Concept of Operations of Battery and Hydrogen-Powered Aircraft at Aerodromes

Airport Compatibility of Alternative Aviation Fuels Task Force,
International Industry Working Group

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AUTHORS AND ACKNOWLEDGEMENTS

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1. EXECUTIVE SUMMARY

New generation aircraft, capable of operating with hydrogen or batteries, are expected to enter service in the foreseeable future[1] and contribute to ICAO's Long-term Aspirational Goal (LTAG) of Net Zero CO_2 emissions by 2050. These aircraft will coexist with traditional kerosene-powered aircraft in new and existing aerodromes as they are introduced into the market. The aviation industry (aircraft manufacturers, airlines, airports, and air service navigation providers) is closely working with governments and ICAO to ensure aerodrome compatibility and to facilitate the integration of these aircraft technologies into the aviation ecosystem in a safe, efficient, timely, and harmonized manner.

This document contains the Concept of Operations (CONOPS) of aircraft powered by batteries or hydrogen (non-drop-in aviation cleaner energies[2]) at aerodromes, and highlights some of the changes required, as well as some of the aspects that are not expected to change (only fixed-wing passenger aircraft considered, electric vertical take-off and landing aircraft (eVTOLs) are excluded). The aerodrome operations addressed in this document are landing; taxiing; arrival on stand and parking at the gate; passenger disembarking; aircraft servicing; refueling/recharging; passenger embarking; pushback; engine start-up; taxi-out; and departure. A chapter is also included on abnormal and emergency operations, as well as appendices that list initiatives around the world involving hydrogen or battery use for aviation, including standards, research projects, and industry initiatives. This document describes the current state of the knowledge regarding how these aircraft will operate on the ground and highlights the multiple gaps that were identified throughout each phase of aerodrome operations. The primary objective of this CONOPS is to help ICAO prepare the pathway for the regulatory changes that will be needed for achieving full integration of these aircraft concepts into aerodromes (particularly *Annex 14*)[3]. The document is a first step in analyzing, identifying, and planning global provisions, where necessary, to facilitate the safe, efficient, and timely integration of hydrogen and battery-powered aircraft.

This CONOPS was developed as part of the International Industry Working Group (IIWG) by the Airport Compatibility of Alternative Aviation Fuels Task Force (ACAAF-TF), which was jointly led by the International Air Transport Association (IATA), Airports Council International (ACI), and Airbus (as a member of the International Coordinating

[1] IATA. (2024). Evolution of Hydrogen aircraft to 2050. https://www.iata.org/en/iata-repository/publications/economic-reports/evolution-of-hydrogen-aircraft-fleet-to-2050/

[2] For ease of reference, unless specified, this CONOPS generally refers to "hydrogen and battery-powered" aircraft which is intended to include liquid or gaseous hydrogen, electric or hybrid-electric aircraft as described in section 8.

[3] ICAO. (2024). Future Aerodromes to accommodate new aircraft technologies, 14th Air Navigation Conference, ICAO. https://www.icao.int/Meetings/anconf14/Documents/WP/wp_006_en.pdf

Council of Aerospace Industries Associations – ICCAIA), and will be updated as necessary.

2. BACKGROUND

The IIWG was established in 1970 under the sponsorship of the Airport Associations Coordinating Council (now ACI and ICCAIA), and IATA.

The IIWG was initially established to study and coordinate the integration and aerodrome compatibility of new aircraft being produced and put into operation. This facilitated the introduction of these aircraft into the aerodrome environment and streamlined the regulatory change process with global regulators.

Looking to the future, one of the most significant changes to aerodromes worldwide will be the aircraft powered by alternative fuel types – mainly hydrogen and electricity. These two new fuels have been identified as important contributors to the decarbonization efforts underway across the industry, but they also have the potential to generate some new challenges for aerodrome operators that need to be identified and managed appropriately.

At the IIWG/69 meeting, the decision was taken to establish a Task Force that will identify the possible impacts on aerodrome operations due to the use of hydrogen and batteries to power aircraft. The ACAAF-TF was established to address this topic with the primary objective of preparing the pathway for the regulatory changes that will be needed within the ICAO framework. Following the completion of this task and achievement of its deliverables, the Task Force will be disbanded unless additional elements are added to its work plan by the IIWG or directly by the ACAAF-TF.

3. SCOPE

The aim of the CONOPS developed by the ACAAF-TF is to identify:

- The changes to aircraft operations at aerodromes, including related aircraft ground movement, ground handling, and aerodrome operational procedures, resulting from the introduction of aircraft powered by alternative aviation fuels.
- The gaps in operations, procedures, and risks.

This CONOPS only considers fixed-wing aircraft and does not investigate eVTOL or Advanced Air Mobility concepts currently under development. In some cases, however, the findings of the ACAAF-TF may apply to these concepts.

The document focuses on the implications of alternative fuels yet briefly considers the size and geometry of the aircraft.

This CONOPS does not cover aspects related to energy (hydrogen or electricity/batteries) production, distribution or storage, or other fuel types considered for the decarbonization of aviation operations, such as Sustainable Aviation Fuels (SAF).

However, it is recognized that electricity demand, and other alternative fuels-related infrastructure will be a challenge for aviation, particularly at airports. For example, the electrification of ground handling equipment and other vehicles is already creating energy challenges at airports, which will be exacerbated by the introduction of battery-powered aircraft. Concurrent efforts will be required to make sure airports can either produce and/or have access to sustainably generated electricity/hydrogen to meet all the additional needs.

4. METHODOLOGY

A CONOPS that describes how an aircraft powered by hydrogen or electricity will operate at an aerodrome was developed as the first step in a regulatory gap analysis that examined how these new aircraft would influence the current aerodrome design and operations.

The ACAAF-TF separated the aircraft operation on the aerodrome into phases defined as approach, landing, taxi-in, arrival on the stand, turnaround (passenger disembarking, aircraft servicing, fueling, and re-embarkation), taxi-out, and take-off, including abnormal operations. Using this process-oriented approach, the operation was described and documented in as much detail as currently known by the experts and members of the Task Force and considers the variability of some tasks due to aircraft configuration or ground operation. Along with the description of the operations and their interaction with aerodrome design, operational procedures, services, and related enablers (e.g., aerodrome operator organization and management system, apron management services, aerodrome data, equipment and installations), the Task Force also identified knowledge gaps that need to be filled or aspects of the operation that are unknown.

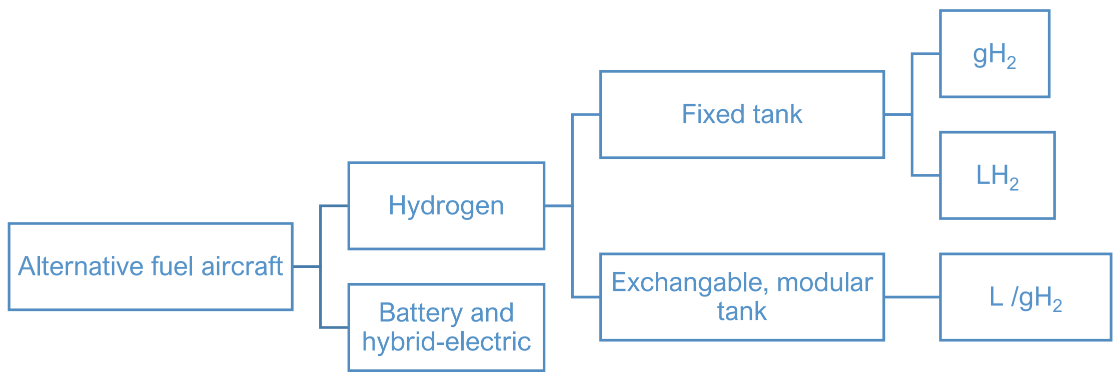
In developing this CONOPS, the ACAAF-TF has coordinated with other organizations/entities working on hydrogen or battery-electric-powered aircraft concepts (see *Appendix 1* for a list of organizations). These collaborative approaches have aimed to ensure that the work of groups, such as the European Organization for Civil Aviation Equipment (EUROCAE), SAE International, the Alliance for Zero Emission Aviation (AZEA), the US Federal Aviation Administration (FAA) or the European Union Aviation Safety Agency (EASA), is aligned and coordinated with the work of the ACAAF-TF.

5. KEY ASSUMPTIONS

As part of the analysis conducted by the Task Force, an initial list of assumptions was identified for the introduction of aircraft powered by hydrogen or electricity at aerodromes. These were clustered in three different categories:

- Aspects that are not expected to change
- Aspects that will need to change
- Aspects that may change but are currently unknown

These assumptions are relevant for the different aircraft concepts considered within this CONOPS (refer to *Section 8* for a detailed description). They are mentioned briefly below:



Hydrogen-powered aircraft concepts (fuel cell H_2-Electric or gas turbine H_2 combustion) with:

- Fixed tank concept: The hydrogen (liquid or gaseous – LH_2 or gH_2) is transferred into the aircraft via refueling operations with a hose (sometimes referred to in this document as ‘direct refueling’)
- Modular tank concept: The hydrogen storage is not transferred via a hose but rather by using exchangeable tanks that are swapped within the aircraft fuselage during turnaround (referred to as Modules)[4]

Battery-powered aircraft concept: For cases where 100% of the energy comes from the battery, and hybrid-electric aircraft, which use electric motors powered by batteries to provide additional power during specific flight segments to reduce the overall fuel consumption. Some concepts explore using electric energy only during the most fuel-

4 Universal Hydrogen was the only company exploring the modular approach, and most of what is included on the CONOPS’s modular approach comes from their contributions. However, in 2024, Universal Hydrogen has ceased operations.

intensive flight phases (take-off and climb). In contrast, others explore a focus on fully electric propulsion with a hybrid range extension (electric plus jet fuel or SAF).

The assumptions presented below are further substantiated in the rest of this CONOPS. For those identified in the third category – aspects that may change but are currently unknown – further analysis will be needed to better understand the assumptions and substantiate the base understanding developed through the CONOPS.

5.1. ASPECTS THAT ARE NOT EXPECTED TO CHANGE

The following items are not expected to change with the entry into service of aircraft powered by hydrogen or batteries.

- Aerodrome safety and compatibility assessments for the introduction of new types of aircraft and fuels should be conducted as per PANS-Aerodromes (Doc 9981).
- The aircraft will fit within the existing design code definitions. As a principle, if it exceeds existing code definitions, folding wing tips may be considered to ensure stand compatibility of wider aircraft in existing infrastructure, for example.
- The aircraft will integrate into the ground operations portion of Air Traffic Flow Management (ATFM) seamlessly in normal operations.
- The aircraft will operate within existing aerodrome infrastructure considered under the current aerodrome rules and standards (such as runway, taxiway, terminals), except for parking stands for which specific equipment could be required (for example, battery chargers or hydrogen refuelers)
- The approach and departure speeds will remain within existing parameters for similar aircraft types.
- The general turnaround activities (passenger embarking, aircraft catering, loading, etc.) not linked to refueling/recharging will not change; however, the order of those activities or the capacity to parallelize them may change (refer to 9.3).
- The aircraft will coexist within the existing aerodrome and ATFM operational requirements and meet the established normal and contingency operating procedures for the aerodrome when such methods are available. However, some new contingency operating procedures may need to be established.

5.2. ASPECTS THAT ARE EXPECTED TO CHANGE

The following items are expected to change with the entry into service of aircraft powered by hydrogen or electricity.

- For hydrogen aircraft, refueling procedures, operator training/qualification, and ground support equipment will change. This includes the need for specific gH_2

or LH_2 trailers (or hydrants in the longer term) for direct hydrogen refueling processes or exchangeable LH_2 modules.

- For battery-electric-aircraft, charging procedures, operator training/qualification, and equipment will change. This could include exchangeable batteries or the need for ground support equipment for the charging procedure.
- For electric and hydrogen fuel cell aircraft, engine start-up procedures will change (as propulsion will be electric in both cases).
- Rescue and Fire Fighting (RFF) procedures, emergency response profile, equipment, and operators' training/qualification will need to change to accommodate different fuels (battery and H_2). Hydrogen and battery fires, leaks, and spills will have different types of impact to existing fuels and present different hazards and potentially different environmental impacts.
- Passenger and cargo loading procedures will be adapted to consider swap procedures (batteries or modular liquid hydrogen).

5.3. ASPECTS THAT MAY CHANGE BUT ARE CURRENTLY UNKNOWN

The following list of items may change with the entry into service of aircraft powered by hydrogen or electricity. For many of these, the degree of uncertainty is still high and requires further analysis or practical experience through aircraft testing and operation.

- Air operators may need to communicate the fuel types transported through flight plan and/or communication to air traffic control (ATC). This information would be essential in case of emergency operations.
- Fuel safety zones[5] while fueling/recharging/transporting fuel/swap (batteries or H_2 modules) require further analysis and may change. The objective of the Original Equipment Manufacturers (OEMs) and operators is, where possible, to keep fuel safety zones relatively unchanged to avoid a significant impact on operations.
- Turnaround times may change, even though the objective of the OEMs and operators is to keep them unchanged to avoid affecting aerodrome operations.
- Some levels of parallel turnaround activities will remain the same. However, sequences of activities may need to change depending on the fuel safety zones while fueling/recharging/transporting fuel/swap (batteries or H_2 modules).
- Existing aircraft stands will, in principle, accommodate all fuel types (common use approach). However, the outcome should be based on risk analysis and may differ in the early entry into service phase before confidence and experience grows.

