Blockage	**System failure.** Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warns for "controlled" landing on battery power.	1	3		
	2. Pressure too high	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	3. Pressure too low	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	4. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
2.3 FC 308 Hydrogen purge solenoid valve Normally (unpowered) closed	1. Fails closed	**Failed start.**	2	1		
		System failure. Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warns for "controlled" landing on battery power.	2	3		
	2. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
2.4 VC 309 Hydrogen inlet 5V relay	1. Fails to close	**Failed start.**	2	1		
		System failure. Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warns for "controlled" landing on battery power.	2	3		

FAILURE MODE AND EFFECT / HAZARD ANALYSIS
Aircraft Fuel Cell Power System
FAA Contract DTFACT-16-C-0038

Component	Failure Mode	Failure Effect	F	S	Comments	Proposed Action
2.5 VC 310 Hydrogen purge 5V relay	1. Fails to close	**Failed start.** **System failure.** Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warns for "controlled" landing on battery power.	2 2	1 3		
2.6 VC 311 Battery voltage sensor 5V relay	1. Fails to close	**Failed start.** **System failure.** Mission abort. Voltage Sensor, VI 701, warns for "controlled" landing on battery power.	2 2	1 3		
3.1 TI 101 Fuel cell temperature sensor Stack monitor for control	1. Indication too high 2. Indication too low 3. Sensor out-of range	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2 2 2	2 2 2		
3.2 VI 102 Fuel cell total voltage sensor Stack monitor for control	1. Indication too high 2. Indication too low 3. Sensor out-of range	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2 2 2	2 2 2		
3.2.1 VC 801 Resistor 56k Ohm	1. Fails open	**Reduced mission time.** Voltage sensors warn for mission termination.	1	2		
3.2.2 VC 802 Resistor 12k Ohm	1. Fails open	**Reduced mission time.** Voltage sensors warn for mission termination.	1	2		
3.2.3 VC 803 Resistor 5.6k Ohm	1. Fails open	**Reduced mission time.** Voltage sensors warn for mission termination.	1	2		
3.3 CI 103 Fuel cell current sensor Stack monitor for control	1. Indication too high 2. Indication too low 3. Sensor out-of range	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2 2 2	2 2 2		

FAILURE MODE AND EFFECT / HAZARD ANALYSIS
Aircraft Fuel Cell Power System
FAA Contract DTFACT-16-C-0038

Component	Failure Mode	Failure Effect	F	S	Comments	Proposed Action
3.4 PI *303* Hydrogen tank pressure transducer	1. Indication too high	**Negligible**	2	1		
	2. Indication too low	**Reduced mission time.** Transducer warns for mission termination.	2	2		
	3. Sensor out-of range	**Reduced mission time.** Transducer warns for mission termination.	2	2		
	4. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
7. PI 306 Hydrogen inlet pressure transducer Used for Stack, FC 100, controll	1. Indication too high	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	2. Indication too low	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	3. Sensor out-of range	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	4. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
4.1 FC 500 Reactant air blower Reactant and cooling	1. Reduced output	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	2. Fails off	**System failure.** Mission abort. Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warn for "controlled" landing on battery power.	2	3		
4.2 FC 503 Air blower filter Protection for reactant and cooling flow	1. Internal leakage (contaminated air supply)	**Negligible**	2	1		
	2. Blockage	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
5.1 PS 300 Hydrogen storage tank	1. Rupture	**Double failure.** Tank protected by Burst Disc, PC 302.				
	2. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		

FAILURE MODE AND EFFECT / HAZARD ANALYSIS
Aircraft Fuel Cell Power System
FAA Contract DTFACT-16-C-0038

Component	Failure Mode	Failure Effect	F	S	Comments	Proposed Action
5.2 PC 301 Hydrogen fill port Quick disconnect/ Check valve function	1. Blockage	Non flight function. For fill only.				
	2. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
5.3 PC 302 Burst disc Protects H2 tank, PC 300, from over pressurization	1. Fails to activate	**Double failure**				
	2. Inadvertent activation	**System failure.** Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, initiate "controlled" landing on battery power.	1	3		
	3. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 indicates excess hydrogen consumption and terminates mission.	2	2		
6.1 SC 800 Fuel cell controller Arduino uno rev 3 board	1. No output	**System failure.** Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warn for "controlled" landing on battery power.	2	3		
7.1 BT 700 Battery 8s LiPo battery	1. Loss charge	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		
	2. Fire	**Major equipment damage.**	1	4	An unlikely event.	
8.1 VI 701 Battery voltage sensor	1. Indication too high	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		
	2. Indication too low	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		
	3. Sensor out-of range	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		
8.2 VC 311 Battery 5V relay	1. Fails to close	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		

FAILURE MODE AND EFFECT / HAZARD ANALYSIS
Aircraft Fuel Cell Power System
FAA Contract DTFACT-16-C-0038

Component	Failure Mode	Failure Effect	F	S	Comments	Proposed Action
9.1 **Zahn VC 804** PMAD Power management	1. Failed function	**Major equipment damage.** Loss of power for flight. Crash.		4	Component under development. Assume appropriate reliability can be established with analysis and testing.	
9.2 **Zahn VC 804** BMS Battery management	1. Failed function	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		
9.3 **Zahn VC 804** DC/DC	1. Failed function	**Major equipment damage.** Loss of power for flight. Crash.		4	Component under development. Assume appropriate reliability can be established with analysis and testing.	

APPENDIX B DESIGN STUDY APPLICABLE TO CFR 25 FAA REGULATIONS

Appendix B-1 Introduction/Study Goals

Appendix B-2 Part 25 Subpart B - Flight Requirements

Appendix B-3 Part 25 Subpart C - Structure

Appendix B-4 Part 25 Subpart D – Design and Construction

Appendix B-5 Part 25 Subpart E – Powerplant

Appendix B-6 Part 25 Section F – Equipment

Appendix B-7 Part 25 Section G – Operating Limitations and Information

Appendix B-8 Part 25 Section H – Electrical Wiring Interconnection Systems (EWIS)

Safety risks referenced in Appendix B are summarized below:

Hazard ID #	Safety Risks
F2	H_2 Fire & Explosion Risk
F3	Mechanical and Material Hazards
F4	Hazard Dependent on Application / Implementation
F5	Physiological Hazards
F6	Operational and Maintenance Hazard
F7	Hydrogen Fire Extinguishing
F8	Cryogenic Hazards
F9	Non-Hydrogen Fuel and Oxygen Hazards
F10	Electrical Hazards

Examples Part 25 Compliance Summary Format Portion of Subpart B

	Code Section	Section Title/Text	Require Revision	Address Which Hazard	Drone Applicability	Drone Compliance	Drone Verification / Compliance Method	Drone Compliance Comments	Part 25 Applicability	Compliance Method	Part 25 Comments
CS 25.23 Load distribution limits	25.23	**Load distribution limits.**									
(a) Ranges of weights and centres of gravity within which the aeroplane may be safely operated must be established. If a weight and centre of gravity combination is allowable only within certain load distribution limits (such as spanwise) that could be inadvertently exceeded, these limits and the corresponding weight and centre of gravity combinations must be established.		(a) Ranges of weights and centers of gravity within which the airplane may be safely operated must be established. If a weight and center of gravity combination is allowable only within certain load distribution limits (such as span wise) that could be inadvertently exceeded, these limits and the corresponding weight and center of gravity combinations must be established.	No	F3/F6	Applicable	Compliant	1) Design Analysis, 2) Test with CG Balance Tool, 3) Test	Requirement relates to effects on aircraft structure as this relates to aircraft flight characteristics. In drone application fuel cell and H2 tank comprise large percentage of mass of vehicle and as such will require detailed review. For example a loss of a tank support could allow a tank to become mobile and affect aircraft flight stability.	Applicable	1) Design & Analysis 2) Test	Requirement relates to effects on aircraft structure as this relates to aircraft flight characteristics. In MedEvac application fuel cell and H2 tank comprise low percentage of mass of vehicle and as such are less likely to affect flight in a failure. For example a loss of a tank support that allowed a tank to become mobile may affect cabin occupants but not affect aircraft flight stability by itself.
(b) The load distribution limits may not exceed –		(b) The load distribution limits may not exceed—	No	F3/F6	Applicable	Compliant	ditto				
(1) The selected limits;		(1) The selected limits;	No	F3/F6	Applicable	Compliant	ditto				
(2) The limits at which the structure is proven; or		(2) The limits at which the structure is proven; or	No	F3/F6	Applicable	Compliant	ditto				
(3) The limits at which compliance with each applicable flight requirement of this Subpart is shown.		(3) The limits at which compliance with each applicable flight requirement of this subpart is shown.	No	F3/F6	Applicable	Compliant	ditto				

Examples Part 25 Compliance Summary Format portion of Subpart H

0	14 CFR 25 Section	Topic of Statute	Require Revision	Address Which Hazard	Drone Applicability	Drone Compliance Method	Drone Verification / Compliance Method	Drone Compliance Comments	Part 25 Applicability	Compliance Method	Part 25 Comments		Currently Applicable	Referenced Air Circulars
CS 25.1701 General (See AMC 25.1701)	25.1701	Definition.												
(a) Electrical wiring interconnection system (EWIS) means any wire, wiring device, or combination of these, including termination devices, installed in any area of the aeroplane for the purpose of transmitting electrical energy, including data and signals between two or more intended termination points. Except as provided for in subparagraph (c) of this paragraph, this includes:		(a) As used in this chapter, electrical wiring interconnection system (EWIS) means any wire, wiring device, or combination of these, including termination devices, installed in any area of the airplane for the purpose of transmitting electrical energy, including data and signals, between two or more intended termination points. This includes:	No	F10	A						Definiton Section		Applicable	AC 25-1701-1
(1) Wires and cables. (2) Bus bars. (3) The termination point on electrical devices, including those on relays, interrupters, switches, contactors, terminal blocks, and circuit breakers and other circuit protection devices. (4) Connectors, including feed-through connectors. (5) Connector accessories. (6) Electrical grounding and bonding devices and their associated connections. (7) Electrical splices.		(1) Wires and cables. (2) Bus bars. (3) The termination point on electrical devices, including those on relays, interrupters, switches, contactors, terminal blocks and circuit breakers, and other circuit protection devices. (4) Connectors, including feed-through connectors. (5) Connector accessories. (6) Electrical grounding and bonding devices and their associated connections. (7) Electrical splices.	No	F10	A								Applicable	AC 25-1701-1
(8) Materials used to provide additional protection for wires, including wire insulation, wire sleeving, and conduits that have electrical termination for the purpose of bonding. (9) Shields or braids. (10) Clamps and other devices used to route and support the wire bundle. (11) Cable tie devices. (12) Labels or other means of identification. (13) Pressure seals.		(8) Materials used to provide additional protection for wires, including wire insulation, wire sleeving, and conduits that have electrical termination for the purpose of bonding. (9) Shields or braids. (10) Clamps and other devices used to route and support the wire bundle. (11) Cable tie devices. (12) Labels or other means of identification. (13) Pressure seals. (14) EWIS components inside shelves, panels, racks, junction boxes, distribution panels, and back-planes of equipment racks, including, but not limited to, circuit board back-planes, wire integration units, and external wiring of equipment.	No	F10									Applicable	AC 25-1701-1
(b) The definition in subparagraph (a) of this paragraph covers EWIS components inside shelves, panels, racks, junction boxes, distribution panels, and back-planes of equipment racks, including, but not limited to, circuit board back-planes, wire integration units and external wiring of equipment.			No	F10										
(c) Except for the equipment indicated in subparagraph (b) of this paragraph, EWIS components inside the following equipment, and the external connectors that are part of that equipment, are excluded from the definition in subparagraph (a) of this paragraph:		(b) Except for the equipment indicated in paragraph (a)(14) of this section, EWIS components inside the following equipment, and the external connectors that are part of that equipment, are excluded from the definition in paragraph (a) of this section:	No	F10	A								Applicable	AC 25-1701-1
(1) Electrical equipment or avionics that is qualified to environmental conditions and testing procedures when those conditions and procedures are - (i) Appropriate for the intended function and operating environment, and (ii) Acceptable to the Agency.		1) Electrical equipment or avionics that are qualified to environmental conditions and testing procedures when those conditions and procedures are— (i) Appropriate for the intended function and operating environment, and (ii) Acceptable to the FAA.	No	F10	A								Applicable	AC 25-1701-1
(2) Portable electrical devices that arenot part of the type design of the aeroplane. This includes personal entertainment devices and laptop computers.		(2) Portable electrical devices that are not part of the type design of the airplane. This includes personal entertainment devices and laptop computers.	No	F10	A								Applicable	AC 25-1701-1
(3) Fibre optics.		(3) Fiber optics.	No	F10	Applicable	Compliant							Applicable	AC 25-1701-1
CS 25.1703 Function and Installation; EWIS (See AMC 25.1703)	25.1703	Function and installation: EWIS.											Applicable	
(a) Each EWIS component installed in any area of the aeroplane must: (1) Be of a kind and design appropriate to its intended function. (2) Be installed according to limitations specified for the EWIS components. (3) Function properly when installed. (4) Be designed and installed in a way that will minimise mechanical strain.		(a) Each EWIS component installed in any area of the aircraft must: (1) Be of a kind and design appropriate to its intended function. (2) Be installed according to limitations specified for the EWIS components. (3) Perform the function for which it was intended without degrading the airworthiness of the airplane. (4) Be designed and installed in a way that will minimize mechanical strain.	No	F10	applicable	Design and Analysis	Reviews and Inspection		A	Design and Analysis			Applicable	AC 25.1353-1A

APPENDIX C Air Circulars

Please find included in this section the text of selected Air Circular reports which provide the necessary context to inform the design efforts relating to certain sections of section 25. In the final document these will be included as embedded objects that can opened in full text by clicking on the icon or image. A sample embedded document, AC 1353-1A is included below.

