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Evaluation for a Lightweight Fuel Cell Containment System for Aircraft Safety

June 2019

Final Report

U.S. Department of Transportation
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16. Abstract

This project evaluated the potential impacts for a notional future solid oxide fuel cell- (SOFC) based power system to be integrated into a light aircraft, as described in Title 14 Code of Federal Regulations part 23. A notional SOFC hybrid system operating on liquid fuel was assessed for impacts to existing aircraft safety regulations, introduction of failure modes, and approaches for safe integration into the aircraft. Modeling and analyses were performed to assess worst-case failure effects. A test unit was built, and controlled failure testing of two different SOFC stacks was performed.

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LIST OF ACRONYMS

AIT	Auto-ignition temperature
APU	Auxiliary power unit
ATR	Auto-thermal reformation
BR&T	Boeing Research & Technology
CC	Combustion chamber
CFR	Code of Federal Regulations
CMC	Ceramic matrix composite
CV	Constant volume
DDT	Deflagration-to-detonation transition
FUELEAP	Fostering Ultra-Efficient Low Emitting Aviation Power
HEX	Heat Exchanger
ICE	Internal combustion engine
ITAR	International Traffic in Arms Regulations
LEL	Lower explosive limit
MSL	Mean sea level
P&ID	Piping and instrumentation diagram
PLC	Programmable logic controller
PMG	Permanent magnet generator
RCB	Recycle blower
SO	Solid oxide
SOFC	Solid oxide fuel cell
T/C	Turbo-Compressor

EXECUTIVE SUMMARY

The FAA project “Evaluation of a Lightweight Fuel Cell Containment System for Aircraft Safety” evaluated the potential impacts for a future solid oxide fuel cell- (SOFC) based power system to be integrated into a small aircraft, as described in Title 14 Code of Federal Regulations part 23. A target SOFC system using a liquid desulfurized fuel, onboard reformation, and a hybrid battery was assessed for impacts to existing aircraft safety regulations. Integration effects of the target system were studied in the context of failure modes, similarity to existing systems, and potential approaches for safe integration into the aircraft. Analyses of worst-case failure modes introduced by the SOFC technology were performed to bound the expectations of the failure effects and to help characterize the timing for failure identification. An SOFC stack test unit was built to support controlled failure testing to verify the analyses. Controlled failure testing was performed on two development stacks of different designs, made by different suppliers. Data from the stack tests and teardowns indicated that a worst-case sudden failure inside an SOFC stack can be identified with existing sensor technology. Also, testing showed that damage from an internal SOFC stack failure can be limited by shutting off the fuel flow to the stack to stop the propagation of the failure from the stack to surrounding components or systems.

Significant SOFC development, system optimization, and testing is necessary to support a future SOFC-based power system integration into the aircraft. Early assessment of the challenges of new technology to aircraft safety helps to identify potential issues prior to integration on an aircraft. The analyses, modeling, trades, and testing performed under this project suggest that safe aircraft integration of a future matured SOFC power system is feasible within the use of existing technology.

1. INTRODUCTION AND OBJECTIVES

The use of electric power for aircraft propulsion is a topic of increasing interest in the aviation community, largely due to the significant increase in efficiency over traditional internal combustion engines (ICEs). These devices are also quieter and more environmentally friendly than the reciprocating combustion engines that are currently used for primary propulsion for small or light aircraft.

In recent years, technology investments in solid oxide fuel cell (SOFC) stack design and fabrication approaches have reduced the weight of the stacks such that fuel cells offer a higher energy density alternative to the much heavier battery technology options. The Boeing Company leveraged its SOFC experience to support the NASA-led Fostering Ultra-Efficient Low Emitting Aviation Power (FUELEAP) program, which is aimed at a flight demonstration of an advanced fuel cell power plant that operates on infrastructure-friendly hydrocarbon fuel. SOFC powered aircraft have the potential to dramatically reduce fuel consumption, emissions, and noise over a comparable internal combustion engine. Depending on the selected technology of the various system components, an SOFC electrical power system can achieve efficiencies in excess of 60% on hydrocarbon fuels, approaching double that of an ICE [1]

History has shown that the introduction of new technology into an aircraft may also introduce new failure modes that can impact flight safety. Early assessment and testing to assist in understanding the intricacies of each new technology can help the safe integration of new technology into a flight vehicle. Boeing, under the FAA project "Evaluation of a Lightweight Fuel Cell Containment System for Aircraft Safety," has performed an analysis to identify worst-case failures in a future SOFC-based power system and has investigated methods of first mitigation and then control and containment of such possible failures. Boeing has also identified areas in existing FAA regulations that would be applicable to an SOFC-based power system, as well as recommendations for the regulations to help incorporate an SOFC power system into the existing safety requirements. Finally, Boeing has performed controlled failure testing to mimic the worst-case failure scenario to provide data on identifying and stopping propagation of the failures.

The FAA project "Evaluation of a Lightweight Fuel Cell Containment System for Aircraft Safety" is intended as a first step to provide analysis and hard data toward the technical understanding of SOFC-based technology for flight to help with future aircraft integration.

2. BASELINE AIRCRAFT DESCRIPTION

2.1 FUELEAP TARGET VEHICLE OVERVIEW

Boeing supported NASA's Langley Research Center on the FUELEAP program. The purpose of this program was to continue the development of an SOFC stack operating on heavy hydrocarbon fuel as the primary power source for a commuter class airplane. The potential application for the FUELEAP SOFC power system is the NASA X-57 Maxwell flight demonstrator, based on a Tecnam P2006T shown in figure 1. Mod 2 of the X-57 is an all-electric version of the Tecnam, which will maintain the outer mold line of the vehicle, but will include battery packs to supply the necessary power instead of a traditional combustion engine. A hybrid SOFC power system is

envisioned to replace the battery packs as the primary power source for a spiral demonstrator flight as a step toward a commercial aircraft SOFC power system.

Figure 1. Tecnam P2006T aircraft

For the FAA program "Evaluation of a Lightweight Fuel Cell Containment System for Aircraft Safety," Boeing used the Tecnam P2006T aircraft as a baseline reference for an SOFC-based power system to assess and analyze containment and mitigation approaches. The system has to mature significantly and demonstrate multiple performance and safety targets before it can be considered for a commercial application. For this reason, where possible, requirements and analyses focused more on the general aspects of the system that would be relevant to both the FUELEAP demonstrator and a future commercial aircraft system.

A hybridized SOFC-based power system based on near term technology will require more space for aircraft integration than traditional ICE-based power systems. An SOFC-based power system would not fit in the existing engine volume located in the wings; therefore, the integration volume focus for the hybridized SOFC power system was in the aircraft cabin, behind the pilot and passenger. The envelope available for the demonstrator aircraft SOFC-based power system is depicted in figure 2. The volume shown is used to incorporate the entire hybridized power system with the exception of the fuel tank, which is currently located in the wing of the existing vehicle.

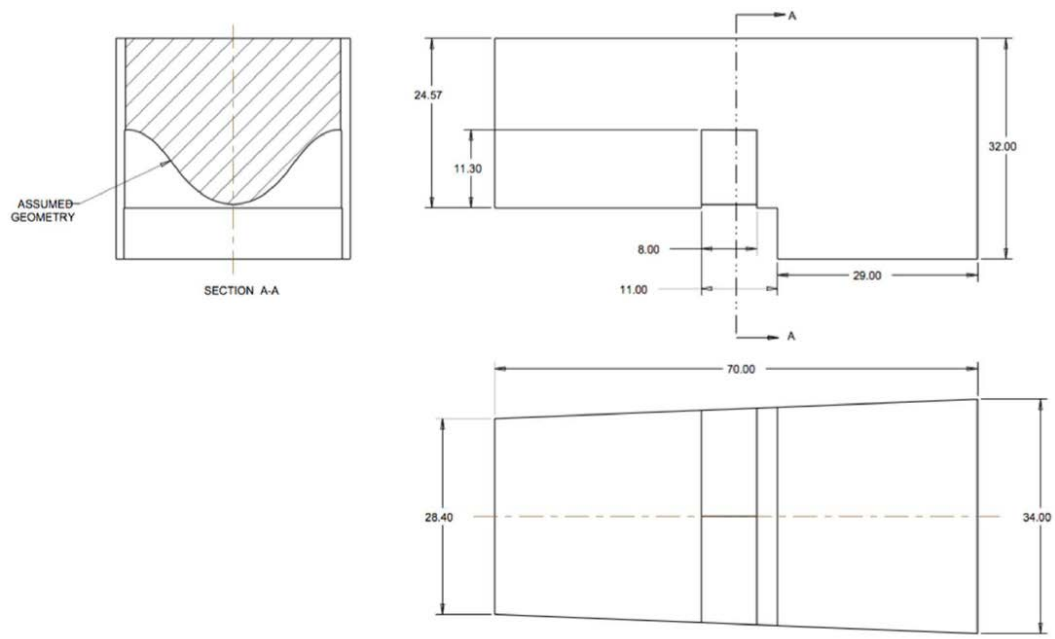

Figure 2. Envelope for SOFC-based power system

The layout identified under the FUELEAP program was used as a basis for the integration assessment for this FAA program. The SOFC-based power system was configured [2] in the envelope to keep the highest temperature components away from the pilot or passengers of the aircraft. The SOFC-based power plant, battery system, insulation, firewall, and ventilation were targeted for this area. The layout overview internal to the aircraft is shown in figure 3.

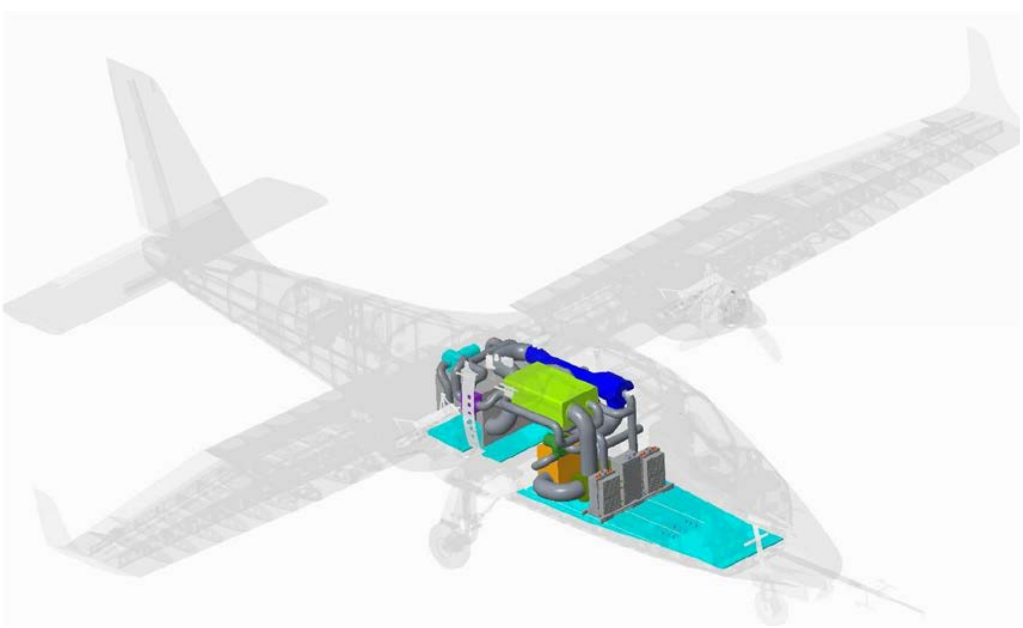

Figure 3. Hybridized SOFC system layout in aircraft

2.2 FUELEAP SOFC-BASED POWER SYSTEM OVERVIEW

A hybrid power system [3] comprised of an SOFC operating as the primary electrical power source and a rechargeable battery for supplemental power is envisioned for both the FUELEAP demonstrator and future commercial aircraft systems. For the FUELEAP demonstrator system, the SOFC will be sized to provide the cruise propulsion power and power to recharge the battery. The battery will provide the additional power required for take-off and climb, coasting power in the event of a fuel cell system emergency shutdown, and power for sudden power demands. Figure 4 shows the proposed system configuration.

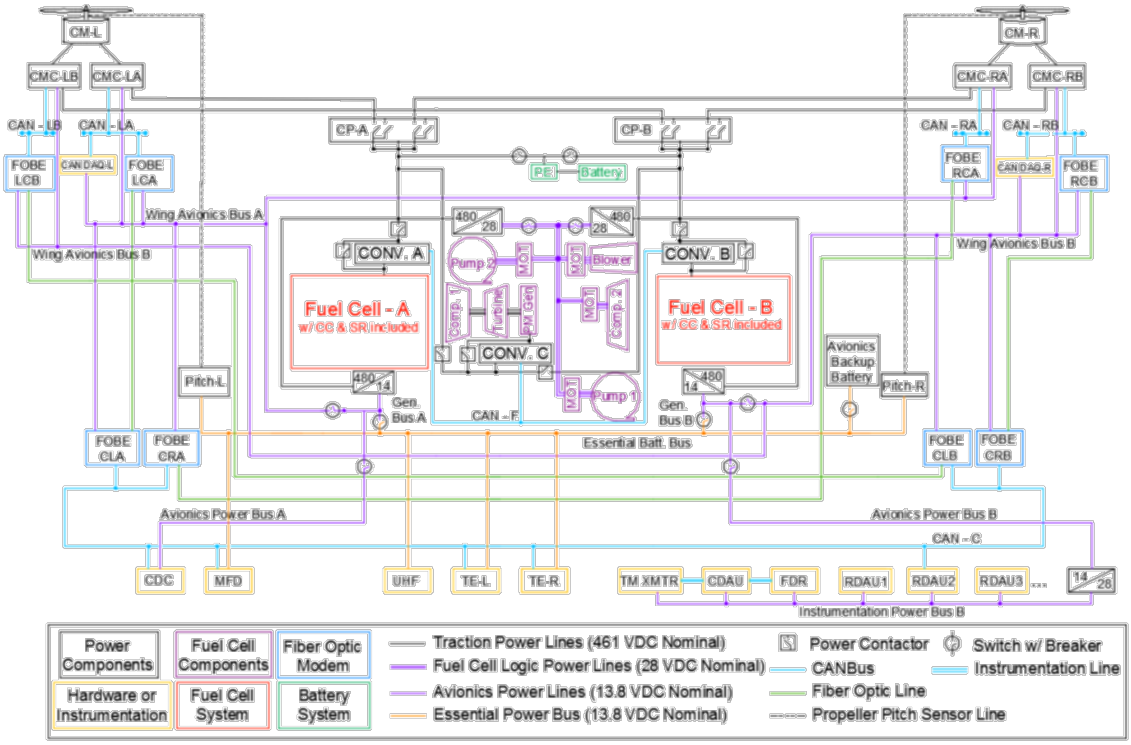

Figure 4. FUELEAP hybrid power system architecture

Both the SOFC and the high voltage batteries are tied to a high voltage bus, which powers the inverter that drives the electrical propulsion motor. The SOFC's output is regulated to provide appropriate voltage to the inverter. The SOFC system uses turbomachinery, which incorporates a motor and generator. A starter/regulator unit powers the motor during startup conditions and regulates the power from the generator during normal operation, therefore providing extra power to the high voltage bus. The aircraft's low voltage bus is retained to power the aircraft's heritage loads and instruments. The low voltage bus is powered from the high voltage bus via a regulator and has a battery backup.

