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William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Aircraft Fuel Cell and Safety Management System

January 2020

Final Report

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16. Abstract

The safe implementation of three fuel cell power system (FCPS) technologies to provide auxiliary power for commercial air transport aircraft was evaluated. The first implementation is polymer electrolyte membrane FCPS for narrow-body, short to mid-range aircraft, using pressurized hydrogen gas as fuel. The second implementation uses regenerative fuel cell power system (RFCPS) for the same type of aircraft. The third implementation uses solid oxide (SO) FCPS for wide-body, long-range, intercontinental aircraft, converting liquid jet engine fuel through onboard fuel reformer. During the research, assumptions were made for these implementations to be practical and probable. The high-level notional concept design of each implementation is intended to expose new safety hazards associated with these new technologies.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AC	Alternating Current
APS	Auxiliary power system
APU	Auxiliary power unit
BOP	Balance of plant
CB	Catalytic Burner
CC	Cathode Compressor
CG	Center of gravity
COP	Coefficient of performance
CSR	Catalytic steam reformer
DC	Direct current
DFZ	Designated fire zone
DOE	Department of Energy
DRFCPS	Discrete regenerative fuel cell power system
ECS	Environment Control System
ESD	Energy storage device
ETOPS	Extended twin engine aircraft operations
FAST	Fast accurate simulation turbine
FC	Fuel Cell
FCPS	Fuel Cell Power System
FCAPS	Fuel Cell Auxiliary Power System
FID	Flight Idle Descent
FSS	Fuel storage system
FTIS	Fuel Tank Inerting System
GT	Gas turbine
HVDC	High voltage direct current
HEX	Heat exchanger
LE	Leading edge
LHV	Lower heating value
ME	Main Engine
MES	Main Engine Start
MG	Electric Generator
NCD	Notional concept design
NFT	Non-flow-through
NTIA	Near-Term Implementation Analysis
ODA	Oxygen-depleted air
PEM	Polymer electrolyte membrane
PEMFCPS	Polymer Electrolyte Membrane Fuel Cell Power System
PGU	Power generation unit
PRD	Pressure relief device
PT	Power turbine
RAT	Ram air turbine
RFC	Regenerative fuel cell
RFCPS	Regenerative Fuel Cell Power System
SCU	Start Converter Unit
SG	Steam Generator

S/G	Starter/Generator
SHO	Steam Heated Oven
SL	Sea Level
SO	Solid Oxide
SOA	State of The Art
SOFC	Solid oxide fuel cell
SOFCPS	Solid Oxide Fuel Cell Power System
SPU	Start Power Unit
SR	Steam Reformer
SSPC	Solid-State Power Controller
ST	Steam Turbine
SWaP	Size, Weight, and Power
TMS	Thermal Management System
TRU	Transformer-Rectifier Unit
TSO	Technical Standard Order
URFC	Unitized Regenerative Fuel Cell
URFCPS	Unitized Regenerative Fuel Cell Power System
VCC	Vapor cycle compressors
VCS	Vapor cycle system
WIPS	Wing-icing protection system

EXECUTIVE SUMMARY

Honeywell has been funded by the Federal Aviation Administration (FAA) to study the safe implementation of aircraft fuel cell (FC) auxiliary power unit (APU) on commercial air transport aircraft and develop a Recommended Technical Standard Guideline (RTSG) to address aircraft safety hazards associated with such implementations.

In this effort, the installation and operational concepts were developed for three diverse FC technologies on notional commercial air transport platforms. The systems studied were:

- Polymer electrolyte membrane systems
- Regenerative fuel cells
- Solid oxide fuel cell

In each case, a technically plausible FC application was conceived, which, at least minimally, assumed the role of a conventional jet fuel-powered gas turbine auxiliary power unit. Plausibility meant that the FC system installation was comparable in weight and accommodated the critical/emergency functionality of the APU role. Weight parity was achieved on a system level with conventional systems through a higher integration with the aircraft non-APU systems. Many non-critical APU functions and services were compromised or deleted. The hazards of service, maintenance, and operation were assessed for each system in the context of these notional installations. The RTSG includes these hazards and is separately published and appended to this report. Due to time and scope constraints, note that none of these FC systems/installation concepts were optimized.

The study provides the following conclusions:

- The implementation of any of the FC technologies in the role of an APU is impractical without making significant changes in the aircraft energy architecture to offset the lower power density of the fuel cell auxiliary power system (FCAPS) and the lack of pneumatic bleed capability in the FCAPS. A more electric architecture (MEA) will be optimal for FCAPS applications.
- PEM fuel cell power systems will require a significant change in airport energy infrastructure, with the requirement for high-pressure, gaseous hydrogen refueling services.
- Solid oxide fuel cell power systems will require sulfur-free or ultra-low sulfur content, aviation-fuel refueling services.

Based on the findings, the RTSG incorporates the following elements:

- High-pressure hydrogen gas storage, regulation, and control
- High-pressure hydrogen storage vessel mounting vulnerability
- Hydrogen transmission through/near flammable and combustible materials
- Active combustible gas monitoring and ventilation
- Flammable materials in oxygen-rich environment
- FC reactant mixture in oxygen-enriched environment
- FC reactant system cleanliness

- Two-phase fuel handling in fuel reformer
- Steam system integrity and safety
- Draining, ventilating, and energy channeling

The RTSG reflects these findings in the minimum performance standard.

1. INTRODUCTION

The aviation industry has been studying, performing tests and developing prototypes to support several applications of solid oxide fuel cell (SOFC), polymer electrolyte membrane (PEMFC) and regenerative fuel cells (RFC) on airplanes. Honeywell performed the Aircraft Fuel Cell and Safety Management System study funded by the Federal Aviation Administration (FAA) under contract DTFACT-16-C-00037. To conduct this study, Honeywell leveraged its significant experience in the research, development, and production of military, commercial, and general aviation pneumatic, electrical, and mechanical systems, including APUs in the aviation industry. The findings in this report do not represent Honeywell's position on aircraft fuel cell power system as APU.

1.1 GOALS AND OBJECTIVES

The purpose of this program is to study and develop FC technology for safe and certifiable aircraft installations. This research also develops data and recommendations for FAA and global partners to support appropriate standards, regulations, and means of demonstrating safe compliance.

This effort develops installation and operational concepts for three diverse FC technologies for notional commercial air transport platforms.

- Polymer electrolyte membrane (PEM) systems — Draw oxygenated air from the ambient or pressurized cabin environments, using stored/replenished pressurized gaseous hydrogen.
- Regenerative FCs — Contain high-pressure hydrogen gas and high-pressure oxygen gas in a hermetic system. In a closed system, they generate electrical power by reacting the captive hydrogen and oxygen in a PEM stack, producing captive water; and then hydrolyzing the water in a reverse reaction back into hydrogen and oxygen gas on the ground between flights, or in flight using excess electrical energy on the aircraft.
- SOFC — Uses recovered water onboard to reform ultra-low sulfur jet fuel from the fuel tanks on board the aircraft into hydrogen, and carbon monoxide, and then reacts the hydrogen with ambient or cabin air oxygen in a high-temperature ceramic fuel cell stack to produce electric power for the aircraft.

The specific objective of this work is to develop a Recommended Technical Standard Guidelines (RTSG) document that serves to complement the FAA energy storage device (ESD) aviation rulemaking committee objective, in support of regulatory agency certification requirements for fuel cell power systems (FCPS) installed on commercial aircraft for auxiliary power.

1.2 GENERAL APPROACH

1.2.1 Create RTSG Framework

The initial step is to create a framework for the RTSG, based on Technical Standard Order (TSO) C77b, for certifying APUs on commercial air transport aircraft. The findings of safety impacts related to the design, installation, operation, and maintenance of the FCPS implementation were captured from the notional concept design (NCD) and consolidated and documented during the course of this effort, which is the deliverable at the conclusion of this study.

1.2.2 Assess Plausible FCPS Implementation Architecture

This study focuses on three representative FC system architectures featuring various technologies:

- PEM fuel cell power system (PEMFCPS) using pressurized hydrogen gas stored on board
- Regenerative FC closed system
- Solid oxide fuel cell power system (SOFCPS) using hydrogen and carbon monoxide-enriched gas from onboard jet fuel reformation technology

The technology for the PEM fuel cells is mature in the automotive industry. While several major automobile manufacturers have developed hydrogen-fueled vehicles with PEM/electric drive, production has been limited. Most operate in the western states, where hydrogen refueling stations have been built and located in major metropolitan areas. This same technology has been suggested for application on commercial aircraft. GM recently partnered with Liebherr-Aerospace to develop hydrogen-fueled FCs for aircraft auxiliary-power applications, providing power for aircraft lighting, air-conditioning, backup systems, and other auxiliary functions. (Wayland, Michael, "How aerospace could be a key to GM's future in fuel cells," *Automotive News/Crain Communications*, June 18, 2018, https://www.autonews.com/article/20180618/OEM06/180619766/how-aerospace-could-be-a-key-to-gm-s-future-in-fuel-cells.)

Regenerative FCs are essentially a bi-directional fuel cell that operates in a closed system. It catalyzes gaseous hydrogen and oxygen, both captive in the system, into water, simultaneously producing electric power. It recharges when external electrical power is applied to the fuel cell, hydrolyzing the captive water back into gaseous hydrogen and oxygen. NASA initially developed this system for low-orbit satellites, and later, a unitized regenerative PEM fuel cell for high-altitude, solar-powered research aircraft (Helios), though it was not used. A regenerative system that uses excess electrical power from Main Engine (ME) generators (or ground power) to electrolyze water into hydrogen and oxygen has been suggested for application on commercial air transport aircraft to assist in the auxiliary-power generation.

1.2.2.1 SOFCPS with Hydrogen Enriched Gas from Onboard Jet Fuel Reformation

SOFCPS technology was developed in the late 1990s and early 2000s with significant funding through the Department of Energy (DOE) for use in various stationary and automotive applications. Ceres Power, Bloom Energy, and others have been developing products in this area for stationary and marine applications. As applied to aerospace for auxiliary power, this technology/architecture would use an onboard jet fuel reformation system to process jet fuel into hydrogen-enriched gas for the fuel cell. Waste heat from the process is also available for aircraft use, such as cargo compartment or battery heating. Because these systems require elevated temperatures for optimal operation, and because system startup takes a comparatively long time, frequent starts may be impractical, as is characteristic of current aircraft power demand profiles. An optimal SOFCPS requires continuous operation.

The operation of a full-time APU alleviates the relatively long start-up time and transfers secondary power demand from the MEs at an equivalent or higher efficiency, enabling the use of advanced high-performance engine configurations.

1.2.3 Assumptions

The traditional gas turbine (GT) APU assumes the role of extending all functions of the ME besides the propulsive power, when the MEs are off or compromised. This includes providing full electric-power capability and compressed air "bleed" for pneumatic power. The GT APU is a miniaturized internal combustion engine that shares the same power generation principle and construction, uses the same fuel, and services the same power system architecture as the MEs. The mimicking and sharing between the APU and ME allow for a most compact and elegant APU package. The current state-of-the-art (SOA) GT APU provides integrated shaft to power the load compressor, and geared drive to power electric generator(s), at an impressive specific power in excess of 3 kW/kg, while the DOE's ultimate goal for integrated transportation fuel cell power systems of 0.65kW/kg.

Direct drop-in GT APU replacement with FCPS is not feasible. To accept FCPS as a viable replacement, modifications have to occur from aircraft systems level up to fleet concept of operation. Therefore, the following reasonable technologically grounded assumptions are made:

- These FC technologies are at various states of maturity. Reasonable and optimistic assumptions are based on the advancement of these FC technologies for aircraft implementation.
- To be feasible, the FCPS implementation requires significant modifications to the aircraft power system architecture. The modifications range from a refresh of the existing platform to a clean-sheet design of a brand-new aircraft.
- Different infrastructures are needed for different FCPS technology, from gate power to hydrogen refilling, to pre-treatment of liquid aviation fuel.
- Each FCPS favors its own and different concept of operation, from minimal use to all-time operation.
- The operational characteristics of each FCPS need to match the characteristics of the market segments and platforms.

1.3 NEAR-TERM IMPLEMENTATION ANALYSIS

Before developing the notional concept design for each FCPS technology, a high-level, preliminary design exercise was performed to help narrow down the possibilities and to avoid creating a more detailed concept design and safety assessment around an FCPS implementation that was not credible. This effort considered each system's high-level attributes and attempted to match them up with aircraft power system architectures, identifying potential synergies, and gaps, and generating a preliminary weight and fuel consumption assessments.

1.4 CREATE NOTIONAL CONCEPT DESIGN FOR EACH FCPS TECHNOLOGY IMPLEMENTATION

The notional concept design (NCD) of each FCPS is created to expose new safety hazards introduced by the new technologies. The NCD approach is qualitative design supported by quantitative requirements, which also considered multiple design options.

The output of the NCD is neither a specific system design nor a suggestive trade study.

1.5 METHODOLOGIES

The nature of this study is geared toward the future. It is high-level speculative work aimed to expose potential new safety hazards associated with the most unlikely implementation examples. Industry norm or projected values from "Fuel Cell Technologies Office Multi Year Research Development Demonstration Plan" are used where appropriate.

A multitude of engineering modeling tools was used to support the definition of FCPS implementation requirement, including these physics-based models:

- RDS — Off-the-shelf aircraft performance model for engine thrust requirement
- FAST — In-house proprietary engine performance model for engine fuel burn requirement
- Excel — Various customized spreadsheet models for FCPS performance and iteration between aircraft and engine model input/outputs

When information was not readily available, qualitative analogous technique and engineering judgment were used.

2. NEAR-TERM IMPLEMENTATION ANALYSIS

2.1 BACKGROUND

The modern Air Transport APU assumes the role of extending all ME non-propulsive functionalities, when the MEs are off or compromised. The typical APU today is a relatively small gas turbine that shares the same power generation principle and construction, uses the same fuel, and services the same power system architecture as the ME. These similarities between the APU and ME allow for a most compact and elegant APU package. The current state-of-the-art (SOA) GT APU provides an integrated shaft to drive the load compressor for pneumatic power, and a reduction gearbox to drive electric generator(s) and other accessories, at a specific power in excess of 3 kW/kg. Except for extended twin-engine aircraft operations (ETOPS), the GT APU operates mostly on the ground. The fuel consumed before the flight reduces the aircraft weight, and the fuel consumed after the flight comes from the required flight reserve. Therefore, there is no weight penalty for fuel consumed by the APU.

By comparison, DOE's "Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen" ultimately targets on specific power to 0.65kW/kg, not including hydrogen storage, power electronics, and electric drive, according to the Fuel Cell Technologies Office Multi-Year Research Development Demonstration Plan. The ultimate target specific power for "Fuel Cell Auxiliary Power Units" is an order of magnitude lower at 0.045 kW/kg albeit at a much lower power range of 1 to 10 kWe. As a result, for the same power requirement, the fuel cell systems weigh significantly more than a GT system.

As hydrogen for a PEMFCPS or RFCPS is required exclusively for the FC operation, dedicated onboard storage is needed. The gravimetric efficiency of hydrogen fuel storage is near 7%, so the heavy tanks used for fuel storage are always required.

2.2 APPROACH

2.2.1 Assumptions

The current reality is that none of the fuel cell power systems evaluated in this study can provide the same aircraft auxiliary functionality as the conventional gas turbine powered APU does within the constraints of the prevailing pneumatic mechanical-system aircraft architecture and transportation system energy infrastructure. However, to make a meaningful safety assessment, the FCPS design and configuration must be reasonably capable of delivering the minimum basic services required of the future aircraft. At the same time, it must provide these services within, or be reasonably comparable, to the weight and volume constraints of current aircraft systems. This means that for each FCPS evaluated, optimistic assumptions are made that might enable this new technology, even to the point of adding functionality with a corresponding benefit unique to the FCPS, that may not currently exist on commercial air transport aircraft.

The FCPS implementations are assessed based on 2020 target performance factors published by the *DOE Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan*. *(US Department of Energy/Office of Energy Efficiency and Renewable Energy, April 2013, DOE Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan,* https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22) **.**

Future aircraft system architectures are based on various industry published reports and prior Honeywell internal studies. This analysis uses values and factors from these studies for electrical power demand, system weight impact, and an overall fuel burn assessment.

These assumptions apply to the following areas:

Market Segment: Each FCPS technology may have unique characteristics that are better suited to a specific air transport market segment. Each assessment identifies these market segments, including aircraft platform class, relevant flight routing, and operating procedures.

Infrastructure: Required airport infrastructure will be available, including gate power and services, high-pressure hydrogen gas refueling services, and/or the availability of sulfur-free jet fuel.

Concept of Operation: The concept of operation of the aircraft with a FCPS is changed to accommodate the specific characteristics and operational requirements of the FCPS. While the aircraft's functional requirements are still met, depending on the system being evaluated, ground operations may require increased dependency on terminal services, and/or additional synergies between the FCPS and adjacent aircraft systems and services assumed to meet these requirements. ETOPS is also a consideration in some FCPS implementations.

Aircraft Power System: New system architectures, and smart load management will be key to a successful FCPS implementation. Since the FCPS produces direct current (DC) electrical power, architectures will be assumed, which are biased towards using electrical power for services that previously used pneumatic power, such as the ME starting function and the cabin environmental (temperature) control.

2.2.2 Assessment

The approach to define characteristics necessary for implementation are: (1) practical power draw from the aircraft for feasible sizing; (2) system weight; and (3) potential fuel-burn savings, if any. The shape and volume of the system will be highly dependent on the level of system integration and will be addressed later in each individual FCPS assessment.

Conventional APUs are sized for the maximum power within the operating envelope. This peak load may only occur for short periods of demand, such as during main engine start (MES) or emergency electric power at altitude. Because all FCPSes have a relatively low specific power compared to a GT APU, an alternative approach will be used, which assumes that a more sophisticated power management system utilizes the FCPS over a level power demand profile and uses the ESDs such as batteries to supplement the peak power demand and assist transient states. The average power demand will be used for the FCPS size calculation.

To determine plausibility, a base, or critical level of functionality must be met, along with weight parity. A rough concept for the system footprint also will be created. The weight differential between a GT APU and a FCPS will be projected using published APU data and DOE factors. This weight comparison considers a conventional GT APU on an aircraft with a conventional pneumatic bleed architecture and compares it with a more electric aircraft (MEA) architecture. Weight differentials of affected systems will be assessed based on values from industry publications and proprietary Honeywell internal studies. Various aircraft and engine performance models are used to project fuel burn.

2.3 POTENTIAL IMPLEMENTATIONS

Current aircraft GT APUs have very high gravitational specific power and volumetric power density. As noted earlier, FCPS APU cannot compete in a like-for-like aircraft implementation based on size, weight, and power (SWaP), and fuel burn.

Many other factors weigh into decisions to adopt FC technology for GT APU replacement that are beyond the scope of this analysis, such as emissions, noise, regulations and mandate, costs, start-up time, reliability, life, etc.

Weight is a primary factor for system implementation possibilities, with respect to assessment uncertainty. No hard pass/fail criteria are used to determine the likelihood of FCPS technology implementation. Rather, the best effort projection of FCPS and associated aircraft changes are used for assessing the most likely implementation for certification safety issues and concerns.

2.3.1 Polymer Electrolyte Membrane Fuel Cell Power System

The key factors of successfully implementing a PEMFCPS are to minimize its size and weight. The key parameters affecting size and weight are the power (FC stack size) and energy (fuel quantity/storage size). High-power demand functions need to be satisfied by other means (such as ME generators or ground power) and hydrogen fuel use needs to be minimized by using this system only in necessary instances or if it enables higher benefit from other systems.

2.3.1.1 Target Market Segment

The obvious target market segment for PEMFCPS is commercial air transport, narrow-body aircraft, of Boeing 737 and Airbus A320 class, operating domestically for short to mid-range flights, without ETOPS certification. Advancement of PEMFCPS technology for the automotive industry makes it the most mature FCPS with power ranges potentially suitable for this aircraft application/implementation. The large production quantities of this aircraft class make it an attractive market sector encouraging manufacturer investment.

In this initial assessment, ETOPS certification would significantly increase the size of the PEMFCPS, potentially making it infeasible. However, there are sufficient domestic routes that do not require ETOPS certification to potentially justify the PEMFCPS.

These aircrafts assume the following: be equipped with internal hydrogen storage to support PEMFCPS operation; the air for the PEMFCPS will be fed from the cabin air outflow valve; the aircraft to employ a more electric power architecture, with an electric starter-generator mounted on each engine; the main engines to provide bleed air for cabin pressurization; and the cabin environmental control system to use an electric-driven vapor cycle system to manage the temperature of the bleed air pressuring the cabin.

2.3.1.2 Concept of Operations

United Airlines announced back in March of 2015 that it was going to change its procedures on APU operation, and cease starting the APU after landing. (Sumers, Brian, March 16, 2015, “United to change APU procedures after successful Denver test,” https://atwonline.com/avionics/united-change-apu-procedures-after-successful-denver-test.) More recently, United also announced that it would use terminal services whenever available and further limit/reduce the usage of aircraft APUs. These moves by United suggest a concept of operations (CONOPS) where APU services are only routinely used for ME starting. Extending this CONOPS to the future state, a PEMFCPS similarly might also be used only on the ground for ME start, during the transition between gate (ground) power and ME power (a necessity).

In addition, it is anticipated that these future aircrafts with MEs that use an advanced high-pressure ratio engine core may need the PEMCPS to provide electrical power during descent, so that the MEs can be pulled back to flight idle. This ability enables ME operability improvement and related fuel-burn reduction. Here is a summary of the preliminary CONOPS:

1. The aircraft is connected to ground power and conditioned air at the gate.
2. The hydrogen tank is topped off at the gate at each airport.
3. The aircraft switches to PEM FC APU power from ground power when ready to depart the gate.
4. The PEM FC APU power starts the first ME.
5. The first ME starts the second ME.
6. The PEM FC APU shuts down after both engines are operating.
7. The MEs power the aircraft through taxi, takeoff, climb, and cruise phases of the flight as currently operated today.

8. The PEM FC APU starts at the top of descent and provides all electric power during the descent phase of the flight.
9. During approach, the main engines resume supply of power, and the PEM FC APU shuts off.

2.3.1.3 Assumptions

1. All airports have gate ground power and conditioned air connections, which operators will use.
2. Hydrogen refueling infrastructure is mature, reaching all commercial airports.
3. The aircraft Environment Control System (ECS) operates at a higher coefficient of performance (COP) that is a multiple of COP of the current pneumatic system.
4. MES by electric starter motor, or starter/generator (S/G).
5. Load-shedding employed during MES, some failure modes, and emergencies.
6. The ME control allows lower idle speed and fuel flow to save fuel.
7. The cabin is pressurized by engine bleed air.
8. In case of a non-operational PEMFCPS in flight, the aircraft reverts to ME power.
9. Electrical load on ground is 120 kW for sea level (SL), hot-day (design case) condition. Duration is 15 minutes.
10. PEMFCPS effective lower heating value (LHV) efficiency is 45 percent (69 percent of peak efficiency).
11. MES requires 75 kW (hot day), 85 kW (cold day). Duration is 2 minutes.
12. Starting current is augmented by two onboard 40AH Li-Ion batteries.
13. Vapor cycle system (VCS) will be idling (compressors off) during MES.
14. Electric load in Flight Idle Descent (FID) is 86 kW. Duration is 30 minutes.
15. Electric load in emergency mode is 40 kW. Duration is 60 minutes.
16. Hydrogen fuel to storage system weight ratio is 5.5 percent.
17. FC APU specific power without fuel tank is 0.65 kW/kg.
18. 1,500 NM flight fuel burn weight penalty is 14.5 percent of added weight.
19. ME fuel burn saving during descent is 50 percent of baseline.

