Argonne
NATIONAL LABORATORY

H2@AIRPORTS WORKSHOP
SUMMARY REPORT
November 4–6, 2020

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UNITED STATES OF AMERICA
FEDERAL AVIATION ADMINISTRATION
U.S. AIR FORCE
DEPARTMENT OF THE NAVY
UNITED STATES OF AMERICA

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H2@Airports Workshop Summary Report

November 4-6, 2020

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Abstract

This report serves as the proceedings of the H_2@Airports Workshop held virtually by the U.S. Department of Energy (DOE) in collaboration with the U.S. Department of Transportation (DOT) and Department of Defense (DOD), November 4-6, 2020. Presentations from the workshop can be found at *H_2@Airports Workshop:* *https://www.energy.gov/eere/fuelcells/h2airports-workshop.*

The workshop was held to assess the state of the art for electric aircraft and airport applications specifically using hydrogen fuel cells, to discuss operational requirements and lessons learned on early fuel cell aviation and airport projects, to understand current technology gaps, to identify collaborative research and development (R&D) opportunities, to highlight codes, standards, safety, and regulatory challenges, and to identify potential actions that address them. Experts and stakeholders from industry, government, and academia met to discuss the current state of the art of hydrogen and fuel cell technologies and the requirements for using these technologies in aviation applications and land-based applications at airports. This report summarizes the discussions and diverse opinions expressed at the workshop.

Acknowledgments

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We would like to thank Roberto I. Guerrero, Deputy Assistant Secretary of the Air Force for Operational Energy, Office of the Assistant Secretary of the Air Force for Installations, Environment and Energy; Jim Caley, Director for Operational Energy, U.S. Navy; Dr. Jim Hileman, Chief Scientific and Technical Advisor for Environment and Energy for the Federal Aviation Administration; Steven Schneider, Research Aerospace Engineer in the Chemical and Thermal Propulsion Systems team at NASA Glenn Research Center; and Leslie Goodbody, Engineer, Innovative Heavy Duty Strategies, California Air Resources Board.

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Executive Summary

This report summarizes the proceedings of the H2@Airports Workshop organized by the U.S. Department of Energy (DOE) Hydrogen and Fuel Cell Technologies Office (HFTO) in collaboration with the U.S. Departments of Transportation (DOT) and Defense (DOD). The virtual workshop was attended by representatives from more than 70 organizations across academia, government, and industry.

The objectives of the workshop were to:

- Assess the state of the art for aviation applications using hydrogen fuel cells
- Discuss operational requirements and lessons learned from early fuel cell projects
- Understand current technology gaps and identify collaborative R&D opportunities
- Identify regulatory challenges and necessary safety codes and standards

Federal agencies like DOE consider hydrogen to be part of a comprehensive energy portfolio. Hydrogen can couple with many other primary energy sources and end uses to address certain applications, such as aviation, that are hard to decarbonize by other means. A three-fold strategy for hydrogen is being pursued that (1) addresses scaling-up hydrogen production and use, (2) continues to support R&D to improve performance and reduce costs, and (3) addresses enablers of hydrogen technology.

Attendees indicated that there are numerous opportunities for hydrogen and fuel cell (FC) technologies in aircraft, such as unmanned aerial vehicles (UAVs), urban air mobility (UAM), and commercial fixed-wing aircraft, as well as for ground support equipment (GSE) and vehicles at and near airports. UAVs (drones) are a promising application, with markets developing for inspection and surveillance and emergency response. Endurance is one of the major pain points for UAVs, and FCs have demonstrated double or triple the flight duration of batteries. The increased endurance and the faster refueling times of hydrogen FC UAVs result in a large increase in operational efficiency for hydrogen FC-powered UAVs over battery-powered UAVs. Longer flight times can enable beyond visual line-of-sight (BLOS) operations and provide additional operational cost savings. For military applications, hydrogen provides longer operating ranges and more persistence than batteries, and FCs can provide reduced heat and noise signatures, enabling their use for silent watch missions. Challenges for hydrogen FC UAVs include the lack of reliable hydrogen delivery and a nationwide hydrogen supply chain.

Aviation traffic is projected to increase by three to four times its current level by 2050, causing CO_2 emissions within the industry to triple. Reducing emissions will not be enough to reach aviation industry climate goals: Zero emissions options appear to be the only way to achieve them. The options for zero-emission commercial aviation that are considered to be viable are synthetic fuels (such as ammonia or hydrocarbon fuels produced from CO_2 and "green" hydrogen) and hydrogen. Hydrogen can be used as a fuel for internal combustion engines (ICEs) in conventional propulsion systems or for FCs in electric propulsion systems. Aircraft manufacturers are pursuing both approaches. The industry is currently focusing its hydrogen and FC development efforts on smaller fixed-wing aircraft for regional passenger service and new platforms such as electric vertical takeoff and landing (eVTOL) multirotor aircraft for urban air mobility (UAM). ZeroAvia has demonstrated a hydrogen-fueled 6-seat commercial-grade FC plane and is working to extend its range to 300 miles. A study by Argonne National Laboratory compared the total cost of ownership (TCO) of a 6-seat regional passenger plane equipped with a hydrogen-fueled FC powertrain to a conventional aviation gas-fueled piston engine powertrain and showed that the lifetime operating cost of the FC plane was $48/h lower than that of the piston engine plane. ZeroAvia is developing a 19-seat aircraft with a range of 500 miles that it plans to have certified for commercial operation by 2023. Alaka'i has developed Skai, the first hydrogen-FC eVTOL multicopter for urban air mobility (UAM).

Hydrogen and FCs currently have several key advantages over batteries for use in UAV and UAM applications, including increased range and payload, higher mission flexibility, shorter refueling times, and lower lifecycle costs. For multi-rotor UAVs, the Argonne TCO study compared the TCOs for FC- and battery-powered multi-rotor hexa-copter UAVs used for aerial inspection of a gas drilling area and concluded that the FC system provided a cost savings of $18/h of operation over the battery system. For fixed-wing UAVs, the study compared the TCO for FC-, battery-, and piston engine-powered fixed-wing UAVs used in a surveying application and showed that the FC provides a $88/h savings over the battery-powered system and $43/h savings over the piston engine system. For UAMs, the study compared a multirotor FC-dominant hybrid (FCD), a tilt-rotor FC-battery hybrid (FCH), and a tilt-rotor battery system and concluded that the tilt-rotor FCH had the lowest TCO: $0.63 per passenger-mile (PAX-mi), compared to multi-rotor FCD ($0.79/PAX-mi) and the tilt-rotor battery ($0.99/PAX-mi), with operating and maintenance cost being the biggest cost factor for all three aircraft.

There are numerous challenges for deploying hydrogen and FCs in fixed-wing and eVTOL aircraft. A major challenge is storing a sufficient quantity of hydrogen on board to meet the flight demand. Liquid hydrogen provides a higher volumetric energy storage density than gaseous hydrogen; however, there are operational challenges with cryogenic liquid handling and storage. There are concerns that liquid hydrogen, even with its higher volumetric energy storage density, may not be adequate for longer flights with the larger planes currently in use. Transportation, bunkering, and handling of liquid hydrogen is a challenge. The hydrogen supply infrastructure, including liquefaction facilities, needs to be increased to meet future demand. The lower operating temperature of polymer electrolyte membrane fuel cells (PEMFC) compared to ICEs causes thermal management issues in, for example, eVTOL operation, where the highest heat load occurs during takeoff, when the air flow over cooling surfaces is at its lowest.

Safety is a major area of emphasis, and government agencies such as the Federal Aviation Administration (FAA) and organizations such as the joint Society of Automotive Engineers (SAE) and the European Organisation for Civil Aviation Equipment (EUROCAE) working group have begun to develop protocols to address the safety of hydrogen and FCs in aviation. The FAA is looking at disruptive technology for aircraft and how it impacts safety, including electrification, batteries, and hydrogen and FCs. They recently completed several research programs, and the reports are available on the FAA Technical Library web site.[*] The SAE/EUROCAE group has published several documents, including *Aircraft Fuel Cell Safety Guidelines* (AIR6464/ED-219), technical guidance for the safe integration of PEMFCs in aircraft; *Considerations for Hydrogen Fuel Cells in Airborne Applications* (AIR7765/ER-20), a comprehensive document for decision makers on hydrogen, its applications and its benefits for aircraft; and *Installation of Fuel Cell Systems on Large Civil Aircraft* (AS6858/ED-245), which discusses the use of FCs for auxiliary power units (APUs) and emergency backup propulsion power. Sandia National Laboratories' safety R&D has focused on the need for risk assessment and consequence modeling in safety studies.

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[*] https://www.faa.gov/about/office_org/headquarters_offices/ang/library/

Airports are facing significant regulatory pressure to reduce emissions from GSE, providing an incentive for deploying hydrogen and FC technologies in GSE. Battery technology currently being employed has many challenges, including long charge times (generally overnight or 2–3 hours with rapid charging), which has resulted in airlines and ground handling companies purchasing twice the number of vehicles previously needed. In addition, battery charging infrastructure does not scale well from 100 to 1,000 vehicles and is expensive and difficult to install at the megawatt scale needed to support operations at large airports. The fact that GSE never leaves the airport simplifies the hydrogen refueling infrastructure needed. The power requirements for many types of GSE are similar to those found in material handling equipment (MHE), a market where FCs have become the dominant power system, thus enabling more rapid integration of FC technology into GSE. Demonstrations of FC GSE include FC-powered push-back tractors or "tugs" at the Memphis and Albany airports in the UnitedStates and at the Hamburg airport in Germany. The FC-powered tugs provided exceptional performance even in cold weather. Cargo tractors, trucks, air start units, preconditioned air, and ground power units are additional potential opportunities for FC GSE. Hydrogen generation, delivery, and storage are key challenges, and there is a need for safety codes and standards, protocols, and training.

Hydrogen and FCs were also identified as a solution to decarbonizing airport ground transport, including airport buses and shuttles. FCEVs provide benefits such as a longer operating range and higher payloads than battery vehicles, and FC buses are already in commercial operation in transit applications. Results from the National Fuel Cell Bus Program indicate the driving range of the FC buses operated in daily service by the Stark Area Regional Transit Authority (SARTA) in Ohio averaged 220 miles daily and achieved a fuel economy of about 7 miles per kg of hydrogen, compared to 4 mpg for their diesel ICE buses. Developers indicated that FC buses provide a more favorable TCO than battery-powered buses for operating ranges above 160 miles.

While hydrogen is already being produced industrially in quantities that would satisfy airport demand, delivery and distribution at the scale required is a challenge. For example, it is estimated that it would require 35 tons per day (tpd) to fuel all the ground operations at Los Angeles International Airport (LAX). Providing this amount of hydrogen would require delivery of eight liquid hydrogen or 70 gaseous hydrogen trailers a day. Bunkering this amount of fuel at the airport to ensure a steady supply is also a concern, and likely eliminates its storage as compressed gas. Hydrogen pipelines are considered the best option for delivery and backup storage to meet airport demand.

Hydrogen can play a key role in reducing airport emissions. Given their large energy demand, airports can act as hydrogen hubs by building demand to develop the hydrogen market. However, supplying and storing the amount of hydrogen needed at a large airport, developing the hydrogen infrastructure to support it, and the current cost of hydrogen are all challenges. Zoning issues are another major barrier, and codes and standards that serve as a guidebook for setting up hydrogen fueling stations at an airport are needed.

Initial applications for hydrogen at airports are likely to be on the ground-based applications, such as transit buses, shuttle buses, rental cars, forklifts, and ground support equipment. Distribution of hydrogen across the airport is a key issue, and codes and standards developed specifically for airports as well as education and training of airline and airport workers on the use and safe handling and storage of hydrogen are critical.

Hydrogen can also reduce emissions when aircraft are in the air. However, scaling hydrogen and fuel cell equipment down to the smaller footprint of UAVs and developing regulations and standards for operating FC UAVs are challenging. For UAM and small fixed-wing planes, R&D is needed for lightweighting FCs and hydrogen storage systems and to optimize designs for aeronautic conditions (lower temperature and air pressure at elevation, etc.). Liquid hydrogen appears to be the best option for larger aircraft, but liquid hydrogen supply, refueling infrastructure, and handling and safety are concerns.

Attendees indicated that government funding for demonstrations and pilots of pre-commercial products in “real world” operating conditions is important to prove that the technology is cost effective and safe. They also saw R&D for lightweighting fuel cell systems, fuel cell operation at altitude, and liquid hydrogen production, storage, and dispensing systems, including robotic systems, as areas in need of government support. Safety, codes, and standards, and permitting are also areas where attendees indictaed government support is needed.

Introduction

Government and industry technology developers worldwide are realizing the potential for hydrogen aviation applications, including electric aircraft, airport vehicles, airport related equipment, and airport mass transit vehicles. This workshop was held to help identify research needed to accelerate technology development and address barriers to industry commercialization. The workshop was developed in collaboration with the U.S. Navy and the U.S. Federal Aviation Administration (FAA). The objectives of the workshop were to:

- Assess the state of the art for electric aircraft and airport applications specifically using hydrogen FCs
- Discuss operational requirements and lessons learned from early FC aviation and airport projects
- Understand current technology gaps and identify collaborative R&D opportunities
- Identify regulatory challenges and needed safety codes and standards

The workshop was held over three days. The first day focused on government perspectives and safety codes and standards, the second day on developments in electric aviation and on FCs and hydrogen for use on board aircraft, including UAVs. The third day focused on hydrogen and FCs for airport ground support equipment and refueling. Polling questions and breakout sessions on days two and three provided additional opportunities for attendees to provide input.

Session I — Government Perspectives on Hydrogen for Airports and Aviation Applications

Sunita Satyapal, Director, Hydrogen and Fuel Cell Technologies Office, U.S. Department of Energy
"U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office Opening Remarks"

Dr. Satyapal indicated that fuel cell industry shipments exceeded 1 GW for the first time in 2019. Most of this growth was due to the transportation sector, with over 12,300 FC electric vehicles (FCEVs) sold worldwide in 2019, doubling the global number of FCEVs and bringing the total to over 25,200. In parallel with the growth in FC shipments, the hydrogen infrastructure is growing, with 25 times more electrolyzers deployed now than a decade ago and a 20% increase in the number of hydrogen refueling stations since 2018, bringing the total number of hydrogen refueling stations to 470.

In the United States, the largest deployment of hydrogen FCs is in materials handling equipment: There are now more than 35,000 FC-powered forklifts. There are also substantial stationary FC deployments, with more than 500 MW of FC stationary power installed, including approximately 8,000 FC backup power units. In the transportation sector there are over 60 buses and more than 8,800 cars.

The United States produces 10 million metric tons (MMT) of hydrogen annually and has more than 1,600 miles of hydrogen pipelines. The United States is also home to the world's largest hydrogen storage cavern. While most of the hydrogen is currently used in the petroleum industry, the United States currently has 45 public hydrogen refueling stations (or about 145 stations if private stations for refueling forklifts are included). Plans to increase the hydrogen refueling infrastructure are in place, with California planning 200 stations and 12–20 additional stations planned in the Northeast.

The United States sees hydrogen as one part of a comprehensive energy portfolio. Hydrogen isn't just for one application but can couple with many primary energy sources and end uses. Hydrogen's potential role can be seen in the H_2@Scale plan, enabling affordable, reliable, clean, and secure energy across sectors. Hydrogen can address applications across sectors that are hard to decarbonize by other means, such as steel production, industrial heating, heavy-duty transportation such as shipping, and potentially aviation. Today's U.S. hydrogen demand of ~10 MMT could double or quadruple.

DOE's strategy is three-fold: (1) scale up hydrogen production and use, (2) continue R&D to improve performance, and (3) reduce costs and address enablers of hydrogen technology. DOE has recently announced new projects for H_2@Scale over a range of applications and regions, including hydrogen production from wind, solar, and nuclear energy and from renewable natural gas to be used in multiple applications including data centers, FCEVs, maritime applications, and steel production.

DOE's R&D focuses on increasing performance and affordability. To increase affordability and scale up hydrogen use, DOE is looking for sites where a hydrogen supply for multiple applications can be located. Airports are one example where hydrogen could be used for aircraft, ground support equipment, delivery vehicles, etc.

DOE is involved in multiple collaborations and global partnerships, including the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and the Center for Hydrogen Safety (CHS).

