WHITE PAPER

FUEL CELL POWERED UAS: HYDROGEN SAFETY, HANDLING, AND FIELD EXPERIENCE

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The unmanned aerial system (UAS) industry has recognized that hydrogen fuel cell power systems are a critical enabler for beyond visual line of sight (BVLOS) operation of Group 1 and 2 platforms (< 55 lb) as they offer a 2-3x increase in flight time over state of the art batteries. Fuel cell technology is mature, having been practically demonstrated on a variety of multi-rotor and fixed wing platforms, and UAS ready fuel cell products are now being offered by several manufacturers. As fuel cell power systems continue to proliferate the drone industry so too will the use of the hydrogen fuel that drives system operation. Hydrogen is a novel fuel to many in the UAS community and, unfortunately, many misconceptions exist around its handling and safety characteristics. The community has converged upon the use of high pressure, gaseous hydrogen storage, as opposed to liquid hydrogen or chemical hydrides, due to its low cost, availability, and storability. Lightweight, composite overwrapped pressure vessels (COPVs), filled to 5,000-6,000 psi, are used to store hydrogen onboard the aircraft. On the ground, flight tank filling may involve the use of high pressure industrial gas cylinders and positive displacement boost compressors. The goal of this presentation is to educate the broader UAS community about general high pressure gaseous hydrogen safety considerations and guidelines. Instruction in proper design, handling, and operation of hydrogen filling and storage components will also be provided through examples from field operation of hydrogen fuel cell systems on UAS platforms. Through adherence to proper procedures and engineering techniques, hydrogen may be safely and broadly used by the UAS industry to provide game changing platform capability.

INTRODUCTION

Hydrogen fuel cell systems are being developed, evaluated, integrated into aircraft, and trialed in controlled and operational environments, because they can significantly increase unmanned aerial system (UAS) flight range and duration. While fuel cells have been powering defense UAS for more than a decade, these flights have typically been executed by highly trained technicians with significant hydrogen experience. As fuel cell power systems have transitioned to commercial use, storage, transport, refueling, and power generation systems must be designed, built, and operated such that safety is paramount, even when operated by relatively untrained and unsophisticated users.

This paper discusses hydrogen safety standards and efforts underway that can be applied to hydrogen drone use, and also explores safety and hazard analysis and mitigation methodologies.

Accepted and widely adopted safety standards are a hallmark of mature businesses. As an immature business, the hydrogen powered drone industry is actively applying, and modifying safety and operational standards developed for other applications, and producing standards that address unique UAS challenges specifically. The goal of the industry is to assure standards and practices

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are in place to encourage a safety record similar to the recent U.S commercial air record: zero deaths in a decade.

While several safety standards are in place and being widely used in the automotive world, UAS specific hydrogen safety standards are still in developmental and early test phases. In many cases these UAS specific standards can point to many of the designs, methodologies, and processes standardized for automotive use, while also specifying those areas where the automotive standards are not applicable to aircraft use. Several standards bodies, including ASTM and SAE, have initiated standards committees and workgroups to pursue component and system level safety standards specific to UAS use. These efforts are still underway, but are expected to bear fruit in the near future.

The goal of these efforts, as well as of the industry as a whole, is to have hydrogen powered UAS systems being operated widely and safely by properly trained, professional users. The standards are not aimed at general consumer usage – at least not today. The approach being applied is the accepted (in both aviation and hydrogen markets) methodology of safety planning – at the product definition as well as the operational levels.

BACKGROUND

Proton exchange membrane fuel cell (PEMFC) powered unmanned aerial systems, or drones, offer improved operational duration relative to their battery powered counterparts (2-3x), with the same benefits of an all-electric power system such as: high throttleability, low thermal and noise signature, payload/motor flexibility, and zero emission operation. Relative to internal combustion engine-powered systems, fuel cells provide reduced acoustic signature (up to 2x), limited altitude derating (10% at 15 kft), and reduced maintenance (5x increase in time before overhaul).

![Figure 1. Examples of fuel cell powered VTOL multi-rotor drones: a) Intelligent Energy, b) Doosan, and c) Ballard Unmanned Systems.](image)

Several examples of PEMFC powered vertical takeoff and landing (VTOL) multi-rotor drones are shown in Figure 1. The following subsections provide an overview of the core on-board and ground based components of a drone fuel cell power system. The intent is to provide the necessary background to support the next section of the paper that covers the safety planning approach that the fuel cell drone community has adopted to ensure the safe operation.

Overview of Drone PEMFC Power System, On-Board Components

**Fuel Cell Plant**

The PEMFC plant consists of the following primary components: 1) fuel cell stack, 2) air delivery subsystem, 3) hydrogen management subsystem, 4) thermal management subsystem, and

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control electronics. Often components 2) through 5) are lumped together and classified broadly as balance of plant (BoP) components; these are all supporting components, but essential to fuel cell plant operation. Each fuel cell plant manufacturer incorporates their own unique design methodologies into each subsystem, but all fuel cell power systems must contain these core components and subsystems. The method of thermal management is a distinguishing feature for PEMFC systems and can have a strong impact on system metrics, environmental ruggedness, and reliability. In general, two types of thermal management techniques are most often employed: 1) air and 2) liquid cooling. Further detail regarding PEMFC plant BoP functionality and performance may be found in New Fuel Cell Technologies Extend Missions for Vertical Take-Off and Landing Unmanned Aerial Vehicles (Sisco et al). Figure 2 provides several examples of available drone fuel cell plants, including both air and liquid cooled designs.

![Figure 2. Examples of drone PEMFC plants: a) HES Energy Systems (air-cooled), b) Ballard Unmanned Systems (liquid cooled), and c) Intelligent Energy (air-cooled).](image)

**Power Management Electronics**

VTOL drone PEMFC power systems predominantly incorporate battery hybridization to augment fuel cell power output during climb and other short duration high power maneuvers. The approach makes use of the high power density (power per unit weight) of lithium polymer batteries to reduce fuel cell size and provide a higher performing overall solution. As a result, the majority of drone PEMFC power systems incorporate power management electronics that act to match fuel cell output voltage to that of the hybrid battery, which is typically connected electrically in parallel with the fuel cell, over the full power output range of the system. Additionally, the power management electronics facilitates battery charging in flight by controlling the battery charge rate. Fuel power system power management electronics may also include battery management systems to monitor and adjust cell balance, and protect the battery from over charge, under voltage, and over temperature.

**Hybrid Battery**

The hybrid battery present in a drone fuel cell power system is typically constructed of a lithium-based cell chemistry, lithium polymer (LiPo) or lithium ion (Li-ion), due to its higher power output capacity. The battery pack is configured in a series arrangement to match the desired motor input voltage, typically in the 6S-12S range, and the fuel cell power management electronics act to match the fuel cell output voltage to the battery top charge level. The energy capacity of the pack is typically selected to provide only several minutes of flight time for emergencies, since

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under normal operation the battery is used for brief periods (< 1 minute) and then recharged in flight.

