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Study of Unitized Regenerative Fuel Cell Systems for Aircraft Applications

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Final report



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16. Abstract Unitized regenerative fuel cells (URFCs) have been explored as potential high energy density power systems for aerial and space applications due to their potential to provide multiple functions with a single set of stack hardware. System designers and researchers have developed demonstration-scale URFCs using low temperature proton exchange membrane (LTPEM) and solid oxide fuel cell (SOFC) technologies. Both technologies have shown promise but exhibit features that are disadvantages for integration into an aircraft. High temperature proton exchange membrane (HTPEM) technology could have the ability to achieve the advantages of the previous technologies explored without the downsides. A 125-kW HTPEM URFC system design was developed specifically for an electric propulsion application. The system consists of a URFC stack stored within the oxygen reactant storage tank to save volume, simplify water management, and reduce system complexity. A hydrogen storage tank, thermal control system, pressure/flow control devices, and the control logic required to maintain safe and effective system operation were included and system concepts, operational parameters, and alarm conditions were defined. A system model was developed to explore the performance of the system in fuel cell mode during flight and electrolysis mode to recharge the reactant storage tanks while on the ground. The system was shown to be effective in providing power for one, two, and five-hour flights with a recharge time approximately equal to the time of the flight. Despite the projected success of the simulation, the mass and volume of components required to implement the HTPEM URFC into an aircraft may be prohibitive without extensive development and improvements in the system design and performance of individual components, including the URFC stack.					
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Acronyms

Acronym	Definition
APU	Auxiliary Power Unit
COPV	Composite Overwrapped Pressure Vessel
DOE	Department of Energy
ERAST	Environmental Research Aircraft and Sensor Technology
FAA	Federal Aviation Administration
GDC	Gadolinium-Doped Ceria
HALE	High Altitude Long Endurance
HTPEM	High Temperature Proton Exchange Membrane
IMPRESS	Integrated Modular Propulsion and Regenerative Electro-Energy Storage System
LLNL	Lawrence Livermore National Laboratory
LSCF	Lanthanum Strontium Cobalt Ferrite
LSCoF	Lanthanum Strontium Cobalt Ferrite
LSF	Lanthanum Strontium Ferrite
LSGM	Lanthanum Strontium Gallium Magnesium Oxide
LSM	Lanthanum Strontium Manganite
LTPEM	Low Temperature Proton Exchange Membrane
MEA	Membrane Electrode Assembly
NASA	National Aeronautics and Space Administration
P&ID	Piping and Instrumentation Diagram
PBI	Polybenzimidazole
PEM	Proton Exchange Membrane
RFC	Regenerative Fuel Cell
RMIT	Royal Melbourne Institute of Technology
RSOFC	Reversible Solid Oxide Fuel Cell
ScSZ	Scandium Oxide Stabilized Zirconium
SOEC	Solid Oxide Electrolysis Cell
SOFC	Solid Oxide Fuel Cell
UAV	Unmanned Aerial Vehicle
URFC	Unitized Regenerative Fuel Cell
WaMM	Water Management Membrane
YSZ	Yttria-Stabilized Zirconia

Executive summary

This document provides a summary of activities performed by Teledyne for the FAA under contract 692M15-19-C-00005. The scope of this contract was to explore the potential of a unitized regenerative fuel cell (URFC) system to provide power onboard an aircraft. Fuel cell systems are being explored as potentially useful power systems for aerial applications as the industry transitions to more electric aircraft designs that can better utilize their advantages. A URFC system can provide operational advantages for an aircraft, such as long mission durations or persistent flight, reduced requirements for fuel infrastructure, and reduced system mass and volume.

URFC systems have been explored as potential power sources for multiple applications involving mass and volume minimization, including space and aerial vehicles. Much research and development has been performed on developing the technology from the cell level, which requires careful choice of materials that can survive the electrochemical environment in both fuel cell and electrolysis modes, and flexible cell designs that handle reactants and products of each reaction without impeding the process. Developers have attempted to build their designs around either low temperature proton exchange membrane (LTPEM) or solid oxide fuel cell (SOFC) technologies, each built upon several decades of maturation in fuel cell applications. Demonstration hardware at the single cell, short stack, and full stack levels has been manufactured and tested for performance. Both technologies have shown the ability to operate in a reversible mode, but with several technical challenges that make long-term, stable, and durable operation difficult in practice. LTPEM technology struggles with managing the two-phase flow of water, especially during transitions between modes. SOFC technology requires large heat inputs and does not easily handle transitions between power levels or start-stop cycles. High temperature proton exchange membrane (HTPEM) technology has the potential of eliminating the downsides of both previously explored URFC technologies, but has yet to be explored in this application due to the lower level maturity of the technology.

Teledyne has developed a conceptual design of a 125-kW HTPEM URFC system to be integrated into an aircraft. Potential applications include direct power for electric propulsion in small aircraft or a load-balancing device for larger aircraft, such as a 787 Dreamliner. The electric propulsion application was explored in detail during this study. The system consists of an open-cathode URFC stack with HTPEM technology stored within the oxygen reactant storage tank. This provides advantages by simplifying water management, eliminating oxygen flow control devices, and minimizing volume. This arrangement raises multiple safety issues that must be addressed in the detailed design, including the potential for hydrogen-oxygen gas mixtures

due to leakage, product water sloshing, and electrical shorting of the stack. A hydrogen storage tank, thermal control system, pressure/flow control devices, and control logic were defined and described in detail to maintain safe and effective system operation over the length of the proposed flight. The concept of operations, system parameters, and alarm conditions were defined to provide a framework for system operation. Individual components were selected with performance data and physical specifications gathered.

A system model was developed based upon the URFC system design. The model used power consumption data from all of the components required for operation, performance data from HTPEM technology during power production and electrolysis, thermal requirements defined by the stack mass and efficiency, and expected flight profile of one, two, and five-hour flights. Performance was evaluated in both fuel cell and electrolysis modes of operation. The system was shown to be effective in providing power for the electric propulsion application with enough reactant supply to handle the worst-case scenario. Refueling times were shown to be less than or equal to the mission duration. The major disadvantage of this system is the power and energy density of less than 100 W/kg and 200 Wh/kg, which is not competitive with lithium ion battery technology of similar scale, largely due to the size and mass of the reactant storage tanks. Recommendations include scaling the system down to the kW or sub-kW scale to reduce the reactant tank mass, exploring Failure Modes and Effects Analysis (FMEA) studies to explore the safety implications and identify areas of improvement, and putting resources into improving the HTPEM technology itself to maximize efficiency and durability.

1 Introduction

This document contains the details of the study completed by Teledyne for the FAA in exploring URFC systems for aircraft integration. The program started with a survey of URFC technology described in Section 2, including the research and development history, hardware development, and recommendations for future direction. Using those recommendations, a system design was developed, as described in Section 3, that details the URFC stack, reactant storage tanks, thermal control system, pressure and flow controls, control logic, concept of operations, operational parameters, alarm conditions, and safety implications. A simulation of an electric propulsion aircraft using this URFC as its power system was developed and it is described in Section 4, followed by overall conclusions of the study in Section 5.

2 Unitized regenerative fuel cell technology report

This section provides a summary of the literature review, technology selection, and definition of aircraft application performed by Teledyne on unitized regenerative fuel cell systems. Teledyne participated in discussions with aircraft industry representatives and the FAA regarding possible applications for a URFC on an aircraft. These discussions culminated in a proposed URFC application for analysis under this program. Teledyne gathered and reviewed published research and commercially available information on URFC technology. The material was summarized and reviewed by a team of fuel cell subject experts. The team made recommendations for the best available technology to satisfy the performance requirements of a potential URFC aircraft application.

A definition of a regenerative fuel cell is provided along with the differences between discrete and unitized regenerative fuel cell systems. Previous research and development of URFC technologies is reviewed and discussed. LTPEM technology has an extensive history of development by NASA, universities, and private organizations because of a high technical maturity level through parallel developments in the fuel cell industry. Reversible Solid Oxide Fuel Cell (RSOFC) have been researched with interest in recent years due to its ease of reversibility found experimentally. HTPEM, although the least mature of the available technologies discussed in this report, can also be used for regenerative fuel cell (RFC) applications. The technology selection made by the Teledyne review team is derived from the information summarized above.

2.1 Regenerative fuel cell definition

Regenerative fuel cell (RFC) systems have been studied as a potential power system concept that can provide many operational benefits to the user. RFCs are fuel cell power systems that are reversible, meaning that they can be operated both in fuel cell mode to produce power with reactant inputs and in electrolysis mode to produce reactants with power input. When designed as a closed loop system, the reactants produced during electrolysis are kept in storage to be used later in fuel cell mode for power production. Conserving reactants through closed loop system design in RFCs enables long duration power system operation in a smaller package by eliminating the need to refuel.

In theory, RFCs can be composed of any combination of fuel cell and electrolysis technologies, provided that the same reversible reaction is used for the fuel cell and electrolysis modes of operation. There are two types of RFC systems: discrete and unitized. The differences between the two types of RFCs are described in sections 2.1.1 and 2.1.2 below.

2.1.1 Discrete regenerative fuel cells

Discrete RFCs are reversible fuel cell systems that employ separate hardware units to perform the power-producing and reactant-evolution processes. A system diagram of a discrete RFC utilizing the hydrogen-oxygen reaction is shown in Figure 1. The system can start in any state if a source of power is available.

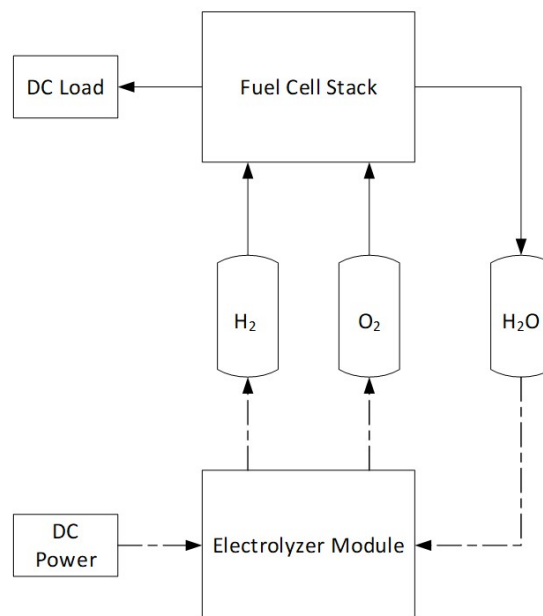


Figure 1: Discrete regenerative fuel cell system diagram

The following is how a discrete RFC functions assuming a proton exchange membrane (PEM)-based system that is fully supplied with hydrogen and oxygen reactants at the beginning of operation. When power is required, hydrogen and oxygen reactants are withdrawn from the storage tanks and routed to the fuel cell stack. The fuel cell stack reacts the hydrogen and oxygen to produce DC power that can be used by an available electronic load. The hydrogen-oxygen reaction produces water, which is removed from the fuel cell stack and stored in a separate vessel. The fuel cell continues to produce power until either the demand from the electronic device is removed or the reactant storage tanks are emptied. When power is available for the system to use, the water produced during fuel cell mode is withdrawn from the storage tanks and routed to the electrolyzer module. The electrolyzer uses the available DC power to electrochemically split the water into hydrogen and oxygen gas. The gasses are pumped back into the storage tanks to be used again by the fuel cell stack later.

A discrete RFC system is simple in that the fuel cell stack and electrolysis module hardware used can be similar to, if not the same as, those used in standalone power generation or gas production applications. The hardware configuration can be optimized for each reaction with the use of separate devices. Discrete RFCs can quickly transition between the two modes of operation with very few restrictions and could even run in both modes simultaneously if the application required the system to do so. Although simple in concept, discrete RFC designs can increase the mass and volume of the power system beyond what is normally acceptable for mobile power applications.

2.1.2 Unitized regenerative fuel cells

Unitized RFCs are reversible fuel cell systems that can generate power or reactants using a single electrochemical unit. A system diagram of a unitized RFC utilizing the hydrogen-oxygen reaction is shown in Figure 2. The operation of a unitized RFC is similar to a discrete RFC. When power is required, hydrogen and oxygen are withdrawn from the reactant storage tanks and routed to the unitized stack. The unitized stack reacts the hydrogen and oxygen to produce DC power that can be used by an available electronic load. The water produced from the reaction is removed from the stack and stored in a separate vessel. Power is produced until either the demand from the electronic device is removed or the reactant storage tanks are emptied. The water produced during fuel cell mode is withdrawn from the storage tanks and routed back to the same stack when power is available. The water is electrochemically split into hydrogen and oxygen gas, which are pumped back into the storage tanks for later use.

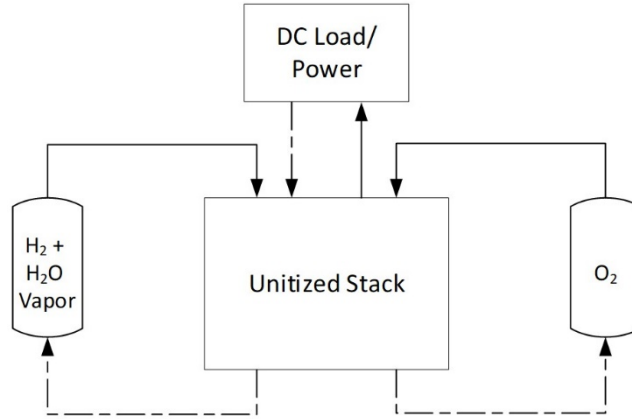


Figure 2. Unitized regenerative fuel cell system diagram

Unitized RFC systems have promise as power systems for aircraft, especially those employing electric power for some or all the propulsion and device power requirements. These aircraft require an increased specific energy to meet target aircraft weight requirements. A unitized RFC requires less mass and volume than a discrete RFC due to the use of a single electrochemical stack that performs both reactions. Proper integration of a unitized RFC into an aircraft can enable successful operation of new aircraft designs.

Unitized RFCs come with performance limitations. They can be more difficult to manage and operate than discrete RFCs. The hardware design must be capable of performing each electrochemical reaction at an efficient rate without compromising operation in the reverse mode or sacrificing stack durability. Transitions from one mode to the other are challenging because the products of the previous reaction must be cleared and the optimal operational conditions for each mode are different. Simultaneous operation in both modes is not an option with unitized systems.

2.2 Unitized regenerative fuel cell technology

The potential benefits of unitized RFCs in mobile applications have driven various organizations to invest in research and development of URFCs. The main challenge is to find technologies that can perform well as both fuel cells and electrolyzers. Research has focused on incorporating materials into the stack design that perform both functions efficiently while remaining stable and durable over an extended period of use. Other system design challenges have been investigated as well, such as handling transitions between operating modes and optimizing thermal management. This work has led to hardware demonstrations to test the concepts, mostly consisting of single cell or small, subscale stack tests.

A literature survey of unitized RFC technology was conducted to provide an understanding of the current capabilities of unitized systems and potential hardware available. The survey focused on two electrochemical technologies: Proton Exchange Membrane RFCs and Solid Oxide RFCs. These two technologies represent the most mature electrochemical processes used for mobile power for terrestrial, aerial, and space applications by both commercial and government users. The survey focused on research efforts that included demonstration hardware to help increase the applicability and practicality of the conclusions drawn.

2.2.1 Low temperature PEM RFCs

The most mature electrochemical technology for mobile applications is the PEM fuel cell. PEM fuel cell technology was originally developed in the 1960s and used by NASA on the Gemini missions and other subsequent space programs. Most PEM cells use Nafion, a fluoropolymer material that conducts protons when hydrated, to allow the transport of protons derived from the hydrogen used in the reaction. The insulating properties of Nafion divert the electric current produced by the reaction through an external circuit, thus generating power for electrical devices. Recent development of PEM fuel cell technology in the industry has focused on cost reduction and increased reliability to optimize the technology for commercial automotive, material handling, and unmanned aerial vehicle (UAV) applications. An extensive development history of the technology for over 50 years along with established component materials, designs, and supply chains make PEM technology a logical choice for a unitized RFC system.

2.2.1.1 Applications and demonstrations

The history of LTPEM URFCs goes back almost as far as PEM technology itself. In the early 1970s, General Electric explored the concept of a LTPEM URFC for providing power onboard a geosynchronous satellite with a seven to ten year lifetime (Mitlitsky F. , Lightweight Pressure Vessels and Unitized Regenerative Fuel Cells, 1996) (Mitlitsky F. , Unitized Regenerative Fuel Cell Systems, 1998). Using alternate but similar materials to today's PEM technology, GE performed single cell testing for over 700 cycles to show that the concept could work with minimal performance degradation ($< 40 \text{ mV}$ at 108 mA/cm^2). Despite the successful demonstration, the technology was never advanced to the point of integration into the intended application.