2.3.1.4 Potential System Description

The PEMFCPS was initially envisioned with dual-stack arrangement, co-located or integrated with the ECS for close coupling of the electric power and purge air from ECS. The FCPS cathode is fed by boosted cabin air; the stack is water cooled, and the final heat sink is ambient (ram) air.

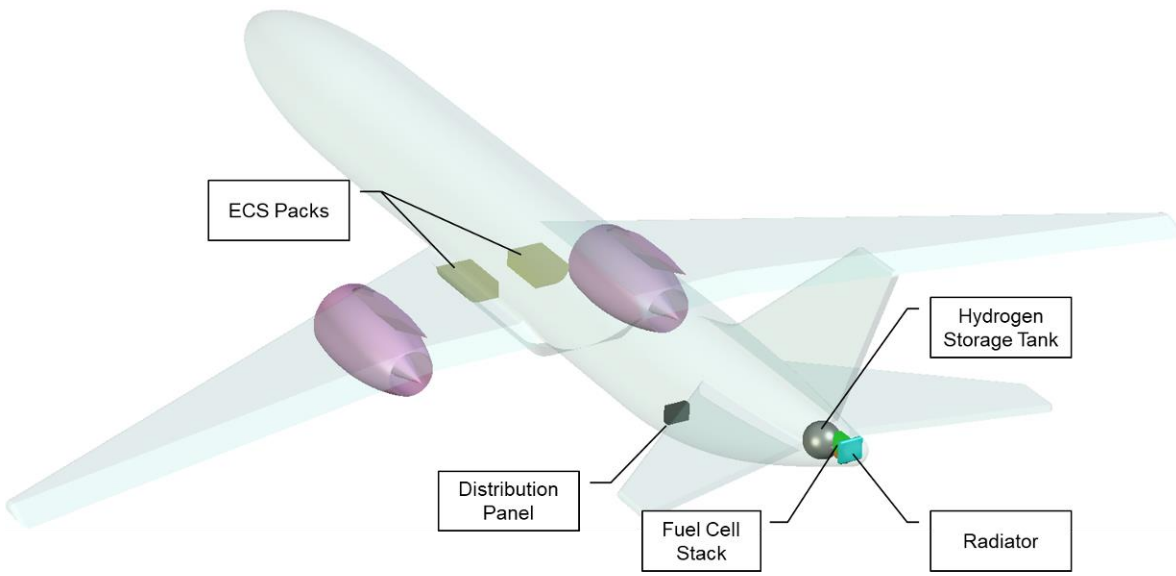

Figure 1. Potential layout of PEMFCPS in commercial twin-engine narrow-body air transport

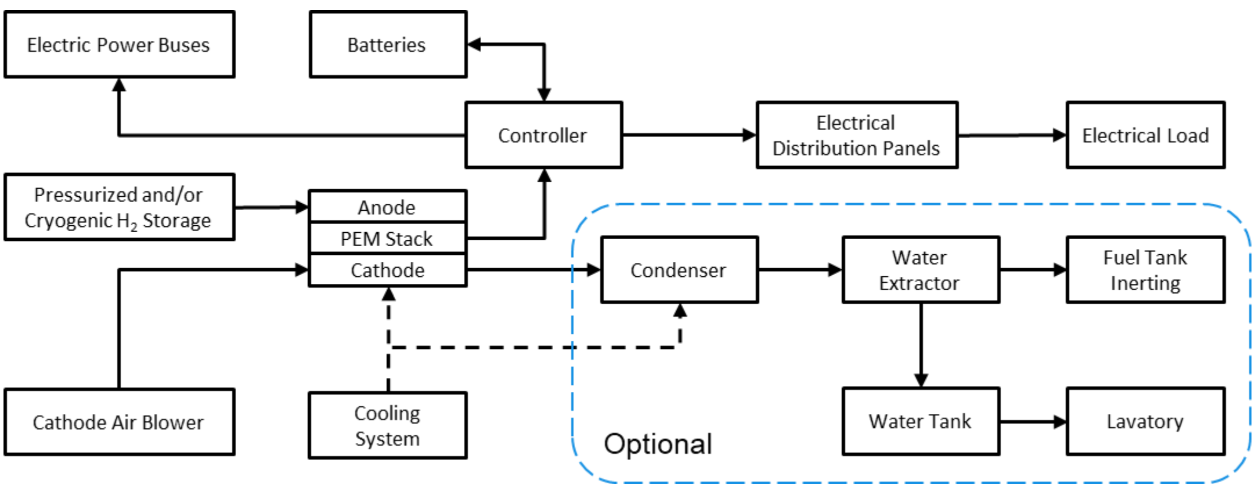

Figure 2. PEMFCS concept schematic with stored pure hydrogen

Table 1 lists power demands during flight segments when the PEMFCPS is providing power, a best-effort estimate. These power demands are used as average values for the purpose of PEMFCPS system-sizing and hydrogen-fuel quantity calculations only.

Table 1. Aircraft secondary power demand at various phases of operation

Power Demand, kW	Ground	MES	Descent
ECS Total (compressors, blowers, fans)	69	18	39
Fuel Pumps	12	12	12
Hydraulic Pumps	16	0	8

Power Demand, kW	Ground	MES	Descent
Galley	9	9	11
Lighting	6	6	6
Anti-Icing	0	0	10
Main Engine Start	0	75	0
Total	112	120	86
Duration, min.	15	2	30

2.3.1.4.1 Hydrogen Fuel

The required hydrogen fuel, and the fuel storage size, is calculated based on the assumed load, operating time, and DOE target FC efficiencies and weight factors (see Table 2).

Table 2. Hydrogen fuel required

	Ground & MES	Descent
Energy demand, kWh	32	43
Hydrogen fuel required, kg	2.4	3.2
Total hydrogen fuel required per flight, kg	5.6	

The total hydrogen required per flight is 5.6 kg, without margin and reserve for runway delay use, because the MEs could provide power during flight descent if necessary.

2.3.1.4.2 Weight

The overall weight estimates are based on data derived from the public domain (GT APU, FCPS, hydrogen fuel system, etc.), prior Honeywell proprietary internal studies (MES and ECS, weight fuel-burn penalty, etc.), and Honeywell proprietary engine models (FID fuel saving potential) (see Table 3). In this assessment, the PEMFCPS in a more electric architecture (MEA) with electric MES and electric-driven VCS/ECS is compared with a conventional GT powered system using pneumatic AC/ECS and MES. In the table below, the FCPS benefits from being sized to an average power requirement, which is much smaller than the conventional GT APU, and from the much smaller ducting required to feed and exhaust the PEMFCPS. The value reflected in Aircraft Systems reflects the adjusted results of a previously unpublished Honeywell study, which traded the benefits of a MEA vs pneumatic bleed aircraft architecture. These adjustments accounted for PEMFCPS-specific requirements that were not in the original study.

Table 3. System weight comparison

Additions, kg		Reductions, kg	
FCPS	185	APU	192
Fuel & Storage System	100	Descent Fuel Burn Saving	65
Aircraft Systems			40

Additions, kg		Reductions, kg	
Fuel Burn Weight Penalty			1
Sum	285	Sum	298
Net Weight Increase	-13		

Note that the PEMFCPS can provide emergency power but did not take weight credit of the ram air turbine (RAT) because some narrow-body air transport aircrafts, such as Boeing 737, are not equipped with one.

2.3.1.4.3 Fuel Burn

The impact of the PEMFCPS on jet fuel burn or aircraft fuel consumption was assessed, together with the PEMFCPS dedicated hydrogen fuel requirement. As noted in Table 3, the lower weight of the PEMFCPS resulted in a net decrease in jet fuel burned during flight.

MEs are very efficient in providing electric (shaft) power during climb, and particularly cruise, due to its high derivative efficiency adjacent its power setting. But when idling, the electric (shaft) power demands a speed higher than necessary due to operability consideration, thereby producing excess thrust, and corresponding high fuel burn. Thus, when the APU or PEMCPS can provide this electric power, the MEs can pull back to idle during descent, resulting in fuel savings.

Table 4 compares the overall fuel burn difference between GT APU and FCPS-equipped aircraft for reference only.

Table 4. Comparison of overall fuel-burn differences between GT APU and FCPS-equipped aircraft

Fuel Type	Aviation Fuel, kg	Compressed Hydrogen, kg
APU Fuel Burn Saving	-37	2.4
ME Descent Saving	-65	3.2
Weight Penalty	-1	
Overall Fuel Burn Delta	-103	5.6

2.3.1.5 Preliminary Assessment

The preliminary conclusion is that the PEMFCPS could be a technically plausible solution for secondary or auxiliary power in the midsize narrow-body commercial air transport segment. In this assessment, the system appears to have comparable weight as conventional systems. It brings the additional benefit of producing none of the exhaust emissions, including CO, CO2, NOx or non-volatile particulates of either environmental or health concerns. This system also is inherently quiet, to the benefit of passengers, ramp workers, and airport neighborhoods. The system weight will certainly change and likely to increase as development progresses. However, it is not expected to increase beyond the plausible limit.

This finding, of course, is contingent on several basic assumptions, which may or may not come to pass. Key among these assumptions are:

- The implementation of an MEA in future aircraft.
- The implementation of a hydrogen infrastructure at airports to support refueling of the aircraft secondary/auxiliary power systems.
- The willingness of air carriers to forgo terminal independence, to require that airport terminals provide both cabin air ventilation and temperature control, as well as electric power. Given that these aircraft will have an efficient ECS, electric power for the VCS/ECS could be a substitute for conditioned air from the terminal.
- These aircraft are not required to operate with ETOPS.

Extended operation of the PEMFCPS will affect the on-board hydrogen fuel system size and weight. The system used in this plausibility assessment operates only for 47 minutes per flight. System/value trades could dedicate more storage weight for additional PEMFCPS operating time, enabling ETOPS or time-limited terminal independence. Technology improvements in hydrogen storage gravitational efficiency would benefit the system with longer durations.

2.3.2 Regenerative Fuel Cell Power System (RFCPS)

Regenerative fuel cells are a relatively recent technology. In concept, they are a reversible fuel cell, with integrated gaseous reactants. Functionally, they use external electrical power to internally electrolyze pure water (H2O) into separate internal reservoirs of gaseous hydrogen and oxygen gas and are then capable of providing electrical power by catalyzing the H2 and O2 back to water. The size of the PEM stack defines/limits the voltage of the unit. The flow rate of the reactants defines the current. The capacity of the integrated gaseous reactants defines the total energy storage capacity. While the concept of a reversible fuel cell goes back to the 1960s, significant development occurred in the 1990s and early 2000s. NASA prototyped the development of a fuel cell, integrating a PEM stack, electrolyzer, balance of plant, and high-pressure storage for reactants with the vision of using the device on a high-altitude, solar-powered research aircraft (Helios). Various government funded and commercial development efforts have further refined the technology, making it more compact and affordable. There appears to be active efforts to market this technology for stationary, temporary energy storage, as well as for space applications.

The attraction of the RFCPS for air transport aviation is that it does not require any hydrogen infrastructure. Unlike the PEMFCPS, there is no need to refuel this system unless a maintenance action.

2.3.2.1 Target Market Segment

Like the PEMFCPS, the RFCPS may be best suited for commercial air transport narrow-body aircraft, of the Boeing 737 and Airbus A320 class, operating domestically for short to mid-range flights, without ETOPS certification. While this technology is less developed than the PEMFCPS, there is no infrastructure change that is required for its implementation. The large production quantities of this aircraft class make it an attractive market sector, encouraging manufacturer investment.

In this initial assessment, ETOPS certification would significantly increase the system size, potentially making it infeasible. However, there are sufficient domestic routes that do not require ETOPS certification to potentially justify the RFCPS.

It is assumed that these aircrafts employ a more electric power architecture, with an electric-starter generator mounted on each engine, with MEs that provide bleed air for cabin pressurization, and a cabin environmental control system that uses an electric driven, vapor-cycle system to manage the temperature of the bleed air pressuring the cabin.

2.3.2.2 Concept of Operation

Because the RFCPS can provide continuous power for a duration limited by its reactant capacity, like the PEMFCPS, a similar concept of operation will be followed. The difference for the RFCPS is that during the period following RFCPS operation, when not providing power, the RFCPS is in regenerative mode converting water back into high pressure hydrogen and oxygen gases using electric power from the MEs. For the RFCPS, the concept of operation is :

1. The aircraft connects to ground power and conditioned air at the gate.
2. The onboard electrolyzer replenishes the hydrogen and oxygen tank, using gate power.
3. The aircraft switches to RFCPS power from ground power when ready to depart the gate.
4. The RFCPS power starts the first ME.
5. The first ME starts the second ME.
6. The RFCPS switches to regenerative mode after both engines are operating.
7. The MEs power the aircraft and the RFCPS electrolyzer through taxi, takeoff, climb, and cruise phases of the flight as currently operated today.
8. The RFPS switches to power-generation mode at the top of descent and provides all electric power during the descent phase of the flight.
9. During approach, the MEs resume supply of electric power, and the RFCPS will be switches to regenerative mode.

2.3.2.3 Assumptions

1. No hydrogen refueling infrastructure at airports.
2. All airports have gate ground power and conditioned air connections, which operators will use.
3. The aircraft electric load profile allows the ME generators to recharge the RFCPS.
4. The aircraft ECS operates at a higher COP that is a multiple of COP of the current pneumatic system.
5. MES by electric starter motor, or (S/G).
6. Load-shedding is employed during MES, some failure modes, and emergencies.
7. The ME control allows lower idle speed and fuel flow to save fuel.
8. During FID, the cabin is pressurized by engine bleed air.
9. In case of a non-operational RFCPS in flight, the aircraft reverts to ME for electric power during FID.
10. Electric load on ground is 120 kW for SL, hot-day (design case) condition. Duration is 15 minutes.
11. RFCPS effective LHV efficiency is 56 percent.

12. MES requires 75 kW (hot day), 85 kW (cold day). Duration is 2 minutes.
13. Starting current is augmented by the one onboard 40AH Li-Ion battery.
14. VCS momentarily idles (compressors off) during MES.
15. Electric load in flight idle is 86 kW. Duration is 30 minutes.
16. Electric load in emergency mode is 40 kW. Duration is 60 minutes.
17. Hydrogen fuel to reactants storage system weight ratio is 2.7 percent.
18. FC APU specific power without fuel tank is 0.8 kW/kg.
19. 1,500 NM flight fuel burn weight penalty is 14.5 percent of added weight.
20. ME fuel-burn saving during descent is 50 percent of baseline.

2.3.2.4 Potential RFCPS System Description

The RFCPS can be discrete (separate stacks for water electrolyzer and FC) or unitized (common stack).

The unitized stack is attractive due to its simplicity. Figure 3 shows a basic concept for the unitized regenerative fuel cell power system (URFCPS). It features a single unitized stack that performs both electrolysis and power-generation process. In its simplest form, no operational pressure regulation or flow control is necessary. However, URFCPS technology is still in early development, and may see significant changes as performance, durability, cost, and safety issues are identified and resolved ahead of successful commercialization.

Currently, the URFCPS lacks the flexibility to tailor the electrolyzer and FC stack functions to the system duty cycle. Because the FC and electrolyzer operate under different conditions, substantial compromises must be made in the design of URFCPS, which may make it less competitive than other options. Most importantly, the potential hazard of inability to isolate reactants from failure mode such as autoignition in the stack will result in catastrophic consequence due to the high-pressure, high-energy reactants stored in close proximity. The overall assessment makes URFCPS for commercial aircraft implementation implausible, and, therefore, no further action is considered.

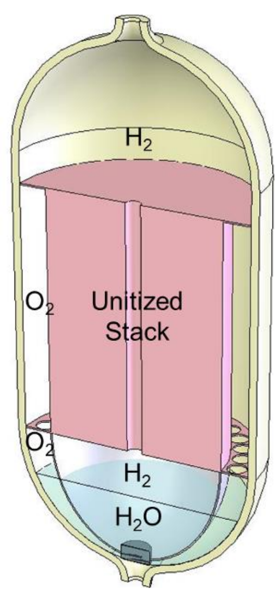

Figure 3. Unitized stack concept example

Depending on the electrolysis pressure, as its power density is higher than that of the PEMFCPS, the system may consist of multiple smaller units. Since the RFCPS does not rely on air for oxygen source, it opens many more installation options. And because it's a closed system, maintenance is minimized. A distributed power network could be realized with this technology.

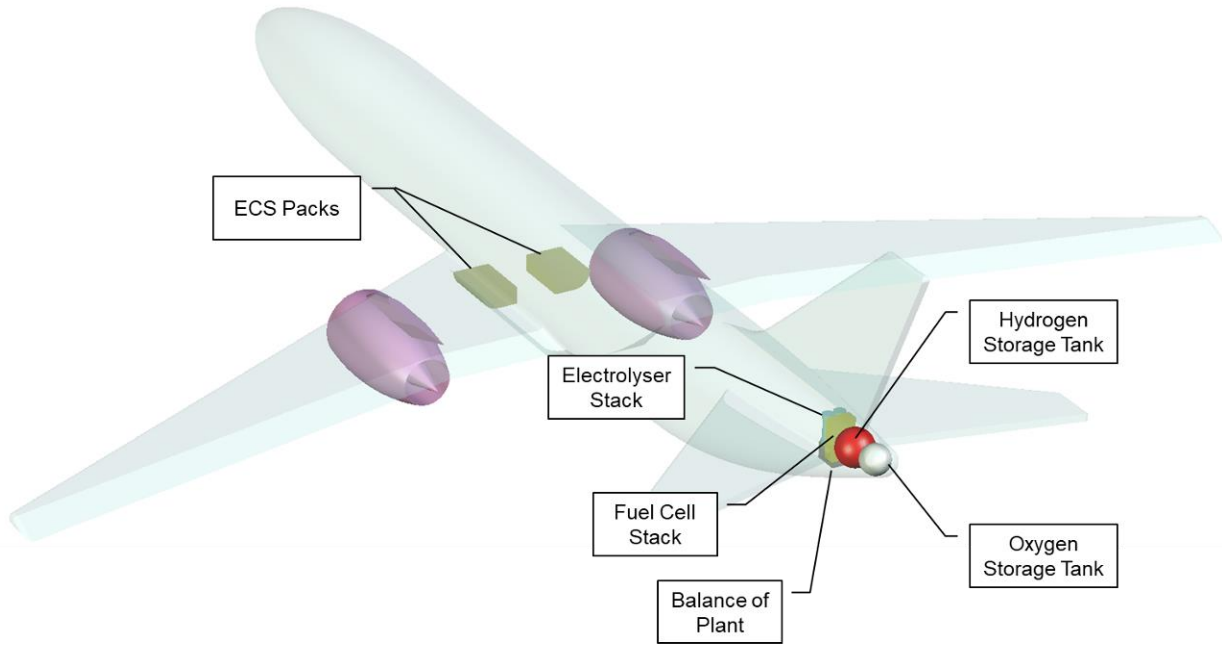

Figure 4. Potential layout for RFCPS in commercial twin-engine, narrow-body air transport

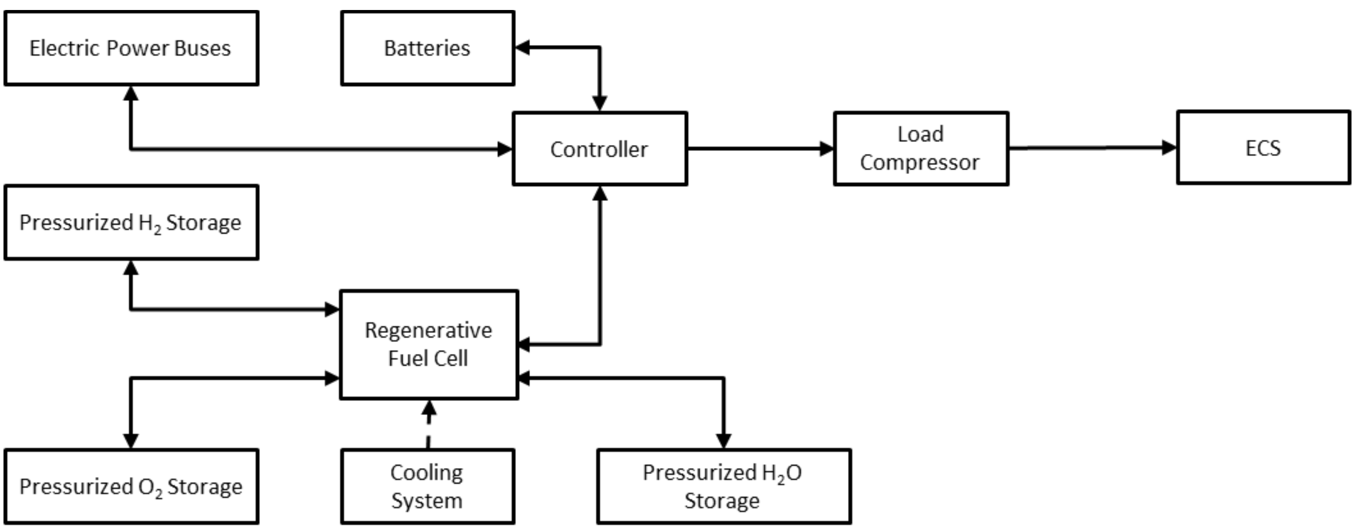

Figure 5. RFCS concept schematic

<u>2.3.2.4.1 Power Demand</u>

Table 5 defines the power demand for the FCPS.

Table 5. Aircraft secondary power demand at various phases of operation

Power Demand, kW	Ground	MES	Descent
ECS Total (compressors, blowers, fans)	69	18	39
Fuel Pumps	12	12	12
Hydraulic Pumps	16	0	8
Galley	9	9	11
Lighting	6	6	6
Anti-Icing	0	0	10
Main Engine Start	0	75	0
Total	112	120	86
Duration, min.	15	2	30

2.3.2.4.2 Fuel

Because the gaseous hydrogen fuel storage system (FSS) consumes the most energy of the three operating conditions (listed in Table 5), it is sized for the FID energy requirement, and because any fuel consumed during MES or ground operation prior to takeoff can be regenerated by MEs during the subsequent flight. MEs can generate fuel required for ground and MES during taxi or at the terminal from ground power. This allows the size of the RFCPS fuel system to be reduced from the 5.6 kg required for the PEMFCPS to 2.3 kg. Since a stoichiometric amount of oxygen is also required, an additional 18.4 kg of oxygen is necessary.

Table 6. Hydrogen fuel required

	Descent
Energy Demand, kWh	43
Hydrogen Fuel Required, kg	2.3

2.3.2.4.3 Weight

The overall weight estimates are based on data derived from the public domain (GT APU, FCPS, hydrogen fuel system, etc.), prior Honeywell proprietary internal studies (MES and ECS, weight fuel-burn penalty, etc.), and Honeywell proprietary engine models (FID fuel-saving potential). The value reflected in Aircraft Systems reflects the adjusted results of a previous unpublished Honeywell study, which traded the benefits of a MEA vs pneumatic bleed aircraft architecture. In this assessment, the RFCPS in a MEA with electric main engine start and electric driven VCS/ECS is compared with a conventional GT-powered system using pneumatic AC/ECS and MES.