Compressed Hydrogen Storage Tank

Hydrogen needed for PEMFC power production is stored as a high pressure compressed gas on-board the drone. Carbon composite overwrapped pressure vessels (COPV) with polymer liners (Type IV) are typically used to provide a lightweight and structurally sound storage solution. Tank fill pressures may range from 310-413 bar (4,500-6,000 psi) to achieve meaningful storage density. Tank geometry is typically cylindrical with spherical ends; at least one end includes a boss fitting to support interfacing of a pressure regulator and other flow control components. For VTOL drone applications tank water volume may range from 1 to 10 L with larger volumes translating to longer flight times at the cost of added weight. Further detail regarding COPV tank metrics may be found in *Hydrogen Long-Duration UAV Fielding: Refueling Options* (Sisco and Robinson). Figure 3 provides several examples of available drone fuel cell hydrogen storage tanks.

![Figure 3. Examples of drone fuel cell hydrogen storage tanks: a) HES Energy Systems† and b) Ballard Unmanned Systems.](image)

Hydrogen Supply System

The operating pressure of most drone PEMFC plants may range from 0.5 to 2 bar above local ambient (7 to 30 psig) depending on the manufacturer; for this reason, drone fuel cell systems incorporate a hydrogen supply system that acts to condition the hydrogen stored in the COPV tank and deliver it to fuel cell plant. The most critical component in the system is the mechanical pressure regulator that acts to reduce the hydrogen supply pressure from the high levels in the storage tank to safe fuel cell operating levels. The regulator is designed to install directly into the COPV tank boss, and is sized to provide stable flow over the full operating range of the fuel cell and tank. The system also may include tank pressure and temperature sensors, pressure relief devices, tubing, and isolation valves.

Overview of Hydrogen Re-Fueling Systems, Ground-Based Components

Blow Down Fill System

The most straightforward method of re-fueling a compressed hydrogen COPV tank is by filling from a higher pressure, higher volume compressed hydrogen source; such as a gas cylinder available from most industrial gas suppliers. In this so-called “blow down” scheme, the source is typically connected to the flight COPV tank through a: 1) pressure regulator, to set the flight tank fill pressure, 2) a control valve, to isolate the flight tank, and 3) a quick-disconnect fitting, to ena-

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ble quick removal of the flight tank from the system. A drawback of the blow down fill scheme is that the source pressure and volume limits the achievable flight tank fill pressure. Several vendors have developed all-inclusive, portable blow down fill apparatus that include all the regulators, valves, plumbing, interfaces, and electronic control necessary to facilitate drone flight tank fill operations; one such system that incorporates a cascade fill scheme, and was developed by NanoSUN, is shown in Figure 4.

![Figure 4. Portable compressed hydrogen blow down fill system developed by NanoSUN* for drone flight tanks.](Image)

**Boost Compressor Fill System**

A variation on the blow down fill system incorporates a boost compressor between the hydrogen source and the flight tank to enable full control of the fill pressure to the design target. The approach also broadens the range of allowable hydrogen sources to those that are at lower pressure than the flight tank fill target. The boost compressor is a sophisticated mechanical device that typically employs a multi-stage positive displacement compression system. The pump is typically driven by an AC-driven electric motor, and does require regulator maintenance. Several vendors have developed portable boost compression systems that include the compression cylinder assembly, electric motor and drive, pressure regulator, isolation valves, relief valves, and plumbing necessary to facilitate drone flight tank filling. Further detail regarding flight tank fill system options and performance metrics may be found in Sisco and Robinson.

**Fill Safety Considerations**

Drone fuel cell flight tank fill safety motivates much of the safety planning discussion that will follow in the next section of this paper. There are three primary parameters that must be monitored during the fill process: 1) tank fill pressure, 2) tank fill rate, and 3) tank temperature. The tank fill pressure must be maintained within the structural limits of the COPV tank design at all times. Failure to observe tank pressure specifications could compromise the structural integrity of the tank during operations and may lead to leakage, rupture and decompression, and/or hydrogen ignition.

Over the range of temperatures that tank fill process might be expected to occur, hydrogen possesses a negative Joule-Thomson coefficient; meaning that it will warm as it expands into the flight hydrogen tank. The flight tank internal temperature must be monitored during the fill process to ensure that it does not heat the tank beyond the recommended limits of the composite overwrap. The rate of heating increases with the rate of fill and so in some cases, typically for large tanks, the room temperature fill rate may be restricted due to thermal considerations. If the

* NanoSUN UK Drones product page, [https://nanosun.co.uk/drones](https://nanosun.co.uk/drones), accessed 4/18/2019.
tank is overheated it could compromise the structural integrity of the tank and lead to the failure modes described above.

SAFETY PLANNING APPROACH

The proton exchange membrane fuel cell (PEMFC) community takes safety very seriously and has adopted a safety planning approach that is universally accepted, regardless of industry, as a method of ensuring the safe operation of potentially hazardous systems. This approach has been in use by the industry for more than forty years and has been applied to a wide range of power system development efforts for applications such as automobiles, material handling, and mass transit among others. The systematic method includes four key components for guiding the safe design and operation of PEMFC systems:

1. Recognize Safety Standards
2. Systematic Internal Safety Review
3. Independent Safety Review
4. Communication Plan

The fuel cell powered unmanned aerial vehicle (UAV), or “drone” community is conducting its development efforts with strict adherence to this tried and true safety planning approach. Each component of the approach is described in detail in the following subsections, within the context of drone application.

Recognize Safety Standards

Engineering standards serve as a knowledge repository gathering a range of information on a given topic including; design methodologies, engineering rules of thumb, quantitative technical data, lessons learned, and test approaches. The fuel cell powered drone community, along with the engineering community at large, have recognized the need for dedicated design standards. Several fuel cell drone standardization efforts are presently underway and are still in the early stages of development.

An example targeted specifically at fuel cell powered drones is ASTM WK60937 - Fuel Cell Power Systems for Use in Small Unmanned Aircraft Systems (sUAS). This proposed new standard is being developed under the F38 Unmanned Aircraft Systems committee within the F38.01 Airworthiness sub-committee. The standard will define the requirements for fuel cells and fuel cell based power systems used in sUAS and aims to encompass all aspects of the fuel cell solution including fuel storage systems, re-fueling systems, and battery hybridization systems.