The process flow and layout for the SOFC-based power system is shown in figure 5. Use of a low sulfur fuel or desulfurized fuel is needed to meet weight and performance targets for a flight SOFC system. This can be accomplished on the ground, using a ground cart desulfurization system to remove sulfur prior to loading the vehicle; however, this approach would require additional infrastructure at the airport. Steam reformation has been selected for the demonstrator application

because of the potential for increased overall system efficiency compared to an auto-thermal reformation- (ATR) based system. Steam reformation adds complexity to the system and requires further technology development for flight use. Fuel reformation for an SOFC provides hydrogen and carbon monoxide along with some unusable, but benign, byproducts to the SOFC stacks. As the stacks generate power, the effluent, which includes unused fuel and air, water vapor, and carbon dioxide, is either recirculated back to the fuel cell to be used by the reformer or directed to the combustion chamber. The catalytic combustion chamber, which reaches ~950°C, provides heat for steam reformation, with the remainder used by a turbine to generate additional power. The SOFC power system targeted for light aircraft application does not require liquid cooling, which would normally support an internal combustion engine. Depending on the system design, either waste heat can be exhausted directly overboard or a ram air heat exchanger can be incorporated to reject additional heat to ambient [1].

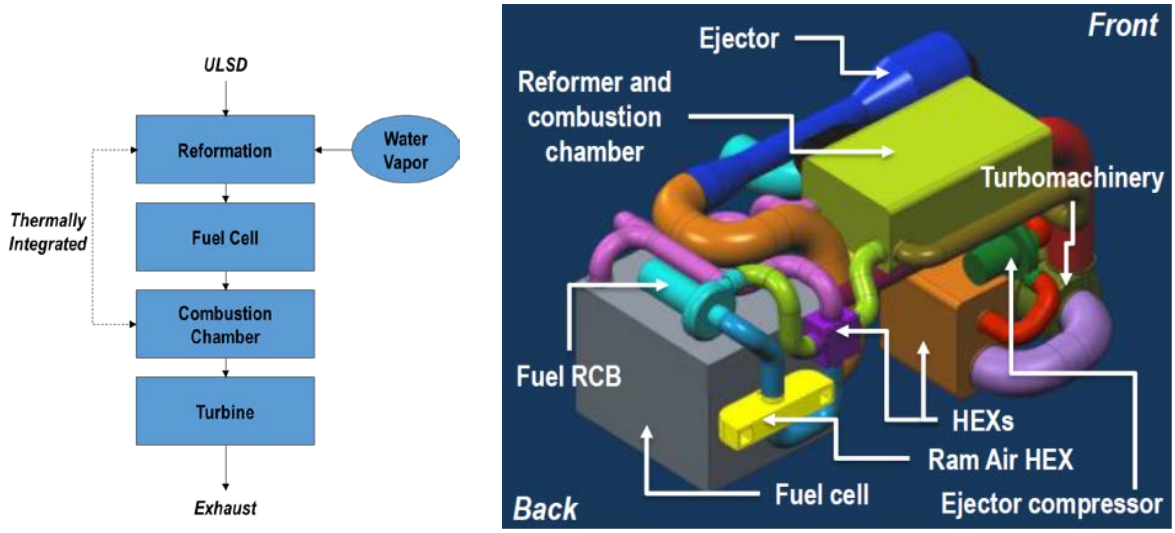

Figure 5. SOFC power system process flow and layout

3. HYBRIDIZED SOFC POWER SYSTEM AIRCRAFT INTEGRATION

3.1 REQUIREMENTS ASSESSMENT FOR SOFC-BASED POWER SYSTEM

Under the FAA project "Evaluation of a Lightweight Fuel Cell Containment System for Aircraft Safety," Boeing reviewed existing light aircraft Title 14 Code of Federal Regulations (CFR) Part 23 regulations [4] to ascertain commonality of existing aircraft requirements to an SOFC power system. Table 1 shows a generalized overview of similarities/differences between existing aircraft power system functions and future SOFC systems. Two main differences are the cooling of the unit and the location. Light aircraft engines are usually cooled by both incoming air and liquid cooling systems (oil and glycol-type coolant), whereas the targeted SOFC system is designed to only be cooled by incoming air. The SOFC system is expected to have a larger volume than a standard engine and will be a single-power unit in the fuselage instead of in a wing nacelle or in the nose of a light commuter aircraft.

Table 1. Comparison of standard 14 CFR 23 aircraft propulsion systems and SOFC-based hybrid power system functions

Function	Standard Engine, Turbine, or APU System	SOFC
Fuel	Avgas/Mogas	Multiple available: Desulfurized liquid fuel (Jet A, JP8, etc.)
Oxidizer	Air	Air
Power Production	Combustion driven rotating machinery	Solid state electrochemical reaction (both battery and fuel cell)
Cooling	Oil cooling, glycol/coolant cooling & air cooled	Air cooled system planned, although it is possible that future battery systems could incorporate liquid cooling
Compression	Compression integrated into engine	Compressor separate unit in power system
Operating temperature	~1500–2000F	~1350–1600F
Location	Nacelles under wing directly coupled to propellers	Inside Fuselage, providing power to separate electric motors in wing.
# of Engines (for Tecnam)	2 ICE	Hybrid SOFC with Battery for Backup/Peak loads

APU = Auxiliary power unit

Although an SOFC/battery hybrid system providing power to light aircraft would be unique, many safety hazards for an SOFC system would be similar to those found for existing propulsion systems operating at high temperatures with similar liquid fuels. Table 2 breaks down the main components of the SOFC hybrid power system in comparison to components with existing flight history. Many components for the SOFC hybrid power system are similar to flown components, with design requirements already covered by traditional aircraft engines and auxiliary power systems. For example, there is a significant amount of historical data behind flight systems using turbines and compressors. The components analyzed for the FUELEAP power system used data from existing hardware that could be used for flight. Depending on changes to the future power system configuration, a turbine or compressor might need to be resized from existing available hardware; therefore, the turbine and compressor are listed in both the “SOFC System Components with Flight History” and “SOFC System Components Similar to Flown” columns in table 2.

Table 2. Summary of component flight history relevance

SOFC System Components with Flight History	SOFC System Components Similar to Flown	SOFC System Components with Minimal Flight History
Low & mid temp fluid components (Fuel pumps, fluid valves, etc.)	High temperature HEX	Solid Oxide Fuel Cell Stacks (planar design)
Low/mid temp instrumentation	High temperature fluid connections	Steam reformer
RAM HEX (some)	Medium Temp Gas Blowers (some)	Medium Temp Gas Blowers (some)
Turbine (some)	Mid temp electrical connections	System control software
Compressor (some)	Generator	High temp electrical connections (some)
Low/mid Temp HEX	RAM HEX (some)	
Insulation	Turbine (some)	
Electronic control equipment	Compressor (some)	
Component control software	High temp electrical connections (some)	

HEX = Heat Exchanger

Many of the low temperature components and the control software available for those components that would be used in a hybridized SOFC power system are readily available from existing flight qualified hardware. However, once integrated into a power system, it would be critical to develop and test the system responses and control of the system for safety of flight, including off-nominal flight conditions. The obvious components that have little or no flight history are the SOFC stacks and reformation hardware. Although limited SOFC and reformation systems have been operated from a mobile ground vehicle [5] or on small micro-tubular-based SOFC Unmanned Aerial Vehicle [6] demonstrators, there are no data that would be directly comparable to the targeted flight application. Significant development and testing of the SOFC and reformer would be required for a flight application.

Although some components, such as an SOFC stack and reformer, are not specified in the 14 CFR 23 requirements, the hazards associated with those components and rules to ensure safety are similar to existing engine requirements. Most of the regulations that would be required to implement a future SOFC system are already in place for existing technology, and only minor changes to include SOFC systems are needed. For example, most of the rules associated with an engine fire or high temperature failure would be directly applicable to a high temperature failure in an SOFC stack.

An SOFC-based power system, including a battery hybridized SOFC-based power system, has many similar failure modes for which protections are already captured through 14 CFR 23 requirements. By including an SOFC into some of the existing sections for engine requirements, safety design requirements for an SOFC hybrid system would be covered. This is primarily due to

the fact that although an SOFC-based system would operate differently than an ICE, most of the system interfaces are similar as they are both higher operating temperature liquid fueled, external air flow supported systems. Some of the existing ICE engine interfaces, such as various cooling loops, would not be necessary with an SOFC-based system; however, an SOFC-based system would not have the performance and failure history of a standard engine system. Some examples of existing engine requirements [4] that would be directly applicable to an SOFC-based system are as follows:

- Fuel line & fuel feed design requirements (e.g. "In each area where flammable fluids or vapors might escape by leakage of a fluid system, there must be means to minimize the probability of ignition of the fluids and vapors, and the resultant hazard if ignition does occur.")
- Firewall compartment design requirements (e.g. "Each engine, auxiliary power unit, fuel burning heater, and other combustion equipment, must be isolated from the rest of the airplane by firewalls, shrouds, or equivalent means.")
- Flammability and fire sensing requirements (e.g. "There must be means that ensure the prompt detection of a fire in … Airplanes with engine(s) located where they are not readily visible from the cockpit")
- Air duct design and location and design (e.g. "The airplane must be designed to prevent water or slush on the runway, taxiway, or other airport operating surfaces from being directed into the engine or auxiliary power unit air intake ducts in hazardous quantities. The air intake ducts must be located or protected so as to minimize the hazard of ingestion of foreign matter during takeoff, landing, and taxiing.")
- Electrical system design and protection (e.g. "Electric power sources, their transmission cables, and their associated control and protective devices, must be able to furnish the required power at the proper voltage to each load circuit essential for safe operation")
- Battery system design and safe operation (e.g. "Safe cell temperatures and pressures must be maintained during any probable charging and discharging condition. No uncontrolled increase in cell temperature may result when the battery is recharged [after previous complete discharge.])

The vast majority of existing safety regulations for internal combustion, turboprop, turbine, and APU power sources are applicable to a future SOFC system. Only minor language changes, such as updating the terminology of "engine" to include SOFC or to use the more inclusive term of "power plant" or a similar equivalent, are necessary to incorporate a liquid fueled SOFC. Areas of regulations, including existing power loss, structural loads, performance, flammable fluid, fire protection, and other requirements, are directly applicable to an SOFC power system. The majority of electrical design and battery safety regulations are directly applicable to an SOFC hybrid power system with only minimal changes to wording. For a hybrid SOFC/battery, definitions would need to be updated to clarify the existing regulations in regard to using both SOFC and battery power in parallel, rather than the battery as only a starter and backup system. Examples of modifications that might be needed for 14 CFR 23 are listed in table 3. The performance limitations identified in the Airplane Flight Manual and Approved Manual Material would also need to be updated based on the SOFC/battery system's detailed testing and operational history specific to the system configuration.

Table 3. Standard 14 CFR 23 aircraft example modifications for including SOFC-based hybrid systems

Section	Example Changes for Incorporation of an SOFC-Based Power System into 14 CFR 23
All Sections	Terminology change to be inclusive of SOFC-based power systems. For example, change unique engine specific call-outs such as “reciprocating engine-powered airplane of more than 6,000 pounds maximum weight, single-engine turbine, and multiengine turbine airplanes of 6,000 pounds or less maximum weight” to include alternative power systems. In all sections, one suggestion would be to change the word “engine” to “power plant” or redefine the word “engine” to include an SOFC-based system.
§23.361 Engine torque, 23.363 Side load on Engine Mount, 23.371 Gyroscopic & Aerodynamic loads	Terminology change to include systems where engine is not directly physically coupled to motors. Mounting requirements for propellers driven by electric motors would be distinct from power system mounting requirements.
§23.903 Engines.	Terminology would need to be updated to include SOFC/battery hybrid system as a “power plant” which would fall under most of the same regulations where applicable as “Engines” or auxiliary power units. For example, existing regulations regarding firewall, component failures not cascading, compressor, and installation are directly applicable. Definition of “starting and stopping” for an SOFC/battery hybrid system would have to be reconsidered as the SOFC system may not have a traditional rotating component producing power. An alternate approach would be to make a separate subcategory for SOFC specific requirements. This would be similar to how there are separate call-outs for engine turboprop or turbocharger specific requirements.
§23.909 Turbocharger systems.	Although it is not necessary, a separate category similar to the one called out for Turbocharger Systems could be made to consolidate existing requirements that are applicable to an SOFC system into one section.