- AC 20-32B
-AC 25-9A
-AC 25-16
-AC 25-795-3
-AC 25.869-1A
-AC 20-144
-AC 20-128A
-AC 25.981-1C
-AC 25-30
-AC 25-994-1
-AC 20-135
-AC 25.1435-1
-AC 25.1362-1
-AC 25-795-7
-AC 1353-1A
-AC 20-107
-AC 20-29B
-AC 20-175
-AC 25-795-3
-AC 25-795-9
-AC 120-80A
-AC 25.795-9
-AC 20-136B
-AC 20-155A
-AC 20-158A
-AC 1360-1
-AC 25.1455-1
-AC 25-27A
-AC 120-42B

-AC.1701-1

U.S. Department of Transportation
Federal Aviation Administration

Advisory Circular

Subject: ELECTRICAL EQUIPMENT AND INSTALLATIONS

Date: 10/22/07

Initiated by: ANM-100

AC No: 25.1353-1A

1. PURPOSE. This advisory circular (AC) provides guidance for demonstrating compliance with the transport category airplane certification requirements of § 25.1353 *Electrical equipment and installations*.

2. APPLICABILITY.

a. The guidance provided in this document is directed to airplane manufacturers, modifiers, foreign regulatory authorities, Federal Aviation Administration (FAA) transport airplane type certification engineers, and designees.

b. This material is neither mandatory nor regulatory in nature and does not constitute a regulation. It describes acceptable means, but not the only means, for demonstrating compliance with the applicable regulations. We will consider other methods of demonstrating compliance that an applicant may elect to present. While these guidelines are not mandatory, they are derived from extensive FAA and industry experience in determining compliance with the relevant regulations. On the other hand, if we become aware of circumstances that convince us that following this AC would not result in compliance with the applicable regulations, we will not be bound by the terms of this AC, and we may require additional substantiation as a basis for finding compliance.

c. This material does not change or create any additional regulatory requirements nor does it authorize changes in or permit deviations from existing regulatory requirements.

d. Terms such as "shall" or "must" are used in this AC only in the sense of ensuring applicability of this particular method of compliance when the acceptable method of compliance described herein is used.

APPENDIX D Major Subsystem and Component Cut Sheets and Manuals

The following section includes critical component data provided by part manufacturers relating to key components of the current design.

AMS 5812

Amplified pressure sensor with analog and digital output (I²C)

FEATURES

- Amplified, calibrated and temperature compensated pressure sensor
- Differential/relative, bidirectional differential, absolute and barometric versions
- Ratiometric analog voltage output of 0.5 – 4.5V
- Digital output for pressure and temperature via I2C interface
- High accuracy at RT
- Small overall error within a temperature range of -25 ... 85°C
- Supply voltage range 4.75…5.25V
- High long term stability
- Programmable I²C-address
- Small DIP package
- Ready to use
- RoHS compliant

GENERAL DESCRIPTION

AMS 5812 pressure sensors are a series of high-precision OEM sensors with an analog 0.5 – 4.5 V voltage output and a digital I2C-interface. They are calibrated and compensated for across a wide temperature range of -25 to +85°C.

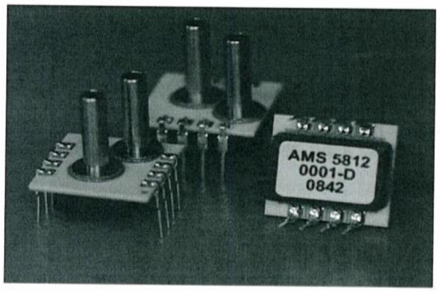
AMS 5812 comes as a dual in-line package (DIP) for assembly on printed circuit boards (PCBs) and is fully operational without the need for any additional components. The electrical connection is made via the DIP solder pins; pressure is connected via two vertical metal tubes.

AMS 5812 combines micromachined, high quality piezoresistive measuring cells with a modern, signal conditioning mixed-signal ASIC on a ceramic substrate. This enables high precision measurements and excellent drift and long-term stability.

The sensors in the AMS 5812 series are available for various applications and pressure ranges: differential (relative) devices in pressure ranges from 0 – 0.075 PSI up to 0 – 100 PSI, absolute pressure variants for 0 – 15 PSI, 0 - 30 PSI and a barometric type. Bidirectional differential devices are available from -0.075 /+ 0.075 PSI up to -15/ +15 PSI. Custom specific pressure ranges and modifications are available on request.

TYPICAL APPLICATIONS

- Static and dynamic pressure measurement
- Barometric pressure measurement
- Vacuum monitoring
- Gas flow
- Fluid level measurement
- Medical instrumentation
- Heating, Ventilation and Air Conditioning (HVAC)



analog microelectronics

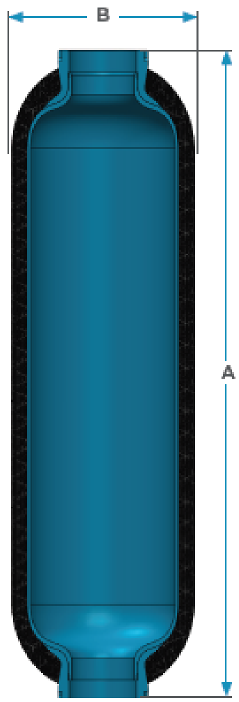
Analog Microelectronics GmbH
An der Fahrt 13, D – 55124 Mainz

Phone:+49 (0)6131/91 0730-0
Fax: +49 (0)6131/91 073-30
Internet: www.analogmicro.de
E–Mail: info@analogmicro.de

May 2012 - Rev. 2.0

Selection of tank manufacturer is still in final stages of review. All vendors remaining for consideration at this stage meet the essential safety and functionality requirements of design. Acquisition will be based on a balancing of various beneficial elements offered by each manufacturer. Data from potential source Steel Head is included to provide understanding of current industry capabilities for this crucial component.

HYDROGEN GAS STORAGE
350 BAR - 700 BAR



POTENTIAL APPLICATIONS

- Unmanned air vehicles
- Robotics
- Small Vehicles

SPECIFICATIONS

- Weight optimized Type 3 Pressure Vessel
- Maximum Operating Pressure: 414 - 700 Bar
- Minimum Burst Pressure: 788 - 1575 Bar
- Safety: Benign leak-before-burst avoids catastrophic failure
- Liner: Seamless, impermeable 6061-T6 Aluminum
- Structural Shell: Carbon fiber and epoxy composite
- Protective Barrier: Glass fiber and epoxy composite
- High thermal conductivity and specific heat of Aluminum liner achieves a better fill capacity under fast-fill conditions

NOMINAL VOLUME L*	OPERATING PRESSURE BAR**	DIMENSION A MM	DIMENSION B MM	WEIGHT (KGS)	KGS OF H2
10	414	657	180	12.7	0.26
10	700	657	190	16.0	0.36

*Custom volumes available upon request.
**Additional pressures available upon request.

AMS 5812
Amplified pressure sensor with analog and digital output (I²C)

MAXIMUM RATINGS

Parameter	Minimum	Typical	Maximum	Units
Maximum supply voltage: V_S (max)			6.0	V
Operating temperature: T_{op}	-25		85	°C
Storage temperature: T_{amb}	-40		125	°C
Common mode pressure p_{CM} [1]			175	PSI

Table 2: **Maximum ratings**

Notes:

1) The common mode pressure is defined as the maximum pressure that can be applied on both pressure ports of a differential pressure sensor simultaneously without damaging the sensors housing.

SPECIFICATIONS

All parameters apply to V_S = 5.0V and T_{op} = 25°C, unless otherwise stated.

Parameter	Minimum	Typical	Maximum	Units
Analog output signal (pressure only) [2]				
@ specified minimum pressure (see "pressure range")[1]		0.5		V
@ specified maximum pressure (see "pressure range")[1]		4.5		V
Full span output (FSO) [3]		4		V
without pressure (bidirectional differential)		2.5		V
Digital output signal (pressure) [4]				
@ specified minimum pressure (see "pressure range")[1]		3277		counts
@ specified maximum pressure (see "pressure range")[1]		29491		counts
Full span output (FSO) [3]		26214		counts
without pressure (bidirectional differential)		16384		counts
Digital output signal (temperature) [5]				
@ minimum temperature T = -25°C		3277		counts
@ maximum temperature T = 85°C		29491		counts
Accuracy [6] **(pressure measurement) @ T = 25°C**				
Ultra low pressure sensors (0.075, 0.15 PSI)			±1.5	%FSO
Low pressure sensors (0.3, 0.8, 1.5 PSI)			±1.0	%FSO
Standard pressure sensors			±0.5	%FSO
Overall error [7] **(pressure meas.) @ T = -25...85°C**				
Ultra low pressure sensors (0.075, 0.15 PSI)			±2.0	%FSO
Low pressure sensors (0.3, 0.8, 1.5 PSI)			±1.5	%FSO
Standard pressure sensors			±1.0	%FSO
Total error for temperature measurement				
All types of AMS 5812 T = -25...85°C			±3.0	%FSO
Long term stability			<0.5	%FSO/a
Ratiometricity error (@V_S = 4.75 …5.25V)			500	ppm

GO REGULATOR

LG-1 Series

Ultra Miniature Pressure Regulator

The LG-1 is an ultra-miniature pressure regulator that has many of the same features found in the time tested design of the CPR-1 & PR-1 Series pressure regulators. Designed for surface, panel or manifold mounting, the LG-1 offers the utmost in versatility to the systems designer. It's low internal volume of less than 2.7cc makes the LG-1 the perfect choice for systems that require rapid purge cycles. Standard features permit using this regulator in a wide variety of services, including corrosive fluids. The LG-1 can be tailored to virtually any application by utilizing the optional features. All of this is attainable while achieving as low as 0.2% accuracy during supply pressure fluctuations. This regulator is designed to allow the construction of compact and sophisticated analytical instrumentation where the optimum in pressure control is required and space is at a premium.

Features & Specifications

- Gas or liquid service
- 316L stainless steel construction
- Internal volume is less than 2.7cc
- Electropolished body with better than 25 Ra finish in diaphragm cavity
- 20 micron inlet filter
- Bubble-tight shutoff
- Outlet pressure ranges are 0–10, 0–25, 0–50, 0–100, 0–250 and 0–500 psig
- Cv flow coefficient 0.025 or 0.06
- Option: surface mount (for manifolds)

pressure regulators

GO Regulator
405 Centura Court - PO Box 4366 - Spartanburg, SC 29303
Phone (864) 574 7966 Fax (864) 574 5608
www.goreg.com • sales@goreg.com

To control the rigorous system pressure demands informed by the sensors detailed above the design makes use of the Ultra Miniature LG-1 series produced by GO Regulator.

LG-1 Series

How to Order

LG1 –

BODY MATERIAL
- **1** 316L stainless steel
- **2** Brass
- **3** Aluminum
- **4** Monel®

PORT CONFIGURATION
- **A** Standard

For more port configurations, see page 35.

PORT TYPE
- **0** ¼" FNPT (all ports)
- **1** Surface mount (consult factory for configurations)
- **A** ⅛" FNPT (all ports)
- **B** ¼" FNPT inlets; ⅛" FNPT outlets

SURFACE FINISH OF DIAPHRAGM CAVITY
- **1** < 25 Ra

SEAT MATERIAL
- **A** Tefzel®
- **C** Polyimide
- **H** PCTFE (formerly Kel-F® 81)
- **I** High density Teflon®
- **D** PEEK™

FLOW COEFFICIENT (Cv)
- **3** 0.06
- **C** 0.025

CAP ASSEMBLY
- **1** Hand knob (0–100 psig maximum)
- **2** T handle
- **3** T handle, panel mount
- **4** Hand knob, panel mount (0–100 psig maximum)
- **8** Tamper-proof
- **E** Tamper-proof, panel mount

DIAPHRAGM FACING/BACKING/ O-RING MATERIAL
- **1** Tefzel® ring/stainless steel/Teflon®
- **7** Tefzel® ring/stainless steel/Viton®
- **8** Tefzel® ring/Inconel®/Teflon®
- **H** Tefzel® ring/Inconel®/Viton®

DIAPHRAGM TYPE
- **1** Standard, Nylon dia. slip ring (170° F maximum temperature)
- **2** Standard, Polyimide dia. slip ring (high temperature service)

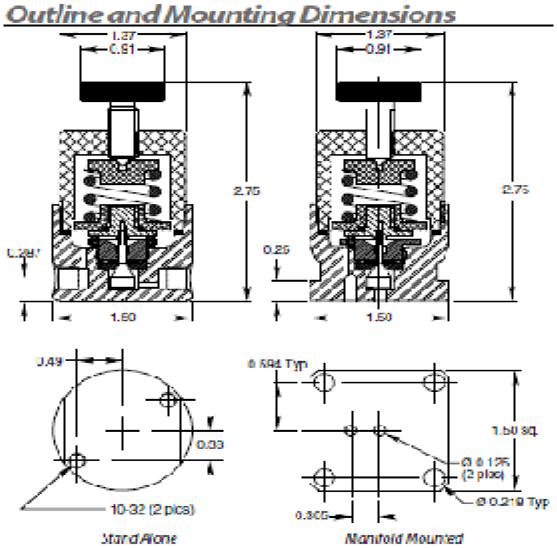
OUTLET RANGE
- **C** 0–10 psig
- **D** 0–25 psig
- **E** 0–50 psig
- **G** 0–100 psig
- **I** 0–250 psig (requires T-handle or tamper-proof)
- **J** 0–500 psig (requires T-handle or tamper-proof)

NOTE: The choices above represent an abbreviated list of the more commonly ordered options. For a complete listing of all available options, please see the Selection Wizard on the GO website at www.goreg.com or contact the factory.

