



ARL-TR-10040 • DEC 2024



Atmospheric Intelligence for Hybrid Power Advancements: Volume 4 (Hydrogen Fuel Cell Background)

**by Gail Vaucher, Robert Jane, Michael Lee, Massimo Luciano,
Andrew Gatzke, Noah Keith, and Adam Johnson**

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.



Atmospheric Intelligence for Hybrid Power Advancements: Volume 4 (Hydrogen Fuel Cell Background)

Gail Vaucher, Robert Jane, and Michael Lee
DEVCOM Army Research Laboratory

Massimo Luciano, Andrew Gatzke, Noah Keith, and Adam Johnson
United States Military Academy

REPORT DOCUMENTATION PAGE

1. REPORT DATE		2. REPORT TYPE		3. DATES COVERED	
December 2024		Technical Report		START DATE 7/01/2024	END DATE 12/03/2024
4. TITLE AND SUBTITLE Atmospheric Intelligence for Hybrid Power Advancements: Volume 4 (Hydrogen Fuel Cell Background)					
5a. CONTRACT NUMBER		5b. GRANT NUMBER		5c. PROGRAM ELEMENT NUMBER	
5d. PROJECT NUMBER		5e. TASK NUMBER		5f. WORK UNIT NUMBER	
6. AUTHOR(S) Gail Vaucher, Robert Jane, Michael Lee, Massimo Luciano, Andrew Gatzke, Noah Keith, and Adam Johnson					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) DEVCOM Army Research Laboratory ATTN: FCDD-RLA-ID White Sands Missile Range, NM 88002				8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-10040	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.					
13. SUPPLEMENTARY NOTES ORCIDs: Robert Jane, 0000-0001-6742-7306; Michael Lee, 0000-0002-0419-6069					
14. ABSTRACT Diversifying power sources is one way to prepare for the ever-increasing electrical demands on the battlefield, while reducing Soldier vulnerabilities, and producing both physical and fiscal savings. The U.S. Army Combat Capabilities Development Command Army Research Laboratory is proactively investigating power resource hybridization with the exploitation of environmental intelligence to optimize integrated energy sources. This report documents foundational information needed to assess and optimize the integration of a hydrogen fuel cell (HFC). The HFC atmospheric dependency assessment was divided into two areas: atmospheric thermodynamics (pressure, temperature, and humidity) and atmospheric composition (oxygen and particulates). A positive correlation between ambient temperature and HFC efficiency was noted. Without a physical unit to test (Phase 2), this Phase 1 investigation defined specific atmospheric variables, sensors, and sampling locations in and around the HFC for study, based on the projected atmospheric impact evaluations. Anticipating favorable Phase 2 field results, key points for integrating an HFC unit into a hybridized power testbed were described. Once the field tests are completed, the proven results will refine the proposed integration design. Ultimately, the integrated design will enable future Soldiers to reduce tactical resupply convoys and to increase the power diversification and resilience required to successfully complete their missions.					
15. SUBJECT TERMS hydrogen fuel cell; HFC; hybridized power; hydrogen; oxygen; water; atmospheric intelligence; temperature; humidity; pressure; dust; aerosols; particles; Energy Sciences; Military Information Sciences; Network, Cyber and Computational Sciences					
16. SECURITY CLASSIFICATION OF:				17. LIMITATION OF ABSTRACT	
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED	UU		18. NUMBER OF PAGES 46
19a. NAME OF RESPONSIBLE PERSON Gail Vaucher				19b. PHONE NUMBER (Include area code) (575) 678-3237	

STANDARD FORM 298 (REV. 5/2020)

Prescribed by ANSI Std. Z39.18

Contents

List of Figures	v
List of Tables	v
Acknowledgments	vi
Executive Summary	vii
1. Introduction and Background	1
1.1 Army Interest in Hybridized Energy	1
1.2 Current Renewable Energy Investigations	2
2. Hydrogen Fuel Cell	3
2.1 H ₂	3
2.2 HFC	4
3. Anticipated HFC Test Unit	5
3.1 Test System	5
3.2 Test HFC	5
4. HFC Strengths and Weaknesses	6
4.1 HFC Strengths	6
4.2 HFC Weaknesses	6
5. HFC Atmospheric Dependencies in General	7
6. HFC Atmospheric Thermodynamic Dependencies	7
6.1 Humidity and Temperature	7
6.2 Mixing Ratio (r)	8
6.3 Atmosphere Stability	8
6.4 HFC Atmospheric Thermodynamic Impacts	11

7. HFC Atmospheric Composition Impacts	12
7.1 Four Major HFC Chemical Processes	12
7.1.1 PEM HFC Process	12
7.1.2 H ₂ Storage	13
7.1.3 Proton Exchange Membrane	14
7.1.4 Platinum Catalysts	14
7.2 Atmospheric Composition	15
7.2.1 Mixing Ratio (O-MR)	15
7.2.2 Number Density	16
7.2.3 Partial Pressure	16
7.2.4 High-Desert Atmospheric Composition	16
7.3 Atmospheric Composition Effects on HFC Performance	18
7.4 Quantifying HFC Atmospheric Composition	18
7.4.1 Laser Spectrometer	19
7.4.2 Particulate Matter Monitor	20
7.4.3 Barometer	21
8. Integrating an HFC	21
9. Summary and Conclusions	23
10. References	25
Appendix. Conducting a Hydrogen Fuel Cell Site Survey	27
List of Symbols, Abbreviations, and Acronyms	33
Distribution list	35

List of Figures

Figure 1.	AIHPA Testbed (MMT and PT systems).....	2
Figure 2.	HFC (left) and electrolysis (right).....	4
Figure 3.	Mixing ratio shows the temperature and RH relationship.....	8
Figure 4.	2024 July 11: Temperature gradient time series.	10
Figure 5.	2024 July 11: RH and absolute humidity.....	10
Figure 6.	HFC temperature (blue diamond) and humidity (red diamond) sensors placement.....	12
Figure 7.	HFC PEM chemical processes.....	13
Figure 8.	Atmospheric composition as a function of height.....	17
Figure 9.	HFC sensor placement where L = laser spectrometer; P = particulate matter monitor; and B = barometer.	20
Figure 10.	Schematic of HFC-1 integration into the ARL testbed.	22
Figure 11.	HFC/PV downwind (right side) position with respect to testbed/MMT (left side).	22
Figure A-1.	Measuring wheel: for horizontal distance measurement.....	28
Figure A-2.	Site Cp (measurements taken for these instructions).	29
Figure A-3.	Site C was a mirror layout from the original.....	31
Figure A-4.	Example of a WSI with points needing numerical values.....	31

List of Tables

Table 1.	Three H ₂ states.	14
Table 2.	Composition of the atmosphere at sea level.....	15
Table 3.	O-MR, ND, and PP as a function of elevation.	17
Table A-1.	X, Y, Z values assigned to a 2-D image.....	32

Acknowledgments

The authors wish to thank the following personnel: Carol Bailey for including the interns in the Engineering Research and Development Center's hydrogen fuel cell (HFC) evaluation process; Bruce Geil (U.S. Army Combat Capabilities Development Command Army Research Laboratory), whose practical and visionary power and energy subject-matter expertise was an inspiration to all four summer interns; Robert Brice (DEVCOM Army Research Laboratory) who provided timely materials needed to complete the field investigation effort; Senior Archeologist Jim Bowman (White Sands Missile Range, U.S. Army Installation Management Command), who hosted the remote tour of the proposed HFC installation. Appreciation is extended to John Raby (ARL) whose consistent technical insights and detailing continue to ensure a high-quality document. Finally, special thanks go to the ARL Technical Publishing Branch for its excellent technical editing, specifically to Technical Editor Sandy Montoya and Team Lead Jessica Schultheis.

Executive Summary

Tactical electrical power requirements are perpetually multiplying due to the ever-increasing arsenal of energy-dependent devices created and deployed for Soldiers. Diversifying power sources is one way to prepare for these future electrical demands, which also reduces Soldier vulnerabilities and produces both physical and fiscal savings. The U.S. Army Combat Capabilities Development Command Army Research Laboratory is proactively investigating power resource hybridization and the exploitation of environmental intelligence supporting the optimization of integrated energy sources. Using a DEVCOM Army Research Laboratory-designed hybridized power testbed equipped with coincident atmospheric measurements, a study to evaluate and possibly integrate a hydrogen fuel cell (HFC) was conducted. This report documents foundational information needed to assess the potential for integrating an HFC into future hybridized tactical power resources.

The HFC is a renewable power-generating resource that uses hydrogen and oxygen gasses to drive a spontaneous electrochemical reaction, which moves electrons along a wire and produces water and heat as by-products. Hydrogen is not an energy source, but an energy carrier. That is, an independent tool harnesses the energy stored in hydrogen and then releases that energy to generate electricity.

The HFC process for producing electricity is hydrogen (H_2) divided into its proton and electron parts at an anode. The proton then advances through an electrolyte, while the electron flows through a wire (producing electricity) before rejoining the proton at a cathode. Oxygen (O_2) is then introduced, resulting in water and heat by-products. The initial HFC atmospheric dependency assessment found potential impacts with (1) the storage of water and hydrogen, and (2) the provision of ambient oxygen. To evaluate these impacts, the study focused on atmospheric thermodynamics and atmospheric composition.

The atmospheric thermodynamic investigation found three variables (pressure, temperature, and humidity) most relevant to the HFC process. H_2 is stored in a low-pressure solid form; therefore, pressure was seen as playing a significant role in the H_2 diffusion processes. Humidity and temperature are correlated in that when temperature decreases, less water can be held in the atmosphere. Typical single-digit desert humidities were flagged for HFC impacts. Published observations reported a positive correlation between ambient temperature and HFC efficiency. The electrolyte requires saturation to remain functioning at high operating temperatures, which could be an issue in a high-elevation desert location. To characterize the air ingested into the HFC, sampling humidity and temperature upwind from the HFC device was recommended. To quantify the ambient water

vapor, it was suggested that temperature and humidity sensors be placed at the HFC inlet and outlet locations. For characterizing the temperature's impact on HFC productivity, an internal electrolyte temperature was flagged as informative, since high temperatures decrease saturation, which increases resistance in the electrolyte. Likewise, low temperatures create excessive saturation and thus the electrolyte reaction rate decreases.