Table 3. Standard part 23 aircraft example modifications for including SOFC-based hybrid systems (continued)

Section	Example Changes for Incorporation of an SOFC-Based Power System into 14 CFR 23
§23.951 General (Fuel System)	Existing fuel system requirements are considered to be directly applicable to a SOFC system with minor terminology modifications (i.e., changing “engine” to a more general term such as “power plant,” changing “engine starting” to “power plant activation.”)
§23.1043 Cooling tests.	Terminology change to include SOFC power systems where currently “engine” specifically called out or a separate section for SOFC/battery system testing needed.
§23.1047 Cooling test procedures for reciprocating engine powered airplanes.	Terminology change to include SOFC power systems where “engine” is called out, or a separate section for SOFC/battery system testing needed.
Liquid Cooling	The SOFC power plant itself does not need liquid cooling, however it is possible that the battery portion of the hybrid system may need liquid cooling depending on the specific installation into the aircraft. This section could be updated to call out “power plant” instead of “engine” to accommodate the hybrid system into existing requirements.
§23.1103 Induction system ducts.	Terminology change to include SOFC power systems where “auxiliary power unit” is called out. Backfire is not a concern for SOFC power systems.
§23.1143 Engine controls.	Terminology change to include SOFC power systems where “engine” is called out. Also, in an SOFC hybrid power system, a single power plant may control multiple propellers, which are electrically driven. Although the intent of the regulations would remain intact (i.e., positive and immediate response), the terminology would have to be updated to include the electrically driven system approach.
§23.1145 Ignition switches.	The hybrid SOFC system will not have a standard ignition circuit and would need different terminology for power plant shut-off.
§23.1163 Power plant accessories.	A hybrid SOFC system would not be able to utilize most traditional power plant accessories. It is likely that most accessories would be powered electrically via the bus.

Table 3. Standard part 23 aircraft example modifications for including SOFC-based hybrid systems (continued)

Section	Example Changes for Incorporation of an SOFC-Based Power System into 14 CFR 23
§23.1165 Engine ignition systems	A hybrid SOFC system would use the SOFC itself to recharge the battery system during use. Also the traditional approach of ignition would not apply with an SOFC system. This section would have either a large amount of terminology change or a separate section added to describe similar reliability requirements for activating an SOFC system.
§23.1181 Designated fire zones	The SOFC high temperature section would need to be designated as a fire zone.
§23.1189 Shutoff means	Terminology change to include SOFC power systems where "engine" is specifically called out. In an SOFC hybrid power system, a single power plant may control multiple propellers, which are electrically driven. Additional terminology may be needed to differentiate between an SOFC power plant shut-off versus an electrical motor shut-off. The intent to be able to safely shut-off fuel or power to a failed portion of the system would still be maintained.
§23.1195 Fire extinguishing systems	Terminology change to include SOFC power systems where "engine" is specifically called out. Clarification will be needed as to fire extinguishing system needed for "auxiliary power unit compartment" versus an SOFC power plant installed as a main power system.
§23.1305 Power plant instruments	Suggest to add section (f) to identify SOFC power system-specific minimum instrumentation: fuel quantity, fire warning, SOFC voltage indicators, battery voltage indicators; SOFC unit power output, battery power output, battery charge level, reformer exhaust temperature, stack exhaust temperature, turbo compressor rpm, SOFC system pressure, fuel flow, fuel filter indication, air inlet temperature, propeller rpm, and heater functionality indicator. Sensors would be dependent on final SOFC hybrid power system configuration.
§23.1353 Storage battery design and installation	Suggest clarification of "primary" electrical systems for a hybridized SOFC/battery system operation where both the battery and SOFC provide power for normal flight.

Table 3. Standard part 23 aircraft example modifications for including SOFC-based hybrid systems (continued)

Section	Example Changes for Incorporation of an SOFC-Based Power System into 14 CFR 23
§23.1521 Power plant limitations	SOFC hybrid power system will generally be limited by temperatures, pressures and charge/power production rates. This section will need to be updated based on the final system configuration installed into the aircraft. Although the system studied under this effort is for pressurized operation, other potential SOFC-based systems may operate at near ambient pressures depending on the system design. The terminology also needs to be changed to include SOFC power systems where "engine" is specifically called out.
§23.1581 General (Airplane Flight Manual and Approved Manual Material)	Throughout this section, the terminology should be changed to include SOFC power systems where "engine" is specifically called out. The design and operating information in the manual will need to reflect any installed SOFC hybrid power system.

3.2 PHYSICAL INTEGRATION ASSESSMENT FOR SOFC-BASED POWER SYSTEM

An integration of a hybridized SOFC-based power system into an aircraft is not a drop in replacement and would affect multiple aspects of the target application.

The X-57 Mod 2 flight demonstrator is initially certified up to an altitude of 15,000 ft mean sea level (MSL), which was the focus of the FUELEAP study. Depending on the configuration, 14 CFR 23 type aircraft may be able to fly as high as 25,000 ft MSL without significant modification. A hybridized SOFC-based power system could be designed to support the full 25,000 ft altitude, although this was outside the scope of the FUELEAP target application. Typical cruise altitudes for the FUELEAP application are between 5,000 and 10,000 ft MSL. Flight performance requirements, such as climb and glide, would be similar between a conventional propulsion system and an SOFC-based power system driven aircraft.

The hybridized SOFC power system has the majority of its power produced electrochemically and has a more extensive electrical system than a standard ICE engine. Both higher voltage and lower voltage buses are incorporated with multiple power sources (i.e. SOFC, battery, generator) and different load distribution approaches, as identified in figure 4. A single hybrid SOFC power system supplies the power usually generated by two separate engines. Power[2] used to size the FUELEAP system is shown in table 4. Because there is a single hybrid power system, the system must be designed with the intent of redundancy so that safe flight is achieved even if there are component failures within the system.

Table 4. Power system sizing requirements

Mission Phase	Duration	Motor Shaft Power, each	Power System Output
Takeoff/Initial Climb	2 – 5 min	72.1 kW	158 kW
Cruise Climb	10 min	60.0 kW	131 kW
Cruise	Indefinite	50. kW	110 kW

The 14 CFR 23 regulations delineate between high or low voltage bus requirements. Even though the hybridized SOFC power system will operate a higher voltage bus, the design of the higher voltage system is bounded by existing commercial and military flight electrical design specifications.

Structural and load requirements in 14 CFR 23 regulations for power systems mounted in the fuselage of an aircraft would be applicable to the hybridized SOFC power system. This would include design factor of safety, nominal loads, vibration, crash loads, and mounting.

3.2.1 Expected Interfaces for Hybrid SOFC Power System

Necessary interfaces for an SOFC-based power system are expected to be similar for both the targeted demonstrator and future commercial aircraft systems. Interfaces between an SOFC-based power system and the environment, ground cart, or vehicle include:

- Access for installation, checkout, and maintenance
- Fluid interfaces:
    - Air intake, primarily for SOFC reactant. Some smaller portion of air intake might be necessary for cooling flow for power and control electronics. The SOFC stack and fluid components are not expected to need additional cooling flow beyond what is fed through the stack and system.
    - Fuel inlet, from fuel tank(s)
    - Exhaust port(s)
    - Cooling fluid, if needed
    - Ground support fluid connections for startup and shutdown (demonstrator only): variable temperature air inlet, variable temperature gaseous fuel (hydrogen and helium or nitrogen mixture) inlet, air exhaust, and fuel exhaust.
    - Fire suppression system, dependent on system location, system design, and testing of controllability of fire containment.
- Mechanical interfaces for mounting and support (notional layout for FUELEAP demonstrator, as shown in figure 8). Mechanical interfaces will support the SOFC system for the following:
    - Thermal isolation
    - Electrical isolation
    - Vibration/shock isolation and dampening

- Instrumentation (see table 5)
- Electrical power from ground support to start or checkout (if necessary)
- Electrical interfaces from/to the vehicle (see table 6)

Table 5. SOFC system instrumentation

Temperature	Pressure	Power	Miscellaneous
Compressor exit	Compressor inlet	SOFC stack current /voltages*	Turbomachinery speed*
Turbine inlet	Compressor exit	Generator current /voltage*	RCB speed
Turbine exit	Fuel pump exit	Battery current /voltage*	Fuel pump speed
Reformer exit	SOFC Stack*		Fuel flow rate
Catalytic combustor exit			Accelerometer
Bearings for RCB and turbomachinery			Controller health & system monitoring*
Stack inlet			Back-up fan speed
Stack exit*			
SOFC area external temps*			

RCB = Recycle blower

** Expected to be needed for pilot indication in future commercial aircraft operation*

Table 6. SOFC demonstrator electrical interfaces

Description	Type	Comments
Traction Power Bus A	Power	High voltage power bus (redundant) supported by SOFC stacks, battery and generator in SOFC system
Traction Power Bus B	Power	
Altitude	Input Data	
Air Temperature	Input Data	
Air Speed	Input Data	
Power Required	Input Load	
SOFC System Data/Instrumentation	Output Data	See table 5
Ground Power	Power	Power used for maintenance/checkout for future aircraft; used for ground start on demonstrator
Pilot Commands for SOFC system controls	Command	Commands to start and shut down system and to operate in emergency modes in case of component failures

Caution and warning indicators for a pilot of an SOFC powered aircraft will need similar indicators for safety as those used for a standard ICE powered aircraft. The caution and warning indicators would be in addition to the instrumentation listed in table 5, or the result of the instrumentation data processed for the caution and warning display. Caution and warning lights (i.e., green, amber, and red) may be necessary for a hybrid SOFC power system for the following indicators:

- SOFC Power System Health Indicator
- SOFC Power Generator Health Indicator
- Fuel Pump Health Indicator
- Compressor Health Indicator
- SOFC System Fire Indicator

4. SOFC SYSTEM FAILURE ANALYSIS

More detailed data on the failure analysis can be found in the Boeing Proprietary Appendix A to this report.

4.1 SOFC POWER SYSTEM FAILURE ASSESSMENT

A system level failure assessment was performed on the sample SOFC Power system described in section 3.0. As many of the components are similar to ones previously used in aerospace applications, many of the failure modes are well understood. Specific failure mode possibilities and probabilities are highly dependent on the final configuration of the SOFC power system and the design of the specific components. Examples of possible failure modes for components are listed in table 7.

Table 7. Sample SOFC power system component failure modes

Sample SOFC Power System Components	Sample Component Failure Modes
SOFC Stacks	Internal or external gas leakage causing overheating above fuel auto-ignition temperature (AIT) or explosive mixture below AIT, external gas leakage of hazardous gas, fouling causing loss of performance or increased pressure drop, electrical overload causing performance loss, electrical shorting of stack
Steam Reformer	Fouling causing reduced performance or increased pressure drop, internal leakage of gas causing reduced performance, external leakage of fuel or hazardous gas
Fuel pumps / coolant pumps	Stoppage of flow, leakage of fluid externally, reduced pump flow
Turbo-compressor	Turbine-compressor (T/C) wheels seizing, T/C wheels cracking or producing shrapnel, leakage of oil, leakage of gas, overheating, loss of control
Heat Exchangers	HEX fouling causing blockage, increased pressure drop or reduced effectiveness, internal leakage of gas/liquid, external leakage of gas/liquid
Sensors	Erroneous reading, off-scale reading, breaking of sensor parts causing debris into fluid flow
Blowers	Blower wheels seizing, blower wheels cracking or producing debris, leakage of gas, overheating, loss of control
High temperature electrical connectors / wiring	Shorting/arcing, overheating, leakage of gas/liquid if penetrating fluid barrier, increased resistance due to corrosion
Fluid valves	Failed open, failed shut, leakage through valve, leakage external from valve
Fluid lines	Fouling or blockage reducing flow, leakage, burst of line
Insulation	Loss of heat capacity due to mechanical failure, degradation
Battery	Battery failure resulting in thermal runaway, loss of performance, battery hazardous outgassing, shorting

Safety of flight for any aircraft depends on minimizing and controlling any potential catastrophic failures of an aircraft. A catastrophic failure is defined as one that could result in multiple fatalities of aircraft occupants or incapacitation or fatal injury to a flight crewmember normally with the loss of the airplane. Many of the existing 14 CFR 23 requirements are put in place to restrict designs that would result in a catastrophic failure and to provide design guidance toward system redundancy and reliability based on flight operations. Based on the aircraft power system design, some power system component failures would be benign, whereas others, if not controlled, could be catastrophic. Failures with a higher criticality would be those that occur suddenly, reducing any pilot or system reaction time and that have the potential to cause significant damage, or propagate

to the point where they can cause significant damage to the aircraft. Some examples of a critical failure would be uncontrolled fire or a sudden loss of power.

Failure modes newly introduced to a lightweight aircraft by an SOFC-based power system would be associated with components of the system with minimal flight history. As mentioned in table 2, the components in this category would be the SOFC stacks, steam reformer, and the software used to control the system. A brief overview of the SOFC stack and steam reformation technology are discussed below. Control software would be highly variable and is considered beyond the scope of this assessment.

There are multiple types of fuel reformation; steam reformation was studied for this example system. Steam reformation occurs at temperatures ~600°C and uses incoming fuel mixed with steam to break down the higher hydrocarbons in the fuel in the presence of a catalyst. The reaction is endothermic and requires a heat source, either from the incoming fluids or an external heat source, to be stable. Steam reformers are typically passive devices with large internal surface areas for the reaction. Valves and heaters control the flow going to the reformer, although heaters can also be integrated into the reformer unit itself. Figure 6 shows an example of a steam reformer developed by Precision Combustion, Inc. [7]. In a steam reformer, any internal leakage would be between the fuel and steam flows, which would not be a combustible mixture. The worst-case failure mode for a steam reformer would be that of fuel externally to ambient. This is considered a lower probability, as most reformer units use metal components with limited sealing surfaces in the design.