The maturity of mobile regenerative FC technology lags that of the automotive PEMFCPS. As no credible data exists for quantitative implementation assessment, an analogous analysis technique is therefore used for qualitative assessment. As with the PEMFCPS, the RFCPS benefits from being sized to an average power requirement, which is much smaller than the conventional GT

APU. The weight of the system is estimated to be slightly lighter than that of the PEMFCPS because:

- The energy required is less than 50 percent of a PEMFCPS implementation; therefore, the hydrogen fuel system weighs less.
- Oxygen and its storage is required, which weighs less than that of the hydrogen for half the volume required.
- The stacks construction is non-flow-through (NFT) design, therefore, smaller in size for the same power.
- The stack can be of smaller size due to ~10X higher reactant partial pressure resulting in higher current density.
- Since the system does not require air blowers/compressors, the balance of plant should consume less power and weigh less.
- Only one battery is required to supplement the transient-power capability on the RFCPS because its transient response is faster than the air breathing PEMFCPS. The conventional/baseline system has two batteries.

Table 7 lists the weight-assessment result.

Table 7. Rough net weight

Addition, kg		Credit, kg	
FCPS	264	APU	192
Reactants & regenerative system	78	Descent fuel burn saving	65
Fuel burn weight & shaft penalty	27	Aircraft Systems	65
		Battery	23
Sum	369	Sum	345
Net	24		

2.3.2.4.4 Fuel Burn

Even though the RFCPS provides functionality identical to the PEMFCPS and weighs slightly more than the PEMFCPS, a typical flight burns somewhat more fuel than the PEMFCPS. Since the RFCPS is charged by energy from the MEs, the ME fuel burn will be higher than the PEMFCPS. The calculation is based on the following:

- Same fuel saving during descent as PEMFCPS
- Additional fuel burn during the RFCPS regeneration period by the MEs to electrolyze the liquid water into gaseous hydrogen and oxygen
- Slightly less weight penalty

Table 8. Net aviation fuel

Fuel Type	Aviation Fuel, kg
APU fuel burn saving	-37

Fuel Type	Aviation Fuel, kg
Main engine descent saving	-65
Weight & shaft penalty	27
Overall fuel burn delta	-75

2.3.2.5 Preliminary Assessment

Both PEMFCPS and RFCPS system weights are within estimation uncertainty, as are potential aviation fuel savings.

The preliminary conclusion is that the RFCPS could be a technically plausible solution for secondary or auxiliary power in the midsize narrow-body commercial air transport segment. In this assessment, the system appears to have comparable weight as conventional systems. Because it requires main engine operation to regenerate H2 and O2 in flight, it cannot claim to completely eliminate system exhaust emissions. However, since these occur in flight, the impact on ground-level pollution is still minimized. This system is inherently quiet, to the benefit of passengers, ramp workers, and airport neighborhoods. The system weight will certainly change and will likely increase as development progresses; however, it is not expected to increase beyond the plausible limit.

This finding is, of course, contingent on several basic assumptions, which may or may not come to pass. Key among these assumptions are:

- The implementation of an MEA in future aircraft. As such, the fuel cell system is required only to produce DC electrical power at a specific voltage, which is subsequently conditioned/controlled as needed by the system. Likewise, electrical power required for balance of plant (BOP) functions, including sensors, fans, pumps, actuators, are provided from either an internal source or the aircraft power buses.
- Onboard battery power is used to supplement or absorb RFCPS power during transients. For this application only, a single 48v XX Amp Hr battery is assumed.
- The implementation of a hydrogen infrastructure at airports to support refueling of the aircraft secondary/auxiliary power systems.
- The willingness of air carriers to forgo terminal independence, to require that airport terminals provide both cabin air ventilation and temperature control, as well as electric power. Given that these aircraft will have an efficient ECS, electric power for the VCS/ECS could be a substitute for conditioned air from the terminal.
- These aircrafts are not required to operate with ETOPS.

Extended operation of the RFCPS will affect the size and weight of the onboard hydrogen fuel system. The system used in this plausibility assessment operates only for 47 minutes per flight. System/value trades could dedicate more storage weight, for additional RFCPS operating time, enabling ETOPS or time-limited terminal independence. Technology improvements in hydrogen storage, gravitational efficiency would benefit the system with longer durations.

2.3.3 Solid Oxide Fuel Cell Power System (SOFCPS)

Solid oxide fuel cells have been in development in one form or another since the 1950s. They were initially developed as stationary power sources, often as part of a bottoming cycle, or cogeneration application. Characteristic of SOFCPS, the stack operates at elevated temperatures, >800C. As a result, it has the capability to reform conventional logistics fuels, and does not use precious metals for catalysis. Also, characteristic of these systems, they use high-temperature materials and have poor cyclic life and poor transient operational characteristics. The SOFCPS is also more tolerant to sulfides in the fuel than a low temperature PEMFCPS, though sulfides do contribute to a performance reduction.

The ideal implementation in commercial transport aircraft is a power system that continuously stays on, except for scheduled maintenance. For the same reason, the SOFCPS is ineffective/inefficient in dealing with transient states; and is better suited for providing base loading. The SOFCPS provides power throughout the flight profile, so the ME can be relieved of all parasitic power extraction and be more efficient in providing propulsive power.

To improve the overall system performance and weight, the SOFCPS provides additional functions, such as heat for galley services, oxygen-depleted air (ODA) for fuel tank inerting, and recovered water to support the various aircraft hotel services.

2.3.3.1 Target Market Segment

Future A SOFCPS is most likely to be used in a wide-body aircraft designed for intercontinental flights (similar to the Boeing 777/787 and Airbus A350), with a typical range between 3,000 – 9,000 nautical miles. As high-utilization aircraft can operate for more than 20 hours per day, the SOFCPS can operate continuously without shutdown, except for scheduled maintenance.

2.3.3.2 Concept of Operation

The SOFCPS provides all-time power supply, even when parked. System shutdown is for maintenance only.

Functions:

- Provides all electric power for aircraft operation, including emergency power
- Provides thermal power for galley operation and wing anti-ice
- Water for cabin lavatory use
- ODA for fuel tank inerting and cargo-hold fire suppression.
- Emergency oxygen

2.3.3.3 Assumptions

- Clean-sheet design for wide-body air transport platform.
- Sulfur-free or ultra-low sulfur (< 1 ppm) jet fuel is available at all airports.
- The aircraft ECS operates at a higher COP that is a multiple of COP of the current pneumatic system.

- Hybrid power system – SOFCPS to provide base-load power and RFCPS to smooth the load profile.
- The ME provides propulsive power only.
- The SOFCPS provides all non-propulsive power.
- Cabin is pressurized using power recovered from cabin outflow air, boosted by engine bleed air.
- Cabin is pressurized by ME bleed during FID.
- Solid oxide fuel cell (SOFC) stack cooling air is used for wing icing protection.
- Use published Boeing 787 data as baseline for comparison.
- Electric power base demand is 520.
- Electric Power System peak demand – 520 kVA (explained in next section)
    - SOFC stack (64 percent)
    - SOFC turbo generator (13 percent)
    - Regenerative fuel cell (RFC) stack (23 percent)
- SOFC stack efficiency is 40 percent.
    - SOFCPS specific power (0.045 kW/kg)
- 5,400 NM flight fuel burn weight penalty is 50 percent of added weight.
- Main propulsive engine fuel burn improvement is 5 percent

2.3.3.4 Potential System Description

The schematic in Figure 6 describes the system concept for application of the SOFCPS to a large, wide-body commercial air transport. A fraction of the cabin outflow air is compressed with the cathode compressor (CC) and flows into the SOFC cathode. Liquid fuel from either a dedicated fuel tank or from the aircraft fuel tank with ultra-low or de-sulfurized fuel is pumped into a steam reformer, where it is converted into a gaseous mixture of CO, CO2, H2, and H2O, and fed into the SOFC anode at high temperature. The pressure on both cathode and anode streams are similar. The catalytic reaction within the stack reacts the H2 in the anode gas stream with O2 in the cathode gas stream to generate DC electric power which is conditioned and fed into the DC electrical power bus. The anode and cathode discharge gas streams are mixed and sent through a catalytic burner that augments the steam reformer, and further depletes the residual oxygen from the cathode reaction, reacting it to consume the CO and residual H2 from the anode stream. This high-pressure effluent is then expanded through a power turbine (PT) that drives the CC. The expanded gas is cooled through a steam generator (SG), pre-cooler, economizer, and condenser to distill out water for cabin use and ODA for fire suppression and fuel tank inerting. Excess power from the cathode turbo-compressor (CC+PT) can be extracted through a generator and fed back into the electrical power bus.

As noted, the SOFC is intended to provide only base power since it does not tolerate thermal cycling, so a discrete regenerative PEM fuel cell is used to provide or absorb power during load transients.

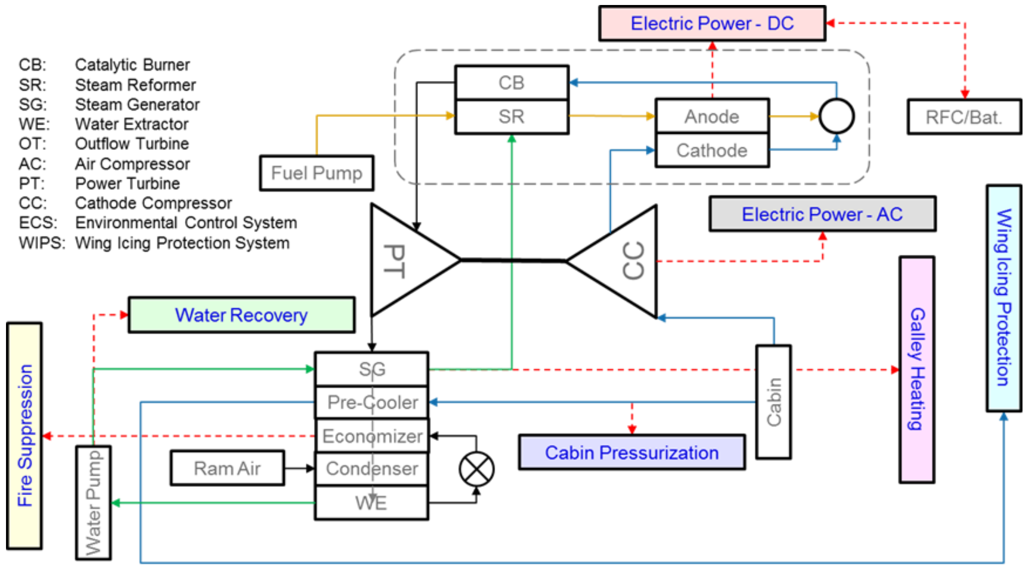

Figure 6. Preliminary integrated and hybridized SOFCPS for wide-body aircraft

2.3.3.4.1 Power Demand

Power demand is based on scaling from the Boeing 787 to a new system architecture. The Boeing 787 can provide 1 MW of electrical power, which covers peak demand and failure cases. If the SOFCPS is to provide like-for-like replacement of 1 MW power generation, the system weight would weight 22 metric ton. This is extremely impractical and unlikely to be implemented.

Based on the assumptions, at 43,000-feet cruise altitude, the cabin air compressor consumes approximately 320 kW, to maintain enough fresh air flow to support 440 passengers (787-10 maximum seating). Wing anti-icing consumes up to 160 kW of electric power. Based on the assumptions, the total of 480 kW can be excluded from the SOFCPS demand.

The remaining peak electric power demand from SOFCPS is 520 kW. The hybridized RFCPS covers the 120 kW, and the integrated GT covers the 65 kW. The actual size of the SOFC is 335 kW.

The SOFCPS also provides up to 250 kW of continuous thermal power for wing-icing protection.

2.3.3.4.2 Fuel

One unique aspect of the SOFCPS is that it reforms hydro-carbon fuel to create its own hydrogen-enriched fuel. This hydro-carbon fuel can be shared with the ME. However, common jet fuel contains sulfur, which is a poison to the FC and must be removed. Fuel desulfurization equipment is heavy and hazardous; therefore, it’s assumed the aircraft will have a dedicated fuel tank to accept sulfur-free fuel, either processed on ground at the airport, or specialty fuel such as bio-fuel. The sulfur-free fuel can be used by the GT engine, so it can count as reserve fuel, without adding weight to the aircraft fuel system.

2.3.3.4.3 Weight

As apparent in system description 2.3.3.4 , the SOFCPS requires extensive integration with the aircraft to minimize the weight impact and maximize the overall system efficiency.

In this case, the 335-kW-rated SOFCPS will weigh over 7,000 kg. Roughly half the weight can be credited from equipment it replaces, water it recovers, or fuel-burn saving from improved MEs. There may be other areas within the aircraft structure that can be improved, but the gains from wholesale change are difficult to speculate, and the system size and weight are too complex to assess under this study. There may be areas to uncover in the NCD that can further justify the adaptation of SOFCPS.

2.3.3.5 Preliminary Assessment

Unlike the other fuel cell systems evaluated, the SOFCPS (as described in the integration example above) can operate from logistics-type fuels, though a sulfur-free, or extremely low sulfur content will be required. It also augments, or replaces existing aircraft systems for:

- Provides all electric power for aircraft operation, including emergency power
- Provides thermal power for galley operation and wing anti-ice
- Water for cabin lavatory use
- ODA for fuel tank inerting and cargo-hold fire suppression.
- Emergency oxygen

On the negative side, the system is very heavy. In this preliminary assessment, less than half of the 7000 kg SOFC system weight was offset by synergy and fuel-weight savings. The NCD may further improve and optimize in the areas below to make the architecture plausible for implementation and expose inherent safety hazards.

2.4 CONCLUSIONS

This analysis concludes that the implementation of PEMFCPS, RFCPS, and SOFCPS is plausible. The next three sections discuss the NCD of each technology. The goal is not about whether a certain FCPS will be implemented, but to explore and expose potential safety hazards associated with these new technologies for aircraft application.

3. NOTIONAL CONCEPT DESIGN – PEMFCPS

3.1 PRODUCT DESCRIPTION

With the objective of identifying potential hazards and safety-related concerns, the NCD builds upon the initial plausibility assessment by establishing, in as much detail as possible, the functions of the candidate fuel system within the aircraft; identifying the components of the system, their location within the aircraft; identifying installation interfaces; and the potential safety issues around system service, including refueling and maintainability.

Having established plausibility for the PEMFCPS, this target market segment is for service in a commercial narrow-body air transport aircraft with less than 180 passengers, with short to mid-range capability, servicing US domestic routing. The typical aircraft would need the PEMFCPS to provide:

- Electric power—both 28 VDC and ±135 VDC—for basic and necessary functions during periods when no other means of power storage devices can reasonably achieve the similar result. The ±135 VDC powers high-electrical, power demand systems such as vapor-cycle compressors (VCCs) motor and ME starter motor.
- Electric power to start an ME on ground. PEMFCPS provides such power while maintaining functionalities of the aircraft flight deck, internal lighting, and communication.
- In-flight emergency electrical power in the event of an engine or engine-mounted generator failure; providing 50 percent of emergency power in flight within 5 seconds and full emergency power in 30 seconds, in order to maintain control of the aircraft in functions such as flight deck, communication, and flight control, to safely land the aircraft.
- Electric power to meet aircraft electric-power demand during the flight's descent phase so the MEs can be set to lower throttle position to save a considerable amount of liquid aviation fuel.
- Standby power mode to produce minimum power (at highest efficiency) to support functions while the aircraft is unattended, e.g., functions such as keeping temperature-sensitive equipment in desired condition.

The PEMFCPS consumes compressed hydrogen gas, which is stored on board the aircraft, and will be replenished before each flight. The fuel truck services the hydrogen fuel tank, like the way that the liquid fuel truck services the jet fuel tank. The PEMFCPS cathode is supplied with pressure-boosted air from the cabin, and the exhaust is discharged overboard. A liquid-cooling circuit is used to transfer PEMFCPS waste energy to ambient air as heat sink. The PEMFCPS may include Li-ion main aircraft batteries for optimized performance.

Table 9 summarizes PEMFCPS functions during different phases of the operation.

Table 9. PEMFCPS functions summary

Operational Functions					
Services	Parked	Gate→MES	MES	FID	Emergency
PEMFCPS Controls & Monitor	Y	Y	Y	Y	Y
Cockpit Avionics		Y	Y	Y	Y
Communication		Y	Y	Y	Y
Interior Lighting		Y		Y	Y
Cabin Air Conditioning		Y		Y	Y
Flight Control					Y
Main Engine Start			Y		

3.1.1 Secondary Functions

There are secondary functions that the PEMFCPS can potentially provide, usually at the expense of size, weight, and complexity. The implementation of these functions will be case-by-case detailed design options, which is not in the scope of this research. While these functions were not included in the top-level assessment discussed in the previous sections, they could be justified given the following discussion.

Fuel Tank Inerting

The waste products from PEMFCPS operation is steam-saturated ODA. Based on general design practice, the dry ODA contains in the range of 9–13 percent of oxygen. Though the oxygen content is within the right range for fuel tank inerting, there are two barriers:

- Fuel tank inerting requires a supply of ODA to replace the volume of the consumed fuel during the entire duration of the flight. However, the concept of operation for PEMFCPS implementation in narrow-body, air transport aircraft limits the inflight operation to emergency operation and during aircraft descent.
- The cathode outflow ODA is over-saturated with water from FC reaction. This water must be removed from the ODA, otherwise the condensed water will cause serious damage to the aircraft fuel system.

Operating the PEMFCPS in fractional power during flight to produce the correct amount of ODA for fuel tank inerting is plausible but may not have an obvious benefit. The part power efficiency would be noticeably higher, and the ME fuel burn would benefit by not providing bleed air for the fuel tank inerting system (FTIS) and lessened load on electric generators.

Simple calculation suggests that to continuously provide adequate fuel tank inerting ODA to the tank, the PEMFCPS must operate at approximately 40 kW, or 35 percent of full electric power during the entire flight. At an efficiency of 60 percent, the hydrogen burn rate will be approximately 2.0 kg/hour, and for a five-hour flight, 9.8 kg of hydrogen fuel is consumed, resulting in 178 kg increase in FSS. Add the weight of water-removal equipment (assuming 20 kg), subtract 44 kg for the SOA FTIS and 84 kg water that is no longer needed on board, the net is 13 kg weight gain.

Combined with the recovery of water removed from the ODA for lavatory use, the additional weight is in the estimation uncertainty range. The additional volume of 171 liter is significant but may be tolerable. One side benefit of this configuration is that there is sufficient hydrogen fuel on board for ETOPS certification. Table 10 shows the weight comparison.

Table 10. Additional weight for extended function PEMFCPS

Weight Addition, kg		Weight Subtraction, kg	
Hydrogen Fuel Storage System	178	Potable Water Recovered	84
Water Condensing System	20	SOA Fuel Tank Inerting System	44
		ME Fuel Burn Reduction	57

Weight Addition, kg		Weight Subtraction, kg	
Sum	198		185
Net Increase, kg	13		

3.1.1.1 Potable Water Recovery

The ODA contains water as a byproduct, which may be recovered to reduce the amount of water the aircraft has to carry at takeoff. A trade must be made between the weight of water recovery equipment and water recovered. However, if the configuration is set to provide fuel tank inerting, then water recovery is part of the system

Based on the Near-Term Implementation Analysis (NTIA) and assumptions, only about 3 kg of hydrogen is used during routine flights, if 90 percent of the water byproduct is recovered, it amounts to 24 kg of water. It may sound plausible for a positive trade against water recovery equipment. However, the PEMFCPS only begins to produce water at the end of the cruise, when water usage from that point on is minimal.

3.1.1.2 Cargo Hold Fire Suppression

Like fuel tank inerting, ODA can also be used to suppress cargo-hold fire to save the weight of halon bottles. An experiment done at Federal Aviation Administration’s (FAA) Technology Center Laboratory has demonstrated that the ODA alone is inadequate to distinguish fire in cargo hold but maintains suppression after the fire was distinguished by halon. Also, same shortcoming as fuel tank inerting function, there is no reliable and sufficient source of ODA to perform this function when needed in a timely fashion.

3.1.1.3 Waste Heat Reuse

Although the FC stack generates slightly more waste heat as its output electrical power (40 percent average system efficiency assumed), due to its relatively low temperature, very little heating application can benefit from it.

The nearest consumer of this low-quality waste heat would be the aft galley for pre-heating food and beverages. Based on the NTIA rationale and assumptions, the single-aisle aircraft usually doesn’t provide heated meals, and the wasted heat is not quite hot enough for heated beverages such as coffee. The assumption is these services are unlikely to be provided when the plane starts to descend, the only time the system is on during the flight.

Even if the design intended to use PEMFCPS during flight, the ambient temperature at cruise altitude is extremely cold; the heat load from solar, in-flight entertainment, and passenger’s metabolism can offset the heat loss through the skin of the aircraft. For most of the time, the ECS is in cooling mode. On rare occasions such as an empty cabin with no warm body, the heating is needed, which will be easily satisfied through the heat of compression by cabin pressurization.

3.2 REQUIREMENTS

The requirements will be based on the assumptions listed in the NTIA.

3.2.1 Performance

The top-level performance requirement for notional design is derived from NTIA, which includes high-level trade against modern GT APU in terms of hardware and ME fuel-burn credits and penalties.