Roberto "Bert" Guerrero, SES, DAF, Deputy Assistant Secretary of the Air Force Operational Energy *"Innovative Energy Solutions for an Optimized Air Force"*

Roberto Guerrero discussed the Air Force's efforts and interest in innovative energy solutions. The Air Force uses ~2 billion gallons of aviation fuel annually to fly ~800,000 sorties. The Office of Air Force Operational Energy's vision is to create an energy-optimized Air Force that maximizes combat capability for the warfighter through improved engineering and processes. This includes optimization of fuel supply scheduling—from whiteboard to war-gaming—and bringing commercial practices, such as advanced engine washing, winglets, microvanes, and future designs, such as body-wing integrated designs, hybrid designs, and so on to military aviation.

The Air Force sees FCs as plug-and-play for unmanned aerial systems (UAS) and believes that with hydrogen FCs they can get 6–8 hours of endurance. The Air Force is receiving funding for alternative energy from congressional special interest items. Two examples are projects at Hickam Air Force Base: a PEM electrolyzer and a hydrogen refueling station for FC ground support equipment. The PEM electrolyzer is tied to a 146 kW photovoltaic array to provide "green" hydrogen. Over 1,100 kg of hydrogen have been dispensed since 2014. The hydrogen is used for ground support equipment, including a standard U-30 tug converted to a hydrogen FC electric hybrid, and a FC-powered F-22 weapons loader. Testing of a multi-passenger vehicle is underway. The multi-passenger vehicle is a bus designed and built by US Hybrid that uses a 30 kW hydrogen FC. The vehicle is in its fifth year of operation. A hydrogen-powered maintenance van is also being demonstrated. The van contains a 35 kW hydrogen FC mobile generator and onboard battery energy storage. The vehicle has 16 configurable modes and is emergency response exercise capable.

As funding has become tighter, the Air Force has pursued new avenues for funding efficiency initiatives, including using previous years' efficiency savings for future efficiency initiatives. These initiatives must advance combat capability for the Air Force to have an interest in them. Efficiency improvements are important to the Air Force because with no fuel, there is no fight.

Jim Caley, Director of Operational Energy Research, Development, Test, and Evaluation, U.S. Navy *"U.S. Navy Operational Energy Program"*

Jim Caley discussed the Navy's operational energy goals and how hydrogen and FCs may fit. The Navy's goals are to extend the operational reach of current and future weapons, reduce energy consumption and logistics issues for forward-deployed groups, increase energy resilience, increase effective use, conversion, storage, and distribution of energy to enable future weapons, and foster an energy culture. Mr. Caley summarized these goals by stating that the Navy measures its success in this area in terms of how they can enable "breaking their enemy's toys" from as far away as possible. Fuel supply logistics are a large concern for the Navy. Naval operations require ships to stay on station for at least 10 days. Replenishing fuel supplies for ships while underway requires 4-6 hours, and during that time they are an easy target. Therefore, the Navy wants forward operating bases to be able to perform their missions with as few refuelings as possible.

Hydrogen and FCs provide several advantages to weapons systems and platforms of the future. FCs can provide reduced heat and noise signatures and provide silent watch capabilities. The Navy is very interested in the capability of FCs to provide reduced audio/vibration signatures. Hydrogen can also provide extended ranges and increased persistence compared to battery operation. The increased persistence of unmanned vehicle platforms to operate days at a time has been a big driver toward hydrogen. An example of this is the "Hybrid Tiger" demonstration of multi-day endurance by the Naval Research Laboratory (NRL): The combination of solar wings with a hydrogen FC and soaring algorithms can keep a drone airborne for four to six days.

Hydrogen does have its challenges for use in naval applications. A major challenge is safety: putting hydrogen, a flammable gas, on board a naval vessel. Generating hydrogen on board is difficult, and fire-fighting ramifications must be considered. To get hydrogen on board ships, tools such as gas leakage and gas dispersion modeling, material selection criteria for hydrogen in a marine operating environment, and design criteria for hydrogen generation, storage, distribution, and utilization are needed. In addition, system specifications must be developed, qualification testing performed, and operating procedures and technical manuals prepared.

The Navy is looking at participating in an interagency demonstration of hydrogen and FC technology in the future.

James I. Hileman, Chief Scientific and Technical Advisor for Environment and Energy, Office of Environment and Energy, U.S. Federal Aviation Administration (FAA)
"Perspectives on Hydrogen for Airports and Aviation Applications"

James Hileman discussed applications for hydrogen and FC in civil aviation. He noted that (pre-pandemic) civil aviation was responsible for over 10 million jobs and accounted for ~5% of the GDP and $1.6 trillion of economic activity in the United States annually. Aviation equipment is the largest export sector in the U.S. economy, accounting for over 8% of total exports. The environmental impacts of aviation include noise, combustion emissions, impacts on the ozone layer, global climate change, and health impacts on the general population from exposure.

Many communities are concerned about noise from aircraft and helicopter operations. Similar concerns could be expected with noise from UASs and UAMs. Electrification could enable dramatic reductions in noise levels, depending on design choices. Electrification with batteries or FCs could be an enabler for these changes in vehicle architecture. The choice of primary energy source for these vehicles will depend on the specific needs for the vehicle and application (range, payload, utilization, refueling time).

Aircraft for commercial long-distance travel require considerable power for flight. For example, maximum power requirements for an Airbus A380 are on the order of 1,000 MW (1 GW). To provide this power, the aircraft needs considerable amounts of energy stored on board, and due to weight and volume restrictions this means aviation fuels need to have high specific energy and volumetric energy density. Compressed hydrogen is unlikely to provide the energy density needed for commercial aviation, and either cryogenic liquid hydrogen or power-to-fuels liquids (synthetic jet fuels, methanol, ammonia) will likely be needed to decarbonize long distance flights.

Airports are energy hubs, and commercial service airports handle large quantities of jet fuel. As an example, LAX loads ~100,000 barrels of jet fuel per day. Fuel transport and handling must be considered when discussing alternative fuels. Replacing jet fuel with green hydrogen would require considerable amounts of electricity for water electrolysis and hydrogen liquefaction. Power-to-liquids (PTL) would require much the same amount of energy that liquid hydrogen does; however, infrastructure changes would not be needed. Additional factors that must be considered for liquid hydrogen are the placement or location of liquefaction facilities and delivery of liquid hydrogen from the tank farm/bunker to individual planes and, if it is used for combustion in jet engines, any potential NOx emissions. Hydrogen can also be used for renewable aviation fuel production, which could provide an immediate reduction in the industry's carbon footprint and enable the use of sustainable aviation fuels using biomass and waste resources. This would allow the use of the existing fuel infrastructure.

The FAA is currently funding a project at MIT to quantify the costs, emissions and resulting impacts of different advanced approaches for commercial aviation. The detailed systems analysis is to determine the relative merits of different ways that commercial aviation could use electricity in aviation, including hydrogen and PTL produced from renewable electricity

Steven Schneider, Research Aerospace Engineer, NASA Glenn Research Center
"Some NASA Perspectives on Hydrogen"*

NASA has a long history of exploring applications for hydrogen and fuel cells for both space and aero/automotive applications. These extend from the use of proton exchange membrane (PEM) fuel cells for Gemini in the 1960s through to the present. NASA's recent research portfolio includes a project at the Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft (CHEETAH), to explore the use of cryogenic LH2 energy storage for all-electric transport aircraft, and Fostering Ultra-Efficient, Low Emitting Aviation Power (FUELEAP), which looked at the feasibility of a hybrid solid oxide fuel cell (SOFC) with onboard fuel reformation for aircraft primary propulsive power and secondary power.

There is renewed commercial interest in hydrogen for flight, as exemplified by ZeroAvia's commercial H2 flight, Airbus' H2 transport concepts, and Alaka'i's H2 concept for UAM. Based on their extensive history with hydrogen and fuel cells, NASA sees challenges for hydrogen related to the size and weight of on-board hydrogen storage, the increased complexity of systems associated with H2 combustion in a gas turbine, integrating the fuel cell system, and the power density and specific power of the fuel cell system, including balance of plant. There are also questions about the atmospheric impact of contrails, particularly at higher altitudes. Using hydrogen at airport facilities also presents system challenges, including producing, storing, and delivering, hydrogen at the scale needed for an airport, managing fueling, and the interactions with surrounding infrastructure (e.g., the power grid).

Leslie Goodbody, Air Resources Engineer, Innovative Heavy-Duty Strategies, California Air Resources Board (CARB)
"Hydrogen and Fuel Cell Activities at California Airports"

California has historically had air-pollution problems, and the San Joaquin Valley and South Coast Basin are the worst air emission districts in the country. California Governor Gavin Newsom has set ambitious zero emission vehicle (ZEV) targets for both light-duty and heavy-duty vehicles, and California has put key policy drivers in place to help reduce emissions. These drivers include air quality goals and new ZEV milestones requiring that 100% of medium- and heavy-duty vehicles be ZEVs by 2045. California has zero-emission transit and shuttle bus regulations, which include airport shuttle bus fleets, requiring 33% zero emission buses (ZEBs) beginning in 2027 and full implementation of ZEBs by 2035. California also has rules for trucks and truck fleets—covering trucks from Class 2b to Class 8—to achieve a full transition to

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* Mr. Schneider was not able to deliver his presentation at the Workshop; the summary and link are provided here for completeness.

zero emissions. The South Coast Air Quality Management District has brought airports on board and entered into a voluntary memorandum of understanding (MOU) with commercial airports to reduce greenhouse gas (GHG) emissions. Among other actions, airports will replace airport owned and operated buses with ZEBs, electrify parking and shuttle buses, and install jet fuel pipelines to eliminate fuel delivery trucks.

California has also implemented incentive programs to help spur adoption of zero emission technologies. Among these are several California-funded demonstration projects, including two FC hybrid delivery van projects demonstrating 19 delivery vans in total, and clean technology vouchers, which have included ZEV truck and bus vouchers and the clean off-road equipment (CORE) voucher incentive program. CORE includes zero-emission airport cargo loaders, aircraft tugs, and aircraft ground power equipment. California has also assigned $423 million from the Volkswagen Environmental Mitigation settlement to NOx mitigation, including funding for zero-emission transit and shuttle buses, zero emission freight and drayage trucks, and hydrogen infrastructure.

Session II — Safety

Michael. Walz, Aircraft Electrical Systems Research Program Manager, U. S. Federal Aviation Administration
"FAA Hydrogen Fuel Cell Research"

The FAA is looking at disruptive technology for aircraft, including electrification, batteries, and hydrogen and FCs, and how it impacts safety. Several recently completed research program reports are available on the FAA Technical Library web site.

FAA funded a program with Infinity Fuel Cell and Hydrogen, Inc. looking at incorporating FCs into UAVs for long-duration flights at both low and high altitudes. The project investigated a lightweight and flexible fuel cell system with hydrogen and oxygen storage. Building on reports from the Energy Supply Device–Aviation Rulemaking Committee (ESD-ARC), the project also involves mapping ARC recommendations for applicable parts of the regulations to both a generic fuel cell system and the UAV fuel cell system under development. The program is summarized in DOT/FAA/TC-19/55 *Aircraft Fuel Cell System*.

FAA also funded a Teledyne Energy Systems Inc. project looking at using FC for emergency power systems and for medevac power systems. The study found that FC stacks are not a reliability problem, and reliability issues are mainly associated with supporting balance-of-plant (BoP) components—pumps, valves, sensors, fittings, piping, etc. (see DOT/FAA/TC-18/49 *Failure Mode and Effects Analysis on PEM Fuel Cell Systems for Aircraft Power Applications*).

The FAA supported several projects looking at solid oxide fuel cell (SOFC) technology, including a project with Boeing looking at a safety management approach for SOFC architecture. The study assessed SOFC systems for possible safety hazards and identified ways to contain potential hazards or mitigate their effects. Testing was performed on an SOFC stack that underwent a controlled failure to evaluate the containment of the hazards identified during analysis.

A project with Honeywell looked at developing a Recommended Technical Standard Guidelines (RTSG) document to serve as a basis for an industry standard and eventually support government issued certification requirements for fuel cell systems installed on aircraft. Research involved replacing airplane auxiliary power units (APUs) with SOFC technology. The results indicate that there would be a weight penalty associated with replacing an APU with a FC and that using an SOFC would require a large number of changes to the aircraft, especially for an SOFC that runs the APU during flight (currently, most APUs are only used while the aircraft is on the ground).

The FAA is also looking at reversible or regenerative FCs for aircraft and has projects with Giner Inc. and Infinity. The Giner project is looking at a small regenerative FC the size of a service cart. It would run in electrolysis mode while on the ground to charge hydrogen and oxygen storage tanks and in FC mode to provide power. The Infinity project is a design feasibility study for a regenerative FC to replace the ram air turbine (RAT) generator. The FC would provide emergency power and provide high pressure oxygen for the FC and for emergency pilot oxygen.

The FAA is also looking at the safety aspects of reformate-based FCs, including projects with Teledyne and Honeywell. Jet fuel can be used as a source of hydrogen, eliminating the need to store high pressure or cryogenic hydrogen on board. However, reforming jet fuel to hydrogen requires extensive processing.

The FAA also has capabilities for testing modern motors up to 50 hp in the More Electric Aircraft Lab as well as capabilities for testing PEMFCs and SOFCs. It is active in early engagement and certification projects on FCs, electric aircraft, and emerging concepts, such as Alaka'i's 6-rotor electric propulsion multi-copter and ZeroAvia's FC plane.

Olivier Savin, SAE/EUROCAE Chairman
"Standardization Activities on Hydrogen & Fuel Cell Technologies for Airborne Applications"

The Joint SAE (AE-7AFC)/EUROCAE (WG-80) Hydrogen and Fuel Cells Working Group was established in 2008 to develop guidelines for qualification and certification of hydrogen and FC systems in various aircraft applications for members across the industry. The working group has 80+ members in the EU and America. It holds three face-to-face meetings per year and biweekly virtual meetings. Members are interested in hydrogen for aviation due to its potential to provide zero emissions locally, its high gravimetric energy density, the potential for short refueling times, and its potential low life cycle costs (low operational costs and high aircraft availability). In addition, hydrogen can be produced locally. Aviation can build on existing knowledge and experience with hydrogen and FCs in the automotive, truck, and rail industries and their investments and experience with safely handling hydrogen. Globally, the hydrogen market is expanding rapidly, including the production of green hydrogen.

The working group has developed several documents for hydrogen and FCs for aviation. *Hydrogen Fuel Cells Aircraft Fuel Cell Safety Guidelines* (SAE AIR6464/EUROCAE ED-219) was the first document released, in 2013, and provided technical guidance for the safe integration of PEMFC, including risk assessment and flammability considerations, liquid and gaseous hydrogen storage systems, and considerations for crashworthiness, handling, and fueling. The document was reaffirmed in 2020.

Installation of Fuel Cell Systems in Large Civil Aircraft (AS6858/ED-245) focuses on detailed specifications for PEMFCs using gaseous hydrogen for three applications: power supplies for medical equipment, standalone power supplies for galley power, and emergency power supplies in case of loss of electrical power from the aircraft engines.

Considerations for Hydrogen Fuel Cells in Airborne Applications (SAE AIR7765/EUROCAE ER-20) is a comprehensive document for decision makers on hydrogen, its applications and its benefits for aircraft, and it provides information on why and how to use hydrogen and FCs in aviation. This document introduces hydrogen and FCs and their current use in mobile and stationary applications, hazards and mitigation methods, and benefits for airborne applications.

Working group members were invited to support FAA's efforts on the Energy Supply Device Aviation Rulemaking Committee (ESD ARC), and they provided recommendations with respect to airworthiness, standards, and guidelines. While the *Energy Supply Device ARC Recommendation Report* is focused on hydrogen and FCs, other electric drive systems are also addressed. The report was published by the FAA in 2019. The working group is now addressing liquid hydrogen storage and systems and safety requirements for cryogenic liquid hydrogen, and they expect to complete a document for liquid hydrogen by the end of 2021. Workshop participants asked if there were related activities for liquid hydrogen fueling systems. The speaker responded that the liquid hydrogen related efforts do include fueling systems and that they are looking at the whole system, including ground support.

Brian Ehrhart, Sandia National Laboratories
"Hydrogen Safety Codes and Standards"

Sandia's hydrogen program focuses on materials and safety. It provides deep quantitative understanding and a scientific basis for materials for hydrogen production, storage, and utilization as well as risk analysis and work to create risk-informed standards for hydrogen. Existing technologies have established requirements and extensive experience, which allow for prescriptive requirements and performance-based risk assessments. Quantitative risk assessments can be useful for analyzing new systems and applications, but they require an extensive amount of data, which may not be available. In addition, it is difficult to develop risk acceptability criteria. One method is to compare the risk of new systems with those of known systems, for example comparing the risks of a hydrogen refueling station to those for a gasoline refueling station.