5 « Fuel Safety Zones during refueling operations are areas in which no ignition sources are allowed and might extend around tank vents and refuel adaptor points. Currently the zones extend down to the ground during refueling operations and the recommended harmonized safety zone for conventional aviation fuel is a 3m radius » (IATA IFTP Standard Fueling Procedures).

- The weight of aircraft and impact on the pavement is likely to change compared with the equivalent conventional aircraft category and the effects must be considered in aerodrome design.
- Aircraft shape and design, including fuselage length, may change for clean sheet alternative propulsion aircraft.
- Permitting passengers to remain on board an aircraft during gH_2/LH_2 refueling operations or electric charging needs further study.
- Aircraft parking pavement should be constructed from materials, such as concrete, that reduce the risk of combustion in case of a LH_2 spillage during direct refueling operations.

6. REGULATORY OVERVIEW

A number of regulations and industry guidance documentation will need to be updated to appropriately reflect the changes brought about by the entry into service of hydrogen and batteries powered aircraft. However, the scope of the ACAAF-TF is limited to ICAO's Aerodromes Design and Operations-related regulatory materials. The list below only presents the relevant documents in that domain.

- ICAO Annex 14 Vol 1 – Aerodromes
- ICAO Doc 9981 – PANS Aerodromes
- ICAO Doc 10121 – Manual on Ground Handling
- ICAO Doc 9137 – Airport Services Manual (ASM) (series)
    - ASM Part 1 – Rescue and Fire Fighting
    - ASM Part 5 – Removal of Disabled Aircraft
    - ASM Part 7 – Airport Emergency Planning
    - ASM Part 8 – Airport Operational Services
    - ASM Part 9 – Airport Maintenance Practices
- ICAO Doc 9157 – Aerodrome Design Manual (ADM) (series)
    - ADM Part 2 – Taxiways, Aprons and Holding Bays
- Doc 9774 – Manual on Certification of Aerodromes
- Doc 9184 – Aerodrome Planning Manual Parts 1 and 2
- ICAO Doc 9977 – Manual on Civil Aviation Jet Fuel Supply – New Manual to be developed for hydrogen supply management

The ACAAF-TF's initial priority is to conduct a regulatory gap analysis for Annex 14 vol. 1 and PANS Aerodromes. These two documents contain Standards and Recommended Practices (SARPS) that must undergo a lengthy update process within the ICAO mechanisms before becoming applicable.

The following ICAO documents may also need to be considered:

- ICAO Annex 6 – Operations of Aircraft
- Annex 15 – Aeronautical Information Services
- ICAO Annex 16 – Environmental Protection
- ICAO Doc 9640 – Aircraft Ground De-Icing and Anti-Icing Operations

7. STAKEHOLDERS INVOLVED

To properly address the impact of the introduction of hydrogen and battery-powered aircraft at aerodromes from design and operational standpoints, and to secure a holistic understanding, a collaboration with a large number of stakeholders is anticipated, including but not limited to:

- Aerodrome operators
- Aircraft operators
- Ground handling service providers
- Ground support equipment manufacturers
- Air traffic services
- Aircraft, engine, and systems manufacturers (Tier 1, 2, 3)
- Supply chain actors, including fuel providers
- Maintenance, repair and overhaul (MRO) organizations
- Civil aviation authorities and local relevant government organizations
- Regional and global aviation or fuel-related standard-making bodies or regulators
- International industry organizations

The ACAAF-TF has tried to engage with as many organizations as possible, including representatives of some of the industry's sectors mentioned above (see full membership in *Appendix 1*).

8. NOVEL AIRCRAFT OPERATING WITH ALTERNATIVE FUELS

To create a common understanding of the aerodrome operations of aircraft powered by hydrogen or batteries, this section briefly describes the concepts and the general operating model of these concepts.

8.1. USE OF HYDROGEN AS A FUEL FOR AIRCRAFT

There are two main pathways to extract the energy from hydrogen and use it to power an aircraft. One is reversing the electrolysis process and recombining hydrogen with oxygen in a fuel cell to generate electricity. The electrical energy generated through this process can then power an electric aircraft. In this case, liquid water is a by-product of the fuel cell chemical reaction.

Hydrogen gas is flammable, just like kerosene, so using it in a purpose-built gas turbine engine is possible. In this way, thermal energy is extracted from the combustion of hydrogen to power a turbine, similar to the way conventional fuels work in existing gas turbine engines.

Challenges exist for using gaseous and liquid hydrogen as aircraft fuel, such as refueling/defueling operations, LH_2 module swap procedure, H_2 storage in the aircraft, H_2 storage and distribution at the aerodrome, and maintenance. Importantly, thermal/pressure management within the hydrogen tank while the aircraft operates at the aerodrome will have to be adequately managed. For example, aircraft designs should consider extended or overnight stays where liquid hydrogen could warm up and boil off to avoid extra equipment requirements and minimize the burden on aerodromes and operators.

Maintenance procedures for hydrogen-fueled aircraft, both fixed tank and modular types, will need to be developed to manage the hydrogen contained in the aircraft system, particularly when operating in a closed environment like a hangar.

HYDROGEN FUEL CELL AIRCRAFT

Some companies are studying new aircraft or retrofitting existing sub-regional and regional aircraft with a hydrogen electric engine. ZeroAvia, GKN Aerospace, H2FLY, Cranfield Aerospace Solutions, Stralis Aircraft, and Airbus are examples of companies working on hydrogen fuel cell-powered aircraft. The critical challenges under study relate to the limitations of fuel cell and electric propulsion technology power density, heat management, electric power distribution systems, and the weight of the new components.

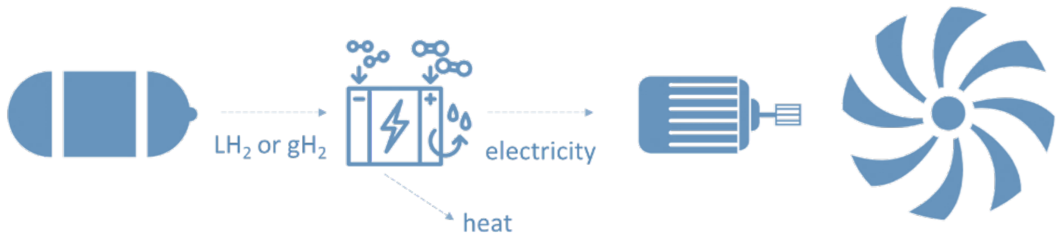


Figure 1. Simplified schematic of hydrogen fuel cell operating system. Source: IATA

Fuel cell-powered aircraft will have unique requirements compared with jet engine aircraft. For example, if hydrogen is stored in its liquid state it will need to be conditioned from its liquid cryogenic state to a gaseous state before it is introduced into the fuel cell (or the gas turbine, if combusted).

The fuel cell aircraft will also have high-power electronics and devices like inverters. High-power (greater than 0.5 MW) electrical motors will be needed to turn the propellers, and these will be fed with high-power cables, plus all the enablers needed to transfer the energy from the fuel cell via inverters to the engines. This could pose different hazards to those present in combustion engines.

A by-product of using hydrogen in a fuel cell is liquid water. The amount of liquid water produced depends on the amount of hydrogen utilized, which directly correlates to the power required. A fuel cell-powered aircraft may leave a water trail on the tarmac during powered operation. Data from Universal Hydrogen suggests that in the case of 2 x 2MW powertrains, this will be up to 5 liters per minute at ground idle. Hence, the management of this water needs to be further assessed.

These aircraft will not produce NOx, SOx, or other greenhouse gas emissions or hot jet blasts given that there will be no combustion process, thus helping to increase local air quality and significantly reducing overall GHG emissions.

HYDROGEN GAS TURBINE ENGINE (COMBUSTION) AIRCRAFT

To power medium and long-range aircraft like the A320 or the A330 types, hydrogen may be used as a combustion fuel in a gas turbine engine. In the 1950s, NACA (now NASA) flew a B-57 with one of its engines fed by hydrogen, and in the 1980s Tupolev converted a Tu-154 to fly on hydrogen. Since then, Airbus, NASA, Boeing, Lockheed Martin, Cranfield University, DLR, and the ATI have performed low technology readiness level (TRL) research on aircraft powered by hydrogen jet engines. Gas turbine developers like Rolls-Royce, General Electric, and Siemens have demonstrated ground gas turbines running with different blends of hydrogen that go all the way to 100%.

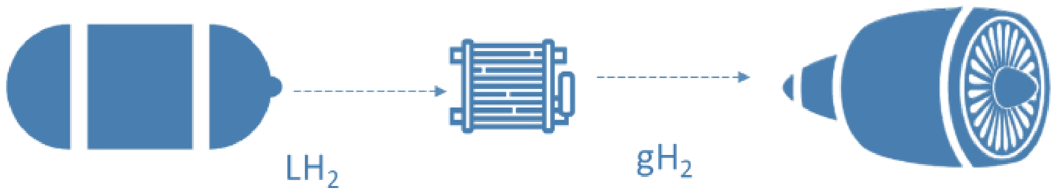


Figure 2. Simplified schematic of hydrogen-powered gas turbine operations. Source: IATA

These larger aircraft will naturally require larger quantities of LH_2 stored, 4-5 tonnes instead of less than 1 tonne for smaller fuel cell aircraft. The aircraft engine will combust the hydrogen, so thermal NOx will still be produced, though possibly in smaller quantities compared with conventional fuel aircraft. Given that the powertrain is not electric, none of the mega-watt power electronics will be required.

8.2. BATTERY AND HYBRID-ELECTRIC AIRCRAFT

Two options are considered for battery electric aircraft: Aircraft using only battery power and a combination of battery and standard kerosene or SAF as a hybrid combination.

Legacy (mainly hybridization) and start-up aircraft manufacturers are exploring battery-powered aircraft. The initial flight tests and demonstrators flying with 100% battery-powered powertrain have been on a sub-megawatt scale. For example, a DHC-2 de Havilland Beaver was flown by Harbor Air with a 0.5 MW motor with a capacity of 6-19 passengers and autonomy of less than 30 minutes. The Eviation Alice was the first clean-sheet fully battery electric aircraft to take off and has a range of 450km, including reserve, with similar passenger capacity, using two 0.7 MW motors. Heart Aerospace has the largest hybrid-electric concept with a 30-passenger capacity on a 200km range (all electric), which could be extended to 400km on a hybrid configuration. Legacy manufacturers such as Pratt & Whitney, General Electric, and ATR are also exploring hybrid concepts with megawatt capacity (1-2 MW) for regional aircraft to operate in a hybrid manner.

Hybrid-electric or full battery-electric aircraft will have batteries, which will fully or partially power the aircraft. These batteries will potentially need to be recharged at the airport (on a plug-in hybrid configuration) with careful sequencing between fueling, in the case of hybrid concepts, and charging. High-power charging stations will be required at the gate, and the corresponding infrastructure and safety procedures will be needed. It is still to be defined whether the recharging operation time will be similar to the refueling time of a similar size and range aircraft and what the fuel (or charge) safety zones could be.

The batteries could also be exchanged instead of recharged. To the best knowledge of the authors of this CONOPS, however, no company has matured this concept yet, and thus these operations are not covered in detail here.

The maintenance and recharge procedures will need particular attention to avoid battery damage, overheating, or fire. For hybrid concepts, firefighting and rescue teams must know that the aircraft has two energy carriers with distinctive hazards and fire properties.

Utility electricity supply capacity and infrastructure may also need to be upgraded, with the potential for airport substations being required.

9. AIRCRAFT OPERATIONS AT AERODROMES

This section describes how a hydrogen or battery-powered aircraft will operate at and around an aerodrome, from approach and landing to taxiing, arrival on the stand, turnaround procedures, push-back, taxiing out, and take-off. The following sections describe the operation of the aircraft, sometimes split between electric and hydrogen-powered aircraft. Identified knowledge gaps are also offered at the end of each section to capture further research or information that may be needed.

Although an initial view of the ACAAF-TF is provided here, a thorough risk assessment at each operational stage will be required to corroborate the findings and recommendations of the Task Force. Relevant examples of detailed risk assessment (severity, mitigation strategy, risk management plan, etc.) are proposed to be formalized in the PANS-ADR (Doc 9981) and Manual on Ground Handling (Doc 10121) as relevant. An aerodrome compatibility study is recommended for a certified aerodrome operator before the commencement of operations of a hydrogen or battery-powered aircraft on the aerodrome[6]. This includes a complete analysis of the impact on operations and design of the aerodrome.

9.1. AERONAUTICAL INFORMATION

With the intent of providing information to aircraft operators on the types of fuels available at the aerodrome, aerodrome operators will need to publish fuel handling capabilities, aircraft rescue and fire fighting resources for aircraft types using alternative aviation fuels, and any aerodrome constraints in the Aeronautical Information Publication (AIP). This information will be needed for the flight planning activities of aircraft operators.

9.2. APPROACH, LANDING, TAXI, ARRIVAL ON STAND

APPROACH

Alternative fuel-powered aircraft are expected to approach the airport in the same way as conventional aircraft and fit within existing approach speed categorizations. Design features like high-lift devices could address potential changes (due to the additional landing weight) in aircraft approach speed and required separation distances. It must be noted that wake vortex categories are currently based on maximum take-off weight (MTOW) and wingspan.