Table 11. Top-level performance requirements for notional design

Electric Power, Rated	120 kW
LHV Efficiency at Rated Power	45%
LHV Efficiency at 25% Power	65%
Electric Voltage	28 VDC
	±135 VDC
Cold Start Time at -22°F	30 seconds
Hydrogen Fuel System Weight	100 kg

3.2.2 Installation

Table 12. Installation requirements

Attitude	X = ± 15°	X = Roll
	Y = ± 15°	Y = Pitch
	Z = ± 180°	Z = Yaw

3.2.3 Operation

Table 13. Operational requirements

Operating Envelope	Sea level to 14,000 ft	Ground operation
	Sea level to 50,000 ft	Loss of cabin pressure, de-rated
Attitude	X = ± 20°	X = Roll
	Y = ± 40°	Y = Pitch
Emergency Landing	9G	Forward
	1.5G	Aft
	3G	Side
	6G	Down
	3G	Up
	9.86G	Vector Sum
Gust Load	9.86G	Down
	7.89G	Up

Ambient Temperature	-67° - 185°	

3.2.4 Maintenance

Table 14. Maintenance interval requirements

Maintenance Interval	1,200 hrs minimum

3.2.5 Reliability

Table 15. Reliability requirements

Startup/Shutdown Durability	5,000 cycles
Life (Degradation<10%)	5,000 hours

3.2.6 Safety

Table 16. Safety requirements

Condition	RTCA/ DO-160G	Requirement	Operating	Non-Operating
Operating Low Temp	Section 4	Category D2 (-55° C)	X	
Operating High Temp	Section 4	Category D2 (+70° C)	X	
Short Time Operating High Temp	Section 4	Category D2 (+70° C)	X	
Ground Survival Low Temp	Section 4	Category D2 (-55° C)	X	X
Ground Survival High Temp	Section 4	Category D2 (+85° C)	X	X
Altitude	Section 4	Category D2 (50,000 ft.)		X
Temperature Variation	Section 5	Category B Operating: -55 to 70° C Ramp: (5° C minimum/min.)	X	X
Humidity	Section 6	Category B (minimum 95% relative humidity at +65° C)	X	X
Operational Shock	Section 7	Category B sawtooth pulse, with an acceleration peak value of 6 G's for 11 ms	X	
Crash Shock	Section 7	Category B PROC 1 same as operational shock except 20 G's		X
Crash Safety Sustained Acceleration	Section 7	Category B PROC 2 non-operating – 9.0g along any axis		X
Vibration	Section 8	Category S Test Curve C, Standard Vibration, 1 hr/axis	X	X
Explosion	Section 9	Category A or B* Site altitude, 70C fuel type recorded in test report	X	X
Waterproofness	Section 10	Category Y or W* Drip proof test, 280 1/M** 2/h for 15 minutes operating	X	X
Sand and Dust	Section 12	Category D Sand and dust jet along each direction of each major orthogonal axis at 25C and 55C non-operating	X	X
Fungus Resistance	Section 13	Category F Cultures of 5 Fungi, 28 days incubation	X	X
Salt Spray	Section 14	Category S 5% salt solution spray at 35C for 48 hrs non-operating	X	X

Table 16. Safety requirements (continued)

Condition	RTCA/ DO-160G	Requirement	Operating	Non-Operating
Magnetic Effect	Section 15	Magnetic field of 14.4 A/m for specified deflection, distance is determined by test	X	
Power Input	Section 16	Category A normal and abnormal operating voltage, interrupt, normal and abnormal surge, undervoltage	X	
Voltage Spike	Section 17	Category A 600V, 10 □sec transient	X	
Audio Frequency Conducted Susceptibility, Power input leads	Section 18	Category R or Z* Sine wave audio frequency superimposed on power lead	X	
Induced Signal Susceptibility	Section 19	Category Z Magnetic and electric fields and spikes induced into equipment and cables	X	
Radio Frequency Susceptibility Conducted	Section 20	Category Y* Cable injection to 10kHz to 400MHz	X	
Radio Frequency Susceptibility, Radiated	Section 20	Category Y* Radiated field to 18GHz Freq. Avg (V/M) Peak (V/M) 10kHz to 1 GHz 200 N/A 1 to 2 GHz 200 1700 2 to 4 GHz 200 3000 4 to 6 GHz 200 2300 6 to 8 GHz 200 530 8 to 12 GHz 200 1400 12 to 18 GHz 200 850	X	
Emission of Radio Frequency Energy	Section 21	Category M* Radiated and conducted	X	

Table 16. Safety requirements (continued)

Condition	RTCA/ DO-160G	Requirement	Operating	Non-Operating
Lightning Induced Transient Susceptibility	Section 22	Category A 4XX Pin Injection: ECU only Multiple stroke: Waveform 1 (750V/1500A peak) and 3 (1500V/300A peak). Tests per AC20-136 Multiple burst: Waveform 3 (damped sinusoid) at 1 MHz, 300V/60A peak. Tests per AC20-136	X	X
Lightning Direct Effects	Section 23	The ECU is category X and no tests were required	X	
Electrostatic Discharge	Section 25	Category A 10 discharges, each polarity	X	

3.3 NOTIONAL DESIGN

The notional design of the PEMFCPS is intended to be generic. The goal is to explore and expose new safety hazards introduced by the introduction of new technologies.

The design of any system is an iterative process. This notional design presents the final representation because of these iterations. Efforts has been made to capture some of the rationale during the design process.

3.3.1 System Description (Schematics)

The core of the PEMFCPS is well defined in automotive industry implementations and is directly applicable for aircraft. The schematic diagram in Figure 7 illustrates the basic design of the system. Most of the functions such as flow control, reactants hydration, etc. are somewhat proprietary to individual manufacturers, and are considered internal to the unit, therefore, not discussed in this report.

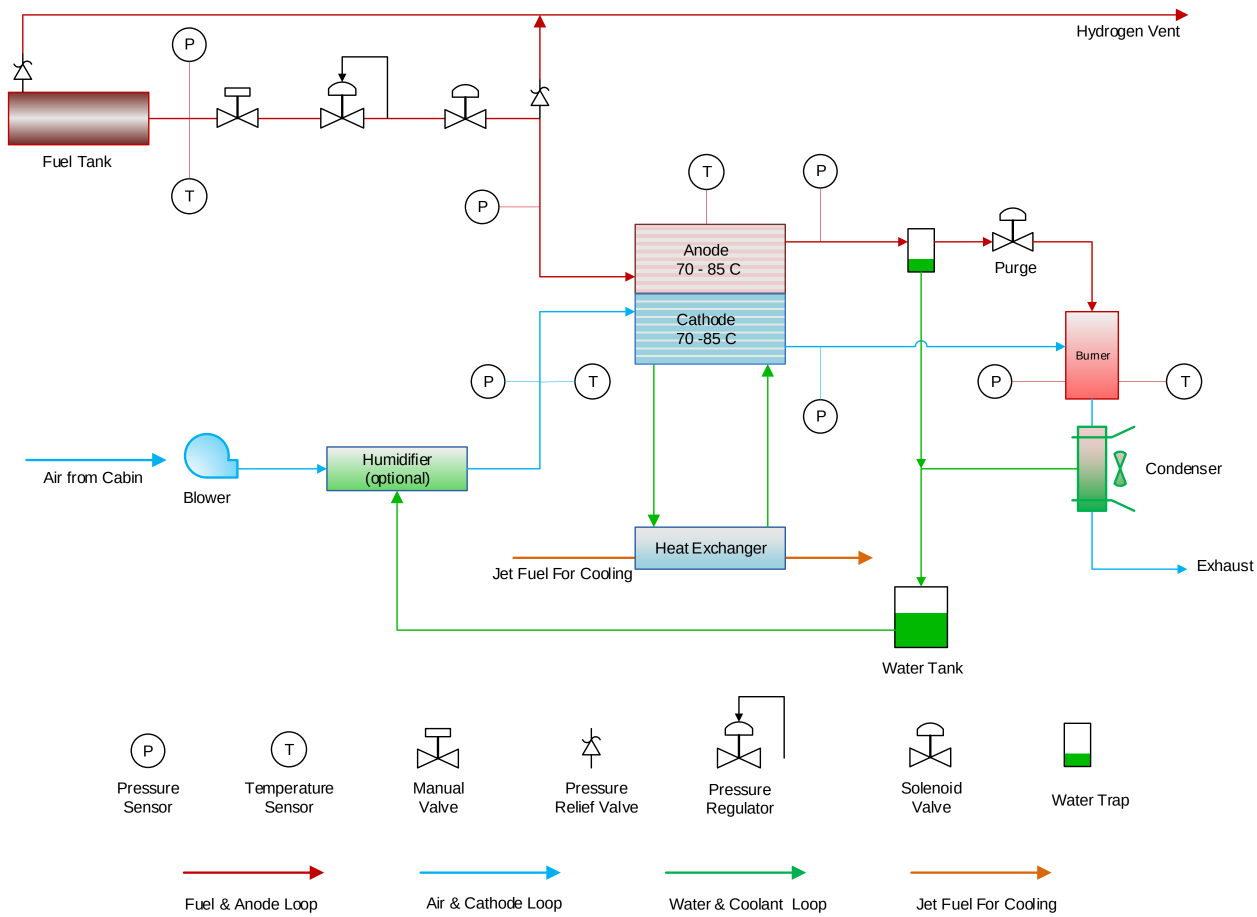

Figure 7. Typical PEMFCPS schematic diagram

3.3.2 System Layouts

For aircraft implementation, the PEMFCPS can be configured in many ways to better integrate into other existing aircraft systems. Two system configurations with high implementation potential were examined.

3.3.2.1 System Configuration #1

The rationale for this configuration is to have two half-sized (60kW) subsystems for redundancy, co-located with ECS pack to take advantage of synergy in thermal handling characteristics and potential sharing of common equipment among the two. The other consideration is to separate the power generation unit (PGU) [stack and BOP] from the energy source (hydrogen storage system) for isolation by space, in case of failure. Figure 8 illustrates the high-level system layout.

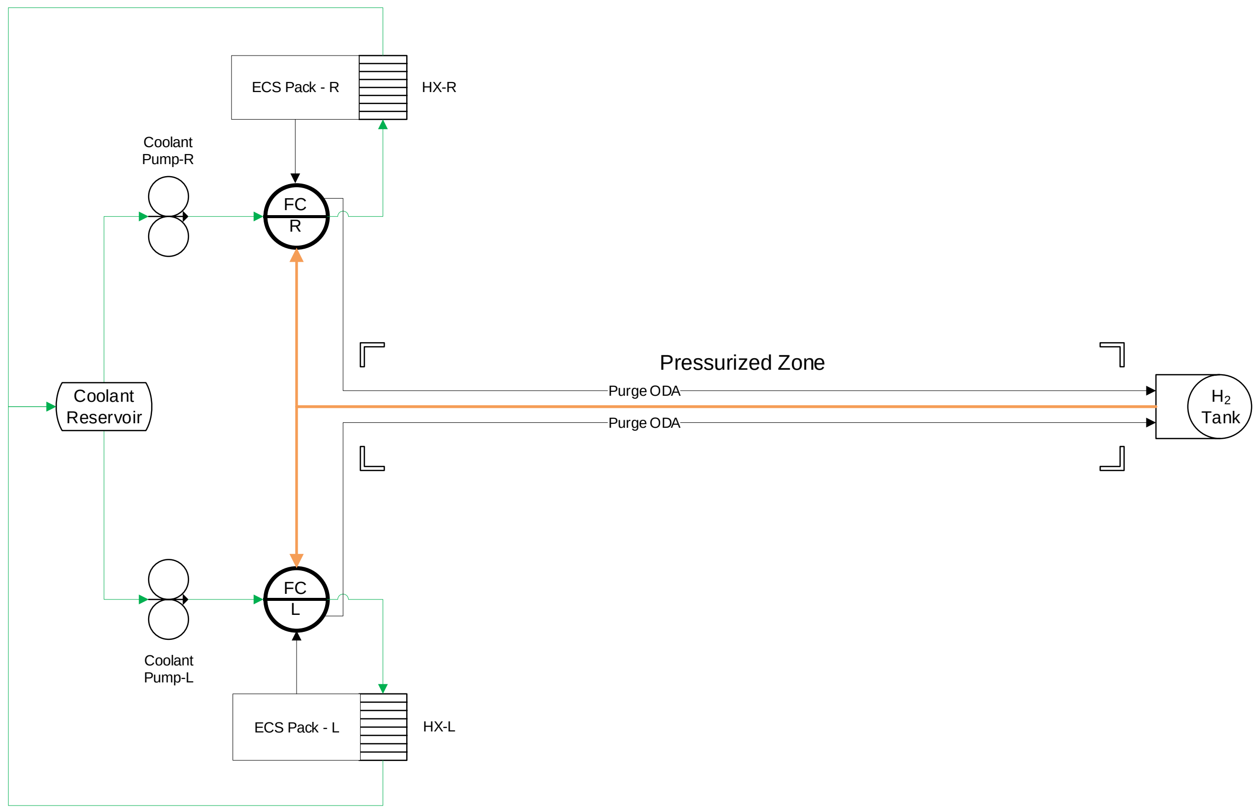

Figure 8. PEMFCPS configuration #1

A digital model of a generic aircraft was created to illustrate the configuration and potential interactions between systems (Figure 9).

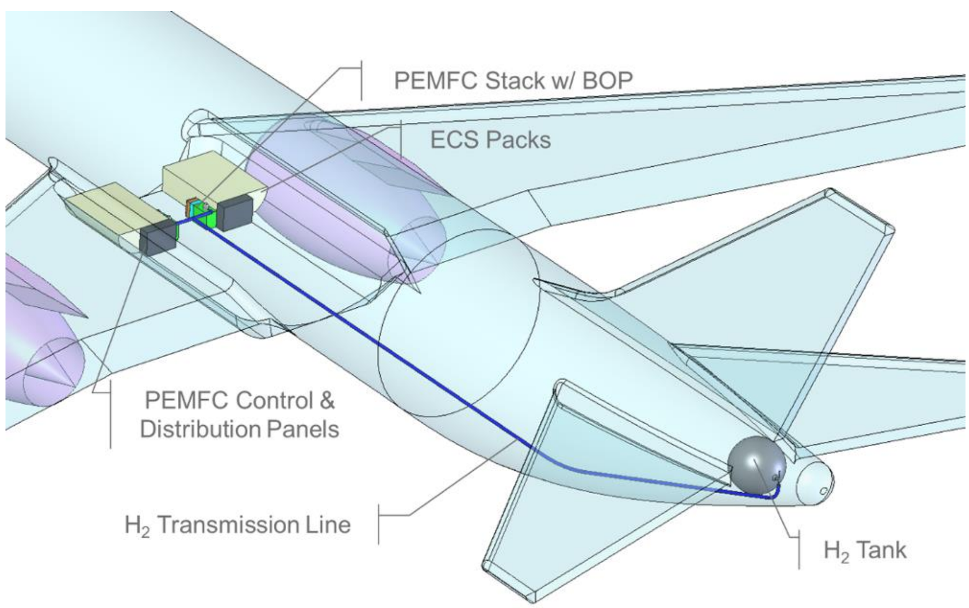

Figure 9. Digital model rendering of the PEMFCPS configuration #1

The potential benefit of co-locating the PEMFCPS and ECS are:

1. Cathode air can be taken from cabin at recirculating duct.
2. Cooling air can use the same ambient cooling air system, including the cooling fan (ground operation), ram air (flight) inlet and exhaust plenum and ducting.
3. Large electric power users such as VCCs and ME S/G are short coupled or even through private bus for less weight on cable and electric power control and distribution.

The FSS will be located inside the tail cone where the traditional GT APU is usually located. There are many irregularly shaped spaces behind the pressure bulkhead, where a large size spherical pressure vessel may be situated.

Other perceived benefits also include no designated fire zone (DFZ) due to its relatively low operating temperature and maintains aircraft center of gravity (CG).

The downside of this layout is that the long, pressurized hydrogen fuel transmission line between the FSS and PGU, most likely must go in and out of the pressure vessel in the cargo hold area. Double containment of the fuel transmission line and active purge within the second containment is needed.

3.3.2.2 System Configuration #2

The rationale for this system layout is to eliminate the hazard of bringing pressurized hydrogen gas through pressurized zone and the close proximity to the liquid jet fuel tanks.

The entire PEMFCPS will be located inside the unpressurized tail cone behind the pressure bulkhead. Since this arrangement is in an unpressurized enclosure and does not require long, pressurized hydrogen fuel transmission run, the double containment and active purge air are unnecessary. However, passive ventilation must be provided for the PEMFCPS compartment by at least two ventilation openings, preferably with bottom intake and top-vent exhaust, to avoid flammable gas from accumulating during the period when the system is off. Provision for introducing ram air to purge out the compartment when the aircraft is in motion is also required.

The main drawback of this layout is that the total weight of the system (including dedicated cooling fans, plenums, and doors) is located at the extreme aft of the aircraft and may impact the CG of the aircraft unless it is designed into the aircraft structure.

The generic aircraft digital model shown in Figure 10 illustrates the configuration and potential impact to the aircraft weight balance.

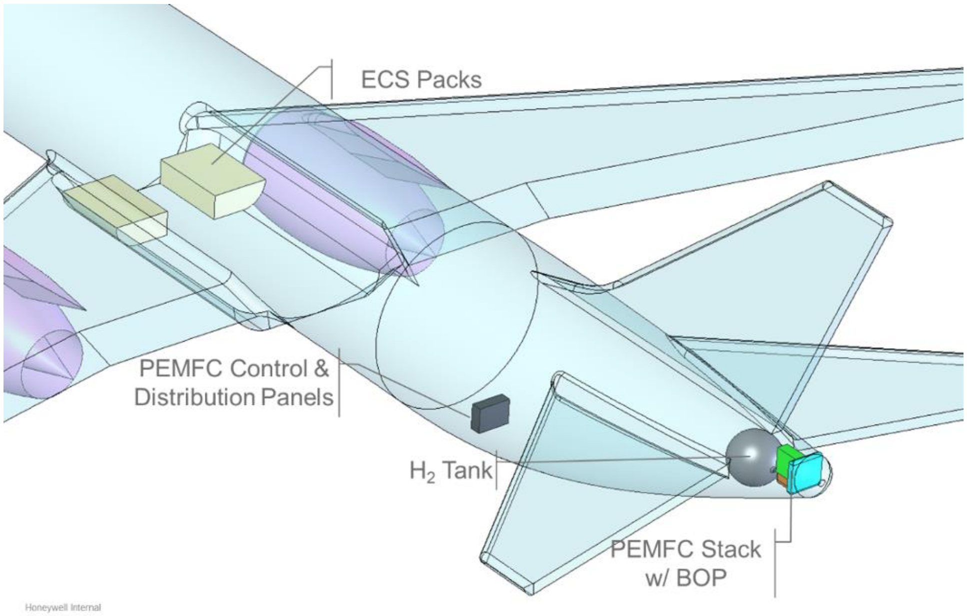

Figure 10. Digital model rendering of the PEMFCPS configuration #2

3.3.3 Subsystems

This section provides a verbal description of the subsystems.

3.3.3.1 Stack

Use of cabin air as cathode reactant can improve performance during flight and keep stack from icing. Electric strip heater and thermal insulation shall be applied to the stack to keep it from freezing and cause damage to the membrane.

To keep the stack from icing, a combination of the following steps may be taken:

- Keep a minimum stream of cabin air flowing around the stack, or
- Wrap the stack with electric strip heater and thermal insulation, or
- Set to standby mode to have a minimum flow of reactants to keep system above freezing while providing power for control and monitoring system.

All safety features from automotive fuel cell implementation may be applied.

3.3.3.2 Fuel System

3.3.3.2.1 Pressure Vessel

The high-pressure hydrogen will be stored in a 700 bar, Type IV pressure vessel. Spherical is preferred over cylindrical for better fuel weight fraction performance, due to more accommodating space available inside the aircraft tail cone.

The pressure vessel shall be strap-mounted to avoid any concentrated stress-loading, which may compromise the integrity of the pressure vessel. Figure 11 shows an example of the strap-mount vessel of Saturn V engine.

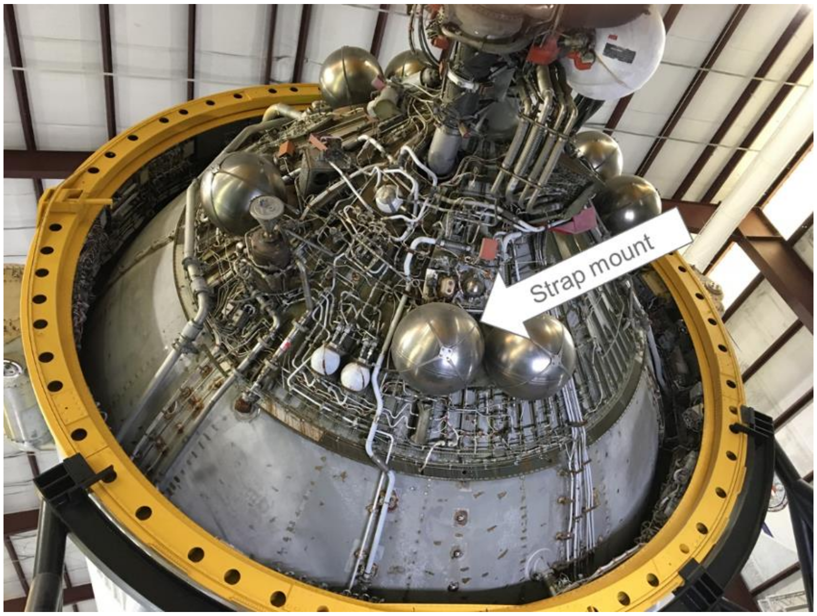

Figure 11. Example of the strap-mount vessel of Saturn V engine

Hydrogen gas leakage may pose an explosion hazard due to the enclosed nature of aircraft fuselage. Gas accumulation inside the compartment shall be avoided by passive ram air purge and natural draft design.

3.3.3.2.2 Pressure Relief Devices

The fuel tank will be protected by multiple pressure-relief devices (PRDs) for various conditions:

- Rupture disc for overfilling, overheating-caused gas expansion
- Fusible plugs placed strategically to protect from localized high temperature
- Safety relief valve at each pressure segment of the fuel system

All gas relief shall be connected into a protective passage and vent to ambient away from potential ignition source.

3.3.3.2.3 Pressure Regulating Valves

The hydrogen gas pressure must be reduced to a safe value for handling before the flow can be modulated for load control. There shall be in-tank pressure-reducing valve, and back-pressure regulating valve to safeguard the low-pressure fuel lines due to potential pressure built up by allowable leakage through the rate of the pressure reducing valve.

3.3.3.2.4 Fuel Transmission

The high-pressure hydrogen gas shall be reduced from its storage pressure of up to 10,000 psig to medium pressure (100 – 150 psig) for transmission once it leaves the storage system. Cascade pressure-reducing arrangement shall be considered when appropriate. The pressure of the hydrogen gas is further reduced to stack pressure (15 – 60 psig) for consumption.

Efforts shall be made to minimize gas line connection fittings to minimize leakage.

The transmission line shall be doubly contained when trespassing closed or pressurized spaces to avoid accumulation of hydrogen gas. The secondary containment volume shall be purged by air or inert gas actively or passively always.

Hydrogen gas monitoring devices shall be employed to monitor the secondary volume in case of insufficient purge flow.

3.3.3.2.5 Fuel System Purge Control

Purge of the anode is often necessary to rid of impurities during hydrogen gas production to clear out gas impurities. This purge of concentrated hydrogen gas with impurities happens inside the pressurized vessels and shall be led to ambient safely.

The purge of the space between the fuel line and its secondary containment, i.e., double-walled pipe/tube shall be continuous either by natural draft, or actively purged by other gases such as air or inert gas to maintain a combustible gas outside the explosion limits. When active purge system is employed, the combustible gas concentration shall be monitored when the active purging is off.

3.3.3.2.6 Leak Detection

Since the current SOA hydrogen gas detector is relatively slow to react in time to prevent sudden release of hydrogen-caused fire or explosion, and the installed location may not always have the worst gas mixture condition, computational fluid dynamics analysis must be performed to determine optimal sensor location.

3.3.3.3 Power Generation System

The power generation system consists of FC stack and its immediate surrounding devices to maintain its healthy and productive condition.

3.3.3.3.1 Air Management System

The air management subsystem focuses mainly on the management of cathode air to condition it to the optimal condition in temperature, pressure, humidity, cleanliness, and mass rate of flow.

Components include turbomachinery for pressure manipulation, heat exchangers (HEXs) for temperature control, filter for cleanliness, and valves and fitting.

3.3.3.3.2 Air Distribution and Control

Cathode air is taken from the pressurized cabin, which maintains tight range of conditions for FCs stability in performance and life.

The air can be branched from the main ECS recirculating duct for system configuration #1, or through the rear-pressure bulkhead for system configuration #2. An in-line air filter should be placed before the air enters the PEMFCPS.

The aircraft PEMFCPS can take advantage of the pressure difference between cabin and high-altitude ambient to recover energy to augment compressor drive. Although this feature may not be implemented in automotive applications, it is common for aircraft air management system. No new safety hazard is expected.

3.3.3.3.3 Turbomachinery

The turbomachine comprises three major components—inlet air fan/booster/compressor, motor/generator, and a turbine—that are connected through a common shaft. This is the only device in the PEMFCPS implementation that involves kinetic energy from rotating components with a very high rate of speed. The size and energy contained is much smaller when compared with the APU or ECS of the existing aircraft.

3.3.3.3.4 Compartment Area Purging and Ventilation

In either layout arrangement, the FCPS resides in an unpressurized compartment. This compartment shall be constantly purged by ambient air and vents overboard while in operation.