Safety is application specific, and different applications have different requirements for safety. For example, an automatic fuel shutoff when a hydrogen leak is detected may be appropriate for a stationary application but would be problematic for an aircraft in mid-flight. The lack of operational data in new environments and for new applications makes risk assessment uncertain. The different operating conditions for different applications, such as vibrations, temperatures, pressures, crash environments, all can play a role.

Sandia's work has included risk assessment and consequence modeling. Examples were provided showing modeling of gas dispersion from a leak with ventilation in a repair garage, jet fire modeling of the effect of a hydrogen leak in a tunnel, and an event tree for hydrogen in a vehicle crash. Sandia has also looked at the feasibility, economics, and safety of hydrogen in maritime applications, performing design studies and hazard area assessments, and economic comparisons of hydrogen FC and diesel-powered vessels.

Session III — UAV Development and Refueling

Doo Soon Lee, CEO
"Doosan Mobility Innovation"

Doo Soon Lee, CEO of Doosan Mobility Innovation (DMI), discussed DMI's efforts to develop hydrogen FC drones and hydrogen FC aircraft for UAM. Endurance is one of the major pain points for drones. DMI's FC drone model DS30 can achieve a flight time of two hours with a 10 lb payload, providing the endurance needed for many applications. The drones currently store hydrogen in a 10.8 L type 4 cylinder that holds ~250 g at 350 bar.

Two demonstrations highlighted the endurance of Doosan's hydrogen FC drones. The first demonstration discussed was emergency delivery between islands in the Virgin Islands. Doosan demonstrated hydrogen FC drone delivery of blood and biological samples across 45 miles of ocean in the Virgin Islands using their hydrogen FC drone in November 2019. The application requires delivery in populated areas, so a low-emissions, low-noise power source is needed. To address this, Doosan used a hydrogen FC multi-copter. The hydrogen-powered drone successfully completed the delivery, covering the 72 km distance between islands and demonstrating the range and endurance of this platform.

Doosan also discussed a demonstration and project in Jeju Province, South Korea. Jeju is a self-governing province with a special interest in renewable energy. The project seeks to establish an emergency supplies delivery system to islands and mountain regions with little access to existing transportation infrastructure. DMI successfully delivered 15,000 face masks to prevent spread of COVID-19 to an island using their delivery drone and delivered an automated external defibrillator (AED) to climbers to prevent cardiac arrest. DMI plans to provide a regular drone emergency delivery service for the Korea Fire Department in the region and to develop a fully autonomous delivery service. DMI plans for commercialization of this delivery platform in 2022.

Another promising application for drones is inspection. A project using FC drones for autonomous inspection and analysis of the solar panels in a 100 MW solar power plant was described. DMI's role included developing a flight mission, developing drones for thermal image mapping of the whole solar farm, and AI analysis. Another application discussed was the use of HFC drones for inspections of powerlines, pipelines, and the like. Long flight times are important for these applications. Projects for inspecting transmission towers and power lines for the Korea Electric Power Research Institute and Korea Gas Corporation with flight distances over seven miles were discussed, with commercialization of drones for these applications planned for a 2021–2022 timeframe.

DMI also discussed their plans for hydrogen FCs for UAMs. The Korea UAM Roadmap has a goal of reducing commuting time and related social costs by 70% and creating a market for UAMs of ~$1.3B. The roadmap calls for setting up the regulatory framework and initiating a pilot project by 2024, with commercialization of initial routes at major base points by 2029 and expansion into urban areas by 2035.

In the United States, DMI's activities are currently focused in Texas, Utah, and Georgia, with expansion into Florida, California, Arizona, and Minnesota planned by 2021, and further expansion in 2022. They believe HFC drones offer a new solution for inspection and surveillance of large-scale infrastructure in the energy sector and for emergency response. For refueling DMI's hydrogen drones,U.S. customers can either have hydrogen cylinders delivered to their site (through ReadyH_2), with the gas supplier collecting and refilling empty drone cylinders or fueling the cylinders themselves from either hydrogen refueling stations installed on their site or from mobile refueling trailers (through IGX).

Phil Robinson, Sr. Director, Engineering: Zero Emissions Aviation, Honeywell Aerospace
"Fuel Cells in Aviation"

Honeywell recently acquired Ballard Unmanned Systems (BUS), a leading UAS FC provider that has been working in hydrogen-powered flight since 2009. Their UAS FC system is liquid cooled to provide an all-weather solution. Combining Ballard's technology with its own activities in aviation components, propulsion, and certification, Honeywell is positioned to deploy hydrogen-powered UAS at scale. Honeywell recently announced a partnership with Ballard, which will help transition Ballard's larger automotive stacks for aviation use. Honeywell is also involved in airport operations, including airport building control, HVAC, and optimized ground control.

Flight duration is the big driver for FC drones. FC drones typically offer three times the flight duration of battery-driven drones, with even larger advantages in cold weather, when battery performance drops. They also provide low operational costs, with ~2,000 hours between overhauls, and silent operation. The longer range/duration is critical for package delivery, infrastructure inspection and defense applications. Honeywell is also excited about the potential for FCs in future large UASs and manned aviation. Thermal management is one of the most difficult aspects to address. The acquisition of BUS offers Honeywell a liquid-cooled system, unlike some other FCs offered for aviation. Honeywell is looking to adapt Ballard's 140 kW stacks and use Honeywell's aerospace BoP components to provide aircraft FC systems for UAM, regional and narrow body aircraft.

For FC applications in aviation to be successful, Dr. Robinson observed that it will be essential to enable the value chain, which includes hydrogen storage (both on the ground and on the aircraft), refueling infrastructure, and safety, including codes and standards. Honeywell has an interest in enabling green airports, not just green aircraft, and an interest in hydrogen combustion and FC technologies for airport building control and HVAC, utilizing their AI technologies to optimize operations and hydrogen consumption. Dr. Robinson was asked about the power density of the Ballard 140 kW stack and replied that it provides 4.7 kW/kg for the stack alone. The goal for the entire FC system is 2 kW/kg, but it will take several years to get there. There was also a question about the applicability of the F38 standard for larger UAM. Dr. Robinson responded that ASTM-F38 was a good starting point, but it is not sufficient.

Chris Dudfield, CTO, Intelligent Energy
"Beyond Batteries: Hydrogen Fuel Cells for UAVs"

Dr. Dudfield provided a brief introduction to Intelligent Energy and its air-cooled FC technology, then discussed FCs for commercial UAVs. FCs offer much faster fueling than batteries, which results in a large increase in operational efficiency over batteries and provides significantly longer flight times, which in turn can enable BLOS operations. Intelligent Energy's FC is a hybrid system with some onboard battery energy storage. Since compressed hydrogen has a higher specific energy density than the LiPo batteries used for drones, the FC system generally provides two to three times the mission duration of a battery system with the same weight. Comparisons of Intelligent Energy's FC systems and pure battery systems were illustrated with two examples: a smaller drone (~1.3 kW average power demand) and a larger drone (~2.4 kW average power demand). For the smaller system, the FC drone provided a typical flight time of 108 minutes, compared to 49 minutes for a battery drone with the same power system mass. For the larger drone, the FC system provided a flight time of 110 minutes compared to 45 minutes for the battery drone. The load cycle for a typical flight for the larger drone was illustrated, outlining the benefits of a hybridized system. The peak power demand was approximately double the average demand of 2.4 kW. The FC can be operated at the 2.4 kW average load, and peak power demand in excess of 2.4 kW can be supplied from the hybrid battery. The hybrid batteries can be recharged in flight. The hybrid battery also offers power system redundancy.

Intelligent Energy's hydrogen UAVs offer quicker refueling than batteries (typically less than two minutes for the hydrogen FC UAV), near silent operation, and built-in system redundancy. These result in increased operational efficiency and reduced total cost of ownership (TCO) and enable drone applications previously impossible with battery UAVs due to range limitations (e.g., BLOS operation). Dudfield presented the example of a power line inspection. Individual power lines need to be inspected every five years and are currently inspected by helicopter. With line-of-sight (LOS) inspection by battery powered drone, costs were estimated at $500 per mile, with an inspection rate of ~100 miles per month per crew with two crews and operators needed to accomplish the task. With BLOS operation, the task can be done with a single operator, and FC downtime is significantly reduced. While capital expense is increased, operational costs decrease to ~$65/mi.

Intelligent Energy's UAV FC products are available in 650 W and 800 W modules, as well as 2.4 kW plug-and-play FC power modules that include all FC stack management and standard interfaces for power and communications. Intelligent Energy FCs have been used in multiple companies' UAV applications, including Meta Vista's UAV, which logged world-record flight times of over 12 hours.

There are challenges for FC UAVs, and a fundamental part of ensuring a commercial FC UAV market is ensuring straightforward access to hydrogen fuel, including breaking through perceptions of hydrogen safety and educating customers on the safety and safe handling of hydrogen. There is not a one-size-fits-all approach for supplying hydrogen to the end user. For a captive fleet, a back-to-base scenario can be used. Alternatively, refueling systems can be portable, or a supplier can provide filled cylinders for the UAV directly to the customer. Hydrogen can enable BLOS operations, which can have significantly reduced costs. Using liquid hydrogen can further increase flight duration. A 6-L liquid hydrogen tank would provide a flight time of ~11 hours, compared to the current two hours for a compressed hydrogen tank.

Tom Jones. Director of UAV/Aerospace Technology, Plug Power
"Fuel Cell/Battery Hybrid Systems for UAV Applications"

Plug Power is a leader in hydrogen and FC technology and was the first to create a market for FC technology with FC forklifts. They will have more than 40,000 FC forklift units deployed as of the end of 2020, making Plug Power, at 35 tons per day, the largest consumer of hydrogen as a transportation fuel. Plug Power has recently expanded into the electrolyzer market and green hydrogen production and hopes to become the largest provider of green hydrogen in the next several years. Plug Power has been active in FCs for UAVs for some 15 years, with several key accomplishments, including achieving a 10-hour endurance flight in 2011, being the first to integrate a FC into a multi-rotor platform and fly it, and developing the first FC eVTOL UAV.

Plug Power offers a modular system for UAVs based on its 300 W EO-310-LE and -XLE FC systems that includes a hydrogen storage tank and a hybrid battery. The EO-310 provides higher energy storage density than a Li battery. For example, to provide 900 Wh, the total power system mass for the EO-310 was slightly less than 3 kg using liquid hydrogen and slightly more than 3 kg using gaseous hydrogen, compared to 6 kg for the Li battery. Doubling the on-board energy to 1800 Wh only slightly increased the mass of the FC system, to about 3 kg using liquid hydrogen and 4 kg using gaseous hydrogen, compared to doubling the mass of the Li battery to 12 kg. Hybridization of a UAV is very important. The load profile of a fixed-wing aircraft was shown to illustrate the large variability in demand over time and the flexibility of a hybrid system, which can take advantage of the high specific energy density for hydrogen FC systems and high specific power density of batteries to optimize the hybrid system for a given duty cycle.

Three different FC architectures and their respective advantages and disadvantages were discussed. First, air-cooled, open-cathode architecture provides a lightweight solution that is simple to operate and easy to scale; however, this architecture is restricted to low altitudes and is susceptible to cathode contamination due to the larger air flow used for cooling (up to 200 times the air flow needed for reaction). Second, liquid-cooled closed-cathode architectures can operate at higher altitudes and at higher ambient temperatures, provide higher cell current densities, and are less susceptible to cathode contamination. These systems are more complex and heavier, requiring air compressors, humidifiers, and large radiators. A third architecture, air-cooled closed-cathode, provides a compromise that has low cathode contamination and allows operation at higher altitudes while eliminating much of the complexity of the liquid-cooled systems. Plug Power offers air-cooled closed-cathode platforms for aviation applications in battery hybrid configurations that offer three to four times the operational endurance of LiPo batteries of the same mass, or six to nine times the endurance of liquid hydrogen storage. These platforms provide reduced logistics and operational costs while providing broader mission capabilities and the ability to power more energy-intensive payloads.

Plug Power's ProGen 1 kW FC UAV was developed for applications with high utilization or that require long endurance and provides zero-emissions and less maintenance than IC engines. Plug Power is developing larger systems, including 30 kW, 125 kW, and larger, including a project for a regional aircraft with 4 MW of FC power. Plug Power sees a significant opportunity to reduce the weight of BoP components to meet aviation application needs.

Joe Uhr, SVP of Operations and Repair, ReadyH$_2$
"ReadyH$_2$—Superior Hydrogen Fuel Solutions"

Hydrogen supply is important to developing the FC UAV market. ReadyH$_2$ provides hydrogen refueling services to the FC UAV market, including supply hydrogen with the new MRXL "micro-refueler" trailer developed by IGX and Doosan Mobility. With the MRXL refueler, ReadyH$_2$ can deliver 350 bar hydrogen to a UAV customer's site and provide ~40 tanks worth of fuel (at two hours of flight time per tank), allowing the customer to focus on flight operations rather than hydrogen supply. The trailer is capable of filling six tanks simultaneously. ReadyH$_2$ personnel are hazardous shipment certified, enabling the company to ship hydrogen-filled DOT-certified UAV tanks to customers nationwide, providing an option for customers with smaller fleets or less demanding mission profiles. However, returning empty tanks to ReadyH$_2$ still poses a challenge.

While MRXL trailer delivery is a good solution for some customers, the trailers still need to be filled with high-purity, high-pressure hydrogen. This can be accomplished from tube trailers, though tube trailer rental overhead costs can be an issue. The MRXL trailer can also be filled via cascade filling from 16 packs of compressed gas cylinders using an onboard compressor. The lack of availability of FC-grade hydrogen and an established hydrogen supply chain restricts wider adoption of FC technology. ReadyH$_2$ is exploring partnerships with higher volume hydrogen users (not producers) for filling ReadyH$_2$ trailers to alleviate supply chain issues. Regulatory differences between cities, counties, and states adds complexity to fuel delivery to customer sites. Federal codes would be helpful. Some local fire marshals have no experience with hydrogen, even in larger cities.

It is important to improve customer knowledge about hydrogen safety. The general public mostly falls in one of two categories: worried/concerned about hydrogen as a fuel for safety reasons and not worried at all due to a lack of knowledge or experience using hydrogen. Both viewpoints can be problematic. Those who are worried will need to be convinced that hydrogen can be handled safely and will need to be trained to do so when appropriate. Those who are not worried will need to be trained to make sure they take the appropriate safety measures to handle hydrogen to avoid accidents when working with it. While drone-handling workers will only be handling, transporting, and storing drone tanks, this still requires training.

Michael Koonce, CEO, IGX Group
"IGX Group H2@Airports"

IGX Group's objective is to develop a profitable hydrogen-centric business supporting FC development. Their main business products include high-pressure hydrogen gas transports, zero emissions FC mobile generators, hydrogen refueling services, and cylinder testing and retrofitting. IGX has hydrogen tankers in sizes up to semi-trailer tanker and currently offers ~400 kg 20 ft hydrogen storage containers. IGX also offers zero-emission generators through their H_2Pwr products, which replace diesel generators and provide FC power to U.S. Customs and Border Protection surveillance towers, DOD for surveillance systems, and others. IGX's hydrogen refueling services started with high-pressure hydrogen fueling services for the cell-tower industry and expanded to include delivery for UAV applications. They have four service centers and a fleet of delivery vehicles for supplying hydrogen for cell towers, fiber-optic networks, DOE projects for Class 8 trucks, and for the Scripps Institution of Oceanography hydrogen-powered research vessel project. It was noted that FC-powered generators for cell towers continued to operate during recent forest fires in California, while diesel powered ones did not.

Hydrogen fueling and support are essential for a successful hydrogen UAV program. A dependable hydrogen supply, hydrogen storage, and hydrogen refueling infrastructure are needed. IGX is planning to expand to 25 hubs across the country by 2023 to provide the needed support, with eight hubs planned by 2021.

The NorAm technical group is affiliated with IGX. NorAm manufactures high-pressure lightweight hydrogen cylinders and is developing low-cost 1.5 to 9-L cylinders for UAV applications. NorAm also produces valves and regulators for reducing pressure from 6,000 inlet to 0-20 psig outlet. IGX produces 5.6 kg capacity and 13.4 kg capacity micro-refuelers to allow on-site refueling of UAV tanks. All the refuelers have an electric booster pump to allow refilling at pressure up to 6,000 psig. The refuelers operate using the J2601 refueling protocol.

