THE SOCIETY OF FLIGHT TEST ENGINEERS

Things Flight Testers Should Know About Hydrogen

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Abstract

Hydrogen powertrains are an area of significant interest in aviation and other industries today. All types of systems ranging from direct combustion to hybrid electric powertrains with fuel cells are under development. While the use of hydrogen in aircraft is not new, it is not commonplace and there are specific design and operational issues that are unique to hydrogen fueled systems. The focus of this paper is the development, design, and testing of systems using hydrogen and specifically the areas that are of primary concern to test teams. This paper will discuss the safety approaches recommended and the design implications that flow from typical recommended safety analyses. Hydrogen risks, design mitigations to risks, leak detection approaches and test specific considerations will be discussed.

1. INTRODUCTION

Hydrogen powertrains have been around for many years and have been successfully implemented in the automotive and civil transportation industries. It has only been recently that companies have started developing hydrogen powertrains for aviation applications. AeroTEC was recently part of the development and testing of a hydrogen powertrain test aircraft. Safety, reliability, weight, system complexity and development cost were among the challenges that the team faced when developing a hydrogen powertrain system for aviation applications. This paper will walk through several design considerations that were key to meeting the design challenges while maintaining a safe system for the test team. The paper focuses primarily on the design and testing aspects important to the test team and not the entire scope or challenges with the system.

2. HYDROGEN POWERTRAIN OVERVIEW

A hydrogen powertrain refers to a system that utilizes hydrogen as the primary fuel source to generate power for aircraft propulsion. Typically, these systems consist of four main components: hydrogen storage system, hydrogen fuel delivery system, hydrogen fuel cells in some cases, and an electric motor. In addition to these primary systems, there are other safety systems such as leak detection, shutoff valves and system monitoring, that are not required for providing propulsion but are necessary for mission safety.

The electric motor can drive various power output devices, such as a propeller or ducted fan. Additionally, hydrogen can be burned directly in traditional power plants like a piston or turbine engine. In this case, the hydrogen storage, detection, and fuel line routing would be similar or identical to a hydrogen-electric system, so the same design and testing precautions would be applicable. These common systems for a hydrogen powered aircraft can be further defined:

1) Hydrogen Storage System: Hydrogen is a lightweight gas and needs to be stored at high pressures or low temperatures to achieve sufficient energy density. Common methods of hydrogen storage include compressed hydrogen gas (GH_2) and cryogenic liquid hydrogen (LH_2). Compressed hydrogen is stored in high-pressure tanks, while liquid hydrogen is stored in insulated cryogenic tanks. Both methods have their advantages and disadvantages in terms of energy density, cost, and safety considerations which will be discussed further.
2) Fuel Supply System: a set of tubes, manifolds, valves, and sensors that contribute to safely deliver hydrogen from the storage system to consuming devises. Typically, stainless steel tubes are used to transfer high and medium pressure hydrogen. For lower pressures (<3 bar) a special aluminum tubing can be utilized. Tubes can be interconnected with swaging or AN type fitting. Some tubes may have a secondary wall or shroud to protect the tube and prevent GH_2 leaking into non-vented compartments.
3) The Hydrogen Fuel Cell: is the heart of the powertrain. It converts the chemical energy stored in hydrogen gas into electricity through an electrochemical reaction. The basic fuel cell consists of an anode and a cathode separated by an electrolyte membrane. Hydrogen gas is fed into the anode, where it splits into protons and electrons. The protons pass through the electrolyte, while the electrons travel through an external circuit, creating an electric current that powers the system. Oxygen from the air combines with the protons and electrons at the cathode, forming water as the only byproduct.
4) Electric Motor: The electric motor in a hydrogen powertrain is responsible for converting the electrical energy generated by the fuel cell into thrust. The electric motor drives the propeller or fan directly or indirectly through the gearbox.

In addition to the above listed main components, a hydrogen powertrain may have other secondary systems that increase overall system complexity. Secondary systems may include a compressed air supply system, fuel cell and motor cooling systems, auxiliary power supply system, air humidifying system, and hydrogen heating and cooling systems. All of these systems are typically synchronized and governed by a system control module with dedicated software.

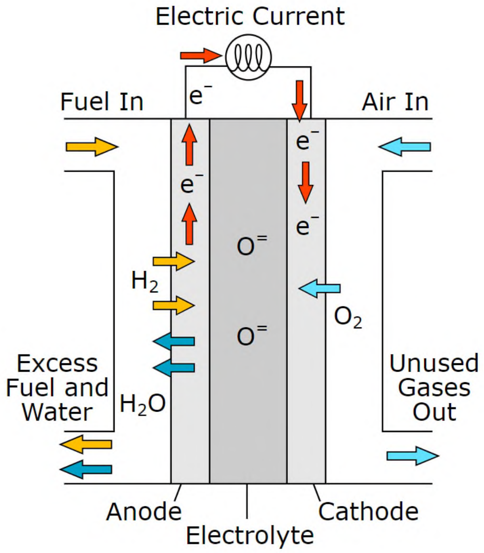

Figure 1 Generic Fuel Cell Diagram

3. INDUSTRY GUIDELINES FOR HYDROGEN SAFE HANDLING AND SYSTEMS DESIGN

Hydrogen is a colorless, odorless, tasteless, and nonpoisonous gas. The most famous property of hydrogen is its flammability. Hydrogen can ignite in both low and high concentrations with oxygen from approximately 4% to 94% volume (4%-77% with Air by Volume). This ignition range is broader compared to other flammable substances such as methane, propane, gasoline, and jet fuel. It requires only 0.02 millijoules of energy to ignite the hydrogen-air mixture above 10% of concentration, which is less than 7% of the energy to ignite natural gas [1] [2]. While the lower flammability limit (LFL) is similar to other flammable gases, the upper flammability limit (UFL) for hydrogen is significantly higher. This means that hydrogen can ignite even in rich mixtures, where there is a low concentration of oxygen and a high concentration of hydrogen. This distinction requires extra precautions, as vessels containing hydrogen must be purged with inert gas to remove any presence of oxygen. Furthermore, hydrogen flames are typically invisible, necessitating the use of specialized equipment for detection. Additionally, hydrogen can explode, deflagrate, or detonate, posing significant risks and potential damage. Given its propensity to ignite not only from open flames but also from hot surfaces, friction, or even static sparks below the threshold of human sensation, it is imperative to keep hydrogen separated from oxygen. It is also important to note that the ignition energy goes up past the minimum ignition energy (MIE) point of approximately 28% in air at 1 atmosphere. Concentrations from 4-28% are increasingly likely to ignite while concentrations from 28% to 77% have increasing ignition energy requirements and are less likely to ignite but everything from 4-77% can present a hazard.