Maximum Temperature & Operating Inlet Pressures

SEAT MATERIAL	MAXIMUM TEMPERATURE	@	MAXIMUM OPERATING INLET PRESSURE
Tefzel®	150° F (65° C)	@	3600 psig (24.82 MPa)
High density Teflon®	150° F (65° C)	@	3600 psig (24.82 MPa)
PCTFE (formerly Kel-F® 81)	175° F (80° C)	@	6000 psig (41.37 MPa)
Polyimide	500° F (260° C)	@	3600 psig (24.82 MPa)
Polyimide	175° F (80° C)	@	6000 psig (41.37 MPa)
PEEK™	500° F (260° C)	@	3600 psig (24.82 MPa)
PEEK™	175° F (80° C)	@	6000 psig (41.37 MPa)

Outline and Mounting Dimensions

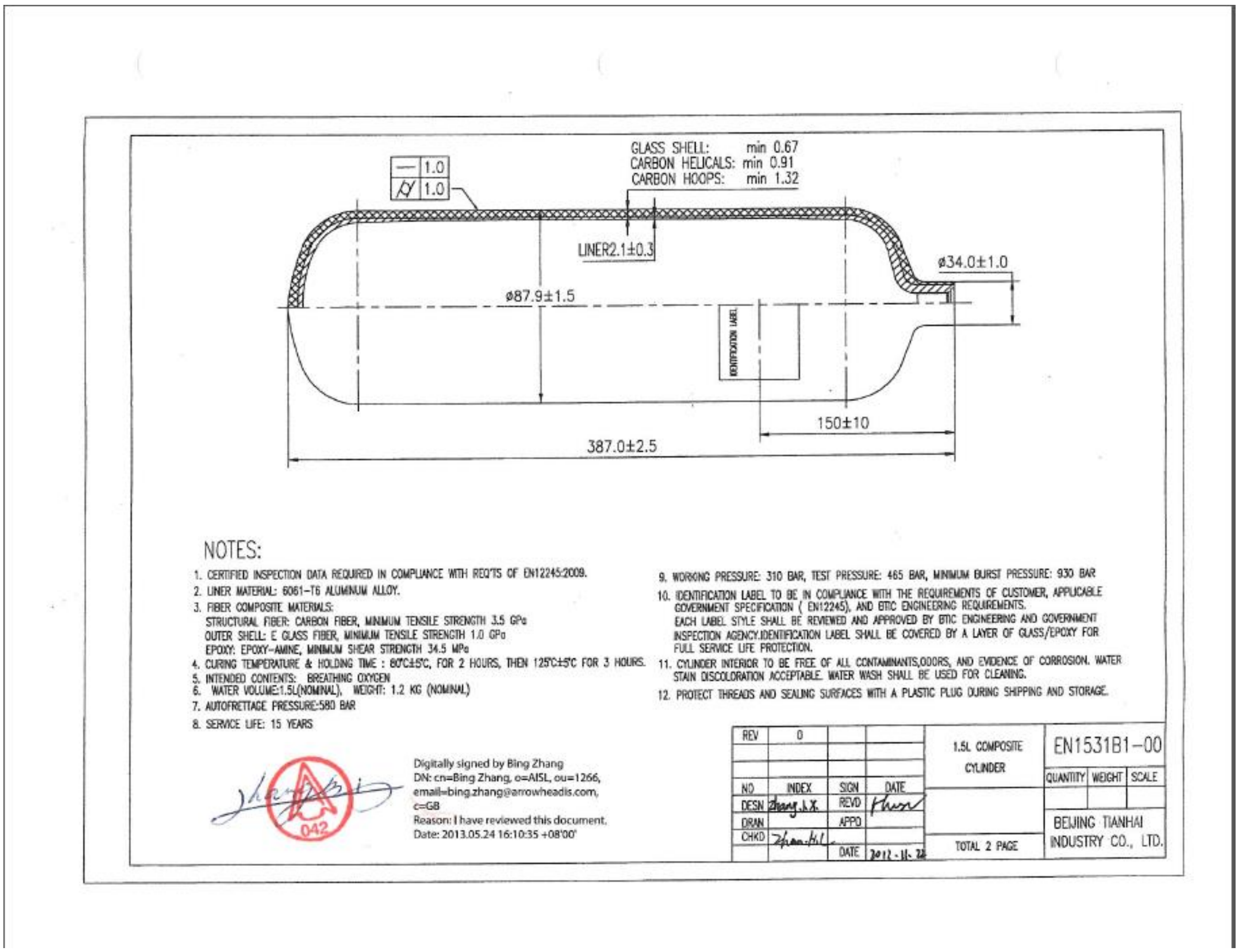


Inconel® and Monel® are registered trademarks of Special Metals Corporation.
Teflon® and Tefzel® are registered trademarks of the DuPont Company.
Kel-F® is a registered trademark of 3M Company.
PEEK™ is a trademark of Victrex PLC.
Viton® is a registered trademark of DuPont Dow Elastomers.

74 | **GO Regulator Single Stage Pressure Regulators**

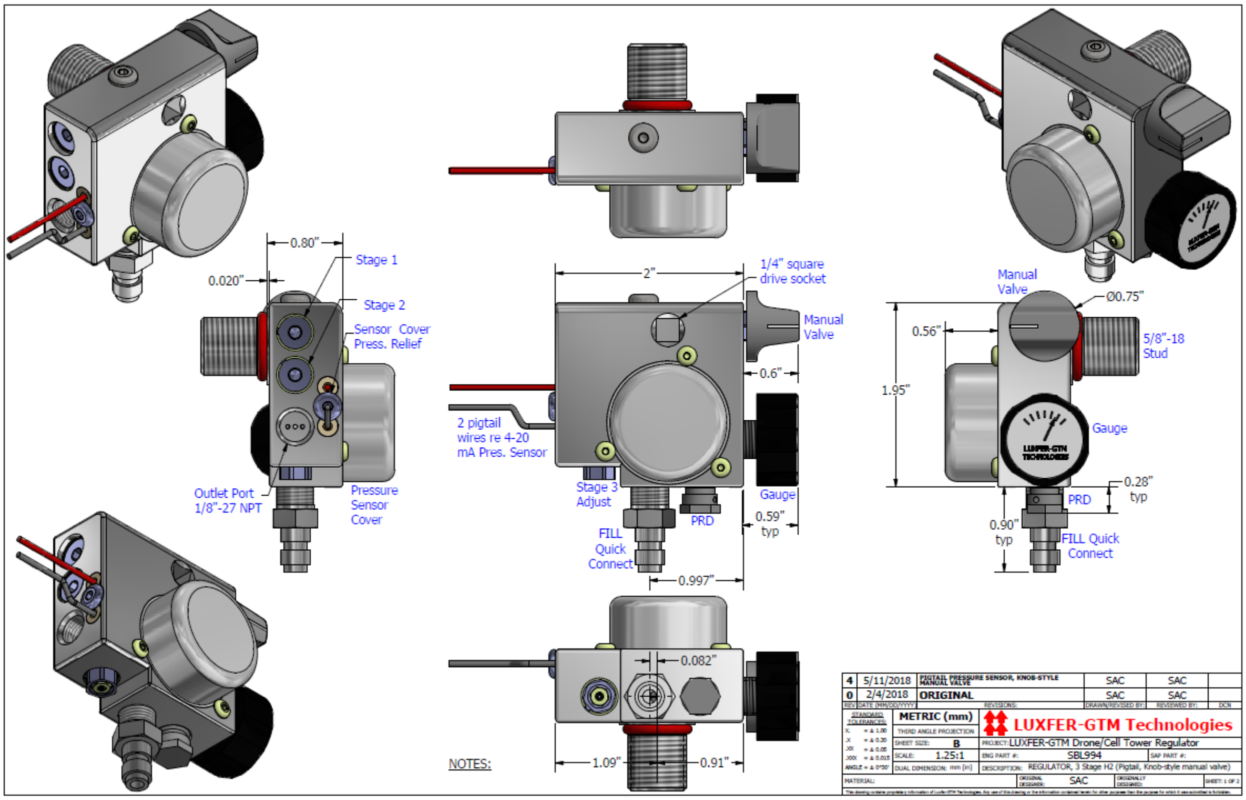
End of data sheet insert.

Luxfer GTM Lightweight Pressurized Cylindrical Hydrogen Tank Cut Sheet



Luxfer GTM Pressure Sensor/Regulator Cut Sheets

The following sensor/regulator design has been specifically created to fulfill the demands of our current design. These sensors have been created to be ultra-lightweight while retaining ability to precisely assess and control fuel flow and to provide this data to onboard electronics so as to adjust to the demands of the flight.



DRAFT
Aircraft Fuel Cell System (AFCS) Environmental Test Plan

Customer: FAA		
Approvals (required for each revision)		
Approver Title & Printed Name	**Signature**	**Date**
Program Manager,		
Engineering Manager,		
Design Engineer		
Systems Engineering		
Manufacturing Engineer, TBD		

Infinity Fuel Cell and Hydrogen, Inc.
431A Hayden Station Road
860-688-6500 tel
860-688-6511 fax
www.infinityfuel.com

Modification Revision	Date	Modification Request Number	Document Evolution (Pages removed, added or modified)	Modification Reason (If no Modification Request)
0	1-28-2019	/	Draft	/

1 SCOPE

1.1 Identification

This Environmental Test Plan establishes the requirements for qualifications and environmental testing of a Fuel Cell System for the UAV Factory Penguin Unmanned Aerial System (UAS).

This Test Plan details testing anticipated for the end item production system detailed in the Product Performance Specification X19-001.

2 APPLICABLE DOCUMENTS

2.1 Government and Standards Organizations Reference Documents

- MIL-STD-704 Aircraft Electric Power Characteristics
- MIL-STD-810G - Department of Defense Test Method Standard Environmental Engineering Considerations and Laboratory Tests
- RTCA/DO-160E Environmental Conditions and Test Procedures for Airborne Equipment
- MIL-STD-461F - Department of Defense Interface Standard Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment
- MIL-STD-464C - Department of Defense Interfaces Standard Electromagnetic Environmental Effects Requirements for Systems

2.2 Infinity Documents

- xxx – Infinity Part Marking and Serialization Instruction
- xxx - Product Finish Specification
- xxx – Supplier Quality Requirements

3 QUALITY ASSURANCE TEST PROVISIONS

3.1 General

The Fuel Cell System comprises all fuel cell components and specifications necessary to provide compliance with the Product Performance Specification.

This document focuses on requirements that will be verified by environmental and other testing. A complete quality assurance compliance will include all quality requirements including those identified here. This document also compares initial currently defined test requirements for the Drone fuel cell power and energy system to “RTCA/DO-160E Environmental Conditions and Test Procedures for Airborne Equipment”.

The following table documents the expected verification evidence needed to confirm the product meets the environmental and related performance requirements for the drone powerplant application. The 'ID' is the alphanumeric code used to uniquely identify each requirement.

'Method' generically identifies whether the verification evidence will be an:

- Inspection (I),
- Demonstration (D),
- Analysis (A) or
- Test (T).

A demonstration is normal operation of the product. This is differentiated from a test which requires specific initial conditions, typically at boundary conditions, and measurement or data collection using equipment that is not part of the delivered product. 'Artifact' expands on the verification method and identifies the type of file that would be retained and presented during a quality audit as evidence the requirement is met.

3.1.1 Preliminary Environmental and Related Requirements Verified by Test

The following summarizes relevant AFCS requirements to be verified by test

100- AFCS-101 Peak Power

The Fuel Cell System shall achieve peak power of 1,300 Watts minimum (threshold), 2000 Watts (objective), regardless of efficiency or Voltage output.   The Fuel Cell System shall output power with DC Voltage ranging from 38Vdc to 26Vdc.

100- AFCS-102 Maximum Continuous Power

At no time during the Fuel Cell System’s rated service life shall maximum continuous Power output degrade below the requirements of 100-AFCSE-101 and 100- AFCS-510.

[100-AFCS-107] Electrical

At a minimum, the Fuel Cell System will have electrical interface, in accordance with Table 3-2.

Electrical Interface to the Fuel Cell Power System

Signal Name	Description	IN/OUT
Power In	12Vdc to 28Vdc input power to fuel cell system (<18W)	In
Ground	Ground reference for system	In/out
Power Out	26Vdc to 38Vdc output power to aircraft (30W to 2000W)	Out
Communications	As defined in section 100-AFCS-221,	
Power Enable (optional)	Digital or analog input power on function (as required)	In

100- AFCS-500 Operating Temperature

The Fuel Cell System shall operate in an ambient temperature range of -30C to +57C in a density altitude defined by 100-AFCS- 509 and in a relative humidity (RH) range defined by 100-AFCS-504.

To achieve operation. ground support procedures can be applied to start up the Fuel Cell System when integrated in the AFCS Module and aircraft).

100-AFCS-501 Orientation

All performance requirements shall be met with the Fuel Cell System at all aircraft flight attitudes between and including 0 and +/- 60 degrees from the horizontal plane.

100- AFCS-502 Non-Operating Temperature - Low

The Fuel Cell Module shall survive non-operating in ambient air temperature down to -40C.

100-AFCS-503 Non-Operating Temperature - High

The AFCS Module shall survive non-operating in an ambient air temperature up to 60C minimum threshold, and 85C objective. (to be revised)

100-AFCS-504 Humidity

The Fuel Cell Module shall be designed to operate after being stored per manufactures recommendation in a 100% humidity environment for at least 30 days at 40C. Method 103B in MIL-STD-202 can be used as a guide. (to be evaluated)

100-AFCS-505 Dust

The AFCS Module shall operate in a dust environment. MIL-STD-810, Method 510.5 can be used as a guide. Considerations for the Fuel Cell module in a dust environment shall be addressed (i.e. provisions for filtering of inlet/outlet air should be addressed).

100-AFCS-506 Sand

The Fuel Cell System shall be able to operate in a sand environment. DO-160 Section 12

100-AFCS-507 Vibration

The Fuel Cell System shall survive TBD random vibration environments.

100-AFCS-508 Shock & Acceleration

The Fuel Cell System shall operate without a drop in power and survive through nominal TBD forward axial acceleration e.g. typical launch profile and nominal TBD sustained deceleration (all orientations) typical recovery profile.

Verification to requirements shall be demonstrated with proof testing in accordance with MIL-STD-810G Method 516.6, Procedure I- Functional shock,

100-AFCS-509 Altitude

The Fuel Cell System shall operate in a density altitude range between -1,000 ft and 20,000 ft

100- AFCS-510 Altitude Power

At a Density Altitude (DA) of 15,000 feet (0.7709 kg/m3) the peak power of the Fuel Cell shall be greater than 900 W.

100-AFCS-511 Electromagnetic Interface/Electrostatic Discharge and Compatibility

The Fuel Cell System will NOT be subjected to magnetic radiation, conducted emissions, conducted susceptibility or radiated emissions as a standalone assembly. The complete AFCS Module assembled in flight configuration shall be compliant with the applicable tests in MIL-STD-461F as described below.