A major benefit for the fuel cell drone community in developing dedicated standards is that it can leverage the extensive body of standards developed for the automotive application. While these existing standards may be used as a guideline, there are distinct differences between automobile and drone applications (most obviously that one operates on the ground and the other in the air), and so the community must exercise caution and work to identify both gaps and inapplicable requirements in existing automotive standards when they are applied to airborne operations. Relevant automotive fuel cell reference standards include:

SAE J2579 – Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles: This standard defines design, construction, operational, and maintenance requirements for hydrogen fuel storage and handling systems in on-road vehicles. It also defines performance-based requirements for hydrogen fuel system design verification and test protocols to qualify designs against requirements. The standard covers both compressed and liquid hydrogen based storage and handling systems, but does not cover hydrogen re-fueling system design or testing requirements.

Compressed gaseous hydrogen storage is the current baseline for the drone fuel cell community, and SAE J2579 provides extensive guidance for compressed hydrogen storage and handling system design and testing. The design requirements cover automatic shutoff, over-pressure protection, thermal protection, expected service, and material selection. The standard also outlines performance verification tests for fuel storage and handling system design qualification that is broken down into baseline, expected service, extreme conditions and extended usage, and service terminating conditions. Additionally, the standard provides guidance for production quality control testing and vehicle integration requirements. Review of these requirements and guidance is necessary to assess what gaps may exist for the drone application.

SAE J2601_201612 – Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles: This standard defines the protocol and process limits for hydrogen fueling of light duty vehicles up to target pressures up 700 bar (10,000 psig).† The standard provides two methods (tabular or formula) by which to estimate limits to fuel delivery temperature, maximum fuel flow rate, rate of pressure increase, and ending pressure based upon ambient temperature, fuel delivery temperature, and initial pressure of the compressed hydrogen storage system. Through definition of process limits the standard aims to minimize fill time to within a few minutes while preventing over-pressure and/or over-temperature of the compressed hydrogen storage tank during the fill process. (Caution – SAE J2601 is not intended for hydrogen drone fueling.)

The process limits defined in SAE J2601 are also adjusted depending upon whether the fueling system is able to communicate with the vehicle. A separate standard, SAE J2799,‡ defines the data fields incorporated in the communications stream; these include tank type and volume along with measured temperature and pressure. With communications in place the fueling system knows more about the tank status and may adjust process limits accordingly to reach a high state of charge (95-100%). In a non-communication fill scenario the fueling system must operate using tabular data. Incorporation of a communication capability should be considered for drone fueling system designs.

The SAE J2601 standard provides very detailed compressed hydrogen tank filling requirements for light duty hydrogen surface vehicles; however, significant gaps exist that limit applicability as a guideline to the drone fuel cell community. The standard is geared toward much larger tanks, 49.7 to 248.6 L water volume, than those currently being considered for the drone application, approximately 1 to 10 L water volume. Additionally, the standard assumes a fueling system provides a chilled hydrogen supply (-40 to -20°C); this will likely not be available in drone fueling systems. Careful review and consideration of fill process parameters such as fill rate, temperature will be necessary to develop a fill protocol for drone fuel cell systems.

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3 SAE J2799 - Hydrogen Surface Vehicle to Station Communications Hardware and Software, April 2014.
The fueling protocols of SAE J2601 were developed based on a set of key assumptions for light duty hydrogen surface vehicles, as described in Section 7 and Appendix A of the standard. These assumptions must be carefully reconsidered in the development and implementation of an on-board compressed hydrogen storage system with properties which do not fall within the parameters in Table A3 of the standard. While future versions of SAE J2601 may incorporate warmer fuel delivery temperatures (−10 °C and ambient) and smaller compressed hydrogen storage systems for motorcycles and other light duty applications, the present standard does not cover these applications in its present (2016) scope.

SAE J2601/3 – Fueling Protocol for Gaseous Hydrogen Powered Industrial Trucks: This standard has been developed to establish safety limits and performance requirements for gaseous hydrogen fuel dispensers used to fuel Hydrogen Powered Industrial Trucks (HPITs). It also describes several example fueling methods for gaseous hydrogen dispensers serving HPIT vehicles. While HPIT tank volumes and dispensed H2 quantities addressed by J2601/3 still exceed those of exemplar hydrogen drones, they are closer in range than those addressed by J2601 for light duty vehicles. (Caution - SAE J2601/3 is not intended for hydrogen drone fueling).

SAE J2601/3 offers performance-based fueling methods and provides guidance to fueling system builders as well as suppliers and operators of HPIT fleet(s). This fueling protocol for HPITs can support a wide range of hydrogen fuel cell hybrid electric vehicles including fork lifts, tractors, pallet jacks, on and off-road utility, and specialty vehicles of all types. This document is suitable for ground vehicle tank fueling systems above 18 L water volume. However, as hydrogen drone tank volumes of approximately 1 to 10 L water volume are not addressed in this standard, direct applicability cannot be assumed. Fill target pressures up to 350 bar (~5000 psi) are addressed. Of interest to the developers of drone fueling protocols may be the descriptions of multiple HPIT industry fueling methods that do not pre-cool hydrogen and use fixed area flow-limiting devices as well as variable area flow-limiting devices to achieve HPIT tank fills of about a kilogram in approximately 10 minutes.

J2601/3 Section 6 details three dispensing methods, allowing for present market differentiation, and includes a schematic of fueling control components. These methods are examples of how dispensers may function but are not intended to limit options for new dispenser technologies or fueling methods, provided they meet the performance-based requirements.

SAE J2600 - Compressed Hydrogen Surface Vehicle Refueling Connection Devices: The mechanical connector geometry for 25 MPa (‘H25’), 35 MPa (‘H35’), and 70 MPa (‘H70’) vehicle fueling connectors are defined in this standard, which the hydrogen drone community will need to consider as already proven for hydrogen fueling HPIT and light duty surface vehicle devices.

CGA G-5.5-2014 Hydrogen Vent Systems: This publication presents design guidelines for hydrogen vent systems used in gaseous and liquid hydrogen systems at user sites and provides recommendations for safe operation of these vents. Safe hydrogen venting systems and procedures must address proper separation from personnel, exposures, and ignition sources as well as assuring proper materials and air dilution.

NFPA 2-2016 Hydrogen Technologies Code: This code provides fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas systems.