Session IV — Electric Aircraft Development

Amanda Simpson, Vice President Research and Technology, Airbus Americas
"Clean Commercial Aircraft ZEROe—Powered by Hydrogen"

Airbus's current generation of aircraft provides a 25% reduction in CO_2 emissions compared to previous models. However, Airbus believes reducing emissions will not be enough to reach climate goals without zero emissions aircraft. Airbus's goal is to bring the first zero emissions commercial aircraft to market by 2035. They believe hydrogen can provide clean energy on board the aircraft and are pursuing three concepts demonstrating hydrogen for aviation: a turboprop concept, a turbofan concept, and a blended-wing body concept.

The turboprop concept is being considered for aircraft that are carrying fewer than 100 passengers and have a range of more than 1,000 nautical miles (NM). The engines for this concept are hybrid turboprop engines fueled by hydrogen combustion, with the liquid hydrogen being stored on board behind the bulkhead. The turbofan concept and blended-wing body concepts are being considered for aircraft with more than 200 passengers and a range greater than 2,000 NM. Propulsion comes from hybrid turbofan engines powered by hydrogen combustion. Electric engines and FCs will be considered for supplementing the turbo engines and providing galley power. Liquid hydrogen storage is being pursued for these aircraft. For the turbofan concept, designs with hydrogen storage behind the rear bulkhead are being considered, while for the blended-wing body aircraft designs, hydrogen storage below the wings is being considered.

Airbus hopes to mature all the hydrogen systems and technology by 2024–2025, enabling hydrogen-powered aircraft to be commercially available by 2035. Airports need to start the decarbonization process now to be ready for 2035 commercialization. Airbus is pursuing lightweight FCs of all types and lightweight liquid hydrogen fuel tanks. Airbus will also look at storing compressed air or oxygen on board.

Airbus was asked about the aircraft range they see being a good fit for hydrogen and Ms Simpson replied that for now they are looking at hydrogen for smaller aircraft carrying 200 passengers or fewer. Airbus believes that larger and longer-range aircraft (>2,000 NM) will still be using kerosene or synthetic (renewable) jet fuels in 2035. Airbus was also asked whether they plan to use sub-scale systems. She replied that they are using sub-scale systems, but they hope to have full-scale systems by 2025.

Sean Newsum, Director Environmental Sustainability Strategy, Boeing
"Renewable Energy and Hydrogen in Commercial Aviation"

In collaboration with Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO), Boeing is studying opportunities for hydrogen in aviation. Three opportunities are being considered: hydrogen at or adjacent to the airport for GSE and mobility to and from the airport, green hydrogen for producing sustainable fuels that use the existing infrastructure, and an emerging infrastructure to support hydrogen for both propulsion and non-propulsion applications. In particular, applications that use hydrogen at or adjacent to the airport can provide a significant scale for hydrogen use, with a lower risk profile that can use "off-the-shelf" commercial technologies such as FC forklifts, cars, buses, and stationary FC products. These applications can create a starting point from which to develop and utilize hydrogen infrastructure. In some cases, this development has started, as there are multiple public refueling stations operating at airports such as LAX, Tokyo, and Gatwick.

Boeing looks at hydrogen for propulsion in three ways: for use in FCs, to augment fuels for combustion, and for combustion. Boeing believes hydrogen and FCs are limited to shorter flights with smaller planes carrying fewer than 100 passengers. They believe that for longer flights and larger aircraft, hydrogen is best suited augmenting other fuels, such as ammonia or methanol, or direct hydrogen combustion. Boeing and CSIRO believe that it is unlikely there will be a significant penetration of hydrogen in aviation before 2050. The Air Transport Action Group (ATAG) Waypoint study concludes that it is difficult to see applicability for hydrogen and electric propulsion for the medium-haul and long-haul markets that account for ~70% of industry CO_2 emissions. Hydrogen as a fuel by itself cannot make substantial contributions; we need to develop sustainable aviation fuels (with higher volumetric energy density).

Boeing's path to 2050 includes airline fleet replacement, improving network operational efficiency, and a transition to renewable energy and future airplane technology. Green hydrogen can contribute in many ways; however, Boeing believes we need to scale up sustainable aviation fuels (synthetic jet fuel, methanol, ammonia) and future airplane technology to get there. Finally, Boeing pointed out that to address climate change, we need system strategies, not just airplane strategies.

Val Miftakhov, CEO, ZeroAvia
"ZeroAvia—The First Practical Zero Emission Aviation Powertrain"

Climate change is a real problem, and aviation is a significant contributor to climate change, contributing 5–10% of total human climate impact today, with its impact expected to increase to 25–50% by 2050. The impacts from aviation are not solely due to CO_2. While other sectors are beginning to address climate change and are reducing their impact, there are not truly scalable solutions available today for the $1.5 trillion aviation market.

Options to reduce aviation's climate impact are limited. Battery electric options provide 1/40th the energy density of jet fuel, and battery specific energy (kWh/kg) will need to more than quintuple to start to be relevant in aviation. Biofuels lack the scalability needed to provide enough fuel to serve the aviation market. Synthetic fuels can be scaled to appropriate volumes; however, there are significant challenges with the high cost of the fuel since green hydrogen is required, and combustion engines provide lower efficiencies than electric options. Hydrogen offers three times the specific energy of jet fuel, and hydrogen can be combusted for use in turbine engines. While use of hydrogen in turbine engines provides good power density, it also results in lower efficiency than hydrogen FC options while still producing NOx emissions.

ZeroAvia believes hydrogen electric propulsion has advantages over all other alternative propulsion types. Momentum for hydrogen for aviation is accelerating, and many entities, including the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and Airbus, support hydrogen for the future of aviation and see hydrogen as having no blockers and fixable secondary issues. Hydrogen offers true zero emissions that can credibly be scaled to 100+ seat aircraft within 10 to 15 years.

ZeroAvia has built and demonstrated a Piper 6-seat prototype to prove the hydrogen FC powertrain design. The first flight took place on Sept. 24, 2020, with more than 10 flights since then. ZeroAvia is working on optimizing the aircraft for a 300-mi flight scheduled to take place at the end of 2020. As a first step towards commercialization, ZeroAvia has designed the ZA-600, a 19-seat aircraft with a 500-mi range and plans to have the plane certified for commercial operation by 2023. After the 19-seat plane, they plan to develop a

50–100-seat plane and UAMs by 2027, a 100–200-seat plane with a range of 3,000 NM by 2030, and a 200+-seat plane with a range of 5000 NM by 2040.

Current hydrogen prices are adversely affected by high transportation costs, so the best approach will likely be to produce hydrogen at or near the airport. Demand from an airport will be high enough that it would make economic sense. Projections for future hydrogen production costs suggest that with distributed production, hydrogen could beat jet fuel at a cost of $2.50/kg. which would be equivalent to jet fuel at $1.50/gal. ZeroAvia is working on a hydrogen airport refueling ecosystem (HARE) consisting of on-site electrolysis, storage, mobile airport refueling, and support for refueling for multi-modal transport.

The attendees asked ZeroAvia what hydrogen storage options they are considering and whether they were planning to store oxygen on board the aircraft. Mr. Miftakhov stated ZeroAvia is not planning on storing oxygen on board, and that it is starting with compressed hydrogen storage but then plan to move to liquid hydrogen storage. ZeroAvia was also asked if they plan on entering the eVTOL market, and Mr. Miftakhov stated that potentially they will do that as well.

Bruce Holmes, Chief Technical Officer, Alaka'i Technologies
"eVTOL Air Vehicles—The Killer App" for Hydrogen?"

Alaka'i has developed *Skai*, the first hydrogen FC-powered eVTOL air vehicle for urban air mobility, which uses Alaka'i's advanced air mobility (AAM) system, and which focuses on reliability and simplicity.

Dr. Holmes stated that we are all on the same journey to hydrogen solutions, even those pursuing batteries; we are just at different points on the path. He noted that the aviation industry took a long time to align on current plane designs, and that he sees the same thing happening when it comes to transitioning to hydrogen. Hydrogen and FCs have key technology differentiators that offer advantages over batteries for eVTOLs, including increased range and payload, higher mission flexibility, lower lifecycle costs, and much shorter refueling times. Hydrogen offers 8 to 12 times the flight distance and duration that Li-ion battery technology does.

Hydrogen supply is a key issue. Alaka'i's near-term plans for flight testing and certification are to purchase liquid hydrogen from commercial suppliers, store it in local hydrogen storage tanks, and use mobile storage tanks and refuelers to refuel their aircraft. The long-term plan is to have liquid hydrogen generated onsite with both liquid hydrogen and gaseous hydrogen storage. Fueling would use automated fuel dispensers that provide a personal protective equipment- (PPE-) free refueling capability. They believe air portals providing fuel for air vehicles could also provide fuel for land vehicles and act as a hydrogen hub.

Alaka'i believes the technology for hydrogen FC multi-copters is at a technology readiness level (TRL) of 4, and, at this level, one can predict the costs within +/- 30% of the cost when commercialized (TRL 9). Dr. Holmes observed that pre-competitive collaboration between public and private sectors is needed to accelerate development to commercialization and share the risks. Public-private partnerships should be able to reduce development time by as much as 50%. As an example of the benefits of public-private partnerships, Dr. Holmes cited the turbine industry, which greatly benefitted from physics-based modeling efforts. Hydrogen FC R&D needs that could benefit from a private–public partnership include electrochemical physics-based modeling of FCs, improved stack efficiencies, BoP optimization, improved bipolar plate materials, life cycle modeling and testing, liquid hydrogen crash dynamics and design, development of PPE-free refueling system, and better gaseous hydrogen and liquid hydrogen storage systems.

W. Kyle Heironimus, Head of Powertrain, Hyundai Motor Group, Urban Air Mobility Division
"Electric Aircraft Development"

Hyundai believes that aircraft should be safe, quiet, affordable, and passenger-centered (i.e., green), which fundamentally aligns well with hydrogen FC technology. Hyundai has a long history in the development of FC technology for cars, beginning in 1998.

Batteries can enable eVTOLs to carry a higher payload for some short-range applications, but FCs can make possible heavier payloads over much longer distances. FCs also offer a higher operational tempo and higher utilization than batteries due to their longer range and their ability to be refueled much faster than batteries can be recharged.

However, there are challenges for hydrogen and FC technologies in eVTOL applications. While hydrogen provides higher gravimetric energy storage than batteries, hydrogen storage is a challenge. Current compressed hydrogen storage tanks in cars have a 1:20 fuel-to-tank weight ratio. Liquid hydrogen could provide higher hydrogen content; however, there are operational challenges with cryogenic liquid storage and handling. Hydrogen storage materials would be desirable, but current systems do not provide the gravimetric density of compressed or liquid hydrogen. Thermal management is also an issue. Heat rejection for a PEMFC is much more difficult than for an ICE due to the low operating temperature of the PEMFC. For eVTOL operation, the highest heat load occurs when there is zero horizontal velocity (e.g., conditions in which there is low air flow over cooling surfaces), which exacerbates thermal management issues. Requirements for batteries for FC hybrid electric aircraft are not inherently aligned with car battery technology. FC electric aircraft require large battery systems to provide power in case of emergencies. Batteries for aviation will require higher specific power than batteries for BEVs. Industrial innovation is needed to overcome these technical challenges.

Finally, FC propulsion systems are not covered in current FAA certifications, and there are gaps in codes and standards. This presents an opportunity for industry collaboration to define a safe and effective framework for FC certification for aviation.

Session V — Hydrogen Aviation Research and Assessments

***Grigorii Soloveichik**, Program Director at the U.S. Department of Energy Advanced Research Projects Agency-Energy (ARPA-E)*

"Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEAC)"

Today's air travel is dominated by intra-regional routes in the 1,500–2,000 km range with narrow-body single- and twin-aisle planes being the primary carriers. Aviation traffic is projected to triple or quadruple by 2050, causing CO_2 emissions within the industry to triple (ICAO estimate). Replacing fossil-based jet fuels with renewable fuels, such as bio jet fuel, is not considered to be economically viable. Other renewable liquid fuels could be viable options, but their lower energy densities will require higher conversion efficiencies.

Electrification of airplanes will be critical to reducing carbon emissions. The National Aeronautics and Space Administration (NASA) projects that a fully electric aircraft will require a specific energy density of at least 1,000 Wh/kg. In theory, batteries could meet the target; however, 500 Wh/kg seems to be the practical limit, and there are additional challenges associated with charging times and the infrastructure required for charging that need to be addressed. One approach to electrification is a hybrid system that uses a direct liquid FC.

The U.S. Department of Energy Advanced Research Projects Agency-Energy (ARPA-E) has two complementary programs to develop hybrid system propulsion technologies for commercial aircrafts that decrease energy usage and the associated carbon emissions: Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives (ASCEND) and Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH). ASCEND focuses on the all-electric powertrain targeting decreasing the weight of the propulsion system and enabling distributed propulsion. REEACH focuses on developing highly efficient energy storage and power generation systems that use energy-dense renewable liquid fuels to provide the targeted flight range and payload.

The REEACH program objectives are to develop high-efficiency hybrid energy storage and power generation (ESPG) systems that use energy-dense renewable liquid fuels and integrate the fuel conversion device with a high-power device (e.g., a battery) to support takeoff and climb. The programmatic metrics for REEACH are defined to provide the range and required takeoff energy and to be cost-competitive with current jet technology. The fuel is to be a carbon neutral renewable liquid fuel. The fuel cost per delivered power is <\$0.15/kWh. The system energy density is >3000 kWh/kg to provide range, and the power density, including fuel, is >0.75 kW/kg is to assure takeoff. The system cost is <\$1000/kW for cost parity with incumbent jet technology. The deliverables are to demonstrate at least a 5 kW takeoff and 1.75 kW cruise ESPG FC breadboard system and at least 100 kW takeoff and 35 KW cruise ESPG combustion engine breadboard system to be tested at conditions simulating flight.

Phillip Ansell, Assistant Professor of Aerospace Engineering, University of Illinois at Urbana-Champaign
"*Hydrogen-Electric Transport Aircraft System Technologies*"

This presentation provided an overview of the Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA), which is a multi-disciplinary consortium established in 2019 consisting of experts in aeronautics, electrical systems, and material science from seven universities and two industrial groups funded under the NASA University Leadership Initiative (ULI) Program. Funding for the project is $6 million. Its goal is to develop, mature, and design disruptive technologies for electrical commercial aviation. It addresses several implementation challenges for electrifying aircraft using hydrogen related to components, energy storage, and aircraft design/configuration. Research areas include distributed propulsion and high-efficiency electrical power conversion, high-power, flight-weight cryogenic electric machines and power electronics, materials and systems for superconducting high-power transmission and large current density, and integration and optimization of unconventional and complex aircraft systems. One of the key technology development areas is a liquid hydrogen superconducting power system to reduce ohmic losses, reduce transmission voltage, and yield smaller, lightweight conductors. In this design, hydrogen serves a dual purpose as an energy carrier (fuel) and as a cryogen for the superconducting system.

Dr. Rajesh Ahluwalia, Manager, Fuel Cell and Hydrogen, Argonne National Laboratory
"*Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Aviation – Preliminary Results*"

This presentation compared the total cost of ownership (TCO) for conceptual hydrogen-fueled, FC-powered aircraft to incumbent battery or piston engine technology for four aviation applications: unmanned air vehicles (UAVs), urban air mobility (UAM) air taxis, UAM-helicopters, and regional airplanes. The objective of the study was to identify performance and cost attributes for hydrogen and FC to be competitive with the current technology and to develop performance metrics for DOE technical targets for promising applications.

TCO case studies were developed for both multi-rotor hexa-copters and fixed-wing UAVs. For the multi-rotor hexa-copter, the case study compared FC and battery-powered UAVs for aerial inspection of a gas drilling area. The study found that the FC system provided a cost savings of $18 per hour of operation over the battery system. Despite higher fuel costs and higher replacement costs for the FC, the FC system was able to reduce the number of UAVs required by 25%, which reduced the capital expense and reduced the labor costs by $46/h. The TCO was found to be most sensitive to the FC system cost, the battery and FC lifetime, and the non-productive time cost. For the fixed-wing UAV, the TCO case study compared FC-, battery-, and piston engine-powered fixed-wing UAVs for the same application. The study found that the FC system provided a $88/h savings compared to the battery-powered system, because of the smaller fleet size and smaller number of operators required, and a $43/h savings compared to the piston engine, due to lower costs associated with replacing the FC system over the aircraft's lifetime and the longer lifetime of the FC system.