Figure 6. Catalytic steam methane reformer from PCI (7.5 kWth)

Planar designed SOFC stacks were assumed for this study, as they have the potential to provide lower volume for higher power out than tubular SOFC technology. Figure 7 shows example planar SOFC stacks made by OxEon Energy [8], as well as a close-up of flow within the stack. In planar SOFC stacks, individual cells are stacked up in series with interconnect plates in-between. Fuel flows across one side of the cell and oxidant flows across the other side. The fuel and oxidant streams are separated by seals on each side of each cell, as well as seals separating the fuel streams from surrounding environment. Planar SOFC stack designs vary greatly, but all require sealing on each side of each cell. Because both air and fuel are flowing in close proximity in an SOFC stack, it is a worst-case failure location for leakage than a steam reformer.

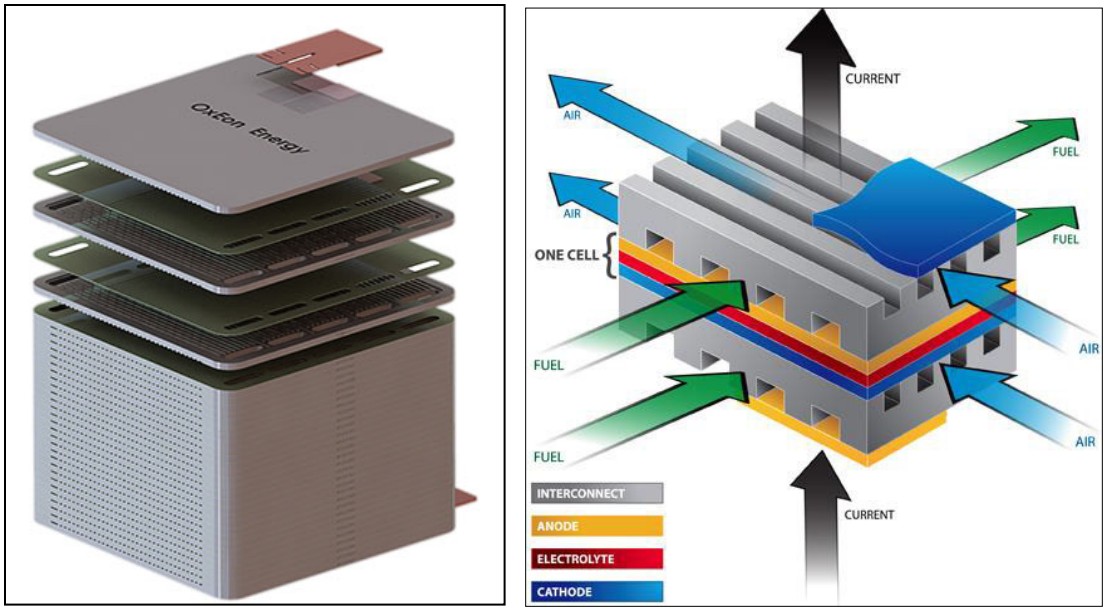

Figure 7. Example SOFC Planar stack & flows in a cell by OxEon Energy

SOFC technology operates at high temperatures, between 600° to 1000°C, depending on the stack design. These temperatures are above the AIT of most fuels. Historically, most failures internal to SOFC stacks are slow to develop and occur over tens or hundreds of hours of operation. SOFC planar stack technology is considered to be at a lower technology readiness level than Proton Exchange Membrane Fuel Cell technology, which has already been commercialized in automobiles.

Assessment of the SOFC power system failure modes, in conjunction with the amount of similar flight or non-flight data available on component failures, identified the worst-case failures to be those capable of causing a fire or explosion. Of the components introduced by an SOFC power system, the SOFC stack component was determined to have one of the higher probabilities of being a source of a critical failure, mainly due to the lack of development data, the amount of sealing surfaces, and the availability of both a fuel and oxidizer being used in the component.

4.2 SOFC SYSTEM HIGH TEMPERATURE LEAKAGE FAILURE ASSESSMENT

Analysis of SOFC power system additional worst-case failure modes introduced by SOFC technology, such as high temperature leakage and material degradation of the SOFC stack, was performed. The purpose of the analysis was to help better understand any potential damage that could be introduced by a worst-case SOFC failure scenario. As discussed previously, the worst-case SOFC system failure scenario is assessed as a leakage between the fuel and oxidant in the SOFC stack.

Two primary leakage scenarios were identified for SOFC failures, based on the temperature at which the leakage occurred:

1. At leakage above the fuel AITs, a worst-case leakage could result in a sustained flame of burning gas producing a heat flux that may heat surrounding structures to the point of failure.
2. At leakage below the fuel auto-ignition temperatures, a worst-case leakage could result in rapid combustion producing a pressure load that may damage surrounding structures from overpressure.

A liquid fueled SOFC-based power system would be using a fuel reformation process to break down the higher hydrocarbon chains into a mixture usable for an SOFC cell (e.g., mixture of hydrogen, methane, carbon monoxide, carbon dioxide, steam, and nitrogen). The actual percentage of each species would vary greatly depending on the type of reformation used (i.e. Catalytic Partial Oxidation, ATR, or Steam). For the analysis, a steam reformation case was used to represent a nominal fuel mixture that would be input to the SOFC, and a pure hydrogen case was used to represent an upper bound of the maximum energy that could be released in a failure. It should be noted that no hydrocarbon liquid fueled SOFC would be using pure hydrogen as a fuel; therefore, the pure hydrogen case is not a realistic scenario for this application.

4.2.1 Sustained Flame Scenario

SOFC electrolyte becomes electrochemically active at high temperatures, generally between 600–1000°C. This operating temperature is above the 536°C AIT of hydrogen and the 200–300°C AIT of other liquid hydrocarbon based fuels; therefore, at SOFC operating temperatures, any quantity of fuel and oxidant mixing from leakage immediately reacts to produce heat and water. The lower explosion limit and higher explosion limit of a fuel/oxidant mixture does not apply above the AIT since any fuel and oxidant immediately reacts. In this manner, at SOFC operating temperatures no buildup of fuel and oxidant is possible, removing the hazard of an explosive mixture forming. Instead, the worst-case failure scenario of a leakage would result in a sustained heat source at the leak site from the resultant continuous combustion reaction between the leaking fuel and oxidant. The analysis for this scenario is discussed further as a sustained flame failure case.

4.2.1.1 Sustained Flame Analysis Approach

A sustained flame failure case is when a pressurized reservoir of fuel gas mixture, as specified by molecular molar ratios x_1 at pressure p_1 and temperature T_1, is leaking into a surrounding atmosphere with molecular molar ratios x_2 at pressure p_2 and temperature T_2 through an orifice of diameter d. This scenario is shown in figure 8. In this scenario, the system is operating above the AIT, and combustion will instantaneously occur when the fuel and oxidizer are mixed together. This will result in the creation of a diffusion flame centered at the region of fuel leakage. Therefore, in this scenario, there will be no build-up of fuel or potential for large pressure effects. Instead, there will be a constant or sustained thermal impact as the fuel combusts and releases energy. This thermal energy will be divided among 1) heating the baseplate through which the fuel is leaking, ($\dot{q}_{base}$), 2) radiation ($\dot{q}_{rad}$), and 3) heating of the surroundings ($\dot{q}_{other}$). The following analysis is primarily concerned with estimating the magnitude of these heat flux terms.

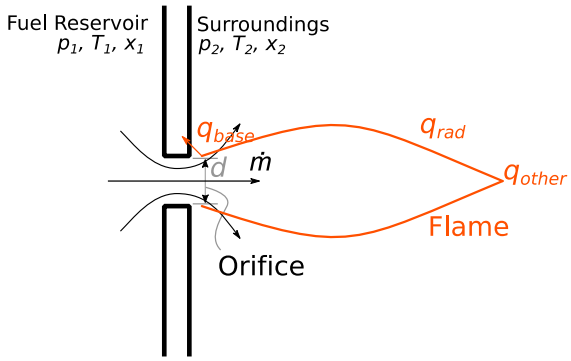

Figure 8. Important parameters in determining heat loads to surrounding structures

The conditions considered in estimating the heat flux are:

Fuel, x_1. Two extremes were considered for the fuel that could be leaking:

1. Reformed fuel gas flow: A mixture of 28.5% hydrogen, 21.0% carbon monoxide, 27.6% water, 22.8% carbon dioxide, and 0.1% methane by volume.
2. Pure (100%) hydrogen representing the absolute worst potential mixture from a combustion safety point-of-view.

Oxidizer, x_2. The surrounding atmosphere is air; for this analysis, air was taken to be exactly 21% oxygen, 79% nitrogen.

Reservoir Pressure, p_1. Two cases were considered for the reservoir pressure:

1. 45 psia (310.3 kPa), the higher pressure case.
2. 20 psia (137.9 kPa), the lower pressure case.

Note that the greater reservoir pressures result in greater fuel flow rates and consequently greater heating, and, therefore, the maximum pressure case is the limiting case.

Surrounding Pressure, p_2. The surrounding atmosphere was considered to be at 1 atm (14.7 psia or 101.3 kPa).

Temperature, T. Both the initial unburned temperature and the temperature of the surroundings is $T_1 = T_2 = 800$ C for both the reservoir and surroundings. Note that this temperature is above the AIT for hydrogen, and, therefore, spontaneous combustion is expected upon mixing of the fuel and oxidizer.

4.2.1.2 Sustained Flame Analysis Method

The analysis to determine the heat flux loads was broken into three steps:

1. Calculate the properties of the flame's burned gas. These calculations were performed using the computational chemical kinetic software Cantera and the GRI-Mech 3.0[1] high temperature mechanism to provide realistic estimates of the thermodynamic properties of the flame.
2. Determine the mass flow rate of fuel as a function of orifice size and reservoir pressure using choked or isentropic flow equations as appropriate for the ratio of the reservoir pressure to the surrounding pressure. It should be noted that viscosity was not incorporated in this analysis and, therefore, the overall fuel leakage is overestimated. This produces a conservative estimate on the total heating that could occur.
3. Estimate the regions where the available thermal energy will be deposited. The available locations are:

    - Base plate through which gas is leaking
    - Radiation
    - Other nearby structures and/or heating of the gas

4.2.1.3 Sustained Flame Calculation of Flame Properties

The general chemical formula for complete combustion of the reformed gas flow is:

$$x_{\mathrm{H_2}}\mathrm{H_2} + x_{\mathrm{CO}}\mathrm{CO} + x_{\mathrm{H_2O}}\mathrm{H_2O} + x_{\mathrm{CO_2}}\mathrm{CO_2} + x_{\mathrm{CH_4}}\mathrm{CH_4} + x_{\mathrm{O_2}}(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow A\,\mathrm{H_2O} + B\mathrm{CO_2}$$

The coefficients are those appropriate for either the estimated composition of the reformed fuel gas ($x_{\mathrm{H_2}} = 0.285,\ x_{\mathrm{CO}} = 0.210,\ x_{\mathrm{H_2O}} = 0.276, x_{\mathrm{CO_2}} = 0.228, x_{\mathrm{CH_4}} = 0.001$) or for the limit case of pure hydrogen ($x_{\mathrm{H_2}} = 1,\ x_{\mathrm{CO}} = x_{\mathrm{H_2O}} = x_{\mathrm{CO_2}} = x_{\mathrm{CH_4}} = 0$). The adiabatic flame properties were calculated using the chemical kinetic software Cantera and the GRI Mech 3.0 high temperature chemical mechanism; these calculations provide the enthalpy of combustion for both the reformed fuel gas mixture, $\Delta h_{comb,rfgm}$, and for pure hydrogen, $\Delta h_{comb,H_2}$:

$$\Delta h_{comb,rfgm} = 5.8\ \frac{\mathrm{MJ}}{\text{kg-fuel}}$$

$$\Delta h_{comb,H_2} = 123\ \frac{\mathrm{MJ}}{\text{kg-fuel}}$$

Note that the reformed fuel gas mixture contains species that are denser and less energetic than hydrogen. This results in the reformed fuel gas mixture having an enthalpy of combustion that is only 5% that of pure hydrogen.

4.2.1.4 Sustained Flame Calculation of Mass Flow Rate

The mass flow rate of fuel was calculated as a function of the pressure drop, Δp, and the orifice diameter, d, assuming either choked flow ($M = 1$ through the orifice for Mach number M) or

[1] GRI-Mech 3.0 is an optimized mechanism designed to model natural gas combustion based on computational and experimental research sponsored by the Gas Research Institute, http://combustion.berkeley.edu/gri-mech/index.html

isentropic flow as appropriate given the pressure ratio. Specifically, if the pressure ratio across the orifice is less than the critical amount:

$$\frac{p_2}{p_1} < \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}}$$

where γ is the ratio of specific heats, then the flow is choked and $M = 1$. Otherwise, the Mach number, M, may be calculated assuming isentropic expansion:

$$M = \sqrt{\left[\left(\frac{p_1}{p_2}\right)^{(\gamma-1)/\gamma} - 1\right]\frac{2}{\gamma - 1}}$$

Once the Mach number is calculated for a given pressure drop, the mass flow rate per unit orifice area of diameter d may be calculated:

$$\frac{\dot{m}}{0.25\pi d^2} = p_1\sqrt{\frac{\gamma}{RT_0}}M\left(1 + \frac{(\gamma - 1)M^2}{2}\right)^{-(\gamma+1)/(2(\gamma-1))}$$

The results from this calculation using calculated parameters for the ratio of specific heats (γ) and gas constant (R) as given by Cantera are shown in figure 9. In this figure, the fuel mass flow rate is calculated using the thermodynamic parameters for both reformate gas and a worst-case pure hydrogen system at two different pressures. Observe that reformate gas has a substantially larger mass flow rate than pure hydrogen. This is largely caused by increased density of reformate gas ($\rho_{1,ref} = 0.68$ kg/m^3) relative to pure hydrogen ($\rho_{1,\mathrm{H}_2} = 0.06$ kg/m^3).