NASA has devoted much funding and attention to developing a LTPEM unitized RFC system that could be used in a space or aerial application. NASA began to research LTPEM technology for use in an RFC system to power High Altitude Long Endurance (HALE) aircraft, extraterrestrial outposts, and terrestrial secondary battery applications in the 1990s. Initial system concepts and design studies showed that an RFC based on PEM technology could provide mass

reduction over batteries in applications when discharge times were greater than one hour (Burke, Unitized Regenerative Fuel Cell Development, 2003). One such concept showed that indefinite operation is possible in an ultralight aircraft design on a 12-hour charge, 12-hour discharge cycle (Burke, High Energy Density Regenerative Fuel Cell Systems for Terrestrial Applications, 1999). The system concept uses solar panels mounted to the wings to power the engines and perform water electrolysis during the day. The hydrogen and oxygen generated from electrolysis would provide 3.5 kW of power through twelve hours of fuel cell operation when no solar power is available. NASA's study showed that energy density approaching 800 Wh/kg was achievable through implementation of passive system design components and clever integration of the RFC system hardware into the aircraft structure. Passive system design concepts included wrapping the gas tubing around the tank to serve as a gas dryer/humidifier, a pressure-loaded bellows for water storage, and implementation of heat pipes that reject heat from the unitized stack to the reactant storage tanks (USA Patent No. 7,410,714 B1, 2004) (Burke, Unitized Regenerative Fuel Cell System Gas Storage-Radiation Development, 2005).

Physicists at Lawrence Livermore National Laboratory (LLNL) began investigating unitized LTPEM RFC systems for potential use in HALE aircraft in the mid-1990s with NASA and Department of Energy (DOE) support. The lightweight power system requirement for the application drove LLNL to develop URFCs and novel pressure vessels that could be integrated into the aircraft (Mitlitsky F. , Lightweight Pressure Vessels and Unitized Regenerative Fuel Cells, 1996). LLNL built a 46 cm² single cell Nafion-based LTPEM URFC and completed testing to match the work completed by GE in the 1970s, and explore operational parameters such as temperature and current density. Operating at pressures below 160 psi, LLNL was able to achieve over 2000 cycles with less than 50 mV of degradation, which is equivalent to less than a few percent. LLNL was able to demonstrate high current operation (greater than 1 A/cm²) in both fuel cell and electrolysis mode using an improved cell design with a lower resistance membrane (Mitlitsky, Myers, & Weisberg, 1998). LLNL also developed a URFC concept to power small spacecraft, much like the original GE application. Called the Integrated Modular Propulsion and Regenerative Electro-Energy Storage System (IMPRESS), the concept combined the URFC stack with a hydrogen/oxygen propulsion system to reduce spacecraft mass (Mitlitsky, de Groot, Butler, & McElroy, 1996). The IMPRESS concept gained the attention of the Air Force as a potentially beneficial efficiency improvement for satellite operations (Coalson, 1996).

NASA and the DOE also funded private electrochemical companies to develop unitized regenerative fuel cell stack hardware. Proton Energy Systems was one such company. Proton worked with LLNL on testing their URFC stacks, first matching the 46 cm² format before doubling the area to 92 cm² (see Figure 3). These units operated at a pressure of 400 psi,

allowing for higher system energy density by minimizing reactant storage volume without the need for mechanical pumping. A DOE report generated from a Unitized Regenerative Fuel Cell Workshop in 2011 showed that Proton continued to develop both discrete and unitized RFC technology for much of the previous decade (Remick & Wheeler, 2011). Proton developed a URFC stack under the product line UNIGEN to satisfy multiple applications that require long endurance, high energy density power systems. Those applications include a zero-gravity URFC concept under the DARPA Water Rocket program that would work much like the IMPRESS concept from LLNL, a terrestrial URFC serving as a backup UPS, and energy storage devices for the electrical grid. The UNIGEN technology demonstrated over 1,000 cycles with 37% round trip efficiency in 2003 (Remick & Wheeler, 2011) but has not found a use in commercial applications (Wang Y. , A review on unitized regenerative fuel cell technologies, Part-A: Unitized regenerative proton exchange membrane fuel cells, 2016).

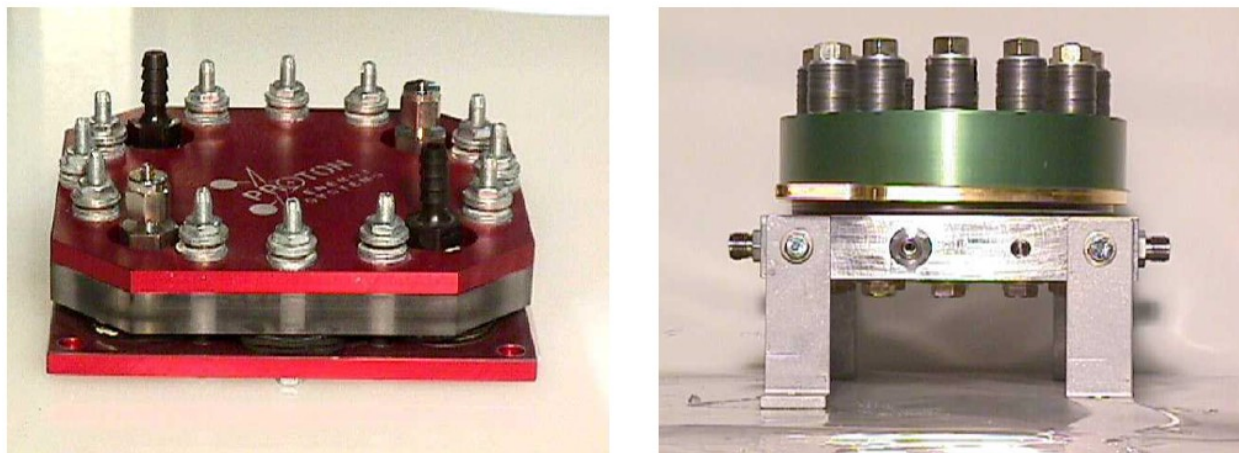


Figure 3. URFC single cell hardware, Proton Energy Systems, a) 46 cm² and b) 92 cm²

Multiple organizations have filed patents on LTPEM URFC technology (see Figure 4). Hydrogenics Corp. filed a patent for a URFC with a bifunctional humidifier in 2004 (USA Patent No. 6,833,207 B2, 2004). The design is unitized in the sense that the physical stack is only one piece of hardware but includes individual fuel cell and electrolyzer sections sharing a single interface plate. The patent claims include the ability to perform rapid transitions between fuel cell and electrolyzer modes, to provide instantaneous full-power operation, and to reduce system components. Despite these benefits, the system would not provide the mass and volume savings of fully unitized RFC stack designs in lightweight applications. Giner Inc. has filed patents on unitized RFC technology, focusing on methods to improve water separation in the unitized stack through what is called a Water Management Membrane (WaMM) (USA Patent No. 9,595,727 B2, 2017). The WaMM provides a means of transporting water to the cell during electrolysis and

removing water during fuel cell power generation by maintaining water in the vapor phase. This method also allows for rapid transitions between modes. The concepts developed by Hydrogenics and Giner appear to be technically successful but have not been developed into commercial products available for integration into mobile power applications.

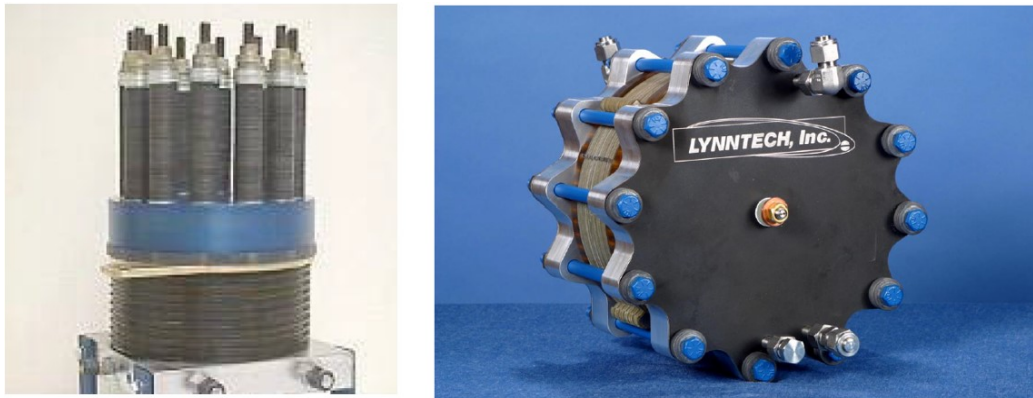


Figure 4. Unitized regenerative fuel cell stack hardware, LTPEM, manufactured by a) Proton Energy Systems and b) Lynntech, Inc. (Burke, Unitized Regenerative Fuel Cell Development, 2003)

NASA had been scheduled to demonstrate LTPEM RFC hardware in a solar-powered, high-altitude aircraft for a long endurance flight under the Environmental Research Aircraft and Sensor Technology (ERAST) project in 2003. After a gate review in late 2001, the unitized RFC hardware was abandoned in favor of a primary fuel cell only version. The URFC under development had not been “working reliably” and it would not be ready for the demonstration with the schedule and budgetary restraints of the program (Noll, et al., 2004). NASA continued developing RFC technology after the conclusion of the program but focused on discrete system designs instead. A closed loop RFC using Lynntech fuel cell and electrolyzer hardware was built and demonstrated for the first time at NASA Glenn Research Center in 2003 (Bents, 2007). Testing continued into 2005, demonstrating operation at the full power rating of 15 kW electrolysis / 5 kW fuel cell, five continuous charge-discharge cycles, and fully automated controls.

Studies on using URFCs for long duration power systems by NASA and other organizations continued after the ERAST program ended. A NASA study in 2006 on HALE for science and communication applications showed that solar-RFC hybrid propulsion systems are only attractive in applications with longer (multiple week) cycle times (Nickol, Guynn, Kohout, & Ozoroski, 2006). Only discrete RFC systems were analyzed because URFC technology was

considered not mature enough to be included as a viable option on the projected application development timeline.

Boeing and Ishikawajima-Karima Heavy Industries (IHI) completed a demonstration on a regenerative fuel cell system onboard a Boeing aircraft in 2012 under the Boeing ecoDemonstrator program (Okaya, Arastu, & Breit, Regenerative Fuel Cell (RFC) for High Power Space System Applications, 2013) (Carlo, 2014), see Figure 5. The RFC was designed to be an auxiliary power unit (APU) for the aircraft and has a discrete RFC configuration rather than a unitized stack. Calculations of the performance of the RFC system showed that it was capable of 300 Wh/kg for a 15 to 30 kW system. To our knowledge, an RFC, unitized or discrete, has not been integrated into an aerial application beyond this demonstration.



Figure 5. RFC Hardware installed in cargo bay of 737, Boeing/IHI, ecoDemonstrator program (Carlo, 2014)

2.2.1.2 Cell design and material research

Many research organizations have attempted to address the performance issues related to unitized RFC stack materials and designs. New oxygen electrode materials have been reviewed due to the accelerated degradation observed in this area during extended operation and cyclic mode switching. Degradation in URFCs appears to be driven by the oxygen reactions, especially in electrolysis mode, making the choice of designs and materials in this region critical to a

successful LTPM URFC (Sadhasivam, et al., 2017). Catalyst materials must be bifunctional, meaning that they remain active in both fuel cell and electrolysis operation. The carbon-based materials typically used for catalyst supports, diffusion layers, and bipolar plates in fuel cell mode must be replaced because they are not stable during electrolysis. Various passive water management structures and materials have been incorporated into the cell to simplify water delivery to and removal from the cell without the need for extensive external equipment.

2.2.1.2.1 Catalysts

URFC electrode configuration can take two different approaches to reversibility. The most common approach is to dedicate each electrode to an individual reactant species, hydrogen or oxygen. This simplifies gas management when switching between operational modes, but places significant stress on electrode materials by forcing them to operate across a wide voltage range. The second approach is to dedicate each electrode to either reduction reactions or oxidation reactions independent of operating mode. This has the potential to maximize efficiency of the reactions in a unitized cell, but complicates gas management and the mode transition process.

Many institutions have researched bifunctional catalysts for URFCs. A typical approach includes combining catalyst materials that perform well in fuel cell reactions with other catalyst materials that perform well in the electrolysis reaction on the same electrode. Combinations of platinum, ruthenium, iridium, and their oxides are most commonly used (Sadhasivam, et al., 2017) (Wang Y. , A review on unitized regenerative fuel cell technologies, Part-A: Unitized regenerative proton exchange membrane fuel cells, 2016) (Wang, et al., 2018). Methods of combining the catalyst include homogenous mixing, layering, or segmented catalyst sections in a single layer. Platinum-iridium mixtures have been identified as an efficient catalyst on both a dedicated oxygen electrode and as a dedicated oxidation electrode. A collaboration between the University of Paris and Kurchatov Institute demonstrated a two-cell, 250 cm² URFC stack with a layered Pt-Ir catalyst as the oxidation catalyst. Performance was stable although inferior to dedicated PEM fuel cell and electrolyzer units (Ranjbari, Millet, Grigoriev, & Fateev, 2010). A research group at Santa Clara University used a layered approach of Pt-black and IrRu oxide in the oxygen electrode of their URFC single cell design (Lele, 2016).

2.2.1.2.2 Diffusion layers and plates

Titanium has become the material of choice for components in contact with the oxygen side due to the high corrosion resistance of the material. Contact resistance issues may arise with titanium due to the propensity of the material to form a passive oxide layer on the surface. Modifying the form of the titanium or coating the titanium with a conductive layer helps to mitigate the contact resistance problem. The Energy Research Center of the Netherlands examined porous titanium

gas diffusion layers and supports for the oxygen electrode in 2004 (Grootjes & Makkus, 2004). Incorporated with a platinum-iridium oxygen catalyst, they were able to demonstrate stable operation in a small, single cell test over tens of hours. Sintered titanium electrodes and titanium flow field plates electroplated with gold were used in the URFC cell from Santa Clara (Lele, 2016). Researchers at the University of South Carolina demonstrated that titanium bipolar plates with electrochemically deposited platinum greatly reduced corrosion when compared to a carbon-based plate, while maintaining sufficient electrical conductivity (Jung H.-Y. , 2009).

2.2.1.2.3 Water management

Passive water management schemes for URFCs are necessary to maintain a low mass system that can handle both operating modes. They have often employed wicking structures and materials, much like the WaMM developed by Giner. A unitized cell design known as Passive Unitized Regenerative Fuel Cell developed at Santa Clara University employs a two-stage porous polymer wicking element to remove water during fuel cell mode and supply water during electrolysis through capillary action (Lele, 2016). The first attempt at demonstrating the concept with a 5 cm² single cell prototype was built, but the performance struggled at higher current densities. The rate of water generated or consumed in the original design outpaced the maximum transport rate of the capillary forces in the wicking structure. A second design attempted to shorten the capillary transport length by removing or supplying water at the center of the cell but was not successful during experimental testing.

The Royal Melbourne Institute of Technology (RMIT) explored URFCs paired with solar power for remote area power supplies (Doddathimmaiah & Andrews, 2006) as a way to reduce costs. Using URFC LTPM MEAs supplied by Lynntech, RMIT built a 10 cm² single cell test unit with an integrated reservoir to manage water delivery to and from the cell for each operational mode. The unitized cell performance matched that of a standalone electrolyzer but was much less efficient than a standalone fuel cell stack.

Others have tried to handle water management issues through novel control schemes and mode transition sequences. Switching from electrolysis to fuel cell mode is particularly difficult because the electrodes can become flooded with water, preventing the reactions from occurring and causing a failure to start power production (Liu, Guo, Yuan, & Ye, 2018). Two-phase flow consisting of liquid water and oxygen gas occurs during this transition, where the drag force of the oxygen flowing into the unitized stack must clear the water droplets from the surface of the oxygen electrode. A delay time before drawing power must be incorporated into the mode transition so that the water can be cleared. Other beneficial mitigation techniques for the

transition include temporarily increasing the cell temperature to evaporate water or limiting the power of the stack until enough water is cleared (Liu, Guo, Yuan, & Ye, 2018).