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1 SAE J2601/3 – Fueling Protocols for Gaseous Hydrogen Powered Industrial Trucks, June 2013.
2 SAE J2600 - Compressed Hydrogen Surface Vehicle Refueling Connection Devices, October 2015.
3 CGA G-5.5-2014, Hydrogen Vent Systems, Compressed Gas Association, Inc.
In addition to fundamental chapters 1-6, particularly pertinent sections of interest to the hydrogen drone fueling community are Chapter 7, Gaseous Hydrogen with a subsection on packaged hydrogen equipment enclosures (HEE), and Chapter 10, Hydrogen Fueling with sections on vehicle fueling installations and fueling appliances (VFA) in nonresidential occupancies. (A significant revision is planned for 2020)

ANSI HGV 2 – Compressed Hydrogen Gas Vehicle Fuel Containers: This standard contains requirements for the material, design, manufacture, marking, and testing of serially produced, refillable containers for storage of compressed hydrogen for on-road vehicles. Covered in the standard are vessels that are permanently attached to the vehicle, less than 1,000 L in water volume, and <70 MPa nominal working pressure. The standard addresses Type 1 (metal), Type 2 (hoop-wrapped composite vessels with metal liner), Type 3 (full-wrapped composite vessels with metal liner), and Type 4 (composite wrapped vessels with non-metallic liner) containers.

The drone community has baselined Type 4 containers for flight storage of hydrogen, due to their low weight. The ANSI HGV 2 standard provides very detailed guidance for Type 4 container designs for a wide range of service conditions. The standard provides guidance on material requirements, allowable stresses and factors of safety (FOS), inspection requirements, manufacturing, marking and dispatch, and quality assurance. Additionally, the standard provides test guidance including material qualification, design qualification, production, and batch testing. Many in the fuel cell drone community are using ANSI HGV 2 as a baseline for Type 4 container design, but caution should be observed as the standard was developed with on-road vehicles in mind. For example, the ANSI HGV 2 standard stipulates that tank service life ends after use in a single vehicle, and prohibits transfer between vehicles. The standard should be reviewed in detail to assess its applicability to drone applications.

Systematic Internal Safety Review

Safety standards provide the foundation for the design of a potentially hazardous system, but must be supplemented with a well-defined review process to ensure that the designers have identified system failure modes and methods of mitigation, followed the standards appropriately, defined system operating procedures, and adequately documented the system design and operation. The following subsections cover these topics in more detail and provide examples relevant to fuel cell powered drones.

Hazard Analysis

Component or subsystem failure may lead, directly or indirectly, to a potentially hazardous situation when operating any complex system. It is difficult, if not impossible, to completely eliminate the potential for failures in a system, but the potential for creating an unsafe situation may always be eliminated by designing appropriate failure mitigation schemes into the system. Design of failure mitigation schemes requires not only an understanding of the operation of individual components or subsystems, but also the interactions of these components and subsystems with one another.

Hazard analyses requires the contributions of a multi-disciplinary team that should include personnel with experience in component failure modes and scenarios. Hazard analyses should also consider maintenance and inspection operations in addition to standard operation of the sys-
tem under consideration. A number of structured approaches have been developed to aid in the hazard analysis of complex systems, but an introduction to two approaches that have been successfully applied to PEMFC systems in the past will be covered in what follows. More comprehensive descriptions of hazard analysis techniques may be found in the AIChE Guidelines for Hazard Analysis Procedures or the lessons learned section of the Hydrogen Safety Panel website.

Failure Mode Effects Analysis (FMEA)

A failure mode effects analysis is a qualitative, bottom-up approach to hazard analysis that begins with specific, known failure modes and assesses the potential effects of the failure on system operation. FMEA is often used for well-defined electrical and mechanical processes or systems, such as the fuel cell plant itself in the case of the fuel cell powered drone.

A FMEA typically begins at the component level and identifies ways through which the component may fail to meet its intended function. In complex systems, a component failure could lead to a subsystem failure thus creating a multi-layered analysis. Often a qualitative assessment of the probability of failure is incorporated into a FMEA. The potential consequences of the failures are estimated along with the severity of the impact at a qualitative level as well. The qualitative probability of failure and severity of impact ratings are then used to define an overall risk value for potential failures.

Extensive FMEA studies have been performed on hydrogen fuel cell vehicles and provide strong guidance for similar studies applied to the drone fuel cell application. One extensive study, conducted by the U.S. Department of Transportation (USDOT), broke the fuel cell system down into three main subsystems: 1) compressed-hydrogen fuel storage and filling, 2) hydrogen fuel delivery, and 3) fuel cell. The study addressed failure modes of 28 different components in total. Representative results from the study, focusing on two critical fuel cell plant components, are outlined in Table 1 and Table 2 below.

Table 1. Sample results from fuel cell vehicle FMEA: failure mode and likelihood.

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Component Function</th>
<th>Cause of Failure Mode</th>
<th>Potential Failure Modes</th>
<th>Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack Coolant Pump</td>
<td>Pumps coolant fluid through the fuel cell stack and back through the radiator</td>
<td>Inadequate design/test/manufacture/installation</td>
<td>Fails to function</td>
<td>Medium</td>
</tr>
<tr>
<td>Cathode Air Blower</td>
<td>Forces ambient air into the cathode of the fuel cell</td>
<td>Electrical/mechanical failure</td>
<td>Fails to function</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Table 2. Sample results from fuel cell vehicle FMEA: consequence, risk, and controls.

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Failure Consequences</th>
<th>Consequence</th>
<th>Risk</th>
<th>Controls</th>
</tr>
</thead>
</table>

The two components summarized in Table 1 and 2

Table 2 are the stack coolant pump and cathode air blower. The stack coolant pump, present in liquid cooled fuel cell systems, is responsible for driving coolant through the fuel cell and radiator, and is critical to the control of fuel cell thermal management. The cathode air blower is responsible for delivering air/oxygen through the cathode side of the fuel cell, and is critical to driving fuel cell power production. Table 1 describes the potential failure modes of each component and likelihood of that failure. The results for both components are identical with the failure mode being loss of functionality with a qualitative likelihood of occurrence rating of medium. (In an air cooled fuel cell, the function of the coolant pump and cathode air blower are combined and replaced by a large air mover, such as a fan, that drives both thermal management and power production. As such the failure modes and likelihood assessments would be very similar for an air cooled system.)

Table 2 describes the potential consequences of the defined failure modes and provides a qualitative rating of the consequences of the failure. For both components, a loss of functionality may initiate a series of events beginning with stack overheating, then to failure of the membrane, direct mixing of hydrogen and oxygen, and fire. If the cathode air blower were to fail, an additional initial consequence would be sudden loss of power due to a lack of oxygen supply. For both components, the impact of failure is significant enough to warrant a qualitative consequence rating of high that subsequently makes the overall risk rating high.

As part of the FMEA process the USDOT study also recommended control strategies for each failure. For both components, an important aspect of the strategy is the definition of and adherence to design, manufacture, quality control, qualification test, and installation requirements to ensure proper component functionality. Additionally, the control strategies note the use of fuel cell voltage monitoring and temperature sensors as means to detect failures of these components. The FMEA has highlighted that mitigating the results of these failures is critical to ensuring the safe operation of the fuel cell system. Efforts to apply the FMEA approach to drone fuel cell power systems are ongoing.