The HFC atmospheric composition investigation focused on ambient O₂ and dust particles. Given that an open HFC system obtains O₂ from the surrounding environment, the ambient air needs to provide sufficient reactant O₂ to operate, which could be handicapped in high elevations. Likewise, desert sandstorms, wildfires, and pollutants could also potentially reduce the O₂ resource, as well as interfere with the electricity production. To quantify the HFC atmospheric composition impact, O₂ quantity, particles, and partial pressure were considered. The variables selected to address each attribute included the oxygen-mixing ratio (O-MR), the particle number density (ND), and the partial pressure (PP). The O-MR was chosen to represent the percent composition of O₂; a laser spectrometer was suggested to quantify O-MR. The ND captures particulate matter and could be sampled by a particulate matter monitor. The PP focuses on the partial pressure of O₂; a barometer was recommended to quantify PP. HFC performance impacts that correlate with O-MR, ND and PP are reactant concentrations, particulate matter, and reactant pressure, respectfully.

A closed-loop HFC design (recycling O₂) is less likely to be affected by ambient conditions, and more versatile for deployment in nearly any atmospheric condition. The disadvantage is that the system is pressurized, and could become imbalanced, requiring more maintenance.

The open-loop HFC draws O₂ from the ambient air and is directly impacted by O₂ availability and purity. Filters can extract most particles; however, any that pass through have a potential for causing chemical or physical damage to the HFC. Open-loop systems require an air compressor for the external O₂ supply. The power needed to run the compressor must be weighed against optimizing air compressor pressures with the surrounding air. Methods and tools for quantifying particle impact were presented. With limited information, generic descriptions for the future field test HFC-Solar System (labeled "HSS-1") and HFC product (called "HFC-1") were provided.

Presuming a favorable HFC field test performance, plans for integrating the HFC into the current ARL hybridized testbed were sketched. Methods for engineering and documenting the field design were described. For the HFC physical integration, the associated research meteorological measurements unit was placed upwind of

the HSS-1/HFC-1. The electronic integration saw the HFC and ARL testbed DC converters as a possible gateway between systems.

Ultimately, power independence and resilience are the goals. The HFC was seen as able to support tactical “quiet” missions and sustained operations. When deployed, the HSS-1 was seen as potentially operating independently, as well as being a part of existing grids. Once the field tests are completed, the proven results will refine the proposed integration design. Ultimately, the integrated design will enable future Soldiers to reduce tactical resupply convoys, and to increase the power diversification and resilience required to successfully complete their missions.

1. Introduction and Background

This report represents a collaborative background investigation into the atmospheric effects and impacts on hydrogen fuel cells (HFCs). The investigators included U.S. Army Combat Capabilities Development Command Army Research Laboratory researchers, as well as multiple short- and long-term Academic Individual Advanced Development (AIAD) interns. The results are intended to establish foundational information needed to assess the potential for integrating an HFC into future hybridized tactical power resources.

1.1 Army Interest in Hybridized Energy

Battlefield electrical power requirements are perpetually expanding due to the ever-increasing arsenal of energy-dependent devices created and deployed for Soldiers. Historically, fielded power resources focused on centrally located one-time-use fuels. Future tactical electrical demands lean toward mobile applications. With fuels targeted by aggressors, diversifying the electrical source could significantly reduce Soldier vulnerabilities, and facilitate both physical and fiscal savings. Future tactical hybridized electrical microgrids could be designed as fixed or mobile, and able to support a variety of power-generating resources.

The key to successful microgrid hybridization is understanding each power-generating contributor's strengths and weaknesses so the net productivity can be optimized for all operational settings. While traditional fossil fuel can reliably support most microgrid load requirements, the integration of renewable energy resources can reduce the frequency of the one-time-use fuel resupplies, and it can empower "quiet" missions. The shortfall of most renewable energy, however, is a systematic need for power storage devices operating concurrently. For example, renewable energy based on solar and wind are time and weather dependent. At night and during cloudy days, solar fuels defer to stored battery power in the absence or reduction of energy from the sun. Wind energy also relies on stored energy during calm or hurricane conditions. Consequently, for the hybridization of resources to be profitable, any future tactical or disaster relief system needs to include guidance via environmental intelligence and a resource and load-optimization algorithm. Anticipating these future requirements, DEVCOM Army Research Laboratory is proactively investigating the hybridization of multiple power resources and the exploitation of atmospheric and environmental intelligence as it optimizes the integrated energy sources.

Section 1.2 describes the ARL experimental hybridized power testbed.

1.2 Current Renewable Energy Investigations

The Atmospheric Intelligence for Hybrid Power Advancements (AIHPA) Testbed was designed as a research-grade tool, constructed for investigating relationships between atmospheric variables and a diversity of power-generation assets (Vaucher et al. 2023). The testbed includes a meteorological measurement tripod (MMT) and a power train (PT) system (Figure 1). The MMT characterizes the atmosphere using meteorological sensors to quantify atmospheric pressure, temperature, relative humidity (RH), wind speed and direction, and solar radiation. The PT quantifies the hybridized performance of a south-facing photovoltaic (PV) panel, three batteries, an emulated diesel generator model, and a digital load programmed to use the testbed power. Mounted on the PV panel is a whole sky imager (WSI), and for some testbeds, solar radiation sensors, which are used to access real-time atmospheric conditions. As the PV array generates power, the MMT records the concurrent atmospheric data, allowing the relationship between the two to be analyzed. A maximum-power point-tracking unit optimizes PV array power output by managing current and voltage across the panel. Multiple installed shunts reduce the current flowing to a Raspberry Pi microprocessor, which collects and records all PT and WSI testbed data. The WSI takes fish-eye-lens images to visually record and assess cloud coverage. Excess electricity produced by the PV array is directed to batteries and a digital load (Vaucher et al. 2019).



Figure 1. AIHPA Testbed (MMT and PT systems).

The AIHPA Testbed is an ongoing experiment intended to simulate a forward-looking, versatile mobile microgrid, and to investigate how the atmosphere impacts power production, storage, and distribution. The operational thesis for this project is that current and advanced knowledge of atmospheric conditions can significantly improve the optimization of a hybridized power grid. Thus far, the testbed experimentation has shown the feasibility and some first-order benefits from hybridized power using both traditional (generator, and battery) and nontraditional (e.g., PV) power resources. The next step being considered is to expand the renewable energy options by integrating a HFC into the AIHPA. Before including the HFC, a background investigation was needed to evaluate the known pros and cons of adding an HFC to the current hybridized power unit. Section 2 describes the HFC.

2. Hydrogen Fuel Cell

The HFC is a renewable power-generating system that uses hydrogen (H_2) and oxygen (O_2) gasses to drive a spontaneous electrochemical reaction that moves electrons along a wire and produces water (H_2O) and heat as by-products. Before explaining the HFC, the primary chemical—hydrogen—is described.

2.1 H_2

The name “hydrogen” stems from two Greek words—hydro and genes—meaning “water former.” H_2 as a chemical is a colorless, tasteless, odorless gas that can be liquified by cooling under pressure. Its molecular formula is H_2 ; Lewis structure is $H:H$; and molecular weight is 2.02. As the most abundant of all elements in the universe, it is estimated to make up more than 90% of all atoms or three-fourths of the universe’s mass. Molecular hydrogen at ambient temperature is relatively innocuous to most metals; however, atomic hydrogen is detrimental to most metals (Chemical Book 2024).

Referencing the National Fire Protection Association description, the generic H_2 is listed as having no health, no reaction, and no special hazardous issues. It is, however, flammable, especially under prolonged exposure to fire or intense heat. Its melting point is $-259.2\text{ }^{\circ}\text{C}$ and boiling point is $-252.8\text{ }^{\circ}\text{C}$. While listed as practically nontoxic, high concentrations of H_2 gas vapors were noted as possibly causing dizziness or loss of consciousness. Contact with gas or liquefied H_2 gas may cause burns, and/or frostbite (Chemical Book 2024).

2.2 HFC

H₂ is not an energy source, but an energy carrier, that is, an independent tool that harnesses the energy stored in H₂. Then, H₂ releases that energy to generate electricity. The complimentary tools enabling this cyclical process include an electrolyzer, which uses H₂O and electricity to produce H₂, and a fuel cell that uses H₂ and electricity, to produce electricity, H₂O, and heat. Figure 2 shows a schematic depiction of these two devices (DoE 2022).

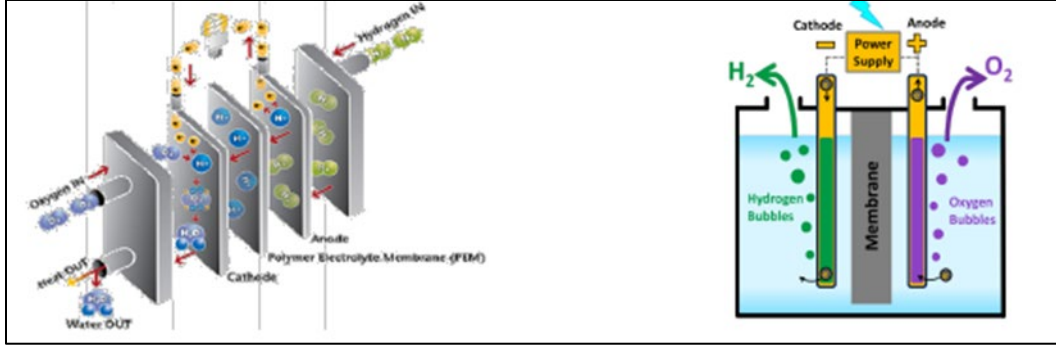
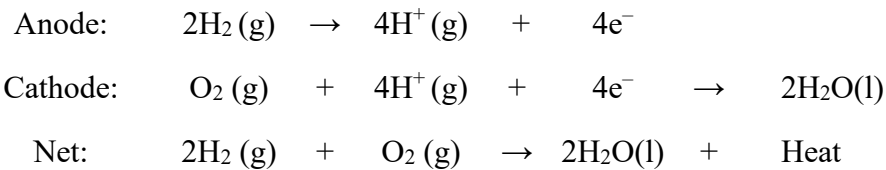


Figure 2. HFC (left) and electrolysis (right) (DoE 2022).