2.2.1.2.4 Multi-cell stacks

Some research organizations have been able to advance their URFC concepts to the level of larger area, multi-cell stacks. A group at the South China University of Technology built a microscale URFC system complete with hydrogen gas storage and balance of plant components centered around a 6-cell, 28.5 cm² LTPEM URFC stack (Su, Liao, & Xu, 2009). The system went through 10 cycles of operation without degradation but was only capable of a low current density due to hydrogen storage limitations. Takasago Thermal Engineering built and demonstrated a 100W LTPEM URFC stack with 17 cells for the Japanese Aerospace Exploration Agency (Sone, 2011). The Japanese National Institute of Advanced Industrial Science and Technology tested a 10-cell version of this stack from Takasago in a pilot application for combined heat and power known as the Totalized Hydrogen Energy Utilization System. Their testing and analysis showed that heat recovery could increase the round trip efficiency of the system above 60% (Ito, Miyazaki, & Nakano, 2016) (Bhogilla, Ito, Kato, & Nakano, 2016). The University of Paris/Kurchatov Institute collaboration built a 7-cell, 256 cm² LTPEM URFC stack using dedicated reduction/oxidation electrodes capable of 500W in fuel cell mode with a 30% round trip efficiency in short term testing (Grigoriev, Millet, Porembsky, & Fateev, 2011). To date, no organization or institution has demonstrated a LTPEM URFC system that can deliver power above 1 kW.

2.2.2 Solid oxide RFCs (RSOFCs)

SOFC technology has generated interest for use in mobile applications in recent years. SOFC technology can trace its origins to 1897 when Nernst developed the Nernst lamp, an incandescent lamp that used a yttria-stabilized zirconia (YSZ) filament (Mobius, 1997). The material is a natural choice for a fuel cell electrolyte material because it is a mixed oxide solid solution that allows for oxide ion conduction at elevated temperatures (500-1000°C). Research into solid electrolyte cells proceeded slowly for the first half of the 20th century, with the first use of zirconia-based ceramics in tubular fuel cells in 1937 and in planar cells in the 1950s. Companies such as General Electric and Westinghouse began collecting patents and developing SOFCs for potential power generation applications.

Recent development of SOFC technology in the industry has focused on new and improved electrolytes and electrode materials to reduce cost, simplify manufacturing, and increase durability and lifetime. SOFC manufacturing and supply chains are not as advanced as PEM but continue to develop to the point where the technology is reaching the marketplace in a handful of

applications. SOFCs have begun to enter the market as stationary power systems in the kW to MW range and as kW-scale auxiliary power units for vehicles in both commercial and military applications.

2.2.2.1 SOEC and RSOFC Research

Interest in using solid oxide electrochemical technology as a reversible fuel cell system originated from research into solid oxide electrolysis cells (SOEC). High temperature electrolysis processes were viewed as a potential way to increase the efficiency of hydrogen production processes beyond the efficiency found in alkaline technology that was, and largely remains, the industry standard (Gomez & Hotza, 2016). Researchers at Dornier, a German aircraft company, engaged in development of high temperature solid oxide electrochemical cells as early as the 1970s. In 1987, they began researching their technology for use in fuel cells as well.

Experimental testing of both modes on a 10-cell tubular stack operating at 1000°C revealed that zirconia-based solid oxide electrochemical cells “can be reversibly changed from the electrolysis mode to the fuel cell mode and vice versa without any discontinuity,” (Erdle, Donitz, Schamm, & Koch, 1992). They immediately recognized the importance of this observation, noting that “this technology offers the potential of establishing a regenerative fuel cell system for electrical energy storage applications, where the fuel cell and the electrolysis function are combined in only one unit,” (Erdle, Donitz, Schamm, & Koch, 1992). Kansai Electric Power Company and Mitsubishi developed and tested a 750 cm² planar version of the technology at around the same time to be paired with a nuclear power plant as an energy storage device (Wang Y. , A review on unitized regenerative fuel cell technologies, part B: unitized regenerative alkaline fuel cell, solid oxide fuel cell, and microfluidic fuel cell, 2016) (Shimaki, et al., 1992) (Kusunoki, et al., 1995).

Much like LTPEM technologies, the challenge in creating a reversible fuel cell technology that can handle a wide operating voltage range over multiple mode cycles is in selecting the right combination of materials in the electrodes and electrolyte. RSOFCs have had difficulty finding their way into applications despite a superior round trip efficiency because the electrolyte and electrode materials chosen have shown poor long-term stability and cycle life (Wang Y. , A review on unitized regenerative fuel cell technologies, part B: unitized regenerative alkaline fuel cell, solid oxide fuel cell, and microfluidic fuel cell, 2016) (Gomez & Hotza, 2016). YSZ remains the most popular electrolyte for RSOFC research, but other oxide ion conducting electrolytes such as scandium oxide stabilized zirconium (ScSZ), Lanthanum Strontium Gallium Magnesium Oxide (LSGM), samaria-doped ceria (SDC), and gadolinium-doped ceria (GDC) have also been employed. A blend of nickel and the electrolyte material is commonly used on the hydrogen electrode, but is particularly susceptible to oxidation during electrolysis mode, resulting in a reduction in activity and delamination from the electrolyte. Lanthanum strontium

manganite (LSM) is commonly used for the oxygen electrode but has similar degradation issues to the hydrogen electrode in electrolysis mode. Cycling between operating modes and operating at high current densities ($> 500 \text{ mA/cm}^2$) appear to accelerate degradation problems in these materials.

2.2.2.1.1 Materials Research

Pacific Northwest National Laboratory and the National Energy Technology Laboratory explored various combinations of electrode materials with a YSZ electrolyte to form an RSOFC (Marina, et al., 2007). Nickel/zirconia cermet (Ni/YSZ) and LSM/ceria composites were used as hydrogen electrodes. Lanthanum strontium ferrite (LSF), lanthanum strontium copper ferrite (LSCuF), lanthanum strontium cobalt ferrite (LSCoF), and LSM were used as oxygen electrodes. Single cell tests were performed on a 33.6 cm^2 cell to observe electrochemical behavior in both fuel cell and electrolysis modes. Ni/YSZ and LSCoF were found to be the optimal material combination, but still showed high resistance during electrolysis at 750°C .

Researchers at the European Institute for Energy Research (EIFER) performed high temperature solid oxide water electrolysis studies by operating an SOFC in reverse with Ni/YSZ and LSM electrodes and YSZ electrolyte (Brisse, Schefold, & Zahid, 2008). 45 cm^2 single cell testing at 800 and 900°C proceeded with fuel cell operation for four days, followed by electrolysis experiments totaling 160 hours of operation, without any signs of degradation. The unit was not continuously cycled between modes as it would be in an RFC application, which could significantly accelerate degradation mechanisms.

The University of Science and Technology of China took the approach of changing the electrolyte from YSZ to $\text{BaCe}_{0.5}\text{Zr}_{0.3}\text{Y}_{0.2}\text{O}_{3-\delta}$, a proton-conducting material (He, Song, Peng, Meng, & Yang, 2010). Using a proton-conducting electrolyte provides the advantages of producing pure hydrogen without the need for separation and lowering the activation energy at moderate temperatures for ionic conduction in solid oxide technologies ($600\text{-}700^\circ\text{C}$). Single cells with less than 1 cm^2 active area were fabricated and tested reversibly in SOFC and SOEC mode, showing variations in performance with steam concentration in SOEC. SOFC performance of this cell appeared inferior to LTPM fuel cell technologies. No cycle life testing was completed.

A group at Yuan Ze University in Taiwan developed an RSOFC with a NiO/YSZ, YSZ, LSM/YSZ configuration (Jung, et al., 2016). Single cell testing was performed on a 5 cm^2 cell. Addition of YSZ into the LSM oxygen electrode increased SOEC performance but decreased SOFC performance. Cyclic durability testing showed that the performance in fuel cell mode degraded 10% in 10 cycles corresponding to an increase in ohmic resistance of the cell arising from delamination of the electrode and electrolyte layers.

Researchers at Kyushu University in Japan experimented with an RSOFC stack configuration consisting of an LSGM electrolyte, an LSF cathode, and a $\text{Ba}_{0.6}\text{La}_{0.4}\text{CoO}_3$ (BLC) anode (Ishihara, 2017). Testing was performed in both electrolysis-only mode and in cyclic operation between electrolysis and fuel cell modes. The LSF material showed no signs of degradation in electrochemical characteristics or physical appearance after 40 cycles. The material did show promise as a reversible fuel cell material but is noted to be not as conductive as materials used in dedicated fuel cells or electrolyzers.

A complete summary of materials combinations attempted in RSOFC research can be found in comprehensive review articles on RSOFC cell development provided in the references (Wang Y., A review on unitized regenerative fuel cell technologies, part B: unitized regenerative alkaline fuel cell, solid oxide fuel cell, and microfluidic fuel cell, 2016) (Gomez & Hotza, 2016).

2.2.2.1.2 Symmetric Cell Designs

A consortium of Spanish researchers and St Andrews in the UK developed a “symmetrical” Solid Oxide Fuel Cell (SSOFC) concept where the same electrode material is used on both the anode and cathode, as well as the electrical interconnects (Ruiz-Morales, Marrero-Lopez, Canales-Vasquez, & Irvine, 2011). This approach would greatly simplify the manufacturing process for an SOFC/SOEC cell by allowing for a single thermal treatment step. Both SOFC and SOEC studies were performed, making them a candidate for an RSOFC. $\text{Sr}_2\text{Fe}_{1.5}\text{Mo}_{0.5}\text{O}_{6-\delta}$ was identified as the best candidate for a symmetric RSOFC, but no manufacturing or experimental work was completed with the material.

NASA developed a symmetric RSOFC design concept that used YSZ electrolyte with Ni-YSZ electrode and replaced the metallic interconnects with a thin LaCaCrO_3 (LCC) layer (Cable, Setlock, Farmer, & Eckel, 2009). System design analysis of this stack in a UAV HALE application showed that the interconnect material replacement could reduce the stack mass by 40%, achieving a power density far superior to PEM or internal combustion-based power systems for the application. A novel manufacturing technique known as freeze-casting was used to create Ni-YSZ electrodes with built-in micro-channels to boost performance in electrolysis mode by enhancing gas diffusion through the cell. Degradation testing showed mixed results, with stable performance in electrolysis mode but accelerated degradation of 20-30% per 1000 hours when cycling between operational modes.

2.2.2.2 Multi-cell RSOFC Stacks

Some multi-cell RSOFC stacks have been built and tested but have often been plagued by degradation problems. General Electric was able to build and test 3-cell and 10-cell, 200 cm^2 stacks (as shown in Figure 6a) with Ni/YSZ hydrogen electrodes, YSZ electrolytes, and

lanthanum strontium cobalt ferrite (LSCF) oxygen electrodes that performed water electrolysis and methane reforming in fuel cell mode (Minh, 2011). The 3rd cell in the 3-cell stacks showed rapid degradation by resistance increases associated with the increase in contact electrode/interconnect resistance from chromium and strontium migration. The 10-cell stack produced over 6 SLM of H₂ in electrolysis mode with 1110 W of DC power at 800°C using a 70% H₂O / 30% H₂ feed. The 10-cell stack was able to operate for over 1000 hours with two total cycles and 100-400 hours per operating mode but showed accelerated degradation during electrolysis.

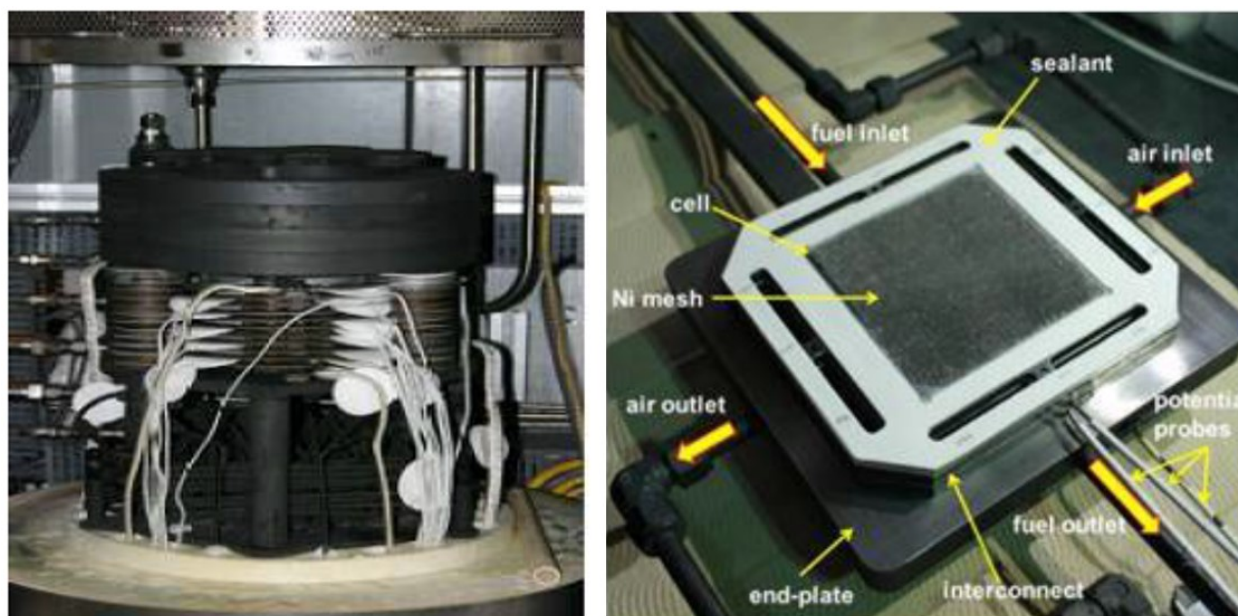


Figure 6. RSOFC multi-cell stack hardware by a) General Electric, 10-cell, 200 cm² and b) Korea Institute of Science and Technology, 3-cell, 100 cm², 200W

The Julich Institute of Energy and Climate Research developed an RSOFC based on a Ni/YSZ, YSZ, and LSCF configuration (Nguyen, Fang, Packbier, & Blum, 2013). They built a 2-cell, 80 cm² stack and completed 4000 hours of fuel cell testing along with over 4000 hours of steam electrolysis and co-electrolysis of steam and CO₂ at various conditions. Minimal degradation was observed in both fuel cell and steam electrolysis modes, with higher degradation during co-electrolysis and at higher current densities. The results show that the Julich cell design is promising for an RSOFC, although testing did not feature any cycling between fuel cell and electrolysis operational modes.

The Korea Institute of Science and Technology developed and built a 3-cell, 100 cm² RSOFC capable of up to 200W (see Figure 6b) (Hong, et al., 2014). The stack employed an ScSZ

electrolyte with Ni-YSZ and LSC-GDC electrodes. Stable operation in electrolysis mode was achieved for over 1000 hours, with less than 8% degradation achieved. Operational mode switching was found to greatly accelerate degradation resulting from delamination of the electrode and electrolyte layers.

2.2.2.3 System Analysis

Little analysis has been done on integrating RSOFCs into real-life applications. The Colorado School of Mines has investigated using a RSOFC for distributed energy storage applications in the range of 100 to 800 kW (Wendel & Braun, 2016). The RSOFC was considered able to handle a wide range of fuels, including methane, hydrogen, and carbon monoxide, and electrolysis feeds, including water and carbon dioxide. The analysis considered thermal aspects, configurations with other power system equipment, and operating conditions to maximize the overall efficiency of the system and built upon previous steady state, 1D RSOFC models based on a LSGM electrolyte, nickel with strontium lanthanum titanium oxide fuel electrode, and LSCF-GDC oxygen electrode configuration. The author of the study notes that the area-specific resistance of this cell at 600C is notably higher than standard LSGM or YSZ-based cells at their optimal temperatures. Despite that, an optimized system in this range can achieve a round trip efficiency of 65 to 75%. RSOFCs were found to outperform LTPEM URFCs for these applications if water could be kept in the vapor phase and the cycle time was over 8 hours.

The German Aerospace Center (DLR) developed a theoretical system model of an RSOFC for energy storage applications (Sanatham, Heddrich, Riedel, & Friedrich, 2017). The energy system employed thermal energy storage to help maximize overall system efficiency when switching between fuel cell and electrolysis modes. A “commercially available” 10-cell, 300W RSOFC stack was tested as part of this work to provide experimental data in both fuel cell and electrolysis mode for comparison with the analysis. The stack could operate at up to 115 psi with an open-air electrode and consisted of a LSCF-GDC/YSZ/Ni-GDC electrode/electrolyte configuration. Analysis and experiments showed that a roundtrip efficiency of 55% was possible with this stack, better than what has been achieved with LTPEM.

Both system analyses described above were for larger-scale stationary applications. Solid oxide technologies do have some characteristics that make mobile applications difficult, such as high temperature operation, relative fragility to forces and vibrations, and long startup times.