6 As provided for in the provisions found in Chapter 4 of Part 1 of the ICAO PANS Aerodromes (Doc 9981).

One less noticeable change with hydrogen-powered aircraft concepts is the relationship between operating empty weight (OEW) and the MTOW. Unlike kerosene-fueled aircraft, whose mass diminishes significantly during a flight due to the kerosene consumed, the mass of hydrogen consumed will be relatively small, as the hydrogen itself is lighter than kerosene. However, the tanks and fuel systems will be heavier, particularly with liquid hydrogen.

The available literature for clean-sheet hydrogen aircraft presents ranges from 20-30% heavier OEW to 20-30% lighter. The OEW saving opportunities are more likely on larger aircraft (100+ pax) than on smaller regional aircraft due to the significant fuel weight. On regional aircraft and particularly on retrofitted aircraft, the OEW is expected to be higher for hydrogen than for kerosene aircraft[7].

Depending on the aircraft design and configuration, there may be an impact on the pavement due to different weight distribution or possibly higher landing weight. Pavement compatibility will be assessed as per Aircraft Classification Rating – Pavement Classification Rating (ACR/PCR) method (*Airport Development Manual Part 3*).

The potential affects of different landing weights and landing speeds on the runway occupancy time will need to be considered.

Battery-powered aircraft will be heavier at landing compared with their counterparts for the same payload due to the weight of the batteries. When conventional jet-fuel-powered aircraft land, the fuel has been consumed, so landing weight is considerably lower than take-off weight. Coordination between electric aircraft manufacturers and aerodromes will need to take place to ensure pavement limits are not exceeded[8].

Whatever the source of fueling energy, new aircraft types will have to be designed to meet targeted aerodrome pavement requirements as per the ICAO ACR-PCR method.

TAXI AND ARRIVAL ON STAND

BATTERY-ELECTRIC POWERED AIRCRAFT

Operationally, the taxi and arrival on the stand are expected to be conducted in much the same way for alternative fuel-powered aircraft concepts as it is done for their kerosene counterparts. However, the aircraft stand's electrical power capability (i.e., availability of sufficient power) will need to be considered in the stand planning process.

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7 For example, the hydrogen powered ATR72 which was considered by Universal Hydrogen aimed to operate at the original 23T MTOW, but with a usable fuel capacity of around 400 Kg H_2 (1.7% of MTOW), compared with 5T of kerosene (21,7% of MTOW).

8 This is common practice for any new aircraft type.

Consideration may be needed for the use of extended towing taxi systems at aerodromes to support aircraft ground movement, as aircraft may need to economize battery power when taxiing. This would be the case if there are long taxi times, both on arrival and departure.

On arrival on the stand, the charging system, including the battery conditioning system, will need to be plugged in immediately, allowing the batteries to be conditioned for charging (cooling or warming). The time required for battery conditioning will need to be considered in the turnaround time. Additional information from aircraft and battery manufacturers will be required.

Figure 3. Taxibot in use at Schiphol Airport. Example of extended towed taxiing operations. Courtesy of Schiphol Group.

Aerodromes will also need to consider the possible challenges related to the potential use of segregated aircraft parking stands due to different fuel types. This, in turn, could create challenges in stand capacity at aerodromes and the ground support equipment (GSE) required.

HYDROGEN AIRCRAFT

Hydrogen-powered aircraft operated by a fuel cell will produce droplets of liquid water as a by-product of the fuel cell reaction. At ground idle, a regional aircraft using 2MW electric motors will disperse around 5 liters of water per minute[9]. It is unknown whether the continuous ground operation of hydrogen-powered aircraft would impact the pavement surface, particularly in below-freezing conditions while taxiing or while parked at the stand. This could be addressed by capturing the water while taxiing, but it is still a knowledge gap.

Liquid hydrogen direct refueling operations could require implementing capabilities to properly manage return gaseous hydrogen from boil-off or exchanges between the aircraft and the refueller tanks. This could be handled by rejecting this gaseous hydrogen via dedicated venting systems or by implementing storage capabilities at aircraft and refueler GSE and/or stand level. This need will have to be considered during the design, operations, and safety analyses stages. Stands and refuellers may be equipped with hydrogen sensors for leak detection, and compatibility with required turnaround GSE must be considered while managing the venting or capturing the vented gaseous hydrogen.

A spill of liquid hydrogen poses new risks, unlike that of kerosene. Liquid hydrogen must be stored at temperatures below -253°C. In the case of a liquid hydrogen spill, the air around it will become solid as oxygen freezes at -218°C and nitrogen at -209°C. A liquid hydrogen spill onto a bituminous tarmac surface increases fire risk because the fuel and oxygen are readily combined during the spill. The combustion risk can be lowered by the use of a concrete stand.

Similarly, as with electric aircraft, aerodromes will need to define whether the stands can be mixed-use or used exclusively for hydrogen aircraft. This will depend on the fixed infrastructure available, GSE, and possibly fueling safety distances (if these are to change).

IDENTIFIED KNOWLEDGE GAPS

The identified knowledge gaps related to the approach, landing, taxiing, and arrival at stand phases are:

- Weight (MTOW, OEW, lift weight) of alternative fuel-powered aircraft concepts and their potential impact on the aerodrome pavement, particularly at landing.
- The potential impact of liquid water by-product of hydrogen fuel cell reactions during the taxi and on-stand operations, particularly at and below freezing conditions.
- Pavement material and compatibility with liquid hydrogen spills.
- The possibility of aircraft stands to cater to different aviation fuels.

9 Data provided by Universal Hydrogen.

9.3. TURNAROUND OPERATION: PASSENGER DISEMBARKATION AND AIRCRAFT SERVICING

DESCRIPTION OF OPERATIONS

The turnaround operations described in this section are considered from the moment chocks are positioned. Overall, the objective for the whole turnaround is to remain as close as possible to the existing process to parallelize as many servicing and management activities as possible. However, some changes are expected, particularly regarding refueling or charging procedures and related/required GSE. Because of this, refueling is addressed in detail in a separate section. The main turnaround activities included in this section are the following:

- Arrival/departure to/from the parking stand (no changes expected)
- Power servicing/fueling/charging (changes expected, addressed in 9.4)
- Ramp securing (no changes expected)
- Passengers disembarking (no changes expected)
- Passengers embarking (no changes expected)[10]
- Cabin cleaning (no changes expected)
- Cargo loading (no changes expected)
- Catering (no changes expected)
- Potable water and lavatory servicing (no changes expected)
- De-icing at the parking stand or a dedicated pad (no changes expected)

Figure 3. Turnaround schematic of a regional hydrogen aircraft: Courtesy of Airbus.

10 Although passengers are expected to board and disembark the aircraft in the same way as conventional aircraft, the capacity to do so at the same time as the aircraft is being refueled/recharged, is still unknown.

Passenger disembarkation is expected to remain the same. Aircraft manufacturers should aim to avoid disruption that could significantly impact such activities.

It is possible that extra procedures and GSE are required on parking, depending on the energy type carried on board and before refueling starts. For example, thermal GSE might be needed for electric aircraft to condition the batteries in hot/cold climates and during fast charging. This should be plugged in directly when the aircraft has arrived on the stand to shorten the turnaround time.

For liquid hydrogen-powered aircraft, there may be a need to connect a gaseous hydrogen vent line on landing to extract boil-off hydrogen from the tanks and stabilize the tank pressure. This will be defined by the tank specifications, dormancy period, and operating procedures. For direct refueling aircraft, there may be a need for potential pre-conditioning or pre-chilling of the refueling lines, such as nitrogen purging, to avoid oxygen entering the aircraft tank.

As with existing refueling operations, suitable fuel safety zone requirements will need to be established for hydrogen refueling, electric charging, or possibly battery conditioning operations. These will need to be established through risk assessments that consider aspects related to the specificities of the fuels, aircraft, aerodrome design, and operations. These fuel safety zones will, in turn, determine which ground servicing activities can occur during refueling-related operations.

On a global level, coordination will be necessary to develop industry-wide guidelines pertaining to certain critical aspects of refueling operations, particularly the safety and quality of the fuel, even though the characteristics and processes or protocols applicable for each aircraft/OEM could be proprietary. A harmonized approach will be necessary to ensure application on a global level.

IDENTIFIED KNOWLEDGE GAPS

The identified knowledge gaps related to the turnaround operation are:

- Level of parallelization of H_2 refueling, battery recharging, or tank/battery swap with other turnaround activities.
- Specific procedures for direct LH_2 refueling at the aerodrome, including pre-chilling or pre-conditioning and purging the fuel lines before refueling, if required.
- Possible changes to fueling safety distances, vehicle approach protocols, or interfaces with other services.
- Loading and unloading procedures for LH_2 modules, if applicable.

9.4. TURNAROUND OPERATION: REFUELING/RECHARGING OPERATIONS (REFUELING OR MODULAR APPROACH)

HYDROGEN-POWERED AIRCRAFT

The framework considers two primary methods: fixed tank direct refueling and LH_2 modules. Each approach presents unique advantages, and the optimal choice depends on various operational factors.

FIXED TANK DIRECT REFUELING

Here, H_2 is stored in large H_2 tanks at an aerodrome's specified location (or off-site) and transported in specialized refuellers. The aircraft would then be refueled directly on the apron in a similar general process to jet fuel refueling today. During refueling, the hydrogen is transferred directly from these storage tanks into the aircraft's fuel tanks through transfer lines pumps or pressure differential. Pipeline supply, such as today's jet fuel hydrant systems, could be considered in the future.

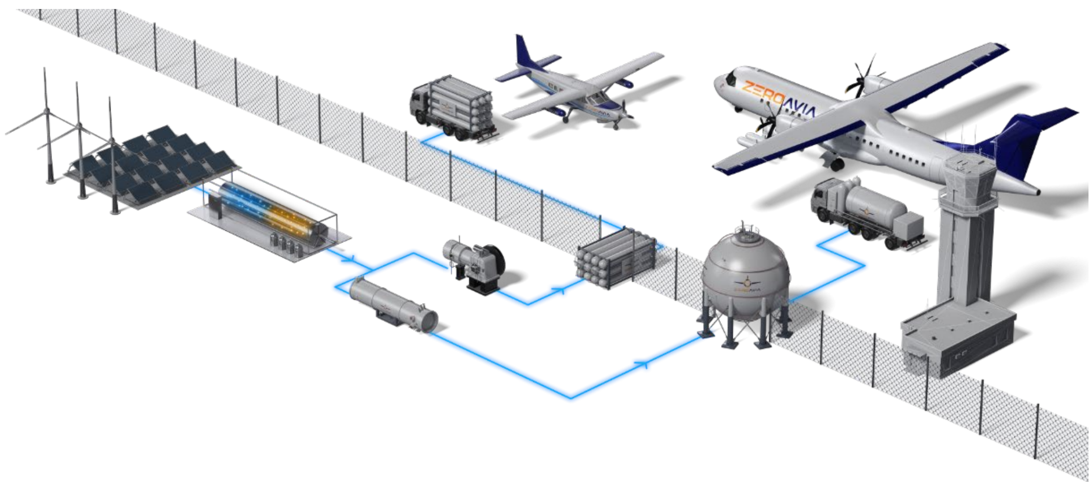

Figure 5. Concept of operations of gaseous and liquid hydrogen supply & direct refueling: Courtesy of ZeroAvia.

If hydrogen was eventually delivered via a hydrant system, it is expected that a suitably designed hydrant dispenser would be required with all the relevant safety, quality, and operational protocols. However, in both the hydrant and the bowser model, a hydrogen dispenser may be required to manage refuel line pre-cooling, conditioning, and purging and gH_2 venting during LH_2 refueling.

Fuel safety zones must be analyzed via suitable risk assessments. It is expected that the aircraft will have to be electrically bonded, as happens today for conventional jet fuel and other fuels (Avgas) to minimize electrical static hazards between the refueler and the aircraft.

FIXED TANK – GASEOUS HYDROGEN

Initially, hydrogen is expected to be delivered by refueling trucks, much like kerosene bowser trucks today. The truck will arrive and park adjacent to the aircraft. The fuel will be stored in high-pressure vessels on the refueler. The fuel safety zone between the bowser truck and the aircraft will need to be determined.

The aircraft will first be bonded to the ground through a bonding cable. The operator will then connect the hose to the aircraft. Similar to refueling a road vehicle with gH_2, it is probable that once the coupling is connected, there will be a pressure system check for leakages before the injection of hydrogen.

The manufacturers' aim is to keep turnaround times the same. This would require some of the activities mentioned in 9.3 to occur in parallel to refueling.

Once the hose is connected, and the fuel safety zone cleared, the transfer of gH_2 will begin until the desired tank pressure or state of charge is reached (it is likely that the refueling of gaseous hydrogen will be controlled by the receiving tank temperature and pressure to a defined protocol e.g. SAE J2601 or similar see *Appendix A.2.1*) as opposed to fuel flow.

Once the fueling is complete, the hose will be disconnected and stowed. The bonding cable is then disconnected and stowed.

The operation will probably require gH_2 sensors at different points, including by the bowser truck, near the connection point, and possibly at the terminal building where the aircraft is parked, to detect any hazardous leaks. However, the exact requirement and location are still unknown and should be subject to risk assessment and follow-up actions.

FIXED TANK – LIQUID HYDROGEN

Liquid hydrogen storage will be required for larger aircraft and/or aircraft intended for longer regional missions. It has a higher density and allows more fuel to be stored on board, thus extending the range of aircraft.