Table 3-II: EMI/ESD Requirements Table

	EMI/ESD	
Low Frequency magnetic fields*	<1nT, 0-1kHz	Measured 25cm from board
Magnetic Radiation	MIL-STD-461F, RE101	Navy
Conducted Emissions	MIL-STD-461F, CE102	Figure CE101-4
Conducted Susceptibility	MIL-STD-461F, CS101 MIL-STD-461F, CS102	
Radiated Emissions	MIL-STD-461F, RE102	
Electrostatic Discharge		

*Desired, not required

100-AFCS-707

All electrical wires and connectors shall be water resistant achieving IP67 rating.

DO-160 and Internal Test Selection Approach

The approach for selection of tests is as follows:

1) Define initial intended application as propulsion power for unmanned 50lb TOW drone fixed wing aircraft

2) Define Objective level quality and performance requirements including environmental factors. Incorporating various customer defined requirements including:

- MIL-STD-810G - Department of Defense Test Method Standard Environmental Engineering Considerations and Laboratory Tests
- RTCA/DO-160E Environmental Conditions and Test Procedures for Airborne Equipment
- MIL-STD-461F - Department of Defense Interface Standard Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment

3) Define initial quality characteristic verification method for each requirement;

- Inspection (I),
- Demonstration (D),
- Analysis (A) or
- Test (T).

4) Summarize test/demonstration verification items in one table

5) Review DO-160 and relevant MIL specifications to determine areas of overlap and similarity

6) Develop a preliminary DO-160 compliance matrix for drone aircraft application.

Table X below summarizes anticipated internal tests required to demonstrate the un,m,anned drone power system can meet requiremennt of a system intended for dual commercial and military use.

Requirement Identifier	Description	Method	Artifact
100-AFCS-101	Peak Power	T	Test Results
100-AFCS-102	Maximum Continuous Power	T	Test Results
100-AFCS-107	Electrical	T	Test Results
100-AFCS-500	Temperature Operation Range	T	Test Results
100-AFCS-501	Gravity Orientation	T	Test Results
100-AFCS-502	Low Non-Op Temp	T	Test Results
100-AFCS-503	High Non-op Temp	T	Test Results
100-AFCS-504	Humidity	T	Test Results
100-AFCS-505	Dust	T	Test Results
100-AFCS-506	Sand	T	Test Results
100-AFCS-507	Random Vibration	T	Test Results
100-AFCS-508	Shock & Acceleration	T	Test Results
100-AFCS-509	Altitude	T/D	Test Results and or flight demo
100-AFCS-510	Power at Altitude	T/D	Test Results and/or flight demo
100-AFCS-511	EMI/EDC	T	Test
100-AFCS-707	Waterproofing	I/T	Bill of Material

Draft Compliance Test Matrix

The table below summaries Infinity draft drone requirements and compares to related DO-160 compliance tests.   Each is discussed in the following table.

Infinity Spec. I.D.	DO-160 Section	Name	MIL Requirement or comment	DO- 160 Requirement	DO-160 Test
100- AFCS-500	4.0	Operating Temp. Deg. C Low High	- 30 +57	-45 +70	4.5.2 4.5.4
100- AFCS-502 100-AFCS-503	4.0	Non-Op. Temp. Deg. C Low High	- 40 + 85	- 55 + 85	4.5.1 4.5.3
100- AFCS-509	4.0	Altitude	-1000 to + 20,000	25kft. (7.6km)	4.6.1
NA	5.0	Temp Variation	Possibly add?		5.3.1
100- AFCS-504	6.0	Humidity	100% 30 days 40 deg C non-op.		6.3.3
100- AFCS-508	7.0	Op. Shocks and Crash Safety	MIL-STD-810G Method 516.6, Procedure I- Functional shock	DO-160: 6 g Objective: higher for military	7.2.1 modified for higher loads for drone
100- AFCS-507	8.0	Vibration	MIL-STD-810G Method 514.6 ANNEX C for Category 4- Secured Cargo- Common Carrier AND Category 4- Composite Wheeled Vehicle		Likely 8.2.2.1 (Category S) But highly application dependent
NA	9.0	Explosion Proofness		Requires Review with FAA	
100- AFCS-707	10.0	Waterproofness		Recommended: Category R when installed in drone	10.3.3 Spray Proof Test
NA	11.0	Fluids		NA: Typical aircraft fluids do not apply in targeted drone	
100- AFCS-505	12.0	Dust	Required		12.3.1
100- AFCS-506	12.0	Sand	Required		12.3.2
NA	13.0	Fungus	TBD Stack materials not inherently susceptible		Verify by analysis
TBD	14.0	Salt Spray	Required for Navy?		Verify by analysis- filtration provided
NA	15.0	Magnetic Effect	Do not deflect compass. Unlikely to be required for drone		15.2 Verify by analysis if required
100- AFCS-107	16.0	Power Input (Power Out*)	Comment: DO-160 input is FC output. Test is relevant as output test		16.6 DC Power
100- AFCS-511	17.0	Voltage Spike	MIL-STD-461F CS106?	Applicable for drone and transport	17.0

100- AFCS-511	18.0	Audio Frequency Conducted Susceptibility - Power Inputs	MIL-STD-461F CS106 includes this frequency range	frequency normally harmonically related to the power source fundamental frequency.	18.0
100- AFCS-511	19.0	Induced Signal Susceptibility	MIL-STD-461F CS101, CS106 CS101: 30Hz to 150 Hz CS106: Transient	Applicable DO-160 Category BC?	
100- AFCS-511	20.0	Radio Frequency Susceptibility (Radiated and Conducted)	MIL-STD-461F, CS102, CS106, RE101?	10 kHz to 400 MHz	
100- AFCS-511	21.0	Emission of Radio Frequency Energy	MIL-STD-461F RE102 10 kHz to 18 GHz	Category B	
TBD	22.0	Lightning Induced Transient Susceptibility		Requires further analysis. Drone itself may not survive strike	TBD
TBD	23.0	Lightning Direct Effects		Requires further analysis. Drone itself may not survive strike	TBD
TBD	24.0	Icing		Not applicable to power system as a stand-alone system	TBD
100- AFCS-511	25.0	Electrostatic Discharge		Applicable. ESD possible hydrogen ignition hazard	TBD
TBD	26.0	Fire, Flammability		Likely applicable as a drone design consideration especially for H2 fuel storage	TBD

Discussion:

The intended application is as the prime power system for an unmanned 50lb maximum TOW drone capable of flight to an altitude of 20,000ft. As such the equipment is located in an unpressurized, ventilated location and the aircraft it is housed in is exposed to ambient conditions.

This drone power system application is the reference application being used to evaluate the categories of tests required both as internal requirements to meet anticipated military needs and as a starting point revaluation relative to manned applications.

While the unmanned drone application may not *require* the defined tests for certification, the design requirements are demanding. Operation is in an unpressurized enclosure, subject to an uncontrolled external environment. The system is required to survive often severe shock and vibration and maintain EMI/RFI compatibility and be stored and operate over wide temperature ranges.

DO-160 Relevant Tests Under Consideration

Equipment intended for installation in non-pressurized and non-controlled temperature locations on an aircraft that is operated at altitudes up to 25,000 ft (7,620 m) MSL.

Power Quality Test Matrix

Test Procedures

Temperature and Altitude

4.5 Temperature Tests

4.5.1 Ground Survival Low Temperature Test and Short-Time Operating Low Temperature Test

At the ambient pressure and with the equipment not operating, stabilize the equipment at the appropriate ground survival low temperature specified in Table 4-1 Maintain this temperature for at least three hours. Then with the equipment not operating, subject it to the short time operating
4-5

low temperature specified in Table 4-1 for a period of not less than 30 minutes. Place the equipment into the operating state and maintain the test chamber air temperature at the appropriate short time operating low temperature specified in Table 4-1. Operate the equipment for at least 30 minutes. Verify equipment operation per note 1 during this operating period. The test profile is shown graphically in Figure 4-1.

Note: 1) This test simulates temperature conditions that may be encountered by equipment while the aircraft is on the ground. In determining the level of performance required during the period of this test, the operational requirements of the particular equipment or systems shall be stated in the test procedure and report or in the specific equipment performance standard

2) *If the short time operating low temperature and operating low temperature are the same, the short-time operating low temperature need not be conducted. The ground survival low temperature test may not be deleted, even if the shorttime operating low temperature is identical to the operating low temperature.*

4.5.2 Operating Low Temperature Test

With the equipment operating, adjust the test air chamber air temperature to the appropriate operating low temperature specified in Table 4-1 at ambient pressure. After the equipment temperature has become stabilized, operate the equipment for a minimum of the two hours while maintaining the temperature of the air in the test chamber at the operating low temperature. DETERMINE COMPLIANCE WITH APPLICABLE EQUIPMENT PERFORMANCE STANDARDS during this operating period. The test profile is shown graphically in figure 4-2.

4.5.3 Ground Survival High Temperature Test and Short-Time Operating High Temperature Test

At ambient pressure and with the equipment not operating, stabilize the equipment at the appropriate ground survival high temperature of Table 4-1. Maintain this temperature for at least three hours. Then with the equipment not operating, subject it to the short-time operating high temperature specified in Table 4-1 for a period of not less than 30 minutes. Place the equipment into the operating state and maintain the test chamber air temperature at the appropriate short-time operating high temperature specified in Table 4-1. Operate the equipment for at least 30 minutes. DETERMINE COMPLIANCE WITH APPLICABLE EQUIPMENT PERFORMANCE STANDARDS during this operating period. The test profile is shown graphically in Figure 4-3.

Note: 1) This test simulates temperature conditions that may be encountered by equipment while the aircraft is on the ground. In determining the level of performance required during the period of this test, the operational requirements of the particular equipment or systems must be considered.

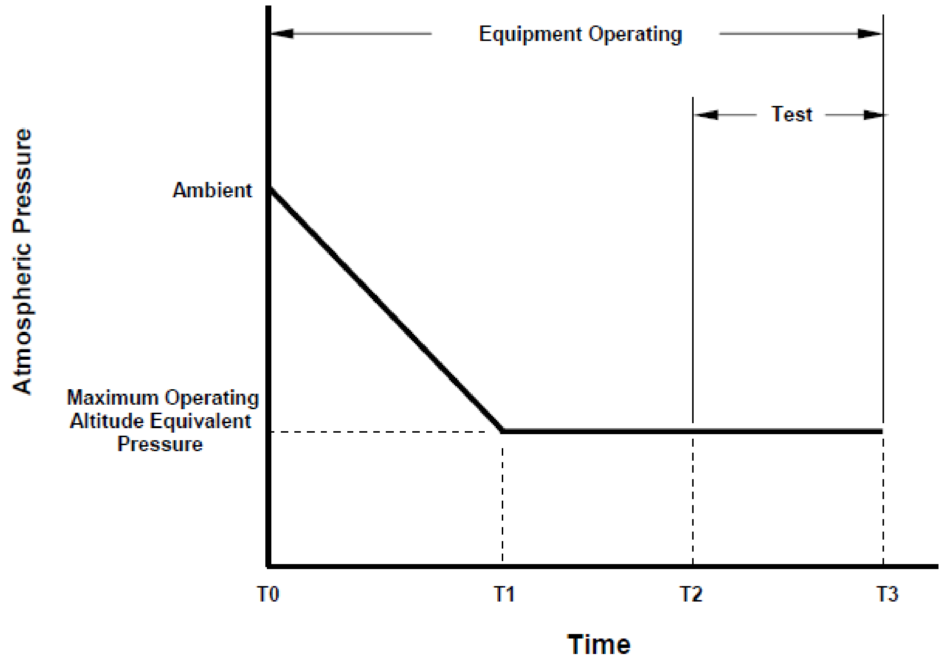
2) If the short-time operating high temperature and operating high temperature are the same, the short-time operating high temperature test need not be conducted. The ground survival high temperature test may not be deleted, even if the short-time high temperature is identical to the operating high temperature.

4-6

4.5.4 Operating High Temperature Test

With the equipment operating, adjust the test chamber air temperature to the appropriate operating high temperature specified in Table 4-1 at ambient pressure. After the equipment temperature has become stabilized, operate the equipment for a minimum of two hours while maintaining the temperature of the air in the test chamber at the operating high temperature. DETERMINE COMPLIANCE WITH APPLICABLE EQUIPMENT PERFORMANCE STANDARDS during the operating period. The test profile is shown graphically in Figure 4-4.

4.6 Altitude Test



Note: *1) Pressure change rate from T0 to T1 is not specified.*

2) T1 to T2 is time for equipment temperature to stabilize.

3) T2 to T3 is 2.0 hours, minimum.

Figure 4-6 Altitude Test

Section 5.0 Temperature Variation

Temperature Change Rates
The rates applicable to the temperature variation procedures defined in Subsection 5.3 are as follows:
Category A - For equipment external to the aircraft or internal to the aircraft:
10 degrees Celsius minimum per minute.