2.2.3 High temperature PEM RFC

HTPEM fuel cells have been under research and development as an alternative fuel cell technology with potential operational benefits for specific applications. HTPEM technology uses

alternate membrane materials that can conduct protons at temperatures in the range of 150-200°C, above the 100°C limit of Nafion found in LTPEM technology. The higher operational temperature enables HTPEM technology to use dirtier fuels without significant performance penalties, eliminates liquid water reactant/product management issues, and provides potential efficiency improvements in an RFC from the thermal effects. The most common and mature HTPEM membrane material is polybenzimidazole (PBI), a fibrous material first manufactured in the 1960s and used by NASA and the Air Force for thermal protection applications. Doping PBI with phosphoric acid gives the material proton conductivity, an idea that was first introduced by researchers at Case Western Reserve University in the 1990s (Wainright, Wang, Weng, Savinell, & Litt, 1995). PBI and other proton-conducting membranes have been a subject of research and development for the past twenty years to the point of manufacturing kW-scale stacks. However, HTPEM technology has not found much use in actual power system applications to date.

HTPEM electrolysis has been explored by researchers, but to a lesser extent than power production. Investigation has been limited to theoretical system studies and catalyst research (Goni-Urtiaga, Presvytes, & Scott, 2012) (Xu, Ma, Li, Zhao, & Zhongxue, 2012) (Nikiforov, et al., 2012). This means that a unitized PEMFC stack based on this or similar technology in the intermediate temperature range (100-300°C) has not been explored. HTPEM systems have been considered as the fuel cell portion of a discrete RFC system. CMR Prototech and the European Space Agency (ESA) have developed a concept for a discrete RFC with a HTPEM fuel cell and LTPEM electrolyzer to replace batteries for long-term operation of geostationary orbit telecommunication satellites (Farnes, et al., 2017). Although progress was made on hardware for each operational mode, the system has not been integrated and operated as a single unit.

2.3 Aircraft application and technology selection

2.3.1 Aircraft applications

We studied the advantages of developing a URFC system as either an electric propulsion device for an all-electric aircraft or hybrid auxiliary power unit (APU) for use in a Boeing 787 passenger aircraft. This URFC system will be designed with enough reactant storage to support one, two, or five hours of operation in fuel cell mode. The advantage of the URFC in this scenario is that energy storage and power generation are independent of each other, thus the same 125 kW power source can be used in a 125 kWh, 250 kWh, and 625 kWh energy storage system. The URFC in the Boeing 787 is expected to be hybridized with the present generator that composed the current APU. The APU in the Boeing 787 is used to provide ground power and serves as backup power in flight. The URFC component of the auxiliary power unit would

produce 125 kW of power and thus it could be used as a building block for other more-electric aircraft applications like electric propulsion. For the APU, the proposed system would consist of two URFCs systems working with one half of the current Boeing 787 APU. It is envisioned that the hybrid APU for the Boeing 787 would require 125 kWh of storage whereas a more-electric aircraft requiring electric propulsion would utilize the 625 kWh of storage. For the Boeing 787 application, the aircraft may operate on a single URFC to provide ground power and thus maximize aircraft fuel efficiency.

2.3.2 Selected technology and rationale

In reviewing the technology available, we have proposed one based on HTPEM technology for the development of a URFC system. An issue that is common to all URFC systems is supporting two electrochemical reactions on the same surface. In charge mode, a fuel cell cathode, which would traditionally electrochemically reduce oxygen to water, would also need to oxidize water to oxygen. Although catalysts for a reversible electrode as described exist, the electrode structure to support the reaction would require development to ensure consistent and durable performance. In a LTPEM fuel cell, liquid water is a byproduct of the fuel cell reaction. Thus, the electrode structure of the cathode in a LTPEM fuel cell would be required to remove the fuel cell product water during a discharge event and accept water during a charge event. The cathode electrode structure in a traditional LTPEM fuel cell is designed to expel water. This electrode structure would not readily accept water during a charge event. The water byproduct in a HTPEM fuel cell is in a gas phase. This allows for a simpler electrode structure when considering the requirement for a reversible electrode. This approach would be similar to SOFC-based URFC systems. One advantage of a HTPEM-based versus a SOFC-based URFC is that the HTPEM allows for multiple stop-start cycles without damage to the stack hardware. The HTPEM-based URFC also allows for pressurization, allowing for more compact reactant storage when taking the entire URFC fuel cell system into consideration.

3 System design

3.1 Scope statement

Teledyne has proposed an energy storage system design using a unitized regenerative PEM fuel cell stack to support an aircraft application. A system piping and instrumentation diagram (P&ID), list of components, and list of operational parameters have been composed to define the system that has been studied and modeled in the simulations described in Section 4. The system

defined in the following section reflects what was within the scope of the energy storage system and what was excluded from the analysis.

3.1.1 Within scope

Teledyne has developed a system design that encompasses components relevant to simulating the unitized RFC system in aircraft applications. Only items that are critical to evaluating the operation of the system for performance purposes are included. The list of components and supporting information includes the following:

- Unitized fuel cell stack
- Reactant storage tanks
- Thermal control system
- Valves/devices for pressure/flow control
- Control logic
- CONOPS for system startup/shutdown

The system piping and interface diagram is shown in Appendix A and the bill of materials is listed in Appendix B.

3.1.2 Outside of scope

Items that are not necessary for evaluating the performance of the system are eliminated from consideration in this study. This will enable a proper assessment of the merits of the system prior to investing resources into developing a fully mature system design. The list of components to be excluded is as follows:

- Power conditioning equipment
- Items for physical mounting (brackets, fasteners, structural members)
- Wiring
- Controller design
- Ground support equipment and infrastructure
- Connections to existing aircraft equipment

3.2 System components and features

This section defines the major system components shown in Appendix A and Appendix B along with the assumptions behind the design decisions and a general description of how each component operates. The unitized fuel cell system developed under this program employs creative ideas that make it a unique concept for a regenerative fuel cell system. Passive controls were employed as much as possible to maximize the reliability and simplify operation. The system also represents the most volumetrically dense regenerative fuel cell system of its type by

incorporating a unitized stack design within a reactant storage vessel. The combination of these attributes makes the system an attractive option for aerial applications.

3.2.1 Unitized fuel cell stack

The regenerative fuel cell stack (RFC1) produces power in fuel cell mode and generates hydrogen and oxygen reactants in electrolysis mode. While operating in fuel cell mode the stack receives a supply of hydrogen and oxygen, converts them into power, water, and heat. When running in electrolysis mode, the stack receives a supply of water and electrical power, produces hydrogen and oxygen, and generates heat as a byproduct.

HTPEM technology was chosen for the aircraft electric propulsion application. For the duration of each operational cycle, the system will maintain a high operating temperature of 160°C to 180°C. Operating at such temperatures ensures the product water remains in gaseous phase while avoiding the large thermal energy input required for fuel cell technologies that operate at much higher temperatures (> 600°C). An external thermal control system will control the operating temperature with a liquid coolant loop and ambient air supply.

The fuel cell membrane electrode assembly (MEA) design will consist of a commercially available PBI-membrane, for which performance data is publicly available. The stack will be sized to meet the full power condition of 125 kW. Using the best available performance data from MEAs of this design (Advent High Temperature Membrane Electrode Assemblies, 2019), the fuel cell stack will consist of 400 cells with 844 cm² of active area for each cell. The stack will produce 125 kW at 233.1 VDC and 541 A and encompass a physical envelope of 30.5 cm by 106.7 cm by 223.5 cm (726.8 L).

The unitized stack will consist of an open cathode design, which are typically employed in air-breathing fuel cells as a method of eliminating oxidant gas storage and simplifying flow control. The fuel cell stack will be horizontally mounted within the oxygen tank to take advantage of these beneficial attributes for aircraft applications. Excess water vapor allowed to cool below 100°C will condense on the walls of the tank and collect in the clearance space below the mounted fuel cell stack.

3.2.2 Reactant storage tanks

The reactant storage tanks contain pressurized hydrogen and oxygen gas that is consumed by the unitized stack in fuel cell mode and refilled with reactants during electrolysis mode. The reactant tanks were sized with a 20% margin to account for worst-case energy use and unforeseen circumstances during flight missions. The hydrogen tanks were sized for the individual missions

to allow consideration of weight and volume in optimizing the system design while the oxygen tank volume is fixed to account for internal housing of the fuel cell system. The tanks will be manufactured with carbon fiber in a composite overwrapped pressure vessel (COPV) design of type III to minimize their weight. Type III COPVs employ a metal liner, usually aluminum, around which the fibers are wrapped. This approach is quite common for lightweight pressure vessel designs used for man-portable and fuel cell vehicle applications.

The hydrogen tanks were designed to employ high-pressure hydrogen storage of a maximum value of 20,684 kPa (3000 psi) to minimize the required volume per unit mass. For a one-hour flight in the electric propulsion application, the hydrogen tank will have a volume of 790 L and hold 7.76 kg of hydrogen. During a two-hour flight mission, the tank will have a volume of 1460 L and hold 14.3 kg of hydrogen. A five-hour flight mission requires 34.5 kg of hydrogen stored in a tank with a volume of 3510 L. Tank mass was determined by using an industry derived metric of 0.75 lbs./L (Legault, 2012).

The hydrogen holding tank V3 was implemented to help balance the stack pressure during electrolysis mode to account for varying reactant production rates within the stack. The tank will hold hydrogen until the pressure differential between the hydrogen and oxygen volumes builds to +15 psi (103 kPa). A compressor will transfer the reactant to the main hydrogen storage tank V1. As hydrogen builds at a steady rate of 1154 SLM, a small volume of gas will be held in V3 while the pressure builds. The tank was sized to a volume of 400 L of gas capable of containing the maximum storage pressure achievable in the main hydrogen storage tank.

The oxygen tank is required to store the fuel cell stack that encompasses a physical envelope of 0.30 m by 1.07 m by 2.24 m. The tank was sized to be 2.44 m long with a diameter of 1.27 m for a total volume of 3089 L and net internal volume of 2692 L that is not filled by the fuel cell stack. In addition to the internally mounted stack, the oxygen tank houses a heating element to evaporate product water during fuel cell mode and excess supply water during electrolysis mode. The oxygen tank dimensions account for the recirculation fan required to maintain proper reactant flow and water vapor supply during both operational modes. The oxygen tank will have a maximum volume of 2700 L capable of holding 362 kg of oxygen at a maximum storage pressure of 15,168 kPa (2200 psi) when filled completely. The tank will only store the required amount of reactant needed to complete specific flight durations. During a one-hour flight mission, the tank will hold 61 kg of oxygen at a maximum pressure of 2,758 kPa (400 psi). For a two-hour flight mission, the tank will hold 114 kg of oxygen at a maximum pressure of 5,000 kPa (725 psi). A five-hour flight mission requires 274 kg of oxygen at a maximum pressure of 11,721 kPa (1700 psi).

Both tanks will include pressure and temperature monitoring (PT1, PT3, T1, T2) to ensure that they are in safe operating regimes for the duration of operation. The hydrogen tank will include isolation valves, a manual valve/check valve assembly for external pressurization, and a relief valve in case of over pressurization. The oxygen tank will include a water fill and drain port as well as liquid level monitoring to ensure that the tank does not become flooded with water.

3.2.3 Thermal control system

The thermal control system will be sized to heat the fuel cell prior to start-up and to reject heat for the duration of flight missions. The system will contain a 170 L carbon fiber water tank (V4) with a 9-kW heating element (HT1) to achieve initial temperature requirements. A multistage centrifugal pump (P3) will be set to a constant flowrate to circulate the coolant stream during fuel cell and electrolysis modes. For in-flight temperature control, the system will utilize an air-cooled heat exchanger (HX1) to reject heat from the coolant stream. A variable frequency drive (VFD1) will control the speed of the direct drive fan to adjust the air flow rate traveling through the heat exchanger.

The coolant tank will be manufactured to incorporate a flange-style immersion heater (HT1) from the top of the vessel. The dimensions of the tank were sized to fully submerge the 76.2 cm heating element HT1 required to heat the fuel cell system to 160°C prior to operation. The level switch (LS1) will monitor the liquid level and temperature in the tank while serving as an alarm when the tank volume is too high or low for operation. The water pump (P3) has a maximum flow rate of 113.5 LPM and specialized mechanical seals to withstand high operating temperatures. The pump is equipped with a 3-phase, totally enclosed and fan controlled 60 Hz motor that can operate at a maximum of 3550 RPM. There will be a flow switch (FS1) located at the outlet of P3 to monitor the flow and temperature of the coolant stream for pump failure.

An air-cooled heat exchanger (HX1) will rely on the ambient air supply at high altitudes in flight and an external air blower on the ground during electrolysis mode. The exchanger has been sized to 0.23 m x 0.61 m x 0.61 m and contains eighty tubes in a 16 by 5 arrangement with a diameter of 2.5 cm for coolant flow. There will be a 0.61 m x 0.61 m direct drive fan mounted on the larger face of the heat exchanger to force air flow through the tube bundles. The speed of the direct drive fan will be controlled by a 3-phase, 746 W variable frequency drive to control the airflow traveling through the bundles.

The amount of heat generated within the fuel cell stack changes as the system fulfills various power levels through flight missions. At 25% of full power or 31.25 kW, the system generates 33.7 kW of heat. When operating at 50% of power or 62.5 kW, the system generates 74.7 kW of

heat. At 75% of full power or 93.75 kW, the system generates 125.3 kW of heat. When the system is at maximum power of 125 kW, 192.4 kW of heat are generated. While operating at maximum power, the system requires an ambient air flow rate of 82,000 LPM to reject 192.4 kW of heat. As the system completes various flight missions, the ambient air flow rates will range from 21,200 LPM to the maximum of 82,000 LPM as required to reject heat from the system over the duration of a flight mission.

During electrolysis mode, an external air blower is used to supply ambient air to HX1. As the system operates at constant ground power of 125 kW, the ambient air flow rate is constant during the reactant regeneration process. The stack generates 98 kW of heat requiring an ambient air flow rate of 42,000 LPM to maintain 160°C operating temperature. The coolant flow rate is kept the same at 67 LPM.

3.2.4 Valves/devices for pressure/flow control

Several valves and flow control devices are included in the system design to safely manage the transfer of gas between the fuel cell stack and reactant storage tanks. They enable pressures to be evenly balanced between sensitive components and provide safety relief in the event of a failure of one or more components. The reactant flow rates generated by these devices ensure that the fuel cell stack is operating at optimal conditions where hydrogen, oxygen, and water are introduced and removed in sufficient quantity to sustain the processes. The hydrogen flow controls are divided into dedicated fuel cell and electrolyzer reactant flow regimes. The oxygen flow controls are much simpler than the hydrogen flow controls due to the open cathode stack configuration inside of the oxygen reactant storage tank.

While operating in fuel cell mode, SV1 is opened to enable hydrogen reactant flow from the hydrogen tank (V1) to the unitized fuel cell stack (RFC1) while a check valve (CV3) prevents flow through electrolysis-specific components. Hydrogen flows through the forward pressure regulator (FPR1), which maintains the hydrogen pressure in the unitized fuel cell stack within ± 103 kPa (15 psi) of the pressure in the oxygen tank. The hydrogen inlet line penetrates the oxygen vessel and connects to the unitized fuel cell stack, where the hydrogen gas is consumed to produce power. The remaining hydrogen gas that is not consumed exits the stack and is pumped through the open SV2 and another check valve (CV5) by a hydrogen recirculation pump (P2). The recirculation generated by the pump promotes an even distribution of hydrogen gas throughout the fuel cell stack, ensuring power production at higher efficiencies than that produced by a dead-ended stack design without active flow.

In electrolysis mode, SV1 and SV2 are closed to disable the hydrogen recirculation and pressure regulation components used in fuel cell mode. Hydrogen gas generated by the stack travels through the check valve (CV3) and is compressed (P1) to higher pressures for storage in the hydrogen reactant storage tank (V1). The compressor will be intermittently operated to maintain a balanced pressure in the stack as the gasses are generated. The difference in available gas volumes and in production rate from the reaction stoichiometry means that the pressures of each gas will build at different rates. A differential pressure transmitter (DPT2) measures the relative pressure between the hydrogen and oxygen regimes in the stack. When the hydrogen pressure exceeds the oxygen pressure by 103 kPa (15 psi), the compressor is turned on to pump hydrogen into reactant storage (V1) and reduce the hydrogen pressure inside the stack. The compressor is turned off again when the hydrogen pressure trails the oxygen pressure by 103 kPa (15 psi). A buffer tank (V3) is included and sized to moderate the process of turning the compressor on and off.