For UAM, the study compared three aircraft: 1) a multi-rotor FC dominant (FCD) system, consisting of a 358 kW FC and a 4.9 kWh battery, and 2) a tilt-rotor FC hybrid (FCH), consisting of a 129 kW FC and a 35.5 kWh battery, both designed to match the payload, range, and maximum cruise speed of 3) a battery-powered tilt-rotor urban air taxi. The capital cost for the tilt-rotor FCH ($554,000) was more than $100,000 less than the cost for the multi-rotor FCD ($655,000) or tilt-rotor battery ($659,000), with the airframe being the highest cost item for all three aircraft. Operating costs were similar for the multi-rotor FCD ($127/h) and tilt-rotor FCH ($122/h) and about $50/h lower than the operating cost for the tilt-rotor battery

($147/h) due to the lower lifetime replacement cost of the FC system compared to the battery system. The tilt-rotor FCH had the lowest TCO ($0.63/PAX-mi) compared to the multi-rotor FCD ($0.79/PAX-mi) and the tilt-rotor battery ($0.99/PAX-mi), with operating and maintenance cost being the biggest cost factor for all three aircraft. While the study found that FCs can offer performance and cost savings over batteries for urban air taxis, it was recommended that additional studies should consider the impact of the liquid hydrogen refueling and battery recharging infrastructures on the TCOs.

The UAM study also compared FC and battery air taxi platforms that could match the payload and maximum cruise speed of the Robinson R44 Raven II, a commercial helicopter. Three FC systems and one battery system were analyzed: (1) a multi-rotor FC system consisting of a 426 kW FC, (2) a multi-rotor FCD system consisting of a 268 kW FC and a 12 kWh battery, (3) a tilt-rotor FCH system consisting of a 95 kW FC and a 39 kWh battery, and (4) a tilt-rotor battery system consisting of a 101 kWh battery. The Robinson R44 has a 184 kW engine. The capital costs for the tilt-rotor FCH system ($478,000) and the tilt-rotor battery system ($522,000) were similar to the cost of the Robinson R44 ($506,000), with the multi-rotor FCD system ($573,000) and multi-rotor FC system ($643,000) being considerably higher. The higher costs for the multi-rotor FCD system and multi-rotor FC systems were attributed to the higher maximum take-off weight. The operating costs for the three FC systems—the tilt-rotor FCH system ($87/h), multi-rotor FCD system ($112/h) and multi-rotor FC system ($135/h)—were less than the tilt-rotor battery system ($142/h) and the Robinson R44 ($163/h). The lower operating cost of the FC systems was attributed to the lower lifetime replacement cost of the FCs compared to the battery or engine. The study concluded that the tilt-rotor FCH system could match the range of the Robinson R44.

For the regional plane study, a liquid hydrogen-fueled PEMFC system replaced the aviation gasoline fueled 6-cylinder piston engine in a 4-seat regional plane. The study found that a FC system rated at 186 kW with a liquid hydrogen tank capacity of 32 kg satisfied the mission requirements. The capital cost of the FC plane ($343,000) was $17,000 less than that of the piston plane ($360,000) due to the lower cost of the FC compared to the piston engine. The operating cost of the FC plane ($82/h) was $14/h less than the piston plane ($96/h) due to the longer lifetime of the FC system compared to the piston engine. The TCO of the FC plane ($204/h) was found to be $48/h lower than the piston plane ($252/h) with the capital cost exceeding both the operating and maintenance and fuel costs for both planes.

In summary, the study showed that FCs are promising candidates for deployment in commercial UAVs for the four case studies. FCs provided a longer lifetime and lower maintenance costs than piston engines and longer endurance and smaller fleet sizes than batteries to meet mission requirements. FCs are suitable for urban air taxis, providing the advantage of higher specific power and longer durability over batteries. FCs are competitive with piston engine helicopters in UAM settings and piston engine planes in the regional market.

Session VI — Airport Ground Equipment Perspectives

Joe Blanchard, Plug Power
"*Fuel Cells for Ground Support Equipment***"**

The ground support equipment (GSE) market, including both powered and non-powered systems, is \$20–\$25 billion. GSE operators are facing significant regulatory pressure to reduce emissions and are looking for sustainable solutions, which presents an attractive opportunity for electrifying GSE using hydrogen and FC technologies. The GSE market is considered "low-hanging fruit" for FCs because the power requirements for many types of GSE are similar to the power requirements of material handling equipment (MHE), where FCs have become the dominant power system. The FC infrastructure scales very economically from 100 to 1,000 vehicles, whereas the charging infrastructure for batteries does not. Fast recharging of batteries to compete with fast hydrogen refueling is expensive to install and more costly to operate, and the electrical infrastructure to support charging batteries at the MW scale is expensive and difficult to install. GSE is also attractive for FCs since the equipment never leaves the airport, which simplifies the refueling infrastructure. An overview of demonstrations of FC GSE, including FC-powered tugs at the Memphis and Albany airports in the United States and at the Hamburg airport in Germany, was presented. In all cases, the FC-powered tugs provided exceptional performance even in cold weather.

Abas Goodarzi, President and Chief Executive Officer, US Hybrid
"*US Hybrid***"**

This presentation provided an overview of US Hybrid, which was founded in 1999. The company originally produced balance-of-plant (BoP) systems to support FC stack manufacturers. In 2013, US Hybrid purchased UTC's PEMFC manufacturing business and began producing FC power plants. US Hybrid has been involved in a dozen hydrogen FC vehicle or ground equipment demonstrations, including Air Force logistics vehicles, street sweepers, and drayage trucks. Key to US Hybrid products is their strategy of making FC equipment 100% transparent to the operator, so that the operator has no knowledge of whether the equipment is FC, battery, or diesel-powered: Its operating characteristics are identical to previous technologies. Operators appreciate the smooth operation of a FC-powered vehicle and its lack of noise compared to diesel technology.

Robert Hess, Systems Engineering Manager, Controls & Avionics Solutions, BAE Systems
"*BAE Systems***"**

BAE Systems is well known for its aerospace defense systems but is less known for its electric vehicle propulsion systems. As a systems integrator, it does not develop FCs or hydrogen storage systems but integrates them into electric powertrains, such as its Series H-FC electric propulsion system. Despite their benefits as zero-emissions technologies, hydrogen and FCs face many challenges. Hydrogen generation, delivery, storage, and use are key challenges, and codes and standards, safety protocols, and training are needed. Integrating FCs with other electrification technologies in aviation is an opportunity. Hydrogen-FCs can support recharging battery-electric aircraft where charging the batteries requires MW scale charging capacity. One of the challenges is delivering energy to small airports in remote locations where the cost to build an electrical grid or hydrogen infrastructure to support operations is impractical. A key is to develop an understanding of how we can do more with electric vehicles, including supporting multiple use cases, but this requires an understanding of the operational requirements.

Ryan Sookhoo, Director New Initiatives, Cummins
"*Powering Change—Cummins in GSE*"

While Cummins is a major supplier of traditional power systems in the GSE market, providing more than 3,000 diesel engines per year, it sees a growing demand for sustainable power systems that reduce GHG emissions. Cummins views future powertrain development as a "rainbow effect" as it transitions from diesel to natural gas then to hybrid electric followed by battery electric and finally FCs. FCs are viewed as having the advantages of both batteries and ICEs. Like batteries, FCs provide zero emissions, a quiet drive, high efficiency, and low maintenance, and they can utilize renewable energy. Like ICEs, FCs provide extended runtime, fast fueling, and route flexibility. Both PEMFC and SOFC technologies, as well as hydrogen production technologies, will be important elements in the Cummins product portfolio. Cummins views cargo tractors, trucks, air start units, preconditioned air, buses, and ground power units, as GSE's potential early adopters for hydrogen.

Session VII — Airport Ground Transportation Perspectives

Joel Donham, P.E., Leading Engineering Consultant, Center for Transportation and the Environment
"Role of Non-Profits in H_2@Airports"

Not-for-profit organizations like the Center for Transportation and the Environment (CTE) fill the gaps between airport operators, technology developers, and government for deploying new technologies by providing education and outreach, coordinating prototyping and demonstration, supporting deployment, and strategic planning. Currently, CTE's project portfolio includes 90 active zero emissions projects totaling over $316 million.

Education and outreach efforts focus on coordinating players in the hydrogen transportation industry to exchange best practices, grow market volume to achieve economies of scale, and foster regional coordination to develop efficient local hydrogen economies. In 2018, CTE successfully advocated for the expansion of several FAA programs that support airport zero emissions vehicles. FAA's Voluntary Airport Low Emissions (VALE) grant program was expanded to provide funding for zero-emission vehicles at all airports, not just those that operate in non-attainment areas, as well as vehicles that operate off airport property, such as remote parking shuttles. Coordinating prototyping and demonstrations involves identifying applications for new technologies, conceptualizing relevant projects, securing funding, assembling the right team to execute the project, and providing technical oversight, coordination, and administration. Deployment support focuses on operation planning, such as duty cycles and fuel specifications, procurement and build support, and operations support, including monitoring operations and identifying opportunities to improve usability, reduce costs, and minimize risk.

Rob Lamb, Vice President Sales/Marketing, Charlatte America
"Charlatte America"

Charlatte America is part of the Fayat Group, a family-owned company headquartered in Bordeaux, France. Charlatte is the leading manufacturer of airport ground support equipment, including electric tractors and belt loaders, with more than 25,000 electric vehicles worldwide. The surge in electric ground support vehicles started in Europe. While battery technology is currently being employed for electrification, there are many challenges. Lead acid batteries are affordable, but prone to spills. Lithium ion batteries are twice as expensive as lead acid batteries, with prices ranging about $22–$25,000 for batteries for tugs capable of carrying 40,000 lbs. Battery charging generally takes overnight. Even with rapid charging, it still takes two to three hours to charge a battery. Consequently, airlines and ground handling companies have historically purchased twice the number of vehicles needed to allow for charging times. Hydrogen is a good solution for the market, but there are obstacles, including large upfront and infrastructure costs and unfamiliarity with the technology.

William Kelly, Jr., COO/CTO, Lightning eMotors
"Lightning eMotors"

Lightning eMotors provides complete electrification solutions for urban commercial fleets, including Class 3–7 trucks and buses, as well as selling powertrains to strategic partners and offering a complete range of charging solutions. Lightning eMotors has expanded its interest to FCEVs through a partnership with Plug

Power. Battery and FC hybrid systems can take advantage of the electrified propulsion systems and accessories already in place. A traction battery can respond to dynamic responses and enable the FC to operate at a base load, which improves durability. The battery can also provide power for movement over short distances for refueling or maintenance of the FC. FCs provide benefits such as a longer operating range and higher payloads. FCs also provide a favorable total cost of ownership for longer operating ranges, with the breakeven point for FCEVs compared to battery electric vehicles being a range of about 160 miles. To accelerate the deployment of FCEVs, original equipment manufacturers (OEMs) need to utilize battery electric platforms already in production.

Lauren Skiver, Chief Executive Officer, General Manager, SunLine Transit Agency
"Hydrogen Opportunities at Airports"

SunLine Transit Agency serves the Coachella Valley in California, a service area covering about 1,100 square miles. SunLine's fleet consists of 60 compressed natural gas (CNG) buses, 17 FC buses, 4 FC shuttle buses, and 39 CNG paratransit vehicles that provide service on 14 routes. They are in the process of ordering five additional FC buses, using funds from the Volkswagen Diesel Emissions Mitigation Settlement. Hydrogen is currently produced on site by electrolysis, with a production capacity of 900 kg per day. Hydrogen is dispensed using two dispensers with fast fill rates. SunLine is investigating expanding its hydrogen fueling system, including the use of a solar farm microgrid adjacent to its facility to reduce its "well to wheel" (WTW) emissions.

SunLine Transit's long-range plan includes replacement of all ICE buses with zero-emission buses, and the construction and upgrading of the supporting fueling infrastructure. Regulations will require SunLine to purchase 25% zero-emission buses starting in 2026 and 100% new zero-emission buses in 2029. The long-range plan must identify potential funding sources, describe the impact on disadvantaged communities, and describe the training plan. SunLine's Center of Excellence provides training for its workforce and is available for providing training to other organizations.

Kirt Conrad, Chief Executive Officer, Executive Director/Chief Executive Officer, Stark Area Regional Transportation Authority (SARTA)
"Hydrogen Fuel Cell Buses at SARTA"

The Stark Area Regional Transportation Authority (SARTA) serves the combined greater metropolitan areas of Akron and Canton, Ohio. SARTA transports 2.8 million passengers annually over a transportation network that includes 34 fixed routes and county paratransit routes, plus express routes to Akron and Cleveland. SARTA's annual operating budget totals $23 million, and it employs more than 200 people.

SARTA's transit bus fleet includes 12 40-ft FC transit buses and 5 FC vans, the largest fleet of FC buses outside of California. SARTA acquired these buses as part of the Federal Transit Administration National Fuel Cell Bus Program. These buses are in daily service, and SARTA provides operating data and statistics to the National Renewable Energy Laboratory for reports as required by the National Fuel Cell Bus Program. The driving range of the SARTA FC buses averages about 220 miles. The transit buses can be filled in 15 minutes at an on-site hydrogen station. The fuel economy of the FC transit bus fleet averages about 7 mpg, compared with 4 mpg for the diesel buses in SARTA's fleet.

Session VIII — Refueling System Developer Perspectives

Dave Edwards, Director, Air Liquide Hydrogen Energy U.S. LLC
"Hydrogen Energy at the Heart of the Energy Transition"

Air Liquide has been a leader in the development of hydrogen production and distribution for nearly 50 years. Worldwide, Air Liquide produces 14 billion m^3 of hydrogen annually, operates 1,850 km of hydrogen pipelines, and has 40 electrolyzers in operation. While today's hydrogen production and distribution infrastructure are significant, the current hydrogen infrastructure was built around hydrogen as a molecule for use in the chemical and petroleum industries and not as a transportation fuel.

Supplying hydrogen to airports is a challenge because of the large amount of hydrogen required to meet the demand of current ground operations. Hydrogen is already being produced industrially at a scale that would satisfy airport demand. The ground vehicles that would use hydrogen have been demonstrated in a limited number of applications or are under development. Dispensing hydrogen would leverage existing technologies being deployed for light- and heavy-duty vehicles. Key to addressing the R&D needs is to learn from the current hydrogen infrastructure but to understand the unique needs of the new technologies.

To provide a better understanding of what an airport hydrogen ground fuel infrastructure would look like, an analysis of the hydrogen demand and supply to replace the diesel consumed by ground operations at LAX was presented. Replacing the 25 million gallons of diesel consumed annually would require 35 tonnes per day (tpd) of hydrogen, which is roughly one-eighth the amount of hydrogen produced daily by a world-class steam methane reforming (SMR) plant. Eight trailers would be required to deliver 35 tpd of liquid hydrogen, while approximately 70 trailers would be required to deliver the same amount as gaseous hydrogen. While eight deliveries per day may be feasible, 70 deliveries may not be logistically possible. To provide an uninterrupted supply of hydrogen would require storing 70–100 tons of hydrogen on site, equivalent to two to three days' supply. Storing this amount of hydrogen as liquid hydrogen in spherical storage units would be feasible; however, storing this amount as gaseous hydrogen in high-pressure cylinders is not. A hydrogen pipeline would be the best option for providing storage backup.

Al Burgunder, Director, Clean Hydrogen, Linde Gases US
"*H2@Airports*"

Linde is North America's largest supplier of industrial hydrogen, with production facilities located across the United States. It is capable of providing liquid hydrogen to most of theUnited States, except for the Pacific Northwest. Linde has a 10-year plan to reduce its GHG emissions intensity across its entire gas product portfolio by 35% by 2028. Linde is investing $1 billion to support the development of new decarbonization initiatives, including producing green hydrogen for mobility, power, renewable fuels, and industrial products using renewable electricity. Linde is developing new hydrogen fueling technologies, including a cryopump for liquid hydrogen and an ionic compressor for gaseous hydrogen. Linde views on-site production of hydrogen either by low-carbon SMR or electrolysis as one option for providing hydrogen to airports. However, off-site production with delivery via underground pipelines is considered the optimal method for delivering and distributing hydrogen at airports.