Figure 2 shows the flammability limits for hydrogen-oxygen-nitrogen mixtures.

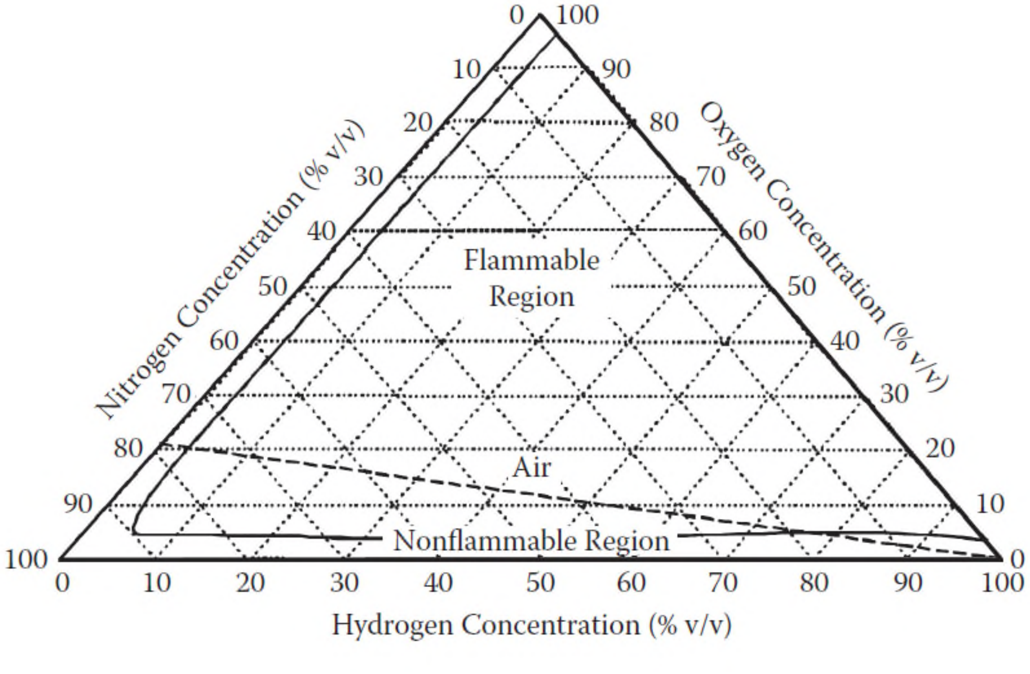

Figure 2 Flammability limits of hydrogen-oxygen-nitrogen mixtures at a pressure of 101.3 kPa (1 atm) and a temperature of 298 K (25°C). [3]

Another important property of hydrogen is its interaction with certain metals. Due to its light and small molecular size, hydrogen can permeate the crystal structure of metals. This phenomenon, known as embrittlement, can cause a substantial loss of ductility in certain metals when exposed to hydrogen. Additionally, at temperatures exceeding 200 °C, steel microstructure can experience non-reversible degradation, a phenomenon referred to as hydrogen attack. These interactions emphasize the need to consider hydrogen's effects on materials when designing systems and selecting appropriate materials to ensure structural integrity and safety. [4]

Special attention must be paid to hydrogen behavior when going through a pressure regulator, as its Joule-Thompson coefficient is negative for a wide range of ambient temperatures. In other words, when throttling through the orifice, unlike other gases, hydrogen gets hot. This can cause a pressure regulator to self-ignite the hydrogen or create a hot surface that is dangerous to maintenance or crew members. In many cases, the hydrogen pressure is regulated at the tank, downstream of which all transfer lines will be hot and in areas where personnel might touch them.

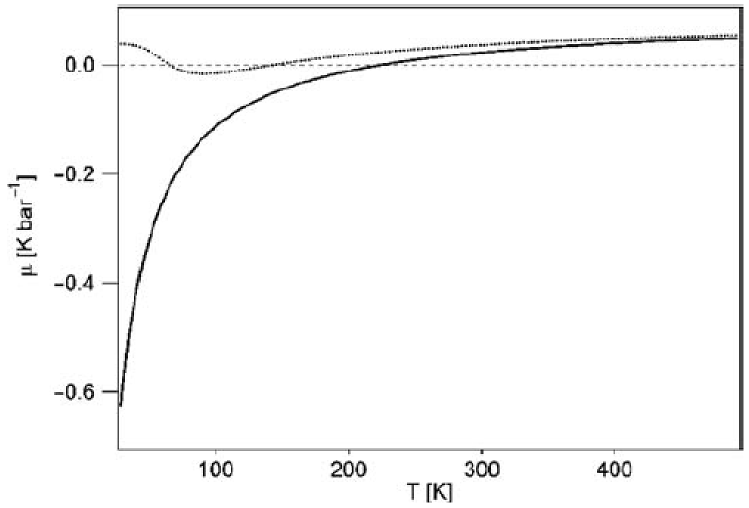

Figure 3 The Joule–Thomson coefficient for H2 in the Van der Waals approximation at a pressure of p=0.1 MPa (solid line) and p=10 MPa (dashed line). *[5]*

Understanding and addressing these properties and behaviors of hydrogen are essential in implementing effective safety measures and engineering practices to mitigate risks associated with its flammability, explosiveness, and interactions with materials.

Considering the fundamental physics behind hydrogen is important for designing with first principles in mind. However, industry standards exist that discuss engineering development approaches for implementing hydrogen systems. An important feature to include while designing a hydrogen system is the ability to prevent hazardous quantities of hydrogen from building up in the shrouding when leaks occur. This involves developing passive and active ventilation systems that can handle the types of leaks that are anticipated. This requires determining what leak rates are acceptable and would not cause the hydrogen concentration in the shroud to reach the LFL at 4% H2 concentration by volume or higher.