A recirculation fan (F1) is all that is required to maintain proper reactant flow to the fuel cell or water vapor supply to the electrolyzer inside of the oxygen tank. The fan maintains a constant, steady flow of gas through the open cathode channels of the stack and ensures even mixing of the oxygen gas and water vapor. Maintaining flow will ensure that water vapor expelled from the fuel cell stack during power production will encounter the walls of the oxygen storage tank. The walls of the tank will be at a lower temperature than the stack, promoting condensation that will encourage any liquid water that forms to collect at the bottom of the tank.

Both reactant flow loops contain mechanisms for venting hydrogen or oxygen gas out of the aircraft in the event of an unsafe pressure condition. RV2 and RV3 provide passive pressure relief in the event of a large increase in pressure. SV3 and SV4 are active venting valves that can assist in balancing the pressure due to a high differential in pressure. Pressure monitoring devices PT2, PT3, and DPT2 will enable alarms and trigger system shutdowns or other safety measures in the event of an unsafe pressure condition.

3.2.5 Control logic

The unitized RFC system was designed with the goal of utilizing as many passive controls as possible, which maximizes the reliability of the system while minimizing parasitic power required for normal operation. Four active control systems are required: stack temperature, stack differential pressure, hydrogen recirculation flow, and oxygen tank water level control. These control systems are shown in black in Figure 7 below.

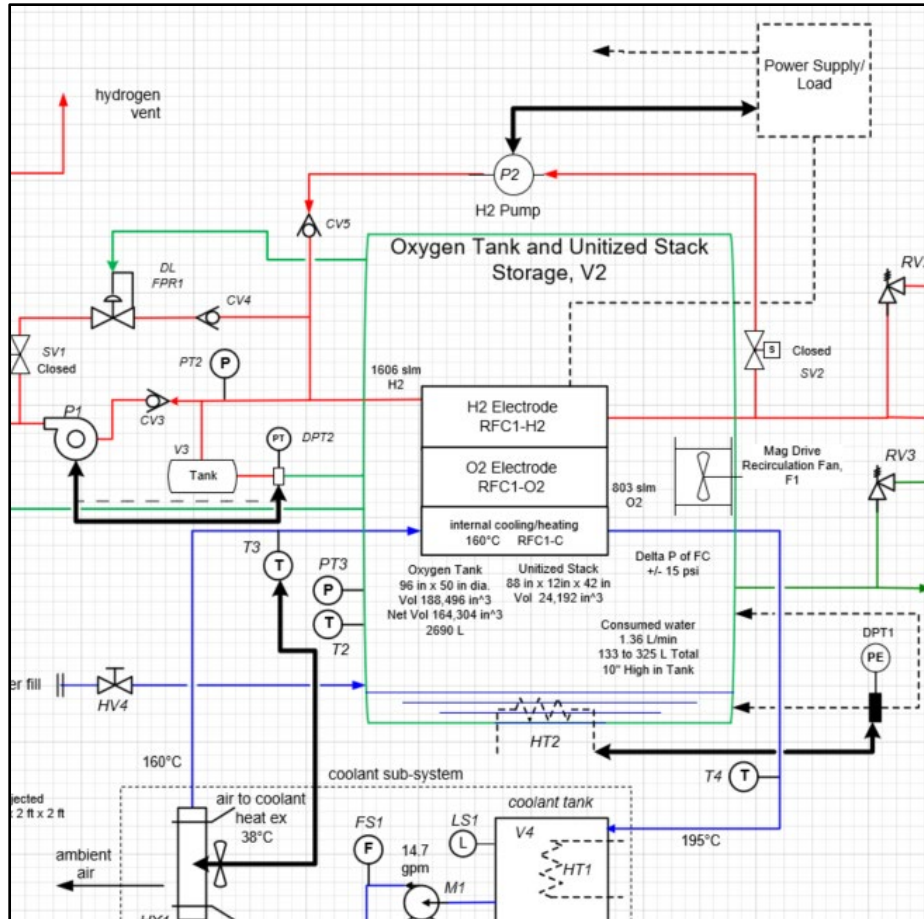


Figure 7. P&ID with control logic: hydrogen flow, temperature, liquid level, and differential pressure

3.2.5.1 Temperature control

The temperature control scheme will be implemented to maintain optimal operating temperatures during fuel cell and electrolysis modes. The amount of heat rejected from the fuel cell system will depend on the stage of the mission profile. As the temperature fluctuates with energy consumption, the ambient air flow will be controlled to maintain operating temperature. The inlet and outlet cooling water temperatures will be measured by TC3 and TC4. The controller will monitor the temperature change and adjust the speed of the fan to a specific airflow rate required to cool the water stream to the temperature setpoint. The same control logic will be used to control the temperature of the system during electrolysis mode.

3.2.5.2 Differential pressure control, electrolysis

As the rate of hydrogen production exceeds that of oxygen, the gasses will build pressure at different rates. The differential pressure between the hydrogen and oxygen vessels will be monitored using a differential pressure transmitter (DPT2). During operation, the hydrogen

pressure in the holding tank (V3) will build to +103 kPa (15 psi). Once the differential pressure reaches that limit, DPT2 will send a signal to start the hydrogen compressor and pump hydrogen gas to the main reactant storage vessel (V1). When the differential pressure begins to approach -103 kPa (15 psi), DPT2 will send a signal to the hydrogen compressor to shut down gradually. If the differential pressure exceeds ± 206 kPa (30 psi), an alarm will trigger a system shut down. The step process will continue as the reactant storage vessels produce enough gas for the next flight mission.

3.2.5.3 Recirculation flow control

The recirculation flow control is designed to provide enough flow of unconsumed hydrogen back into the fuel cell stack for even hydrogen distribution to sustain the reaction. The required rate of recirculation provided by hydrogen recirculation pump (P2) will be proportional to the current produced by the fuel cell stack. The fuel cell controller will increase or decrease the pump speed to a maximum of 1606 SLM at full power based upon the amount of current measured by a current sensor on the power delivery cable. The controls are deactivated for electrolysis mode because the recirculation flow is not required during hydrogen production.

3.2.5.4 Oxygen tank water level control

The water level control is designed to evaporate product water that has condensed from the oxygen exhaust of the unitized fuel cell stack. Water vapor must be present in the stack during electrolysis mode to sustain hydrogen and oxygen generation. Evaporating the product water also provides protection against the liquid level rising too high in the oxygen tank and submerging the unitized stack. A heater (HT2) is submerged in the excess liquid water inside of the oxygen tank. The heater will be activated when electrolysis mode commences and the liquid level in the tank is above 7" as measured by differential pressure transmitter DPT1. The heater will be turned off when the level drops below 5". The heater can also be turned on at any time if the liquid level rises above 15".

3.3 System operation and parameters

3.3.1 Concept of operations

3.3.1.1 Startup procedure

The following is the proposed concept of operations for electric propulsion flight missions ranging from one to five hours. The system will complete a purge cycle with inert gas supplied from ground resources. Once the system has been cleared of possible contaminants, the hydrogen and oxygen tanks will be fully pressurized to their application-specific rated capacity. The oxygen reactant storage tank will contain a small volume (16L or 5% above required) of liquid

water that can be electrolyzed in future cycles to provide extra capacity in the case of venting or losses in the system. The system will start by heating up the unitized fuel cell stack to the 160°C operating temperature by turning on heater HT1 and coolant pump P3. Once the operating temperature has been reached, SV1 will open, allowing FPR1 to introduce more hydrogen into the fuel cell stack when power production begins. SV2 will open and hydrogen pump P2 will turn on to begin recirculating hydrogen through the stack. Once the open circuit voltage of the fuel cell stack is measured and verified, power can be drawn from the fuel cell stack. The startup heater can be turned off, allowing the air to coolant heat exchanger to handle thermal control. This signals the start of the normal mission profile for the electric propulsion application.

3.3.1.2 Operational mode transition

Once the aircraft safely completes the flight mission and powers down at the terminal, the unitized fuel cell can transition to electrolysis mode. The electrical output of the fuel cell system is electrically disconnected from the aircraft. The internal water heater HT2 is turned on to vaporize excess water that has condensed in the oxygen tank. The hydrogen recirculation pump P2 is turned off and SV2 is closed to terminate hydrogen recirculation flow. SV1 is closed to isolate the forward pressure regulator FPR1. The thermal control loop maintains the stack temperature at 160°C by continuing recirculation of coolant and activating HT1. The ground water supply will connect to HV4. The air blower provided from ground resources is connected to the tube bundles on the air-cooled heat exchanger HX1.

3.3.1.3 Reactant regeneration

The unitized stack and balance of plant power supply can then be connected to ground power to run the electrolysis process. Once in place, power application to the unitized stack will start the electrolysis process. Electrolysis will proceed until all the water is consumed or one of the upper limits of reactant storage pressure are reached as measured by PT1 and PT3. Once the set points are reached, power to the unitized stack will be removed. The thermal control system will remain operational until the temperature of the system is lowered to less than 50°C. The system is now ready for the next mission and can disconnect from all ground resources.

3.3.2 Operational parameters

Table 1. Operational parameters of 125 kW URFC system for aircraft, fuel cell mode

P&ID	Description	Value	Unit
F1	Direct Drive Exhaust Fan	753	SLM
FPR1	H2 Dome Loaded Regulator	±15psi O2	psi
P2	H2 Recirculating Pump/Blower	1506	SLM
P3	Coolant Pump	67	LPM
T3	Cooling Stream Inlet Temperature	160	°C

Table 2. Operational parameters of 125 kW URFC system for aircraft, reactant regeneration

P&ID	Description	Value	Unit
F1	Direct Drive Exhaust Fan	576	SLM
P1	H2 Compressor	1154	LPM
P3	Coolant Pump	67	LPM
T3	Cooling Stream Inlet Temperature	160	°C

3.3.3 Alarm conditions

Table 3. Alarm set points, 125 kW unitized RFC system for aircraft

P&ID	Description	Alarm Min	Alarm Max	Unit
DPT1	Water Level, Oxygen Tank	5"	15"	in H2O
DPT2	H2 Differential Pressure Transmitter	-30	30	psi
LS1	Coolant Tank Level Switch	12"	32"	in H2O
PT1	V1 (H2) Inlet/Outlet Pressure Transducer	100	3500	psi
PT2	V3 (H2) Inlet/Outlet Pressure Transducer	0	3500	psi
PT3	V2 (O2) Pressure Transducer	100	2000	psi
RV1	V1 (H2 tank) Relief Valve	None	3500	psi
RV2	H2 Outlet Safety Relief Valve	None	2000	psi
RV3	O2 Outlet Safety Relief Valve	None	2000	psi
T1	V1 (H2) Inlet/Outlet Temperature	None	250	°C
T2	V2 (O2) Inlet/Outlet Temperature	None	250	°C
T3	Cooling Stream Inlet Temperature	140	200	°C
T4	Cooling Stream Outlet Temperature	140	200	°C

3.4 Safety implications

3.4.1 Storage of the fuel cell stack in the oxygen tank

The fuel cell system design proposed in this study takes a unique approach by placing the fuel cell stack inside of the oxygen tank. The major benefit of taking this approach is reducing overall system volume. This design also offers many benefits that improve system safety and reliability, such as simplifying system controls, easing the process of collecting product water, and enabling smoother transitions between fuel cell and electrolysis modes. The system requires fewer controls due to the elimination of tubing, valves, and flow control devices, with only a single recirculation fan needed to ensure even distribution and flow of oxygen and steam. Placing the stack inside of the oxygen tank takes advantage of the natural thermal gradient between the 160°C fuel cell stack and the environmental temperature conditions (30°C or less) outside of the oxygen tank vessel walls. This encourages a portion of the water to condense and gather at the bottom of the tank from the influence of gravity, eliminating a separate water removal subsystem entirely. Maintaining the fuel cell stack and oxygen tank at an elevated temperature ensures that the oxygen gas remains saturated with steam, which enables the system to quickly transition between fuel cell and electrolysis modes if required and without damaging the fuel cell stack or requiring the high risk process of switching the reactant types through the tubing.

Placing the unitized fuel cell stack inside of the oxygen tank greatly improves reliability and has some safety advantages described above, but also introduces some safety concerns that must be addressed in order to ensure successful implementation. Perhaps the most obvious concern is a leak of hydrogen out of the stack and into the oxygen vessel. A leak that is large enough to allow for hydrogen accumulation would result in the creation of a dangerous gas mixture that could start a fire or cause an explosion. A common and proven method of preventing the accumulation of a gas leaking into a vessel is the use of a getter to trap the gas or a catalyst to react the leaking gas with the ambient gas in the vessel. Teledyne has successfully used both methods in power system designs, including catalyst scavenging systems to control reactant leakage out of fuel cell systems inside of enclosures for underwater applications. The presence of the recirculation fan in the URFC system would greatly improve the effectiveness of catalyst scavenging by ensuring that any leaking gas reaches the catalyst surface. The catalyst would use a small amount of the oxygen present to convert the leaking hydrogen into water, which would condense and be collected at the bottom of the tank much like the product water from the fuel cell reaction. Mitigating hydrogen leakage by reacting it into water ensures that the reactant is not permanently lost to the system. The condensed water would be evaporated and split into hydrogen and oxygen during the next electrolysis cycle. Minimizing the number and size of hydrogen penetrations and

using welded connections is also important to help minimize hydrogen leakage into the vessel from the reactant tubing.

The presence of the unitized stack within the oxygen vessel can run the risk of an electrical short. If the stack becomes submerged or covered in liquid water, the water can create a conductive path that allows current to bypass the cells within the stack. This effectively eliminates the power source in fuel cell mode and ceases gas generation in electrolysis mode. The stack must be mounted in an elevated position in the tank with respect to gravity to ensure that it cannot be submerged. The maximum liquid water volume present in the tank at any time is 12% of the tank volume, making the prospect of avoiding submerging the stack achievable within the vessel. If this cannot be guaranteed for all of the potential maneuvers performed by the aircraft, a separate but adjoining vessel can be mounted to the bottom of the oxygen vessel and designed in such a way to achieve all of the functions described above while preventing splashing and sloshing during flight. Section 3.4.2 will discuss this possibility in more detail. The liquid level monitoring device (DPT1) provides further protection against an overaccumulation of liquid water. A high level of greater than 10" will activate the water heater (HT2) to evaporate water back into steam. Coating the stack with a water resistant and electrically insulating material provides an additional layer of protection against this hazard.

3.4.2 Water sloshing, oxygen tank

Using the oxygen tank as the location for product water storage simplifies controls and eliminates extra components. With these benefits do come added concerns in a mobile application. Liquid in a tank that is partially filled is subject to the accelerations and changes in direction of the aircraft on which the tank is installed. The liquid has a free surface inside of the tank, which allows the forces exerted by the walls of the tank on the liquid via aircraft change in direction to generate waves within the liquid. These waves can violently disturb the liquid and create uncontrollable forces reverberating through the tank. Sloshing is commonly seen in propellant tanks for space applications and liquid cargo in tankers transported by truck, train, or ship. If unmitigated, these forces can damage the fuel cell stack or the tank and interfere with the controllability of the aircraft in flight.

The risk of sloshing can be mitigated by installing baffles in the tank. Baffles are internal structures within the tank that break up the waves generated by sloshing forces while still allowing for communication of liquid between the sections partitioned off by the baffles. They are commonly employed in aircraft fuel tanks and in the other applications mentioned above where sloshing is observed. An example of a baffle design for a vertically mounted propellant tank is shown below in Figure 8. If baffles alone do not ensure that sloshing cannot present a

hazard to the fuel cell stack, the oxygen tank, or the aircraft, a separate compartment may need to be installed at the bottom of the oxygen tank that incorporates baffling and water containment.