Conclusions

Airports are facing significant regulatory pressure to reduce emissions. Hydrogen can play a key role in reducing airport emissions both on the ground and in the air. Given their large energy demand, airports can act as hydrogen hubs, building demand by utilizing hydrogen to the maximum extent possible in all airport systems, which will serve to develop the hydrogen market and attract private investment. However, supplying and storing the quantity of hydrogen a large airport would need is a challenge. The hydrogen infrastructure is not developed, and the cost of installing the infrastructure is challenging, given that aviation and diesel fuels are currently cheaper than hydrogen. Zoning issues are another barrier, and codes and standards that serve as a guidebook for setting up hydrogen fueling stations at airports are needed.

Initial applications for hydrogen and fuel cell technologies are likely to be ground-based applications, with transit buses, shuttle buses, and rental car facilities being a good place to start to increase awareness for hydrogen and fuel cells. Forklifts at warehouse distribution centers located on or adjacent to airport properties and ground support equipment, such as baggage tractors and deck loaders, can be deployed in the near term. Distribution of hydrogen across the airport is a key issue. Participants observed that it is also critical to develop codes and standards specifically for airports and to educate and train airline and airport support management and workers on the use and safe handling and storage of hydrogen.

Hydrogen can reduce emissions in the air and enable new aviation markets. Drones/UAVs are promising near term applications with relatively low entry costs, proven business cases, and advantages over battery technology, such as larger payloads, more uptime, longer mission duration, and better durability. Scaling hydrogen and fuel cell equipment down to the smaller footprint of UAVs and regulations and standards, particularly those focusing on beyond visual line of sight operations and airspace usage, are challenges for UAVs. For UAVs, UAM and small fixed-wing planes, R&D is needed to reduce the weight of FC systems and improve designs to align with aeronautic conditions (lower temperature and air pressure at elevation, etc.). Hydrogen storage is another major challenge that needs to be overcome. Liquid hydrogen appears to be the best option from a cost perspective, but lighter weight liquid hydrogen storage tanks are needed, and liquid hydrogen supply, refueling infrastructure, and handling and safety are concerns.

Attendees indicated that government funding for demonstrations and pilots of pre-commercial products under “real world” operating conditions are important to prove that the technology is cost effective and safe. The stringent reliability requirements for manned/passenger flight systems make it difficult to bring new propulsion technologies into this market, and data on UAV system reliability will help. Demonstrations of fuel cells in transit bus, shuttle bus, and rental car fleets at airports, which are areas of high visibility and public use, could be a good place to start to increase awareness for hydrogen and fuel cells as well as collect data. Attendees also saw R&D on lightweighting, fuel cell operation at altitude and liquid hydrogen production, storage, and dispensing systems, including robotic systems, as areas in need of government support. Attendees commented that safety, codes and standards, and permitting are also areas where government funding is needed. Attendees further added that funding is also needed to develop a standardized plan that deals with zoning issues and codes and standards, developed with industry participation, to serve as a guidebook for setting up a hydrogen fueling station at an airport, similar to the DOE guide on cell phone towers.

Abbreviations

AAM	Advanced Air Mobility
AED	automated external defibrillator
AFB	Air Force Base
AI	artificial intelligence
APU	auxiliary power unit
ARC	Aviation Rulemaking Committee
ARPA-E	Advanced Research Projects Agency-Energy
ASCEND	Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives
ATAG	Air Transport Action Group
BEV	battery electric vehicle
BLOS	Beyond Visual Line-of-Sight
BoP	balance of plant
CAPEX	capital expenditure
CHEETA	Center for High-Efficiency Electrical Technologies for Aircraft
CHS	Center for Hydrogen Safety
CNG	compressed natural gas
CORE	clean off-road equipment
CSIRO	Commonwealth Scientific and Industrial Research Organization
CTE	Center for Transportation and the Environment
DMI	Doosan Mobility Innovation
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
eVTOL	electric vertical takeoff and landing
FAA	Federal Aviation Administration
FC	fuel cell
FCD	fuel cell dominant
FCH	fuel cell hybrid
FCEV	fuel cell electric vehicle
ft	foot
g	gram
gal	gallon(s)
GDP	gross domestic product
GHG	greenhouse gas
gse	ground support equipment
GW	gigawatt
h	hour(s)
HAVC	Heat, Air Ventilation, and Cooling
HDV	heavy-duty vehicle
HFC	hydrogen fuel cell
HFTO	Hydrogen and Fuel Cell Technologies Office
hp	horsepower

ICE	internal combustion engine
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
kg	kilogram
kW	kilowatt
L	liter
LAX	Los Angeles International Airport
LDV	light-duty vehicles
Li	lithium
LiPO	lithium phosphate
LNG	liquefied natural gas
LOS	line of sight
mi	mile
MIT	Massachusetts Institute of Technology
MMT	million metric tons
MOU	memorandum of understanding
mpg	miles per gallon
MW	megawatt
NASA	National Aeronautics and Space Administration
NM	nautical mile
NRL	Naval Research Laboratory
OEM	original equipment manufacturer
PEM	polymer electrolyte membrane
PEMFC	polymer electrolyte membrane fuel cell
R&D	research and development
REEACH	Range Extenders for Electric Aviation with Low Carbon and High Efficiency
SARTA	Stark Area Regional Transit Authority
SAE	Society of Automotive Engineers
SOFC	solid oxide fuel cell
TCO	total cost of ownership
tpd	tons per day
U.S.	United States
UAM	urban air mobility
UAS	Unmanned aerial systems
UAV	Unmanned aerial vehicle
ULI	University Leadership Initiative
UTC	United Technologies Corporation, now Raytheon Technologies Corporation
VALE	Voluntary Airport Low Emissions
Wh	Watt-hour
WTW	well-to-wheel
ZEB	zero emission bus
ZEV	zero emission vehicle

Appendix A — Polling Questions

Poll Question 1: The safety codes and standards efforts supporting commercialized alternative fuels, such as CNG/LNG or biofuels, provide a foundation for developing standards for hydrogen and fuel cell technologies?

Answers	**# Responses**
A. Strongly agree	5
B. Somewhat agree	23
C. Somewhat disagree	3
D. Strongly disagree	2
E. Don't know	5

Poll Question 2: What are the highest-priority actions that need to be undertaken by government to ensure widespread and safe operation of hydrogen and fuel cell technologies for aviation applications?

Answers	**# Responses**
A. Government and private industry co-funded R&D programs	5
B. Government-private industry co-funded demonstrations and pilots of near-commercial hydrogen fuel cell technologies under real-world operating conditions	14
C. A coordinated safety codes and standards effort that is supported by major standards bodies	8
D. Closer collaboration between government agencies on aviation research and demonstration programs	2
E. All of the above	15

Poll Question 3: Which challenge represents the greatest barrier to hydrogen adoption in Unmanned Air Vehicles (UAV)?

Answers	**# Responses**
A. Weight and volume associated with onboard storage, including mass of the fuel and storage tank	8
B. Fuel cell system weight and volume	6
C. Refueling technologies to enable refueling times comparable to incumbent systems	7
D. Safety, codes, and standards for onboard aircraft hydrogen storage and refueling	17
E. Other	2

Poll Question 4: Which challenge represents the greatest barrier to hydrogen adoption in Urban Air Mobility (VTOL)?

Answers	# Reponses
A. Weight and volume associated with onboard storage, including mass of the fuel and storage tank	16
B. Fuel cell system weight and volume	4
C. Refueling technologies to enable refueling times comparable to incumbent systems	1
D. Safety, codes, and standards for onboard aircraft hydrogen storage and refueling	17
E. Other	2

Poll Question 5: Which challenge represents the greatest barrier to hydrogen adoption in small fixed-wing aircraft?

Answers	# Responses
A. Weight and volume associated with onboard storage, including mass of the fuel and storage tank	18
B. Fuel cell system weight and volume	2
C. Refueling technologies to enable refueling times comparable to incumbent systems	1
D. Safety, codes, and standards for onboard aircraft hydrogen storage and refueling	16
E. Other	3

Poll Question 6: What are the potential hydrogen fuel cell technologies in aviation applications that could be competitive near term with incumbent technologies?

Answers	# Responses
A. Fuel cell hydrogen technologies for fixed wing aircraft	3
B. Fuel cell hydrogen technologies for Urban Air Mobility (VTOL)	1
C. Fuel cell hydrogen technologies for drones/UAVs	15
D. All of the above	17

Poll Questions 7 and 8: What are the ground support fuel cell applications that represent the best prospects for commercialization at airports?

Answers	# Responses
A. Shuttle buses, including medium duty (MD) and heavy duty (HD) buses	3
B. Aircraft or baggage handling equipment, including baggage tow tractors, tuggers, lifts	1
C. Stationary power equipment, including ground power units	4
D. Stationary power equipment, including ground power units	0
E. All of the above	26

Poll Question 9: What are the key barriers that need to be overcome to enable widespread deployment of hydrogen fueling infrastructure at airports?

Answers	# Responses
A. What are the key barriers that need to be overcome to enable widespread deployment of hydrogen fueling infrastructure at airports?	0
B. Lack of favorable economics for airport operators to transition ground support to hydrogen fuel cell technologies	11
C. Footprint of hydrogen storage, considering land/space constraints at airports	6
D. Safety, codes, and standards for onboard aircraft hydrogen storage and refueling	6
E. All of the above	15

Appendix B — Breakout Sessions

Breakout Session 1

Question 1: What are the most attractive potential opportunities for deploying hydrogen and fuel cell technologies on aircraft?

- Drones/UAVs are promising near-term applications with relatively low entry costs, proven business cases, and advantages over battery technology in terms of larger payload size, more uptime, longer mission duration, and better durability. The current hydrogen delivery system can support demands for fueling drones.
- Small regional airports have early-market potential. Hydrogen infrastructure for small/regional planes would be easier to implement and could be deployed more quickly at these locations than electrical charging infrastructure. The feasibility of transporting hydrogen by truck to smaller airports to meet their needs make them a more viable option than larger airports. Short commuter and cargo flights would also enable hydrogen systems to become viable sooner at smaller airports. There are subsidies for rural airports to help them maintain operations that could be leveraged.
- Urban areas with large airports draw attention, but smaller, remote, regional urban and rural markets will be the early adopters. Electricity demand at large airports is an issue. Large airports aiming to reach zero emissions are hitting the ceiling with the electrical supply. Electrical charging infrastructure is very expensive to install and does not scale as economically as hydrogen infrastructure. The cost to deliver hydrogen via truck to meet demand at large airports will be significant. Current fueling systems at large hubs use pipelines, and hydrogen pipelines will be needed.
- Infrastructure requirements for small airports could support adoption of hydrogen and FCs in emergency aircraft.

Question 2: What are the technical barriers to be overcome for each of the following hydrogen and fuel cell applications?

Unmanned air vehicles

- Power density/energy density. Current FC and hydrogen storage systems are designed for larger land-based applications. For aeronautic applications, R&D is needed for lightweighting FC systems and improving designs for aeronautic conditions (lower temperature and air pressure at elevation, etc.). Scaling down to the smaller footprint of UAVs is particularly challenging.
- Regulation and standards are a challenge that focuses on beyond visual line of sight operations and airspace usage for UAVs.

Urban air mobility (VTOL)

- Power density/energy density are critical to support eVTOL.
- Regulation and standards are more challenging for manned aviation and safety of flight.

Small fixed-wing passenger aircraft

- Power density/energy density. Current FC and hydrogen storage systems are designed for larger land-based applications. For aeronautic applications, R&D is needed for lightweighting FC systems and improving designs for aeronautic conditions (lower temperature and air pressure at elevation, etc.).
- Hydrogen storage is a major problem that needs to be overcome. Liquid hydrogen appears to be the best option, but liquid hydrogen supply, infrastructure, handling and safety are concerns.
- Regulations/standards and certification for airworthiness are also barriers.

Question 3: What are the key economic barriers needing to be overcome for each of the following applications?

Unmanned air vehicles

- For small UAVs, the consumer market is very competitive, and costs are falling quickly.
- Small UAVs have a great use case in the surveillance market because they do not have significant infrastructure barriers.
- For larger, heavy-lift UAVs, the availability of a liquid hydrogen infrastructure and the cost of green liquid hydrogen are issues.

Urban air mobility (VTOL)

- Relatively small market in UAVs that is highly competitive with costs rapidly falling.
- Question as to size of addressable market—different viewpoints among participants.
- Airspace management and safety are going to be challenges in urban areas.

Small fixed-wing passenger aircraft

- The current poor economic state of the aviation industry due to COVID is a substantial barrier. The aviation industry needs to recover economically to free up dollars for new developments.
- Cost of hydrogen is an issue because of the low cost of current aviation fuel.
- "Chicken and egg" problem. Need infrastructure to drive demand for FC aviation. Development of FC aviation is needed to drive infrastructure development.
- Size of capital expense needed for hydrogen infrastructure.
- Policies and incentives would be needed to support early deployments.
- Airports becoming energy hubs could provide economies of scale to reduce cost and drive infrastructure development.

Question 4: What technical and performance information will customers need to see before they consider trials or adoption of fuel cell and hydrogen technologies?

Unmanned air vehicles

- Safety and cost of FCs and hydrogen.
- Demonstration of use and reliability.

- Increased energy density to increase payload.
- Range assurance.

Urban air mobility (VTOL)

- Safety and cost of FCs and hydrogen. Costs are falling rapidly.
- Airspace management and safety is going to be a challenge in urban areas.
- Range assurance.
- Noise reduction benefit of FCs.

Small fixed-wing passenger aircraft

- Sustainability should be the lead in communicating the benefits of FCs and hydrogen to the public.
- Safety and cost of FCs and hydrogen.
- Operating at altitude where the temperatures are colder and could impact range. Range assurance is critical.
- Fueling turnaround time similar to conventional aircraft.

Question 5: What specific RD&D should government agencies, rather than the private sector, be funding? What are the highest priority technical needs?

- Unmanned UAV development could demonstrate use and reliability and would likely be easier to implement. The stringent reliability requirements for manned/passenger flight systems will make UAM and small commercial fixed wing passenger applications harder to bring to market, and data on UAV system reliability will help.
- R&D on lightweighting. The use of lightweight materials, such as graphene, to reduce weight of hydrogen storage tanks. R&D for lightweighting other components, such as electric motors and heat rejection.
- Liquid hydrogen infrastructure, including liquid hydrogen production, storage, and dispensing systems, including robotic filling systems to take humans out of the loop.
- Safety, codes, and standards, and permitting.
- Increased engagement with DOD on pilot demonstration programs would be useful.
- Stack operation at altitude, including catalyst performance and BoP component performance, to evaluate durability and impact on range

Breakout Session 2

Question 1: What are the most attractive potential opportunities for deploying hydrogen and fuel cell technologies at airports?

- Light-duty vehicles in rental car fleets located at airports.
- Forklifts at warehouse distribution centers located on or adjacent to airport properties. Forklifts are a proven technology. The fuel cell technology used in forklifts should be able to migrate to GSE and is already in some GSE as demonstrated by presentations made at this meeting. Fuel cell powered baggage tow tractors have been demonstrated and are at an advanced TRL.
- GSE such as baggage tractors and deck loaders: While a deck loader uses more energy than a baggage tractor, there are considerably more baggage tractors than deck loaders in airport GSE fleets, so baggage tractors are the largest GSE energy user. It was noted that a baggage tractor would use approximately 2 kg of hydrogen per shift.
- Heavy-duty transit buses and medium-duty shuttle buses are at a high TRL and represent an excellent opportunity for increasing the public's experience with hydrogen and fuel cell technologies. Transit agencies could employ fuel cell buses for high daily mileage airport express routes. California has adopted regulations for ZEV airport shuttle buses.
- Last-mile delivery truck vans could be deployed at warehouse distribution centers located on and adjacent to airport properties.
- A commitment from airlines stating what type of E-GSE will be used, how many will be deployed, and when they will be required.
- Transit and shuttle buses, which are already in high public transit use, can raise public awareness of hydrogen and fuel cell technologies. Accordingly, deployment of fuel cell transit and shuttle buses could have a significant impact on accelerating the deployment of these technologies at airports.

Question 2: What are the major technical and economic challenges to deploying hydrogen fuel cell electric technologies and their fueling infrastructures?