The process for generating HFC electricity involves seven key features: (1) H₂ is divided into its proton and electron parts at an (2) anode. The proton then advances through (3) an electrolyte, while the electron flows through a (4) wire (producing electricity) before rejoining the proton at a (5) cathode. (6) O₂ is introduced resulting in (7) H₂O and heat by-products.

Detailing the seven HFC steps from a chemical perspective: pure H₂ gas is pumped into the fuel cell through a pressure regulator, where it reaches an anode and is split into a proton (H⁺) and an electron. The electrons flow through an external circuit as usable electricity (satisfying a load requirement); the proton passes through a proton exchange membrane (PEM). The movement of protons and electrons is explained by the PEM's high-proton and low-electron conductivities. After leaving the PEM, the protons, in combination with O₂ and the returning electrons, encounter a cathode. Here, all three elements assimilate into the cell via a closed electrical circuit, producing pure H₂O and heat as by-products of the HFC power generation cycle and HFC reaction (Jaber 2024). The chemical reactions are as follows:



Section 7 expands on this process in the context of investigating the impact of atmospheric composition on the HFC power production.

3. Anticipated HFC Test Unit

The prompting of this study stemmed from a requirement to test a state-of-art HFC-Solar Nanogrid. In the next subsections, using limited publicly accessible information, the authors' understanding of the not-yet-manifested, proposed HFC system is described. This understanding was subsequently used to speculate the atmospheric dependencies.

3.1 Test System

HFC-Solar System (hereafter called "HSS-1") being manufactured for testing purposes combines fuel and electrical power-generating systems. These systems are noted for producing and consuming their own fuels to generate electricity. For example, an HFC requires H_2 to produce electricity. The HSS-1 manufactures this H_2 gas by using built-in PV panels to generate the electricity required to charge a battery and power an electrolyzer, which is used to produce the H_2 gas product. The H_2 gas is stored as a metal hydride compound until it is needed by the HFC. The HSS-1 simultaneously charges the system battery and produces H_2 gas until the battery is completely charged and the H_2 storage is full.

For this forthcoming test, the HSS-1 housing is described as a CONEX box. The HFC was listed as an independently produced element of the system. Hereafter, the standalone HFC unit for testing will be called "HFC-1." The following is a summary of the publicly accessible HFC-1 unit.

3.2 Test HFC

The commercial producer of HFC-1 produces HFCs for specialized applications, including aviation and unmanned aerial vehicles, construction, automobile and vehicular transportation, and off-grid power needs. The HFC-1 chemistry appeared equivalent to any other HFC.

The anticipated HFC-1 for testing is described as a standalone HFC model. This model uses a PEM as described above while noting two unique features. First, the heat and power systems are combined, and they use additional H_2 gas to raise the temperature of heat by-product from the usual 75 °C to over 100 °C. This higher temperature allows the produced heat to be integrated into the system as thermal energy and not simply discarded. According to the manufacturers of HFC-1, this process raises the cell efficiency from 51% to 78%.

The second feature is that the cell is evaporatively cooled. That is, it no longer depends on glycol and outside air for system cooling. The HFC-1 system replaces the heat exchanger with additional H₂O (approximately 2 L/min) for cooling. The removal of the heat exchanger enables two benefits: (1) the HFC-1 no longer depends on ambient temperature as a performance factor, and (2), this design releases a significant load from the system's air compressor which, according to the company, is the "largest parasitic load on the fuel cell system" (Intelligent Energy Limited 2024).

4. HFC Strengths and Weaknesses

The following is a summary of documented HFC strengths and weaknesses in general, and as applied to a Phase 2 HFC test unit.

4.1 HFC Strengths

The generic HFC strengths published in *Fuel Cell Basics* (DoE 2014) include a (1) higher efficiency than combustion power generation, (2) zero emissions and dependable lifespan, and (3) units that are more easily integrated into existing systems.

Focusing on the anticipated HFC of Phase 2, strengths include (1) a design that could replace the glycol and heat exchanger method of cooling with a water-cooled system. This system necessitates more H₂O but eliminates the need for an external heat exchanger. This strategy alleviates excess pressure on the system's air compressor—one of the highest energy consumers involved in the cell. It also lessens the cell's dependency on ambient temperature since the heat exchanger no longer needs to use the outside air to cool the glycol in the system (Intelligent Energy Limited 2024).

Another strength of the anticipated Phase 2 HFC is that the cell utilizes a turbo expander to increase the amount of H₂ in the system. In turn, this causes the temperature of heat by-product to be higher than a conventionally made cell—a difference between 75 and 100 °C (Intelligent Energy Limited 2024).

4.2 HFC Weaknesses

The HFC weaknesses cited include (1) insufficient cooling of the unit, which leads to degraded power output and possible damage of the PEM, (2) hydrogen is difficult to transport, and (3) electrolysis is an energy intensive method (DoE 2014).

HFCs can be stacked so that more power is created. In this stratified design, the water-cooled stack of the field unit could cause an impractical need for H₂O (2 L/min).

5. HFC Atmospheric Dependencies in General

The initial assessment for potential atmospheric dependencies in the HFC power-generation process included (1) the storage of water and hydrogen, and (2) the provision of O₂ from the ambient air. To evaluate these leanings, the investigation was divided into two areas: atmospheric thermodynamic dependencies and atmospheric composition impacts. The result of each search follows.

6. HFC Atmospheric Thermodynamic Dependencies

The atmospheric thermodynamic variables most relevant to the HFC process included pressure, temperature, and humidity. The original concept reasoned that H₂ is stored in a low-pressure solid form; therefore, pressure may play a significant role in the H₂ diffusion processes. Humidity and temperature are connected variables in that when temperature decreases, less water vapor can be held in the atmosphere. When temperature magnitudes increase, more water vapor can be suspended in the air parcel. With the HFC test area in a high-elevation desert environment, the effect of single-digit humidities was flagged as a notable scenario for evaluation. Since pressure appeared to have a greater impact on the atmospheric composition, this term is expanded on in Section 7.

6.1 Humidity and Temperature

Humidity is the measure of water vapor content in the air and can be quantified as RH and/or absolute humidity. Relative humidity is the ratio of the current water vapor content of a given mass of air to the total possible water content of that same mass of air according to the air temperature. Absolute humidity, also called vapor density, is the total measure of H₂O in a given volume of air. This latter term is commonly measured in g/m³ or kg/m³ (NWS 2009; Campbell 2019).

A hygrometer is used to measure RH in units of percent. This is done by measuring either the capacitance or resistance of the air. Temperature is the measure of hotness and coldness and is related to the kinetic energy of the particles in a system (Vaucher and Bergen 2022). A thermistor measures changes in electrical resistance to determine a change in temperature (Stull 2000; Omega Engineering Inc. 2024).

6.2 Mixing Ratio (r)

To more easily quantify the humidity–temperature relationship, the meteorological mixing ratio (r) term can be used. This mixing ratio variable describes the mass of water vapor (in grams) present in a kilogram of dry air. Figure 3 shows the relationships between temperature, RH, and the mixing ratio for sea level. The various colored lines depict differing RH values from 20% to 100%. When the temperature is low (at 0 °C), the mixing ratio is very low (below 4 g/kg) even for 100% RH. However, when temperature is high (30 °C), the mixing ratio for 100% RH is up to 28 g/kg (Stull 2000)—thus reenforcing that higher-temperature air holds more H₂O than cooler air.

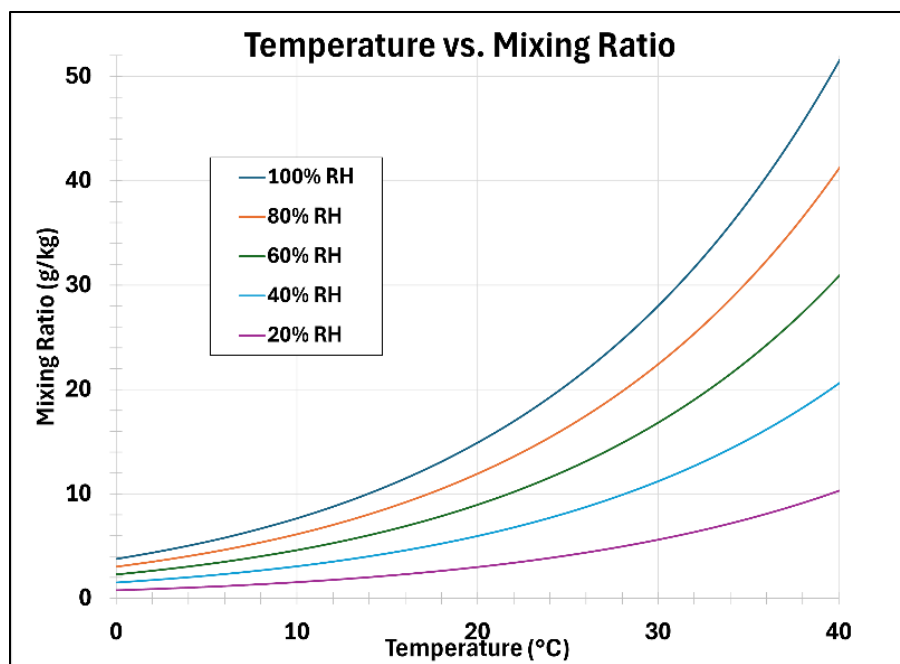


Figure 3. Mixing ratio shows the temperature and RH relationship.

6.3 Atmosphere Stability

When temperature is sampled vertically in the atmosphere, the thermal nature of the atmosphere can be quantitatively characterized via a stability term. Stable air is generally cool and laminar in its flow pattern—whereas an unstable atmosphere brings warmer temperatures from below into the higher levels, especially during daylight hours. This latter mixing mechanism can enable additional potential for a moister environment. To quantify the stability around the HFC, a vertical temperature gradient can be calculated. Using the same sampling sensor types on a meteorological tripod or tower, one can calculate a delta temperature (ΔT). When this term is divided by the distance separating the sensors, the result is the atmospheric lapse rate (Equation 1).

$$\text{Lapse rate} = \Delta T \text{ (C)} / \Delta z \text{ (m)} = (T_{\text{top}} - T_{\text{bottom}}) / (Z_{\text{top}} - Z_{\text{bottom}}) \quad (1)$$

When ΔT is less than 0 °C (negative values), then conditions are considered unstable due to the warmer air at the surface naturally rising to its level of equilibrium (buoyancy) and cooler air mixing down to the surface. If this warm air rises to its level of condensation, then the moisture will condense into a visible cloud. If ΔT is greater than 0 °C (positive values), then the atmosphere is considered stable. That is, cooler air is located near the surface with warmer air aloft with no thermodynamic mechanism for upward motion and mixing. Any atmospheric mixing under a stable environment would have to come from a local or synoptic forcing function (i.e., wind turbine, drainage flow, and cold/warm front).