Hazard and Operability (HAZOP) Study
A hazard and operability study is a qualitative, top-down approach to hazard analysis. HAZOP studies are directed by the use of guide words, such as ‘more’, ‘less’, ‘high’, ‘low’, and ‘reverse’, paired with operational parameters, such as ‘pressure’, ‘temperature’, and ‘flow’ to provide a structured method to brainstorming questions aimed at assessing the effects of deviations from system design or operation. A HAZOP study is often applied to plumbing and instrumentation diagrams (P&ID) representing chemical or fluidic processes, and is well suited to analyze the safety of the fuel cell powered drone hydrogen fuel system operation or flight tank re-fill process.

A preliminary P&ID for a blow down hydrogen flight tank fill system is shown in Figure 5 and will be used to provide an example of how a HAZOP study may be applied to the fuel cell drone application. (Caution: this preliminary P&ID is only an example and does not include results of a HAZOP or represent all necessary hydrogen gas safety precautions). The approach outlined in Figure 5 assumes that the pressure regulator is used to limit the flight tank fill pressure, and the supply control valve isolates the tank from the fill system and may be used to affect the fill rate. For the purposes of the example, it is assumed that the flight tank is designed for a maximum fill pressure of 5,000 psi (350 bar), and will be filled from a standard gas cylinder filled to 6,000 psi (413 bar).

![Diagram of a blow down hydrogen flight tank fill system](image)

**Figure 5. Flight tank fill blow down fill process preliminary P&ID.**

Preliminary results from a condensed HAZOP study based on Figure 5 using ‘pressure’ as the parameter of interest along with the guide word ‘high’ are shown in Table 3. The possible causes for the existence of higher than design pressure in the system are listed, along with the potential consequences, and suggested actions to mitigate them. In this system, given that the source cylinder may be filled to 6,000 psi (413 bar) a functional failure in or improper manipulation of the components between the cylinder and the flight tank could lead to over-pressurization. In a worst case scenario, over-pressurization could lead to structural failure of the flight tank.

Methods to mitigate these consequences include installation of a pressure relief device set to the flight tank design pressure, incorporation of pressure and temperature sensors to monitor tank conditions, review of test procedures to ensure proper sequencing of actions to avoid an over-pressure scenario, and review of tank design requirements to ensure sufficient structural margins in the event of a worst case over-pressurization. Although the above example is straightforward,
it provides an illustration of the process by which the HAZOP study may identify unsafe consequences of deviations in system behavior.

**Table 3. Example from preliminary HAZOP study of blow down flight tank fill process.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Guide Word</th>
<th>Possible Causes</th>
<th>Consequences</th>
<th>Action Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>High</td>
<td>Regulator failure/ improperly set</td>
<td>Tank fill pressure exceeds design</td>
<td>Incorporate pressure relief valve set to 5,000 psi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Supply control valve failure/ improperly set</td>
<td>Tank structural failure</td>
<td>Monitor tank pressure and temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Excessive fill rate leading to elevated gas temperature in flight tank</td>
<td></td>
<td>Review fill procedures to ensure proper sequencing of events</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Review flight tank design to ensure adequate structural margins for 6,000 psi fill</td>
</tr>
</tbody>
</table>

**Definition of Operating Procedures**

As highlighted in the preceding FMEA and HAZOP examples, often safety risks identified may be mitigated through well-defined procedures, not only for operations, but also for design, manufacture, installation, and maintenance. As such, a key aspect of the safety plan focuses on the development of procedures that clearly define the: 1) roles of contributors, 2) key equipment used, 3) limits of design or operation, 4) safety considerations, 5) safety systems and their functions, and 6) proper sequence of actions for each phase of an activity, including how to address potential emergencies. Procedures should be updated as designs, personnel, equipment, and safety systems change over the course of time.

**Equipment and Mechanical Integrity**

A fuel cell powered drone system incorporates a number of devices, including valves, regulators, tubing, fittings, sensors, etc., that are critical to the operation of the fuel cell plant, the onboard hydrogen storage and delivery system, and the ground refueling system; the mechanical integrity of this equipment must be assured as part of the safety plan. The details will vary from component to component, but mechanical integrity may be verified through:††† procedures, proper design and testing, use of fail-safe features, preventative maintenance plans, calibration of safety related devices, regular inspection, training of personnel, documentation, and correction of deficiencies.

**Management of Change (MOC) Procedures**

It is expected that fuel cell drone systems will evolve over time to improve performance and reduce cost. The safety plan must define a procedure to review potential changes to materials, technology, components, equipment, procedures, personnel, and operation for safety impacts prior to implementation. The MOC procedures must define the qualified personnel necessary to review potential changes as well as those responsible for approval. Importantly, the MOC procedures must define revision control and documentation retention requirements.

**Project Safety Documentation**

The safety plan must also outline how safety documentation is maintained, including responsible personnel, filing locations, and accessibility. Safety documentation may include information related to key technology, equipment, safety systems, hazard review documentation, operating procedures, material safety data sheets (MSDS), MOC, and reference materials.
Independent Safety Review

It is important to reiterate that the larger hydrogen fuel cell industry is an excellent resource that may provide a wealth of experience and expertise to the growing fuel cell drone community as it works to develop systems to support drone operations. A fuel cell drone safety plan should include an independent safety review component in early project stages that employs outside experts and unaffiliated independent groups, such as the H2 Safety Panel,* to evaluate the applications, review preliminary system designs, risk analysis, and operational plans, identify potential safety gaps, and advise on safe operation practices and prior lessons learned.

Communication Plan

Ultimately, the goal of the fuel cell community is to deliver fuel cell power systems and supporting refueling systems that may be safely and independently operated and maintained by the professional drone user. Critical to achieving this goal is the communication of design specifications, operating procedures, and safety information. The safety plan must document an approach to delivering needed safety information to all potential users of the system. The following subsections describe the key components of the communication plan.

Personnel Training

The communication plan should document required hydrogen and other safety training for personnel involved with operating the fuel cell power system and re-fueling system to be familiarize users with potential hazards. The training should provide an overview of the system configuration, a thorough review of operating procedures, details on safety and health hazards, emergency procedures, and safe practices. Refresher training should also be incorporated into the plan along with documentation that records participation in and completion of training. Training for maintenance and calibration of equipment and components should also be included for appropriate personnel.

Safety Reviews

Periodic safety reviews should also be incorporated into the communication plan to assess the efficacy of operating, safety, and emergency procedures. The reviews should include all relevant personnel, and the roles of critical participants should be documented along with the general structure of the review itself.