5.3.1 Test Procedure Categories A, B, and C

The temperature variation test (except for Categories S1 and S2) can be combined to

include the procedures of the ground survival low temperature test and short-time operating low temperature test, Paragraph 4.5.1, the operating low temperature test, Paragraph 4.5.2, the ground survival high temperature test short-time operating high temperature test, Paragraph 4.5.3, and the operating high temperature test, Paragraph 4.5.4. The following procedures shall apply:
a. If the test is a combined test, proceed in accordance with Paragraph 4.5.1, which describes the ground survival low temperature test and the short-time operating low temperature test, and Paragraph 4.5.2, the operating low temperature test. After completion of the test defined in Paragraph 4.5.1 and 4.5.2, proceed to Subparagraph c.
If the test is not a combined test, commencing at ambient temperature with the equipment operating, lower the temperature in the chamber towards the operating low temperature level at the applicable rates specified in Subsection 5.2.
b. Stabilize the equipment in the operating mode at this operating low temperature level.
c. Raise the temperature in the chamber towards the operating high temperature at the applicable rate specified in Subsection 5.2. During this temperature change, DETERMINE COMPLIANCE WITH THE APPLICABLE EQUIPMENT PERFORMANCE STANDARDS.
d. Stabilize the equipment at the operating high temperature. If this is a combined test, proceed in accordance with Paragraph 4.5.3, the ground survival high temperature test and short-time operating high temperature test, and subsequently Paragraph 4.5.4, the operating high temperature test. Maintain the equipment in a non-operating state for a minimum of 2 minutes.
e. Turn the equipment on and lower the temperature in the chamber towards the operating low temperature level at the applicable rate specified in Subsection 5.2. During this temperature change DETERMINE COMPLIANCE WITH THE APPLICABLE EQUIPMENT PERFORMANCE STANDARDS.
f. Stabilize the equipment temperature with the chamber at the operating low temperature, and then operate the equipment for at least one hour. Then turn off the equipment for 30 minutes, and restart the equipment while maintaining the chamber at the operating low temperature.
g. Change the temperature of the chamber towards the ambient temperature at the applicable rate specified in Subsection 5.2.
h. Stabilize the chamber and the equipment at ambient temperature. DETERMINE COMPLIANCE WITH THE APPLICABLE EQUIPMENT PERFORMANCE STANDARDS.
A minimum of two cycles (a. through h. above) shall be accomplished. If complete determination of compliance with applicable equipment performance standards can be accomplished during each temperature change period of a single cycle, then testing is required during the second cycle only. If the time during a temperature change period does not allow for complete determination of compliance with
5-3

applicable equipment performance standards, a sufficient number of cycles shall be accomplished so that complete compliance can be determined. When temperature rise induces a potential risk of condensation on the equipment under test, the humidity level of the air in the chamber should be controlled to eliminate this condensation. The test profile is shown graphically in Figure 5-1.
Note: If this is a combined test, it is not necessary to repeat the Ground Survival Low Temperature, Short-Time Operating Low Temperature, Ground Survival High

Temperature, and Short Time Operating High Temperature tests as defined in steps a. and d. above during the second cycle.

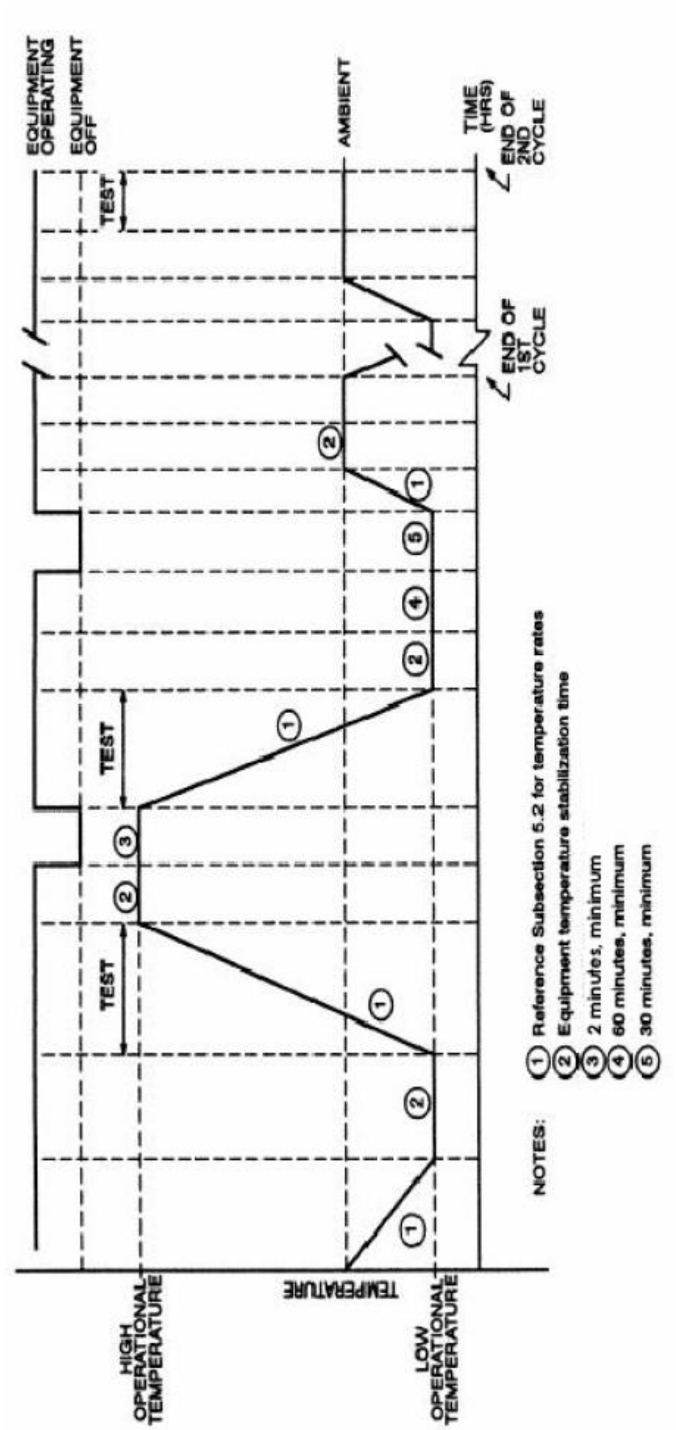


FIGURE 5-1 TEMPERATURE VARIATION TEST

Section 6.0

Humidity Category C - External Humidity Environment

Equipment may be required to be operated under conditions such that it is subjected to direct contact with outside air for periods of time in excess of that specified for the standard humidity environment.

Category C—External Humidity Environment

The test profile is shown graphically in Figure 6-3. The procedure shall be in accordance with the following steps:

Step 1: Install the test item in the test chamber, and ensure its configuration is representative of that used in actual service.

Step 2: Stabilize the test item at 30 ±2 $_{o}$C and 85 ±4 % RH.

Step 3: Over a two-hour period, ±10 minutes, raise the chamber temperature to 55 ±2 $_{o}$C and increase the RH to 95 ±4 %.
6-4

Step 4: Maintain the chamber temperature at 55 $_{o}$C with the RH at 95 ±4 % for six hours minimum.

Step 5: During the next 16-hour period, ±15 minutes, decrease the temperature gradually to 38 $_{o}$C or lower. During this period, keep the RH as high as possible and do not allow it to fall below 85 %.

Step 6: Steps 3, 4 and 5 constitute a cycle. Repeat these steps until a total of six cycles (144 hours of exposure) have been completed.

Step 7: At the end of the exposure period, remove the equipment from the test chamber and drain off (do not wipe) any condensed moisture. Within one hour after the six cycles are completed, apply normal supply power and turn on the equipment. Allow 15 minutes maximum following the application of primary power for the equipment to warm up. For equipment that does not require electrical power for operation, warm up the equipment for 15 minutes maximum by the application of heat not to exceed the short-time operating high temperature test as required by applicable equipment categories. Immediately following the warm-up period, make such tests and measurements as are necessary to DETERMINE COMPLIANCE WITH APPLICABLE EQUIPMENT PERFORMANCE STANDARDS.

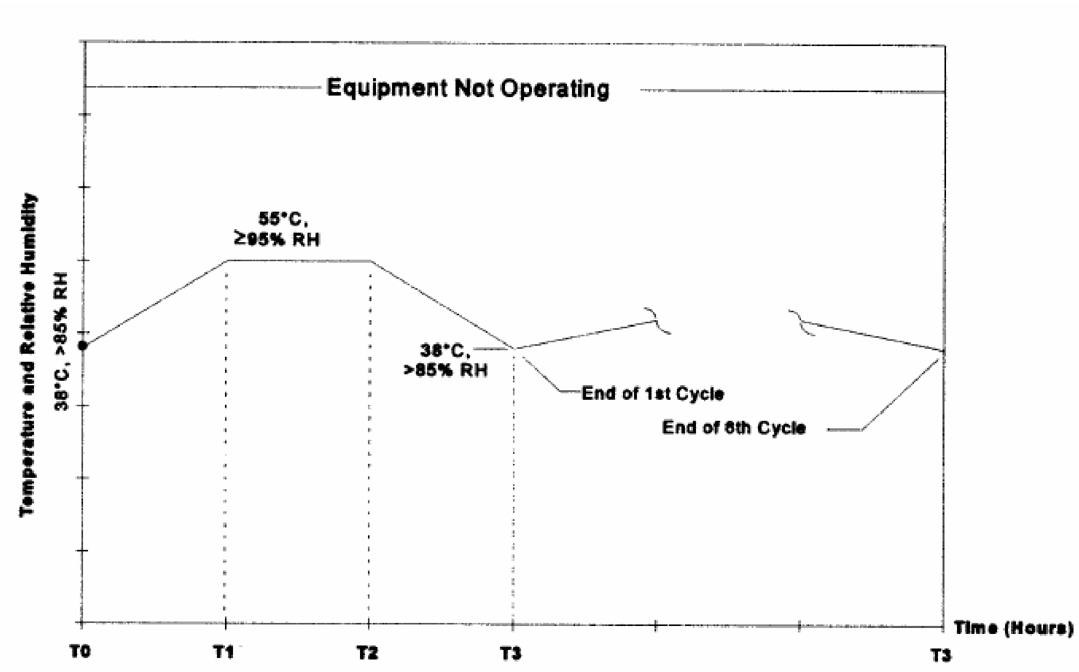


Figure 6-3 Category C - External Humidity Environment Test

NOTES:

1) T0 to T1 is 2 hours ±10 minutes.
2) T1 to T2 is 6 hours, minimum.
3) T2 to T3 is 16 hours ±15 minutes. During this period, relative humidity should not fall below 85%.
4) See paragraph 6.3.3, Step 7, for continuation of test after the end of the 6th cycle.

7.0 Operational Shocks and Crash Safety

7.1 Purpose of the Tests

The operational shock test verifies that the equipment will continue to function within performance standards after exposure to shocks experienced during normal aircraft operations. These shocks may occur during taxiing, landing or when the aircraft encounters sudden gusts in flight. This test applies to all equipment installed on fixed-wing aircraft and helicopters. Two operational shock test curves are provided; a standard 11 msec pulse and a low frequency 20 msec pulse. The 20 ms pulse may not be adequate to test against the effect of longest duration shocks on equipment that have its lowest resonance frequency (as per section 8) below 100Hz.
The crash safety test verifies that certain equipment will not detach from its mountings or separate in a manner that presents a hazard during an emergency landing. It applies to equipment installed in compartments and other areas of the aircraft where equipment detached during emergency landing could present a

hazard to occupants, fuel systems or emergency evacuation equipment. These tests do not satisfy FAR requirements for all equipment, e.g. seats and seat restraints.

Note: For fixed-wing aircraft: a complete installation demonstration, i.e. including aircraft acceleration loads (such as flight manoeuvring, gust and landing) in addition to the crash safety loads, may be accomplished by using the "Unknown or Random" orientations for the "sustained" test procedure.

Using a dummy load on the shock test apparatus may be necessary to ensure that the recorded shock pulse will be within the specified tolerances of Figure 7-2.

7.1.1 Equipment Categories

Category A

Equipment tested for standard operational shocks.

Category B

Equipment tested for standard operational shock and crash safety.

Category D

Equipment tested for operational low-frequency shock.

Category E

Equipment tested for operational low-frequency shock and crash safety.

Table 7-1 Crash Safety Sustained Test Levels

Aircraft Type	Test Type (5)	Sustained Test Acceleration (g Minimum) Direction of Load for Equipment Orientation				
		Up	Down	Forward	Aft	Side (4)
1. Helicopters (1)	F R	4.0 20.0	20.0 20.0	16.0 20.0	NA 20.0	8.0 20.0
2. Fixed-Wing Transport (2)	F R	3.0 9.0	6.0 9.0	9.0 9.0	1.5 9.0	4.0 9.0
3. Fixed-Wing Non-Transport (3)	F R	3.0 18.0	NA 18	18.0 18.0	NA 18.0	4.5 18.0
4. All Fixed-Wing	F R	3.0 18.0	6.0 18	18.0 18.0	1.5 18.0	4.5 18.0
5. Helicopter and All Fixed-Wing	F R	4.0 20.0	20.0 20.0	18.0 20.0	1.5 20.0	8.0 20.0

NOTES: *(1) Reference FAR 27.561*
(2) Reference FAR 25.561
(3) Reference FAR 23.561
(4) Side includes both left and right directions
(5) "F" is known and Fixed orientation. "R" is unknown or Random orientation.

8.2.1.1 Standard Vibration Test (Category S)

The standard vibration test for fixed wing aircraft demonstrates that equipment will meet its functional performance requirements in the aircraft.

9.0 Explosion Proofness
(requires review with FAA)

9.4 Equipment Categories
9.4.1 Category A Equipment
Category A equipment is designed so that:
a. Ignition of an explosive mixture is contained within the equipment without igniting an explosive atmosphere surrounding it and so that it meets the Category A tests specified in paragraph 9.7.1.
b. During normal operation, or as a result of any fault, the temperature of any external surface will not rise to a level capable of causing ignition (subparagraph 9.7.1.4).
Hermetically sealed

10.0 Waterproofness

10.1 Purpose of the Test
These tests determine whether the equipment can withstand the effects of liquid water being sprayed or falling on the equipment or the effects of condensation.
These tests are not intended to verify performance of hermetically sealed equipment. Therefore, hermetically sealed equipment may be considered to have met all waterproofness requirements without further testing. Equipment shall be considered hermetically sealed when the seal is permanent and airtight.
10.2 Equipment Categories

Recommended: Category R when installed in drone

Category Y
Equipment that is installed in locations where it is subjected to condensing water in the course of normal aircraft operations is identified as Category Y. For equipment intended for installation in such locations, the condensing water proof test procedure applies and the equipment is identified as Category Y.

Category W
Equipment that is installed in locations where it is subjected to falling water (generally the result of condensation) in the course of normal aircraft operations is identified as Category W. For equipment intended for installation in such locations, the drip proof test procedure applies and the equipment is identified as Category W.

Category R
Equipment installed in locations where it may be subjected to a driving rain or where water may be sprayed on it from any angle is identified as Category R. For equipment intended for installation in such locations, the spray proof test procedure applies. Equipment that has passed the Category R requirements may be considered to meet the Category W requirement

without further testing.