An example of a typical temperature gradient was calculated from meteorological data sampled next to the testbed (Figure 4). Temperatures at the 0.7-m above ground level (AGL) were subtracted from the 5.7-m AGL temperatures. The positive (above the pink line) gradient timeseries occurred when the sun had set. The negative gradient values coincided with the daytime hours. While the unstable side of this typical diurnal cycle can lead to increased local vertical moisture transport and cloud development (clouds being an effective PV array inhibitor), the larger-scale, synoptic air flows can bring in dry air that usurps moisture produced by the local mixing function. Such was the case for 2024 July 11. As seen in Figure 5, there was an overall downward trend in the relative and absolute humidity magnitudes through the day driven by the development of a wind flow of drier air over the area. Not until evening, after the wind subsided and the atmosphere became more stable, did the pooling of cool air cause a small reversal in the RH and a leveling out in the absolute humidity.

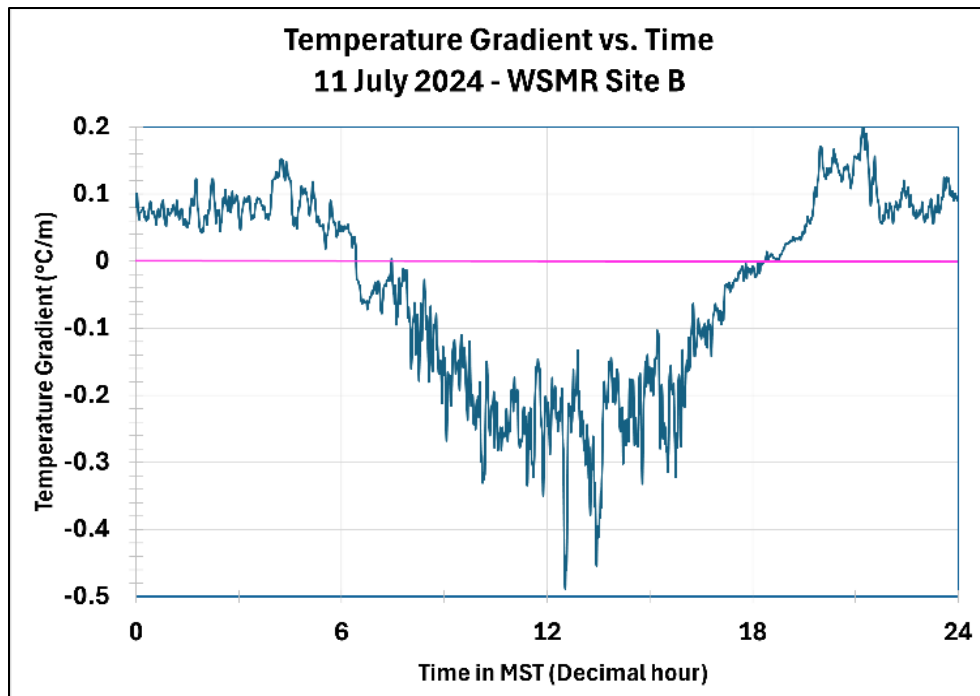


Figure 4. 2024 July 11: Temperature gradient time series.

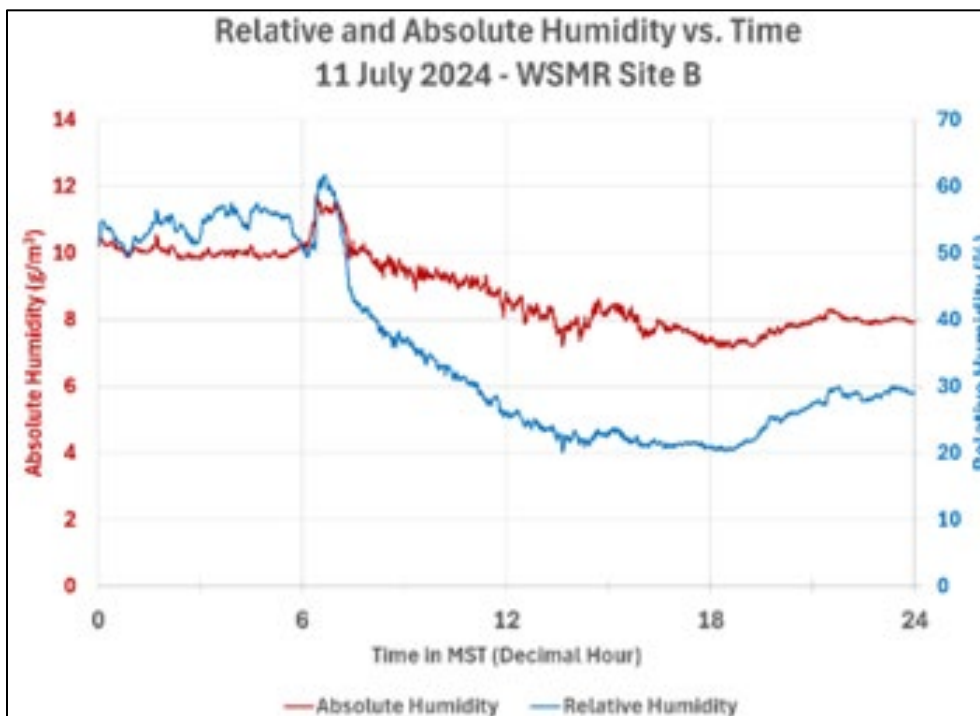


Figure 5. 2024 July 11: RH and absolute humidity.

6.4 HFC Atmospheric Thermodynamic Impacts

Due to a delayed arrival of the HFC test system, published observations were used to generate proposed locations for quantitatively characterizing the atmospheric impacts on a standard standalone HFC unit.

The following observations were noted by the U.S. Department of Energy: There is a positive correlation between ambient temperature and HFC efficiency up to a point. The metal hydride element requires strong heat (300 °C) for state change. The PEM requires saturation to remain functioning at high operating temperatures (DoE 2022).

To characterize the air going into the Phase 2 HFC test unit, sampling humidity and temperature upwind from the HFC device, and within 10× the unit's footprint, is recommended. The prevailing wind direction will help maximize the “fresh air” input character. The expected range of values for the ambient air entering the HFC while operating in mid-latitude, high elevation, and desert locations are as follows:

- RH: 5% to 100%
- Air temperature: -5 to 36 °C

To quantitatively describe the ambient water vapor available to, and generated from, the HFC, temperature and humidity sensors should be placed at the HFC inlet and outlet locations, as seen by the red (T) and blue (H) diamonds in Figure 6. For characterizing the temperature's impact on HFC productivity, the PEM temperature within the HFC would be useful. Observations show high temperatures decrease saturation and thus increase resistance in the PEM, which increases the reaction rate. Low temperatures create excessive saturation and thus the PEM reaction rate decreases. In general, the expected PEM temperature range is between 60 and 90 °C (Tang et al. 2023). A suggested placement for the PEM temperature is shown in Figure 6.

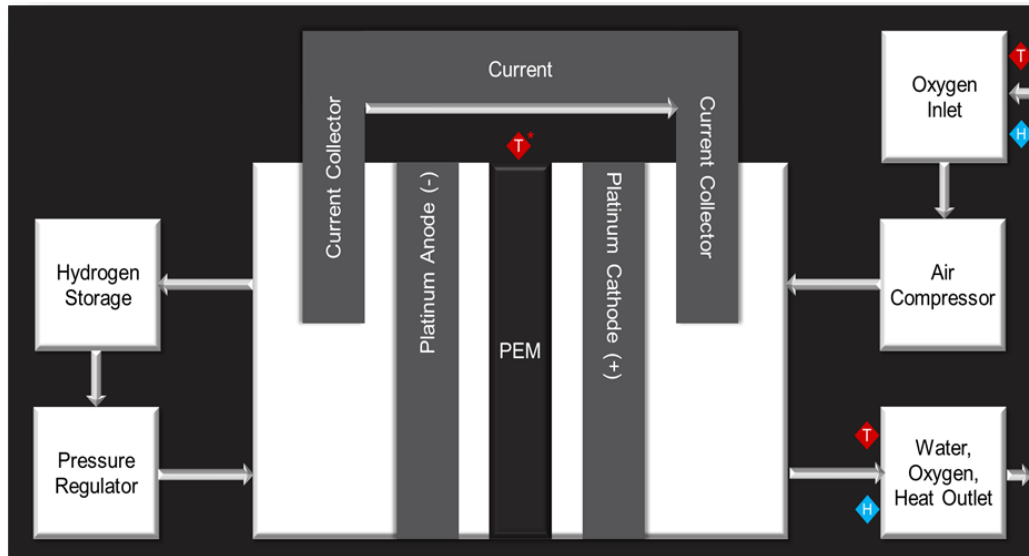


Figure 6. HFC temperature (blue diamond) and humidity (red diamond) sensors placement.

7. HFC Atmospheric Composition Impacts

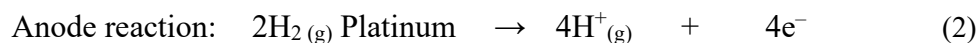
In some HFC systems, the O_2 provided to the cathode is drawn in from the ambient environment. For the anticipated HFC, operating at a “high” elevation might reduce the O_2 resource. Running the system in a desert that is prone to seasonal dust storms could adversely impact the system’s performance. In this section, the atmospheric dependencies during HFC operations are reviewed through a chemistry perspective.

7.1 Four Major HFC Chemical Processes

There are four major HFC chemical processes executed while operating an HFC. Each are reviewed in the following subsections. While the PEM process was explained above, additional atmospheric composition-relevant chemical details are added in Section 7.1.1.