Safety Events and Lessons Learned

The communication plan should also describe how safety events are handled by the team. Safety events include ‘incidents’ and ‘near-misses’. Incidents are events that result in: a lost-time accident and/or injury to personnel; damage to equipment, facilities, or property; impact to the public or environment; or an emergency response. Near-misses are events that would have been an incident under different circumstances; for instance, unintentional release of hydrogen that ignites, but does not trigger any of the results listed above. Any safety event should be investigated as soon as possible to understand root causes and disseminate corrective measures to ensure safe operation for all users (including those that may not have been associated with the originat-

ing event). The investigation team should include at least one independent member external to the project.

Emergency Response

The communication plan should define emergency response procedures and include communication and interaction with neighboring occupancies (businesses, residents, etc.) and local emergency response teams (fire and police departments). The plan may also include definition of emergency training requirements for personnel, if necessary.

Self-Audits

Finally, the communication plan should define a procedure for self-auditing to verify that defined operating procedures and training are being followed appropriately at all times. The self-audit should be conducted by personnel external to the project, and the plan should define compliance audit reporting requirements. The plan should also define the roles of the project team responsible for responding to the audit’s findings, and requirements for any action plan that may result. The team should respond as soon as possible to address any issues to ensure the safety of operators going forward.

FIELD EXAMPLE – HEX-ROTOR FLIGHT OPERATIONS

For the past several years, the fuel cell community has been conducting controlled field operations to assess system performance in multirotor drones under simulated mission scenarios. Efforts have focused on both the on-board systems, as well as the ground-based fueling systems; as users will depend on the industry to provide a complete fuel cell solution to support their operations. The following subsections describe preliminary field operations conducted by Ballard Unmanned Systems using a prototype hex-rotor VTOL platform designed and built by BFD Systems. The safety plan developed for these field operation is described in the context of the approach defined in the preceding section.

System Configuration

H2-6 Hex-rotor VTOL Platform

The BFD Systems prototype H2-6 VTOL platform incorporates a hexagonal rotor layout (29-30-in rotor diameter) with a gross take-off weight of 13-15 kg depending on rotor, payload, and fuel cell configurations. A Ballard, liquid-cooled FCAir 1200h PEMFC system is mounted on the top of the platform’s center hub (each of the two fuel cell stacks in the system are mounted on separate trays), and is capable of providing 1,200 W continuous net power to the aircraft. The system operates on an 8S bus and includes a small LiPo battery pack with a 3300 mAh capacity to supplement the fuel cell in climb and other high power maneuvers. The platform also incorporates a Ballard FCAir high pressure compressed hydrogen storage tank that is mounted on the bottom of the center hub. The tank provides a 4.6 L water volume and 6,000 psi maximum fill pressure and is capable of supporting up to 90 minutes of fuel cell operation at full power. A picture of the platform noting the locations of critical components is shown in Figure 6.

Blow Down Ground Fueling System

A prototype blow down ground fueling system was developed solely to support initial H2-6 hex-rotor field operations, and is not intended for wider usage. The system, shown in Figure 7, utilizes a 413 bar (6,000 psi) standard gas cylinder, sourced from a local industrial gas supplier, to drive the flight tank fill process. A single 413 bar gas cylinder delivered to the flight location filled the 4.6 liter flight tank 1.5 times to at least 310 bar (4,500 psi), or 75% capacity; two gas
cylinders were delivered to the flight test location to provide sufficient hydrogen for three flights with tanks filled to high capacity, without the use of a boost pump.

Figure 6. BFD H2-6 hex-rotor VTOL platform a) on ground with critical Ballard Unmanned Systems fuel cell system components identified, and b) in flight.
Safety Plan

In support of system integration and preliminary flight testing of the prototype hex-rotor, the Ballard and BFD teams developed and followed a preliminary safety plan based on the approach described in the preceding section. The plan was admittedly incomplete as system design and operating schemes were, and are still, in the prototype stage, but the field operations provided the opportunity to exercise the plan and identify areas of improvement. The following subsections touch on those safety plan components described previously, but are applied specifically to hex-rotor field test systems. (Caution – the information below does not represent a refined safety plan)

Recognize Safety Standards

As previously mentioned, dedicated safety standards for fuel cell systems designed for usage in drones do not currently exist. In lieu of dedicated standards, existing automobile fuel cell system standards were used to guide hex-rotor system design and operational schemes. Most notably the flight tank was designed based upon guidance for structural margins provided in the ANSI HGV 2 standard for Type 4 composite wrapped vessels with a non-metallic liner. Similarly, the blow down tank filling system was designed with the guidance provided in SAE J2601 for maximum allowable gas temperature. As drone specific fuel cell standards mature, the system design will be refined to match their corresponding guidance. The ASTM F38.01 WK60937 workgroup leader is part of the Ballard team, and the efforts described here are informing the specification efforts.

Internal Safety Review

The internal safety review process focused upon failure analysis, operating procedures, and equipment and mechanical integrity; in particular, the hydrogen storage, delivery, and fueling systems were considered in detail. Through preliminary FMEA and HAZOP analyses failure modes leading to structural failure of the flight tank, flight regulator, and fueling system were deemed the highest risk items. Mitigation was accomplished through a combination of approaches including design, operating scheme, pressure relief components, pressure and temperature sensors, and detailed operating procedures.
The blow down fill system is considered to illustrate some of the mitigation items incorporated into the system as a result of the hazard analysis. As previously mentioned, limiting flight tank fill rate during the filling process is critical to preventing over-heating of the tank and potential structural failure. The fill system was designed for manual operation to control the fill process slowly and incrementally to ensure that the tank temperate was maintained comfortably within the bounds defined by SAE J2601. A detailed set of fill system operating procedures were also developed to ensure that operating intent was followed precisely.

Additionally, tank internal pressure and external surface temperature were monitored throughout the fill process to provide real time diagnostic information. Finally, pressure relief devices were incorporated in the system to mitigate an over-pressure scenario. Through operations conducted to date, the defined operating scheme enables flight tank fill times ranging from 15-30 minutes depending on final fill pressure and operating conditions. The Ballard team believes that through more refined FMEA and HAZOP analyses, increased automation, and more comprehensive testing fill rates could be improved significantly.

**External Safety Review and Communication Plan**

Due to the prototype nature of the systems involved, the team has not completed an external safety review to date; however, it has sought out and received input from experts throughout the hydrogen fuel cell community. As the system design matures over the course of the next year, and prior to delivery of systems to customers, the team will engage with outside parties to support external safety reviews. The communication plan to date has focused on training of personnel involved in field operations, safety reviews prior to test operations, and definition of emergency response procedures.