There shall be either active ventilation fan (system configuration #1) or passive natural draft ventilation with vent doors below and above the tail cone (system configuration #2) to ascertain there is no hydrogen gas accumulation especially during the time when the system is off.

3.3.3.4 Thermal Management System (TMS)

The PEMFCPS operates at an efficiency range of 45 percent - 55 percent, which means the heat is generated by the stack at a rate that is slightly greater than the electrical power output. This heat must be removed, and temperature maintained for continuous safe operation of the system.

3.3.3.4.1 Liquid Cooling Loop

To achieve higher-power density of FCPS at or above this power level, liquid cooling is necessary to remove the amount of waste heat from such a compact package. The liquid cooling is preferably a closed loop with anti-freezing property due to the very low heat sink temperature at altitude. This system is rather common for aviation application and poses minimal safety hazard.

3.3.3.4.2 Heat Sink

Cathode air provides some level of cooling for the FC stack; the majority of the waste heat is removed by ambient air.

3.3.3.5 Electric Power System

The electrical system shown in the simplified diagram in Figure 12 was set as a baseline typical of a twin-engine, single-aisle commercial air transport aircraft. The primary power generation is from 115/200VAC, 3-phase, 4-wire generators on the MEs, and a 115/200VAC S/G on the turbine APU, or 115/200VAC ground power. Emergency power is provided by a 115/200VAC RAT generator, and by a 28VDC battery. 28VDC power is derived from the 115/200VAC buses via transformer-rectifier units (TRUs). The MEs start pneumatically, with bleed air from the APU being supplied to air turbine starters. The APU start electrically from either 115/200VAC or the 28VDC battery. The start power unit (SPU) either rectifies 115/200VAC to ~270VDC or boosts the battery voltage to ~270VDC. The start converter unit (SCU) converts this 270VDC into variable amplitude, variable frequency alternating current (AC) to drive the S/G.

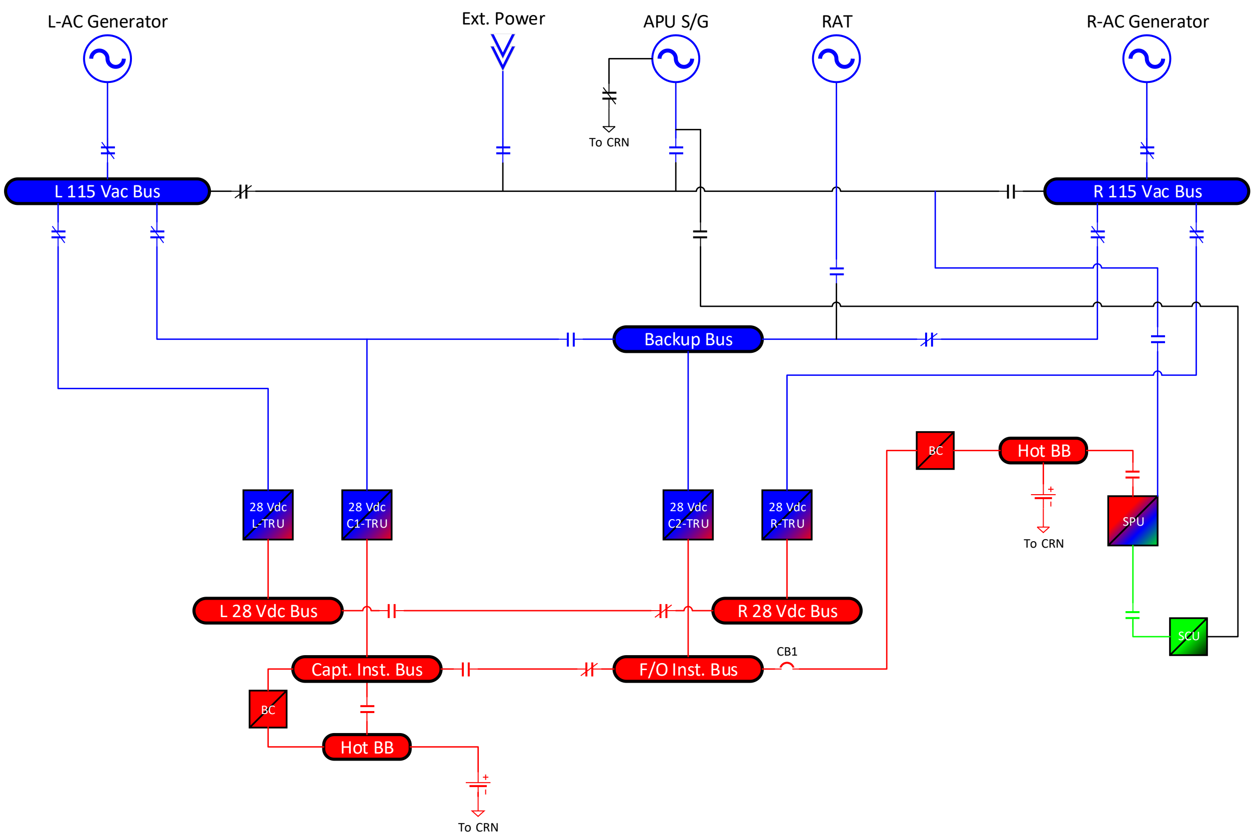

Figure 12. Simplified electrical system diagram - Current

When an FCPS replaces the turbine APU, several changes are needed. While the simplified architecture shown in Figure 13 incorporates the FCPS, it attempts to minimize electrical system changes and consequent power user equipment changes. Since an FCPS supplies DC output, an inverter is required to generate 115/200VAC. Additionally, because the auxiliary power system (APS) no longer has a source of compressed (bleed) air, the MEs must be started electrically via an SCU and S/G. The other function of an APS is to provide power to the aircraft ECS for air conditioning on ground. A turbine APU would typically provide compressed air to an air-cycle ECS, this same ECS being fed by ME bleed air in flight. The FCPS requires that the ECS be electrically powered, which is a significant change to the aircraft systems. This power would be provided from the +/-135VDC bus in volts alternating current.

This increased use of electrical power, and, in particular, higher-voltage DC drives additional considerations and technology needs, as discussed below.

3.3.3.5.1 High Voltage DC Switching and Protection

High-voltage DC primary power distribution contactors are heavier and more expensive than traditional AC contactors to withstand switch contact arcing. Ideally, they need to be high-power, solid-state, power controller (SSPC) modules to provide fast switching since the pass-through fault energy before an electromechanical contactor opens (typically a 20-30mS period) and can cause significant arcing. This effect is much less pronounced in AC systems since the arc self-extinguishes during zero-crossing. Such high-power SSPCs are not commercially available. As in current SSPC-based secondary distribution systems, fail-short protection must be included and must prevent the charging of load capacitance by leakage current, which is particularly important for personnel safety in these high-voltage systems. SSPCs must be lightning-immune and need to be able to withstand or control load-capacitive, inrush currents.

Arc fault detection/protection is an important feature in high-voltage DC systems. It must be able to detect different arc types and minimize false trips due to transients and normal loads. Protection-level coordination is required to ensure that only the furthest downstream protection device is activated.

Corona/partial discharge is an important consideration in high-voltage systems. The choice of +/-135VDC (or even +/-270VDC) allows standard insulation systems and design practices to be used.

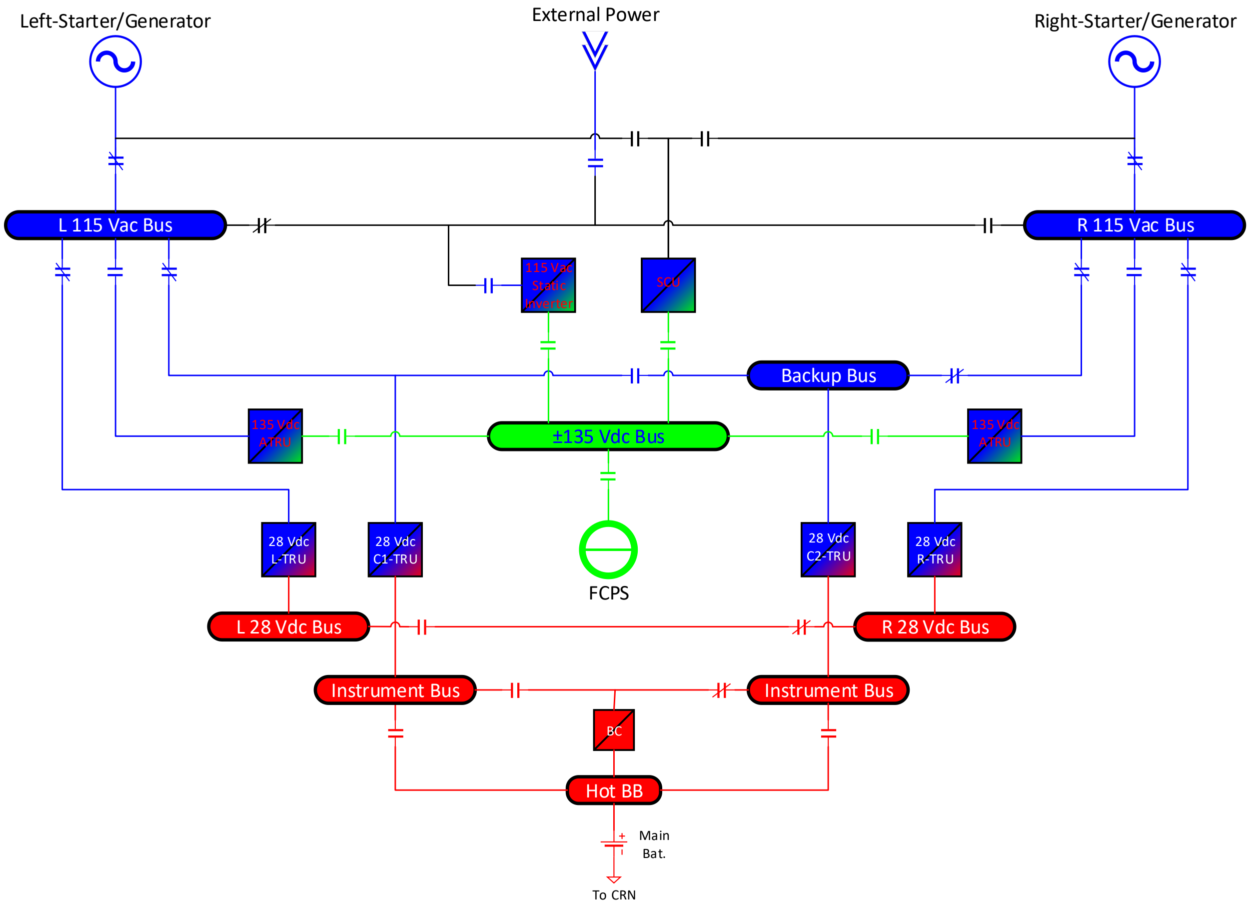

Figure 13. Simplified electrical system diagram - PEMFCPS

3.3.3.5.2 Power Quality Including Transient Response

While 270VDC systems have been used for several years in some military fighter jet applications, use of high-voltage DC in commercial air transport has been limited, and where used, it typically has been locally distributed and used for a few specific loads.

Power quality, including transient response, is an important consideration. To avoid excessive voltage excursions, the transient response of an FCPS needs to be carefully considered. This may necessitate including energy storage (batteries) as part of the FCPS. The FCPS output may need to be fed to the bus via a DC-DC converter to enable sufficient voltage control and energy storage power management. This DC-DC converter could also provide power control/current limiting (by reducing the supplied steady-state voltage), but this is not effective with constant power loads.

Preventing FCPS overload requires load limiting (load-shedding). It also is recommended that the distribution system provides for the staging load-on transient (applying different loads in sequence) so that the FCPS has time to respond and provide the required power without permanently damaging the system components and degrading performance.

While load-off transient cannot be controlled in all circumstances, an FCPS typically responds and operates safely in open-circuit condition.

3.4 MAINTENANCE AND RELIABILITY

Since the PEMFCPS employs a very clean process, the anticipated maintenance activities will be limited to replacement of air filter, coolant filter, and water-accumulation traps.

The individual or groups of stack cells performance shall be constantly monitored, trended for health management. The ability to isolate collapsed cells to maintain integrity of the system is also important.

The implementation approach of the PEMFCPS will likely be modular so most, if not all, subsystems may be line replacement units.

3.5 CONCLUSION

Most systems required for PEMFCPS use currently operative technologies, for which the hazards have been understood and addressed. However, some, such as the high-voltage direct current (HVDC) system, have been well developed in military systems, and have been adapted and studied in MEA applications.

New safety hazards introduced by PEMFCPS technology revolve mainly around high-pressure gas, combustible gases, where ventilation is essential to avoid accumulation. DFZ is not necessary because the PEMFCPS does not involve liquid fuel and is operating in low temperature, like power batteries.

PEMFCPS performance may be hindered by icing due to an abundance of moisture in the system and a wide range of ambient-temperature swing between ground and high altitude. If offered, a fuel tank inerting option may introduce moisture into aviation fuel tanks, causing corrosion to structure and potential ice crystal blocking fuel control system. Overall, while many additional functions considered to boost the PEMFCPS implementation justification are well intended, due to the limitation on hydrogen fuel quantity (volume and weight) and nature of timing, only electrical power generation may be implemented with a potential positive trade outcome.

4. NOTIONAL CONCEPT DESIGN – RFCPS

4.1 PRODUCT DESCRIPTION

As previously noted, the initial target market for the RFCPS is the narrow body with less than 180 passengers, short to mid-range aircraft, servicing US domestic air transport segment. The main function of RFCPS is to provide electric power. Contrary to the current trend of aircraft secondary (non-propulsive) power evolution, the implementation of RFCPS encourages minimized power demand when in power-generation mode and maximized regeneration duration for optimal weight. The role of RFCPS is applicable when other forms of power are unavailable and usually in short duration due to the limited fuel capacity.

In this application, the RFCPS provides electric power for basic and necessary functions during periods when no other means of power storage devices can reasonably achieve the similar result. These basic functions are:

- Electric power—both 28 VDC and ±135 VDC—for basic and necessary functions during periods when no other means of power storage devices can reasonably achieve the similar result. The ±135 VDC powers high-electrical, power demand systems such as VCCs motor and ME starter motor.
- Electric power to start an ME on ground. PEMFCPS provides such power while maintaining functionalities of the aircraft flight deck, internal lighting, and communication.
- In-flight emergency electrical power in the event of an engine or engine-mounted generator failure; providing 50 percent of emergency power in flight within 5 seconds and full emergency power in 30 seconds, in order to maintain control of the aircraft in functions such as flight deck, communication, and flight control, to safely land the aircraft.
- Electric power to meet aircraft electric-power demand during the flight's descent phase so the MEs can be set to lower throttle position to save a considerable amount of liquid aviation fuel.
- Standby power mode to produce minimum power (at highest efficiency) to support functions while the aircraft is unattended, e.g., functions such as keeping temperature-sensitive equipment in desired condition.

The RFCPS is in regeneration mode whenever excess power is available from other sources such as gate power or ME generators, and in power-generation mode whenever power is needed and unavailable economically from other sources.

Table 17 summarizes RFCPS functions during different phases of the operation.

Table 17. RFCPS functions summary

Operational Functions					
Services	Parked	Gate-MES	MES	FID	Emergency
RFCPS controls & monitor	Y	Y	Y	Y	Y
Cockpit avionics		Y	Y	Y	Y
Communication		Y	Y	Y	Y
Interior lighting		Y		Y	Y
Cabin air conditioning		Y		Y	Y
Flight control					Y
Main engine start			Y		

4.1.1.1 Secondary Functions

Though the FC stack generates slightly less waste heat as its output electrical power (55 percent average system power generation efficiency assumed), due to its relatively low temperature and short duration, no viable heating application can benefit from it.

4.2 REQUIREMENTS

Based on the implementation rationale, assumptions, and functions served by the RFCPS, this section discusses the requirement for the notional design.

4.2.1 Performance

The top-level performance requirement for notional design is derived from NTIA, which includes high-level trade against modern GT APU in terms of hardware and ME fuel-burn credits and penalties.

Table 18. Top-level performance requirement for notional design RFCPS

Electric Power, Rated	120 kW
LHV Efficiency at Rated Power	55%
LHV Efficiency at 25% Power	65%
Electrolysis Efficiency	80%
Electric Voltage	28 VDC
	±135 VDC
Cold Start Time at -22°F	20 seconds
Reactants System Weight	80 kg

4.2.2 Installation

Table 19. Installation requirements for RFCPS

Attitude	X = ± 5°	X = Roll
	Y = ± 5°	Y = Pitch
	Z = ± 180°	Z = Yaw

4.2.3 Operation

Table 20. Operational requirements RFCPS

Operating Envelope	Sea level to 14,000 ft	Ground operation
	Sea level to 50,000 ft	Loss of cabin pressure, de-rated
Attitude	X = ± 20°	X = Roll
	Y = ± 40°	Y = Pitch
Emergency Landing	9G	Forward
	1.5G	Aft
	3G	Side
	6G	Down
	3G	Up
	9.86G	Vector Sum
Gust Load	9.86G	Down
	7.89G	Up
Ambient Temperature	-67° - 185°	

4.2.4 Maintenance

Table 21. Maintenance requirements RFCPS

Maintenance Interval	2,000 hrs minimum

4.2.5 Reliability

Table 22. Reliability requirements RFCPS

Power/Regen durability	6,000 cycles
Life (degradation<10%)	8,000 hrs

4.2.6 Safety

Table 23. Safety requirements RFCPS

Condition	RTCA/ DO-160G	Requirement	Operating	Non-Operating
Operating Low Temp	Section 4	Category D2 (-55° C)	X	
Operating High Temp	Section 4	Category D2 (+70° C)	X	
Short Time Operating High Temp	Section 4	Category D2 (+70° C)	X	
Ground Survival Low Temp	Section 4	Category D2 (-55° C)	X	X
Ground Survival High Temp	Section 4	Category D2 (+85° C)	X	X
Altitude	Section 4	Category D2 (50,000 ft.)		X
Temperature Variation	Section 5	Category B Operating: -55 to 70° C Ramp: (5° C minimum/min.)	X	X
Humidity	Section 6	Category B (minimum 95% relative humidity at +65° C)	X	X
Operational Shock	Section 7	Category B sawtooth pulse, with an acceleration peak value of 6 G's for 11 ms	X	
Crash Shock	Section 7	Category B PROC 1 same as operational shock except 20 G's		X
Crash Safety Sustained Acceleration	Section 7	Category B PROC 2 non-operating – 9.0g along any axis		X
Vibration	Section 8	Category S Test Curve C, Standard Vibration, 1 hr/axis	X	X
Explosion	Section 9	Category A or B* Site altitude, 70C fuel type recorded in test report	X	X
Waterproofness	Section 10	Category Y or W* Drip proof test, 280 1/M** 2/h for 15 minutes operating.	X	X
Sand and Dust	Section 12	Category D Sand and dust jet along each direction of each major orthogonal axis at 25C and 55C non-operating	X	X

Table 23. Safety requirements RFCPS (continued)

Condition	RTCA/ DO-160G	Requirement	Operating	Non- Operating
Fungus Resistance	Section 13	Category F Cultures of 5 Fungi, 28 days incubation	X	X
Salt Spray	Section 14	Category S 5% salt solution spray at 35C for 48 hrs non-operating	X	X
Magnetic Effect	Section 15	Magnetic field of 14.4 A/m for specified deflection, distance is determined by test.	X	
Power Input	Section 16	Category A normal and abnormal operating voltage, interrupt, normal and abnormal surge, undervoltage	X	
Voltage Spike	Section 17	Category A 600V, 10 □sec transient.	X	
Audio Frequency Conducted Susceptibility, Power input leads	Section 18	Category R or Z* Sine wave audio frequency superimposed on power lead	X	
Induced Signal Susceptibility	Section 19	Category Z Magnetic and electric fields and spikes induced into equipment and cables	X	
Radio Frequency Susceptibility Conducted	Section 20	Category Y* Cable injection to 10kHz to 400MHz	X	
Radio Frequency Susceptibility, Radiated	Section 20	Category Y* Radiated field to 18GHz Freq. Avg (V/M) Peak (V/M) 10kHz to 1 GHz 200 N/A 1 to 2 GHz 200 1700 2 to 4 GHz 200 3000 4 to 6 GHz 200 2300 6 to 8 GHz 200 530 8 to 12 GHz 200 1400 12 to 18 GHz 200 850	X	

Table 23. Safety requirements RFCPS

Condition	RTCA/ DO-160G	Requirement	Operating	Non-Operating
Emission of Radio Frequency Energy	Section 21	Category M* Radiated and conducted	X	
Lightning Induced Transient Susceptibility	Section 22	Category A 4XX Pin Injection: ECU only Multiple stroke: Waveform 1 (750V/1500A peak) and 3 (1500V/300A peak). Tests per AC20-136 Multiple burst: Waveform 3 (damped sinusoid) at 1 MHz, 300V/60A peak. Tests per AC20-136	X	X
Lightning Direct Effects	Section 23	The ECU is category X and no tests were required	X	
Electrostatic Discharge	Section 25	Category A 10 discharges, each polarity	X	

4.3 NOTIONAL DESIGN

The notional design of the RFCPS is intended to be generic. Since the goal of this study is to explore and expose new hazards caused by the introduction of new fuel cell technologies, the notional design is taken only so far as to develop an understanding of these hazards, but likely short of that required for actual implementation. Efforts have been made to capture some of the rationale during the design process.

4.3.1 System Description

The RFCPS is a closed system that comprises two main functions—electrolysis (regeneration) and power generation. The electrolysis function is a reverse of the power generation function, which reduces water into hydrogen and oxygen gases in an endothermic reaction, using electrical power when there is excess available. When electric power is needed, the process switches to FC mode that generates electric power by combining the reactants. The entire system functions as a battery. This study assumes a PEM-type FC stack. The PEMFC stack in this power range has matured in the automotive industry; and for its integration into a sealed regenerative system, special attention must be paid to changes necessary for the handling of pure oxygen and at a higher pressure.

The RFCPS has two major competing configurations—discrete and unitized. The unitized configuration was determined earlier to be implausible due to its technology immaturity; however, the discrete system has merit and will be discussed further. In the discrete system, separate fuel cell stacks are used, each dedicated to either the electrolysis function or the power generation function. As such, these stacks are designed specifically for their function. As a system, the advantage is in system performance and durability. The discrete system configuration is the most developed of the regenerative fuel cell power systems.

4.3.2 System Configuration

4.3.2.1 Discrete RFCPS

The rationale for this configuration is to have two separate stacks with one optimized for electrolysis, while the other is optimized for power generation. The two stacks may differ in catalysts, electrolytes, and operating conditions. Figure 14 shows the discrete regenerative fuel cell power system (DRFCPS).