Category S
Equipment installed in locations where it may be subjected to the forces of a heavy stream of fluid such as would be encountered in aircraft de-icing, washing or cleaning operations is identified as Category S. For equipment intended for installation in such locations the continuous stream proof procedure applies. Water is used in this test to simulate the actual fluid forces. Equipment that has passed the Category S requirements may be considered to meet the Category W requirements without further testing.

10.3.3 Spray Proof Test
Mount the equipment according to the manufacturer's specification with all connectors and fittings engaged. With the equipment operating, subject it to a shower of water from a shower head nozzle as depicted in Figure 10-2. The water shall be directed perpendicular to the most vulnerable area(s) of the equipment as stated in the applicable equipment performance standards.
Each of the areas under test shall be subjected to the spray for a minimum of 15 minutes. If desired, the test may be applied simultaneously to more than one area at a time by using an appropriate number of showerheads. The showerhead shall be located not more than 2.5 m
10-3

from the area under test and shall emit a volume of water greater than 450 liters per hour. At the conclusion of the test DETERMINE COMPLIANCE WITH APPLICABLE EQUIPMENT PERFORMANCE STANDARDS.

11.0 Fluids: Not Applicable

12.0 Sand and Dust
12.1 Purpose of the Test
This test determines the resistance of the equipment to the effects of blowing sand and dust where carried by air movement at moderate speeds. The main adverse effects to be anticipated are:
a. Penetration into cracks, crevices, bearings and joints, causing fouling and/or clogging of moving parts, relays, filters, etc.
b. Formation of electrically conductive bridges.
c. Action as nucleus for the collection of water vapor, including secondary effects of possible corrosion.
d. Pollution of fluids.
Note: Consideration must be given in determining where in the sequence of environmental tests to apply this test procedure, as dust residue from this test procedure, combined with other environmental synergistic effects may corrode or cause mold growth on the test item and adversely influence the outcome of succeeding test procedures. Sand abrasion may also influence the results of the salt spray, fungus or humidity test procedures.

12.2 Categories of Equipment
Category D
Equipment installed in locations where the equipment is subjected to blowing dust in the course of normal aircraft operations is identified as Category D and should be tested as recommended in the following paragraphs.

Category S
Equipment, possibly with moving parts, installed in locations where the equipment is subjected to blowing sand and dust in the course of normal aircraft operations is identified as Category S and should be tested as recommended in the following paragraphs. Such equipment includes cockpit equipment or equipment at any other location not intentionally protected against sand and dust exposure.

Recommended Category D

13.0 Fungus Resistance: Note: Most materials do not appear susceptible – verify by analysis

13.1 Purpose of the Test
These tests determine whether equipment material is adversely affected by fungi under conditions favorable for their development, namely, high humidity, warm atmosphere and presence of inorganic salts.
Notes:
A. Fungi proximity to other materials, exposure to daily susceptible contaminants such as fluids during routine operation and maintenance, or equipment exposure to solar actinic effects - may break molecular bonds and reduce the item to sub-compositions which may be fungus nutrients.
B. This test shall not be conducted after Salt Spray or Sand and Dust. A heavy concentration of salt may effect the fungal growth, and sand and dust can provide nutrients, which could compromise the validity of this test (see Subsection 3.2, "Order of Tests").
13.2 General Effects
Typical problems caused by fungi growing on equipment are:
a. Microorganisms digest organic materials as a normal metabolic process, thus degrading the substrate, reducing the surface tension and increasing moisture penetration.
b. Enzymes and organic acids, produced during metabolism, diffuse out of the cells and onto the substrate and cause metal corrosion, glass etching, hardening of grease and other physical and chemical changes to the substrates.
c. The physical presence of microorganisms produces living bridges across components that may result in electrical failures.
d. The physical presence of fungi can also cause health problems and produce aesthetically unpleasant situations in which users will reject using the equipment.
The detrimental effects of fungal growth are summarized as follows:
a. Direct attack on materials. Nonresistant materials are susceptible to direct attack as fungus breaks these materials down and uses them as nutrients. This results in deterioration affecting the physical properties of the material. Examples of nonresistant materials are:

(1) Natural material. Products of natural origin (carbon based) are most susceptible to this attack.
(a) Cellulose materials (e.g., wood, paper, natural fiber textiles, and cordage).
(b) Animal- and vegetable-based adhesives.
13-2
(c) Grease, oils, and many hydrocarbons.
(d) Leather.
(2) Synthetic materials.
(a) PVC formulations (e.g., those plasticized with fatty acid esters).
(b) Certain polyurethanes (e.g., polyesters and some polyether).
(c) Plastics that contain organic fillers of laminating materials.
(d) Paints and varnishes that contain susceptible constituents.
b. Indirect attack on materials. Damage to fungus-resistant materials results from indirect attack when:
(1) Fungal growth on surface deposits of dust, grease, perspiration, and other contaminants (that find their way onto materiel during manufacture or accumulate during service) causes damage to the underlying material, even though that material may be resistant to direct attack.
(2) Metabolic waste products (i.e., organic acids) excreted by fungus cause corrosion of metals, etching of glass, or staining or degrading of plastics and other materials.
(3) The acidic waste products of fungus on adjacent materials that are susceptible to direct attack come in contact with the resistant materials.

14.0 Salt Fog: Note: Drone installation provides filtration

14.1 Purpose of the Test
This test determines the effects on the equipment of prolonged exposure to a salt atmosphere or to salt fog experienced in normal operations.
The main adverse effects to be anticipated are:
a. Corrosion of metals.
b. Clogging or binding of moving parts as a result of salt deposits.
c. Insulation fault.
d. Damage to contacts and uncoated wiring.
Note: The salt fog test shall not be conducted prior to the fungus resistance test (see Subsection 3.2, “Order of Tests”).

14.2 Categories of Equipment
Category S
When the equipment is installed in locations where it is subjected to a corrosive atmosphere in the course of normal aircraft operations, the equipment is identified as Category S and the salt spray test is applicable.

Category T
When the equipment is installed in locations where it is subjected to a severe salt atmosphere, such as equipment exposed directly to external unfiltered air on hovering aircraft that may operate or be parked near the sea, the equipment is identified as category

T and the severe salt spray test is applicable..

DO-160: 16.6.1 – NORMAL OPERATING CONDITIONS DC

DO-160: 16.6.1.1. – VOLTAGE (Average value) DC

Nominal voltages:

Equipment category	Nominal voltage
A	28V_{DC}
B	28V_{DC} or 14V_{DC}
Z	28V_{DC}
D	270V_{DC}

Definition of limit voltages:

Voltage at equipment terminals	28V_{DC}	270V_{DC}	14V_{DC}
Maximum	30.3	285	15.15
Minimum	22.0	235	11.0
Emergency operation	18.0	235	9.0

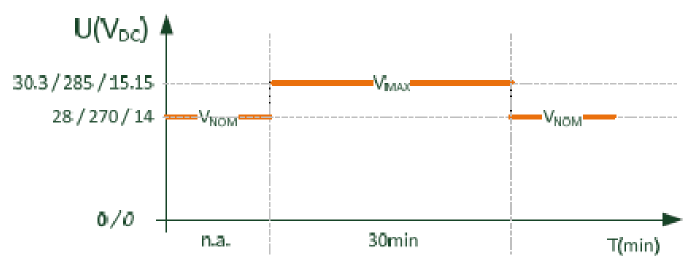
Test requirement 1:

The test may be run with abnormal levels to satisfy both normal and abnormal conditions.

Overvoltage to V_{MAX}

Cat. A, B, Z	Cat. D	Cat. B
28V_{DC}	270V_{DC}	14V_{DC}
30.3V_{DC}	**285V_{DC}**	**15.15V_{DC}**

for 30min



Test requirement 2:

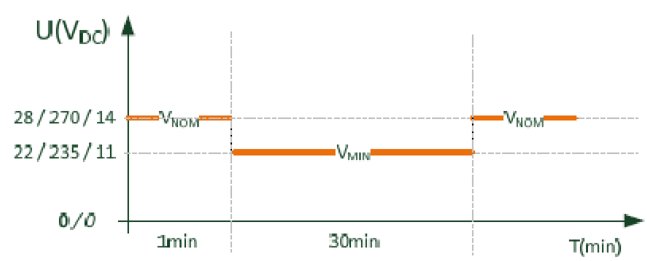
The test can be run with abnormal levels to satisfy both normal and abnormal conditions.

For Cat. A, B and Z equipment the test may be run with emergency levels to satisfy normal, abnormal and emergency conditions.

Undervoltage to V_{MIN}

Cat. A, B, Z	Cat. D	Cat. B
28V_{DC}	270V_{DC}	14V_{DC}
22.0V_{DC}	**235V_{DC}**	**11.0V_{DC}**

for 30min

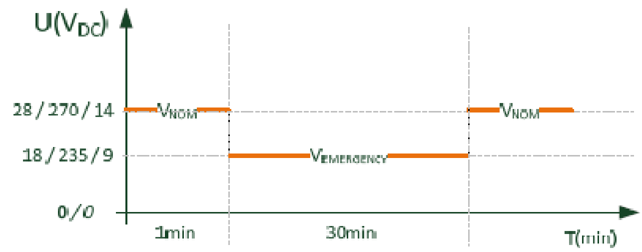


Test requirement 3:
Emergency condition

Undervoltage to $V_{EMERGENCY}$

Cat. A, B, Z	Cat. D	Cat. B
$28V_{DC}$	$270V_{DC}$	$14V_{DC}$
$18.0V_{DC}$	**$235V_{DC}$**	**$9.0V_{DC}$**

for 30min

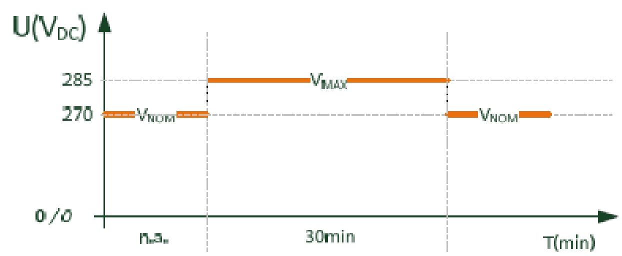


Test requirement 4:
Cat. D equipment only with positive lead connected to earth ground

Overvoltage to V_{MAX}

$28V_{DC}$	$270V_{DC}$	$14V_{DC}$
$30.3V_{DC}$	**$285V_{DC}$**	**$15.15V_{DC}$**

for 30min

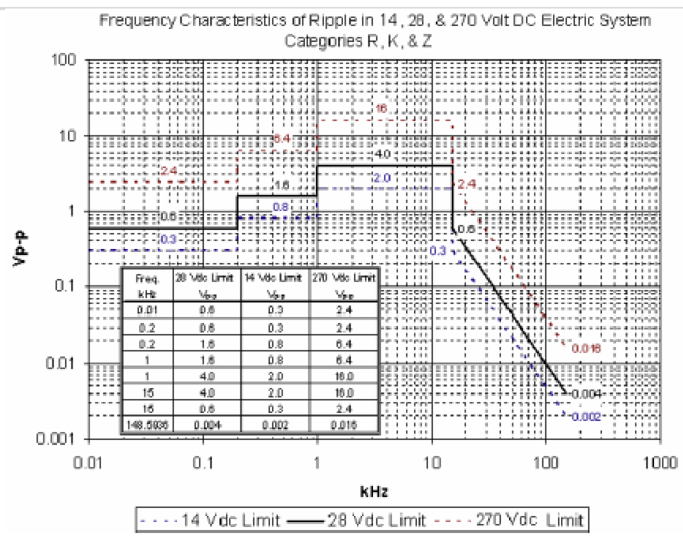


DO-160: 16.6.1.2. – RIPPLE VOLTAGE DC

Refer to Ripple definition in DO-160G chapter 18:

Audio Frequency Conducted Susceptibility

Figure 18-3



Freq. kHz	28 Vdc Limit Vp-p	14 Vdc Limit Vp-p	270 Vdc Limit Vp-p
0.01	0.6	0.3	2.4
0.2	0.6	0.3	2.4
0.2	1.6	0.8	6.4
1	1.6	0.8	6.4
1	4.0	2.0	16.0
15	4.0	2.0	16.0
15	0.6	0.3	2.4
148.5936	0.004	0.002	0.016

15 Magnetic Effect

15.1 Purpose of the Test

This test determines the magnetic effect of the equipment. This test ensures that equipment can operate properly without interference which may affect the nearby equipment, determining equipment compliance with the applicable equipment performance standard or assisting the installer in choosing the proper location of the equipment in the aircraft.

15.2 Test Description

The magnetic effect of the equipment shall be determined in terms of the deflection of a free magnet (e.g., uncompensated compass) in a uniform magnetic field (as produced by the earth) having a horizontal intensity of 14.4 A/m ±10% when the equipment under test is positioned on the east-west line through the pivot of a magnet.

Note 1: If the horizontal component of the magnetic field produced by the earth at the location of the test lab is within the tolerance stated above, the angular deflection used to determine equipment category in paragraph 15.3 shall be one degree (Dc = 1).

Note: 2: If the horizontal component of the magnetic field produced by the earth at the location of the test lab exceeds the tolerance stated above, the angular deflection used to determine the equipment category in Subsection 15.3 shall be adjusted using the following formula:

where,

Dc is the equivalent deflection angle to be used in determining equipment category.

16 Power Input (Regard as power output for DC source)

16.1 Purpose of the Test

This section defines test conditions and procedures for ac and dc electrical power applied to the terminals of the equipment under test. It covers the following electrical power supplies:

- 14 Vdc and 28 Vdc
- 115 Vrms ac and 230 Vrms ac at either a nominal 400 Hz frequency or over a variable frequency range which includes 400 Hz.

Equipment categories and frequency classes, test conditions and procedures for equipment using other electrical power supplies must be defined in applicable equipment performance standards.

16.2 Equipment Categories: Category B 18 VDC Applies

Test designation for equipment consists of:

Category reference:

- For ac equipment: A(CF), A(NF) or A(WF)
- For dc equipment: A, B, or Z

Followed by an additional letter for ac equipment only to indicate if the equipment has to be submitted to ac harmonic tests (letter H) or not (letter X).