Hydrogen is expected to initially be delivered by refueling trucks in a similar way to kerosene bowser trucks today. The truck will arrive and park in the vicinity of the aircraft. The fuel will be stored in a liquid hydrogen tank, where the hydrogen will be stored at temperatures below -253°C, and, therefore, heavy insulation will be required throughout. The fuel safety zone from the refueling port or vents will need to be determined as part of the risk assessment process. It may be different from high-pressure gaseous hydrogen storage, as the hazards may be different[11]. The manufacturer's aim is to achieve a turnaround time similar to that of an existing kerosene-powered aircraft. This would require parallelization of refueling operation with the activities mentioned in 9.3.

The LH_2 hose will be of larger diameter than those used for kerosene and gaseous hydrogen to ensure adequate fuel flow and achieve suitable turnaround times. Because the density of hydrogen is lower than kerosene, it would otherwise take longer to transfer the same mass of fuel through a hose with the same diameter. The hose will also be heavily insulated as the liquid will be cryogenic. For this reason, the hose is expected to be considerably heavier than a hose used to transfer conventional jet fuel. It is possible that the operator will require some form of powered assistance to move and locate the hose.

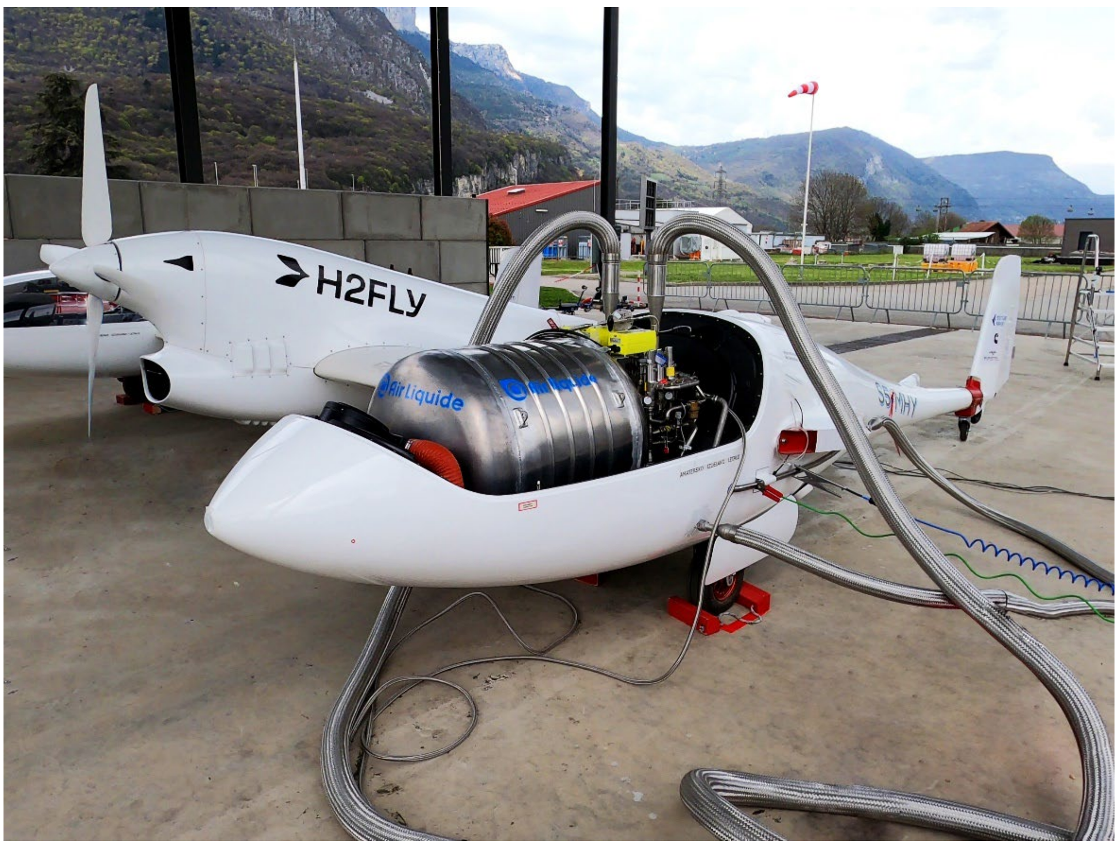

Figure 6. Liquid hydrogen refueling operations of the first-ever LH_2-powered demonstrator flight. Courtesy of H2FLY.

Consideration and further analysis are needed regarding the types of surfaces hydrogen-powered aircraft are parked on, as explained in section 9.2. The operator

11 A potential hazard for high-pressure vessels which would be absent in liquid hydrogen tanks is that any puncture or orifice in the tank would result in a jet of gaseous hydrogen being released which could reach several meters.

might also require personal protective equipment (PPE) to safeguard against extremely cold temperatures in case of a minor spill[12].

The aircraft will be electrically bonded through a bonding cable before the refueling hose is connected. The refueling operation will begin once the hose is connected, and the fuel safety zone is cleared. Aircraft fuel systems' pre-cooling, conditioning, and purging may be required. Priming is a process where nitrogen is injected into the fueling system prior to refueling to ensure that there is no oxygen anywhere in the lines to avoid a flammable mixture of oxygen and hydrogen. Chilling is a process used in space applications where the lines, valves, and connectors are pre-cooled before the cryogenic hydrogen is delivered to avoid thermal shocks. It is unknown if this will be the case for aircraft applications, and those operations are not described in detail here. Experience from liquid hydrogen test flights suggests that a hydrogen fueling nozzle with an internal check valve could allow for disconnection without the need for priming[13].

The liquid hydrogen will be metered with a flow meter (not with pressure as with gH_2), and once the requested fuel mass is reached, the fueling will stop. The gaseous hydrogen contained in the tank (boil-off from the liquid) may have to be addressed.

Venting gH_2 into the environment (no gH_2 retrieval) is not recommended for safety, environmental, and economic reasons, and should be done only on experimental aircraft under controlled conditions and with small quantities, and in emergency procedures. Once the fueling is complete, the hoses will be disconnected, made inert if applicable, and stored. The bonding cable is then disconnected. The hoses' disconnection and the procedure to make it inert, and the traffic flow of the hydrogen transporting trucks will need to be managed and the risks associated considered in a similar manner for refueling vehicles currently.

The operation with LH_2 may also require gH_2 sensors at different points (as suggested in the previous section Fixed tank- gaseous hydrogen) to detect any leaks. However, the exact requirements and location are still unknown.

MODULAR LIQUID HYDROGEN REFUELING[14]

Some aircraft concepts might have one or several exchangeable tanks, which are refueled outside the aerodrome premises. In this case, the used hydrogen module will be removed from the aircraft and replaced by a full module.

12 This might include but is not limited to gloves, eye/face protection and a mobile H_2 sensor on the operator.

13 From the flight test campaign of H2FLY liquid hydrogen flying demonstrator.

14 Based on turnaround concept developed by Universal Hydrogen. Universal Hydrogen ceased operations in 2024, but the ACAAF-TF has opted to keep this CONOPS for future reference.

For these operations, a standard ground handling tug or tractor with dollies and a Unit Load Device (ULD) container loader to unload and load the modules within the aircraft will be needed. On the aircraft, a large module door will be opened to access the module compartment. Fuel safety zones will also have to be defined for this procedure, and before the module is disconnected from inside the aircraft, the fuel safety zone will have to be secured, including passengers outside and inside the aircraft (if applicable). The aircraft may also have to be electrically bonded to the ground.

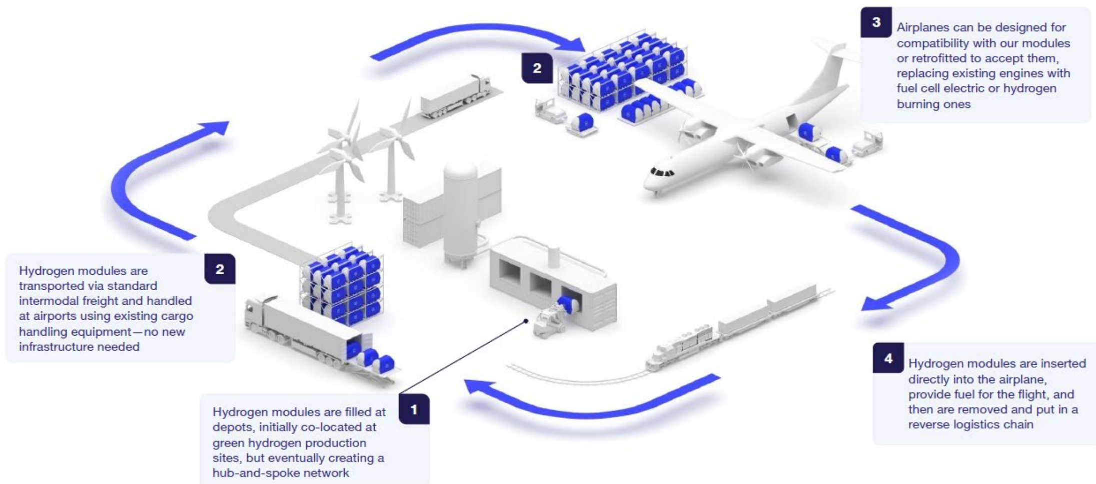

Figure 7. Modular hydrogen tank refueling concept: Courtesy of Universal Hydrogen.

An operator will enter the aircraft module compartment and will disconnect the module from the aircraft. The module will also be de-latched from the floor-mounted loading system. It is expected that the module itself and the compartment will be equipped with sensors to detect any leakage. The operator may need to wear special PPE for these operations.

As with ULD unloading, the operator will use a cargo loading system (CLS) to manipulate the used module towards the module door, before engaging it onto the rollers of the cargo loader. The cargo loader will then be lowered before the used module is transferred to the dolly. It is recommended that a visual inspection of the module be performed to ensure there is no visible damage. Any damage should be logged in, reported, and assessed. Once the dolly is loaded, the tug will take the used module away. The procedures for refueling the tank offsite are outside the scope of this CONOPS, but the traffic flow of these tanks will need to be managed, and the risks will need to be considered.

Figure 8 Hydrogen module exchange, technology demonstrator: Courtesy of Universal Hydrogen.

After the used module dollies have cleared the stand, the dollies with the full modules will approach the cargo loader and be transferred onto it, raised, and positioned inside the module compartment. The modules could have their own on-board systems for health monitoring and will be first latched to the floor mounted loading system and then connected to the aircraft systems via fluidic, venting, and electrical quick connections.

A visual check must then be performed, followed by aircraft systems tests to ensure the end-to-end hydrogen fuel system is operative and safe. Specific processes may be required to attest that the aircraft is in flight condition.

Although it is envisaged that the LH_2 module loading and unloading will be similar to ULD loading and unloading, the skill and approval level of the operators will be greater. This is not only because module handling will require greater care, but module system connections, inspection, and system testing prior to flight may need to be initially covered by B1 and B2 licensed engineers.

KNOWLEDGE GAPS IDENTIFIED FOR HYDROGEN AIRCRAFT

The identified knowledge gaps related to the fueling phase for hydrogen aircraft operations, for all concepts are:

- Fuel safety zones from refueling activities to heat sources or sparks, for the different types of operations will have to be defined, taking into consideration the design of the aircraft and the refueling process/coupling.
- The minimum distance to be maintained between the hydrogen storage on the refueling vehicle and the aircraft, as well as spacing between aircraft, will have to be defined based on a risk assessment.
- Pavement material and compatibility with liquid hydrogen and potential risk of chemical reaction in the event of a spill.

- Personal protective equipment for handling LH_2 and gH_2 must be considered based on the estimated risks.
- Based on risk assessments, the need for hydrogen sensors, their number, and position should be determined to detect any potential hydrogen leaks. Liquid hydrogen leaks will be easily detected by the eye, while sensors in the fuel lines could detect anomalies like pressure drops or abnormal temperature operations.
- Consideration of natural or forced ventilation on infrastructure elements (hangars, parking stands) to avoid accumulation of fugitive/vented gaseous hydrogen. Defueling operations may be required and so would have to be further understood.
- Visual (and other) inspections of LH_2 modules for connection into aircraft fuselage must be defined, along with periodicity of other more detailed inspections, to ensure the integrity of the tank, the valves, and the connectors.
- The need to have a declared capacity/publication of the capacity of available fuel types at an aerodrome and RFF capability.

KNOWLEDGE GAPS SPECIFIC TO LIQUID HYDROGEN AIRCRAFT

The issues of hydrogen tank temperatures and refueling temperature differentials, cooling times, boil-off, and so forth, will need to be considered in the refueling process timeline. On landing, the hydrogen tanks will have at least reserve fuel levels of LH_2 onboard. This LH_2 could warm up if the aircraft is operating in a very hot ambient temperature environment, depending on the tank location and the insulation characteristics of the tank materials and system. If the hydrogen's temperature increases, it would increase H_2 boil-off by evaporation, and the pressure in the tank would rise. This is particularly an issue on landing where the heat sink provided by the fuel would be lower due to the lower volumes of fuel in the tank. It is unknown whether this will be an issue and whether operational procedures will be needed to mitigate this warm-up and boil-off effect, particularly on the last flight of the day or for any other operations where aircraft will be parked for an extended period.

It is unknown whether the aircraft tanks and fueling systems will need to be pre-conditioned (cooled, primed) prior to the start of the LH_2 flow. If this is required, any additional equipment or procedures must be considered.