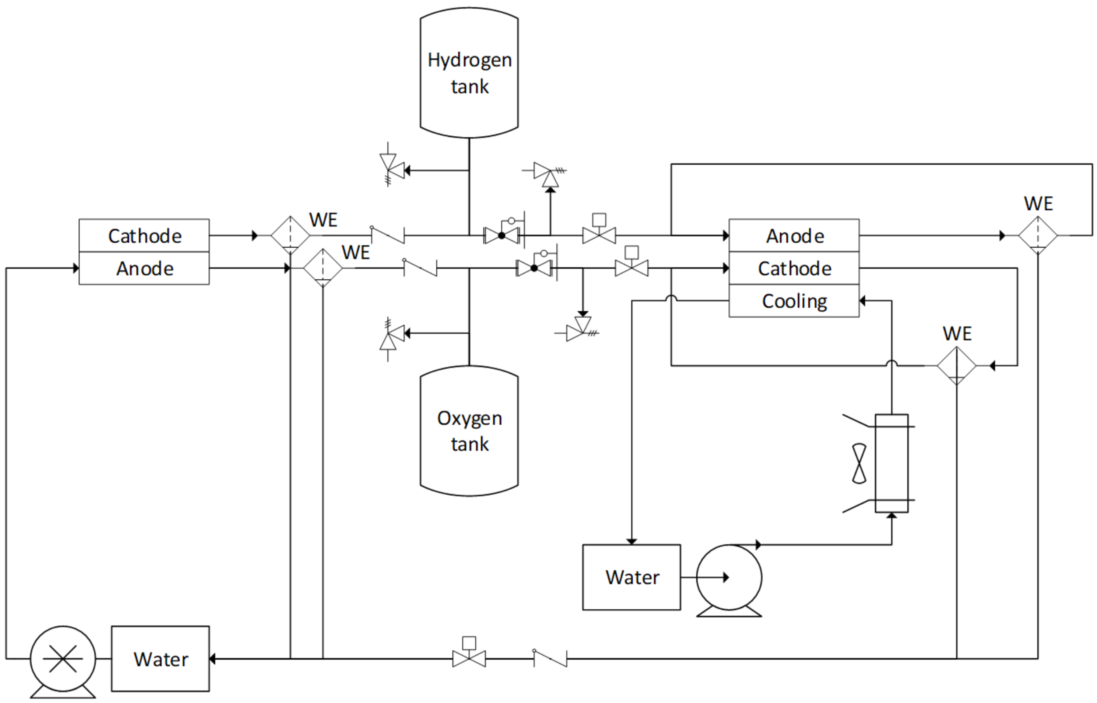

Figure 14. DRFCPS schematic diagram

For the notional design of DRFCPS, the electrolyzer is arranged in cylindrical shape for high-electrolysis pressure of up to 3,000 psia; the reactants are stored in separate spherical pressure vessels. There are water extractors between the electrolyzer and storage tanks to keep water from entering the tanks.

The pressure of the reactants is regulated down before entering the FC stack in power-generation mode. Though the fuel cell stack may be of NFT design, it may be good practice to include recirculating loops, either by passive ejector or active pump, for stack hydration control.

A liquid cooling loop is needed to remove the heat generated during power-generation process and released into the heat sink – ambient (ram) air.

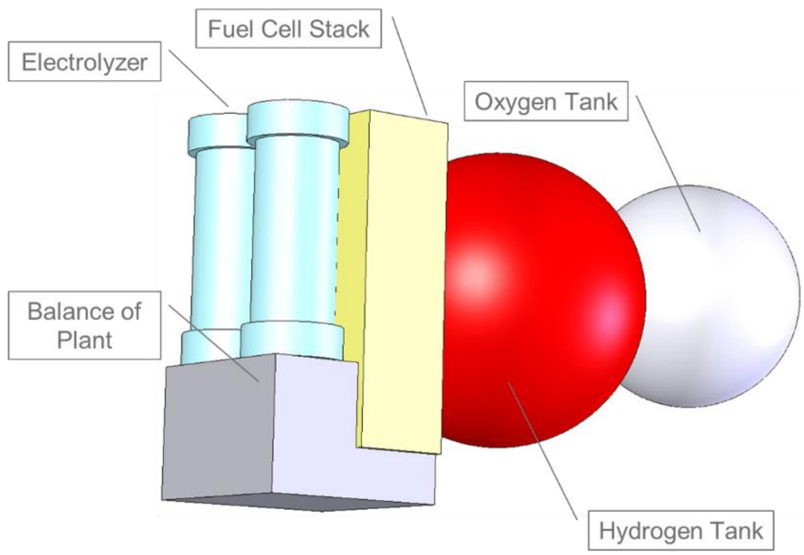

Figure 15. Digital model rendering of the DRFCPS

A digital model of a generic aircraft was used to illustrate the installation and potential interactions between systems.

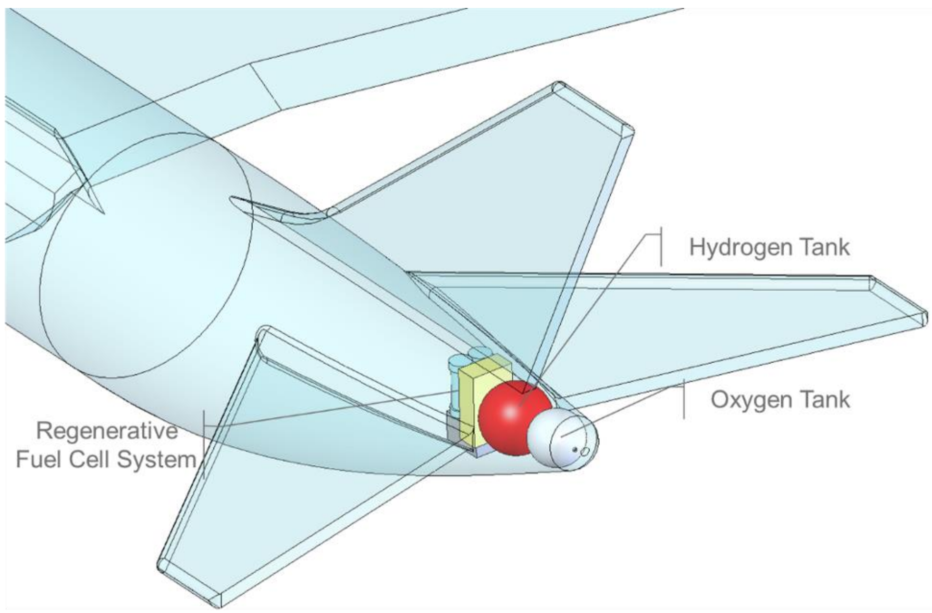

Figure 16. Digital model rendering of the DRFCPS installation example

Though the non-air-breathing RFCPS functions like a battery, it does require access to ambient air for cooling, and more importantly, ventilation.

4.3.3 RFCPS Subsystem Descriptions

With reference to the schematics in Figure 15 and Figure 16, the following sections provide some detail on those subsystems relevant to this study.

4.3.3.1 Discrete Electrolyzer Stack

This PEM stack is designed for high-pressure electrolysis, which can regenerate reactants up to 175 bar (2,500 psia). It is constructed in cylindrical shape to maintain the pressure with reasonable weight. Moderate waste heat from other processes such as power-electronics cooling may be applied for this endothermic reaction.

4.3.3.1.1 Discrete Fuel Cell Stack

This PEM FC stack is typically designed for a hydrogen-oxygen pair, up to 60 psia in pressure. This stack operates at a lower pressure than the electrolyzer stack and requires pressure regulation of the reactants, which are stored at a much higher pressure. As the reactants are stored locally and not ejected, the waste heat ejects from the stack with the mixed-phase steam. Liquid cooling is required to maintain its operating temperature.

4.3.3.2 Fuel Cell Reactants System

4.3.3.2.1 Reactant Pressure Vessels

The high-pressure hydrogen will be stored in the 200 bar, Type IV pressure vessel. A spherical configuration is preferred over cylindrical for better fuel-weight fraction performance and is enabled by space available inside the aircraft tail cone. The pressure vessel shall be strap-mounted to avoid any concentrated stress-loading that may compromise the integrity of the pressure vessel.

Hydrogen gas leakage may pose a hazard due to the “more-enclosed” nature of aircraft fuselage. The potential hazard will be addressed by the rest of the notional design.

Oxygen gas will be stored in a similar type of container with similar mounting approach. In compliance with ASTM G93 and CGA G-4.1, an “oxygen clean” process must be observed while working on oxygen system-wetted components.

4.3.3.2.2 Pressure-Relief Devices

The reactant tanks will be protected by multiple PRDs for various conditions:

- Rupture disc for overcharging, overheating-caused gas expansion
- Fusible plugs placed strategically to protect from localized high temperature
- Resealable safety relief valve in sequential arrangement

All high-pressure reactants relief shall be conducted into a designated protective passage and vented to ambient away from potential ignition source or other flammable materials.

4.3.3.2.3 Pressure Regulating Valves

The reactants gas pressure must be reduced to a safe value for handling before the flow can be modulated for load control. There shall be an in-tank, pressure-reducing valve, and back-pressure regulating valve to safeguard the low-pressure fuel lines due to potential pressure built up by the allowable leakage rate of the pressure-reducing valve.

4.3.3.2.4 Fuel Transmission

The high-pressure reactant gases shall be reduced from its storage pressure of (up to) 3,000 psig to medium pressure (100 – 150 psig) for transmission once it leaves the storage system. The pressure of the hydrogen gas is further reduced to stack pressure (15 – 60 psig) for consumption.

To minimize leakage, efforts shall be made to minimize gas line connections.

To avoid accumulation of hydrogen gas, the transmission line shall be doubly contained when trespassing closed or pressurized spaces. The secondary containment volume shall be purged by air or inert gas actively or passively at all times.

In case of insufficient purge flow, reactant-gas monitoring devices shall be employed to monitor the secondary volume.

4.3.3.2.5 Leak Detection

The current state-of-the-art (SOA) hydrogen gas detector is relatively slow to react in time to prevent a sudden release of hydrogen-caused fire or explosion. The installed location may not always have the worst gas-mixture condition. The most useful installation is to monitor the gas composition within the double containment, reducing the possibility of an ignition source.

4.3.3.3 Power-Generation System

The power-generation system inside the RFCPS mainly consists of the electrolyzer and FC stacks, wiring and insulation, and connectors and interconnects that transmit power into and out of the sealed FC stacks. Power conditioning equipment and switches, etc. would most likely be outside the stack assembly. In addition, there may be various sensors and other immediate surrounding devices to maintain the health of the stacks.

4.3.3.3.1 Compartment Area Purging and Ventilation

The RFCPS resides in an unpressurized compartment in the aircraft. This compartment shall be constantly purged by ambient air and vents overboard.

4.3.3.4 Thermal Management System

The RFCPS operates at an efficiency range of 55 percent - 65 percent, which means the stack generates heat at a rate of moderately less than the electrical power it generates. This heat needs to be removed to maintain a continuous safe operation of the system. There are a number of ways to accomplish this, the most common of which will likely use the water generated inside the stacks as a medium to transport this heat from the stack to an external HEX or separate liquid-cooling media.

4.3.3.4.1 Liquid Cooling Loop

To achieve a higher-power density of FCPS at this power level, liquid-cooling is necessary to remove the amount of waste heat from such a compact package.

The liquid-cooling is preferably a closed loop with anti-freezing property for continued airworthiness operation.

4.3.3.4.2 Heat Sink

This study will assume ambient air as the heat sink.

4.3.3.4.3 Electrolyzer Heating

This endothermic reaction may be supplemented with heat generated electrically, or with waste heat from other systems such as power-electronics cooling loop if so equipped.

4.3.3.5 Electric Power System

The electrical system shown in the simplified diagram in Figure 17 represents a baseline typical of a twin-engine, single-aisle, commercial air transport aircraft. The primary power generation is from 115/200VAC, 3-phase, 4-wire generators on the MEs, and a 115/200VAC S/G on the turbine APU, or 115/200VAC ground power. Emergency power is provided by a 115/200VAC RAT generator, and by a 28VDC battery. 28VDC power is derived from the 115/200VAC buses via transformer-rectifier units (TRUs). The MEs start pneumatically, with bleed air from the APU being supplied to ATS. The APU starts electrically from either 115/200VAC or the 28VDC battery. The SPU either rectifies 115/200VAC to ~270VDC or boosts the battery voltage to ~270VDC. The SCU converts this 270VDC into variable amplitude, variable frequency AC to drive the S/G.

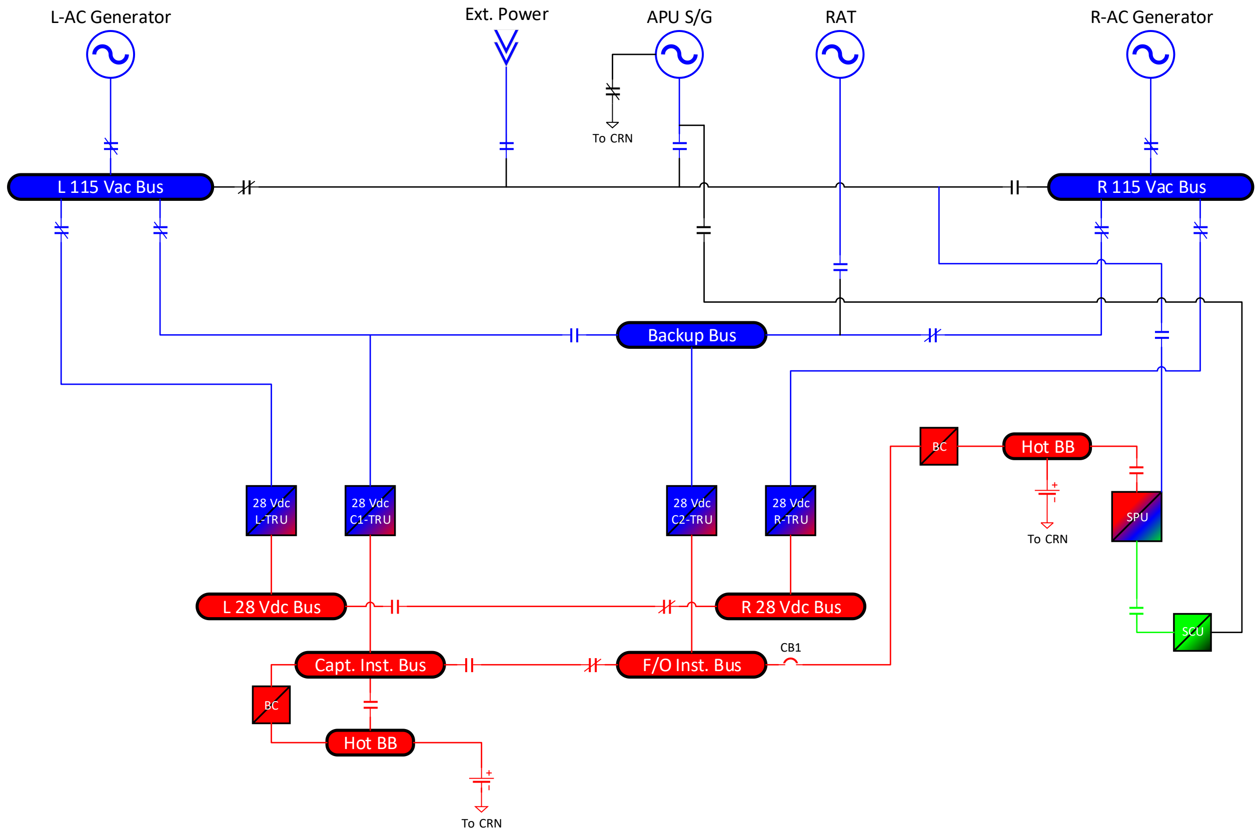

Figure 17. Simplified electrical system diagram - Current

When an FCPS replaces the turbine APU, several changes need are needed. While the simplified architecture shown in Figure 18 incorporates the FCPS, it attempts to minimize electrical system changes and consequent power user equipment changes. Since an FCPS supplies DC output, an inverter is required to generate 115/200VAC. Additionally, because the APS no longer has a source of compressed (bleed) air, the MEs must be started electrically via an SCU and S/G. The other function of an APS is to provide power to the aircraft ECS for air conditioning on ground. A turbine APU would typically provide compressed air to an air-cycle ECS, this same ECS being fed by ME bleed air in flight. The FCPS requires that the ECS be electrically powered, which is a significant change to the aircraft systems. This power would be provided from the +/-135VDC bus in Figure 18.

This increased use of electrical power, and, in particular, higher-voltage DC drives additional considerations and technology needs, as discussed below.

<u>4.3.3.5.1 High-Voltage DC Switching and Protection</u>

High voltage DC primary power distribution contactors are heavier and more expensive than traditional AC contactors to withstand switch contact arcing. Ideally, they need to be high-power SSPC modules to provide fast switching since the pass-through fault energy before an electromechanical contactor opens (typically a 20-30mS period), which can cause significant arcing. This effect is much less pronounced in AC systems because the arc self-extinguishes during zero-crossing. Such high power SSPCs are not commercially available. As in current SSPC-based secondary distribution systems fail-short protection must be included and the charging of load capacitance by leakage current prevented (which is particularly important for personnel safety in these high-voltage systems). SSPCs must be lightning immune and need to be able to withstand or control load capacitive inrush currents.

Arc fault detection/protection is an important feature in high voltage DC systems. It needs to be able to detect different arc types and minimize false trips due to transients and normal loads. Protection level coordination is required to ensure only the furthest downstream protection device is activated.

Corona/partial discharge are important considerations in high voltage systems. The choice of +/-135VDC (or even +/-270VDC) allows standard insulation systems and design practices to be used.

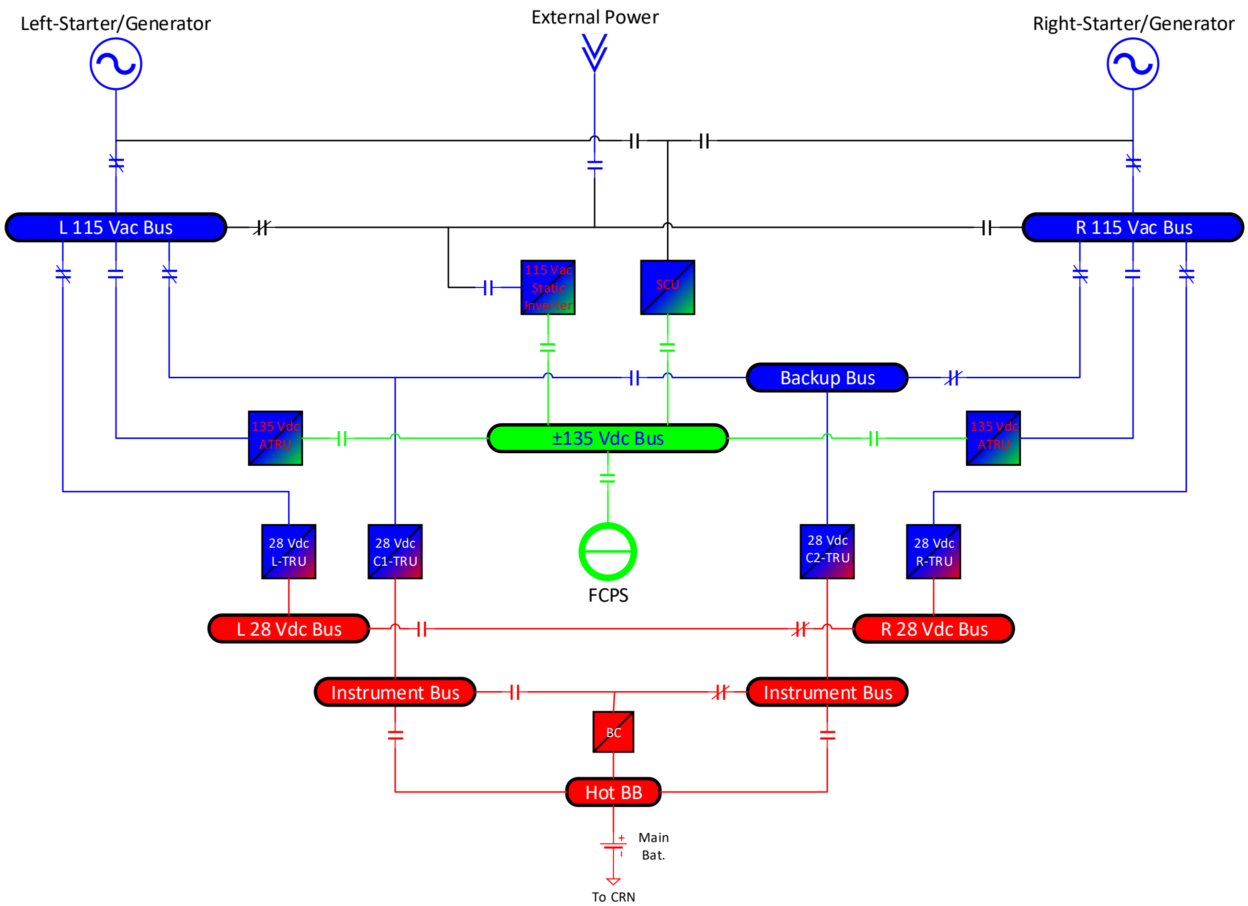

Figure 18. Simplified electrical system diagram - PEMFUPS

<u>4.3.3.5.2 Power Quality Including Transient Response</u>

While 270VDC systems have been used for several years in some military fighter jet applications, use of high voltage DC in commercial air transport has been limited, and where used it has typically been locally distributed and used for a few specific loads.

Power quality, including transient response, is an important consideration. To avoid excessive voltage excursions, the transient response of a FCPS needs to be carefully considered. This may necessitate including energy storage (batteries) as part of the FCPS. The FCPS output may need to be fed to the bus via a DC-DC converter to enable sufficient voltage control and energy-storage power management. This DC-DC converter could also provide power control/current limiting (by reducing the supplied steady-state voltage), but this is not effective with constant power loads.

Preventing FCPS overload requires load limiting (load-shedding). It also is recommended that the distribution system provide for the staging load-on transient (applying different loads in sequence) so that the FCPS has time to respond and provide the required power without permanently damaging the system components and degrading performance.

While load-off transient cannot be controlled in all circumstances, an FCPS typically responds and operates safely in open-circuit condition.

4.4 MAINTENANCE AND RELIABILITY

Since the RFCPS is a closed system, the anticipated maintenance activities will be limited to replacement of coolant filter, and potential water accumulation traps.

In compliance with ASTM G93 and CGA G-4.1, an “oxygen clean” process must be observed while working on oxygen system-wetted components.

- ASTM G93, "Standard Practice for Cleaning Methods and Cleanliness Levels for Material and Equipment Used in Oxygen-Enriched Environments"
- CGA G-4.1, "Cleaning Equipment for Oxygen Service"

The system stack performance shall be constantly monitored. It can isolate collapsed cells to maintain the integrity of the system.

4.5 CONCLUSION

Due to the lack of current market-driven motivation, the matured RFCPSes are limited to low-power, high-cost space applications. As most systems are among currently operative technologies, the hazards have been addressed, including the HVDC system.

New safety hazards introduced by RFCPS revolve mainly around high-pressure combustible hydrogen gas in an oxygen-enriched environment, and materials resistant to strong oxidizer (oxygen). Autoignition of hydrogen/oxygen mixtures need to be evaluated for high-pressure electrolyzer failure modes.

Packaging high-pressure hydrogen and oxygen gases inside a common pressure vessel can be disastrous. A breach of the separating barrier may lead to autoignition of the reactants and result in an explosion proportional to the amount of reactants at a stoichiometry of one. For this reason, a storage system with separately contained reactants may be required for the ability to shut off and isolate the reactants.

5. NOTIONAL CONCEPT DESIGN – SOFCPS

5.1 PRODUCT DESCRIPTION

As indicated earlier in this report, the SOFCPS requires significant integration at the platform level to achieve plausibility. The FC solutions so far have been fairly independent, autonomously providing electric power. There is not much else to support a minimal operational requirement. The amount of power and duration for those systems is severely limited by the poor gravimetric efficiency of the high-pressure gaseous storage on board, and/or the extent of the airport infrastructure developed to support all aircraft with gate power, and hydrogen refueling services. The SOFCPS, on the other hand, can use almost any ultra-low, or no-sulfur hydrocarbon fuel, many of which can be compatible with the aircraft MEs. They also demonstrate a gross thermal efficiency through combined heat and power beyond that of even the MEs. However, these systems are handicapped by their weight and operability, and will also require a different concept of operations than either of the PEM-based FC systems, or the conventional GT-powered start and APS.