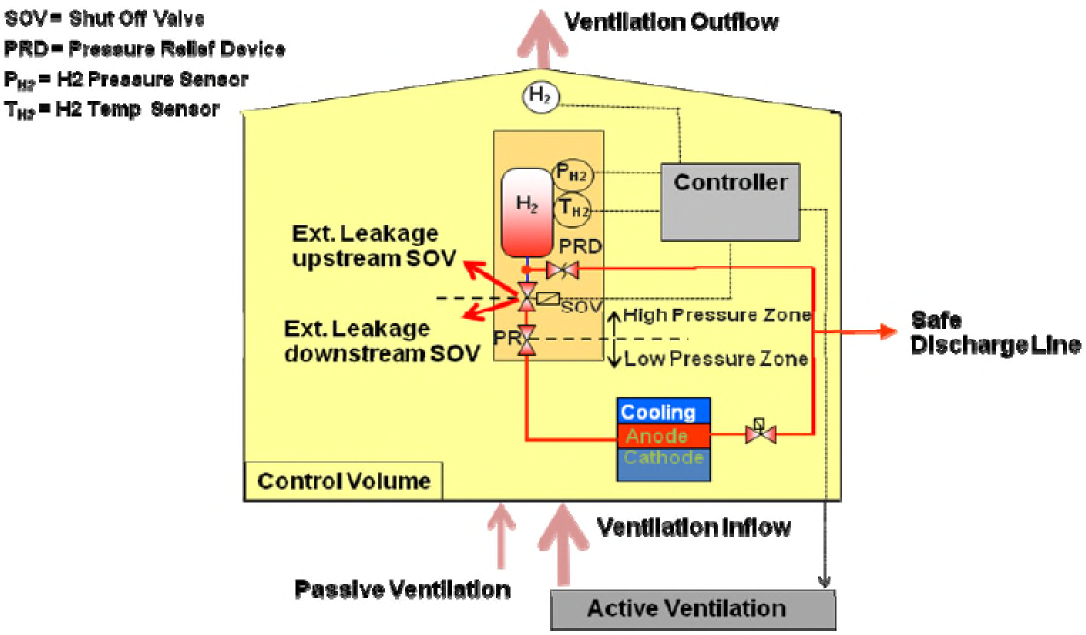

Figure 4 Example diagram of H_2 system using a controlled volume containment approach. *[2]*

Before developing and testing a hydrogen system, the safe handling of hydrogen at the site and on the aircraft must be addressed. OSHA standards for the use of hydrogen are already in place and should be followed for hydrogen storage systems off the aircraft [29 CFR, §1910.103]. These standards can also be used as a basis for storing hydrogen on the aircraft. The OSHA regulations define different mitigations relative to the amount of hydrogen being stored, such as minimum distances to ignition sources and flammable materials. These restrictions are intended to protect buildings or structures where hydrogen is stored and the people working in the area.

4. SYSTEM SAFETY APPROACH

For hydrogen storage systems on aircraft there are multiple system architecture approaches, but the architecture utilized for the project discussed in this paper is the “controlled volume” architecture outlined in Reference [2]. Additional recommendations from that guideline and other industry guidelines were used and are discussed in this paper. The key objective of the controlled volume architecture is to establish a volume around hydrogen carrying components with a shroud that can be safely vented off the aircraft. The shroud slows down hydrogen leaking to areas not designed for hydrogen exposure. While low concentrations of hydrogen are not a major driver of hydrogen embrittlement, all equipment and materials in the controlled volume should be reviewed for sensitivity to hydrogen. Nominal ignition sources in the controlled volume are prohibited, and probable ignition sources are shown to be sufficiently unlikely to occur. Hydrogen leakage into the controlled volume is detected, and the ventilation is adjusted as needed to push the hydrogen overboard and reduce its concentration in the controlled volume to a non-hazardous level.

The principal functions of this architecture are containing hydrogen leakage in a controlled volume, monitoring the hydrogen concentration in that volume, and ventilating the volume to prevent hazardous concentrations from building up. This architecture partitions the aircraft into different hydrogen zones, those intended for hydrogen, those intended for hydrogen leakage, and those not intended for hydrogen.

The controlled volume architecture was deemed necessary for an experimental program with unproven technology because hydrogen's ability to permeate through nearly all materials. Portions of the hydrogen system will therefore nominally leak hydrogen at a "background leakage rate." The team underwent a test campaign to measure the background leakage rate of the hydrogen system while it was in its "safe state", all primary valves closed, and tanks filled. This allowed the team to quantify how long the aircraft could be powered off with no active ventilation before a hazardous quantity of hydrogen built up in the shroud system. Engineers verified the active ventilation system could clear the accumulated hydrogen concentration quickly.

Before testing the background leakage rate of hydrogen, the team had to address the risks associated with fueling the aircraft with hydrogen. Since this system used gaseous hydrogen, it had to have a higher-pressure hydrogen storage system off the aircraft. Therefore, the test team had to protect against over pressuring the aircraft system and needed to provide a means to reduce the pressure if an over pressurization event occurred. These additional systems for handling over pressurization and onboarding hydrogen would also be prone to leaks and would be actively monitored during the fueling process.

The pressure release system introduced its own challenges. No single failure can allow for over pressurization of the system. This drove the need for redundant over pressurization protection mechanisms. Engineers also had to ensure the release of high-pressure hydrogen gas did not cause friction-based ignition. Which as noted above can occur under the right conditions and lead to invisible jet flames. Normal pressure regulating valves and burst disks can ignite hydrogen due to the high velocity hydrogen gas causing a local hotspot above the hydrogen ignition temperature. The team tested a novel over pressurization prevention systems to verify it would not ignite the hydrogen in the event of an over pressurization situation. The testing was conducted successfully with no issues but highlights the need to be aware of special risks when working with a highly flammable gas.