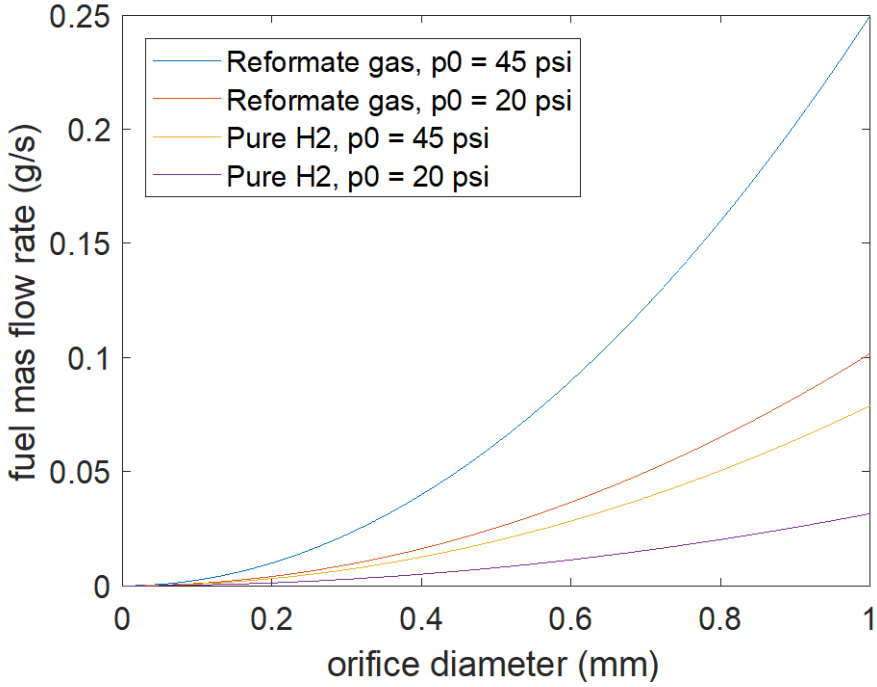

Figure 9. Calculated fuel mass flow rate based on leakage data

4.2.1.5 Sustained Flame Estimation of Heat Flux

Assuming sufficient oxygen exists to fully combust the fuel (such as would occur for a small leak), the total thermal power available for heating, $\dot{e}$, is only limited by the mass flow rate of fuel, $\dot{m}$, and the enthalpy of combustion, Δh_{comb}:

$$\dot{e} = \dot{m}\Delta h$$

This was calculated using the above-determined enthalpies of combustion and mass flow rates as a function of orifice diameter and reservoir pressure, with the calculated thermal powers shown in figure 10. These calculations show that the reformed gas releases approximately 85% less total thermal power than a pure hydrogen mixture stored at the same initial pressure. This reduction is primarily caused by the reduced enthalpy of combustion of the reformed gas relative to hydrogen.

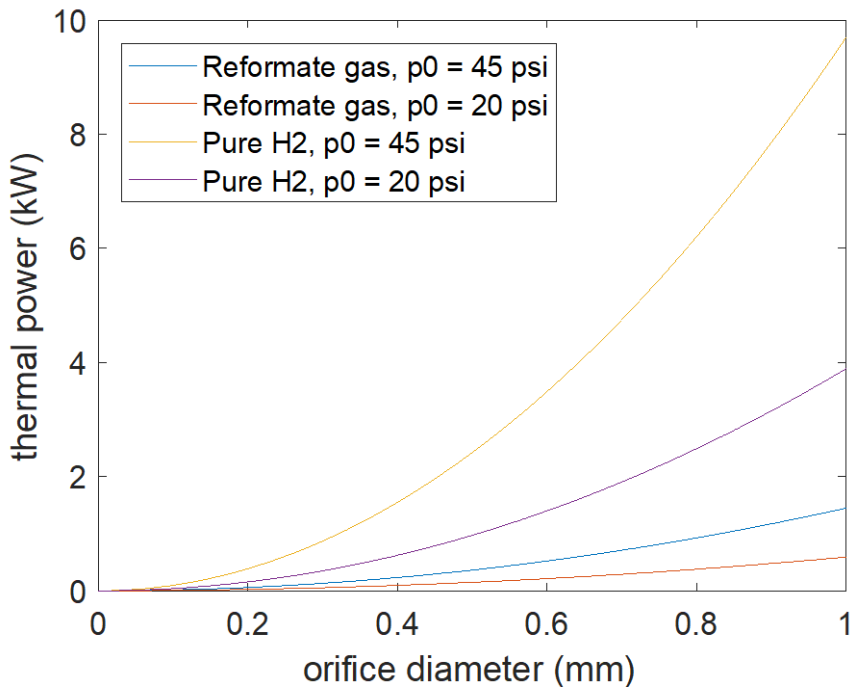

Figure 10. Total thermal power available in flame for different conditions

The total thermal power as calculated in figure 10 is transferred by the following methods:

- Heating the material, or baseplate, through which the fuel is leaking
- Radiating energy evenly in all directions
- Heating the surrounding gas
- Heating any other structures in the immediate vicinity of the flame

The distribution of heat among these destinations may not be calculated without knowing the full geometry and resulting flow field; however; rough estimates may be made based on general SOFC design assumptions:

- Baseplate: Examining the spreading angle of a turbulent flame and assuming that the region of interest for heating the baseplate is 1 orifice radius of fuel/air results in an estimation of 25% of the total thermal power going into heating the baseplate.
- Radiation: The radiation per unit length of flame may be estimated for different fuel mixtures and will largely be driven by soot generation. Limits of radiation for a sooty flame are generally estimated as approximately 25% of the total available power of the flame. Note that this is an approximate upper bound on the radiating power and is highly dependent on the flame properties (i.e., pure hydrogen flames will have less radiation as no soot is created[2]).

[2] Note the present discussion is an order-of-magnitude investigation applicable to generic conditions; multiple models exist capable of providing a more quantitative threat assessment relevant to specific conditions.

- The remaining 50% (approximately) of the total thermal power is then available for locally heating the gas and surrounding structures.

4.2.1.6 Sustained Flame Scenario Summary

An analysis has been performed examining the range of thermal loadings that could exist if a leakage of fuel into a hot air atmosphere occurred. Such a leakage of fuel would produce immediate spontaneous ignition of the fuel and the creation of a diffusion flame centered at the location of fuel leakage. The principle threat posed by a flame is the thermal load produced that may damage nearby structures and components. The total heat flux expected from such a flame was calculated for different fuel reservoir pressures (45 psia and 20 psia), fuel types (either reformate gas or pure hydrogen), and as a function of orifice diameter. It is noted that:

- Viscosity was not included in the above analysis. Incorporating viscosity will result in less fuel leaking out of a given sized orifice and consequently a decrease in actual thermal load. The effect of viscosity will increase as the orifice size is decreased.
- Pure hydrogen yields nearly 7 times the thermal load relative to the reformate gas under otherwise identical conditions. This is caused by the considerably higher heat of hydrogen combustion relative to the hydrogen-carbon monoxide-carbon dioxide-water-methane mixture that composes the reformate gas.
- Although the actual damage incurred by the flame would ultimately be dependent on the location of the flame and surrounding geometry, it is noted that the approximately 360 W released by the reformate gas leaking through a 0.5 mm-diameter orifice is a small thermal load relative to typical hazardous combustion processes.
- The actual geometry in which the leak occurs will strongly affect how the heat is dissipated into the surroundings. The thermal power of the flame will be most efficiently transferred to a structure if the flame directly impinges on the structure. Therefore, it is noteworthy that the flame length is only a function of orifice diameter, and not a function of the pressure drop across the orifice.

4.2.2 Rapid Combustion Scenario

4.2.2.1 Rapid Combustion Scenario Summary

Rapid combustion occurs when a pressurized reservoir of fuel of gas mixture, as specified by molecular molar ratio x_{fuel}, leaks into a surrounding atmosphere composed of air and ignition does not immediately occur, resulting in a pre-mixed combustible mixture defined by the pressure p_0, temperature T_0 and fuel-air equivalence ratio ϕ. After the creation of such a mixture, an ignition source would produce a propagating combustion wave that consumes the mixed fuel-air. The combusting gas will create elevated temperatures that may damage exposed structures and an overpressure that may damage containment. Unlike the sustained flame scenario considered above in which it was assumed that an unlimited amount of fuel may exist, in the case of rapid combustion, it is typical that the finite amount of flammable mixture results in the impulsive pressure load being a greater threat than the elevated temperature. This section examines the factors that affect the overpressure and calculate the upper bounds of such an overpressure.

The conditions considered in estimating the pressure load are:

Gas mixture, *x*. In practice, a localized leak of fuel into a volume of air would produce a range of fuel-air equivalence ratios with the gas near the leak having a higher fuel concentration than regions far from the leak. To examine the safety and range of such a leak's effects, the mixed case was examined wherein the entire volume is at a constant worst-case equivalence ratio.

Two fuels were considered and the range of overpressures as a function of equivalence ratio were examined for both:

1. Reformed fuel gas flow: A mixture of 28.5% hydrogen, 21.0% carbon monoxide, 27.6% water, 22.8% carbon dioxide, and 0.1% methane by volume. The chemical equation is:

$$x_{\mathrm{H_2}}\mathrm{H_2} + x_{\mathrm{CO}}\mathrm{CO} + x_{\mathrm{H_2O}}\mathrm{H_2O} + x_{\mathrm{CO_2}}\mathrm{CO_2} + x_{\mathrm{CH_4}}\mathrm{CH_4} + x_{\mathrm{O_2}}(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow A\ \mathrm{H_2O} + B\mathrm{CO_2}$$

Stoichiometric combustion occurs when:

$$x_{\mathrm{O_2}} = 0.5x_{\mathrm{H_2}} + x_{\mathrm{CO}} + 2x_{\mathrm{CH_4}}$$

And, therefore, the general initial chemical composition of equivalence ratio ϕ may be written as:

$$\phi 0.285\mathrm{H_2} + \phi 0.210\mathrm{CO} + \phi 0.276\mathrm{H_2O} + \phi 0.228\mathrm{CO_2} + \phi 0.001\mathrm{CH_4} + 0.3545(\mathrm{O_2} + 3.76\mathrm{N_2})$$

2. Pure (100%) hydrogen representing the absolute worst-potential mixture from a combustion safety point-of-view. The general initial chemical composition of equivalence ratio ϕ is:

$$\phi\mathrm{H_2} + 0.5(\mathrm{O_2} + 3.76\mathrm{N_2})$$

Initial Pressure, *p_0*. Two cases were considered for the initial pressure:

1. 45 psia (310.3 kPa), the maximum pressure case.
2. 14.7 psia (101.3 kPa), the atmospheric pressure case.

Note that increasing the initial pressure results in increased explosion overpressures and, therefore, the maximum pressure is the limiting case.

Initial Temperature, *T_0*. The unburned temperature of the gaseous mixture is an important parameter in determining the final overpressure that could be achieved in the event of an explosion. Given a fixed initial pressure, as the temperature increases, the density decreases and the stored energy decreases, resulting in a decrease in combustion pressure and, therefore, the minimum temperature is the limiting case. For the present analysis, the temperature was varied over the range $0^{\circ}\mathrm{C} \leq T_0 \leq 536^{\circ}\mathrm{C}$ with the intent to completely cover the range of temperatures that could occur. Note that 536°C is the AIT of hydrogen and is the upper bound of a premixed mixture.

4.2.2.2 Calculation of Constant Volume Explosion Pressure

If ignition occurs in a chamber containing mixed fuel and oxidizer, a flame would grow from the point of ignition and propagate to consume the entirety of the fuel/oxidizer mixture. As the flame

expands and consumes the reactants, the release of energy will result in an increase of pressure in the chamber. Multiple factors of the system design will affect the resulting pressure, including:

1. The degree of venting: A propagating combustion wave will produce a pressure that varies with time. If the chamber is not fluid-tight, the pressure in the chamber will vent as combustion occurs and the resulting explosion pressure will be decreased.
2. The degree of cooling: As the flame propagates, thermal energy will be lost to the surroundings. Per the ideal gas law, the cooling gas will decrease the pressure. Cooling is an important factor in small volumes or other volumes with a high surface area-to-volume ratio.
3. Flame acceleration: As the combustion wave propagates, it induces a flow field in the gas. If this flow field becomes turbulent, the time scale governing the mixing of the unburned reactants with the hot products decreases, therefore, producing an acceleration of the flame. Sufficient acceleration may produce a detonation through the deflagration-to-detonation transition (DDT) process; supersonic detonations are characterized by higher peak explosion pressures than subsonic flames. Even if DDT does not occur, flame acceleration will result in an increase in the combustion pressure because the mitigating factors of venting and cooling will be attenuated. Note that a smaller volume allows for less space in which the combustion wave may accelerate and, therefore, decreases the amount of flame acceleration that may occur.

To understand the range of overpressures that could exist and how the overpressure would be affected by the fuel type (reformate gas or hydrogen) and initial temperature, the constant volume (CV) explosion pressure was calculated. This theoretical pressure assumes complete combustion without cooling. It is the peak pressure that occurs behind a detonation wave and is the upper bound for deflagration waves. Although specialized circumstances such as DDT or reflected detonation may produce short-lived pressures in excess of the CV pressure, for most cases, it is a conservative estimate of the pressures that may be produced by a mixed combination of fuel and oxidizer.