16.6.1.1 Voltage (Average Value dc)

a. Definition:

Voltage (at equipment terminals)	All categories
Maximum:	30.3 V
Minimum:	22.0 V
Emergency Operation:	18.0 V

Note: Nominal dc network voltage is with regards to:
- Category A and Z equipment: 28 V
- Category B equipment: 28 V or 14 V

3
17-1

17.0 Voltage Spike

17.1 Purpose of the Test

This test determines whether the equipment can withstand the effects of voltage spikes arriving at the equipment on its power leads, either ac or dc. The main adverse effects to be anticipated are:

a. Permanent damage, component failure, insulation breakdown.
b. Susceptibility degradation, or changes in equipment performance.

17.2 Equipment Categories

Category A
Equipment intended primarily for installation where a high degree of protection against damage by voltage spikes is required is identified as Category A.
Category B
Equipment intended primarily for installations where a lower standard of protection against voltage spikes is acceptable is identified as Category B.

17.3 Test Setup and Apparatus

The transient generator used shall produce the waveform shown in Figure 17-1. A typical test setup is shown in Figure 17-2. Any method of generating the spike may be used if the waveform complies with Figure 17-1.

17.4 Test Procedure

With the equipment under test disconnected, the transient wave shape shall be verified to be in accordance with Figure 17-1.
With the equipment operating at its design voltage(s), apply to each primary power input a series of positive and negative spikes described in Figure 17-1. Apply a minimum of 50 transients of each polarity within a period of one minute.
Repeat the test for each operating mode or function of the equipment.
After application of the spikes, DETERMINE COMPLIANCE WITH APPLICABLE EQUIPMENT PERFORMANCE STANDARDS.
Note: If performance is measured during the application of this test, then the performance requirements contained in the applicable equipment performance

standard apply.

18.0 Audio Frequency Conducted Susceptibility - Power Inputs (Closed Circuit Test)
18.1 Purpose of the Test
This test determines whether the equipment will accept frequency components of a magnitude normally expected when the equipment is installed in the aircraft. These frequency components are normally harmonically related to the power source fundamental frequency.
18.2 Equipment Categories and Frequency Classes
18.2.1 Equipment Categories
Section 18 utilizes the same designators (CF, NF, and WF) as Section 16: The designator (CF) refers to electrical systems where the primary power is from a constant frequency (400 Hz) ac system, the designator (NF) refers to electrical systems where the primary power is from a narrow variable frequency (360 to 650 Hz) ac system, and the designator (WF) refers to electrical systems where the primary power is from a wide variable frequency (360 to 800 Hz) ac system.
Category reference:
- For ac equipment: R(CF), R(NF), R(WF), K(CF), K(NF) or K(WF)
- For dc equipment: R, B, or Z
Categories R(CF), R(NF), R(WF) and R
Equipment intended for use on aircraft electrical systems where the primary power is from a constant or variable frequency ac system and where the dc system is supplied from transformer-rectifier units, is identified as:
• for ac equipment: Category R(CF), R(NF) or R(WF),
• for dc equipment: Category R.

Category B
Dc equipment intended for use on aircraft electrical systems supplied by engine-driven alternator/rectifiers, or dc generators where a battery of significant capacity is floating on the dc bus at all times, is identified as Category B. Unless otherwise specified, tests levels for 14 Vdc equipment are half those shown for 28 Vdc equipment.
Category K(CF), K(NF) or K(WF)
Equipment intended for use on aircraft electrical systems where the primary power is from a constant or variable frequency ac system and characterized by a voltage distortion level higher than the one for the ac supplies applied on category R equipment.
Category K shall be acceptable for use in place of Category R for ac equipment.
18-2
Category Z
Dc equipment that may be used on all other types of aircraft electrical systems applicable to these standards is identified as Category Z. Category Z shall be acceptable for use in place of Category R or B. Examples of this category are dc systems supplied from variable-speed generators where:
a. The dc power supply does not have a battery floating on the dc bus, or
b. Control or protective equipment may disconnect the battery from the dc bus, or.
c. The battery capacity is small compared with the capacity of the dc generators.

5.16 RE101, radiated emissions, magnetic field, 30 Hz to 100 kHz.
5.16.1 RE101 applicability.
This requirement is applicable for radiated emissions from equipment and subsystem enclosures, including electrical cable interfaces. The requirement does not apply to radiation from antennas. For Navy aircraft, this requirement is applicable only for aircraft with an ASW capability.
5.16.2 RE101 limit.
Magnetic field emissions shall not be radiated in excess of the levels shown in Figures RE101-1 and RE101-2 at a distance of 7 cm.
5.16.3 RE101 test procedures.
5.16.3.1 Purpose.
This test procedure is used to verify that the magnetic field emissions from the EUT and its associated electrical interfaces do not exceed specified requirements.

5.7 CS101, conducted susceptibility, power leads, 30 Hz to 150 kHz.
5.7.1 CS101 applicability.
This requirement is applicable to equipment and subsystem AC, limited to current draws ≤ 100 amperes per phase, and DC input power leads, not including returns. If the EUT is DC operated, this requirement is applicable over the frequency range of 30 Hz to 150 kHz. If the EUT is AC operated, this requirement is applicable starting from the second harmonic of the EUT power frequency and extending to 150 kHz.

5.11 CS106, conducted susceptibility, transients, power leads.
5.11.1 CS106 Applicability.
This requirement is applicable to submarine and surface ship equipment and subsystem AC and DC input power leads, not including grounds and neutrals.
5.11.2 CS106 limit.
The EUT shall not exhibit any malfunction, degradation of performance, or deviation from specified indications, beyond the tolerances indicated in the individual equipment or subsystem specification, when subjected to a test signal with voltage levels as specified in Figure CS106-1.

Aircraft Fuel Cell Power System

Failure Mode & Effect / Hazard Analysis

Summary Report

This analysis evaluated the risks associated with failures in the *FAA Aircraft Fuel Cell Power System* for prioritizing corrective actions in future system developments. The frequency of potential failure modes was categorized as 1. Unlikely, 2. Possibly during life of equipment, or 3. Probable during life of equipment. The Severity of the failure effects was categorized as 1. Negligible, 2. Reduced mission time, 3. Abort mission / immediate "controlled" landing, or 4. Major equipment damage.

High hazard events identified requiring additional examination were:

- Lithium battery fire
- Zahn VC 804 failures resulting in loss of flight propulsion

Serious hazard events identified were:

- FC 100 - Crossover
- FC 304 & 308 – Fails closed
- VC 309, 310, & 311 – Fails to close
- FC 500 & SC 800 – no output

Hazard Cube for this analysis

Risk Index - Frequency / Severity

Risk Index	**1 Negligible**	**2 Reduced mission time**	**3 Abort / controlled landing**	**4 Major equipment damage**
1 Unlikely				
2 Possible during life of equipment				
3 Probable during life of equipment				

Hazard Risk	**Low**	**Medium**	**Serious**	**High**

Infinity Fuel Cell and Hydrogen, Inc.

FAILURE MODE AND EFFECT / HAZARD ANALYSES

FAA Contract DTFACT-16-C-0038

Aircraft Fuel Cell Power System

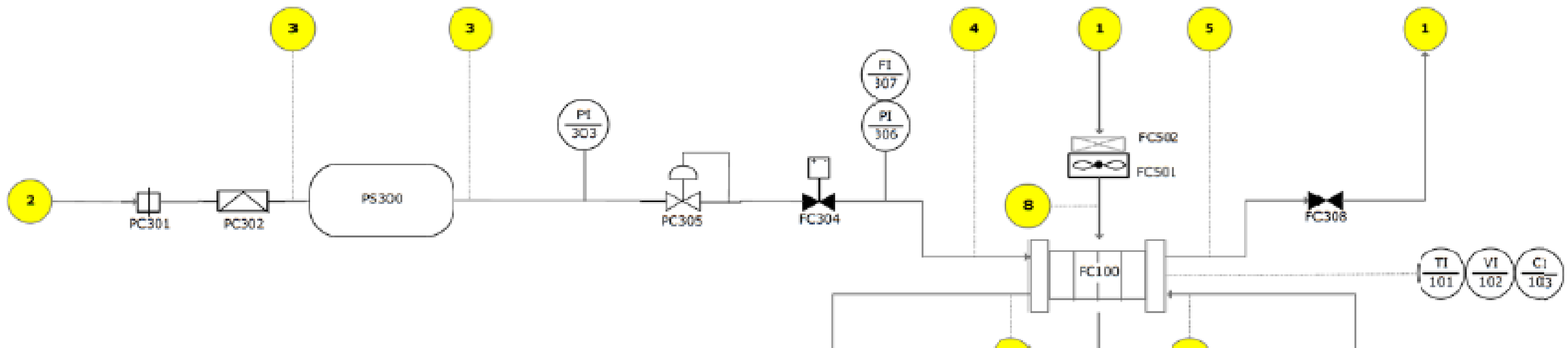
TABLE OF CONTENTS

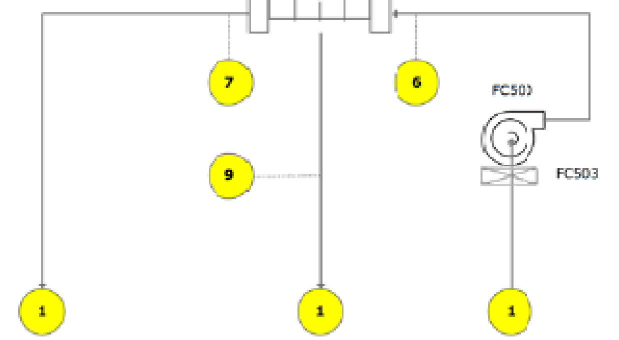
Frequency Code - F

1 Unlikely event during life of equipment
2 Possible event during life of equipment
3 Probable event during life of equipment

Severity Code - S

1 Negligible
2 Loss of efficiency; reduced mission time
3 System failure; mission abort, "controlled" landing
4 Major equipment damage, personnel hazard, fire



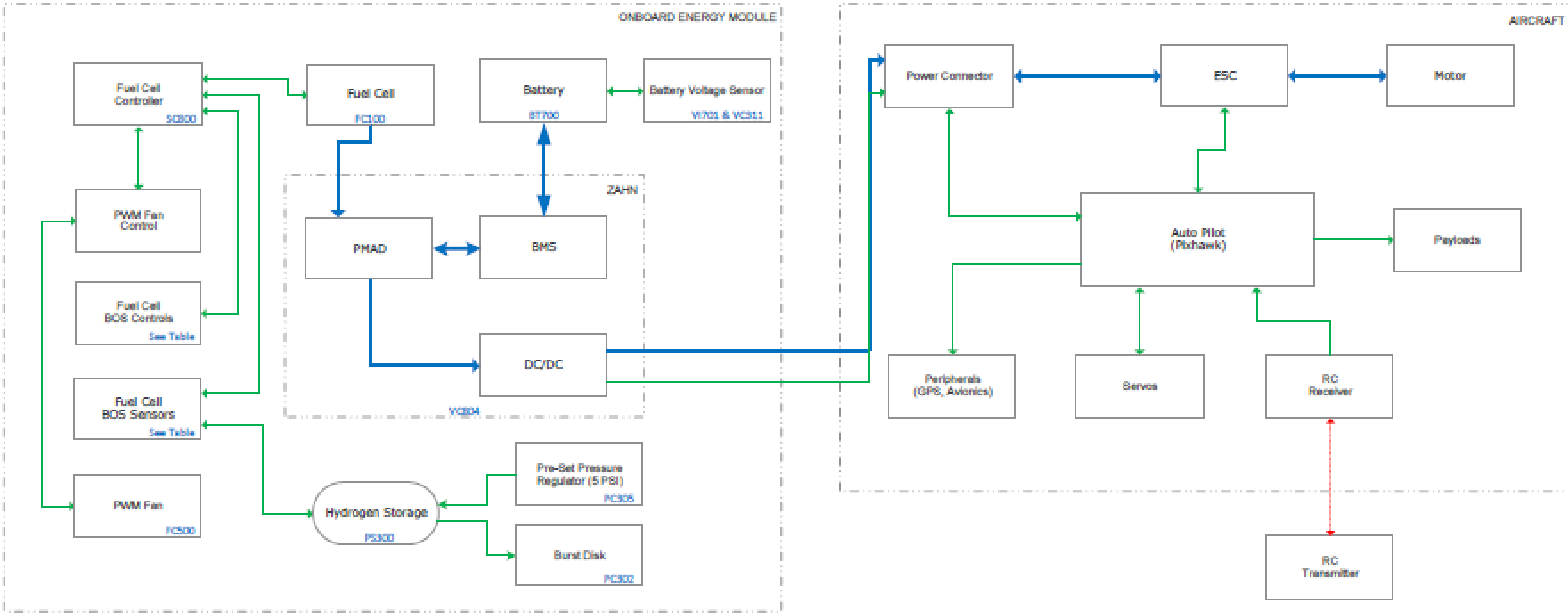


--- STATE TABLE ---								
State	Fluid	Tmin	Tmax	Pmin	Pmax	Vmin	Vmax	RHmax
		°C	°C	bar (a/g)	bar (a/g)	lpm	lpm	%
1	Air (Ambient)	-20	50	TBD (a)	1 (a)	-	-	100
2	Hydrogen (Fill)	-20	50	5 (g)	350 (g)	TBD	TBD	5
3	Hydrogen (Stored)	-20	50	5 (g)	350 (g)	-	-	1
4	Hydrogen (FC Inlet)	-20	50	0.2 (g)	0.5 (g)	0	25	5
5	Hydrogen (FC Outlet, Nom)	65	80	0.2 (g)	0.5 (g)	0	25	100
6	Air (FC Inlet)	-20	50	TBD (a)	1 (a)	0	200	100
7	Air (FC Outlet)	65	80	TBD (a)	TBD (a)	0	200	100
8	Air (Cooling Inlet)	-20	50	TBD (a)	1 (a)	0	200	100
9	Air (Cooling Outlet, Nom)	65	80	TBD (a)	1 (a)	0	200	100