Even after addressing the basic functionality of the hydrogen storage system, the team still needed to define the appropriate safety margins for storing and transporting hydrogen. Given the lack of data for hydrogen systems on aircraft, engineers had to carefully look at the qualifications of all the equipment including the margins for components carrying high pressure hydrogen. The margins for proof and burst pressures of hydrogen equipment are not well defined for aircraft. However, there are published margins for hydrogen powered space vehicles [6] [7] which allowed engineers to use that as a baseline to compare against our expected operating conditions. Additionally, there are suppliers for hydrogen powered ground vehicles who can provide equipment with the necessary functionality and some qualification and testing that can be compared against the system requirements for AeroTEC test campaign.

After considering all the system level implications of using hydrogen and the testing required to demonstrate the necessary functionality, engineers followed the more conventional aircraft and system development process outlined in SAE ARP4754 and SAE ARP4761. This involved identifying and analyzing risks associated with the new aircraft modification to ensure no single points of failure would result in a hazardous or catastrophic failure condition. The safety assessment included an aircraft change impact assessment, an aircraft functional hazard assessment, a preliminary system safety assessment, and a final system safety assessment.

5. HYDROGEN STORAGE & SUPPLY SYSTEM

The hydrogen powertrain supply system is responsible for delivering hydrogen fuel to the fuel cell stack which could be located either in the fuselage or nacelle. The system's major components may include the hydrogen module with a storage tank, hydrogen pressure regulator, fill lines, supply lines, GH_2 vent lines, emergency dump lines, and sensors to detect flow in the lines. The hydrogen module may contain LH_2 or GH_2 and may be removable from aircraft for refilling.

GH_2 can be stored in cylindrical tanks under high pressure, typically between 350-900 bar depending on mass requirements. It is important to note that tanks for storage and supply of GH_2 with pressures over 350 bar become increasingly difficult to source and special consideration needs to be given to all of the components in the system when design pressures exceed 350 bar. The volumetric density of GH_2 is significantly lower than any alternative energy sources. For example, 5kg of gaseous hydrogen requires about 200 L of volume, while LH_2 of same amount can be stored in a 75 L cylinder [8]. Therefore, liquid hydrogen may be preferred over GH_2, but it has its own disadvantages as it must be converted to GH_2 to be used in most powertrains.

Hydrogen tanks are manufactured in five different types: all-metal tanks (Type I), metal hoop-wrapped composite tanks (Type II), metal-lined composite tanks (Type III), plastic-lined composite tanks (Type IV), and all-composite, liner-less (Type V) tanks.

Safety is the major challenge that drives the design of the hydrogen storage system. Both GH_2 and LH_2 will leak from tanks and lines under nearly any pressure. These leaks may go undetected before the hydrogen-oxygen mixture reaches the LFL. To prevent this, active ventilation of the modules and high-pressure manifolds is recommended. Hydrogen tanks and supply control manifolds may be placed in an enclosure that is actively vented during the flight and while stored on the ground. Two or more hydrogen leak detection sensors shall be placed inside the module at the highest points to detect any leaks with as low as 1% concentration of GH_2. This early detection will prevent dangerous gas concentrations and send a notification to the pilot to deactivate that module. For redundancy, it is recommended to have a hydrogen storage system divided into two or more independent compartments or modules, providing hydrogen simultaneously to the main feed lines. In the event one module is shut down due to leaks or other malfunctions during the flight, the other modules can continue feeding GH_2 without interruption.

The nature of hydrogen to constantly leak from any high-pressure vessel makes it a necessity to design a well-ventilated compartment. The vent system may become challenging from a safety standpoint because the system is exposed to both hydrogen and oxygen and can see any mixture combinations. Therefore, the system shall be designed to prevent ignition of the mixture and prevent flame propagation inside the compartment from the vent port. One solution to this can be utilizing flame arrestors at the vent ports.

The hydrogen feed line is another challenging component for safe operation. The feed line carries hydrogen from storage module to fuel cells and may be routed through vented and unvented compartments. The protection of this line from accidental leaks is non-trivial. One solution can be utilizing shrouded lines, where the inner tube carries the GH_2, and the secondary compartment is actively or passively ventilated to prevent any GH_2 accumulation above atmospheric pressure. The feed line can be designed such that it does not allow any static charge buildup on its walls to prevent spark ignition or to properly handle currents from a lightning strike. Similar double wall or shrouded lines have been successfully utilized in airplanes for conventional fuel supply, and with minor modification can be also utilized for hydrogen systems.

6. LEAK DETECTION SYSTEM

The hydrogen leak detection system is a key safety protection against hydrogen leaks and system malfunctions. As this system is safety critical, it is recommended to implement two independent systems, one of which can be fully analog which is robust, and another can be managed by software and signals from sensors that will be used by the main control system. The analog leak detection system is considered as a standalone circuit, designed to detect, and annunciate hydrogen leaks to pilots. This system can be completely independent from the digital leak detection system, to prevent single point failures from causing the complete loss of hydrogen detection in a single area. It can monitor the entire hydrogen system inside the fuselage, inside the double-walled feed tubes, above the fuel cells, and inside the fuel storage ventilation system. An annunciator can be in the cockpit on the main panel and could consist of a single push-to-test indicator with multi-section displays. Figure 5 shows a generic leak detection system diagram similar to which was used during the flight test.