The analysis method to determine the pressure loads was to calculate the CV explosion properties for the conditions specified for the rapid combustion scenario to determine the peak pressure that could be expected in an arbitrary volume. These calculations were performed using the computational chemical kinetic software Cantera and the GRI Mech 3.0 high temperature mechanism. The results of these calculations are shown in figures 11 and 12.

Figure 11 shows the CV explosion as a function of temperature for the different conditions of interest, calculated at a fuel-air equivalence ratio of 1. It is observed that pure hydrogen has a higher CV pressure than reformate gas owing to the increased energy density of hydrogen. In both reformate and hydrogen fuel cases, the CV pressure decreases as temperature increases based on the decreasing number of moles of flammable gas; therefore, at increased temperature and decreased density, the total explosion pressure and energy released from the explosion also decreases.

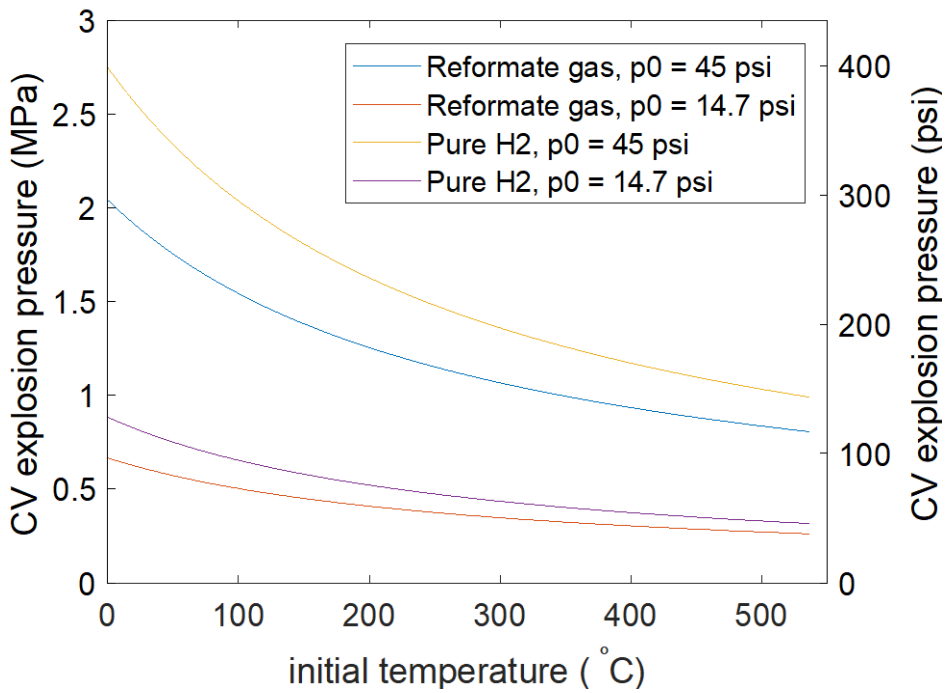

Figure 11. Constant volume explosion pressure vs. initial unburned temperature (ϕ = 1.0)

Figure 12 shows the CV pressure as a function of fuel-air equivalence ratio. It is observed that the CV pressure for all cases peaks at an equivalence ratio greater than 1. Although the peak CV pressure for the reformate gas is not substantially reduced relative to pure hydrogen (the peak CV pressure for reformate gas is 81.9% the peak CV pressure for hydrogen), the reformate gas has a peak explosion pressure at equivalence ratio $\phi = 1.44$, whereas pure hydrogen has a peak pressure at $\phi = 1.11$. This difference in peak explosion equivalence ratio indicates that more moles of reformate gas must be released to achieve the peak pressure as compared to the hydrogen case. The total explosion pressure for the reformate gas is moderately decreased relative to hydrogen, but the biggest reduction in explosion pressure results from decreasing the starting pressure "p0".

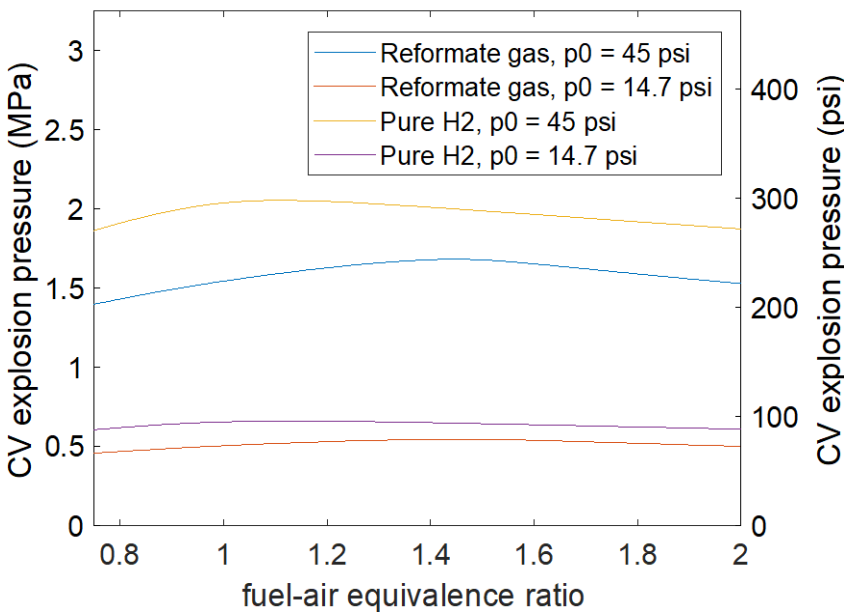

Figure 12. Constant volume explosion pressure as a function of the fuel-air ratio

In figures 11 and 12, the starting pressure substantially increases the resulting peak CV pressure. This is further examined in figures 13 and 14 in which the CV pressure is normalized by the starting pressure. Figure 13 is calculated using a fuel-air equivalence ratio of 1, whereas figure 14 has a variable fuel-air equivalence ratio. These figures show that the CV pressure is essentially linear with starting pressure for all cases considered for a given fuel-air mixture. Both figures show results normalized by the initial unburned pressure.

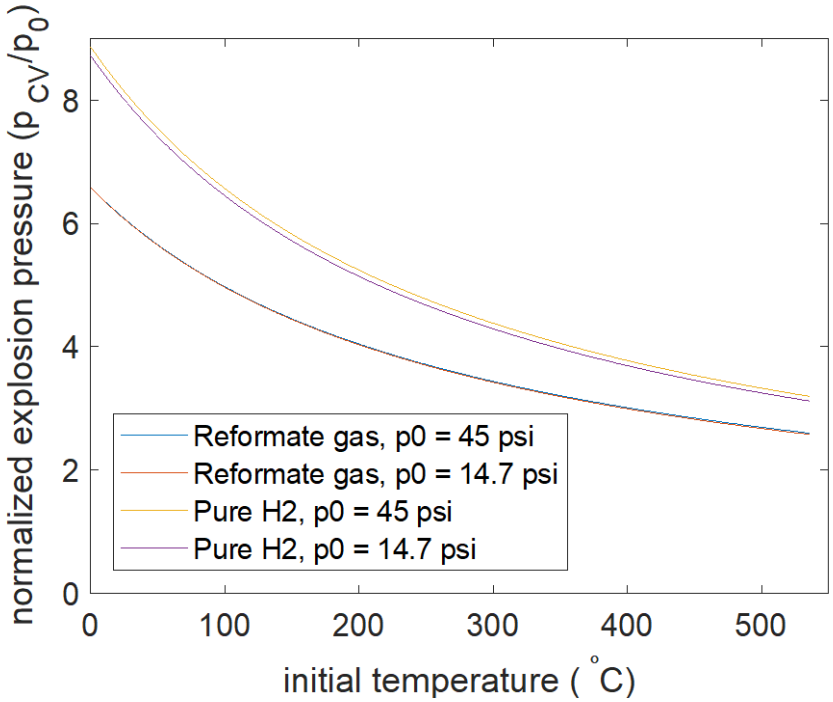

Figure 13. Normalized CV explosion pressure vs. initial unburned temperature

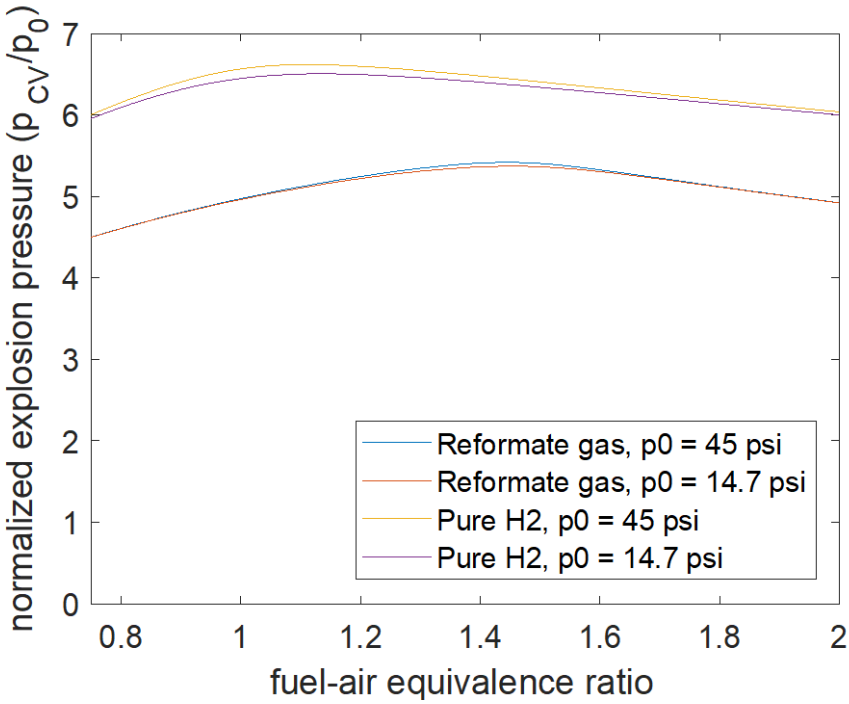

Figure 14. Normalized CV explosion pressure vs. fuel-air equivalence ratio

4.2.2.3 Rapid Combustion Summary

The actual combustion pressure will be time-dependent and substantially affected by the size of the volume in which ignition occurs, the degree of flame acceleration, the presence of venting during the combustion process, and the magnitude of cooling during the combustion process. In this section, the worst-case pressure for a generic geometry was estimated by calculating the CV explosion pressure. This provides a quantitative estimate for the worst-case explosion pressure for a generic geometry and allows for the examination of the quantitative effect of different parameters. The following was observed from the analyses:

- The reformate gas has a peak explosion pressure at an equivalence ratio of $\phi = 1.44$. The reformate explosion pressure is still 81.9% the peak pressure of pure hydrogen but requires more moles of fuel for this pressure to be achieved. (Hydrogen has a peak explosion pressure at an equivalence ratio $\phi = 1.11$.)
- At constant initial pressure, the CV explosion pressure decreases as temperature increases. This is caused by the reduction in the total number of moles of flammable gas. Note that this affect is complicated by flame speed increasing with temperature. Therefore, a hotter mixture in test will produce a faster flame, and the peak pressure will be closer to the CV explosion pressure (i.e., although the CV pressure decreases with increasing temperature, multiple factors will influence the actual pressure that is measured in testing).
- At constant initial temperature, the CV explosion pressure increases as pressure increases and the increase in CV pressure is linear with the initial pressure. Note that DDT more readily occurs at high pressures and, therefore, other factors than the predicted CV pressure may complicate the actual pressures observed in testing. However, unlike the temperature effect, the effect of pressure is consistent. Increasing the initial pressure makes the mixture strictly more hazardous.
- Although geometric effects were not considered in the present analysis, note that decreasing the volume of mixed flammable gas will reduce the overpressure threat in two ways: Decreasing the size of the chamber increases the effect of cooling, therefore, reducing the achieved pressure and decreasing the volume of flammable gas reduces the energy of the explosion.

4.2.3 SOFC High Temperature Failure Analysis Summary

Analysis of the failure modes specific to SOFC technology provides a conservative estimate of what potential impacts may be of a failure in an airborne system. This was used to develop the test plan for later testing. The worst-case failure identified for an SOFC stack would be to have leakage between the fuel and oxidant.

In a higher temperature environment above the fuel AIT, which is the normal range that SOFC technology operates, any leakage between fuel and oxidizer will have a sustained flame or constant thermal release signature instead of an explosion hazard. The fuel used in this scenario has the largest impact in respect to the amount of thermal energy released for a given leak path. For example, a leak of a pure hydrogen fuel would release approximately six times more energy than a leak of a steam reformed fuel. Any increase in pressure differential driving the leak increases the energy released until the flow becomes choked. The thermal energy released at the sustained flame site could impact the surrounding material and potentially increase the leakage area. However, the

method, probability, and rate of a leakage growing is extremely dependent on the leakage location and the individual stack design. Analysis of a sustained flame failure, using conservative worst-case assumptions, shows that, at a minimum, half of the heat from the flame would go into heating the surrounding gas, with 25% of the heat going into radiation of surrounding materials and 25% going into the base material surrounding the leakage. This means that, at a minimum, half of the heat in a failure case, and, likely, much more than half the heat in a less conservative analysis, would most likely be convected away from the original failure location via gas (existing fuel and oxidant) flow in an SOFC stack. This would help minimize the growth of the original leakage source and points to the benefit of ensuring all portions of the stack have adequate gas flow. This information also provides insight into the ability of temperature sensors to identify a failure using design case specific parameters such as geometry, flowrates, gas species, and pressures.