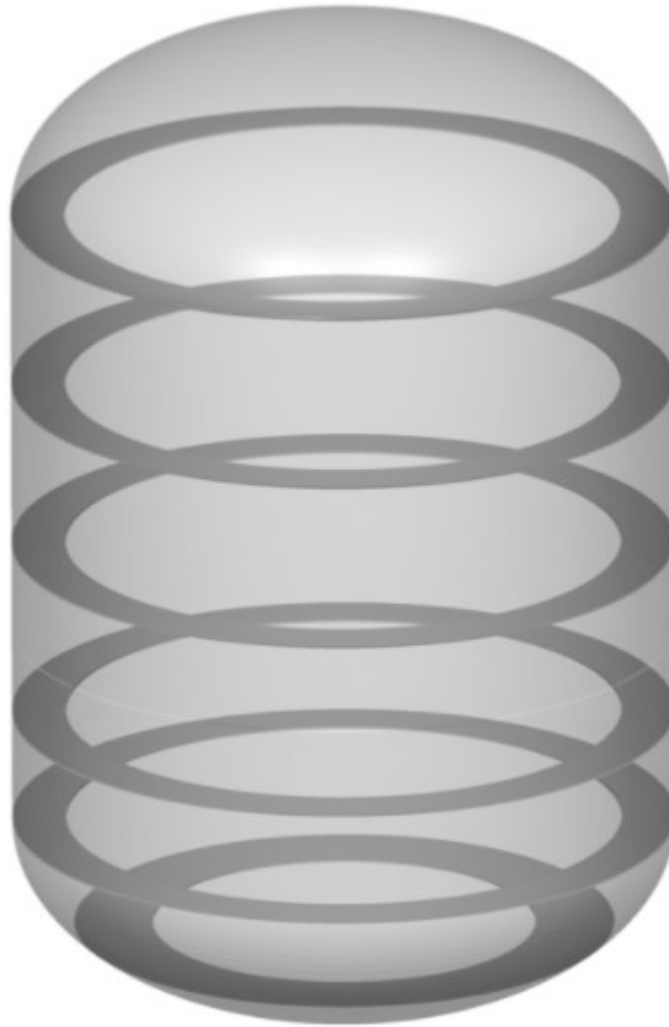


Figure 8. Example of a typical propellant tank with baffles for slosh damping (Yang & West, 2015)

3.4.3 Discrete operation vs fast mode switching

The URFC system design presented in this study provides the ability to alternate between fuel cell and electrolysis modes in short time spans, which can be of great advantage to an RFC system. The URFC system can be used as a load-leveling device, consuming excess power when available to generate gas and using that gas to provide additional power to devices or the aircraft. For the electric propulsion application, the device operates more like a discrete RFC system, with fuel cell mode employed during flight and electrolysis mode only used to refuel the aircraft when

on the ground. The discrete operation configuration is considered more gentle on the stack in terms of operation. The catalysts and electrodes of the cells would be subject to less degradation, increasing the lifetime of the system. The open cathode design of the URFC lends itself well to quick transitions from power production to electrolysis. However, the balance of plant equipment, specifically the valves and pumps required to manage the hydrogen reactant, may have trouble quickly shuttling between each mode if called upon to do so, but would have no issue with the slower transition between modes for the electric propulsion application. A system with this design may be more suitable to the electric propulsion application over the load-balancing application for the reasons mentioned above.

3.5 Applicability to other aircraft applications

The system design for the electric propulsion application can also serve as the basis for a 787 Dreamliner load-balancing application. The reactant storage capacity would be reduced because the system does not need to operate at full power for the duration of the flight and would even be replenishing reactant during certain flight stages by electrolysis. The reactant storage volumes would be sized proportionally to allow for equal pressurization and depressurization rates during both electrolysis and power consumption without the need for active control. This allows for a major simplification of the pressure and flow control by eliminating P1, SV1, SV2, V3, CV3, CV4, CV5, and FPR1. Control logic will be simpler, and the parasitic power observed will be reduced, making this system design promising for the application. Power electronics would need to handle quick alternations between fuel cell and electrolysis mode, although that is outside of the scope of this study.

4 Mission simulation

4.1 Introduction

Teledyne has developed a detailed model to simulate the mission profile of an electric propulsion aircraft using a 125 kW HTPEM URFC system. The model investigates the overall system performance during one, two, and five-hour flight missions as the electric propulsion aircraft goes through multiple power stages. A model simulating reactant regeneration was developed utilizing on-board and ground resources for the operation. The following sections detail the performance and parametric analysis of the unitized regenerative fuel cell technology in both modes of operation.

4.2 Fuel cell mode

The information detailed in the system design was used to model the overall performance of the system in the mission simulation. A power and equipment list (PEL) was compiled using component data sheets to determine power consumption of each component at each power level of the flight profile. Two additional models were developed to account for the power consumption of the hydrogen recirculation blower and thermal control system as a function of the load. The parasitic power for all system components in fuel cell mode is 1520 W at 25%, 1950 W at 50%, 2370 W at 75%, and 2800 W at maximum power.

The steady state performance of the fuel cell system at maximum power for a five-hour flight was used to determine reactant consumption for baseline sizing of the system. The MEA data from the Advent PBI-membrane MEA specifications was used to determine stack efficiency, stack voltage, and current density at each power level since it is the most mature HTPEM technology (Advent High Temperature Membrane Electrode Assemblies, 2019). The total current of the system was then calculated and used to determine hydrogen and oxygen consumption rates during each stage of the flight mission. Table 4 lists the values at each power segment.

Table 4. Specifications by power level

Power (%)	Power (kW)	Parasitic Power (W)	Efficiency (%)	H₂ Consumption (mol/s)	O₂ Consumption (mol/s)
25%	31.25	1520	48.1	0.23	0.11
50%	62.50	1950	45.5	0.49	0.25
75%	93.75	2370	42.8	0.77	0.39
100%	125.0	2800	39.4	1.12	0.56

Table 5. Mission profile definition for electric propulsion, 125-kW URFC

Segment	Power	Time (min)	Required
Take-off	100%	3	Yes
Climb Out	100%	12	Yes
Cruise	75%	Variable	Yes
Descent	25%	20	Yes
Landing	25%	5	Yes
Go Around	100%	2	No
Divert	75%	15	No

Once the reactant consumption rates were determined, the flight mission was modeled using the power profile at each stage of the flight. The performance curves model the overall hydrogen consumption and power level over the duration of each flight mission. Two separate scenarios were modeled for each of the one, two, and five-hour flight durations. The first simulation models the flight profile that fulfills the required stages of take-off, climb-out, cruise, descent, and landing. The second simulation models the flight profile with additional stages for diversion and go-around instances. The second model accounts for the potential to require go-around and diversion phases following the cruise stage of each flight. All stages of the flight are fixed except for the cruise stage. The flight missions including additional stages for diversion and go-around instances are representative of the worst-case reactant consumption. A summary of the stages and their properties, shown in Table 5, was used to build the power profile for each mission and calculate the energy consumption. The performance graphs for each mission simulation are shown in Figure 9 through Figure 14.