- Cost of infrastructure is challenging because of sunk costs, and aviation is a lean business. In general, the technologies are close to ready, but the economics remain the biggest challenge. Liquid transportation fuels are presently cheaper than hydrogen: \$5–\$15/kg for hydrogen vs. \$2–\$3/gal. for jet fuel.
- DOE, FAA, and industry should come up with a standardized platform for hydrogen infrastructure at an airport that could be broadly accepted, similar to what California has done for light-duty vehicle fueling stations. The goal is not to develop standards for a single airport or a few airports but standards that are widely applicable to many airports.
- Cheaper and lighter storage tanks that are application-specific for onboard and stationary storage are needed. Conformable storage tanks with shapes other than cylindrical for more efficient space utilization would be useful for airport and airline operators. R&D needed to mitigate boil-off at large scale. R&D is needed to increase the recertification period of tanks beyond the current 5-year period, which is very disruptive. R&D is needed for tanks that last 30 years.
- Valves and pipework can be expensive as well as material challenges. They must be capable of handling high pressures as well low temperatures. Safety is a critical factor but affects costs.

- Onsite liquid hydrogen or gaseous hydrogen production can be very electricity-intensive. For commercial aviation, providing the electricity needed to produce enough liquid hydrogen on site is a formidable task.

Question 3: What are the opportunities to develop hydrogen refueling infrastructure to support both aircraft and ground equipment at airports?

- Develop airports as "hydrogen hubs." Build hydrogen demand by utilizing hydrogen to the maximum extent possible in all airport systems to develop the hydrogen market and attract private investment required for developing the airport hydrogen infrastructure since airlines and airports are funding-constrained. Consolidating the acquisition and deployment of several fuel cell airport ground vehicle and equipment applications would scale up hydrogen demand at a localized or regionalized level, which should bring economics of scale benefits.
- Until you have the production and distribution in place, it is a challenge (however, some hydrogen industry entities state they are ready to supply).
- Distribution of liquid hydrogen across the airport is a key issue. You cannot have GSE going all over the airport for refueling.
- Airports partnering with regional transit groups to increase infrastructure utilization should be considered. Fuel cell buses servicing airports can lay the groundwork for the infrastructure needed for follow-on applications such as GSE.

Question 4: What do you think is needed to ensure that hydrogen infrastructure is adequate and safe for airport operations? What regulations and compliance processes need to be developed to mitigate the safety risks?

- Education and training are critical, including the development of a standardized curriculum and safety training. Airline and airport support management and workers must be educated and trained on the use and safe handling and storage of hydrogen. First responders need to be trained. Transit agencies that have been operating with liquid hydrogen could be a good learning source. GSE can leverage codes and standards for fuel cell-powered material handling equipment, but airport operations are different from bus depots, seaports, or warehouses operations.
- Codes and standards developed specifically for airports. A starting point could be the application of existing hydrogen standards to aircraft and airport applications, such as NFPA 2 for the fuel infrastructure, ISO TC 20 SC 16 for UAVs, IEC/TC 105 for portable and micro fuel cell technology safety and performance standards, including fuel cartridges. SAE could be leveraged.
- Pressure vessels at airports are a regulatory issue. Tank certification and testing protocols need to be developed.
- eVTOLs typically do not use large airports. Safety issues associated with refueling VTOLs that fly out of small airports is a concern.

Question 5: What specific RD&D should government agencies, rather than the private sector, be funding? What are the high priority technical needs?

- Given the high visibility and public usage of airports, airports are typically conservative and careful in adopting new technologies. Accordingly, demonstrations and pilots of pre-commercial technologies in "real world" operating conditions are important to prove that the technology is cost effective and safe. Rental car facilities and shuttle buses could be a good place to start to increase awareness for hydrogen and fuel cells as well as collect data. DOE/FAA could establish an H2@Airports working group to share lessons learned.
- Liquid hydrogen production, storage, dispensing systems including robotic filling systems to take the operator out of the loop. Demonstration of high capacity fueling to support commercial aviation is needed.
- Funding is needed to develop a standardized plan that deals with zoning issues and codes and standards, which could serve as a guidebook for setting up a hydrogen fueling station at an airport.

Appendix C – Workshop Agenda

Wednesday, November 4 | Day 1 | Government Perspectives and Safety Codes and Standards

Session I — Government Perspectives on Hydrogen for Airports and Aviation Applications

2:00 PM	**U.S. Department of Energy, Fuel Cell Technologies Office** *Dr. Sunita Satyapal, Director*
2:15 PM	**U.S. Air Force** *Roberto Guerrero, USAF SAF-IE*
2:30 PM	**U.S. Navy** *James Caley, DASN Director Operational Energy*
2:45 PM	**U.S. Federal Aviation Administration** *James Hileman, Chief Scientific and Technical Advisor for Environment and Energy*
3:00 PM	**NASA** *Steven Schneider, Research Aerospace Engineer, NASA Glenn Research Center*
3:15 PM	**California Air Resources Board** *Leslie Goodbody, Innovative Heavy-Duty Strategies*
3:30 PM	**Break**

Session II — Aircraft Safety Research Codes and Standards

3:45 PM	**U.S. Federal Aviation Administration** *Michael Walz, Aircraft Electrical Systems Research Program Manager*
4:00 PM	**Joint SAE/EUROCAE Standardization Group on Hydrogen and Fuel Cells - AE-7AFC/WG-80** *Olivier Savin, SAE/EUROCAE Chairman*
4:15 PM	**Hydrogen Safety** *Brian Ehrhart, Sandia National Laboratories*
4:30 PM	**Day 1 Feedback & Adjourn**

Thursday, November 5 | Day 2 | Aviation Development and Refueling Perspectives

Session III — UAV Development & Refueling

10:00 AM	**Doosan Mobility Innovation** *Doo Soon Lee, CEO*
10:15 AM	**Honeywell Aerospace** *Phil Robinson, Sr. Director, Engineering: Zero Emissions Aviation*
10:30 AM	**Intelligent Energy** *Chris Dudfield, CTO*
10:45 AM	***Plug Power*** *Thomas Jones, Director of UAV/Aerospace Technology*
11:00 AM	**ReadyH_2 (Fortress)** *Joe Uhr, SVP of Operations and Repair*
11:15 AM	**IGX** *Michael Koonce, CEO*
11:30 AM	**Break**

Session IV — Electric Aircraft Development

1:00 PM	**Airbus** *Amanda Simpson, V.P. Research & Technology*
1:15 PM	**Boeing** *Sean Newsum, Director Environmental Strategy*
1:30 PM	**ZeroAvia** *Val Miftakhov, CEO*
1:45 PM	**Alaka’i Technologies** *Bruce Holmes, Chief Technical Officer*
2:00 PM	**Hyundai Air Mobility** *W. Kyle Heironimus, Head of Powertrain*
2:15 PM	**Break**

Session V — Hydrogen Aviation Research and Assessments

2:30 PM	**ARPA-E** *Grigorii Soloveichik, Program Director*
2:45 PM	**University of Illinois** *Phillip J. Ansell, Assistant Professor*
3:00 PM	**Argonne National Laboratory** *Dr. Rajesh Ahluwalia, Manager, Fuel Cell and Hydrogen*
3:15 PM	**Breakout Sessions**
4:30 PM	**Breakout Sessions Report Out**
5:00 PM	**Adjourn**

Friday, November 6 | Day 3 | Airport Ground Equipment and Refueling

Session VI — Airport Ground Equipment Perspectives

10:00 AM	**Plug Power** *Joe Blanchard, VP Services*
10:15 AM	**US Hybrid** *Abas Goodarzi, CEO*
10:30 AM	**BAE Systems** *Bob Hess, Systems Engineering Manager*
10:45 AM	**Cummins** *Ryan Sookhoo, Director New Initiatives*
11:00 AM	**Break**

Session VII — Airport Ground Transportation Perspectives

11:15 AM	**CTE** *Joel Donham, Airport Specialist*
11:30 AM	**Charlatte** *Rob Lamb, VP, Sales/Marketing*
11:45 AM	**Lightning Systems** *William Kelley Jr., COO/CTO*
12:00 AM	**SunLine Transit** *Lauren Skiver, CEO*
12:15 PM	**SARTA** *Kirt Conrad, Executive Director/CEO*
12:30 PM	**Break**

Session VIII — Airport Refueling Systems Developer Perspectives

1:00 PM	**Air Liquide** *Dave Edwards, Director*
1:15 PM	**Linde** *Al Burgunder, Director Clean Hydrogen*
1:30 PM	**Break**
1:45 PM	**Breakout Sessions**
3:00 PM	**Breakout Sessions Report Out & Concluding Remarks**
3:45 PM	**Adjourn**

Appendix D — Speaker Biographies

Sunita Satyapal, U.S. Department of Energy

Sunita Satyapal is the Director for the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy, and she is responsible for $150 million per year in hydrogen and fuel cell R&D. She has two and a half decades of experience across industry, academia and government, including managing research and business development at United Technologies, and teaching as a visiting professor. Dr. Satyapal is the current Chair of the International Partnership for Hydrogen and Fuel Cells in the Economy, a partnership of over 18 countries to accelerate progress in hydrogen. She received her Ph.D. from Columbia University and did postdoctoral work in Applied and Engineering Physics at Cornell University.

She has numerous publications, 10 patents, and a number of recognitions, including a Presidential Rank Award.

Roberto Guerrero, U.S. Air Force

Roberto I. Guerrero, a member of the Senior Executive Service, is the Deputy Assistant Secretary of the Air Force for Operational Energy, Office of the Assistant Secretary of the Air Force for Installations, Environment and Energy. Mr. Guerrero is responsible for providing oversight and direction for all matters pertaining to the formulation, review, and execution of plans, policies, and programs for the effective and efficient use of the Air Force's $5 billion operational energy bill in support of its global mission.

Mr. Guerrero earned his commission as an ensign in the Navy though Aviation Officer Candidate School in 1988 and received his wings as a Naval Aviator in 1989. During his military service he participated in operations Deep Freeze, Korean Contingency and Noble Eagle, and flew 24 combat missions over Afghanistan during Operation Enduring Freedom.

He entered civil service in 2010, serving as Deputy Chief of Safety, U.S. Air Force, and Executive Director, Air Force Safety Center, Kirtland AFB, New Mexico. Following this tour of duty, he was Director of Staff, Headquarters Air Force Reserve Command, Robins AFB, Georgia.

James Caley, U.S. Navy

Jim Caley was appointed as the Director for Operational Energy in September 2016. He serves as the Secretary of the Navy's focal point on all matters pertaining to Operational Energy.

Jim came from the United States Marine Corps where he served in the transportation, logistics, and communications fields since 1989, rising to the rank of Colonel. He is an experienced operational and strategic planner on issues relating to Asia-Pacific, South Asia, and the Middle East. He has commanded at the battalion and regimental levels. His final post was as Director of the Marine Corps Expeditionary Energy Office (E2O), where he was tasked with coordinating innovative energy technology and policy development for the Marines. During his time as Director, Jim refocused the Marine Corp's Expeditionary Energy Concepts initiative to focus on developing infantry-related technology in concert with private industry. His current focus is on power and energy for directed energy weapons systems, advanced batteries, advanced propulsion, etc.

James Hileman, Federal Aviation Administration (FAA)

Jim Hileman is the Chief Scientific and Technical Advisor for Environment and Energy for the Federal Aviation Administration. He has responsibility for the environment and energy research portfolio of the FAA, which includes the Continuous Lower Energy, Emissions and Noise (CLEEN) Program, the Aviation Sustainability Center (ASCENT), the FAA Center of Excellence for Alternative Jet Fuels and Environment, and the Commercial Aviation Alternative Fuels Initiative (CAAFI), among other efforts. Dr. Hileman is also the Co-Rapporteur of the Fuels Task Group (FTG) of the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP), which is determining how fuels are credited under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Prior to joining the FAA, Dr. Hileman was a Principal Research Engineer within the Department of Aeronautics and Astronautics at MIT. His work focused on alternative jet fuels and innovative aircraft concepts that could reduce the impacts of aviation on noise, air quality and global climate change. He holds a B.S., M.S., and Ph.D. in Mechanical Engineering from the Ohio State University.

Steven Schneider, National Aeronautics and Space Administration (NASA)

Steven Schneider is a Research Aerospace Engineer in the Chemical and Thermal Propulsion Systems team at NASA Glenn Research Center. Steven is currently working on propulsion modeling on the Advanced Air Transport Technology Program. He has 35 years of experience with NASA Glenn on various programs.

Leslie Goodbody – California Air Resources Board (CARB)

Leslie Goodbody has worked for CARB for 15 years and is currently working in the Innovative Strategies Branch managing incentive programs. She is overseeing numerous projects involving on-road demonstration and pilot deployments of fuel cell trucks, fuel cell and battery electric transit buses, high-capacity hydrogen fueling stations and depot charging. Ms Goodbody is also overseeing administration of $150 million in Volkswagen Environmental Mitigation Trust funding for Zero-Emission Class 8 trucks and low-NOx trucks and freight equipment. She previously worked with CARB's Advanced Clean Cars group focusing on automotive hydrogen fueling and charging infrastructure. She has a bachelor's degree in Environmental Resources Engineering from Humboldt State University and 31 years working in the public and private sectors.

Michael Walz, Federal Aviation Administration

Michael Walz has been working as FAA electrical systems program manager for over 17 years. He has worked on two aviation rule-making committees and many industry standard working groups: mainly SAE Aerospace Electrical Energy Storage, Electric Propulsion Systems, Circuit Protection and Wiring. Before coming to the FAA, he worked in industry for over 23 years as a design engineer. Mr. Walz enjoys working with new technology to discover its safety implications. In other words, he likes breaking things in the lab so they don't break on the aircraft.

Olivier Savin, SAE/EUROCAE

Oliver Savin has been acting Chairman of the joint SAE/EUROCAE standardization group since 2016. Mr. Savin has 22 years of experience with hydrogen fuel cells in aerospace, including five years at Honeywell (Los Angeles, CA) and 17 years at Dassault (business jet manufacturer, Paris, France). He conducted various collaborative development and demonstration projects for fuel cell applications in aviation.

Brian Ehrhart, Sandia National Laboratories

Brian Ehrhart is a Chemical Engineer at Sandia National Laboratories. Since 2017, he has worked to support technical analyses for safety codes and standards for alternative fuels, particularly hydrogen. His current and past work has focused on assessing risk for hydrogen vehicles and infrastructure, developing software codes for various fire and thermal scenarios, and working to improve the National Fire Protection Association (NFPA) 2 Hydrogen Technologies fire safety code.

Doo Soon Lee, Doosan Mobility Innovation

Doo Soon Lee has been CEO of Doosan Mobility Innovation Inc., and a Doosan Corp. affiliate. Doosan Mobility Innovation (DMI) is 100% owned by Doosan Corporation, a global company with $16.5 billion in revenue. DMI focuses on the mobile applications of fuel cell technology, heavily investing in UAV applications to enable reliable long-endurance flight, accelerating the growth of the UAV industry.

Before joining DMI, he served as Vice President of Global Marketing for Doosan Infracore and in positions at A.T Kearney and Hyundai Motors. He holds an MBA from Cornell University and MS and BS degrees in Mechanical Engineering from Seoul National University.

Phil Robinson, Honeywell Aerospace
Bio not available.

Chris Dudfield, Intelligent Energy

Chris Dudfield is the Chief Technology Officer and a member of the management team at Intelligent Energy, where he has worked since the launch of the business in 2001. Over the last 19 years, Mr. Dudfield has held several positions, including R&D Director, Director of Operations, and Director of Programmes. He has worked continuously in the field of fuel cell technology since 1990 and has experience in fuel cell stack, fuel processing and fuel cell systems technology. He has extensive knowledge and expertise in fuel cell and hydrogen generation technologies, including applications across stationary power, motive, and portable power markets. Mr. Dudfield is a Fellow of the Royal Society of Chemistry and holds Chartered Chemist and Chartered Scientist professional status

Thomas Jones, Plug Power

Thomas Jones has worked in the hydrogen fuel cell industry for over 23 years at companies such as Ballard Power Systems, UTC Fuel Cells, EnergyOr Technologies, and now Plug Power. Applications he has worked with include heavy duty truck and bus, automotive, and aerospace, with experience in both stack and system level development. For the past 15 years, he has focused mainly on lightweight, hybrid fuel cell/battery systems for UAV and aerospace platforms. He holds eight patents relating to hydrogen and fuel cell technologies and a master’s degree in Mechanical Engineering.