As envisioned, the SOFCPS is a hybridized power plant that efficiently recaptures chemical and thermodynamic energy from within the SOFC system though auxiliary bottoming cycles, providing low-quality heat to satisfy platform needs for cabin-related services, and fire prevention and control. This system potentially utilizes other devices for temporary energy storage in order to provide both a constant base power capability, along with the ability to handle transient power demand. The power management is done in three tiers:

1. Base load — Provide constant and steady level of power that is slightly higher than the projected average power demand. This is provided by SOFC stack and GT generator.
2. Load shaving — Capable of storing excess energy during low-demand periods and use it during peak-demand period. This is provided by high-specific power RFC.
3. Transient — Provide short burst of energy during sharp demand transient state. This is provided by power batteries.

SOFCPS is an integrated power system that provides multiple extended functions besides electrical power. It is idealized in the high-level schematic in Figure 19. Extended functions include:

1. Thermal power from SOFC stack cooling for wing-icing protection, cargo-hold heating, etc.
2. Superheated steam for galley food heating
3. Reclaimed water for lavatory use
4. ODA for fuel tank inerting and cargo hold fire suppression
5. Compressed oxygen gas for passenger in case of cabin depressurization

As indicated in Section 2.3.3.5 Preliminary Assessment, because this system is so highly integrated in the platform, the form and configuration of the SOFCPS will have a number of variations. Total weight for a 335 kW rated system will likely be over 7000 kg. When implemented, much of this weight will be offset by legacy systems and components that it replaces.

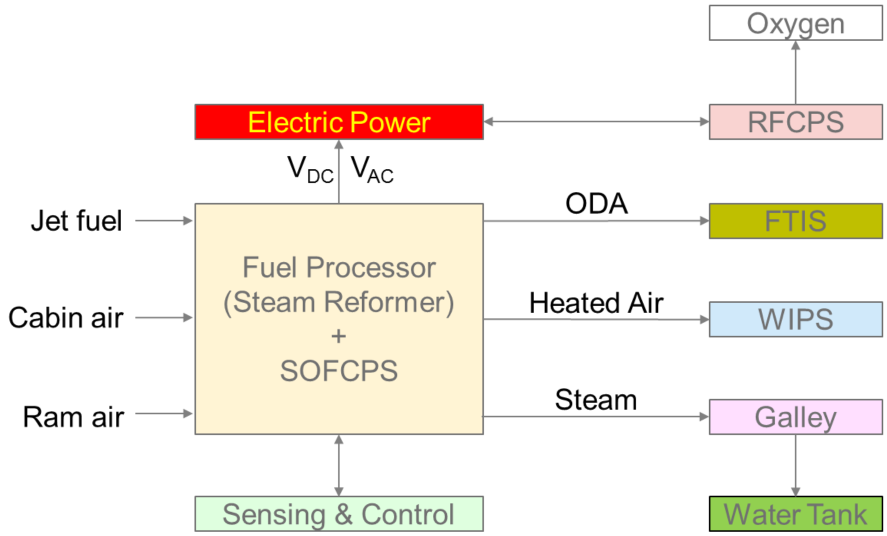

Figure 19. Hybridized solid oxide fuel cell power system schematic diagram

5.1.1 Functions

The function of SOFCPS is to provide complete secondary power, to rid the ME of parasitic extraction duties for its main function, which is to provide uncompromised propulsive power performance.

- Base-load electric power
  - 270VDC generated by SOFC stack.
  - 115VAC generated by gas turbine.
  - 28VDC generated by steam turbine.
- Dynamic electric power
  - Battery bank and/or RFCPS.
- Emergency power
  - Battery bank and/or RFCPS may provide emergency power due to its capacity and redundancy.
- Galley heating
  - Steam generated for both steam reformer and galley heating.
- Lavatory water supply
  - Water condensed from galley heating or steam blowdown to be used for lavatory.
- Fuel tank inerting

- Use ODA from Catalytic Burner (CB) exhaust.

- Cargo-hold fire suppression
  - Use ODA from CB exhaust for cargo-hold fire extinguishing and suppression.
- Wing-icing protection
  - SOFC stack cooling air to heat cargo hold and wing-icing protection system (WIPS), may be hybridized with electric heating ribbons
- Cargo-hold heating
  - SOFC stack cooling air to heat cargo hold and WIPS.
- Emergency Oxygen Gas
  - In case of loss of cabin pressure, oxygen generated from RFCPS may be repurposed for occupants' breathing aid. RFCPS needs to be serviced after such use to maintain its closed system integrity.

5.2 REQUIREMENTS

Based on the implementation rationale, assumptions, and functions served by the SOFCPS, this section discusses the requirement for the notional design.

5.2.1 Performance

The top-level performance requirement for notional design is derived from NTIA, with refined system architecture after several iterations. The detail of the requirement refinement is in Appendix A.

Table 24. Top-level performance requirement for notional design of SOFCPS

LHV stack efficiency at 60 psia, rated power	50%	
Electric Power, Sustained	28 VDC	34 kW
	±270 VDC	306 kW
	115 VAC	110 kVA
Electric Power, Peak	±270 VDC	120 kW
Thermal Power	Superheated steam	44 kW
	Stack cooling air	186 kW
Stack Startup Time	Ambient to 1,300°F	4 hours
Stack Cooldown Time	1,300°F to 120°F	4 hours

5.2.2 Installation

Table 25. Installation requirements for SOFCPS

Attitude	X = ± 5°	X = Roll
	Y = ± 5°	Y = Pitch
	Z = ± 180°	Z = Yaw

5.2.3 Operation

Table 26. Operational requirements for SOFCPS

Operating Envelope	Sea level to 50,000 ft	Loss of cabin pressure, de-rated
Attitude	X = ± 20°	X = Roll
	Y = ± 40°	Y = Pitch
Emergency Landing	9G	Forward
	1.5G	Aft
	3G	Side
	6G	Down
	3G	Up
	9.86G	Vector Sum
Gust Load	9.86G	Down
	7.89G	Up
Ambient Temperature	-67° - 185°	

5.2.4 Maintenance

Table 27. Maintenance requirements for SOFCPS

Maintenance Interval	1,500 hours	Visual inspection, filter replacement

5.2.5 Stack reliability

Table 28. Reliability requirements for SOFCPS

Power/Regen durability	12 cycles	6 cycle/year x 10 year
Life	18,000 hours	Less than 20% degradation

5.2.6 Safety

Table 29. Safety requirements for SOFCPS

Condition	RTCA/ DO-160G	Requirement	Operating	Non-Operating
Operating Low Temp	Section 4	Category D2 (-55° C)	X	
Operating High Temp	Section 4	Category D2 (+70° C)	X	
Short Time Operating High Temp	Section 4	Category D2 (+70° C)	X	
Ground Survival Low Temp	Section 4	Category D2 (-55° C)	X	X
Ground Survival High Temp	Section 4	Category D2 (+85° C)	X	X
Altitude	Section 4	Category D2 (50,000 ft.)		X
Temperature Variation	Section 5	Category B Operating: -55 to 70° C Ramp: (5° C minimum/min.)	X	X
Humidity	Section 6	Category B (minimum 95% relative humidity at +65° C)	X	X
Operational Shock	Section 7	Category B sawtooth pulse, with an acceleration peak value of 6 G's for 11 ms	X	
Crash Shock	Section 7	Category B PROC 1 same as operational shock except 20 G's		X
Crash Safety Sustained Acceleration	Section 7	Category B PROC 2 non-operating – 9.0g along any axis		X
Vibration	Section 8	Category S Test Curve C, Standard Vibration, 1 hr/axis	X	X
Explosion	Section 9	Category A or B* Site altitude, 70C fuel type recorded in test report	X	X
Waterproofness	Section 10	Category Y or W* Drip proof test, 280 1/M** 2/h for 15 minutes operating.	X	X
Sand and Dust	Section 12	Category D Sand and dust jet along each direction of each major orthogonal axis at 25C and 55C non-operating	X	X

Table 29. Safety requirements for SOFCPS (continued)

Condition	RTCA/ DO-160G	Requirement	Operating	Non-Operating
Fungus Resistance	Section 13	Category F Cultures of 5 Fungi, 28 days incubation	X	X
Salt Spray	Section 14	Category S 5% salt solution spray at 35C for 48 hrs non-operating	X	X
Magnetic Effect	Section 15	Magnetic field of 14.4 A/m for specified deflection, distance is determined by test	X	
Power Input	Section 16	Category A normal and abnormal operating voltage, interrupt, normal and abnormal surge, undervoltage	X	
Voltage Spike	Section 17	Category A 600V, 10 □sec transient	X	
Audio Frequency Conducted Susceptibility, Power input leads	Section 18	Category R or Z* Sine wave audio frequency superimposed on power lead	X	
Induced Signal Susceptibility	Section 19	Category Z Magnetic and electric fields and spikes induced into equipment and cables	X	
Radio Frequency Susceptibility Conducted	Section 20	Category Y* Cable injection to 10kHz to 400MHz	X	
Radio Frequency Susceptibility, Radiated	Section 20	Category Y* Radiated field to 18GHz Freq. Avg (V/M) Peak (V/M) 10kHz to 1 GHz 200 N/A 1 to 2 GHz 200 1700 2 to 4 GHz 200 3000 4 to 6 GHz 200 2300 6 to 8 GHz 200 530 8 to 12 GHz 200 1400 12 to 18 GHz 200 850	X	

Table 29. Safety requirements for SOFCPS (continued)

Condition	RTCA/ DO-160G	Requirement	Operating	Non-Operating
Emission of Radio Frequency Energy	Section 21	Category M* Radiated and conducted	X	
Lightning Induced Transient Susceptibility	Section 22	Category A 4XX Pin Injection: ECU only Multiple stroke: Waveform 1 (750V/1500A peak) and 3 (1500V/300A peak). Tests per AC20-136 Multiple burst: Waveform 3 (damped sinusoid) at 1 MHz, 300V/60A peak. Tests per AC20-136	X	X
Lightning Direct Effects	Section 23	The ECU is category X and no tests were required	X	
Electrostatic Discharge	Section 25	Category A 10 discharges, each polarity	X	

5.3 NOTIONAL DESIGN

The notional design of the SOFCPS is intended to be generic. The goal is to explore and expose new hazards introduced by the new technologies.

The design of any system is an iterative process. This notional design presents the final representation as a result of these iterations. Efforts has been made to capture some of the rationale during the notional design process.

5.3.1 System Description

The SOFCPS is a hybrid power system that integrates many functions with its output streams for increased system efficiency and effectiveness.

The SOFCPS comprises several subsystems tightly integrated into one unit. The subsystems included are: fuel processing, fuel cell stack, catalytic burner, turbomachine, SG, stack cooling, condenser, and water separator (see Figure 20).

5.3.1.1 Fuel Processing Subsystem

The fuel processing subsystem reforms sulfur-free or ultra-low sulfur aviation fuel into carbon monoxide and hydrogen enriched gaseous fuel for the stack through a catalytic steam reformer (CSR). The aviation fuel may be shared with the ME. The fuel pump delivers the low-sulfur fuel to the steam reformer (SR) to produce fuel rich reformate. The simplified chemical reaction is expressed in the following formula:

$C_{12}H_{26} + 12H_2O \rightarrow 12CO + 25H_2$

Both hydrogen and carbon monoxide are fuel to SOFC. This endothermic steam reformation reaction takes place between 750°C and 950°C. Additional water is required to avoid coke or soot formation on catalyst. The additional water content effectively lowers the fuel gases partial pressure by 39 percent.

The simplified chemical reaction is expressed in the following formula:

$C_{12}H_{26} + 36H_2O \rightarrow 12CO + 25H_2 + 24H_2O$

This hot reformate mixture of CO, H_2 and H_2O is delivered to the fuel cell anode.

5.3.1.2 SOFC Stack

The SOFC stack takes the hydrogen-enriched gas from the steam reformer (SR) into its anode, and pressure-boosted air from the turbomachine's compressor (CC) into its cathode.

This exothermic reaction takes place between 750°C and 850°C. The pressures of the reactants are balanced and elevated to 60 psia. The reactants utilization rate is approximately 60 percent. Both operating pressure and utilization rate may be adjusted to optimize the system size and weight against overall efficiency.

The SOFC stack is cooled with ambient air, which is then routed through cargo hold for heating, then fed into WIPS before exit into the environment.

5.3.1.3 Catalytic Burner

The stack exhaust gas streams from the anode and cathode are combined and fed into the catalytic burner (CB) to further extract power from the unused reactants. Part of the thermal power is used to sustain the endothermic SR reaction and drive the PT of the turbomachine. The selection of a CB is for maintaining a very highly efficient rich burner without concerns of lean blowout. The gas at the outlet with very low oxygen content at a fraction of a volumetric percent is ODA and may be used for fuel tank inerting or platform fire suppression.

5.3.1.4 Turbomachine

The hot CB exhaust is fed into the PT of the turbomachine and expanded to generate mechanical power to drive the stack CC, which is fed from the cabin air outflow and the electric generator (MG). The CC boosts the cabin air with a 4:1 ratio prior to feeding the fuel cell stack, increasing stack performance. Excess power from the PT is extracted through the MG. The output electrical power from the MG is fed into the 115VAC bus.

5.3.1.5 Steam Generator (SG) and Precooler

The PT exhaust is routed through a steam generator (SG) to transfer the otherwise waste heat into generating steam for the catalytic steam reformer (CSR) and galley food heating. The SG is a two-phase HEX. The hot side receives turbine exhaust gas and the cold side receives the extracted water from downstream coolers, condenser, and water separator. The water vapor contained in the ODA is condensed in the hot side while the water is evaporated and superheated in the cold side of the SG.

The hot side gas is further cooled by cabin outflow air in the pre-cooler and finally chilled by ambient air to condense and separate the water content for CSR and galley use.

5.3.1.6 Condenser/Water-Extractor

The two-phase ODA/water is chilled by the very cold ambient ram air in the condenser to ensure sufficiently dried ODA for fuel tank inerting. The quality of the ODA, when considering total reaction from stack inlets to CB outlet, is expressed in the following formula:

$$24CO + 50H_2 + 48H_2O + 37O_2 + 185N_2 \rightarrow 24CO_2 + 98H_2O + 185N_2$$

When the ODA is chilled to freeze point, roughly 95 percent of the water is condensed and removed, based on 32°F steam pressure of 0.089 psia (ASHRAE steam table). The composition of the ODA is as follows:

$$24CO_2 + 5H_2O + 185N_2$$

The condensed water is then pumped through the SG and the dried ODA is fed back through an economizer to recover some heat from the wet ODA to ensure no water droplet will enter the fuel tank. The dry exhaust is high-quality ODA, which is directed to FTIS.

The steam condenses in galley heating and the condensate is fed into the water tank for lavatory service. When the galley heating is not in use, the steam is routed through a steam turbine (ST) to generate electricity for recharging the ESDs and condensing and reclaim the water for lavatory service.

5.3.1.7 SOFC Stack Cooling Subsystem

The superheated steam leaves the SR cold side and enters a cooling circuit in the SOFC stack to help cool it while elevating steam temperature ready for steam reformation process. Since the SR requires about 50 percent of the steam for the reformation process, the remaining superheated steam can be piped to the galley for oven, then steam turbine, and finally lavatory water tank.

The SOFC stack is cooled by three main streams:

1. Cathode air — Balanced for stack reaction stoichiometry.
2. Superheated steam — Higher heat content than air.
3. Ambient (ram) air — May be used for cargo-hold heating via a radiator then heading to WIPS after leaving the stack.

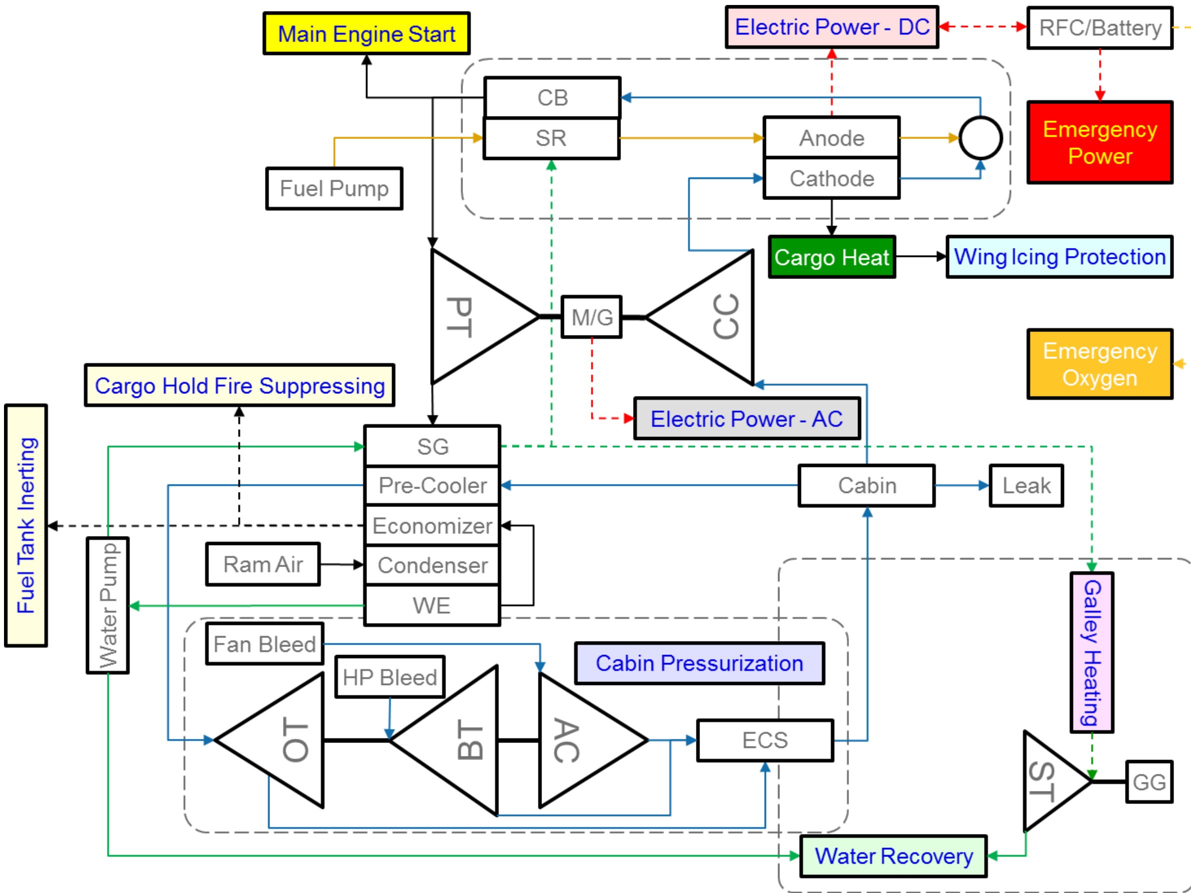

Figure 20. SOFCPS schematic diagram

5.3.1.8 Other Energy Supply Devices

The SOFCPS is designed to provide a flat baseline loading power to support the aircraft systems. It needs to be hybridized with ESDs, such as RFCPS and batteries, to handle peak and transient loads, and regenerate/recharge when there is power surplus.

5.3.2 System Configurations

Due to the large amount of energy storage needed for this hybrid power system, RFCPS is preferred over batteries. The prime location for RFCPS will be the tail cone to accommodate the size and shape of the reactant tanks. Batteries will be distributed where needed.

There are many ways to configure the hybridized, integrated SOFCPS. The three system configurations are illustrated in Figure 21 through Figure 23 for the purpose of exploring hazards and implementation challenges.

5.3.2.1 Belly Mount

The SOFCPS is highly integrated thermally; it would benefit if co-located with ECS, which is traditionally located at the fuselage belly and wing root. This arrangement makes installation easy for its close proximity to the ECS air management, WIPS, fuel tank, and mid galley.

Due to the nature of the SOFCPS, it should be situated inside the DFZ, which poses as a hazard for the closeness to the fuel tanks and the cabin. Figure 21 illustrates the notional installation location.

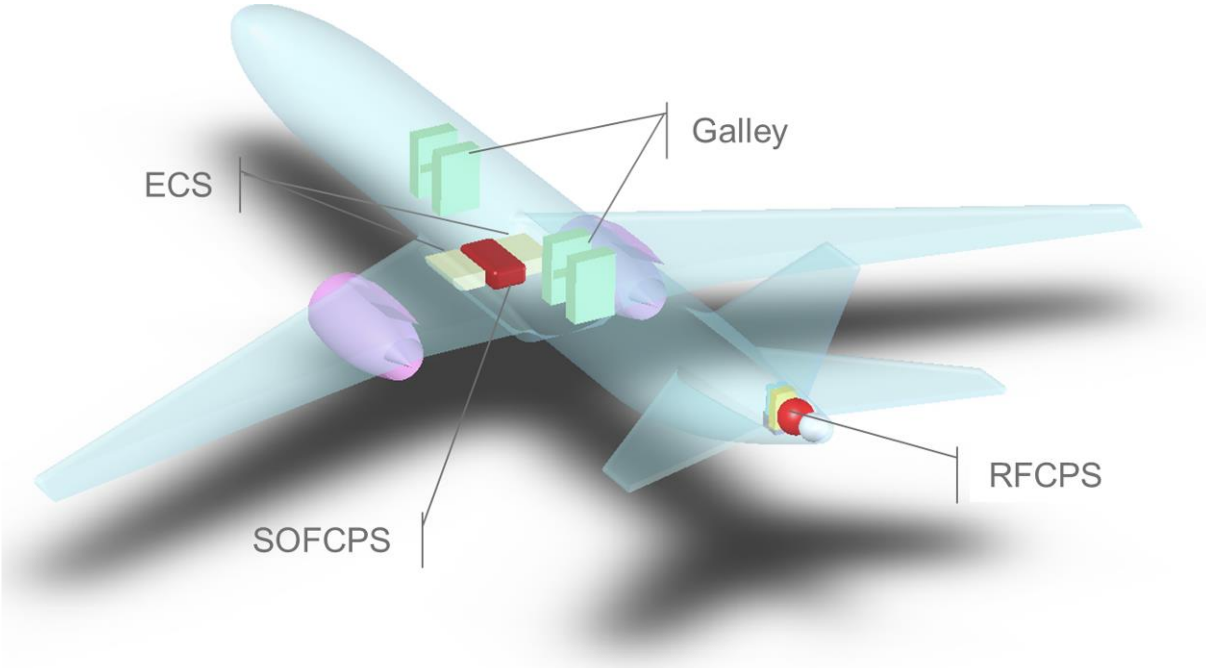

Figure 21. SOFCPS configuration option #1

5.3.2.2 Empennage Mount

The SOFCPS may be installed at the root of the vertical stabilizer, as shown in Figure 22. This location is relatively safe as it has been used to mount the ME for some aircraft. The services it provided such as FTIS and WIPS are ineffective and would not trade well with other installation options.