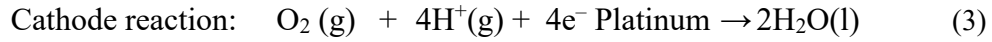
7.1.1 PEM HFC Process

The PEM process (Figure 7) used by an HFC begins with pure H_2 gas being pumped into the fuel cell via a pressure regulator. When it reaches the platinum anode, H_2 is split into a proton (H^+) and an electron. The anode reaction equation follows:



The electrons flow through an external circuit (current collector) as usable electricity, while the protons pass through a PEM. The protons and electron movements are explained by the PEM high-proton and low-electron conductivities.

An air compressor draws O₂ in from the ambient environment. The O₂ combines with the protons (H⁺) leaving the PEM and the returning electrons (e⁻) encountering the cathode. The chemical equation follows:



At the cathode, all three elements flow back into the cell via a closed electrical circuit, producing pure H₂O, O₂, and heat as by-products of the HFC power generation cycle and HFC reaction (Jaber 2024). The net chemical reaction is as follows:

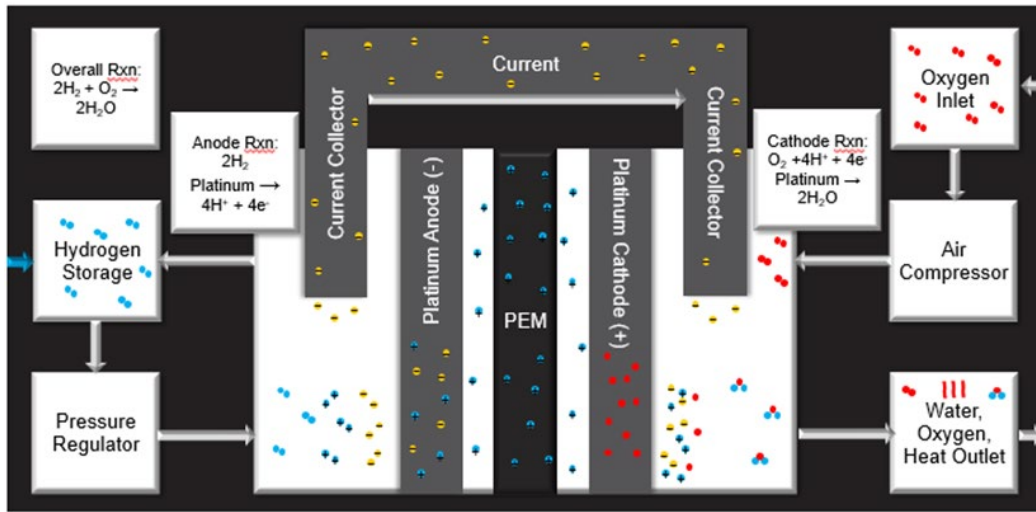
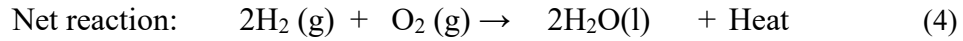


Figure 7. HFC PEM chemical processes.

7.1.2 H₂ Storage

Hydrogen “fuels” the HFC. Consequently, its storage is a critical component to this process. H₂ can be stored in three states: gas, liquid, or solid. Table 1 compares these states. The solid format fills the greatest volume but requires the least cost. The gaseous state uses the least volume and is a moderate price per kilowatt-hour. Both gas and liquid formats are prone to leaks and are associated with extreme conditions (700 bar pressure/gas and -252 °C/liquid). The solid H₂ can be stored in a metal lattice (metal hydride) with a significant release of heat. To liberate the H₂, the metallic hydride needs to be heated to 300 °C.

Table 1. Three H₂ states.

Hydrogen (H ₂) state	Volume (km/m ³)	Cost (\$/kWh)	Atmospheric characteristic	Pros/cons
Gaseous	40	0.04	H ₂ pressurized up to 700 bar	High-pressure storage tank prone to leaks
Liquid	70	0.06	H ₂ stored at -252 °C and still boils off	Cryogenic vessel present evaporation prone to leaks
Solid	80	0.02	H ₂ released when system heated up to 300 °C	Metal lattice allows H ₂ atoms to chemically bond as a solid

7.1.3 Proton Exchange Membrane

Three mechanisms for bringing the H₂ proton from the anode to cathode include: the PEM, the Grotthus mechanism (proton hopping), and the diffusion (or vehicular) mechanism. The PEM characteristics include minimal thickness, maximum proton conductivity, and minimal electronic conductivity. The proton transport through hydrated polymeric matrices includes hydrophilic polymer chains with sulfonic acid groups. The membranes are soaked in H₂O to conduct protons, and once cathodic H₂O is synthesized, it hydrates the PEM.

The Grotthus or proton-hopping mechanism uses a hydrolyzed ionic site (SO₃⁻ and H₃O⁺). Functioning like Newton's cradle, the H₂ is moved over through neighbor impacts.

The diffusion or vehicular mechanism carries H₂O via hydrated protons (H⁺ and H₂O). Hydronium is moved via an accelerated flow or a "lazy river" analogy.

7.1.4 Platinum Catalysts

Platinum (Pt) as an anode and cathode has favorable atomic structure with a weak "d" electron orbital. Pt can be charged to Pt²⁺ or Pt²⁻ for temporary bonding and allows operation at the anode and the cathode. While Pt is not a catalyst for nitrogen (N₂) (an abundant element of air), it is a catalyst for H₂ and O₂.

The anode oxidation reaction separates diatomic H₂ atoms into positively charged protons and negatively charged electrons, whereas the cathode reduction reaction separates diatomic O₂ atoms into two separate O₂ atoms with a neutral electron transfer. The catalysts are not used in the reaction; however, (1) there is Pt disintegration in the acidic environment of the fuel cell from the PEM; (2) Pt moves within the carbon mesh offsetting even coverage; and (3) Pt reacts with air contaminants.

7.2 Atmospheric Composition

The composition of a standard atmosphere at sea level is listed in Table 2. While N₂ comprises the largest volume (78.08%) of an air parcel, the element of concern is the second largest—namely, O₂, which comes in at 20.95%.

Table 2. Composition of the atmosphere at sea level (Steiger 2024).

<i>Gas</i>	<i>Molecular Form</i>	<i>Volume</i>
Nitrogen	N ₂	78.08%
Oxygen	O ₂	20.95%
Water	H ₂ O	0.2-4%
Argon	Ar	0.93%
Carbon Dioxide	CO ₂	415 ppm
Neon	Ne	18.18 ppm
Ozone	O ₃	10 ppm*
Helium	He	5.24 ppm
Methane	CH ₄	1.8 ppm

For the atmospheric composition impact on HFC energy production study, three questions were addressed:

- How much oxygen is in the air?
- How many particles are in the air? and
- How pressurized is the oxygen in the air?

To answer these questions, the atmospheric composition investigation selected three variables: the oxygen-mixing ratio (O-MR), the number density (ND), and the partial pressure (PP). The O-MR was chosen to represent the percent composition of O₂. The ND captured the amount of particulate matter. The PP focused on the partial pressure of O₂. An expanded review of each variable is included in the next sections.

7.2.1 Mixing Ratio (O-MR)

The O-MR is the number of moles of gas per moles of air, also known as percent composition. The only percent composition relevant to this study is that of O₂ (21%). It is important to track the O-MR because the HFC performs ideally at higher reactant amounts due to the increased number of O₂ particles contacting the

PEM. The instrument that could be used to measure the O-MR is a laser spectrometer. A laser placed within the device could turn an air sample into plasma emitting light and spectrally analyze the light.

7.2.2 Number Density

ND is the number of molecules of a predetermined micron (2.5 μm) diameter and the mass in micrograms (μg) of the predetermined particles per meter³ (m^3) of air. It is important to track the ND of particulate matter because the HFC reactions can be greatly reduced if there is an excess amount of particulate matter within the system, requiring more power allocation toward reactant pumps to overcome the blockage. The instrument that could measure ND would be a particulate matter (PM) monitor. This device emits a light beam through an air sample. Particles along the beam's path scatters the light. The scattered light is measured and used to calculate particle concentrations within the air sample.

7.2.3 Partial Pressure

PP is pressure in millibars (mb) of a certain molecule if all other gasses were removed. These measurements account for what makes up the atmosphere. It is important to track the PP of oxygen because the HFC performs ideally at higher reactant pressures due to the increased interaction with the PEM. The instrument used to measure PP would be a barometer. A small silicone capacitive sensor fluctuates under differing pressures, changing the distance between two electrodes that correlate to different pressures. The recorded pressure is then multiplied by the O-MR value to find the partial pressure of oxygen in accordance with Dalton's law.*

7.2.4 High-Desert Atmospheric Composition

The Phase 2 application of this study includes bringing an HFC unit to a high-desert environment. The potential atmospheric composition areas of interest ranged from quantifying O₂ resources to identifying local environmental sources and variations of seasonal suspended particles.

It is well known that within the troposphere, pressure and temperature decrease with height. While most measurement standards use sea level sampling, the HFC test site is anticipated to be at higher elevations. Referencing the variables chosen to characterize the atmospheric composition, Table 3 presents the calculated values

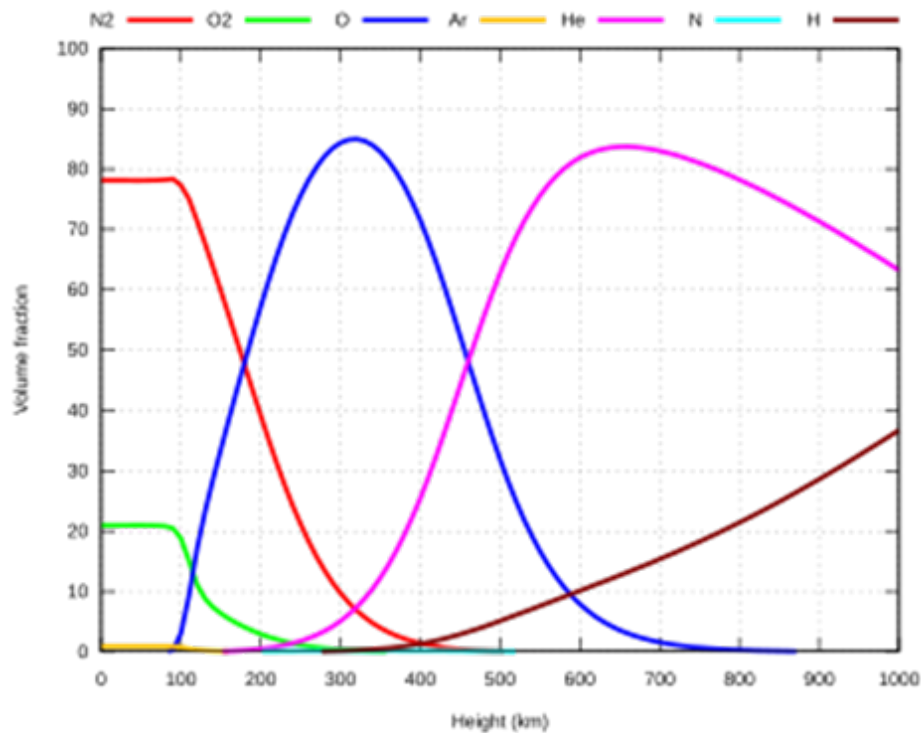
* Dalton's law states that the total pressure exerted within nonreacting gases is equal to the sum of the partial pressures of the individual gases. Any basic thermodynamic or chemistry book includes this.

for sea level and two higher elevations. The O-MR and ND remain the same for the selected elevations; however, the PP shows a slight decrease with height.