BATTERY-POWERED AND HYBRID AIRCRAFT

Battery-powered aircraft would require charging at the aerodrome. This could happen in several different ways:

- Aircraft could be fast charged at the gate under human supervision similar to the way aircraft are refueled today.

- Aircraft could be slow charged overnight with no human supervision.
- A battery swap could take place during the turnaround or during a night stop (not considered in details in this CONOPS).

In general, aerodromes will need to consider the maximum power loads that are going to be required due to the simultaneous charging of aircraft at the aerodrome. Energy capacity will most probably need to be upgraded to cater to increased demand.

CHARGING AT THE PARKING STAND

Once the aircraft is parked, it could be grounded as it is done today with conventional jet fuel aircraft. It is possible, however, that this grounding connection will have to be rated to higher currents and voltages or that this could be different altogether considering the high rate of energy transfer into the batteries. Alternatively, grounding could no longer be necessary if the charging standard includes protected earth like the Megawatt Charging System (MCS) or Combined Charging System (CCS) standard.

An operator will then plug a cable into the aircraft charging point, this cable can come from a parking stand power source or a remote vehicle with very large batteries, which will have to be parked in the vicinity of the aircraft. Fuel/recharge safety zones surrounding the charging point will need to be defined, particularly if the surrounding GSE are not electrically powered.

The electrical connections must be verified before the cable is energized. Potential impact on parking stand design and ground handling procedures would have to be assessed based on risk analysis. It has been identified that battery fires could last for longer, radiate more heat, and emit more toxic fumes than kerosene or hydrogen fires, and thus special considerations might be required to protect the building and other aircraft should a battery fire occur.

Once the desired charge is achieved, the cable will be disconnected and stored.

If the aircraft is hybrid-electric, it is unclear whether charging and fueling will be able to be done in parallel. If not, it is unclear which of these should be done first, or what special considerations should be taken if the aircraft also has kerosene stored in its tanks.

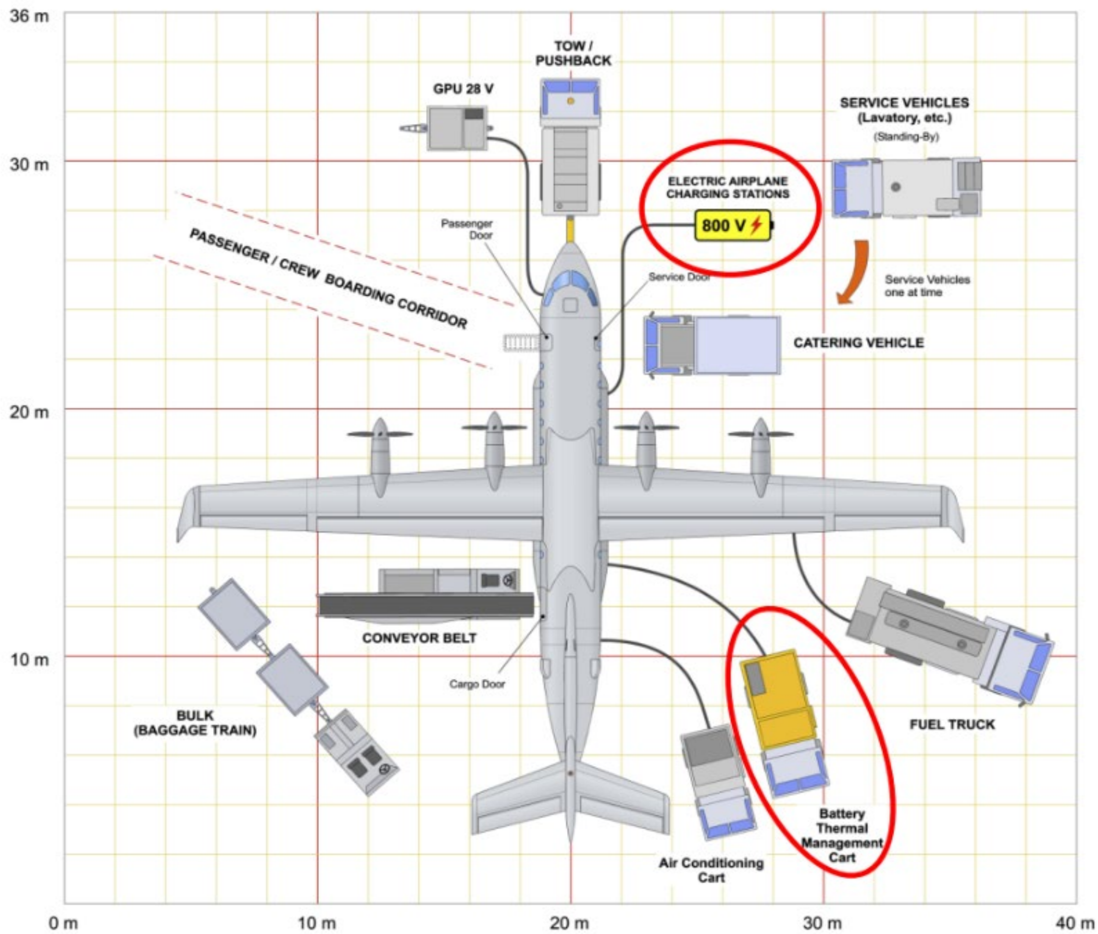

Figure 9. Turnaround procedure of hybrid-electric concept. Courtesy of Heart Aerospace

SLOW CHARGING

For slow charging without human oversight, it is unclear if this can happen at the gate and/or remote parking stand. Certainly, this would have to be done in a safe environment and must have virtual supervision. This virtual supervision could include visual cameras, thermal sensors, and smoke detectors, which could send information to a human-supervised monitoring station.

KNOWLEDGE GAPS FOR BATTERY-POWERED AND HYBRID AIRCRAFT

The identified knowledge gaps related to the charging phase for electric-powered aircraft are:

- A better understanding of the scenarios in which the aircraft will require slow or fast charging is necessary and it must also be decided if there will always need to be full charge or if partial charging may be possible.

- The identification of new hazards related to charging, particularly high-power electricity on the ground and around aircraft, as well as potential issues related to the weight of charging cables.
- The identification of the need for sensors for monitoring and avoiding overheating or overcharging.
- Understanding of the types of GSE thar will be needed to support the charging, for example a battery conditioning cart to manage the heating and/or cooling of the battery.
- Compatibility with kerosene and/or hydrogen GSEs.
- The future possibilities of hybrid aircraft with dual capabilities like hydrogen refueling and electric charging or kerosene refueling and electric charging.

IDENTIFIED KNOWLEDGE GAPS FOR ALL ALTERNATIVE FUEL AIRCRAFT

On top of the knowledge gaps which are particular to specific aircraft concepts, some gaps apply to all the configurations as summarized below:

- The identification of the procedures and possible limitations for refueling/recharging aircraft with passengers on board and embarking/disembarking.
- The level of standardization and regulation of fueling systems and procedures that will be required.
- Understanding potential impacts of refueling requirements and procedures on parking stand design, turnaround times, block time and slot coordination, and the allocation of stands to aircraft operating on different fuel types.
- Understanding how simultaneous operations with different fuel types on different aircraft may be treated or managed on a single aircraft stand or series of stands.
- The impact that different aircraft powered by different fuels could have on the allocation of stands, the identification of the training and qualification requirements, and possible needs of ground staff who perform fueling/charging operations.

9.5. TURNAROUND: PASSENGER EMBARKATION AND AIRCRAFT SERVICING

The operating procedures and activities identified for the passenger boarding phase are the same as those identified in the previous section, *9.3. Turnaround: passenger disembarking and aircraft servicing*. No new impacts or gaps have been identified for this phase.

9.6. PUSHBACK, ENGINE START-UP, TAXI-OUT, DEPARTURE

DESCRIPTION OF OPERATIONS

Hydrogen-powered aircraft are expected to push back from the parking stand or be moved from a parking stand in the same way as conventional aircraft.

Battery-powered aircraft with limited battery capacity might rely more on ground power for aircraft air conditioning (particularly in extreme weather), systems conditioning, and engine start-up. When this is the case, battery-powered aircraft will benefit from being electrically connected to the terminal as long as possible prior to disconnection and pushback. Also, battery-powered aircraft will not have the same need for spool-up and warm-up of the engine as a kerosene engine. The direct power provided to the engine by the battery would allow for a more rapid start-up sequence, potentially improving the flow and movement of aircraft.

Prior to pushback, all cables, hoses, and associated energy equipment will have to be safely removed and packed, and the path for aircraft taxiing must be clear.

Several solutions may be considered for pushback, but these are generally independent of the type of energy carried on board the aircraft. For example, autonomous pushback may be possible for aircraft equipped with an electric motor on the landing gear. Alternatively, a separate towing device may be provided which could be a conventional towing truck, an autonomous or semi-autonomous vehicle like a taxibot, or another innovative technology outside of the aircraft.

Figure 10. Hydrogen-powered aircraft tug being tested at Cranfield University. Courtesy of Cranfield University

Taxiing procedures are expected to be the same as those for current operations for both hydrogen and battery-powered aircraft. Some specificities related to the ground operations of battery-powered aircraft are mentioned in the identified knowledge gaps section below.

Air Traffic Control procedures are expected to remain the same as current conventional aircraft operations.

IDENTIFIED KNOWLEDGE GAPS

The identified knowledge gaps related to the pushback, engine start-up, taxi-out, and departure operations are:

- Standard operating procedures for single-engine taxi operations may need to be changed for hydrogen and battery aircraft.
- Engine start-up procedures may need to be reviewed. The location of the engine startup process will have to be determined, such as start-up clearance at the gate or start-up before entering the runway.
- The potential impact that materials, including fluids, sand, and grit, used for snow/ice control will have on these new aircraft concepts and their systems will have to be analyzed.

HYDROGEN-POWERED AIRCRAFT

The identified knowledge gaps related to the pushback, engine start-up, taxi-out, and departure operations specific to hydrogen-powered aircraft are:

- Ambient temperatures may affect fuel cell startup, and the fuel cell might need to be conditioned.
- Some manufacturers may intend to capture part of the liquid water exhaust from fuel cells under very cold conditions to avoid water accumulation on the ramp. Operating procedures will have to be determined for this.

HYBRID AND BATTERY-POWERED AIRCRAFT

The identified knowledge gaps related to the pushback, engine start-up, taxi-out, and departure operations specific to battery-powered aircraft are:

- The potential impact of weather conditions on battery power consumption will need to be reviewed. For example, de-icing battery-powered aircraft requires a certain holding time, which may be detrimental to energy management. Dedicated procedures may elect to prioritize electric aircraft for de-icing operations or provide Ground Support Equipment (GSE) to avoid using up battery time.
- The duration and the efficiency of the taxi-out and de-icing procedures may impact energy management of the aircraft.
- Pushback procedures may need to be changed, such as the sequence of cable disconnection before the actual pushback.

9.7. ABNORMAL AND EMERGENCY OPERATIONS

GENERAL CONSIDERATIONS

The risks for all aircraft concepts using alternative fuels may differ significantly from those for kerosene aircraft. Kerosene (Jet A, Jet A-1, Jet B) is a flammable liquid at ambient temperatures, and the main risks are generated by occasional spills or accidental leaks that may create a large, contaminated area that may in turn be ignited in the presence of an ignition source.

Any subsequent fire will then easily spread, threaten egress routes and slides, and ignite other fuselage parts.

The principal objective of an RFFS is to save lives in the event of an aircraft accident or incident occurring at, or in the immediate vicinity of, an airport. The RFFS is provided to create and maintain survivable conditions, provide egress routes for occupants, and initiate the rescue of those occupants who are unable to make their escape without direct aid. The rescue may require equipment and personnel other than those assessed primarily for rescue and firefighting purposes.

The most important factors bearing on effective rescue in a survivable aircraft accident are the training received, the effectiveness of the equipment, and the speed with which personnel and equipment designated for rescue and firefighting purposes can be put into use.

Requirements to combat building and fuel farm fires or to deal with the foaming of runways are not taken into account (ref. ICAO (2018), Annex 14, Chapter 9.2).

For any aircraft concept using alternative fuels, in the case of abnormal or emergency situations, it is necessary for both flight crew and RFFS to:

- Identify and confirm the type of fuel(s) and propelling system of the aircraft.
- Identify and communicate the type of situation or emergency (e.g., thermal runaway, gaseous leak, fire, collision with damage).

Then, emergency operations will depend on the assessment of the type of situation and:

- The activity (landing, refueling, taxiing, etc.).
- The location of the aircraft (runway/taxiway, on stands, remote parking, inside a hangar).
- The presence of persons on board or near the aircraft (ground service, terminal, etc.).
- The volume/quantity of flammable substances.

BATTERY-POWERED AND HYBRID AIRCRAFT

For Lithium-ion (Li-ion) batteries[15], once initiated, fires may be more localized (with no creation of spill and ignited ground surface), but they are more difficult to extinguish as traditional extinguishing agents are less effective, and access to battery packs may be restricted.

Emergency operations and firefighting operations are also more complicated and dangerous because of toxic and explosive vapors venting and possible projectiles, such as molten metallic materials. Where battery fires are concerned, there is a very high explosive potential of hydrogen released from the battery even if the battery is not burning.