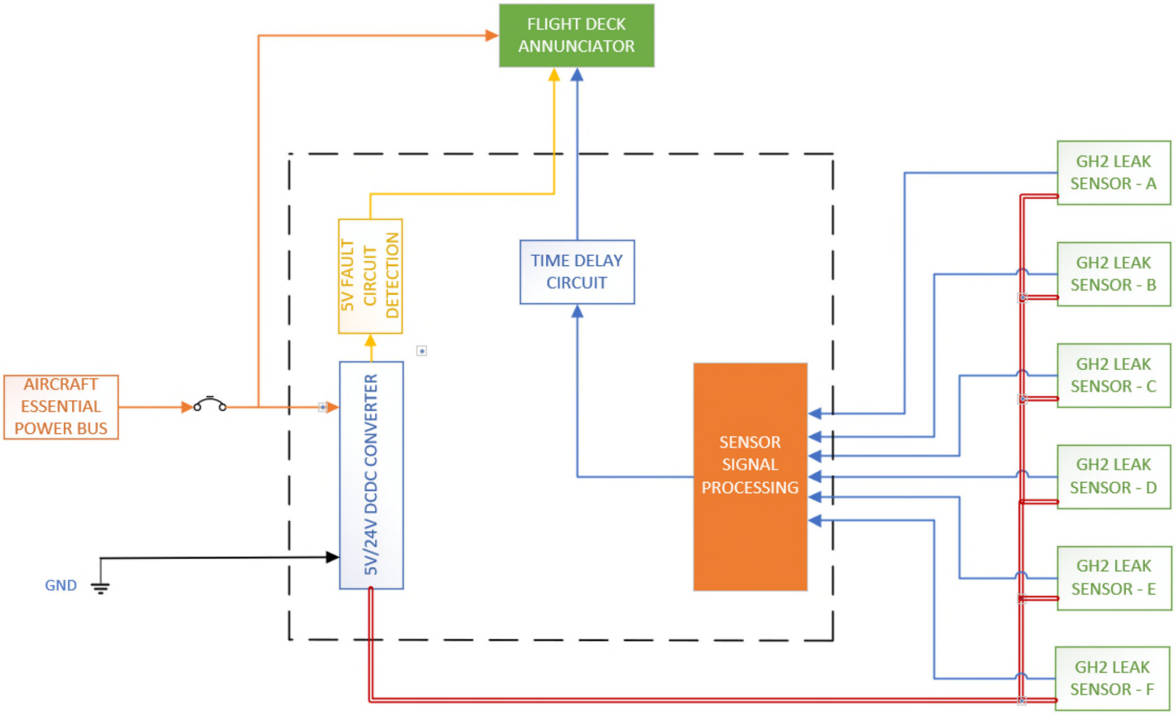

Figure 5 H_2 Leak Detection System Typical Functional Diagram

The array of H2 leak detector sensors was connected to the sensor signal processing circuit board. Each sensor had its own independent signal processing circuit, located on the same PCB. Using analog signal processing, the system detected the output voltage of the sensor and determined the concentration level of the hydrogen. Redundant time delay relays were activated when a signal was present from any of the sensors and would reset after the preset time interval if the signal disappeared. This gave the flight crew adequate time to note the warning/caution light and take necessary actions. Leak detector sensors were powered with a low voltage power supply. The power supply fault monitor system was powered by the aircraft essential bus. Thus, a failure of the power supply wouldn't stop it from causing a fault indication.

To enhance the efficiency of the system, it was crucial to position leak detection sensors in areas where GH_2 concentrations were expected to be elevated, even during minor leaks. Among others, these areas could include the highest points within enclosed volumes or zones with low airflow within the ventilation system.

For optimal monitoring of leaks during the system's initial functional tests, the annunciator was positioned to ensure easy visibility to the flight test crew, even during ground operations. The hydrogen levels were also monitored with software and threshold limits were compared to analog system outputs to verify accuracy.

7. SYSTEMS TESTING

The process of developing and prototyping any innovative technology is challenging for engineers, particularly in the aerospace industry. Engineers face many challenges when working on novel technologies, including components not previously tested for aircraft applications or designed to function in aerospace environments. To streamline the development process and minimize costs, engineers often opt for existing components and subject them to rigorous testing to ensure they meet the necessary requirements.

Throughout the development process, these tests are repeated multiple times. Each iteration helps refine and optimize the system, calibrate parameters, and ensure that all sensors are functioning correctly. The goal is to reach a stage where all components, subsystems, and the complete system are fully calibrated, validated, and ready for flight testing.

By following this iterative approach and gradually progressing from component testing to subsystem testing and finally to complete system testing, engineers can mitigate risks, reduce development time, and avoid additional costs associated with unforeseen issues. The iterative nature of the process allows for continuous improvement and ensures that the technology is thoroughly tested and validated before it undergoes real-world flight testing.

During the development of the hydrogen powertrain, the team encountered various challenges, including concerns for GH_2 spark ignition, the accumulation of static charge in the ventilation system, ensuring flame protection of the vent port, and addressing the hydrogen feed line manifold leakage rate. These problems demanded utmost attention and thorough investigation and resolution.

The spark ignition problem was related to the high-pressure refill manifold overpressure protection system: the engineers decided to solve overpressure protection with a special fitting, called a Safety

Head, that had a protective metal disk, which would rupture under a set pressure. This would allow pressure to be released from high-pressure lines and dump hydrogen overboard through the dedicated port. The energy that would be released during disk rupture could cause hydrogen spark ignition and potential translation of the flame outside of the aircraft, where the oxygen-hydrogen mix would happen.

To mitigate this issue, a special component ground test was planned and executed. Test setup and component selection were maximally close to the original design, to replicate all key aspects of airplane interference.

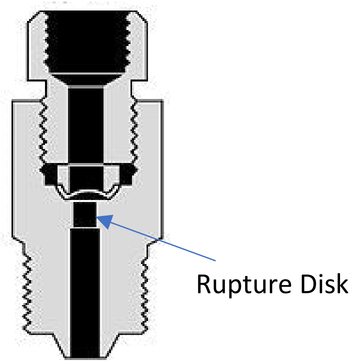

Figure 6 High Pressure Safety Head with Rupture Disk

The system was successfully tested four times, until engineers had a solid answer to safety concerns. Tests were done outside, away from buildings and with necessary safety measures. As a result, the design was finalized, and components were installed on the aircraft with consequent ground functional and flight tests.