Table 3. O-MR, ND, and PP as a function of elevation.

Height (above sea level)	O-MR	ND	PP
1494 m (4900 ft)	21%	PM2.5 mm = 5 mg/m ³	860 mb *0.21 = 180 mb
1280 m (4200 ft)	21%	PM2.5 mm = 5 mg/m ³	880 mb *0.21 = 184 mb
0 m	21%	PM2.5 mm = 5 mg/m ³	1013 mb *0.21 = 213 mb

Were the HFC going into the stratosphere or higher, the characterizing values would have radically changed, as shown in Figure 8. Here, between 100–300-km AGL, the green line, representing O₂, drops significantly. The impact of this condition was noted by scientists preparing HFC power resources as part of a spacecraft launch (Saleh et al. 2018).



Konrad Reif (ed): Dieselmotor-Management im Überblick. 2nd edition. Springer Fachmedien, Wiesbaden 2014, ISBN 978-3-658-06554-6. p. 171

Figure 8. Atmospheric composition as a function of height (Reif 2014).

Regarding potential aerosol contaminants, possible contaminants to the HFC O₂ intake would be increased particulates from the seasonal sandstorms, wildfires, and pollutants. Filters may minimize sandstorm particle ingestion; however, localized

decreases in the available O₂ would be expected in the vicinity of encroaching wildfires and in areas impacted by pollution. The other environmental composition impact would come from a cold/warm-front passage, which could systematically shift the local pressure values.

7.3 Atmospheric Composition Effects on HFC Performance

There are many types of HFC designs. Two major categories include closed-loop HFC and open-loop HFC. A brief review of each class with respect to the atmospheric composition's potential performance impact follows.

Closed-Loop HFC: For the closed-loop system (recycling the O₂), the system is less likely to be affected by ambient conditions and is more versatile in its ability to deploy in nearly any atmospheric conditions, like that of its generator predecessor. There is a slight disadvantage to the closed-loop system in that it is pressurized and over time there can be an imbalance within the system that would require more maintenance to reset the reactants within the system.

Open-Loop HFC: For the open-loop system, the HFC draws its O₂ supply from the air. Consequently, this design is directly impacted by the amount of O₂ and particulate matter in the air.

Focusing on the ingestion of O₂ from the surrounding air, the ambient air needs to provide sufficient reactant O₂ to allow the system to operate. Particle filters and the O₂ purity affect the HFC operation. Specific to an open-loop system is the use of an air compressor for the external O₂ supply. The power required to run the air compressor weighed against optimizing air compressor pressures with the surrounding air is an area of interest, especially when evaluating the HFC for global deployment. In addition to the pressurization of O₂, filters are important when trying to separate out the particles so they do not contaminate the system by causing chemical or physical damage.

7.4 Quantifying HFC Atmospheric Composition

Without an HFC to test, it is proposed that each quantifiable atmospheric composition element (O-MR, ND, and PP) is associated with an HFC performance aspect. Namely, the O-MR, ND, and PP variables can quantify the reactant concentrations, particulate matter, and reactant pressure, respectfully.

The following is a suggested process for quantifying the HFC atmospheric composition:

- To properly record O-MR, ND, and PP measurements, the sensors must be calibrated (tested for accuracy and precision) before being added to the HFC. Thus, Step no. 1 is to independently calibrate all sensors prior to their integration into the HFC. As part of the calibration analyses, the pretest sensor data need to be compared to proven and expected HFC values.
- The validated and calibrated sensors are placed within the HFC design. Suggested placement is described in Sections 7.4.1–7.4.3.
- The measured HFC sensor data are extracted. And finally,
- A comparison of patterns and trends are noted. Where appropriate, data patterns are associated with specific atmospheric events or conditions.

Using measured data to accurately model the atmospheric effects on the HFC requires an understanding of where the sensors are placed and what the quantified values represent. For this investigation, it is assumed that the HFC is an open-loop system with a dependency on the O₂ supply from the ambient air/atmosphere. In the next sections, a suggested sensor and its placement(s) for the O-MR, ND, and PP measurements are provided.

7.4.1 Laser Spectrometer

For measuring O-MR, two laser spectrometers need to be added to the HFC. One suggested instrument might be the TRANSIC100LP laser spectrometer, due to its versatile usages.

The first laser spectrometer would be in the O₂ inlet to monitor the incoming percent of atmospheric oxygen (see Figure 9, red “L” triangle). As a default for Army operations, the expected value is 21% O₂ composition. This value is considered appropriate for the bulk of ground force scenarios. However, once an active battle event occurs, the O₂ content might be challenged by the raised dust clouds from local arms and artillery fires. Natural wildfire, pollutants, etc., are also O₂ content inhibitors.

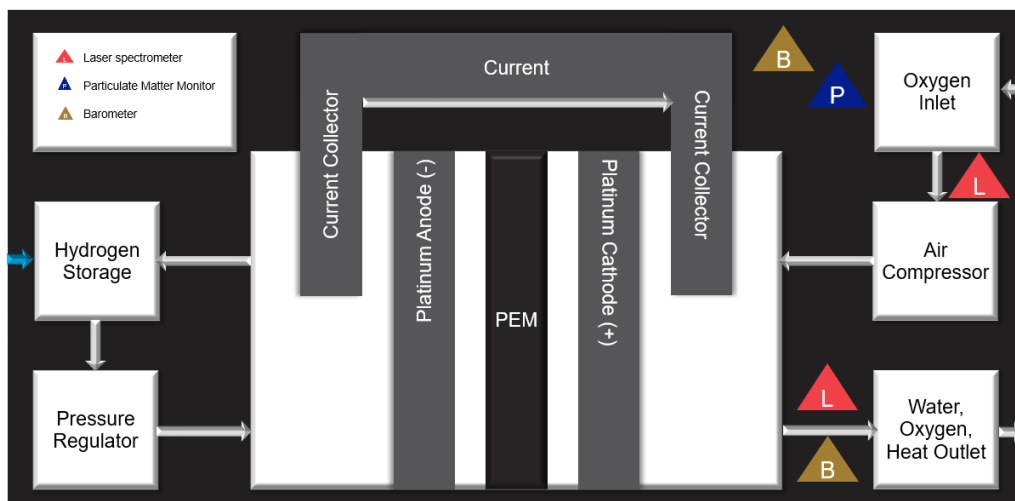


Figure 9. HFC sensor placement where L = laser spectrometer; P = particulate matter monitor; and B = barometer.

A second O₂ monitor is needed at the O₂ and H₂O outlets (see Figure 9, red “L” triangle). This sample would capture any O₂ composition differential between its entry and exit.

The reason for these two sensors is similar to why there are two O₂ detectors integrated in cars: namely, to monitor the O₂ inflow in relation to O₂ consumption and optimized power output.

Optimization is made possible within the HFC because there is an air compressor that sources O₂ from the atmosphere. The air compressor would not need to draw as much power and create excess pressure if there is excess O₂ leaving the system. In contrast, if there is no O₂ leaving the system (closed system), then the air compressor would draw more power and increase the pressure to increase efficiency by allowing the HFC to operate without the “fresh” O₂ supply restriction.

7.4.2 Particulate Matter Monitor

For measuring ND, adding a particulate matter monitor near the HFC is recommended. A GRIMM Model EDM 164 particulate matter monitor is an example of such a monitor that could be used for this study. The monitor should be placed near the O₂ inlet to sample the atmospheric particulates. The reason the sensor is placed near (vs. in) the O₂ inlet is because its size is too large for an HFC integration. However, if an extension into the HFC were possible, placing it near the O₂ input would be informative (see Figure 9, blue “P” triangle). Presuming an external sensor placement, the sensor orientation and positioning around the system needs to avoid nonrepresentative air currents. The key to accurate particulate matter

data is having the sensor in an open area so that air particulates from all angles can be monitored effectively.

7.4.3 Barometer

For measuring PP, a barometer such as the Vaisala PTB110 barometer is needed. To quantify the ambient atmospheric pressure, the sensor should be placed near the HFC O₂ inlet. If PP were sampled within the HFC, the air compressor would systematically skew pressure values downward. Thus, an external sampling would be the more informative. Figure 9 (golden “B” triangle) shows a suggested internal placement to supplement the external sampling. As a minimum, this location would help quantitatively describe the air compressor effects.

8. Integrating an HFC

Presuming favorable HFC field test evaluation results, the next step would be to integrate such a system into a hybridized power-generation resource. For analysis purposes, this section presumes a goal of integrating an HFC-1 power resource into the established ARL hybridized testbed (see Section 1.2), which includes the acquisition of time-synchronized atmospheric conditions.

The physical integration of an HFC system with other power resources is defined by the specific electrical technology designs selected for the task. As explained earlier, only a general description of key components was available at the time of this investigation. Consequently, only a course schematic of components, as shown in Figure 10, could be considered. Unifying the loads from the theoretical HFC and the ARL testbed, the HFC power would be brought into the testbed via the DC/AC power ports. Thus, the untested, physical integration has the potential of being relatively straightforward.