Specific abnormal and emergency operations for battery-powered aircraft may result from issues with the electrical system or with an electrical motor, or from a thermal runaway of the Li-ion battery, which is, to date, the expected technology for first future aircraft.

Electrical risks should also be considered in both cases because of the high voltage systems and equipment found on full battery-electric or hybrid/electric aircraft.

RISKS FROM THERMAL RUNAWAY

A thermal runaway is an internal chemical self-heating chain reaction of a Li-ion battery. It can be due to:

- An internal or electric fault, especially during battery charging.
- Contaminants in the Li-ion battery due to manufacturing errors.
- Physical damage to the battery, for example, in case of an accident (collision with ground, wildlife, or another vehicle).
- Damage due to other external conditions, including an external fire, or extreme temperatures.

Even if the level of risk and characteristics of thermal runaway depend on each chemistry/technology of the Li-ion battery, they have common consequences. There could be several minutes, even several hours, between initial damage and the start of a detectable visible thermal runaway. Once initiated, thermal runaway is hard to stop, and even when stopped and firefighting operations have ceased, it may restart several hours afterward.

15 Recent "More Electric Aircraft (MEA)" like the B787 are equipped with Li-ion batteries for auxiliary systems (not for propulsion). Industry recommendations already exist with regards to firefighting of Li-ion batteries on. aircraft from these cases. The suitability of these recommendations to battery-powered aircraft will have to be assessed.

The consequences are heat, flammable, toxic, and explosive vapors venting with possible projectiles (burned cells), molten metallic materials, and fire. Preventing the propagation of thermal runaway from cell to cell requires continuous and prolonged cooling, for instance, using water. The efficiency of a cooling medium may be limited due to restricted access to the battery.

In the case of thermal runaway, preventing fire propagation to other parts of an aircraft may be a more achievable objective than stopping the thermal runaway.

BATTERY-POWERED AND HYBRID AIRCRAFT ACCIDENT

In the case of a battery-powered aircraft accident, emergency operations should consider the following:

- Confirm if thermal runaway is taking place and locate the affected battery. To this end, appropriate procedures and equipment for RFFS should include investigation equipment, such as thermal imaging cameras and easy access to appropriate information from aircraft sensors/alarms. Where there is limited heat production and vapour emissions, such equipment and information will enable early confirmation that a thermal runaway exists.
- If an emergency is not due to thermal runaway but to a runway excursion, collision with a vehicle, or fire in the landing gear, standard operating procedures should be adopted with special attention to:
    - Electrical hazards.
    - The protection of batteries from external conditions that may damage them and initiate thermal runaway, including an external fire.
    - Battery monitoring, even several hours after the emergency, to confirm that it has not been affected by the event.
- If thermal runaway is confirmed, the objectives of emergency procedures and operations should be:
    - The protection of crew, passengers, and ground operations staff from smoke and vapors.
    - The protection of crew and passengers from electrical risks.
    - The protection of crew and passengers from heat, flames, and projectiles.
    - The protection of other parts of the aircraft or another vehicle or building from flames and heat from the battery.
    - The prevention of the propagation of thermal runaway to other batteries.
- The protection of passengers from direct emission from batteries and from electrical risks would be provided to a large extent by aircraft design, including

the location of batteries, protective cover, safety vent, and electrical isolation systems.

- With the help of RFFS, emergency evacuation would be initiated and conducted, taking into account smoke/toxic vapor dispersion, the location of batteries, and the associated risks of projectiles, flames, or gas venting.

To this end, aerodrome RFFS should be enabled to provide a more comprehensive view of the situation using information from the aircraft and its crew and appropriate scouting equipment and procedures. This might involve thermal imaging cameras, surveillance, and overview camera/unmanned aerial vehicles (UAV).

In addition, appropriate procedures and equipment should be developed to enable aerodrome RFFS to provide protection from electrical risks (detection and isolation procedures) and projectiles.

Emergency operations to protect other parts of the aircraft need to be conducted by RFFS with protective/extinguishing media designed for three-dimensional fires and composite fuselages rather than just foam for hydrocarbon liquids.

To prevent the propagation of thermal runaway to other batteries ("Extinguishing the thermal runaway"), RFFS should be enabled to cool the affected and adjacent batteries as effectively as possible, taking into account the following:

- The aircraft design and the access to cool the batteries.
- The extinguishing/cooling media available and their efficiency on Li-ion batteries.
- The accessibility to batteries in operating and emergency conditions (smoke/heat/flames, projectiles etc.).

As a result, the main changes to dealing with emergency operations involving Li-ion batteries compared with those involving kerosene are:

- The priority of RFFS operations should first be the detection of a Li-ion battery fire and then the protection of passengers and the fuselage from the effects of that fire rather than an extinction/control of the thermal runway.

  Note 1: Unlike a kerosene fire, even if it is a localized or starting fire, any thermal runaway is difficult to fight and may be unstoppable, even with a quick response in the early stages of an incident. In any case, complete control of a thermal runaway event may require hours or days rather than minutes.

  Note 2: Although kerosene has a high spreading and calorific value, whose rapid extinction will directly help to protect fuselage and egress routes, Li-ion thermal runaways and fires may be more localized but have a higher risk of projected materials (solid or molten metal), and from toxic and explosive vapor.

- Appropriate investigation and monitoring procedures and devices, such as thermal imaging cameras, will be needed.

  Note: The area of use and limitations have to be taken into account: for instance, readings from thermal imaging cameras (TIC) may be inaccurate as the vapor released by Li-ion battery fires absorbs infra-red light.

- RFFS's current extinguishing agents (foams) against hydrocarbon fires should be changed. Water may be used, but with limited efficiency.

  Note 1: The foams used by RFFS so far are not as useful for cooling batteries or protecting composite fuselages as they are against bidimensional kerosene fires.

  Note 2: New extinguishing agents should be considered, but, to date, there is no certainty on the availability or the efficiency of such agents, especially in relation to cooling batteries and controlling thermal runaway.

- The minimum quantities and flow rate of water/extinguishing agent (and, therefore, equipment specification) should be reviewed.

  Note: The usual tactic of a massive attack against kerosene fire may no longer be appropriate as, on one hand, cooling batteries requires lower flow rates for a prolonged period, but on the other hand, appropriate protection of the fuselage will have to be considered.

- Rescue and firefighting tactics should consider:

  - Protecting/evacuating passengers and RFFS from the hazards of vapor cloud explosions and projected materials. There is the potential for ongoing explosions even after flammable vapors are extinguished.
  - High voltage electrical hazards, even when batteries are correctly isolated.
  - Cooling batteries to limit thermal runaway in a set of batteries depends on having access to them, which may be hard to achieve in emergency operations.
  - Having detailed knowledge of the design of the aircraft and, possibly, the use of specially designed tools.

- The challenges and safety issues posed by Li-ion battery fires mean that leaving such a fire to burn (after a complete evacuation) while protecting peripheral risks may be considered. It should be a command decision taken in conjunction with aerodrome management and environment teams.
- The pollutants given off during Li-ion battery fires and fireground runoff water will be contaminated, and consideration will need to be given to how this is contained and disposed.

DISABLED AIRCRAFT REMOVAL

After an aircraft accident, with or without a battery fire, the risk of thermal runaway remains, possibly for days, due to potential internal damage.

Electrical energy with the potential to cause an explosion or fire may still be present in aircraft systems.

The battery and the disabled aircraft will have to be continuously or frequently monitored with an appropriate system. This is especially relevant when an aircraft has been removed from the accident site to a dedicated area. This area should be isolated, and hangars should be avoided until batteries have been correctly removed, isolated or secured.

Due to the risk of Li-ion battery reignition, close liaison with aircraft recovery specialists will be essential.

Responders must also be aware of the presence of high-voltage components and cabling capable of delivering a fatal electric shock. Components may retain a dangerous voltage even when batteries have been isolated. Visual indicators to alert responders to the effective isolation of high-voltage components and cabling could be incorporated into aircraft design.

Consideration must be given to containing water runoff, which could be contaminated after it has been used to fight a battery fire or cool down a battery.

EVENTS DURING RECHARGING OPERATIONS

Abnormal events during recharging operations may be mostly:

- Thermal runaway of a battery due to short-circuit, overheating, and damage.
- Other electrical hazards.

Emergency operations will depend on the type of charging operation, for example, a fast (and high voltage/high power) charging or a low (possibly nocturnal) charging. The availability of responders and the presence of people on board or nearby will affect operations. In both situations, charging operations must be monitored to detect abnormalities in batteries and interrupt them as soon as possible when discovered to allow the necessary isolation of the power supply.

When available, emergency operations from responders will be similar to those defined previously in the case of a thermal runaway. The power supply should be isolated where it is safe to do so. However, it should be noted that isolating a power supply may not stop a thermal runaway.

HYDROGEN-POWERED AIRCRAFT

Hydrogen fuels used in aviation are expected in gH_2 and LH_2 forms. Hydrogen is flammable at concentrations between 4% and 75% in air, which is a very wide range compared with other fuels. Conventional aviation fuel has flammability limits of 0.6% to 4.7%, for example. The hydrogen concentration could easily reach the lower flammability limit (4%) if there was a leak in a confined space with no ventilation. An outdoor leak would likely rise quickly and diffuse. However, a large volume of LH_2 leaking quickly can form an ice cloud that does not disperse easily. Hydrogen has a high flame speed and burns with a pale blue flame almost invisible in daylight. Hydrogen fires have low radiant heat, so it is difficult to sense the presence of a flame from afar. But because of this, they could be less destructive than a kerosene fire. Like kerosene, oxygen and an ignition source are required for combustion to occur as hydrogen has a high auto-ignition temperature (AIT) of 585° C. For comparison, kerosene AIT is between 210° C and 240° C.

Accordingly, emergency response procedures, response times, and responders' training will need to be reviewed to mitigate this increased complexity. Importantly, the way hydrogen leaks, concentrates, and burns is different from that of kerosene, so not only do specific procedures and training need to be developed, but so does the mindset of first responders in dealing with a new fuel type.

GASEOUS AND LIQUID HYDROGEN RISKS

If there is no immediate ignition of a gaseous leak, or if a burning leak is extinguished, gH_2 may create a highly flammable and potentially explosive atmosphere, especially in an enclosed environment with a wide effect area. If not constrained, H_2 will diffuse upwards rapidly in air due to its light weight relative to air. When hydrogen burns after an immediate release and ignition, its flame is not very visible and has low radiative heat, creating a more localized risk.

As gaseous hydrogen is colorless and odorless, detecting a gH_2 leak without specific equipment is difficult. Noise emitted by a sizeable under-pressure leak can help, but this may be limited in a noisy environment such as that encountered at an aerodrome. Aircraft design can include monitoring devices to detect significant losses in pressure of the gH_2 tank and raise visual alerts in the interior and exterior of the aircraft when a drop in pressure is detected, signaling to the flight crew and ground personnel a potential hazardous leakage of gH_2.

Liquid hydrogen is stored at a temperature of -253° C: in a leak, the liquid will immediately vaporize and become cold, but still explosive, gaseous hydrogen while liquifying the atmosphere and freezing water and surfaces around the leak. This gH_2 cloud could also be transported by the wind and travel before dissipating.

Specific abnormal and emergency operations for hydrogen-powered aircraft result from:

- Risks associated with a high-pressure gaseous hydrogen leak from hoses, fittings, and so forth.
- An incident causing an emergency vent pressure relief system to operate.
- Risks of a tank explosion, for instance, a rupture due to physical causes (collision) or to temperatures generating a quick high-pressure increase.
- Risks of LH_2 leak, abnormal venting from an LH_2 tank or a simple loss of temperature isolation.

For kerosene-powered aircraft, the main risks are related to large fuel spills following an accident or during refueling. These can create a large flaming surface on the ground, blocking escape routes, with strong heat propagation by thermal radiation and rapid fire spread to the fuselage. With both battery and hydrogen aircraft, the risks are different. With hydrogen, the greater risk is an explosion due to an insufficiently dispersed, invisible cloud of gaseous hydrogen from a gaseous or liquid hydrogen leak or from emergency venting, although these and related aircraft systems are designed to be clear of potential explosion risks. In this case, the available time for any possible emergency evacuation will highly depend on the type of accident but may be significantly shorter than that of a kerosene spill and, in the case of an explosion, affecting a wider area.

If a leak has been ignited (with a long but not very visible flame), the risk of explosion may be reduced if the discharged hydrogen is immediately burned.

HYDROGEN-POWERED AIRCRAFT ACCIDENT

In the case of an aircraft accident, the main objective of emergency operations would be to:

- Detect and assess whether there are any significant leak(s), venting, or concentration of liquid or gaseous hydrogen around or within the aircraft.
- Detect and assess whether there is any damage to tanks or risk of explosion due to exposure to higher temperature (fire, ambient temperature for LH_2 tanks, etc.).

To this end, appropriate procedures and equipment for emergency responders should include investigation equipment such as thermal imaging cameras and easy access to appropriate information from aircraft or other sensors.

If a leak is detected, crew and aerodrome RFFS should aim to isolate, if possible, fuel supply systems and monitor the level and pressure of H_2 storage vessels to detect if conditions are compatible with any evacuation. This will have to be addressed via appropriate aircraft systems design, including detection systems, venting systems, and isolation procedures.

If only ignited leak(s) are detected, and the risk of production of an explosive H_2 cloud is assessed as limited, the objective of emergency operations should then be to identify a safe area for emergency evacuation and the protection of the fuselage from the propagation of fire, without extinguishing the flaming leak.