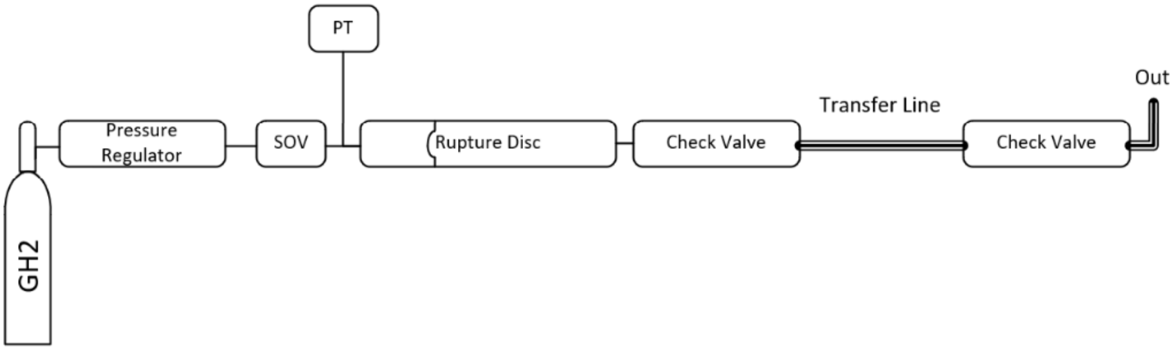

Figure 7 Rupture Disc Test Setup

7.1. Hydrogen storage and supply system test

After completing the assembly and installation of the GH_2/LH_2 storage and supply system, a critical step in the development process was conducting a leak check. This check was essential to ensure that the system was free from any leaks that could compromise safety and performance. To conduct this test safely, it was decided to use helium gas instead of hydrogen.

The use of helium gas for leak testing offers several advantages over hydrogen. One key advantage is that the helium atom is approximately 11% smaller in kinetic radius compared to the hydrogen molecule (H_e kinetic radius = 2.60, while H_2 kinetic radius = 2.89 [9] [10]). This difference in size makes leak detection with helium more conservative and increases the likelihood of detecting micro leaks that could potentially develop into significant leak sources over time. The FAA approved certified spray liquid for leak detection is recommended for such test, to minimize residue and protect aircraft structure.

Despite helium being an inert gas, it is mandatory to monitor oxygen levels in work environment and airplane compartments to prevent hypoxia of the workers and test engineer. During the tests conducted by AeroTEC engineers, all airplane compartments were actively ventilated and oxygen levels were monitored periodically. These safety measures prevented any accumulation of helium gas in fuselage crown sections.

The utilization of helium gas for conducting leak checks proved to be instrumental in revealing several weak points within the GH_2/LH_2 storage and supply system, consider vibrations of components and the need for inspection requirements in ground and flight testing.

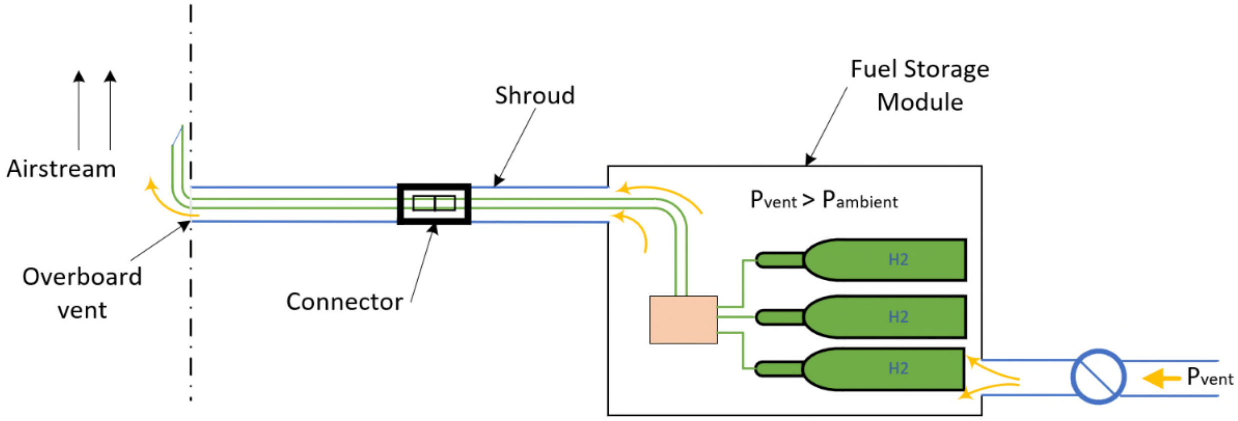

Figure 8 Vent/Shroud system principal schematic

For the primary pressurized system, helium was introduced to the fill and supply lines, as well as high pressure vent lines. A special manifold was used to tap into the line and the tank valves remained closed to save the amount of helium required for the test. The lines were tested to maximum available pressure from the helium bottle. Pressure was maintained for a certain period and leaks were checked for at each line connection. Once the high-pressure system was checked and all leaks were fixed, the secondary shroud system was filled with lower pressure helium and tested for major leaks.

7.2. Ventilation system test.

A significant system-level test was conducted for the ventilation system, which posed a major challenge related to the required airflow within a given compartment and quantifying the leak rates from the shrouding system inside the cabin.

To quantify the shroud system leak rate, mass flow rate measurements were taken at the inlet and outlet of the system. The difference was calculated and compared to allowable mass flow rates for the cabin. This measurement gave engineers the ability to evaluate hydrogen concentrations inside the cabin and define the hazardous threshold for the GH_2 concentration inside the ventilation system.

The airflow requirements varied depending on normal operating conditions and the occurrence of a major GH_2 leak event. The ventilation system needed to be capable of effectively changing the air inside the compartment (Fuel modules and GH_2 line secondary shroud system) under both normal conditions and in the event of a major leak. The challenge lay in determining the appropriate amount of airflow needed for each scenario and designing the system accordingly.

To enable the leak detection sensors to effectively detect a small leak, it was crucial to establish specific ventilation criteria for the compartment. Under normal conditions, the compartment's ventilation rate should not exceed one air change per minute, or the sensors could not effectively sense the gas. However, in the event of a major leak, the ventilation rate needs to be rapidly adjusted from minimum to maximum leak rate to ensure that the concentration of GH_2 within the compartment remained below the LFL (4%), as defined above. With high pressure GH_2 it quickly becomes impossible to ventilate the compartments sufficiently to eliminate the possibility of reaching the LFL. SAE guidance [2] recommends the use of double walled fuel lines or system shrouding to create an ignition free zone to allow for high concentrations of GH_2 for short periods of time. As a further mitigation it is recommended that this zone be actively vented to allow for rapid reduction of the GH_2 concentration.