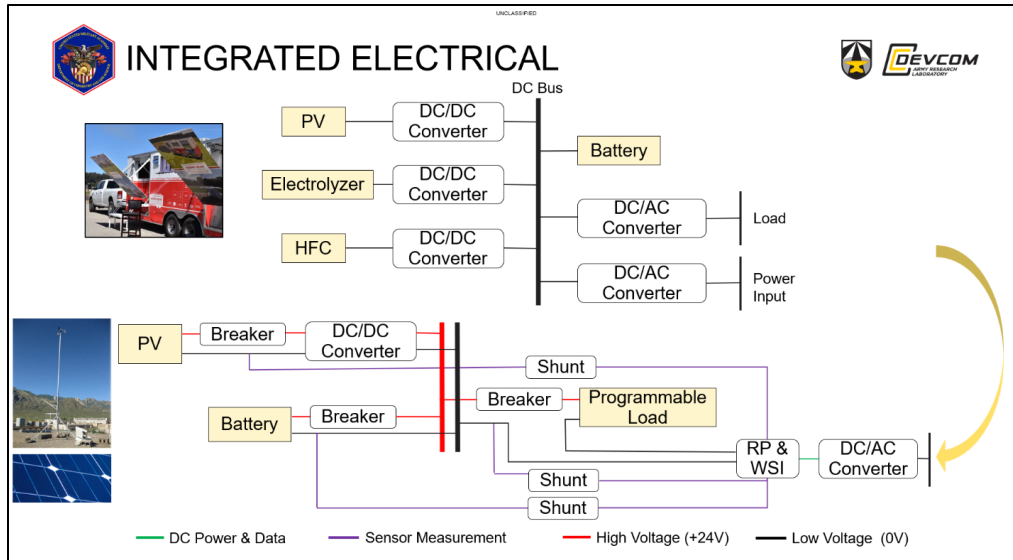


Figure 10. Schematic of HFC-1 integration into the ARL testbed.

The atmospheric data acquisition systems should be placed far enough upwind of the HFC so that (1) it does not interfere with the HSS-1 and PV's ability to collect solar radiation (i.e., no shadows), and (2) it allows the MMT to accurately collect and record ambient (upwind) atmospheric conditions without wind and pressure interferences from the HSS-1 system operations. In Figure 11, the prevailing winds flow from the southwest corner (lower left) to the northeast (upper right). The upwind and slight offset position of the MMT with respect to the HSS-1 better enables an uninterrupted characterization of air composition and disposition for most meteorological scenarios. In this photo, the yellow arrow indicates the direction of the power being provided to the MMT.



Figure 11. HFC/PV downwind (right side) position with respect to testbed/MMT (left side).

One of the not-yet-mentioned challenges in operating an integrated HFC system is the need for H₂O resupplies. At the time of this writing, it was not known what H₂O type (de-ionized, filtered, distilled, etc.) and how much H₂O was required to sustain the HSS-1. Since administering the H₂O requires human intervention, this requirement was noted as a potential operational challenge for unoccupied remote locations.

9. Summary and Conclusions

Diversifying power sources is seen as a way to prepare for future electrical demands for a wide range of conditions, significantly reduce Soldier vulnerabilities, and produce both physical and fiscal savings. ARL is proactively investigating the hybridization of power resources and the exploitation of environmental intelligence supporting the optimization of integrated energy sources. Using an ARL-designed hybridized power testbed equipped with coincident atmospheric measurements, a study to evaluate and possibly integrate an HFC into the testbed was conducted. This report documents foundational information needed to assess the potential for integrating an HFC into a hybridized tactical power resource.

In this report, the HFC was described, and H₂ was recognized as an energy carrier, not an energy source—that is, an independent tool harnesses the energy stored in H₂ and then, releases that energy to generate electricity.

Potential HFC atmospheric dependencies included the storage of H₂O and H₂, and the provision of O₂ from the environment. To evaluate these functions, the investigation focused on atmospheric thermodynamics and atmospheric composition.

The atmospheric thermodynamic investigation found pressure, temperature, and humidity most relevant to the HFC process. Pressure was seen as playing a significant role in the H₂ diffusion processes, since H₂ is stored in a low-pressure solid form. The humidity–temperature relationship observed that as temperature decreased, less H₂O can be held in the atmosphere. Single-digit desert humidities were flagged as having potential HFC impacts.

Literature reported a positive correlation between ambient temperature and HFC efficiency. Metal hydride requires strong heat (300 °C) for the chemical state change. The PEM requires saturation to remain functioning at high operating temperatures, which could be an issue in a high-elevation desert location.

To characterize HFC air ingesting, it was suggested that temperature and humidity sensors be placed at HFC inlet and outlet locations. For characterizing temperature impact on productivity, the internal PEM temperature was flagged, since high

temperatures decrease saturation and thus increase PEM resistance. Likewise, low temperatures create excessive saturation and the PEM reaction rate decreases.

The HFC atmospheric composition investigation focused on ambient O₂ and dust particles. Given that the HFC obtains O₂ from the surrounding air, the ambient air needs to provide sufficient reactant O₂ to operate, which could be handicapped at high elevations. Likewise, desert sandstorms, wildfires, and pollutants could also potentially reduce the O₂ resource and interfere with the electricity production.

To quantify the HFC atmospheric composition impact on three variables (pressure, temperature, and humidity), suggested sensors and sensor placements were described based on an open- and closed-loop HFC design.

The next phase of this study is to apply this report's findings to an HFC test system, so that the knowledge and experiences gained can refine and steer future guidance for HFC power integration into the tactical environment. Ultimately, the net results aim is to meet the growing power requirements, reduce Soldier vulnerabilities, and to establish power independence and resilience.

10. References

- Campbell C. Chalk talk: how to calculate absolute humidity. Environmental Biophysics; 2019 Dec 19 [accessed 2024 July 23]. <https://environmentalbiophysics.org/chalk-talk-how-to-calculate-absolute-humidity/>
- Chemical Book. Hydrogen; last updated 2024 May 27 [accessed 2024 Nov 25]. https://www.chemicalbook.com/ChemicalProductProperty_EN_CB7686195.htm#Safety
- [DoE] Department of Energy. Fuel cell basics. Department of Energy; 2014 Aug 8 [accessed 2024 July 25]. <https://www.energy.gov/eere/fuelcells/fuel-cell-basics>
- [DoE] Department of Energy. Hydrogen and fuel cells 101. Department of Energy (US); 2022 Jan. <https://www.energy.gov/sites/default/files/2022-01/hydrogen-fuel-cells-101-jan2022.pdf>
- Intelligent Energy Limited. Hydrogen fuel cell manufacturer. Intelligent Energy Limited; 2024 June 20. <https://www.intelligent-energy.com/>
- Jaber S. Hydrogen fuel cell: simulation & modeling [blog post]. SimScale. 2024 June 10. <https://www.simscale.com/blog/hydrogen-fuel-cell-simulation-and-modeling/>
- [NWS] RH – relative humidity [glossary entry]. NOAA’s National Weather Service; c2009 [updated 2009 June 25; accessed 2021 Aug 13]. <https://forecast.weather.gov/glossary.php?word=HUMIDITY>
- Omega Engineering Inc. What is a thermistor and how does it work? Omega Engineering Inc. c2024 [accessed 2024 Nov 25]. <https://www.omega.com/en-us/resources/thermistor>
- Powering the hydrogen future[®] with our outstanding fuel cells and service. Intelligent Energy Limited; c2024. [accessed 2024 June 20]. <https://www.intelligent-energy.com/>
- Reif K, editor. Dieselmotor-management im überblick. 2nd ed. Springer Fachmedien, Wiesbaden; 2014. p. 171. ISBN 978-3-658-06554-6
- Saleh et al. Environmental impact of high altitudes on the operation of PEM fuel cell based UAS. J Energy Power Eng. 2018;10(3):87–105. <https://doi.org/10.4236/epe.2018.103007>

- Steiger N. Global warming science: earth's atmosphere and energy balance. Last updated 2024 Nov 21 [accessed 2024 July 15]. <https://njsteiger.github.io/gws/atmosphere-energy-balance.html>
- Stull RB. Meteorology for scientists and engineers. Brooks Cole; 2000.
- Tang X, Zhang Y, Xu S. Temperature sensitivity characteristics of PEM fuel cell and output performance improvement based on optimal active temperature control. *Int J Heat* Mass Transfer*. 2023;206:123966. <https://doi.org/10.1016/j.ijheatmasstransfer.2023.123966>
- Vaucher G, Bergen S. In-situ atmospheric intelligence for hybrid power grids: volume 4 (climate impacts on tactical power generation–part i), sensor comparison and site characterization. DEVCOM Army Research Laboratory (US); 2022. Report No.: ARL-TR-9411.
- Vaucher G, D'Arcy S, Berman M. In-situ atmospheric intelligence for hybrid power grids: volume 1 (feasibility study). DEVCOM Army Research Laboratory (US); 2019. Report No.: ARL-TR-8864.
- Vaucher G, Randall R, Jane R. Atmospheric intelligence for hybrid power advancements: volume 1 (wind impacts on photovoltaic power/panel temperature. DEVCOM Army Research Laboratory (US); 2023. Report No.: ARL-TR-9629. <https://doi.org/10.21236/ad1191356>

Appendix. Conducting a Hydrogen Fuel Cell Site Survey

OVERVIEW: This procedure was prepared to accurately and precisely document and move the physical U.S. Army Combat Capabilities Development Command Army Research Laboratory testbed from the pretest location (Site Cp) to its test site (Site C); and back to Site Cp for a posttest data acquisition.

BACKGROUND: All distance measurements were acquired using a measuring wheel (Figure A-1). All measured units were acquired using a compass on the *iPhone Compass Application* and the protractor on the *iPhone Measure Application*. For Site Cp, flags were installed to mark the testbed equipment. This strategy was used to increase the posttest layout accuracy and precision. Markers (flags on a thin wire) were placed at the legs of the photovoltaic (PV) panel mount, the legs and center location of the meteorological measurement tripod #3 (MMT3) tripod, and at the assigned corner locations for the not-yet-arrived hydrogen fuel cell (HFC) housing.



Figure A-1. Measuring wheel: for horizontal distance measurement.

The PV panel flags were located directly south of the southern legs, and directly north of the northern legs. The MMT3 flags marking the legs were located directly outside of each leg (farthest away from the MMT3 center).