If an external fire risks damaging the H_2 tanks, the objective of the emergency operations should be to protect the tanks from the fire's effects for as long as possible.

With LH_2, aerodrome RFFS should also consider thermal and associated effects in case of spillage, leak, or loss of isolation of any LH_2 pipes, if applicable.

If H_2 releases cannot be controlled by the isolation or overpressure mechanisms of fuel systems or the protection of H_2 tanks, emergency operations should define safety distances and the safest areas for aerodrome RFFS and passengers.

The design of aircraft and rescue vehicles should consider the protection of passengers, crew, staff, and aerodrome RFFS from the effects of explosion.

DISABLED AIRCRAFT REMOVAL

As for kerosene, disabled aircraft removal operations will have to consider the condition of the aircraft fuel system, considering the higher risk of explosion in case of accidental leak during removal, if applicable. Depending on the fuel system design and configuration (fixed tanks or LH_2 modules), purging lines with an inert gas such as nitrogen should be considered.

EVENTS DURING REFUELING/RECHARGING OPERATIONS

The risks associated with hydrogen during refueling operations will depend heavily on the type of hydrogen used (gaseous or liquid) and the refueling methodology, be it modular tanks or direct refueling. The risks of damaging a module during modular LH_2 refueling must be considered. In all cases, emergency operations may have limited action in any explosive atmosphere. This may require reconsidering the planning of aircraft stands to account for these risks.

In the case of aircraft powered by more than one type of fuel (like both battery and hydrogen) or hybrid-electric powered aircraft (with both battery and kerosene), hazards will depend on the combination and design of fuel systems employed. The added complexity of emergency response to multi-fuel-powered aircraft due to interactions of hazards of different fuel types also needs to be understood and considered.

IDENTIFIED KNOWLEDGE GAPS

BATTERY-POWERED AND HYDROGEN AIRCRAFT

The identified knowledge gaps related to the abnormal operations common to both hydrogen and battery-powered aircraft operations are:

- RFFS training requirements.
- RFFS response protocols, such as response times and procedures.
- RFFS responding means requirements.
- RFFS PPE requirements, including protection against projectiles /explosion, and decontamination.
- RFFS safety setback distances and safety cordon-off zones.
- The level of detail in the regulation with regards to required information pertaining to:
    - The location and types of battery and tanks or LH_2 modules.
    - The isolation points and markings for battery, hydrogen, and hybrid aircraft, allowing quick location and accessibility by RFFS.

BATTERY-POWERED AIRCRAFT

The identified knowledge gaps related to the abnormal operations applicable to battery-powered aircraft operations are:

- How to detect thermal runaway.
- How to direct information to crew and aerodrome RFFS about battery condition.
- The efficiency of the means of monitoring thermal runway, fire and smokes in operational conditions (within fuselage, smokes, etc.)
- The speed of a potential development of thermal runaway according to type/chemistry and size of Li-ion battery to assess the available time for evacuation.
- The volume and impact of a dangerous concentration of smoke/vapors for passengers and RFFS.
- Safety areas needed around a battery with thermal runaway.
- An ability to assess the impact of localization of multiple battery packs on the availability of egress routes.
- The type of efficient cooling/extinguishing agents.
- The type of efficient agents to protect the fuselage.

- The location, access, and procedures to cool or extinguish the battery pack as efficiently as possible.
- The location, access, and procedures to isolate the electrical system and prevent electrical hazards.
- The isolation and disposal procedures (safety criteria, duration) after an accident or thermal runaway.
- The efficiency of environmental containment infrastructures to deal with heavy metal runoff from battery fires.

HYDROGEN-POWERED AIRCRAFT

The identified knowledge gaps related to the abnormal operations applicable to hydrogen-powered aircraft operations are:

Gaseous hydrogen

- Understanding the properties and behavior of hydrogen and detecting/managing leaks in an aerodrome environment during an emergency response.
- Training requirements for managing abnormal and emergency operations related to hydrogen-powered aircraft.
- The procedures/systems for the isolation of g systems by crew/emergency team.
- Understanding of aircraft fuel system design and the location of the venting system should access be required.
- The effects of water on the safety valves and risks of icing on the venting systems.
- De-icing operations affecting aircraft venting/refreshing systems.
- The safety area around the aircraft during an emergency will depend on aircraft configuration.

Liquid hydrogen

- Risks and consequences of an aircraft LH_2 leak/loss of thermal insulation.
- Training requirements for managing abnormal and emergency operations related to hydrogen-powered aircraft.
- Risks and consequences of a significant LH_2 leak, such as a potential tank rupture, hose failure, or coupling failure.

IMPLICATIONS FOR AERODROME DESIGN AND OPERATION

These abnormal and emergency operations could have the following impacts on aerodrome design and safety setback distances, which will need to be considered/investigated:

- There will likely be a need for specialized RFFS equipment and procedures.
- There will likely be a need for new environmental management procedures compared with hydrocarbon fuels.
- There will be an impact on aircraft pavement design, which may need to be a concrete pad for liquid hydrogen direct refueling operations.
- The volumes of material involved, either hydrogen or battery (dependent on elements of aircraft design) and what impact this may have on risks and fuel safety zone distances.

10. CONCLUSIONS

This CONOPS has been developed with contributions from the aviation industry and governments (see *Appendix 1*) and attempts to give the most up to date (November 2024) consensus vision of the operations of hydrogen and battery-powered aircraft at and around an aerodrome. Most of the points developed in this CONOPS come from direct experiences from expert practitioners who are active in initiatives developing hydrogen or battery-powered aircraft (or sub-systems), infrastructure at airports, or standards for hydrogen and aviation. Some of those initiatives are listed in *Appendix 2*. The conclusions from the group discussion have also been validated with a literature review. A list of useful references for further reading related to the content of this document is found in *Section 11. List of References*. The authors of this CONOPS acknowledge that many aspects of this work are still evolving. This document does not intend to be a "one–stop" for all the answers and instead focuses on highlighting existing gaps in knowledge that must be addressed while providing some answers to those aspects that are already well understood today.

The two most significant sections of this document, *9.4. Turnaround operations, refueling/recharging operations*, and *9.7. Abnormal and emergency operations* highlight some of key aspects of enabling hydrogen and battery-powered aircraft into commercial service. Other sections of the landing and take-off cycle of these aircraft were seen to be less affected by the type of energy used. Some of the most important gaps identified were:

- The need and specification for personnel training on some stages of aerodrome operations, particularly RFFS personnel and refuelers/rechargers ground operators.
- The definition of fueling/charging safety zones and the knock-on effect of these on the turnaround time, potential parallelization of activities, and parking stand design.
- The requirement for any potential extra ground support equipment to pre-condition the aircraft fuel systems or batteries before refueling or recharging.
- Requirements for extra/different PPE and additional safety monitoring systems needed around the aircraft, such as hydrogen sensors or thermal cameras for monitoring battery health while recharging.
- Rescue and firefighting specific procedures and means for dealing with leaks, fires, and vents.

The members of the ACAAF-TF are confident, however, that these gaps, and others presented in this document, will be addressed progressively as the development of these aircraft and related technological bricks advances and more experience is gained. This document should, hence, be continuously monitored and updated. In addition, experience from using hydrogen in other sectors (road transportation, heavy industry, fertilizers) could help inform or guide aviation on implementing this substance into the air transport system. To this end, a list of existing standards is provided in *Appendix 2* for reference and future work.

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APPENDIX 1.

LIST OF ORGANIZATIONS

Air France	Heart Aerospace
Air New Zealand	International Air Transport Association
Airbus	International Coordinating Council of Aerospace Industries Associations
Airport Straubing-Wallmuehle and European Regional Aerodromes Community	Istanbul Airport
Airports Council International	Japan Airlines
Boeing	KLM Royal Dutch Airlines
Brisbane Airport	Munich Airport
Changi Airport Group	Pratt & Whitney, an RTX Business
Christchurch Airport	Qantas Airways
Civil Aviation Authority of Singapore	Rolls-Royce
Cranfield Aerospace Solutions	San Francisco International Airport
Eurocae	Schiphol Group
EUROCONTROL	STAC - Service Technique de L'Aviation Civile
Federal Aviation Administration, USA	Stralis Aircraft
Geneva Airport	United Kingdom Civil Aviation Authority
Greater Toronto Airports Authority (Toronto Pearson Airport)	Universal Hydrogen
Groupe ADP	ZeroAvia
H2FLY	

APPENDIX 2. LIST OF INITIATIVES

A2.1. REGULATIONS AND STANDARDS FOR HYDROGEN

AVIATION-SPECIFIC WORKING GROUPS/GUIDELINES IN DEVELOPMENT

ASTM WK85474	Specification for aviation hydrogen fuels (in development).
SAE 8466 (ratified and due for publication)	Hydrogen fueling stations for airports, in both gaseous and liquid form.
SAE 8999 Draft (work in progress)	High flow liquid hydrogen fueling process and couplings for aerospace and heavy transport application.
SAE AS6679 (work in progress)	Liquid hydrogen storage for aviation (covers on board the aircraft).
ISO /TC 197 (25 codes in development)	Hydrogen Technologies focused on systems and devices for the production, storage, transportation, measurement, and use of H2.
SAE AS 7373 (codes in development)	Gaseous hydrogen storage for general aviation, refueling for general aviation (gh2) (work in progress).
ANSI/ISO TC 137 WG2 committee	Liquid hydrogen refueling protocols.
SAE AS6679 (work in progress)	Liquid hydrogen storage for aviation and guidelines for LH2 refueling.
SAE AS7373 (work in progress)	Gaseous hydrogen storage for general aviation, including guidelines for refueling.

INDUSTRY STANDARDS GUIDELINES GENERAL (PUBLISHED)

NFPA 2	Hydrogen technologies code: generation, installation, storage, piping, use, and handling of liquid and gaseous hydrogen), including portable and vehicular applications.
ANSI AIAA GO95A -2004	Guide to safety of hydrogen and hydrogen systems: safety systems and controls, usage, personnel training, hazard management, design, facilities, detection, storage, transportation, and emergency procedures.
CAN/BNQ 1784-000/2022	Canadian hydrogen installation code: hydrogen-generating equipment for non-process end use, hydrogen utilization equipment, hydrogen-dispensing equipment,

	hydrogen storage containers, hydrogen piping systems, and related accessories.
ISO TR 15916 2005	Guidelines for the use of hydrogen in its gaseous and liquid forms and its storage in either of these or other forms. Identifies safety risks and hazards.
PRESLHY (Pre-normative Research for Safe use of Liquide Hydrogen)	PRESLHY Handbook of H2 Safety Chapter 5.
OSHA 29 CFR 1910.103	Stationary or moveable hydrogen containers, pressure regulators, safety relief devices, manifolds, and piping.
American Compressed Gas Association CGA G5.5	Standards on hydrogen piping systems at consumer sites and hydrogen vent systems.
NASA NSS1740.16	Safety standard for hydrogen and hydrogen systems: guidelines for hydrogen system design, materials selection, operations, storage and transportation.
SO/TR 15916	Basic considerations for the safety of the hydrogen system.
ANSI/CHMC 1	Test methods for evaluating material compatibility in compressed hydrogen applications – metals.
ANSI/CHMC 2	Test methods for evaluating material compatibility in compressed hydrogen applications – polymers.
ISO11114	(Material compatibility) H2 embrittlement.
EIGA Doc 06/02/E	Guidance on the safe storage, handling, and distribution of liquid hydrogen.

CODES FOR AIRCRAFT INTEGRATION

14 CFR Part 33	Airworthiness standards for the issue of type certificates and changes to certificates for fuel cell operating as part of a hydrogen electric engine (nine or fewer passengers).

SYSTEM DEVELOPMENT AND SAFETY ASSESSMENT STANDARDS: VEHICLES AND AVIATION

EC 79-2009 EU H2 Regulation	Safety-related regulation on hydrogen-powered vehicles of categories M and N ((EU) 2018/858) and

	hydrogen systems and components designed for those vehicles. Its scope addresses both liquid and compressed gaseous hydrogen.

HYDROGEN FUEL CELLS

SAE AS 6464 AKA EUROCAE/SAE WG80/AE-7AFC	Hydrogen fuel cells aircraft fuel cell safety guidelines for proton exchange membrane (PEM) fuel cells.
SAE AS 6858	Installation of fuel cell systems in large civil aircraft, jointly developed by SAE/EUROCAE.
SAE AS 7765 ER20	Considerations for hydrogen fuel cells in airborne applications, SAE/EUROCAE.
SAE AS7141	Hydrogen fuel cells for propulsion, including auxiliary power (work in progress).
IEC /TC105	Fuel Cell (FC) technologies, including APUs, portable units, micro-FC power systems, and others.
SAE j2579	Standard for fuel systems in fuel cell and other hydrogen vehicles.
ISO 23273:2013	Fuel cell road vehicles, safety specifications, protection against hydrogen hazards for vehicles fuelled with compressed hydrogen.
UN Regulation 134 (HFCV) (2019/795)	Uniform provisions concerning the approval of motor vehicles and their components regarding the safety-related performance of hydrogen-fueled vehicles (HFCV).
IEC 62282-2-100	Fuel cell technologies - Part 2-100: Fuel cell modules - Safety related to construction, operation (normal and abnormal conditions), testing, and hazards.
ISO 22734:2019	Hydrogen generators using water electrolysis — Industrial, commercial, and residential applications, considering construction, safety, and performance requirements.