This criterion poses a significant challenge for both design and test engineers. The design engineers must consider the appropriate ventilation rates for different leak scenarios, considering factors such as the maximum leak rate and the desired GH_2 concentration threshold. The test engineers are responsible for validating the system's performance by demonstrating a safe system under multiple conditions with probable leak rates.

Both teams had to work closely to define the parameters for a major leak and develop test protocols that accurately simulated real-world conditions. The test engineers had the important task of conducting rigorous tests to validate the ventilation system's performance and ensure compliance with the specified criteria. This collaborative effort between the design and test engineers was necessary to overcome the challenges associated with defining the major leak amount and verifying that the GH_2 concentration remained within the desired limits throughout the testing process.

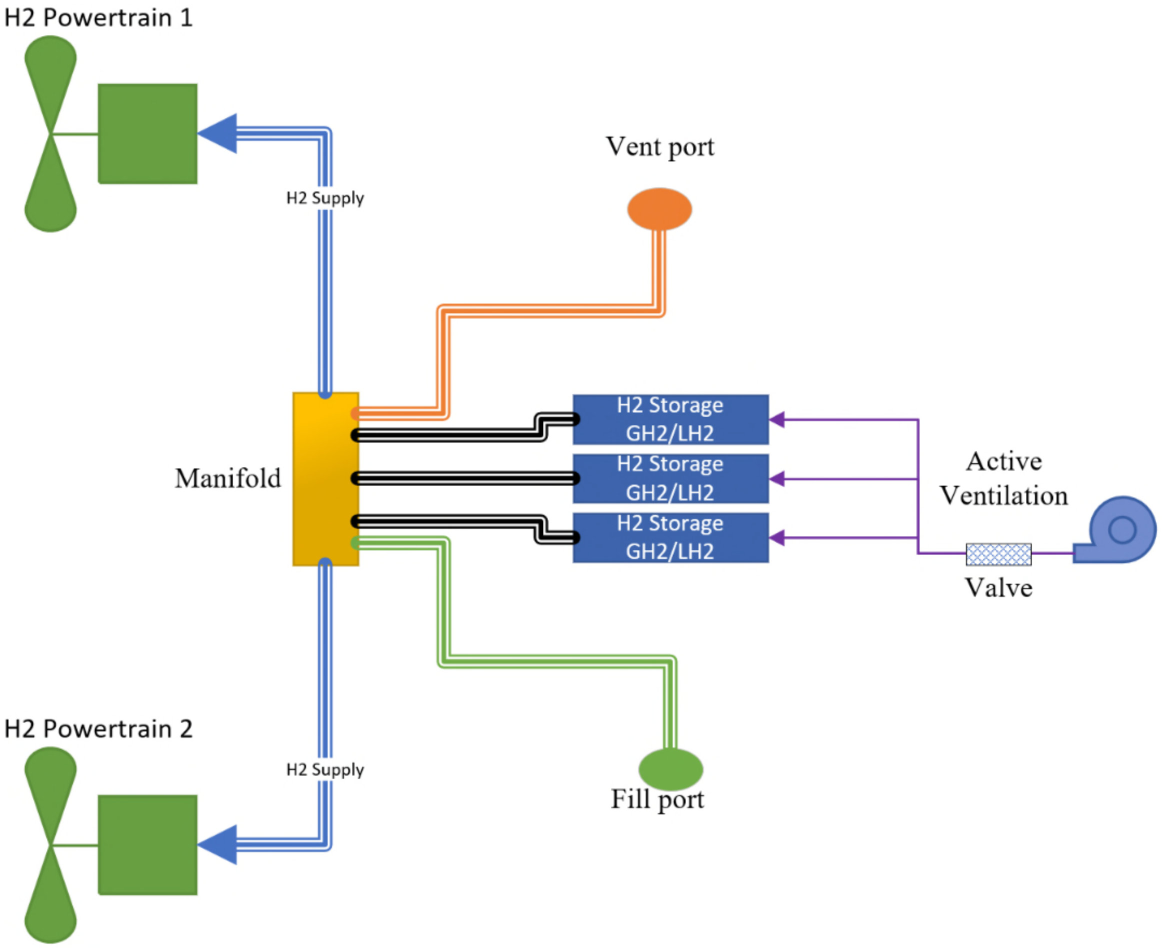

Figure 9 Generic H_2 system layout

The implemented solution to address the ventilation need involved the development of a novel component known as the Differential Butterfly Valve. The valve was designed to remain closed under normal conditions, to limit the flow of the shroud system so that the concentration of GH_2 from small leaks could be detected. Once any sensor within the ventilation system detects a GH_2 concentration exceeding the specified threshold a PCB logic control activates the butterfly valve to transition into a fully open state to allow maximum flow through the system. This provides that system with the maximum airflow and greatest ability to reduce GH_2 concentrations in the shortest period of time. It should be understood that the GH_2 concentration will likely exceed the LFL and potentially by a significant amount. The shroud system provides the “safe zone” for high GH_2 while the ventilation system removes excess GH_2 as fast as possible. The system as designed in this application was setup to indicate unsafe GH_2 levels but once exceeded the entire system would shut down, closing all system valves, and necessitating a stop to all testing.

To facilitate the dilution of high GH_2 concentrations, the incoming air from the aircraft ventilation system was directed through the fuel modules and a secondary compartment consisting of double-walled tubes. This configuration effectively prevented the buildup of hazardous concentrations by allowing the high-concentration air to mix with the incoming fresh air.

To verify the efficacy of this concept, a functional test was conducted. During the test, increasing levels of GH_2 concentrations were manually injected into the vent duct by the test engineers until the desired concentration levels were detected by the leak detector sensors. Once the GH_2 concentration surpassed the designated threshold, the system automatically triggered the butterfly valve, and the gas levels were continuously monitored to observe the dilution process.

Functional testing successfully demonstrated the effectiveness of the developed concept and its ability to dilute high GH_2 concentrations. Test engineers validated the system's performance under various GH_2 concentration scenarios, confirming its effectiveness in maintaining safe conditions by triggering the butterfly valve and monitoring the dilution process in real-time.