In a medium or lower temperature environment below the AIT, there would be the possibility of a hazardous fuel/oxidizer mixture to build up to create an explosion hazard. It should be noted that since most SOFC stacks to date operate above the fuel AIT, this would only be caused by some error in the system design or an additional failure in the system, such as a system heat transfer device failure. This is considered the less likely failure scenario of an SOFC stack. In an explosive mixture buildup, the pressure of the initial mixture would have the largest effect on the energy released in the explosion. The fuel type in the initial mixture would have the least impact. The temperature of the initial mixture does have an impact on the energy that can be released from an explosive mixture, mainly by the temperature effects on the density of the fuel; therefore, as temperature of the gases of the explosive mixture increases, the energy that would be released from that explosive mixture decreases for the same volume.

In all SOFC leakage scenarios, the use of a reformed liquid fuel results in less energy released during a failure than when using hydrogen as a fuel; therefore, any small leakage point in the SOFC stack will have a slower growth rate in a liquid fueled SOFC system, resulting in more time in operation before a failure affects the system.

5. SOFC SYSTEM MITIGATION APPROACHES

More detailed data on the failure mitigation approaches can be found in the Boeing Proprietary Appendix A to this report.

An aircraft power system that is guaranteed not to fail does not exist, and the design of one is an impossible goal. Instead, the development focus of any aircraft power system is to minimize the probability of failure and mitigate the impacts of a possible failure by design. Some design approaches for minimization of system failure occurrences include use of robust components, design factors of safety, minimizing system complexity, component or function redundancy (design for reliability), comprehensive testing, and designing for worst-case environments. Some design approaches for minimizing or mitigating a system failure that has already occurred include component or function redundancy, sensors to identify a failure early, active and passive components to stop the propagation of a failure, and operational changes to minimize the effect of a failure.

Analysis described in previous sections identified on leakage of reactant and oxidant in an SOFC stack as being a worst-case failure mode, which would be introduced into an aircraft by an SOFC-based power system. Protection against such a failure can utilize existing aircraft safety components and approaches that have been identified for other high temperature, liquid fuel driven components, such as the standard light aircraft engine. These approaches of flammable leak detection external to the power system include:

- Hydrocarbon detection sensor
- Carbon monoxide detection sensor
- Fire detection
    - Pneumatic single point detector
    - Thermocouples
    - Thermal switches

Many of existing design protections in use for light aircraft engines are also applicable for an SOFC-based power system. Some of these design protections would be required by existing CFR regulations, assuming an SOFC-based power system meets the same requirements as a standard aircraft internal combustion engine. Sample failure mitigation approaches are listed in table 8.

Table 8. Failure mitigation approaches for SOFC stack

Passive Components for SOFC Stack Failure Mitigation	Active Components for SOFC Stack Failure Mitigation
High temperature insulation around SOFC stack and supporting hot components / lines	External sensors for hazardous gas in ventilation flow or surrounding area
Firewall design around SOFC power system using existing CFR rules (i.e. self-extinguishing, flame resistant, fire shielded, and fire proof material options)	Internal sensors for failure detection (i.e. temperatures, voltages, pressures)
Ventilation penetrations to dilute and remove hazardous gas	Automatic fuel shut-off valves
Filters and flow restrictions to prevent failure propagation upstream	Manual power system and fuel shut-off valves
Minimization of components using both fuel and oxidizer flows to limit possible critical failure locations	Forced ventilation components (i.e. blowers)
Materials, grounding, and coatings to protect against active or static electrical energy igniting flammable mixtures	Overpressure protection devices (i.e. relief valves and burst disks)
	Fire suppression components for installations outside of the pilot’s view or in the fuselage

Timely identification of an incipient failure is essential to active mitigation of failure propagation. As discussed in section 4, one of the worst-case failures in an SOFC stack would be leakage of

fuel and air resulting in a localized combustion, which could then grow. An analysis was undertaken to determine the most sensitive way of identifying a leakage failure scenario is an SOFC stack. Pressure, external temperatures, internal temperatures, individual or group cell voltage, and stack voltage instrumentation were considered in the analysis. Sensors for pressure and external identification of stack temperature were immediately discounted as being sensitive to small developing failures. External temperature sensors are hindered from anomaly detection by thermal insulation surrounding hot SOFC components such that significant energy buildup is necessary before a localized SOFC thermal event could be detected. Most SOFC stacks are designed to operate nominally at similar pressures on the fuel and oxidant side. Because normal operation of an SOFC stack is above the AIT, leakage at the stack would result in thermal energy release instead of a pressure change, making pressure identification of a small emerging failure difficult. Analysis subsequently focused on internal temperature measurement and stack voltages for early failure identification.

Analysis was then performed on a generic stack model to ascertain relationships between a leakage failure occurring and the identification of the failure by internal stack temperature measurements and voltage measurements. It should be understood that this analysis was performed for an assumed stack size and operating conditions to provide a sensitivity comparison; these results would change based on different stack designs.

Previous analysis for sustained flame failure scenarios distinguished that in a leakage between fuel and air above the AIT, the majority of the heat from the reaction is absorbed by the surrounding gas flow. The analysis used conservative assumptions; it is likely that in actual failure conditions, higher amounts of energy than were calculated would be absorbed by the surrounding gas flow. This illustrates the importance of adequate gas flow in SOFC stack design and also makes it more likely that a failure will increase the temperature of the SOFC exhaust gas. There are substantial complications involved in embedding thermocouples or other temperature measurement devices in a high temperature, sealed, planar stack on a cell-by-cell level. A more realistic approach is to locate a thermocouple into fuel and air exhaust stream immediately at the exit of a stack. Measuring the gas temperatures at the inlet and outlet of a stack would identify the temperature rise of the mixed exhaust of all the cells, rather than at a more localized point in the stack. Modeling of the temperature rise on the fuel or air side of the stack based on a percentage of flow leakage is shown in figure 15. In the case modeled, leakage into the fuel side of the stack flow is more sensitive than the air side because in most SOFC stacks, additional air flow above what is needed for the electrochemical reaction is used to transport waste heat away from the cells. The model assumed average flowrates and that the leakage suddenly occurred at the percentage leak identified (i.e. no slow buildup). Results show that there is a time factor on the order of multiple minutes prior to a stable leak showing up in the exhaust temperature, and that a significant leakage would raise the temperature of the outgoing stack air exhaust from 40° at a 10% leakage rate to 90°C at a 20% leakage rate. Given that SOFC stack technology operates at high temperature, a 20% leakage across a cell would result in a 9% to 15% overall temperature change.

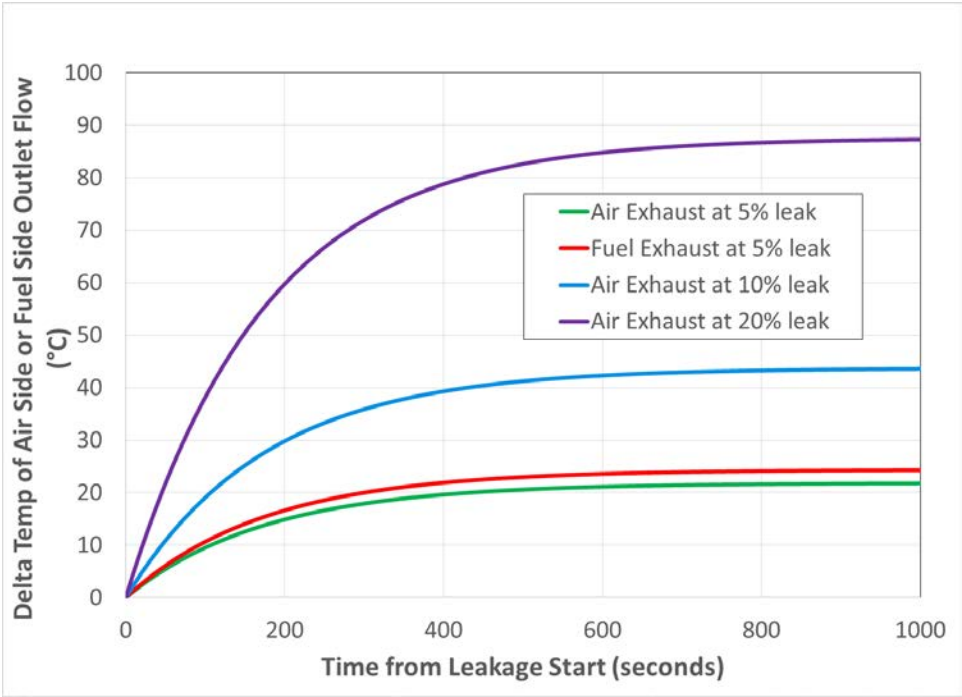

Figure 15. Sensitivity of SOFC stack exhaust temperature sensors to leakage

Modeling of voltage measurement sensitivity of a leakage in an SOFC stack was also assessed. Voltages of electrochemical cells are affected by the partial pressure of the chemical reactants based on the Nernst equation, where voltage is linearly proportional to the natural log of the ratio of the pressure of products over the pressure of reactants. If a reactant leaks to one side of the solid oxide (SO) electrochemical cell, it instantly reacts as SOFC operates above the AIT. The product of that localized instantaneous combustion removes the reactants previously available for electrochemical reactions from that side of the cell, diluting or lessening the available reactants. This dilution of available reactants at the local cell level reduces the Nernst potential and voltage of the cell in real time. In such a way, individual SO cell voltage measurements act as individual reactant leak detectors in a stack. Modeling results of expected cell voltage degradation based on percentage of leakage is shown in figure 16. The results illustrate that the magnitude of cell voltage change based on percent leakage on the fuel side is more sensitive than leakage into the air side. It also shows that a 10% leakage of oxidant into the air side results in a 20% cell voltage change, with larger leakages causing a much sharper voltage drop. It should be noted that voltage monitoring for leak/failure detection would only identify leakage that is upstream or internal to the cell area. Leakage downstream of the active cell area would not be identified by this method. Dependent on SOFC stack design, physical integration of individual cell voltage monitoring can add a level of complexity and additional potential failure points for shorting. In cases where voltages are not realistically able to be monitored at the cell level, monitoring groups of cell voltages or the total stack voltage could be performed. Sensitivity of the voltages in identifying a localized failure is therefore reduced, based on analysis, depending on the voltage drop seen at the cell level compared to the number of cells being monitored. Analysis identified that stack level monitoring, in comparison to cell level monitoring, would lessen visibility of a developing failure. However, the testing described in section 6 showed that the stack voltage was more sensitive to cell failure than was expected by analysis.

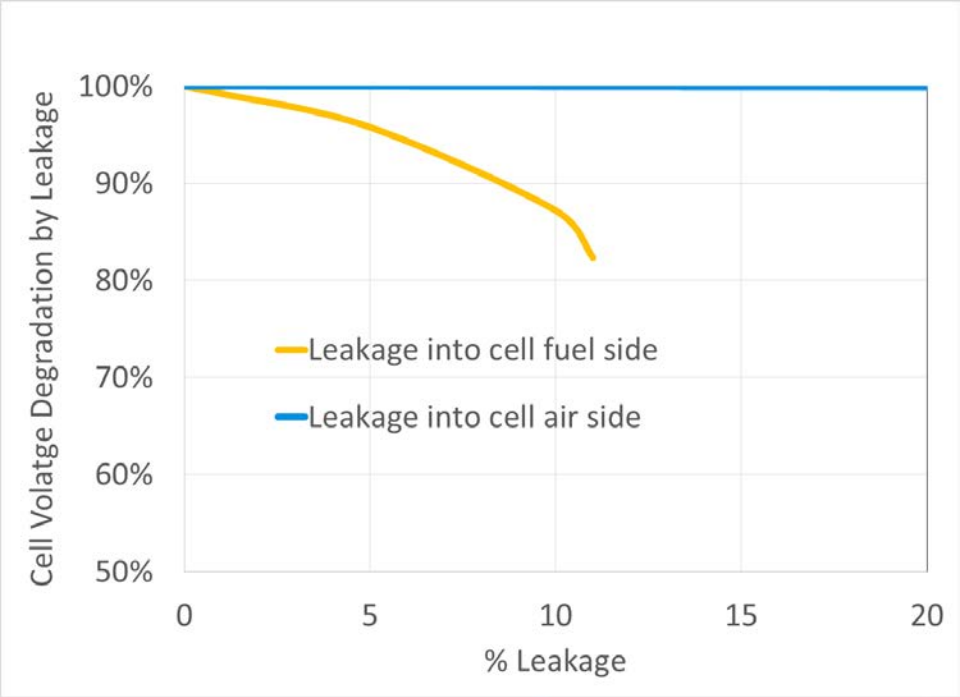

Figure 16. Sensitivity of SOFC cell voltage monitoring to leakage

Modeling of both voltage and temperature sensors in reaction to an SOFC stack internal leakage failure mode determined that voltage monitoring has the ability to identify a leakage growth at a near real-time since it can be sensed nearer to the potential leakage location. Temperature sensing in the SOFC stack exhaust a time lag associated with fluid flow and mixing rate from the leakage location to the sensor. A failure due to leakage can drive a greater magnitude of response change in the voltage sensing of a cell or group of cells than the magnitude response change in the exhaust temperature for the same leakage size. Modeling concludes that for most stack designs, voltage monitoring of SOFC stacks is more sensitive to identification of stack internal leakage than temperature sensors. However, because voltage monitoring would only identify leakage upstream of the electrochemically active area, thermal sensing of the stack exhaust is still required to identify any leakage in the exhaust manifolds of the SOFC stack. Thermal sensing of stack exhaust is also useful as a redundant sensor for failure identification.

6. SOFC CONTROLLED STACK FAILURE TESTING

More detailed data on the failure testing of both SOFC stacks, including additional test data, can be found in the Boeing Proprietary Appendix A to this report.

Failure testing was performed on two planar SOFC stacks to provide examples of worst-case SOFC power system failures to bound effects on failure propagation. The stacks were supplied by two separate suppliers and were both development-level stacks at different stages of design maturity. Stack 1 tested to failure was designed for 250 W with < 12 cells. Stack 2 was designed for 1 kW containing > 30 cells. Both stacks tested had known leakage with intact cells at the start of the test. Each stack was tested within a pressure vessel.