HYDROGEN FUEL QUALITY STANDARDS

ISO 14687	Hydrogen fuel quality - product specification for utilization in road vehicles, boilers, cookers, power generation, aircraft and space vehicles.
SAE J2719-1	Application Guideline for Use of Hydrogen Quality Specification.
SAE J2719 -2	Hydrogen Fuel Quality for Fuel Cell Vehicles (PEM).
BS EN 17124	Hydrogen fuel – Product specification and quality assurance for hydrogen refueling points dispensing gaseous hydrogen – Proton exchange membrane (PEM) fuel cell applications for vehicles.
TUV SUD CMS 77	Low carbon hydrogen certification.
TUV SUD CMS 70	Green hydrogen certification for sustainable energy.

COMPRESSED HYDROGEN STORAGE SYSTEMS / PRESSURE VESSELS/PIPEWORK

ASME B31.12	Hydrogen piping for gaseous and liquid hydrogen, as well as mixes of hydrogen and other gasses. the standard includes joints for piping connection.
BS EN 17533:2020 Gaseous Hydrogen	Gaseous hydrogen. Cylinders and tubes for stationary storage.
BS EN 17339: 2020 Transportable gas cylinders.	Transportable gas cylinders. Fully wrapped carbon composite cylinders and tubes for hydrogen.
ANSI/CHMC HGV2 :2023	Compressed hydrogen gas vehicle fuel containers (material, design, manufacture, marking, and testing of serially produced, refillable type HGV 2 containers intended only for the storage of compressed hydrogen gas for on-road vehicle operation).
ISO 19881	Gaseous hydrogen-land vehicle fuel containers (material, design, manufacture, marking, and testing of serially produced, refillable type HGV 2 containers intended only for the storage of compressed hydrogen gas for on-road vehicle operation).

REFUELING-GASEOUS HYDROGEN

ISO 17268	Gaseous hydrogen land vehicle refueling connection devices.
ISO 20100	Gaseous hydrogen – fueling stations.
SAE J-2600	Compressed hydrogen vehicle fueling connection devices.
SAE J-2601	Fueling protocol for gaseous hydrogen-powered vehicles for heavy-duty transport.
SAE J-2799 – (for 70 MPa)	Requires also special fueling protocols (reference SAE J-2601).
ISO 19885-1	Fueling protocols for gaseous hydrogen-fuelled vehicles – Part 1: Design and development process for fueling protocols. This is intended to coordinate with the ISO 19880 family of documents. ISO 19885-1 is currently under development with subsequent chapters - ISO 19885-2 and ISO 19885-3 - dealing with fueling protocols.
EC-134	Compressed hydrogen storage systems and refueling.
BS EN 17127	The standard for outdoor hydrogen refueling points dispensing gaseous hydrogen and incorporating filling protocols.
ISO 19880-1:2020	Gaseous hydrogen – fueling stations.
PGS 35 Guidelines	Provides details on the legal requirements for hydrogen delivery based on the Environmental Act, the Occupational Safety Act, and the Safety Regions Act (Netherlands).

REFUELING-LIQUID HYDROGEN

ISO 13984:1999	Liquid Hydrogen – land vehicle fueling system interface, applicable to designing and installing LH2 fueling and dispensing systems.
ISO 13985:2006 SAE J2783	Liquid hydrogen – land vehicle fuel tanks – specifies the construction requirements for refillable fuel tanks for liquid hydrogen used in land vehicles as well as the testing methods required. Liquid hydrogen surface vehicle refueling connection specifies the performance requirements and test methods

	for hydrogen fuel cell systems used in automotive applications. it focuses on ensuring the safety, reliability, and efficiency of these systems, particularly in terms of hydrogen storage, handling, and usage.

TESTING

ISO 26142 (2010)	Hydrogen detection apparatus defines the performance requirements and test methods of hydrogen detection apparatus that is designed to measure and monitor hydrogen concentrations in stationary applications. Also includes apparatus needed for multilevel safety operations, such as nitrogen purging or ventilation and/or system shut-off corresponding to the hydrogen concentration.

A2.2. OEMS AND MULTI-PARTNER PROJECTS WITH UNIVERSITIES

The following list includes multi-stakeholder hydrogen projects involving Original Equipment Manufacturers (OEMs), governments, and academic institutions. Although the list is non-exclusive, it does give a sample of the variety and scope of active projects and investments:

Airbus	The Airbus ZEROe project is investigating a new clean-sheet hydrogen aircraft that will be either fuel cell- or gas turbine-powered. Plans include flight tests, the opening of two hydrogen research centers, and the construction of an iron bird for systems demonstrations.
Rolls-Royce	Rolls-Royce is working on the conversion of the AE2100 and Pearl 15 engines, which could potentially fly on a 747 test bed. Additionally, Rolls-Royce was recently granted just over GBP 100 million from the UK's ATI program to advance technologies for hydrogen-powered gas turbines.
ZeroAvia	**ZeroAvia** has already flown a 1-to-1 passenger (6-seater-sized) aircraft entirely on hydrogen, as well as a Dornier 228 during a test flight program with a gH_2 fuel cell-powered engine in conjunction with the UK Civil Aviation Authority (CAA). This is a 600 kW powertrain. ZeroAvia has also developed an iron bird for the 2 MW powertrain in

	Seattle and has successfully test-run this engine on the iron bird.
Cranfield Aerospace Solutions	Cranfield Aerospace Solutions is designing hydrogen fuel cell propulsion systems, initially for the Britten-Norman Islander through Project Fresson, a government-backed initiative that combines government and investor funding. Further platforms, such as Dronamics' Black Swan cargo UAV, are also being explored.
Universal Hydrogen	Universal Hydrogen completed a 10-flight campaign. The campaign included reaching 10,000 ft. in altitude and completing five different legs. The flights were completed on a Dash 8-300 aircraft with a standard capacity of 40 passengers. Universal Hydrogen is no longer operative.
H2FLY	H2FLY completed 14 tests of a one-passenger, all-hydrogen-powered aircraft and plans to scale up to a 40-seater Dornier 328. H2FLY has also performed the only flight to date using cryogenic liquid hydrogen (October 2024).
Joby	Joby flew in November 2024, the first-ever liquid hydrogen electric vertical take-off and landing (eVTOL) aircraft also incorporating liquid hydrogen storage.
General Electric (SAFRAN)	General Electric plans to do a test flight of a CFM56, powered by hydrogen on an Airbus A380 testbed.
Boeing	Boeing is continuing research on hydrogen and electrification. Examples include the testing of a large hydrogen composite tank (DARPA - Defense Advanced Research Projects Agency) and the investment made in Whisk for electric urban air mobility.
De Havilland Canada	De Havilland Canada has signed a Memorandum of Understanding (MoU) with ZeroAvia to explore the feasibility of retrofitting a Dash-8 with hydrogen.

Pratt & Whitney	Pratt & Whitney's Hydrogen Steam Injected, Inter-Cooled Turbine Engine (HySIITE) project combines liquid hydrogen combustion and water vapor recovery to achieve zero in-flight CO_2 emissions.
Fokker Next Gen Aircraft	Fokker Next Gen Aircraft plans to develop a prototype to fly on hydrogen (Fokker 100) in conjunction with Rolls-Royce and funded by the EU. The prototype is scheduled to fly in 2033.
GKN	H2Gear and H2Jet projects looking into hydrogen combustion and hydrogen fuel cell use.
DLR EXACT	Project studying a hydrogen aircraft's turnaround and maintenance procedures.
Cranfield University	EnableH2 is a multi-partner project investigating mature combustion technology and safety aspects for hydrogen aircraft. Cranfield University was recently awarded GBP 69 million to develop a hydrogen integration hub.
Heart Aerospace	Developing a fully electric 200km range, 40-passenger battery-powered aircraft for the Nordic region, with the possibility of a longer range on hybrid configuration.
ATI FlyZero	The ATI FlyZero project was a 1-year UK government-funded sprint project that published 60 reports on hydrogen for aviation. These reports include safety, standards, and infrastructure aspects, which could be a good starting point for this work.
Embraer’s Energia	Project explores a range of concepts for carrying up to 35-50 passengers. These include the 50-seater, 500nm E50 (with a hydrogen gas turbine), and the 19- 30 passenger hydrogen fuel cell concept with a range of 200nm.
Fokker Aircraft	Launched an ambitious project to test a retrofitted Fokker 100 aircraft with hydrogen on its path for a clean-sheet design.

Project NAPKIN (New Aviation Propulsion Knowledge and Innovation Network)	Project has the objective of accelerating the development of zero-emission aircraft technologies.
Project ACORN	Trial of hydrogen fuel cell baggage tractor airside at Bristol Airport in collaboration with Cranfield University, EasyJet, and others.
Project HEAVEN	Project's HEAVEN (high power density fuel cell system for aerial passenger vehicles fuelled by liquid hydrogen) objective is to develop and test a cryogenic hydrogen fuel cell powertrain for aviation.
Project ASCEND	Project's ASCEND (Advanced Superconducting and Cryogenic Experimental Powertrain Demonstrator) objective is to develop superconducting technologies for hybrid-electric aircraft.
Project CAVENDISH	Project's CAVENDISH (Clean Aviation Via Novel Demonstration of Integrated Sustainable H_2 Technology) objective is to demonstrate hydrogen fuel cell and storage technologies for regional aircraft.

A2.3. LIST OF AIRLINES INVOLVED IN ALTERNATIVE AVIATION FUEL INITIATIVES

The following airlines have publicly expressed interest in battery or hydrogen aircraft. The commitments vary, some having signed memorandums of understanding with the OEMs on some of the above-mentioned projects, some have directly invested in those companies, and some have placed pre-purchase order agreements for hydrogen or battery-powered aircraft (last updated November 2024).

Alaska Airlines	EasyJet
ACIA Aero Leasing	Elix Aviation
Air France	IAG - International Airlines Group
Air New Zealand	Icelandair
Amelia	Japan Airlines

American Airlines	KLM Royal Dutch Airlines
ANA Airlines	Korean Air
ASL Aviation Holdings	Logan Air
Austrian Airlines	Lufthansa Group
AvMax (Leasing Inc.)	MONTE (lessor)
Braathens Regional Airlines (BRA)	RAVN Alaska
Connect Airlines	Scandinavian Airlines
Danish Air Transport	Skytrans airline
Delta Airlines	United Airlines
WizzAir	Wideroe

Figure 11. Non-exhaustive list of airlines involved in hydrogen projects around the world. Source: IATA

A2.4 LIST OF AIRPORTS INVOLVED IN ALTERNATIVE AVIATION FUELS INITIATIVES

Similar to the list of airlines, some airports have publicly announced commitments to begin to assess how to deploy hydrogen on-site. Some airports have completed feasibility studies on infrastructure, some have partnered with OEMs and hydrogen providers to start the assessment process, and some are already deploying hydrogen on-site for non-propulsive applications.

Aéroports de Paris	Milan Malpensa Airport
Aeropuerto de Santiago	Montréal International Airport
AGS Airport Group	Riga Airport
APAC Singapore, Changi Airport	Rotterdam The Hague Airport
Atlanta Airport	Schiphol Amsterdam Airport
Birmingham Airport	Shannon Airport, Ireland
Brisbane Airport	Skelleftea Airport
Bristol Airport	Swedavia
Christchurch International Airport	Sylt Airport
Cotswolds Airport, Kemble	Tallinn Airport
Edmonton International Airport	Teesside Airport
Gladstone Airport	Texas George Bush Airport
Glasgow Airport	Torino Airport
Groningen Airport Eelde	Toronto Pearson International Airport
Hambourg Airport	Toulouse-Blagnac Airport
Helsinki Airport	Vancouver Airport
Incheon International Airport	Venice Marco Polo Airport
Kansai International Airport	Vinci Group
Lithuanian Airports	Lyon-Saint Exupéry Airport
London City Airport	Manchester Airport
Lübeck Airport	Memphis International Airport

Figure 12. Non-exhaustive list of airports involved in hydrogen projects around the world. Source: IATA

A.2.5. LIST OF ACRONYMS AND ABBREVIATIONS

AIP	Aeronautical Information Publication
ACAAF-TF	Airport Compatibility of Alternative Aviation Fuels Task Force
ACI	Airports Council International
ACR- PCR	Aircraft Classification Rating – Pavement Classification Rating
ADOP	Aerodrome Design and Operations
ARFF	Aircraft Rescue and Fire Fighting
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
AZEA	Alliance for Zero Emission Aviation
CCS	Combined Charging System
CLS	Cargo Loading System
CONOPS	Concept of Operations
EASA	European Aviation Safety Agency
EIS	Entry Into Service
eVTOL	Electric Vertical Take-Off and Landing
gH_2/ LH_2	Gaseous / Liquid Hydrogen
GSE	Ground Support Equipment
H_2	Hydrogen
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCAIA	International Coordinating Council of Aerospace Industries Associations
IIWG	International Industry Working Group
MCCS	Megawatt Charging System
MTOW	Maximum Take-Off Weight
MW	Megawatt
OEM	Original Equipment Manufacturer
OEW	Operating Empty Weight
PANS	Procedures for Air Navigation Services

PPE	Personal Protective Equipment
RFF	Rescue and Fire Fighting
RFFS	Rescue and Fire Fighting Services
SAF	Sustainable Aviation Fuels
ULD	Unit Load Device


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