During the conduction of such tests, test engineers adhered to stringent safety measures to ensure their well-being and the overall safety of the testing environment. These measures include:

- Training: Test engineers went through specialized training on hydrogen safety protocols, equipment handling, and emergency procedures. This training equipped them with the necessary knowledge to carry out the tests safely and effectively. Hydrogen safe handling is essential to the testing process to assure all personnel are cognizant of risks and mitigations as the consequences of unsafe handling can be catastrophic. With appropriately trained personnel, Hydrogen can be handled as safely as more conventional fuel sources.
- Personal Protective Equipment (PPE): Test engineers were required to wear appropriate PPE, including anti-static clothing. This clothing helped minimize the accumulation of static charges, reducing the risk of sparks or ignition in the presence of hydrogen. Additionally, they utilized handheld hydrogen detectors to detect any small leaks and acoustic sensors to monitor for any unusual sounds associated with leaks or equipment malfunctions.
- Ventilation System: An adequate ventilation system should be in place at a basic design level and during the any testing to mitigate the accumulation of hydrogen and maintain a safe working environment. These systems help prevent the formation of hazardous concentrations and aid in the quick removal of any released hydrogen. Test site ventilation may be needed depending on the testing circumstances but should be considered as part of any test planning.
- Emergency Response Plan: Test engineers should be well-versed in the test emergency response plan specific to hydrogen-related testing. This includes procedures for evacuation, containment of leaks, safe system shutdown and coordination with safety personnel.

By following these safety measures, undergoing proper training, and utilizing appropriate PPE and equipment, test engineers can minimize the risks associated with hydrogen-related tests and ensure the safety of themselves and the testing environment.

8. LESSONS LEARNED

There were many lessons learned within the development and testing of the noted hybrid power train. To minimize the scope the lessons learned are specific to the design and testing of the hybrid system.

Training for design and execution teams is a major consideration which should be specific to hydrogen and high-pressure gas safe handling. Training should be provided to all personnel expected to be supporting the design and test program as both designer and testers should be well aware of the issues associated with hydrogen handling, flammability, and mitigations. Design teams should also be aware of the needs of personnel that will be in direct contact with any high-pressure gas and the unique design issues associated with hydrogen.

Proper PPE must always be considered for safe testing, but all test engineers should wear anti-static clothing and safety glasses, when conducting tests. While safety glasses are a typical test requirement it's important to note that high pressure gas creates additional risks and safety glasses should be considered mandatory. Anti-static clothing is a precautionary measure that helps minimize ignition risks in the event of exposure to GH_2 above ~7% when the mixture ignition energy drops below that of conventional fuels.

Consider an Emergency Response Plan that includes provisions for hydrogen and high working pressures based on the project requirements. It is important to make sure all on-site personnel have appropriate training regardless of organizational affiliation. Within this project there were multiple companies involved and it was clear that different training standards were in place across different organizations. As a test site director, it is necessary to verify all personnel have appropriate training to always maintain test site control when dealing with GH_2 or any flammable gas.

With respect to leak detection systems:

- Consider implementing multiple independent leak detection systems that can be functionally verified independently. Always monitor hydrogen levels during initial ground test to measure the initial background leak rates.
- Provide active ventilation to all applicable compartments when conducting system functional tests on-aircraft with GH_2/LH_2 on board.
- Establish acceptable leak rates early in the program. Define up front so parameters are clear for both the design and the test teams noting that GH_2 leaks through everything at some rate.
- Having proper leak detection equipment on hand that is calibrated specifically to GH_2 is highly recommended as multigas systems can provide false alarms if not properly calibrated and are prone to cross gas detection which can lead to an unclear picture of the situation when testing.
- GH_2 mircoflames pose a unique risk to systems and surrounding structure. Consider that equipment may need to be relocated from possible microflames. Mircoflames are also a potential testing risk which are difficult to detect, having an IR camera on hand or as part of the test system instrumentation should be considered.

Lessons learned with respect to design considerations:

- Material selection is critical when working with a hydrogen system and must be considered at the earliest stages of development and across the entire design. Test engineers need to be cognizant of the risks and aware of the possible failure modes that can be caused by hydrogen when working with inappropriate or highly stressed materials. Refer to appropriate reference material and industry standard guidance specifically in this area.
- Design safety factors for GH_2 storage is an important factor from both a design and test standpoint. Current standards for aviation are conservative and not well suited for efficient

storage of GH_2 under high pressure. This must be considered early in the development process as it will impact the design structural efficiency and the eventual test requirements.

- Ventilation design and testing is a key development philosophy that must be established early. Dual walled transport elements and system shrouds are highly recommended. Plan for dedicated systems functional tests to verify leak detection system are functional and detecting the proper concentrations of GH_2 before relying on the systems for normal operations.
- A robust system safety assessment approach is integral to a safe final design. In this case a conservative approach to system safety was used with the intention of relaxing the safety systems to reduce system complexity after the system under test was shown to be safe and robust. As very few organizations have extensive experience with GH_2 this is the recommended approach until better design best practices have been established for aviation grade GH_2 equipment. The use of industry standards through this process is highly recommended.

9. CONCLUSION

While hydrogen systems and supporting equipment have been around for some time, even in an aerospace environment, they are not commonplace today. Moreover, there are no commercially available hydrogen-based aircraft propulsion systems certified today. As there is a push to use greener fuel sources in the industry, hydrogen system development is expected to continue at a rapid pace. As such, test engineers need to be aware of the specific risks and hazards of dealing with this fuel source along with the best design and test mitigations to reduce the risk of hazardous situations. With proper precautions and design best practices hydrogen can be safely tested and ultimately used as a viable alternative to conventional heavy fuels. As hydrogen-based propulsion systems are in their infancy, expect a lot of development and testing to be needed in the coming years.

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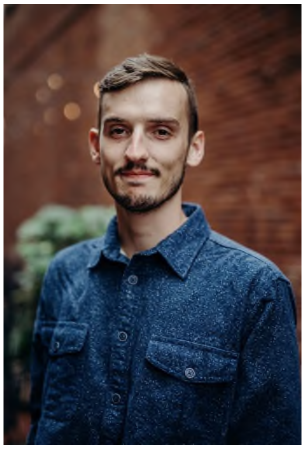

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