System	Code
Fuel Cell	100
Electrolyzer	200
Hydrogen	300
Oxygen	400
Air	500
Water	600
Battery	700
Controls	800
Balance of System	900
Other	1000

Letter Codes	
1st Letter	C = Current
	F = Flow
	T = Temperature
	L = Level
	S = Serial
	P = Pressure
	V = Voltage
2nd Letter	C = Control
	I = Indicator
	S = Storage
Special Letters	FC = Fuel Cell
	EL = Electrolyzer
	BT = Battery
	RF = Reformer

Code	ItemNo.	Desciption
FC	100	fuel cell stack
TI	101	fuel cell temperature sensor
VI	102	fuel cell total voltage sensor
CI	103	fuel cell current sensor
PS	300	hydrogen storage tank
PC	301	hydrogen fill port
PC	302	burst disc
PI	303	pressure transducer, h2 tank
FC	304	solenoid valve, h2 inlet, n.c.
PC	305	pressure regulator
PI	306	pressure transducer, h2 inlet
FC	308	solenoid valve, h2 purge, n.c.
YC	309	5v relay, h2 inlet
YC	310	5v relay, h2 purge
YC	311	5v relay, batt voltage sense
FC	500	air blower, reactant
FC	503	filter media, air blower
BT	700	8s LiPo Battery
VI	701	battery voltage Sensor
SC	800	arduino uno rev3 board
YC	801	resistor - 56k Ohm
YC	802	resistor - 12k Ohm
YC	803	resistor - 5.6k 0hm
YC	804	Zahn PDM



Fuel Cell BOS Controls
FC304
FC308
VC309
VC310
VC311

Fuel Cell BOS Sensors
TI101
VI102
CI103
PI303
PI306

Code	Item No.	Description
FC	100	fuel cell stack
TI	101	fuel cell temperature sensor
VI	102	fuel cell total voltage sensor
CI	103	fuel cell current sensor
PS	300	hydrogen storage tank
PC	301	hydrogen fill port
PC	302	burst disc
PI	303	pressure transducer, h2 tank
FC	304	solenoid valve, h2 inlet, n.c.
PC	305	pressure regulator
PI	306	pressure transducer, h2 inlet
FC	308	solenoid valve, h2 purge, n.c.
VC	309	5v relay, h2 inlet
VC	310	5v relay, h2 purge
VC	311	5v relay, batt voltage sense
FC	500	air blower, reactant
FC	503	filter media, air blower
BT	700	8s LiPo Battery
VI	701	battery voltage Sensor
SC	800	arduino uno rev3 board
VC	801	resistor - 56k Ohm
VC	802	resistor - 12k Ohm
VC	803	resistor - 5.6k Ohm
VC	804	Zahn PDM

WIRE CAPACITY

- 24-32 VDC
- 5-12 VDC
- RF

NOTES:
1. Assumes LiPo battery for startup and limited motor energy for emergency landing.
2. Average motor voltage is 28 VDC.
3. Typical FC BOS, airframe, and payload voltage 5 VDC to 12 VDC.

INFINITY

FAA SYSTEM FUNCTIONAL BLOCK DIAGRAM

DATE: 7 September 2018 | DRAWN: Bob Byron | REV.VER: 1.0

FAILURE MODE AND EFFECT / HAZARD ANALYSIS
Aircraft Fuel Cell Power System
FAA Contract DTFACT-16-C-0038

Component	Failure Mode	Failure Effect	F	S	Comments	Proposed Action
1.1 <u>FC 100</u> Fuel Cell Stack	1. External leakage a. Hydrogen	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
	2. Internal failures a. crossover	**System failure.** Mission abort. Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warning for "controlled" landing on battery power.	2	3		Consider automatic shutdown for high temperature.
	b. Coolant blockage	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	3. Reaction degradation	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
2.1 <u>FC 304</u> Hydrogen inlet solenoid valve Normally (unpowered) closed	1. Fails closed	**System failure.** Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warns for "controlled" landing on battery power.	2	3		
	2. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
2.2 <u>PC 305</u> Pressure regulator Maintain H2 pressure to stack, FC 100.	1. Blockage	**System failure.** Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warns for "controlled" landing on battery power.	1	3		
	2. Pressure too high	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	3. Pressure too low	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	4. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
2.3 <u>FC 308</u> Hydrogen purge solenoid valve Normally (unpowered) closed	1. Fails closed	**Failed start.**	2	1		
		System failure. Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warns for "controlled" landing on battery power.	2	3		
	2. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
2.4 <u>VC 309</u> Hydrogen inlet 5V relay	1. Fails to close	**Failed start.**	2	1		
		System failure. Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warns for "controlled" landing on battery power.	2	3		

FAILURE MODE AND EFFECT / HAZARD ANALYSIS
Aircraft Fuel Cell Power System
FAA Contract DTFACT-16-C-0038

Component	Failure Mode	Failure Effect	F	S	Comments	Proposed Action
2.5 VC 310 Hydrogen purge 5V relay	1. Fails to close	**Failed start.** **System failure.** Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warns for "controlled" landing on battery power.	2 2	1 3		
2.6 VC 311 Battery voltage sensor 5V relay	1. Fails to close	**Failed start.** **System failure.** Mission abort. Voltage Sensor, VI 701, warns for "controlled" landing on battery power.	2 2	1 3		
3.1 TI 101 Fuel cell temperature sensor Stack monitor for control	1. Indication too high 2. Indication too low 3. Sensor out-of range	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2 2 2	2 2 2		
3.2 VI 102 Fuel cell total voltage sensor Stack monitor for control	1. Indication too high 2. Indication too low 3. Sensor out-of range	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2 2 2	2 2 2		
3.2.1 VC 801 Resistor 56k Ohm	1. Fails open	**Reduced mission time**. Voltage sensors warn for mission termination.	1	2		
3.2.2 VC 802 Resistor 12k Ohm	1. Fails open	**Reduced mission time**. Voltage sensors warn for mission termination.	1	2		
3.2.3 VC 803 Resistor 5.6k Ohm	1. Fails open	**Reduced mission time**. Voltage sensors warn for mission termination.	1	2		
3.3 CI 103 Fuel cell current sensor Stack monitor for control	1. Indication too high 2. Indication too low 3. Sensor out-of range	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination. **Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2 2 2	2 2 2		

FAILURE MODE AND EFFECT / HAZARD ANALYSIS
Aircraft Fuel Cell Power System
FAA Contract DTFACT-16-C-0038

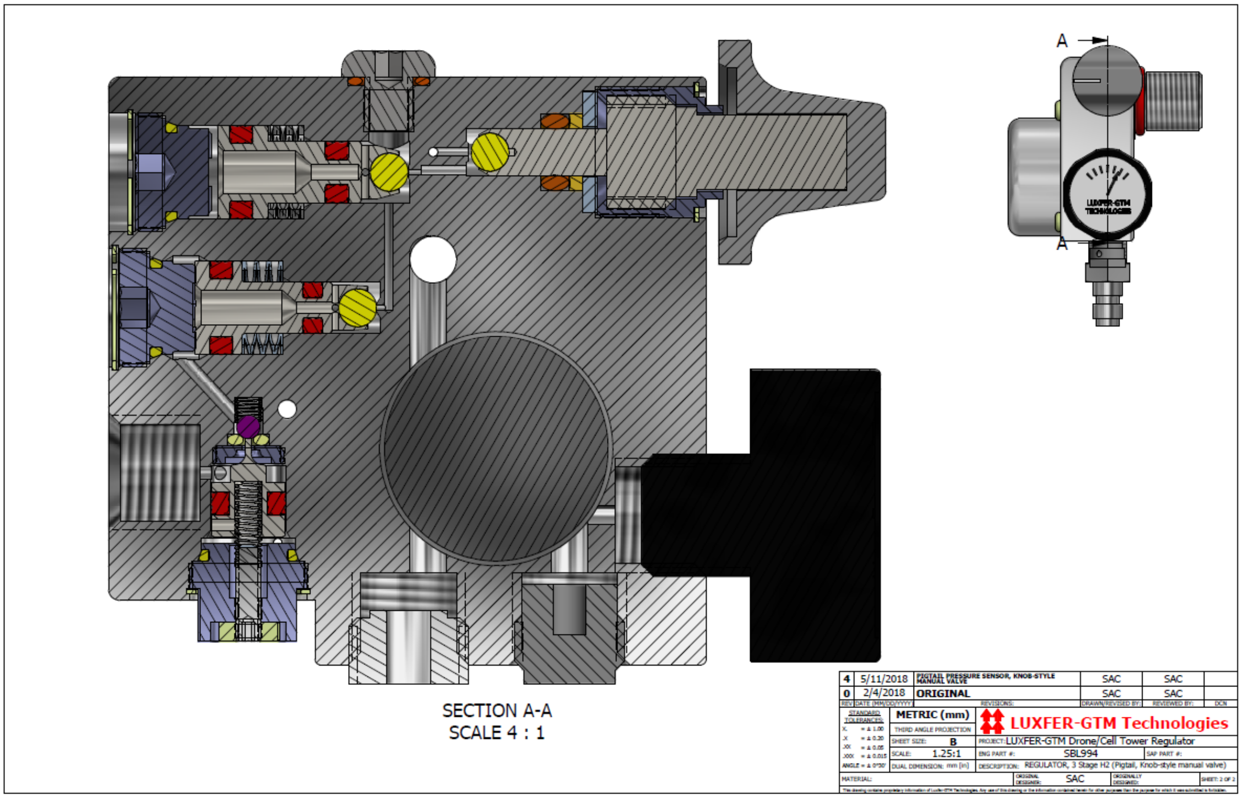
Component	Failure Mode	Failure Effect	F	S	Comments	Proposed Action
3.4 PI *303* Hydrogen tank pressure transducer	1. Indication too high	**Negligible**	2	1		
	2. Indication too low	**Reduced mission time**. Transducer warns for mission termination.	2	2		
	3. Sensor out-of range	**Reduced mission time**. Transducer warns for mission termination.	2	2		
	4. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
7. PI 306 Hydrogen inlet pressure transducer Used for Stack, FC 100, controll	1. Indication too high	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	2. Indication too low	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	3. Sensor out-of range	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	4. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
4.1 FC 500 Reactant air blower Reactant and cooling	1. Reduced output	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
	2. Fails off	**System failure.** Mission abort. Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warn for "controlled" landing on battery power.	2	3		
4.2 FC 503 Air blower filter Protection for reactant and cooling flow	1. Internal leakage (contaminated air supply)	**Negligible**	2	1		
	2. Blockage	**Reduced mission time.** Temperature, Voltage or Current Sensor, TI 101, VI 102 or CI 103, warns for mission termination.	2	2		
5.1 PS 300 Hydrogen storage tank	1. Rupture	**Double failure.** Tank protected by Burst Disc, PC 302.				
	2. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		

FAILURE MODE AND EFFECT / HAZARD ANALYSIS
Aircraft Fuel Cell Power System
FAA Contract DTFACT-16-C-0038

Component	Failure Mode	Failure Effect	F	S	Comments	Proposed Action
5.2 PC 301 Hydrogen fill port Quick disconnect/ Check valve function	1. Blockage	Non flight function. For fill only.				
	2. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 warns of excess hydrogen consumption for mission termination.	2	2		
5.3 PC 302 Burst disc Protects H2 tank, PC 300, from over pressurization	1. Fails to activate	**Double failure**				
	2. Inadvertent activation	**System failure.** Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, initiate "controlled" landing on battery power.	1	3		
	3. External leakage	**Reduced mission time.** Air Blower, FC 500, dissipates hydrogen concentration. Pressure Sensor on Regulator PC 305 indicates excess hydrogen consumption and terminates mission.	2	2		
6.1 SC 800 Fuel cell controller Arduino uno rev 3 board	1. No output	**System failure.** Mission abort. Voltage or Currents Sensor, VI 102 / CI 103, warn for "controlled" landing on battery power.	2	3		
7.1 BT 700 Battery 8s LiPo battery	1. Loss charge	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		
	2. Fire	**Major equipment damage.**	1	4	An unlikely event.	
8.1 VI 701 Battery voltage sensor	1. Indication too high	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		
	2. Indication too low	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		
	3. Sensor out-of range	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		
8.2 VC 311 Battery 5V relay	1. Fails to close	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		

FAILURE MODE AND EFFECT / HAZARD ANALYSIS
Aircraft Fuel Cell Power System
FAA Contract DTFACT-16-C-0038

Component	Failure Mode	Failure Effect	F	S	Comments	Proposed Action
9.1 Zahn VC 804 PMAD Power management	1. Failed function	**Major equipment damage.** Loss of power for flight. Crash.		4	Component under development. Assume appropriate reliability can be established with analysis and testing.	
9.2 Zahn VC 804 BMS Battery management	1. Failed function	**Reduced mission time.** Voltage sensor, VC 701, warns for mission termination.	2	2		
9.3 Zahn VC 804 DC/DC	1. Failed function	**Major equipment damage.** Loss of power for flight. Crash.		4	Component under development. Assume appropriate reliability can be established with analysis and testing.	


A
A
SECTION A-A
SCALE 4 : 1
4
5/11/2018
PIGTAIL PRESSURE SENSOR, KNOB-STYLE MANUAL VALVE
SAC
SAC
0
2/4/2018
ORIGINAL
SAC
SAC
REV
DATE (MM/DD/YYYY)
REVISIONS:
DRAWN/REVISED BY:
REVIEWED BY:
DCN
STANDARD TOLERANCES:
X. = ± 1.00
.X = ± 0.20
.XX = ± 0.05
.XXX = ± 0.015
ANGLE = ± 0°30'
METRIC (mm)
THIRD ANGLE PROJECTION
SHEET SIZE: B
SCALE: 1.25:1
DUAL DIMENSION: mm [in]
LUXFER-GTM Technologies
PROJECT: LUXFER-GTM Drone/Cell Tower Regulator
ENG PART #: SBL994
SAP PART #:
DESCRIPTION: REGULATOR, 3 Stage H2 (Pigtail, Knob-style manual valve)
MATERIAL:
ORIGINAL DESIGNER: SAC
ORIGINALLY DESIGNED:
SHEET: 2 OF 2