The cornerstone (reference point) for the testbed measurements at Site Cp was the northeast corner of the building closest to the testbed (Figure A-2).

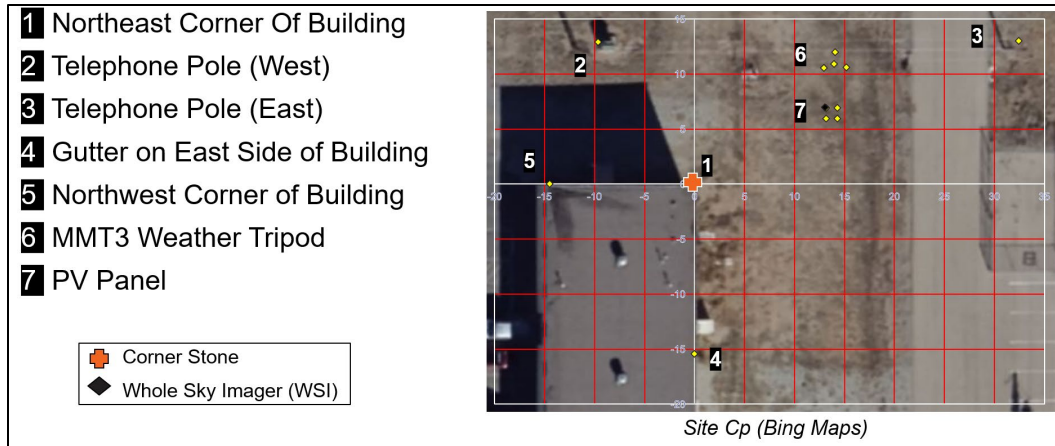


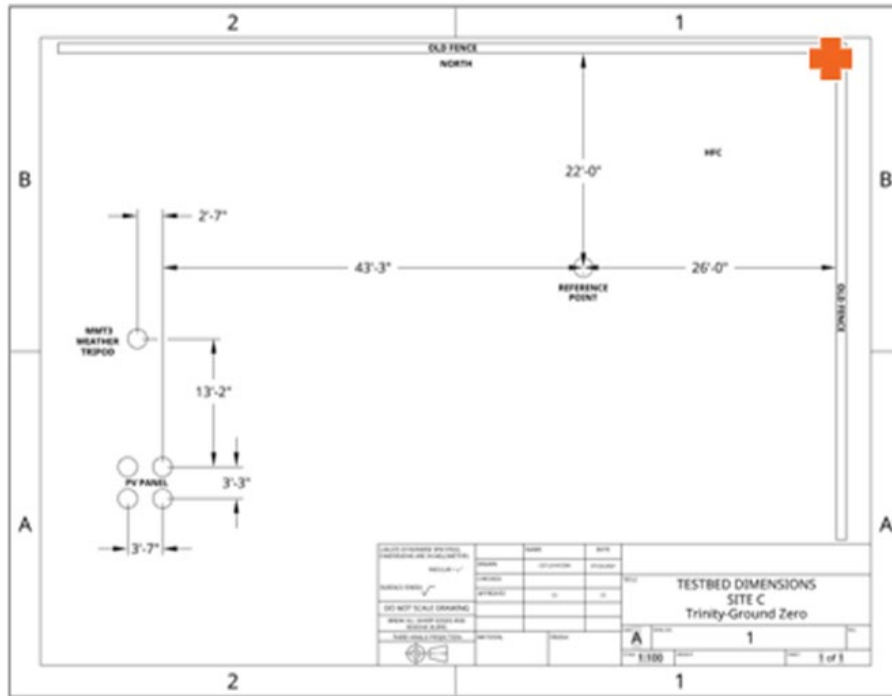
Figure A-2. Site Cp (measurements taken for these instructions).

All measurements using the measuring wheel were taken from points using the center of the spinning wheel.

METHOD – SITING X and Y LOCATIONS of FIELD EQUIPMENT:

- 1) **Materials Needed:** a measuring wheel, a compass of any sort, remote site testbed hardware, documentation medium, and graphics for plotting results.
- 2) **North-South, East-West (N-S, E-W) Instructions:**
 - a. Define a fixed object to use as a cornerstone for the measurements (preferably something easily identifiable). Terrain that is mostly clear and flat produce the best results.
 - b. Determine which direction the measurements will be taken from in accordance with the cornerstone. It must be either east (90°), west (270°); or, north (0°), south (180°).
 - c. Presuming all equipment being sited are north of the cornerstone, measure a distance just south of the subject equipment location.
 - d. From this point, orientate yourself so you are facing north (0°) and measure to the targeted location.
 - e. For this example, the distance was 5.94 m. This was the southwest leg of the southern-facing PV panel. A flag on a thin metal post marked the location.
 - f. Continuing north (0°) to the northwest corner of the PV panel added 1.09 m to the north/south distance. A thin metal post with a flag marked the location.

- g. Turning east, the northeast corner of the PV panel was 0.82 m away. Plotting this distance can be done by adding it to the original east/west length, or using the previous location as a new “cornerstone prime.”
 - h. Turning north (0°) MMT3 tripod center was 5 m away.
 - i. By using only east-west and north-south orientation, the results can be more easily graphically reproduced.
- 3) **N-S, E-W Application:** The N-S, E-W method will work for most test sites. However, if there is not enough area for the testbed to be laid out using a 1-1 ratio, modifications can be made. For example, the original site (Site Cp) used a cornerstone that was southwest of the sensor suite being documented. At the new location—Site C—the cornerstone selected was northeast of all the equipment. Consequently, the layout had to be literally turned upside-down and flipped over to map the spacing. Figure A-3 shows the Site C layout. The issue was that there is not enough room to go north for placing the PV panel, so the unit was placed to the south instead. All other instructions were followed.
- 4) **Angled Survey Method:** Other methods for mapping obstacles include finding the angle (hypotenuse) of points from north, and measuring directly to the object. This method is conducted by standing at the cornerstone facing north (or south), finding the angle north (or south) from the cornerstone to the point being measured, and then finding the distance from the cornerstone to the point. When applying this method, the compass on an iPhone was found to be imprecise (could not be duplicated). Using a hand-held analog compass, and ensuring the same unit was used for all subsequent measurements, kept the results consistent (precise).
- 5) **2-D Mapping Applications:** The above methods were applied to a whole sky image (WSI) with (X,Y,(Z)) locations marked and needing numerical placements values. See Figure A-4.



✚ = Cornerstone for reference distances.

Figure A-3. Site C was a mirror layout from the original.

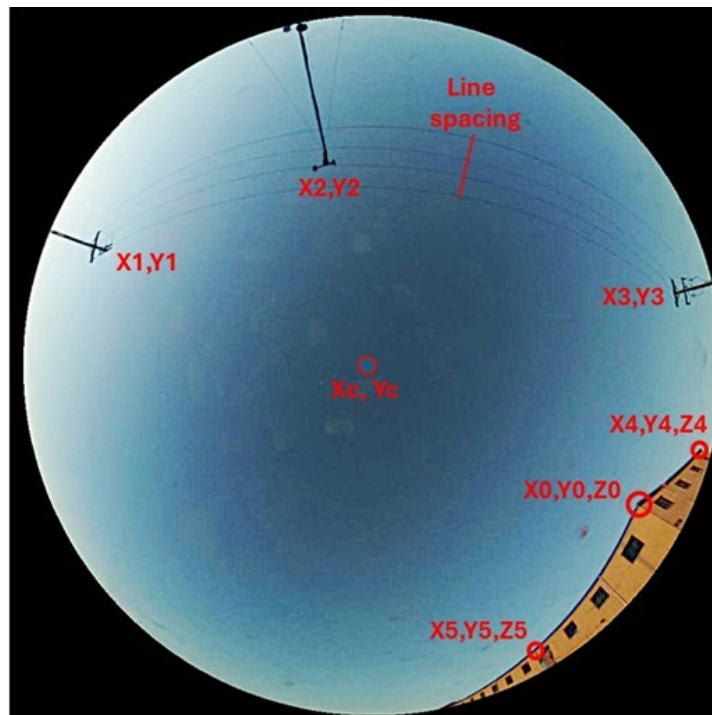


Figure A-4. Example of a WSI with points needing numerical values.

Table A-1 shows the results generated using the N-S, E-W method.

Table A-1. X, Y, Z values assigned to a 2-D image.

Point	X (Meters)	Y (Meters)	Z (Meters)
0	0.00m	0.00m	5.92m
1	32.44m	13.03m	9.39m
2	13.97m	10.95m	6.30m
3	-9.65m	12.93m	10.06m
4	-14.53m	0.00m	5.92m
5	0.00m	-15.42m	5.92m

Additional information referenced in the creation of this procedure included:

- The Leader in Cloud-Native CAD & PDM. Onshape; c2024 [accessed 2024 Nov 25]. <https://www.onshape.com/en/>
- Keson RR112 Roadrunner 1 Measuring Wheel [item description]. B & E Seal Coat Products, Inc.; c2022 [2024 July 26]. <https://safesealofmichigan.com/product/keson-rr112-roadrunner-1-measuring-wheel/>

List of Symbols, Abbreviations, and Acronyms

2-D	two-dimensional
AC	alternating current
AGL	above ground level
AIAD	Advanced Individual Advanced Development
AIHPA	Atmospheric Intelligence for Hybrid Power Advancements
ARL	Army Research Laboratory
C	Celsius
DC	direct current
DEVCOM	U.S. Army Combat Capabilities Development Command
H ⁺	hydrogen proton
H ₂	hydrogen
H ₂ O	water
HFC	hydrogen fuel cell
HFC-1	HFC product
HSS-1	HFC-Solar System
MMT	meteorological measurement tripod
N ₂	nitrogen
ND	number density
O ₂	oxygen
O-MR	oxygen-mixing ratio
PEM	proton exchange membrane
PP	partial pressure
Pt	platinum
PT	power train
PV	photovoltaic
r	mixing ratio (atmospheric variable)

RH	relative humidity
T	temperature
WSI	whole sky imager
ΔT	delta temperature

1 DEFENSE TECHNICAL
(PDF) INFORMATION CTR
DTIC OCA

1 DEVCOM ARL
(PDF) FCDD RLB CI
TECH LIB