**Test Results**

The defined safety plan has produced satisfactory results to date, with no safety events recorded through extensive laboratory testing of the fuel cell and re-fueling systems, several days of hex-rotor ground testing, and several hex-rotor field flight operations. The team has gradually expanded the scope of operations to ensure that the operability of each system is verified before moving to the next. As of the writing of this paper, the hex-rotor has completed hover tests of up to 76 minutes in calm weather conditions. Additional flight tests are planned to include multiple representative payloads and expanded mission sets to demonstrate platform maneuverability and operation in less-than-ideal weather.

**CONCLUSION**

The fuel cell community has demonstrated that drone fuel cell power systems provide significant performance and operational benefits over batteries for drone applications, and drone users have expressed eagerness to evaluate fuel cell powered drones in practical mission scenarios. The potential for widespread use of hydrogen fuel cell power systems along with supporting hydrogen storage and fueling systems has emphasized the requirement that the systems be safe, reliable, and easy to use.

A detailed safety planning approach, followed by the fuel cell industry (among others) for decades, has been outlined to guide the design, manufacture, testing, maintenance, inspection of drone fuel cell systems. The safety plan highlights the need to recognize appropriate hydrogen fuel cell system design standards early in the development process. A number of hydrogen safety standards have been summarized including several that have been developed for light duty vehicles and industrial trucks. Existing standards may provide guidance for drone fuel cell systems, but were not designed for that purpose and so significant caution must be used in attempting to
apply them to the drone space. As a result, several efforts are underway in the industry to create safety standards specifically for the fuel cell powered drones and their supporting systems.

Another critical aspect of the safety plan is to conduct a systematic internal safety review to ensure the safe design and operation of the drone fuel cell systems. Hazard analyses should be employed as part of the review to identify potential failure modes as well as their probability of occurrence, potential consequences, and overall safety risk. Methods of mitigating high risk failure modes should be identified through the process and implemented in the final design or operation. The safety review should also be used to develop detailed operating procedures, outline processes for ensuring the mechanical integrity of system components and equipment, define management of change procedures, and develop plans for safety document maintenance.

The safety plan should also include an external safety review early in the development process, that employs outside experts and unaffiliated independent groups to evaluate the applications, review preliminary system designs, risk analysis, and operational plans, identify potential safety gaps, and advise on safe operation practices and prior lessons learned. The final component of the safety plan is the communications plan which should include procedures and methods for personnel training, safety reviews, and emergency response. The communications plan should also include requirements for documenting safety events and lesson learned as well as rules and reporting requirements for self-audits.

A preliminary safety plan, not intended to serve as refined plan for others to follow, was described and applied to field operations around a fuel cell powered VTOL hex-rotor platform. The 13-15 kg gross weight platform included a 1,200 W fuel cell power system, a 413 bar rated onboard hydrogen storage tank, and a blow down tank fill system driven by a 413 bar gas cylinder. The complete system has been exercised successfully, and without safety events, through extensive laboratory testing, ground based testing on the platform, and several flight tests. The system design and operation will continue to mature with experience and continued observance of the define safety planning approach.

ACKNOWLEDGMENTS

The authors would like to acknowledge the insight and contributions of several members of the Hydrogen Safety Panel (https://h2tools.org/hsp). The authors would also like to thank the BFD Systems team, specifically Max Tubman and Mike Dornish, for their outstanding work in developing the hex-rotor platform described in this paper. Finally, the authors would like acknowledge the dedication and hard work of the Ballard Unmanned Systems team including Ryan Bussett, Alex Lessard, Farnoosh Fadiani, Forrest Harrington, Amy Garcia, Zheondre Calcano, Phil Del Signore, and Brendon Stearns.
Outline

• Hydrogen-fueled PEMFC Power Systems Overview
• Key PEMFC Power System Components
• Safety Planning Approach
• VTOL Multi-Rotor Field Experience
• Summary and Conclusions
Proton Exchange Membrane Fuel Cell (PEMFC) power systems can significantly increase UAV platform performance, utility, and reliability.

**Fuel Cell vs. Battery Systems**
- Group 1 UAS (< 9 kg)
- Fuel cells provide significant improvement in energy density (2-5x LiPO batteries)
- Extend mission times and provide more data to the user

**Fuel Cell vs. Internal Combustion Engines (ICE)**
- Group 2 UAS (9.5 – 25 kg) or larger
- FCPS provide more reliable performance than ICE
  - Time Before Overhaul (TBO) improvements of >5x
  - Lower operational costs and better platform reliability
- Low acoustic signature
- Exceptional throttle control
- Competitive energy density

**PEMFC power systems run on hydrogen → What are safety standards? How do you ensure safe operation?**
PEMFC Power System
Key On-Board Components

Fuel Cell Plant
- Fuel cell stack
- Air delivery subsystem
- Hydrogen management system
- Thermal management subsystem
- Control Electronics

Hybrid Battery
- LiPo or Lilon chemistry
- 6S-12S Voltage
- Low energy capacity

Power Management Electronics
- Manages battery hybridization
- Regulates fuel cell voltage
- Controls battery charge rate
- Battery management system

Hydrogen Supply System
- Pressure regulator (0.5-2 bar)
- Pressure/temperature sensors
- Control/relief/check valves

Compressed Hydrogen Storage Tank
- Composite overwrapped pressure vessel
- Type 3 (metal) or Type 4 (plastic) liner
- 310-413 bar (4,500-6,000 psi) pressure
- Water volume 1-10 L

XPO 2019
PEMFC Power System
Key Ground-Based Components

**Blow Down Fill System**
- High pressure, high volume H₂ source
- Flow control components
- Fills flight hydrogen tank
- Simple design and operation
- Limited fill pressure control

**Boost Compressor Fill System**
- Compressor boosts H₂ source pressure
- Driven by AC powered electric motor
- Expands H₂ source options
- Tight control of fill pressure
- Pump requires regulator maintenance

**Fill Safety Considerations**
- Gas temperature increases during fill
- Tank pressure and temperature must be maintained within design
- Fill rate control limits temperature rise

Courtesy Hydraulics International, Inc.
Safety Planning Approach

• PEMFC community takes safety very seriously
• Universal safety planning approach has been adopted
  o Utilized to many industries employing potentially hazardous systems
  o Successfully applied to automobile and material handling fuel cell systems
• Actively being employed in drone fuel cell community
  o Centered on design of on-board fuel storage and ground fueling systems
  o Includes fuel cell plant, battery, and power management electronics
• Plan includes 4 main components:
  o Safety standard recognition
  o Systematic internal safety review
  o Independent safety review
  o Communication plan
• Hydrogen Safety Panel - https://h2tools.org/hsp
• **Fuel cell powered drones require dedicated design standards**
  - Foundation of hazardous system design