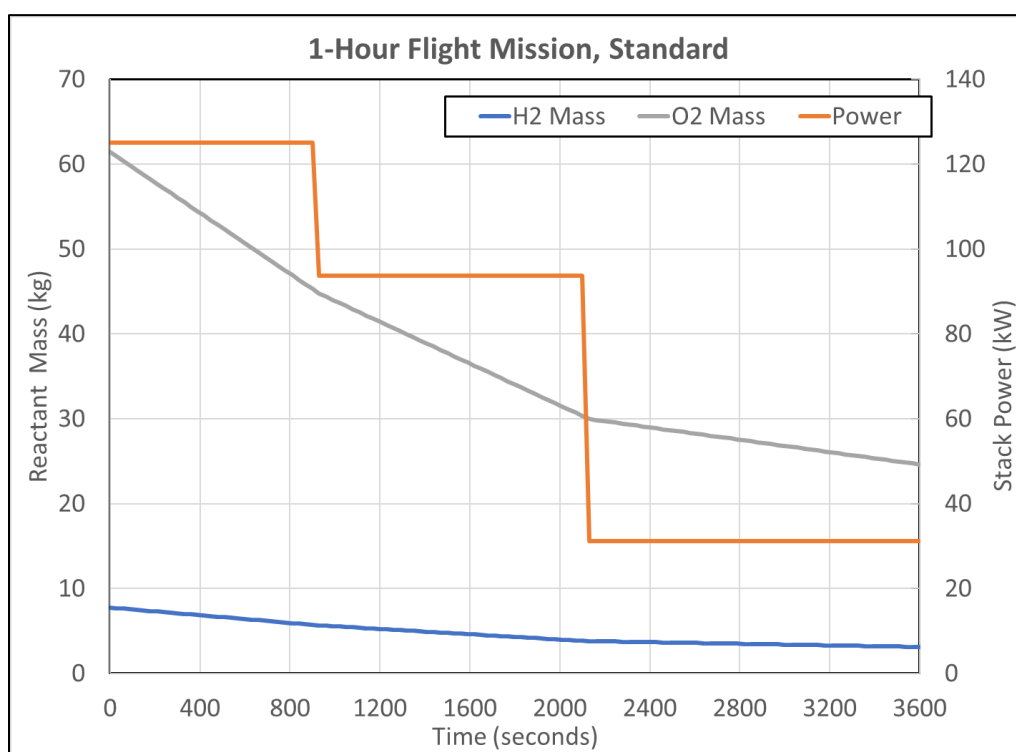


Figure 9. Simulation results, one hour, standard

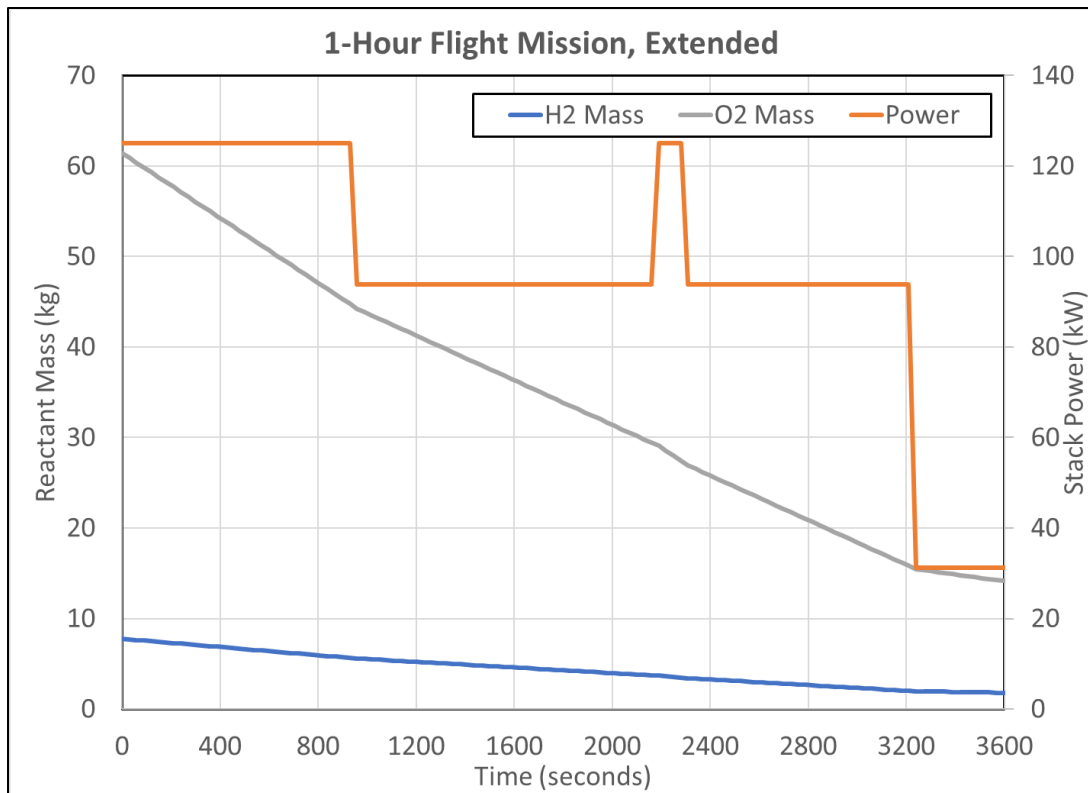


Figure 10. Simulation results, one hour, extended

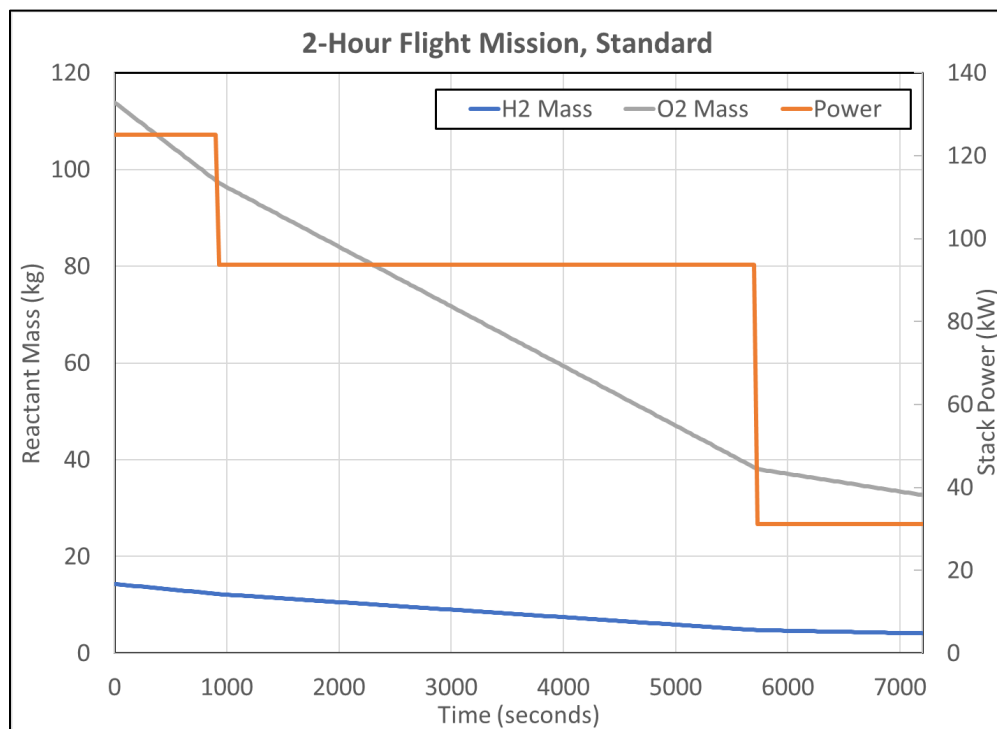


Figure 11. Simulation results, two hour, standard

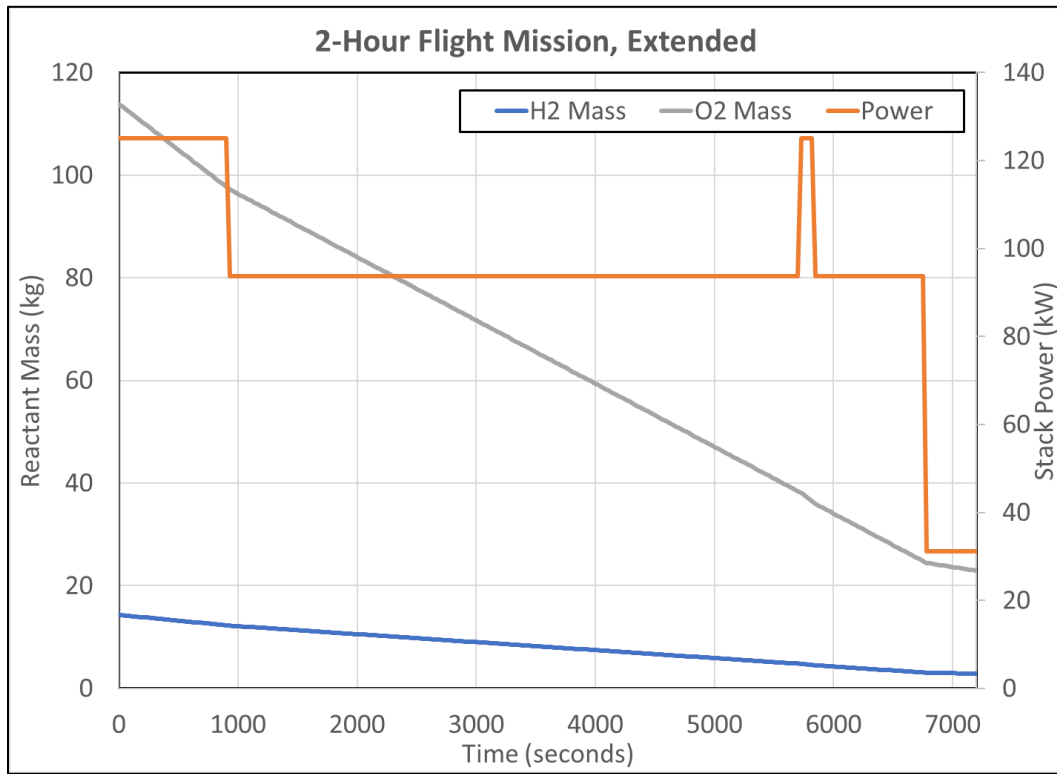


Figure 12. Simulation results, two hour, extended

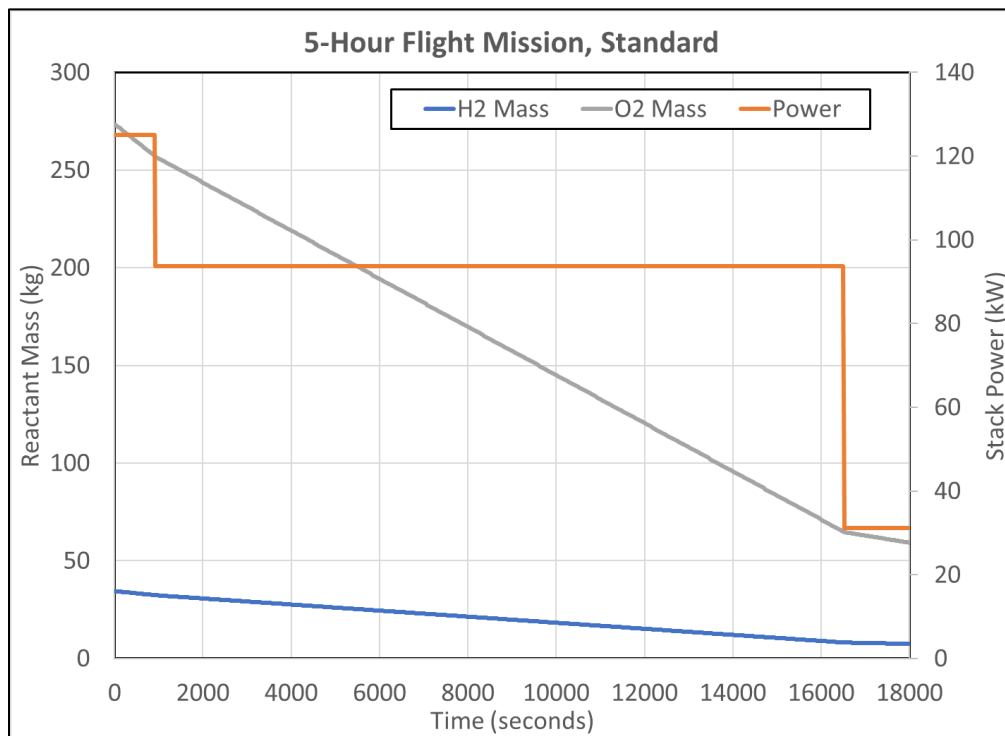


Figure 13. Simulation results, five hour, standard

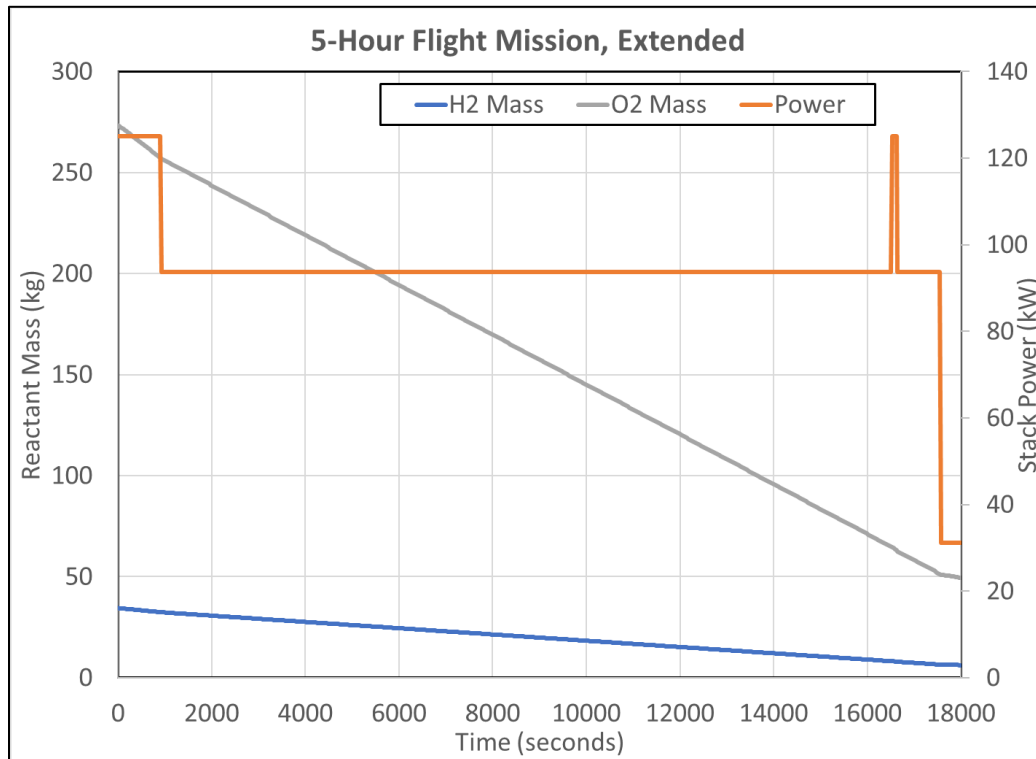


Figure 14. Simulation results, five hour, extended

The aircraft cruises for 20 minutes during the one-hour flight mission, consuming 2303 moles of hydrogen and 1151 moles of oxygen. When the flight mission is extended by 18 minutes for additional stages, the total consumption increases to 3195 moles of hydrogen and 1598 moles of oxygen. For the best-case model, there was an excess of 1648 moles of hydrogen and 767 moles of oxygen. The worst case had an excess of 755 moles of hydrogen and 320 moles of oxygen.

During the two-hour flight mission, the aircraft cruises for 80 minutes consuming 5081 moles of hydrogen and 2541 moles of oxygen. When the model accounts for additional stages, the total consumption increases to 5925 moles of hydrogen and 2964 moles of oxygen. For the best-case model, there was an excess of 1989 moles of hydrogen and 1018 moles of oxygen. The worst case had an excess of 1145 moles of hydrogen and 596 moles of oxygen.

For the five-hour flight mission, the aircraft cruises for 260 minutes consuming 13393 moles of hydrogen and 6698 moles of oxygen. When the model accounts for additional stages, the total consumption increases to 14250 moles of hydrogen and 7127 moles of oxygen. For the best-case model, there was an excess of 3672 moles of hydrogen and 3371 moles of oxygen. The worst case had an excess of 2814 moles of hydrogen and 2942 moles of oxygen.

4.3 Electrolysis mode

The reactant regeneration process proceeds after the aircraft has completed the flight mission. The fuel cell stack is electrically disconnected from the propulsion system of the aircraft. The hydrogen recirculation loop is deactivated during electrolysis mode. The recirculation pump P2 is deactivated and solenoid valve SV2 is fully closed to terminate hydrogen flow through the system. Similarly, solenoid valve SV1 is fully closed to isolate FPR1 to prevent differential pressure control between the hydrogen and oxygen tank.

The unitized stack will transition into electrolysis mode once ground power is connected to the system. The thermal control system maintains operation utilizing a ground air blower for the heat exchanger. In addition to the major components used during fuel cell mode, the hydrogen compressor is operative during electrolysis mode, which increases the parasitic power to 6263 W. Additionally, the water heating element HT2 is activated to vaporize condensed water from the oxygen exhaust and control elevated liquid levels in T2. These components will rely on ground power supply water to operate.

Research studies on HTPEM electrolysis from the Technical University of Denmark were used to determine the expected current density and voltage at a 125-kW power level using the same stack sized for electric propulsion (Hansen, et al., 2012). That information was used to determine the total current, the hydrogen production rate of 0.858 mol/s, and oxygen production rate of 0.429 mol/s. As the system operates at steady state, 1154 SLM of hydrogen and 576 SLM of oxygen are generated while 0.980 SLM of water is consumed. During electrolysis mode, 98 kW of heat are generated as reactants are produced.

As various flight missions were modeled in Section 4.2, minimum and maximum reactant consumption was determined. Although power levels change during flight missions, 8.15 kg/hr of hydrogen and 64.5 kg/hr of oxygen are consumed at 125 kW, while 6.226 kg/hr of hydrogen and 49.4 kg/hr of oxygen are generated during electrolysis mode. During the basic 1-hour flight modeled in Figure 9, 4.64 kg of hydrogen and 36.9 kg of oxygen were consumed. It would take about 45 minutes to regenerate the reactants used during that mission. For the 1-hour flight with additional stages, 6.44 kg of hydrogen and 51.1 kg of oxygen were consumed. The reactant regeneration would take 62 minutes. The basic 2-hour flight mission uses 10.2 kg of hydrogen and 81.3 kg of oxygen, which would take 98 minutes to regenerate. Similarly, the extended 2-hour flight would use 12.1 kg of hydrogen 94.9 kg of oxygen resulting in a 115-minute regeneration period. The standard 5-hour flight mission uses 27 kg of hydrogen and 214.3 kg of oxygen. It would take 260 minutes, about 4.25 hours to regenerate the reactants. The 5-hour flight with additional stages goes through 28.7 kg of hydrogen and 228.1 kg of oxygen, which

would take 277 minutes, or 4.5 hours to regenerate. There is potential to reduce these refueling times even further. The system can operate higher current densities in electrolysis mode by taking advantage of an excess cooling capacity of 96 kW available in the thermal control system, which could potentially reduce refueling times by approximately 50%.

5 Conclusions

Teledyne sought to develop and explore a URFC concept for aircraft applications in this study. We reviewed the history of unitized fuel cell system development and implementation. Both LTPEM and SOFC technologies have been explored in these applications, with single cell, short stack, and even some full-size hardware built and tested. We chose to pursue a HTPEM-based URFC design with the goal of marrying the benefits of handling gaseous water in SOFC with the more manageable heat load of a PEM technology. We developed a system design based on an open-cathode HTPEM fuel cell stack housed inside of the oxygen storage tank and selected components to support its operation. This approach simplifies flow controls, removes the need for complex water management systems, and minimizes volume but adds some operational and safety challenges that need to be addressed in a matured system. We built a system model in Excel using inputs from real HTPEM performance data and information derived from the datasheets of chosen components. The model was used to explore the feasibility of powering an electric propulsion aircraft for one to five-hour flights. The results showed that the system concept could perform well in this application and might have operational benefits but may be challenging to implement due to the mass and volume required for the system.

5.1 System benefits

The URFC system proposed in this study provides benefits for the intended application. Short, regional flights with small numbers of passengers (less than ten) may be well served by this system. The URFC does not require refueling structure by eliminating jet fuel and having the built-in ability to recharge the fuel tanks while on the ground through electrolysis mode. The URFC only needs a source of electrical power at 125 kW at the landing site, which could increase the number of potential destinations serviced by the aircraft. The need to install hydrogen infrastructure at the landing sites has been removed, a requirement that has limited PEM fuel cell system implementations into aircraft due to the capital equipment investment and zoning requirements to ensure reliable and safe hydrogen supplies. When operating in flight, the fuel cell stack has the ability to provide electric power for more aircraft devices beyond just the propulsion system, including personal devices of passengers and avionics, as long as they represent a small percentage (<10%) of the propulsive load. These features combined can

provide operational advantages over battery and primary fuel cell systems being considered for electric propulsion aircraft of this class.

5.2 Obstacles and next steps

Despite the benefits of using the proposed URFC, many obstacles to implementation remain. The URFC system as proposed is quite bulky and heavy at a minimum of 4150 L and 2338 kg for the one-hour and two-hour application and 6870 L and 2837 kg for the five-hour mission, greatly prohibiting implementation on small electric propulsion aircraft. This is almost entirely driven by the reactant storage tanks. This corresponds to a specific power of 42 to 60 W/kg, with the maximum occurring for the one-hour mission, and a specific energy of 57 to 164 Wh/kg, with the maximum occurring for the five-hour mission. These performance metrics are both less than the hundreds of W/kg and 200 Wh/kg or greater from lithium ion batteries. The size of the hydrogen and oxygen tanks (V1 and V2) required to house both the fuel cell stack and the quantity of gas required to support the flight duration at the 125-kW scale prohibits implementation into the aircraft body. The large flow rates of hydrogen and oxygen and cooling load required to sustain the fuel cell reaction at 125 kW requires large fans, pumps, and heat exchangers (P1, P2, P3, F2, HX1) with high parasitic power requirements, as well as many supporting components for alternating operational modes and providing layers of safety.

The system as proposed might be better suited from a volumetric standpoint as an auxiliary power unit on a larger aircraft, such as the 787 Dreamliner application discussed earlier in this study. The magnitude of power delivered versus the overall power of the aircraft results in a fuel cell system volume that has the potential to fit within the available cargo space of the aircraft instead of taking up a large portion of the fuselage. The overall mass of the system may be of greater concern and would greatly impact the aerodynamics of the aircraft. A mass breakdown of the system components is shown in Figure 15. This system concept might demonstrate a better technical fit to applications at a power scale of two to three orders of magnitude lower, with power requirements of 1 kW or less. The size of the oxygen tank and fuel cell stack as well as the reactant flow and cooling required to support operation would be greatly reduced. There may be applicability to UAVs that fall within this class, although ambient air breathing fuel cell systems are sure to have better power density metrics. Applications could still be found for UAVs operating in areas without a source of clean ambient air, such as battlefields, disaster recovery, and other harsh environments.

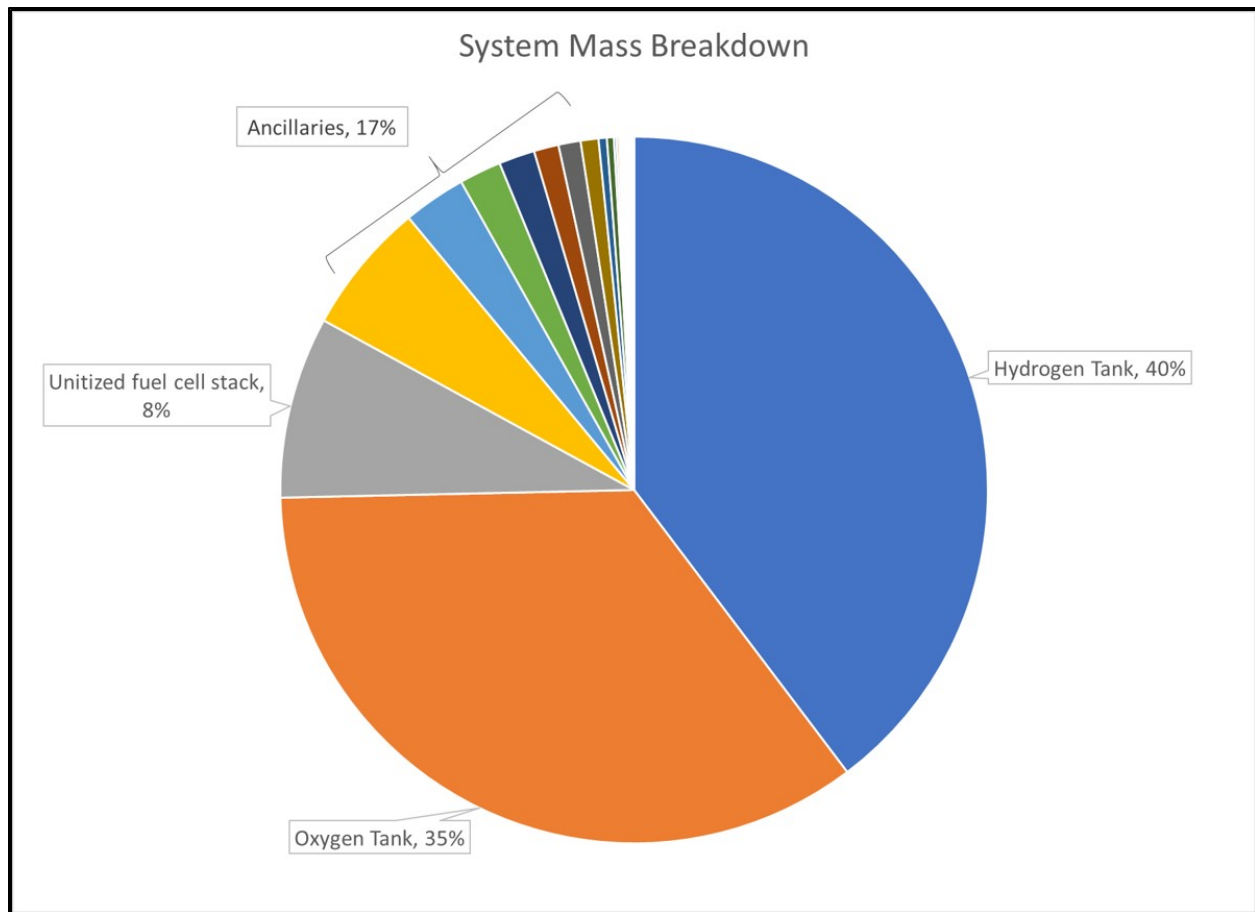


Figure 15. System mass breakdown, 125-kW URFC

Potential applications for smaller electric propulsion aircraft include air taxis, which make several short flights on demand. The URFC system proposed in this study could potentially service these applications. An impediment to successful operation of this system in an air taxi is the time it takes to recharge the reactant storage tanks by electrolysis. Electrolysis-based refueling does eliminate the need for hydrogen and oxygen infrastructure at the site at the expense of refueling time. Refueling by electrolysis is not as quick as filling the tank from a compressor and pressurized storage tanks. A refueling process in URFC system in this study that is on the order of 50-75% of the length of the flight could limit the functionality of an air taxi and other electric propulsion aircraft that require frequent trips with multiple stops. Increasing the power used for electrolysis would reduce the time to refuel but would put stress on the coolant system that is sized for the fuel cell load as well as other components required to maintain operation.