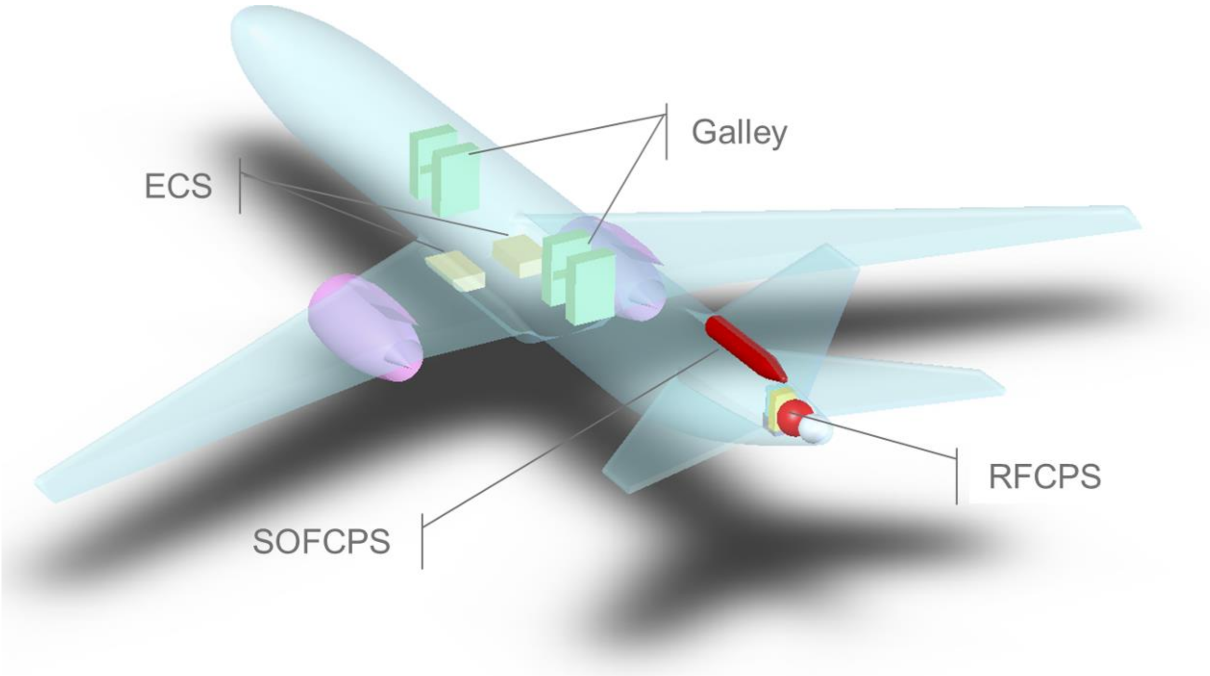

Figure 22. SOFCPS configuration option #2

5.3.2.3 Wing-Root Leading Edge Mount

The third option is to have two half-sized SOFCPSes situated at the leading edge (LE) of the wing root, as shown in Figure 23. This option allows easy thermal integration while at a safe and accessible location outside of the fuselage enclosure.

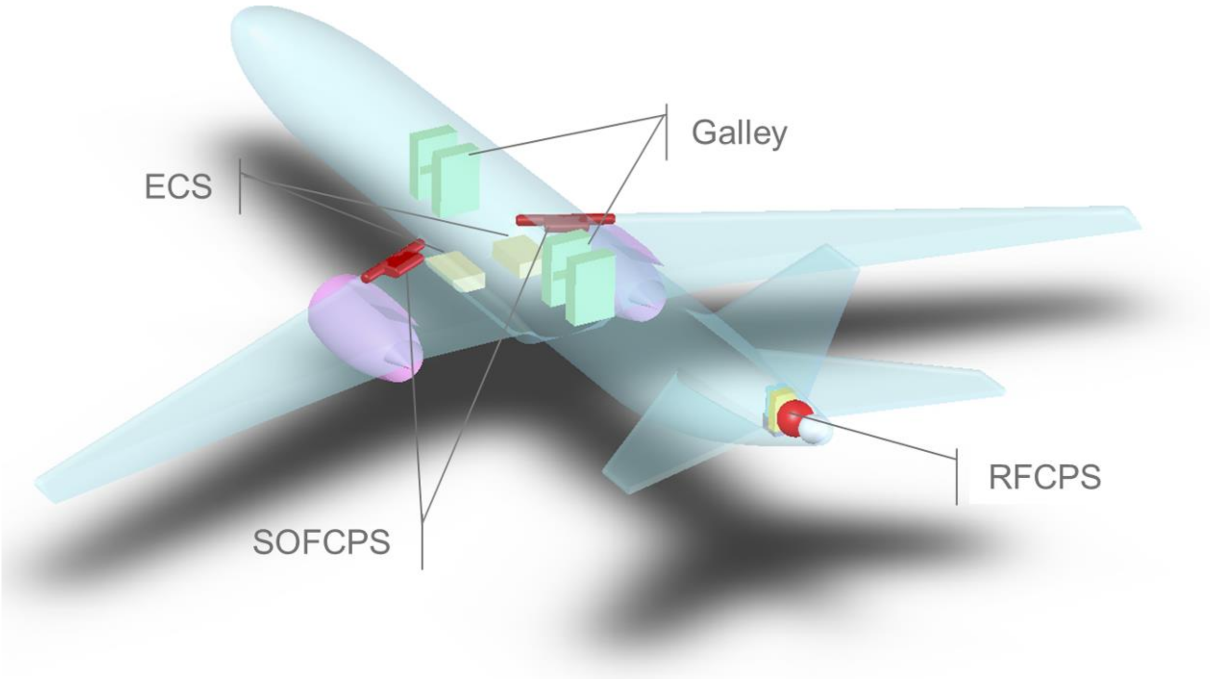

Figure 23. SOFCPS configuration option #3

5.3.3 Subsystem Notional Designs

The implementation of such a hybridized and highly integrated power system presents endless design choices and optimization strategies. This notional design presents one which touches on many aspects of possible configurations.

The thermally integrated main SOFCPS will be packaged similarly as a GT APU with more output fluid streams such as high temperature steam and ODA lines.

5.3.3.1 SOFC Stack

Due to the stack's brittleness, high-temperature seal-material limitations, elevated operating temperature, and pressure condition, the stack shall be in a cylindrical shape inside the system pressure vessel. The stack's thermal management (cooling) is the greatest challenge, though the system mass and thermal balance calculations assume the cooling challenge is overcome.

5.3.3.2 Catalytic Steam Reformer

While the endothermic steam reformation reaction operates at a temperature slightly lower than that of the stack, it shall be concentrically arranged around the stack for better thermal integration. Both steam and fuel are premixed and preheated by the waste heat from the stack and act as part of the stack cooling sink.

5.3.3.3 Catalytic Burner

This exothermic reaction shall also be arranged concentrically around the SR to maintain its temperature.

5.3.3.4 Turbomachine

The PT inlet of the turbomachine is close coupled with the CB exhaust. The turbomachine resembles a small traditional GT APU. The turbomachine output power will be affected by altitude, unlike the stack that generates constant power, with same reactants flow conditions.

5.3.3.5 Steam Generator

SG is a two-phase HEX with water/steam on the cold side, while the hot exhaust ODA from the power turbine on the hot side.

5.3.3.6 Condenser/Water Extractor

The cooled ODA is fed through a series of HEXs to further cool to ~70°F by cabin outflow air and to dried ODA before it enters the ambient air-cooled condenser.

Special care must be taken into the design to avoid ice formation inside the condenser since the sink temperature is subfreezing.

Water condensate will be extracted and pumped through the SG. The dried ODA, with ~95 percent of the water removed, is sent through the wet ODA HEX to ensure it is droplet-free before entering the fuel tank for inerting.

5.3.3.7 Cargo-Hold Heating Radiator and WIPS

The stack cooling air is ducted through a radiator located inside the cargo hold to maintain temperature for cargos. The hot air leaving the radiator is finally sent to the LE of the wings for full time icing protection.

5.3.3.8 RFCPS

Section 4.3.1 discusses the RFCPS.

5.3.3.9 Electric Power System

Figure 24 is the top-level electrical system architecture for this notional SOFCPS-equipped aircraft.

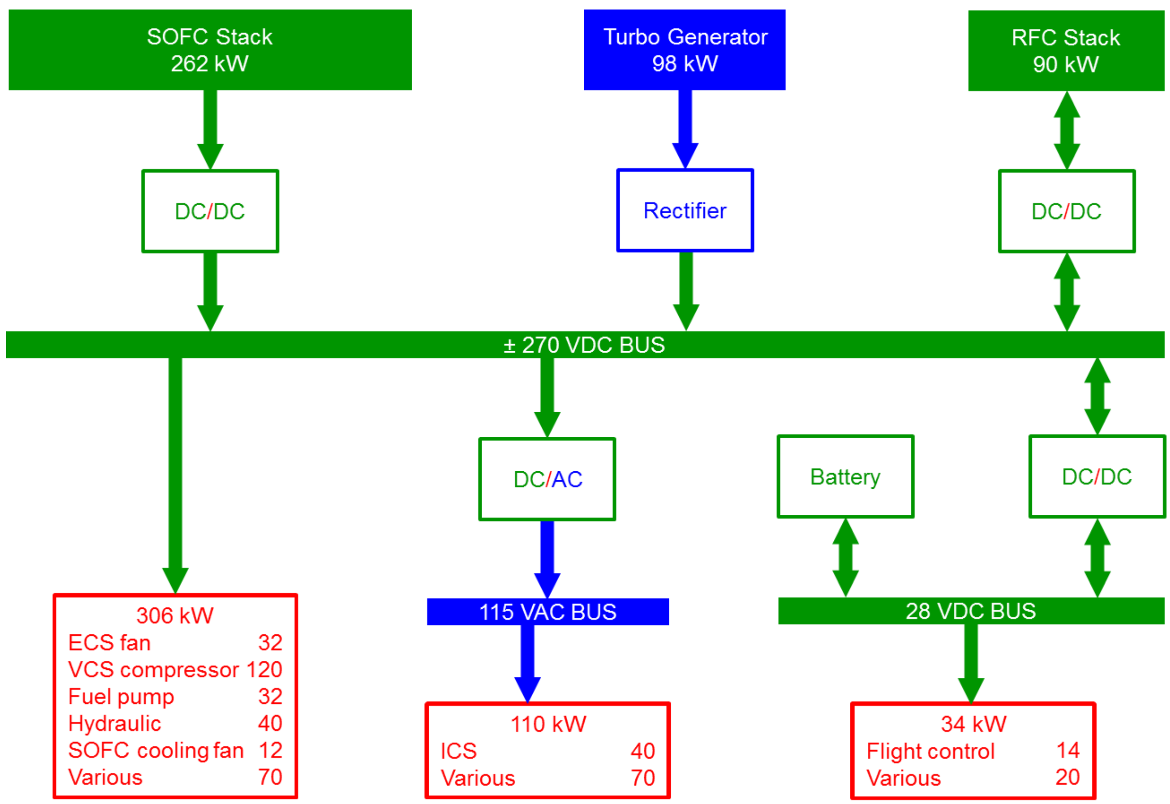

Figure 24. Top-level electrical system architecture – Hybrid SOFCPS

5.3.3.9.1 High Voltage DC Switching and Protection

High-voltage DC primary power distribution contactors are heavier and more expensive than traditional AC contactors to withstand switch contact arcing. Ideally, they need to be high-power

SSPC modules to provide fast switching since the pass-through fault energy before an electromechanical contactor opens (typically a 20-30mS period) and can cause significant arcing. This effect is much less pronounced in AC systems because the arc self-extinguishes during zero-crossing. Such high power SSPCs are not commercially available. As in current SSPC-based secondary distribution systems, fail-short protection must be included and must prevent the charging of load capacitance by leakage current (which is particularly important for personnel safety in these high-voltage systems). SSPCs must be lightning-immune and need to be able to withstand or control load capacitive inrush currents.

Arc fault detection/protection is an important feature in high-voltage DC systems. It needs to be able to detect different arc types and minimize false trips due to transients and normal loads. Protection level co-ordination is required to ensure only the furthest downstream protection device is activated.

Corona/partial discharge are important considerations in high-voltage systems. The choice of +/-270VDC allows standard insulation systems and design practices to be used.

5.3.3.9.2 Power Quality Including Transient Response

While 270VDC systems have been used for several years in some military fighter jet applications, use of high voltage DC in commercial air transport has been limited, and where used, it typically has been locally distributed and used for a few specific loads.

Power quality, including transient response, is an important consideration. In particular, transient response of a FCPS needs to be carefully considered to avoid excessive voltage excursions. This may necessitate including energy storage (batteries) as part of the FCPS. The FCPS output may need to be fed to the bus via a DC-DC converter to enable sufficient voltage control and energy-storage power management. This DC-DC converter could also provide power control/current limiting (by reducing the supplied steady-state voltage), but this is not effective with constant power loads.

Load limiting (load-shedding) would be required to prevent FCPS overload. It also is recommended that the distribution system provides for the staging load-on transient (applying different loads in sequence) so that the FCPS has time to respond and provide the required power without permanently damaging the system components and degrading performance.

While load-off transient cannot be controlled in all circumstances, an FCPS typically responds and operates safely in open-circuit condition.

5.4 MAINTENANCE AND RELIABILITY

The SOFCPS is a sophisticated system that ducts high-pressure reactive gas. It includes high-temperature chemical reaction chambers, sensitive ceramic or metal/ceramic hybrid structures, catalytic materials, high-speed turbomachinery, high-power, high-voltage electrical feeds, and devices for power conditioning and control. Given that this system is intended to operate continuously, while the aircraft is on the ground and in all phases of flight, means that during the expected life of the aircraft, this system will accumulate an unprecedented number of hours. The critical failure of a component in this system is inevitable. How that failure affects the safe operation of the system and the aircraft it is installed in is driven by careful design of the system, and the implementation of appropriate measures and features that manage this risk to an acceptable level. Demonstration of appropriate reliability and system robustness will be key, as it is with any other critical aircraft subsystem.

Many of the components in this system are similar-to components and equipment currently used on commercial air transport aircraft. As such, there are existing methods for reliable design, manufacture, and qualification, including the electrical power and distribution system and the fuel delivery system. The system HEXs and turbomachinery also share a heritage with existing aircraft system technology. Their reliability should be within existing design capability and the maintenance of these systems consistent with current practices.

Unique is the implementation of a FC stack necessarily constructed with brittle materials that could leak reactive gases into the compartment, or fail to function during critical periods of flight, for which there are few mature reliability models that would apply. Reputedly, these systems have shown very long lives in stationary earthbound applications. It remains to be seen how reliably they perform in the air. While the stack core is likely not serviceable, there may be a design need that allows repair, or replacement of external seals, and system components. Since the stack itself is somewhat fragile and cycle-limited there should be appropriate maintainability built into the system to allow economical and safe removal and replacement. As the studied system weighs 7000 kg, the bulk of which is the stack, this could be a significant undertaking.

There is no question that the appropriate health monitoring with effective prognostics that can measure the progressive degradation of key aspects of the system-critical components can provide early warning of the most critical or most common failures. It is a rare argument, however, that health monitoring by itself improves system reliability, unless there is an adaptive feature in this system that enables it to change modes, and provide limited or reduced, but still sufficient operative capability during the worst-failure scenarios.

In any case, all of the components' critical failure modes must be understood. Also, the system design, which includes build quality, as well as operational monitoring and analytics, must be configured to predict, avoid, and where required, safely operate with one or several key components that are not operational or degraded in some way.

5.5 CONCLUSION

The functionalities of the all-time SOFCPS, which appears attractive in a notional design for its higher efficiency, reduced emission, reduced noise, and uninterrupted and independent power supply, encourages a new, uncompromised, and thrust-only ME design. It also allows the airplane to be parked away from the terminal in overcongested or undersized airports around the world.

The NCD of the SOFCPS performance is based on extreme optimism in its technology development and design. The goal is to expose broader areas of implementation possibilities for safety-hazard assessment.

The equipment replaced by the system potentially includes GT APU, S/Gs, motors and motor controllers, RAT, air separation module, potable water and reduced water tank size, all of which will be credited for specific design trade.

The implementation of the notionally designed SOFCPS is contingent upon the paradigm shift in the aerospace industry in determining functions and load management with technology. It also requires a clean-slate platform design opportunity usually driven by business rationale, but which happens infrequently.

The reliability of this system is impacted by its size, and concept of operations. Although implementation of trending analytics can help determine dispatch reliability and avoid failure during critical operation modes, it is dependent on the development and recognition of critical failure modes in this system, including the stack, and developing effective sensors and models that can identify and track progressive structural and performance deterioration.

The greatest caveat of all is the availability of sulfur-free or ultra-low sulfur fuel to support the SOFCPS technology implementation.

6. NEW SAFETY HAZARDS ASSESSMENT

With each implementation of new technology, it brings along new safety hazards whether in system performance, operation, or maintenance. Unlike GA APU, FCPS comes in vast numbers of combinations between fuel type, fuel state, fuel processing, stack chemistry, operating conditions, and services.

Also, unlike the GT APU, FCPS provides fertile ground for various degrees of hybridization between air-breathing FC, turbomachines, self-contained reactants fuel cell, batteries, and even super capacitors, each tailored to its strength as subsystems. The focus of assessing safety hazards shift from specific design to categories of behaviors.

Hybridized power systems add one more layer of safety hazards due to the interdependency between sub-systems, which is difficult to assess categorically and should be dealt with independently for each specific design. To this end, the aim of this study was shifted more toward exploring multiple implementations to expose more categories of safety hazards than any well-defined specific notional design.

As the notional design progresses in discovering new hazard categories, it becomes apparent that the hazard categories contained in each of the three selected FC technologies are hierarchical. That is, most of the safety hazards involved in direct hydrogen PEMFCPS are also inherent in RFCPS. Likewise, all the safety hazards involved in RFCPS are also inherent in SOFCPS implementation because of the inclusivity of RFCPS. By understanding the safety hazards of SOFCPS, the other FCPSes are automatically covered.

A summary of consolidated new safety hazard categories for FCPS is covered in the following sections.

6.1 BATTERIES

The aviation power/energy batteries have been vigorously studied and certification requirement is well developed.

6.2 GT

The GT APU certification requirement is mature and well-defined in TSO-C77b.

6.3 PEMFCPS

The safety standards for PEMFCPS are also well defined by the automotive industry, which may be adapted readily.

6.4 RFCPS

This self-contained power system places energy-dense fuel and strong oxidizer in very close proximity at very high pressure. The new safety hazards categories in this system include:

- System component cleanliness for strong oxidizer. “Oxygen-clean” procedure must be followed rigorously during installation and maintenance periods.
- Elevated fire and explosion potential in oxygen-enriched environment.
- Hydrogen/oxygen autoignition condition in high-pressure reactants gas system.
- Fire potential for surrounding flammable materials.

6.5 HYBRIDIZED SOFCPS

As suggested in SOFCPS NCD, the implementation is unlikely without the integration of all forms of powers and hybridization of other power sub-system such as GT, RFCPS, and batteries. The new safety hazards should be analyzed by fluid circuits and hardware.

6.5.1 Hazard from Each Circuit

6.5.1.1 Superheated Steam

- Galley heating — High-temperature steam transmission line
- Superheated steam oven — Danger to personnel
- Cargo hold heating (condensing) — High-temperature steam transmission line
- Potable water (heating and) replenishment — Cleanliness standard
- Icing (blockage) and collapsing — Vacuum created by steam condensing

6.5.1.2 Stack Cooling Air

- Cargo hold heating (liquid cooled) — Radiator leak proofing
- Wing icing protection (air cooled) — High-temperature over fuel tanks

6.5.1.3 Oxygen Depleted Air

- Fuel tank inerting — Water condensate in fuel tank

6.5.1.4 Regenerated Reactants

- Pressure control and regulation

- Isolation of the reactants
- Double containment in reactants transmission through pressurized zones

6.5.2 Hardware Hazards

6.5.2.1 Steam Reformer

- Flammable liquid
- Combustible gases
- High temperature

6.5.2.2 SOFC Stack

- Combustible gases
- High temperature

6.5.2.3 Catalytic Burner

- Combustible gases
- High temperature

6.5.2.4 Turbomachine

- Kinetic energy
- High temperature

6.5.2.5 Electrical Connections and Sensors

- High voltage
- High temperature

6.6 DESIGNATED FIRE ZONE

The area enclosing turbomachine and steam reformer should be considered a DFZ because turbomachine resembles a GT APU, and the SR operates at a very high temperature with liquid jet fuel.

6.7 FUEL TANK (WATER) CONTAMINATION

The ODA supplied is slightly undersaturated at free point. It could be absorbed by warm fuel or form tiny ice crystals in cold fuel. Current fuel is exposed to saturated ambient air in airport fuel farms, the condition of which is no better than the blanketed aircraft fuel tank.

6.8 PREVENTION

- Isolate energy source from power generation device, isolate between reactants
- Ventilate (passive) to disperse leaked reactants
- Channeling and directing released energy in case of explosion

- Health monitoring on key system components

These assessments are incorporated into the RTSG.

7. CONCLUSION AND RECOMMENDATION

7.1 CONCLUSION

The safe implementation of three FCPS technologies to provide auxiliary power for commercial air transport aircraft was evaluated. The goal is to reveal new safety hazards introduced to the aircraft by new technologies.

Unlike the GT auxiliary power unit (APU) that it replaces in this study, the FCPS comes with many forms of stack chemistry that require different types and forms of fuel operating at different conditions. It is physically improbable that FCPS could replace the full functionality of the GT APU in a modern aircraft without a major modification to the aircraft. To accept FCPS as a viable auxiliary power solution, the system architecture paradigm of the aircraft power needs change.

For each FCPS to be technologically feasible, reasonable and technically achievable assumptions were made in this study. (The study approach is set to explore when, not if, some feasible FCPS can replace GT APU functions, and assess the new safety hazards brought to the aircraft through these technologies.) Three probable FCPS types were examined. The safety hazards nested with the SOFCPS have been all-inclusive (that is, once the study is done on SOFCPS, it also should cover RFCPS and PEMFCPS).

For direct hydrogen PEMFCPS, an implementation with minimally critical functionality was assumed and compared with a GT APU to determine that it could be plausible. As PEMFCPS technology is matured from automotive applications, all learning from automotive FCPS implementation will be of great value. The obstacle for adapting this technology lies in the lack of hydrogen-refilling infrastructure in all airports.

Although RFCPS is independent of hydrogen distribution infrastructure, the maturity of this technology for aviation is low. The added pressurized oxygen as a strong oxidizer increases safety risk for providing an oxygen-enriched environment, as well as reactants system cleanliness requirement and autoignition potential.

To be a viable alternative, SOFC with reformed jet fuel needs extensive platform integration with a pressure-boosting turbomachine and hybridization with RFCPS and/or batteries. The magnitude of a system architecture change demands a paradigm shift in design philosophy, requiring a clean-sheet design opportunity.

Overall, most safety hazards are covered in the final report of the FAA ESD aviation rulemaking committee. Few additional safety hazards identified in the study will be documented in RTSG:

a. RFCPS — Hydrogen autoignition potential in high-pressure reactants system
b. SOFCPS — Superheated steam system and galley appliances

7.2 RECOMMENDATION

1. FAA to establish TSO for FCPS focusing on stack and balance of plant as packaged unit. Refer interconnecting systems such as GT and fuel reforming/processing to other appropriate certification standards.
2. Look for matured PEMFCPS implementation and certification requirement from the automotive industry.
3. Industry collaboration on the following (in the form of FAA aviation rulemaking committee) is recommended:

    a. Maturity level of high-power/energy RFCPS is at its infancy, potential development of URFCPS is desired.
    b. Challenge of onboard fuel processing and miniaturization of SOFCPS demands real life implementation experience and data.