• **ASTM WK60937 – Fuel Cell Power Systems for Use in sUAS**
  - Proposed new standard
  - F38 Unmanned Aircraft Systems committee
  - F38.01 Airworthiness sub-committee
  - Encompasses fuel cell plant, fuel storage, fueling, and hybridization systems

• **May leverage extensive body of standards for fuel cell automobiles**

• **Caution: Existing standards serve as guideline, but are not intended for drone applications**
  - Air vs. ground environment
  - Differences in scale (tank size, fill capacity, etc.)
  - Must identify gaps and inapplicable requirements
Relevant Existing Standards

- SAE J2601 – Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles
- SAE J2601/3 – Fueling Protocol for Gaseous Hydrogen Powered Industrial Trucks
- SAE J2600 – Compressed Hydrogen Surface Vehicle Refueling Connection Devices
- CGA G-5.5-2014 – Hydrogen Vent Systems
- NFPA 2-2016 – Hydrogen Technologies Code
- ANSI HGV 2 – Compressed Hydrogen Gas Vehicle Fuel Containers
- Numerous others that have not been listed here
Internal Safety Review: Hazard Analysis

• **Systematic process to review system design and operation to ensure:**
  - Standards followed appropriately
  - Failure modes and mitigation schemes identified and implemented
  - Operating procedures defined
  - Design documented adequately

• **Hazard Analysis**
  - Failures will happen, but **cannot** create an unsafe situation
  - Structured process for analyzing potentially hazardous systems
  - Multi-disciplinary team effort
  - Many techniques exist
    - Structured brainstorming
    - Often qualitative
    - Defines potential failure modes
    - Evaluates likelihood, consequences, and risks
    - Defines mitigation schemes
Internal Safety Review: Hazard Analysis Techniques

- **Failure Mode Effects Analysis (FMEA)**
  - Bottom-up approach
  - Begins with known failures modes
  - Well-defined electrical/mechanical systems
  - Fuel cell plant

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
<th>Cause of Failure Mode</th>
<th>Potential Failure Modes</th>
<th>Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode Air Blower</td>
<td>Forces ambient air into the cathode of the fuel cell</td>
<td>Electrical/mechanical failure</td>
<td>Fails to function</td>
<td>Medium</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Failure Consequences</th>
<th>Consequence</th>
<th>Risk</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode Air Blower</td>
<td>Sudden loss of power, Overheat fuel cell, membrane failure, fire</td>
<td>High</td>
<td>High</td>
<td>Design requirements, Qualification test requirements, Manufacturing and QC requirements, Installation, design, and test requirements, Fuel cell voltage monitoring, Temperature sensors</td>
</tr>
</tbody>
</table>

- **Hazard & Operability (HAZOP) Study**
  - Top-down approach
  - Directed by guide words/operational parameters
  - P&ID of chemical/fluidic processes
  - Fueling system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Guide Word</th>
<th>Possible Causes</th>
<th>Consequences</th>
<th>Action Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>High</td>
<td>Regulator failure/improperly set, Supply control valve failure/improperly set, Excessive fill rate leading to elevated gas temperature in flight tank</td>
<td>Tank fill pressure exceeds design, Tank structural failure</td>
<td>Incorporate pressure relief valve set to 5,000 psi, Monitor tank pressure and temperature, Review fill procedures to ensure proper sequencing of events, Review flight tank design to ensure adequate structural margins for 6,000 psi fill</td>
</tr>
</tbody>
</table>

Internal Safety Review: Additional Components

• **Definition of Operating Procedures**
  - Safety risks often eliminated through well-defined procedures
  - Procedures clearly define:
    - Roles, key equipment, limits of design/operation
    - Safety considerations, safety systems, proper actions in each phase

• **Equipment and Mechanical Integrity**
  - Verified through:
    - Procedures, proper design/testing, use of fail-safe
    - Maintenance, calibration, inspection, training, documentation, corrections

• **Management of Change (MOC) Procedures**
  - Review potential changes to all aspects of system
  - Defines qualified personnel to review and approve
  - Revision control and documentation retention

• **Project Safety Documentation**
Independent Review and Communication Plan

- **Independent Safety Review**
  - Larger hydrogen fuel cell industry is excellent resource
  - Utilize outside experts and unaffiliated independent groups (H2 Safety Panel)
  - Include in early project stages to review and advise

- **Communication Plan**
  - Ultimate goal is to deliver systems that may be safely operated by users
  - Must communicate specifications, procedures, and safety info
  - Plan components:
    - Personnel Training
    - Safety Reviews
    - Safety Events and Lessons Learned
    - Emergency Response
    - Self-Audits
Field Example: Hexrotor System Configuration

- **Prototype hexrotor (H2-6) platform developed by BFD Systems**
  - 15 kg GTOW, 30” rotors
  - Payload flexible configuration (1-2 kg)

- **Incorporates Ballard FCAir 1200h power system**
  - 1,200 W maximum FC net power output
  - 8S, 3300 mAh battery (>3 kW hybrid output capacity)
  - Full hybridization electronics

- **Compressed hydrogen storage tank (Type 4)**
  - 4.6 L water volume, 6,000 psi max storage pressure
  - Supports 90 min operation at full power

- **Blow down ground fueling system**
  - 6,000 psi gas cylinder source
  - 1.5 flight tank fills to 4,500 psi (75% capacity)
    - With 2 cylinders on site, 3 total fills
Field Example:
Hexrotor Safety Plan

• Preliminary safety plan developed to support flight operations
• Caution – the below does not represent a refined safety plan
• Safety Standard Recognition
  o Auto standard used for guidance
  o Tank design/test guidance, tank fill rate
• Internal Safety Review
  o Focused on H₂ storage, delivery, and fueling
  o Failure modes leading to structural failure deemed highest risk
  o Mitigated by design, scheme, press. relief, sensing, procedures
• Test Results
  o Extensive lab testing, ground tests, several flight ops
  o Scope of operations expanded gradually
  o Safety plan satisfactory to date, no safety events
  o Flights of up to 76 minutes achieved
Summary and Conclusions

- Demonstrated performance/operational benefits of fuel cell drones
- Community eager to evaluate capability
- Potential for widespread usage necessitates safe, reliable systems
- Accomplished through systematic safety planning
  - Well proven approach, used in multiple industries
  - Safety standard recognition
  - Internal safety review
  - External safety review
  - Communication plan
- Field operations involving fuel cell hexrotor described
  - On-board and ground based operations demonstrated
  - Systems continue to mature
- Technology ready for practical mission evaluations
• Three members of the H2 Safety Panel
• BFD Systems team, specifically Max Tubman and Mike Dornisch
• Ballard Unmanned Systems team
  o Ryan Bussett, Alex Lessard, Farnoosh Fadiani, Forrest Harrington, Zheondre Calcano, Phil Del Signore, Brendon Stearns, and Amy Garcia