Joe Uhr, ReadyH$_2$

For the past seven years, Joe Uhr has been Senior VP of Operations for Fortress Solutions, providing network repair services to all major telecoms in North America. He is also responsible for ReadyH$_2$’s hydrogen fuel delivery services in North America.

Michael Koonce, IGX

Michael Koonce is the founder of IGX Group and several other related companies in the MK Group. IGX is a leading distributor of high-pressure hydrogen and a leading manufacturer of high-pressure gas transports for hydrogen. IGX's hydrogen distribution division supports all the major cell carriers in the United States and several government fuel cell projects with mobile hydrogen refueling services. The manufacturing division makes a range of high-pressure transports extending from small mobile hydrogen refuelers to 52-foot transports. A recent addition to the company's portfolio is the H_2Pwr line of hydrogen fuel cell-based power generators ranging from 1kW to 100kW. Other related companies include NorAm Valves, which designs and produces hydrogen-specific valves and safety systems for composite cylinders used for hydrogen storage. Mr. Koonce also owns Gas Transport Leasing, LLC, one of the largest leasers of composite cylinder-based transports used in the distribution of hydrogen, helium, natural gas, and other highly compressible gases.

Mr. Koonce holds an MBA from University of California, Berkeley, and a BS in Economics and Finance from California State University of Sacramento.

Amanda Simpson, Airbus

Amanda Simpson is Vice President for Research and Technology at Airbus Americas and is responsible for coordinating technology development, research activities, and innovation for Airbus in the western hemisphere. Previously she was the Deputy Assistant Secretary of Defense for Operational Energy at the U.S. Department of Defense, responsible for developing the strategy for the utilization of energy for military operational forces worldwide and the senior advisor to the Secretary of Defense for all matters pertaining to energy in our military. She brings 40 years of defense and aerospace experience, both in the public and private sector, to today's workshop.

Sean Newsum, Boeing

Bio not available.

Val Miftakhov, ZeroAvia

Val Miftakhov is a founder and CEO of ZeroAvia, Inc, a California company developing the world's first practical zero emission aviation powertrain. Mr. Miftakhov is a serial entrepreneur in the electric vehicle space—his previous company, eMotorWerks, developed the world's leading platform for EV battery aggregation to provide grid services and was acquired in 2017. Prior to that, Mr. Miftakhov held a number of senior business and product positions at Google and McKinsey & Company and was a nuclear researcher at the Stanford Linear Accelerator Center (SLAC). He holds a PhD in Physics from Princeton University and a master's degree in physics from the Moscow Institute of Physics and Technology, and he was a two-time winner of Russian Nationwide Physics competitions.

Bruce Holmes, Alaka'i Technologies

Bruce Holmes is a five-decade veteran of aviation operations, research and development, aircraft development, and disruptive innovation in his field. His background includes industry and government roles in research, operations, and executive leadership, working at NASA, in the commercial on-demand air carrier world, with aviation software startups, on the U.S. NextGen founding team, and most recently on an electric vertical takeoff and landing (eVTOL) air vehicle. In addition to his role as CTO for Alaka'i Technologies, launching the first hydrogen fuel-cell-powered electric air mobility vehicle, he is a senior advisor to SmartSky Networks, supporting the launch of a unique air-to-ground WiFi aviation connectivity solution and apps development platform, contributing to the Internet of Things that Fly. He serves on special groups for the National Academy of Science, Engineering, and Medicine, and the FAA Administrator's Research, Engineering, and Development Advisory Committee–NAS Operations Subcommittee (REDAC), as well as on corporate boards. He has published over one hundred technical papers, received seven patents in aeronautics, and been honored with numerous NASA medals and professional society awards, including the FAA Wright Brothers Master Pilot Award, recognizing 50 years of safe flying. He is a Fellow of the AIAA and the Royal Aeronautical Establishment. He is an active pilot and thrilled owner of an ICON A5 amphibian aircraft.

W. Kyle Heironimus, Hyundai Air Mobility

Kyle Heironimus is the head of U.S. Powertrain Research & Development for Hyundai Urban Air Mobility. His team's responsibilities include development and integration of electric propulsion technologies into innovative aircraft concepts. Kyle's experience includes design and certification of Part 27 and 29 aircraft systems for a variety of different traditional and novel VTOL aircraft.

Grigorii Soloveichik, U.S. Department of Energy

Grigorii Soloveichik currently serves as a Program Director at the Advanced Research Projects Agency-Energy (ARPA-E). His focus at ARPA-E is electrochemical and chemical energy storage and conversion, including development of electrochemical devices, advanced materials and processes. He created and manages the REFUEL program targeting the production of ammonia and other carbon-neutral fuels from renewable sources and their use for energy storage and transportation. He initiated and developed the REEACH program to develop energy storage and power generation systems for electric aviation. Currently, he is also working with the Office of Energy Efficiency and Renewable Energy (EERE) Hydrogen and Fuel Technology Office as a Senior Advisor.

Prior to joining ARPA-E, Dr. Soloveichik worked at GE Global Research as a Senior Staff Chemist, and as Director of the DOE-funded Energy Frontier Research Center for Electrocatalysis, Transport Phenomena, and Materials for Innovative Energy Storage. While there, he developed novel rechargeable liquid fuel cells and high-energy density flow batteries, designed catalytic and electrochemical processes for functionalization of arenes and phenols, and developed novel electrolytes and electrocatalysts. His previous work includes development of catalysts and lithium-sulfur rechargeable batteries. He is the author/coauthor of 71 issued U.S. patents and more than 125 papers in peer-reviewed journals, and he holds the degrees of MS in Chemistry, PhD in Inorganic Chemistry, and DSc in Chemistry from Moscow State University.

Phillip J. Ansell, University of Illinois at Urbana-Champaign

Phillip J. Ansell is Assistant Professor and Allen Ormsbee Faculty Fellow in the Department of Aerospace Engineering at the University of Illinois at Urbana-Champaign. He is also the director of the Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA), focused on developing advanced technologies for electrified aircraft propulsion. Dr. Ansell earned his PhD and MS from the University of Illinois at Urbana-Champaign, and his BS from Penn State University. He has received several awards for his research, including Young Investigator Awards from the Air Force Office of Scientific Research, the Army Research Office, and he was one of the Forbes 30 Under 30 in Science. His primary areas of work include subsonic and transonic aerodynamics, atmospheric flight sciences, aero-propulsive integration, air-vehicle design, and aircraft propulsion electrification.

Rajesh Ahluwalia, Argonne National Laboratory

Rajesh Ahluwalia manages the Fuel Cell and Hydrogen group in Argonne National Laboratory's Energy Systems division. Dr. Ahluwalia is a co-developer of GCTool (General Computational Toolkit), a software package that helps design, analyze, and optimize automotive and stationary distributed fuel cell power generation systems, as well as other power plant configurations.

Joe Blanchard, Plug Power

Joe Blanchard is currently the Vice President of Services at Plug Power, supporting fuel cell programs spanning mobile and stationary markets throughout the world. He joined Plug Power in 2014 with its acquisition of ReliOn, where he had most recently been the Chief Operating Officer. He has been responsible for fuel cell development, marketing, & services since 2005. Prior to ReliOn, Mr. Blanchard spent 21 years working in the telecommunications industry.

Abas Goodarzi, US Hybrid

Abas Goodarzi is President and CEO of US Hybrid and Chairman of Magmotor Technologies. With over 40 years of EV and HEV experience, he currently directs Technology and Product Development at US Hybrid with a focus on fuel cell engine, electric and hybrid powertrain design and manufacturing for special purpose and medium-duty/heavy-duty commercial applications.

After his experience as a professor at Cal State San Francisco, a Project Engineer at US Windpower, Technical Director of General Motor's EV1 program, and Senior Scientist at Hughes Aircraft Company, Dr. Goodarzi founded US Hybrid in 1999 and directed the development of high-power density electric powertrains, including fuel cell engines.

Robert Hess, BAE Systems

Bob Hess is a Systems Engineering Manager with BAE Systems. He currently leads a number of projects at BAE Systems related to hybrid and all-electric propulsion, design of energy storage systems, airborne power and aircraft electrification. He has been developing products for the aerospace and ground transit industries for over 35 years. Over the past 10 years, he has been primarily focused on energy storage solutions for vehicle propulsion. Mr. Hess has degrees in Mechanical and Aeronautical Engineering, is a member of the Vertical Flight Society (VFS) and the Society of Automotive Engineers (SAE International) and holds several patents related to energy storage and vehicle systems.

Ryan Sookhoo, Cummins

Ryan Sookhoo is the Director New Initiatives at Cummins Fuel Cell and Hydrogen Technologies. Since joining Hydrogenics, now part of Cummins, in 2006 as Project Manager for PEM fuel cell development and commercialization, he has been a dedicated member of the research and development program. In his current role, Mr. Sookhoo feels fortunate to be involved in the early stages of new technology adaptation. As a leader in hydrogen generation and fuel cell industries, Cummins has given Mr. Sookhoo the opportunity to work with various industries and help to define many of tomorrow's energy and power solutions.

Joel Donham, CTE

Joel Donham is a Lead Engineering Consultant at the Center for Transportation and the Environment. Mr. Donham leads the airport applications program at CTE, conducting advocacy and policy support for airport emissions reductions programs. Mr. Donham also consults on numerous zero-emissions truck and bus projects, supporting transition planning, deployment planning, vehicle and infrastructure build oversight, and operations management.

Rob Lamb, Charlatte

Rob Lamb holds a BS degree from Auburn University in International Business. In Rob's 30-year tenure in the airline industry, he worked several years for a large cargo airline and eventually moved over to the airline GSE supplier side to enjoy his next 25 years of service. The last 15 of these have been at Charlatte America as the VP of Sales and Marketing. In addition, Mr. Lamb has spent many years as an advisory board member to the Electric Power Research Institute (EPRI) as well as Ground Support Worldwide magazine.

William R. Kelley Jr., Lightning Systems

Bill Kelley is the Chief Operating Officer and Chief Technology Officer for Lightning Systems, Inc. (LS) of Loveland, Colorado. He joined Lightning Systems in 2017. LS is a leading designer and manufacturer of electrification systems for commercial trucks. In 2019, LS delivered a large number of electrified commercial vehicles to the marketplace, ranging from Class 3 up to Class 7. In 2020, Lightning Systems is slated to deliver more electrified commercial vehicles than any other enterprise in the United States.

Prior to his engagement at LS, Mr. Kelley worked in the automotive drivetrain space as Corporate Vice President of Research and Technology for Borg Warner (BW). Bill spent his entire career at BW in advanced engineering and development. He and his organization developed key growth platforms for BW including "on-demand" technology for 4WD and AWD vehicles and various advanced transmission systems for internal combustion engines and electric vehicles, most notably the first-generation Tesla Roadster. During his time at BW, Mr. Kelley was responsible for advanced engineering, M&A technical analysis and support, investor relations technical communication, and innovation for the enterprise.

Prior to joining BW in 1987, Mr. Kelley was involved in nuclear engineering related activities in both the commercial and military space.

Lauren Skiver, SunLine Transit

Lauren Skiver has served the transit industry for over 20 years. Starting as a maintenance clerk at HART in Tampa, Florida, she advanced to serving as Director of Paratransit Services at HART, Deputy Chief Operating Officer at MTA Maryland, and CEO at Delaware Transit Corporation.

Since 2013, she has been the CEO/General Manager of SunLine Transit Agency, where she remains excited to lead the delivery of transit services to the Coachella Valley and continue the efforts of SunLine's ZEB program. SunLine has long been a pioneer of hydrogen fuel cell and zero emission technology and continues to be a leader in innovative approaches to clean transit service delivery. Additionally, Ms. Skiver served nine years in the U.S. Army specializing in Military Intelligence as an imagery analyst, and she served during Operations Desert Shield and Desert Storm.

Kirt Conrad, SARTA

Bio not available.

Dave Edwards, Air Liquide

Air Liquide is a leader in the global supply of hydrogen to mobility markets. Dave Edwards is responsible for establishing and maintaining internal and external partnerships with industry, academia, and government entities as needed to advance the technology and business opportunities in hydrogen energy for Air Liquide in the United States. Dave has more than 20 years with Air Liquide in R&D and hydrogen business roles, covering all aspects of energy in the transportation and power sectors.

Al Burgunder, Linde

Bio not available.

Appendix E — List of Attendees

Name	Company/Organization
Enass Abo-Hamed	H_2GO Power Ltd.
Rajesh Ahluwalia	Argonne National Laboratory
Richard Ainsworth	The European Marine Energy Centre
Phillip Ansell	University of Illinois at Urbana-Champaign
Dan Berteletti	BGS
Joe Blanchard	Plug Power
Myra Blaylock	Sandia National Labs
Gus Block	Nuvera Fuel Cells
Marty Bradley	Self-employed
Albert Burgunder	Linde Gases U.S.
Jim Caley	Department of the Navy
P. Scott Cary	NREL
Geo Castano	TBP
Kevin Centeck	U.S. Army CCDC GVSC
Shuk Han Chan	Hawaii Center for Advanced Transportation Technologies
Dan Cohen-Nir	Airbus Americas, Inc.
Elizabeth Connelly	International Energy Agency
Kirt Conrad	Stark Area Regional Transit Authority
John Copello	San Francisco International Airport
Jessica Daniels	U.S. EPA
Robert Darling	Raytheon Technologies Research Center
Christine DeJong	GAMA
Pete Devlin	U.S. DOE
Joel Donham	The Center for Transportation and the Environment
Chris Dudfield	Intelligent Energy Ltd
Douglas Dudis	U.S. Air Force
David Edwards	Air Liquide
Brian Ehrhart	Sandia National Laboratories
Bill Elrick	CA Fuel Cell Partnership
Mitch Ewan	HNEI
Abas Goodarzi	US Hybrid
Leslie Goodbody	CA Air Resources Board

Alison Gotkin	Raytheon Technologies Research Center
Ben Gould	U.S. Naval Research Laboratory
Jason Hanlin	Center for Transportation and the Environment
Robert Hess	BAE Systems
Jim Hileman	Federal Aviation Administration
Jamie Holladay	Pacific Northwest National Laboratory
Bruce Holmes	Skai (an Alaka'i Technologies company)
Brian Hunter	U.S. Department of Energy
Dana Jensen	U.S. Air Force
Thomas Jones	Plug Power Inc.
William Kelley	Lightning Motors
Alex (Jiyoung) Kim	Doosan Mobility Innovation
Stella King	ReadyH_2
Benjamin Klahr	Department of the Navy
Adam Klauber	Rocky Mountain Institute
Greg Kleen	DOE Hydrogen and Fuel Cell Technologies Office
Michael Koonce	IGX Group, Inc.
John Kopasz	Argonne National Laboratory
Theodore Krause	Argonne National Laboratory
Chris LaFleur	Sandia National Labs
Rob Lamb	Charlatte of America, Inc.
Michael Lamprecht	FAA
Doo Soon Lee	Doosan Mobility Innovation
DeLisa Leighton	IGX Group
Megan Leppert	AFRL/RX
Britney McCoy	U.S. Environmental Protection Agency
Scott McWhorter	Savannah River National Laboratory
Valery Miftakhov	ZeroAvia, Inc.
Blake Moffitt	Sikorsky Aircraft/Lockheed Martin
David Molinaro	HCATT
Greg Moreland	GDIT contract to Oak Ridge National Laboratory
Charles Myers	GDIT
Melinda Pagliarello	Airports Council International–North America
Dennis Papadias	Argonne National Laboratory
Karen Quackenbush	Fuel Cell and Hydrogen Energy Association
Mark Richards	DOE Hydrogen and Fuel Cell Technologies Office

Phil Robinson	Honeywell
Soonsuk Roh	Doosan Mobility Innovation
Naseem Saiyed	NASA_HQ
Sunita Satyapal	U.S. Department of Energy
Olivier Savin	Dassault-Aviation
Steven Schneider	NASA Glenn Research Center
Shailesh Shah	CCDC, C5ISR Center, CPID, Power Division
Amanda Simpson	Airbus Americas
Neil Skilton	Clear Ascent
Lauren Skiver	SunLine Transit Agency
Grigorii Soloveichik	ARPA-E
Ryan Sookhoo	Cummins
Luke Sperrin	H_2GO Power Ltd.
Kevin Spitzer	Air Force Research Laboratory
David Tamburello	Savannah River Nuclear Solutions
Tony Thompson	FlyShare
Brad Tonnesen	Boeing
Michael Walz	FAA
Dacong Weng	Honeywell Aerospace
Andrew Work	Cummins Inc.

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