The URFC system proposed in this study employs novel system design concepts that promise operational benefits but may also have unforeseen circumstances. Integrating the system into aircraft applications will require multiple phases of development and demonstration to test the subsystems and prove the functionality and safety of the design. Performing FMEAs at each stage of development and completing testing on individual components and subsystems will help identify weaknesses in the system design, as well as the risks most likely to cause performance and safety issues.

HTPEM technology resides in an optimal temperature range for a URFC application. Despite this system-level advantage, HTPEM performance in fuel cell mode shows a lower efficiency than that exhibited by LTPEM and SOFCs. Today's LTPEM and SOFC technologies are built upon several decades of technology development through materials research, cell and stack design, manufacturing improvements, and expertise gained through system integration in real world applications. The relative novelty of HTPEM technologies and lack of widespread implementation in the market puts it at a disadvantage. There is a need for improvements in efficiency for fuel cell operation in order to reduce the mass and volume of the stack. Better data on steam-fed electrolysis, which has almost no published research, is also needed. Durability of HTPEM is a primary concern in each mode. The role of water in degrading the acid-impregnated high temperature membranes is well known and must be properly managed in this application. A unitized system of this design may not be the right approach today with this in mind. The technology maturity is too low for near-term implementation, but might be achievable given time and investment, especially if other potential applications of the technology can be found.

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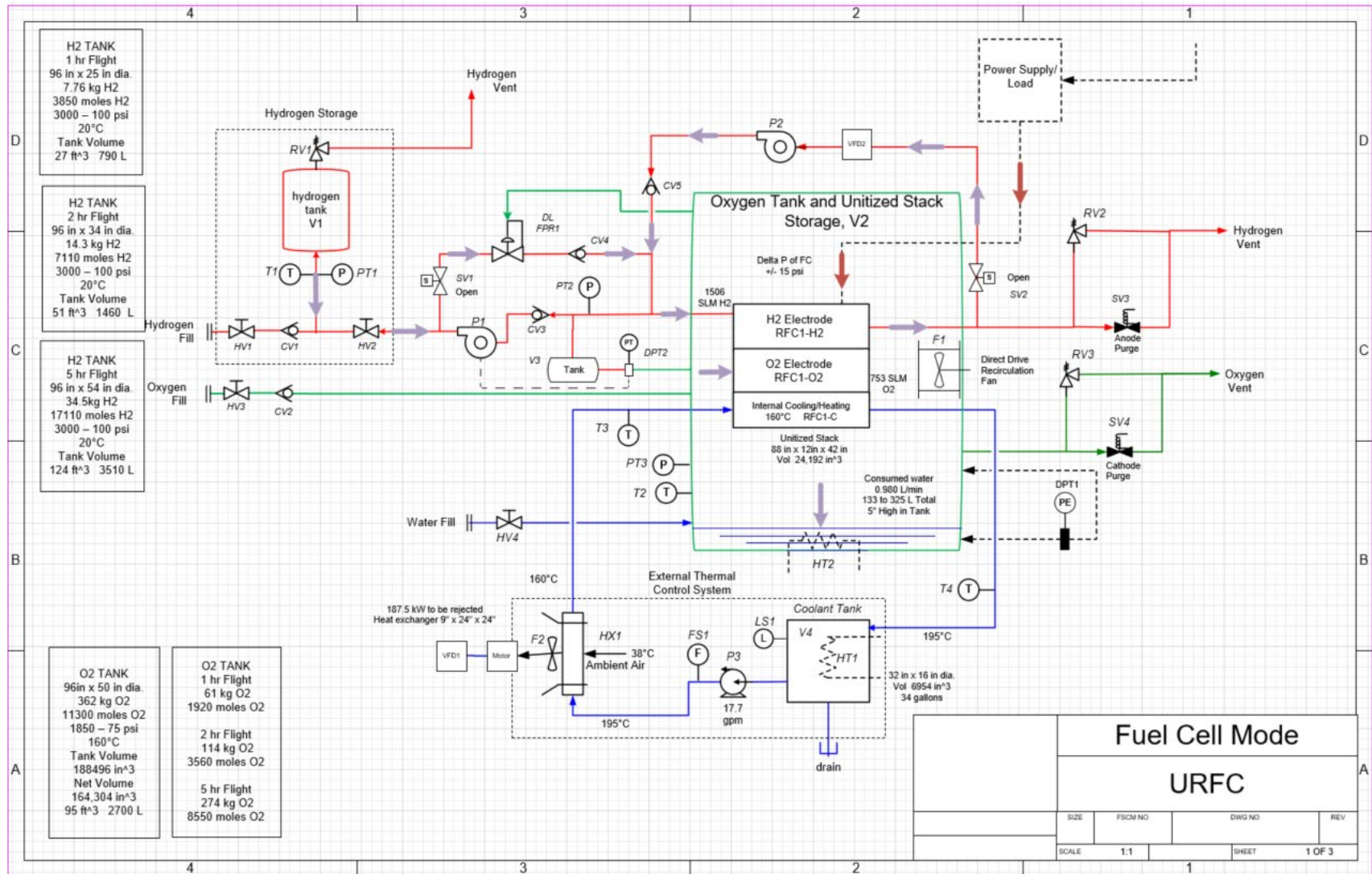
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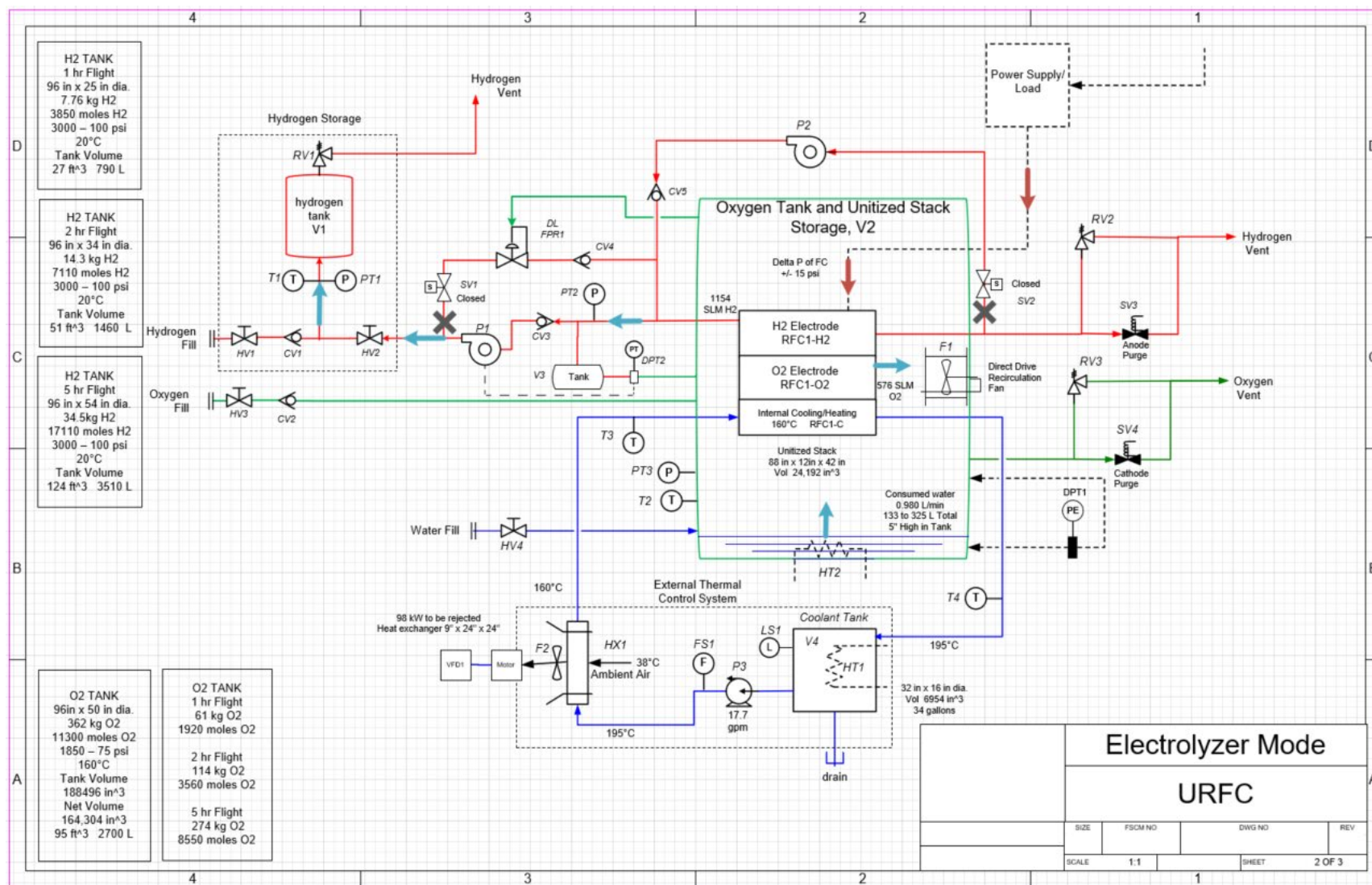
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A Piping and instrumentation diagram, 125 kW URFC





B Bill of materials, 125 kW URFC

P&ID	DESCRIPTION	PART NO.	MANUFACTURER	MASS (LBS)	DETAILS
CV1	H2 fill check valve	H-232T1-4PP-1	Circle Seal Controls	0.92	Viton, 0.7 Cv, 1/4" fnpt
CV2	O2 fill check valve	H-232B-4PP-1	Circle Seal Controls	0.92	Viton, 0.7 Cv, 1/4" fnpt
CV3	H2 outlet check valve	H-232T1-4PP-1	Circle Seal Controls	0.92	Viton, 0.7 Cv, 1/4" fnpt
CV4	H2 inlet check valve	H-232T1-4PP-1	Circle Seal Controls	0.92	Viton, 0.7 Cv, 1/4" fnpt
CV5	H2 recirculation check valve	H-232T1-4PP-1	Circle Seal Controls	0.92	Viton, 0.7 Cv, 1/4" fnpt
DPT1	Water level	2051CP1X27A	Rosemount	4.5	Glass-filled PTFE, -25-25 in H2O, 4-20 mA
DPT2	H2 differential pressure transmitter	2051CP1X27A	Rosemount	4.5	Glass-filled PTFE, -25-25 in H2O, 4-20 mA
F1	Direct drive exhaust fan	1915K82	McMaster-Carr	21	21"x21"x6", 1725 rpm, 1/6 hp, 120VAC
F2	Direct drive exhaust fan	2208K51	McMaster-Carr	109	24"x24"x19", 1725 rpm, 1/2 hp, 230/460VAC
FS1	Coolant line flow switch	FLT93S-1A1A	FCI	7.94	0.003-3.9 MPS, 1" NPT, 1/2" insertion
FPR1	H2 Dome loaded valve	26-1261-2121	Tescom (Emerson)	25	Viton, 3.3 Cv, 3/4" fnpt, 1/4" fnpt
HT1	Heating elements	BLR720L3S7A	Watlow	8	21" x 6.5" diameter, 9.5kW, 240V, 2.5" Flange plug
HX1	Ambient air heat exchanger	F740-274	Xylem	190	Air-cooled heat exchanger, 1/2" tubes, 1750 RPM
LS1	Coolant tank level switch	FLT93S-1A1A	FCI	4.7	0.01-3.0 fps, 1" NPT, 0-50 mA
HV1	H2 inlet hand valve (filling)	SS-1RS6	Swagelok	1.8	Integral Bonnet Need Valve (0.73 Cv, 3/8")
HV2	H2 inlet hand valve (operation)	SS-1RS6	Swagelok	1.8	Integral Bonnet Need Valve (0.73 Cv, 3/8")
HV3	O2 inlet hand valve (filling)	SS-1RS6	Swagelok	1.8	Integral Bonnet Need Valve (0.73 Cv, 3/8")
HV4	Water inlet (filling)	SS-1RS6	Swagelok	1.8	Integral Bonnet Need Valve (0.73 Cv, 3/8")
P1	H2 compressor (filling)	2TX2B	RIX Industries	400	2-stage, 40 HP, 250-1100 RPM
P2	H2 recirculating pump/blower	HP-8E-213T-326T	Cincinnati Fans	67	High pressure blower, 3500 RPM, 20 HP
P3	Coolant pump	2-HMS-3F4D5	Goulds	54	Multistage centrifugal pump, Viton seal, 3550 RPM

P&ID	DESCRIPTION	PART NO.	MANUFACTURER	MASS (LBS)	DETAILS
PT1	V1 (H2) inlet/outlet pressure transducer	PX1004L1-015AV	Omega	0.32	1/4" mnpt, 3 mV/V
PT2	V3 (H2) inlet/outlet pressure transducer	PX1004L1-015AV	Omega	0.32	1/4" mnpt, 3 mV/V
PT3	V2 (O2) pressure transducer	PX1004L1-015AV	Omega	0.32	1/4" mnpt, 3 mV/V
PT4	H2 outlet pressure transducer	PX1004L1-015AV	Omega	0.32	1/4" mnpt, 3 mV/V
RFC1	Unitized fuel cell stack	none	TBD	551	
RV1	V1 (H2 tank) relief valve	HR6032-2MP-EC	Circle Seal Controls	0.65	Viton, 0.27 Cv, 1/4" male npt
RV2	H2 outlet safety relief valve	HR6032-2MP-EC	Circle Seal Controls	0.65	Viton, 0.27 Cv, 1/4" male npt
RV3	O2 outlet safety relief valve	HR6032-2MP-EC	Circle Seal Controls	0.65	Viton, 0.27 Cv, 1/4" male npt
SV1	H2 inlet solenoid valve (filling)	EH30-042-D024	Clark Cooper	2.85	10000 psi, 400°F, ptfe, Cv 0.005
SV2	H2 recirculating solenoid valve	EH30-042-D024	Clark Cooper	2.85	10000 psi, 400°F, ptfe, Cv 0.005
SV3	H2 vent solenoid valve	EH30-042-D024	Clark Cooper	2.85	10000 psi, 400°F, ptfe, Cv 0.005
SV4	O2 vent solenoid valve	EH30-042-D024-OX	Clark Cooper	2.85	10000 psi, 400°F, ptfe, Cv 0.005, oxygen cleaned
T1	V1 (H2) inlet/outlet thermocouple	TJ1-ICSS-IM30U-150	OMEGA	0.18	Type J, 3.0mm diameter, 6" length, ungrounded
T2	V2 (O2) inlet/outlet thermocouple	TJ1-ICSS-IM30U-150	OMEGA	0.18	Type J, 3.0mm diameter, 6" length, ungrounded
T3	Cooling stream inlet thermocouple	TJ1-ICSS-IM30U-150	OMEGA	0.18	Type J, 3.0mm diameter, 6" length, ungrounded
T4	Cooling stream outlet thermocouple	TJ1-ICSS-IM30U-150	OMEGA	0.18	Type J, 3.0mm diameter, 6" length, ungrounded
V1	Hydrogen Tank	Customizable	Multiple vendors	1875	80" x 50" diameter max (2500L), Type III
V2	Oxygen Tank	Customizable	Multiple vendors	2700	96" x 54" diameter max (3600L), Type III
V3	Hydrogen Holding Tank	Customizable	Multiple vendors	75	30" x 8" diameter max (100L), Type III

P&ID	DESCRIPTION	PART NO.	MANUFACTURER	MASS (LBS)	DETAILS
V4	Coolant Tank	Customizable	Multiple vendors	127.5	35" x 10" diameter max (170L), Type III
VFD1	AC Variable frequency drive	GS341PO	Automation Direct	3.9	3-phase, 460V, 1 hp