Both stack tests were conducted using a mixture of 50% hydrogen and 50% nitrogen as fuel for testing, and air was used as the oxidant. As mentioned in previous sections, SOFC technology becomes electrochemically active at high temperatures, generally between 600–1000°C. This operating temperature is above the 536°C AIT of hydrogen and the 200–300°C AIT of other liquid hydrocarbon based fuels. The mixing of fuel and oxidant from leakage immediately reacts to produce heat and water; no buildup of fuel and oxidant is possible above the AIT temperature, which removes any explosive hazard at high temperatures.

The objective of the controlled SOFC stack failure testing was to verify sensitivity of voltage and temperature as a means of detecting cell/stack failure, in comparison to the physical damage to the stack when subjected to an SOFC stack's worst-case sudden failure. This creates the beginning of comparable data between stack failure sensor readings and physical effects of a potential failure propagation in an SOFC-based power system. An understanding of how instrumentation identification of a critical failure relates to actual system effects is necessary for the future development of a safe SOFC-based power system. The tests were conducted above ambient pressures within a pressure vessel using a 50/50 mix of H2/N2 at the anode and dry compressed air at the cathode.

Based on historical test data at Boeing and across the fuel cell industry, the vast majority of air-based SOFC stack failures are slow propagation failures that show up in stack voltage or gas temperatures tens or hundreds of hours prior to critical stack failure. The intent of this test series was to try to simulate a more unlikely worst-case sudden failure scenario, rather than the more usual stack performance degradation failures typically seen in testing; therefore, two methods were used in an attempt to induce a sudden SOFC stack failure:

1. Electrochemical overloading of the stack while on load
2. Application of elevated differential pressure across the stack

6.1 MOBILE STACK FAILURE TESTING

A mobile testing unit was built to support SOFC stack testing. The unit was built to provide heated fuel and reactant gasses to the SOFC stack, while being able to control the pressure the stack was tested at and the incoming gas temperatures. A cooling loop was used to cool the exhaust streams. The fuel side exhaust could be connected to lines in the test cell to route the exhaust to a safe hydrogen exhaust location for the building. Remote operated solenoid and flow regulation valves were used to control the reactant and safety gas flow and gave the ability to shut off the fuel flow without depressurizing one side or other of the fuel cell. The mobile testing unit was assembled, leak tested, pressure checked, and control software checked in a laboratory before the second SOFC stack was installed and the unit was moved to the ventilated hydrogen test area at the Boeing Huntington Beach California facility. Figure 17 shows the piping and instrumentation diagram (P&ID) of the mobile stack failure testing unit.

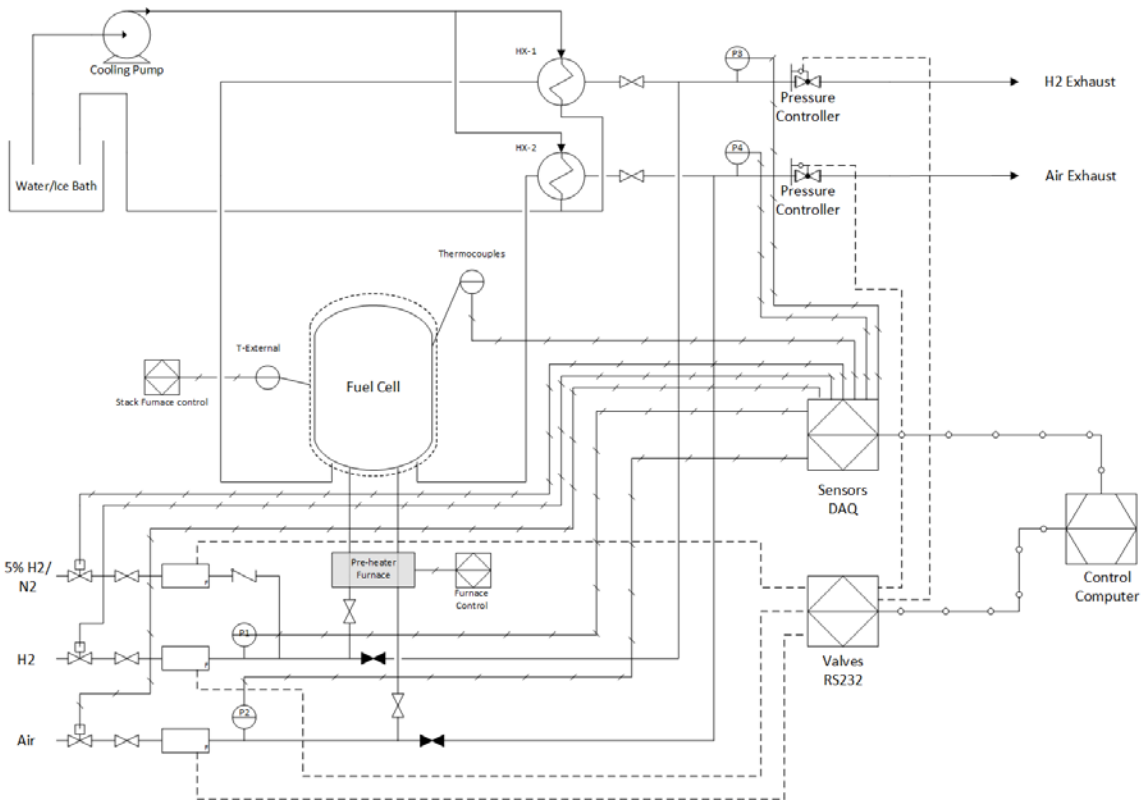

Figure 17. P&ID of mobile stack failure testing unit

6.2 FIRST SOFC STACK FAILURE TESTING

The first stack failure testing was performed on a smaller SOFC stack of <12 cells. The first SOFC test stack used was in the development stage of the design process.

The first stack tested was exposed to a maximum pressure differential of less than 3psid when indications of a cell failure occurred, as shown in figure 18 with the "Normalized Worst Cell Voltage" line. Only one cell in the stack showed early indication of a cell failure. The total stack voltage showed an approximate 20-second delay between the individual cell voltage drop and the total stack voltage drop. The stack voltage showed a total voltage drop greater than what would be expected from the loss of the failed cell voltage drop only. This indicates that once significant cell failure occurs in an SOFC, reactant dilution and thermal impacts from the failed cell can influence the performance of other cells, making the failure more visible at the total stack voltage level. In this test, the stack exhaust temperature did not rise until the test shutdown protocol was performed, which caused additional flow perturbations more than one minute after cell failure. It is believed that if the flows to the test stand were not modified during the test shutdown procedure, the heat increase from the SOFC cell failure would have shown up even later and more slowly. The expected gas exhaust temperature increase during a cell failure is caused by combustion of H2 and air from cracked cell or seal leak. The thermal increase was only seen after one minute due to flow perturbations caused from the test shutdown. Figure 18 shows that the > 50% magnitude of the cell failure effects on the stack voltage was much greater than the ~10% magnitude of temperature change seen in the stack exhaust streams.

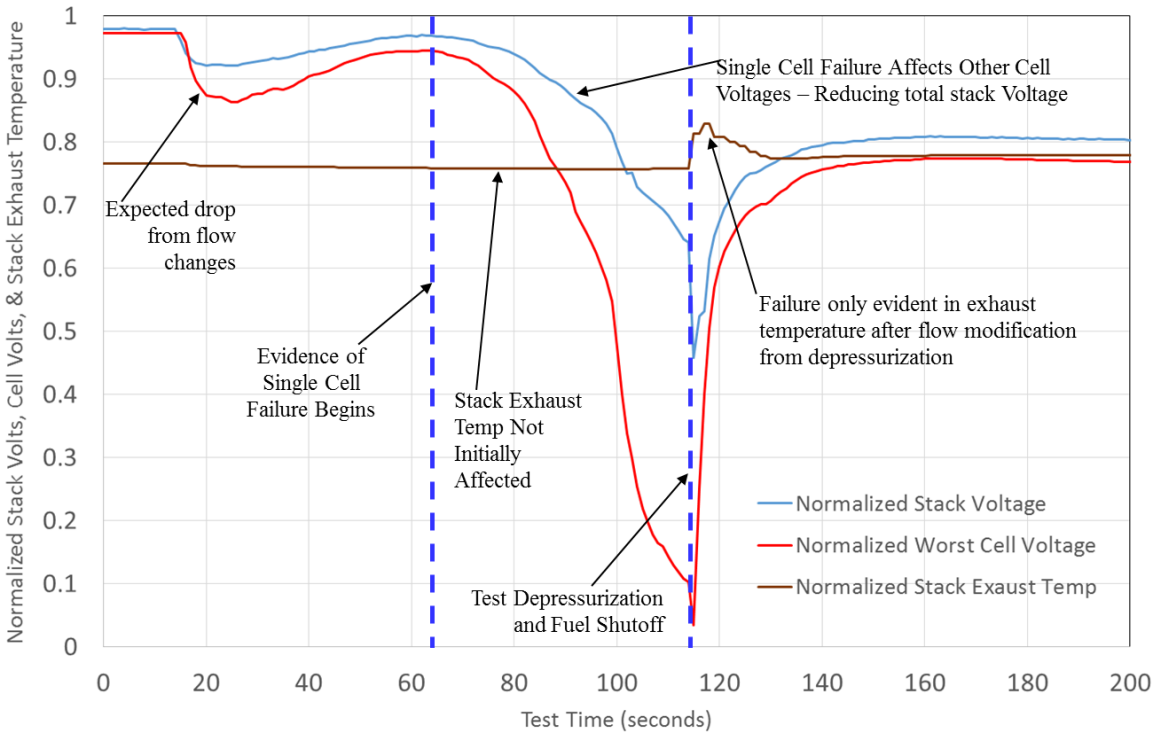

Figure 18. First SOFC stack controlled failure testing

Teardown of the first stack test verified that the cell showing the worst-case cell voltage during testing failed from a crack in the cell. There were indications of some overheating in the area around the cell failure; however, there was no significant thermal damage outside of the cell stack active area. Specifically, there were no overheating effects seen internally in the stack manifolds or gas flow paths to and from the stack. This verified that the shutoff of fuel flow successfully limited failure propagation by reducing the total energy available for combustion of reactants, keeping the total energy released from the stack failure within levels that would not cause any significant damage or material breakdown in components outside of the stack.

6.3 SECOND SOFC STACK FAILURE TESTING

The second stack failure testing was performed on a larger SOFC stack of >30 cells. Although this second SOFC test stack was also in the design development stage, it was a more mature design tested than the first stack. Because of the more mature design of the stack, it was able to withstand additional adverse conditions in operation prior to the stack failing.

The second stack was tested with similar reactant mixtures as used in the first stack testing (50%H2/50%N2 fuel, air). This stack was installed and tested in the mobile stack failure unit described in section 5.1, and testing was conducted in an external test bay designed for hydrogen use. The second stack was exposed to a pressure differential while stack voltages and exhaust temperatures were monitored. The second stack was subjected to electrical loading of cells to drive the stack voltage below normal operation limits and various pressure differential levels on both the anode and cathode sides of the stack. Individual cell voltages were not available for this stack testing, but the total stack voltage was monitored along with exhaust temperatures.

In the second stack test, differential pressure was initially applied more slowly than the first stack test. The second stack was able to withstand while operating a differential pressure of 15psid across the stack with either the fuel side or air side high. During the phase of testing where the fuel/hydrogen side of the stack was pressurized, a failure due to sparking was observed in a wire connection that was routed from the test pressure vessel to the ambient atmosphere. This high temperature, sheathed, wire was used as instrumentation during previous development testing, but was unused/disconnected during the second stack failure testing. Sparks and a small flame were observed coming from the end of the metal sheathed wire (figure 19). On identification of the failure, the main hydrogen fuel flow was shut off and a nitrogen-based safety gas continued to flow to maintain the stack pressure. The removal of the hydrogen flow extinguished the flame at the end of the unused wire. The stack was unaffected by the wiring failure. Post-test inspection identified that there were multiple factors that contributed to the wire failure probable cause. The wire dead-end termination likely caused a reduced insulation gap that reacted with a small hydrogen leak due to the unrealistic operating regime of the unit. The test unit was subjected to operating conditions outside of those that would be allowed in an actual flight system for the purpose of inducing a sudden failure in the SOFC stack.

Figure 19. Sparking observed during second SOFC stack controlled failure test

Testing resumed after the wire failure, but increased pressurization was thereafter limited to the air side of the stack so as not to repeat the suspected cause of the wire failure of hydrogen leakage to ambient. The second stack tested was able to withstand pressure differentials ramped up to 15psid across the stack. The stack had known internal leakage at the start of the test. Although the increase of differential pressure had to result in additional heat generated internal to the stack from the leakage, changes in the exhaust temperature over the relatively short testing time were minimal. To mimic a sudden failure, which would be the worst-case scenario seen in a flight application, the second stack tested was then subjected to sudden pressure changes on one side of the stack. A sudden pressure change of >15psid was applied to one side of the stack and a failure was induced. The failure was evident on both the stack voltage and the stack exhaust temperatures at the same time (figure 20). The magnitude of the change in stack voltage, an approximate 90% change in voltage, was much greater than the exhaust temperature change, an approximate 6% change in temperature, the stack voltage was clearly a more sensitive indicator of stack failure than the stack exhaust temperatures. On identification of the failure, the electrical loading of the stack was stopped, the main hydrogen fuel flow was again shut off, and a nitrogen-based safety gas was flowed on the fuel side. These actions resulted in an immediate stack voltage recovery and a soon after decrease in exhaust temperature, showing that the stack failure was contained.

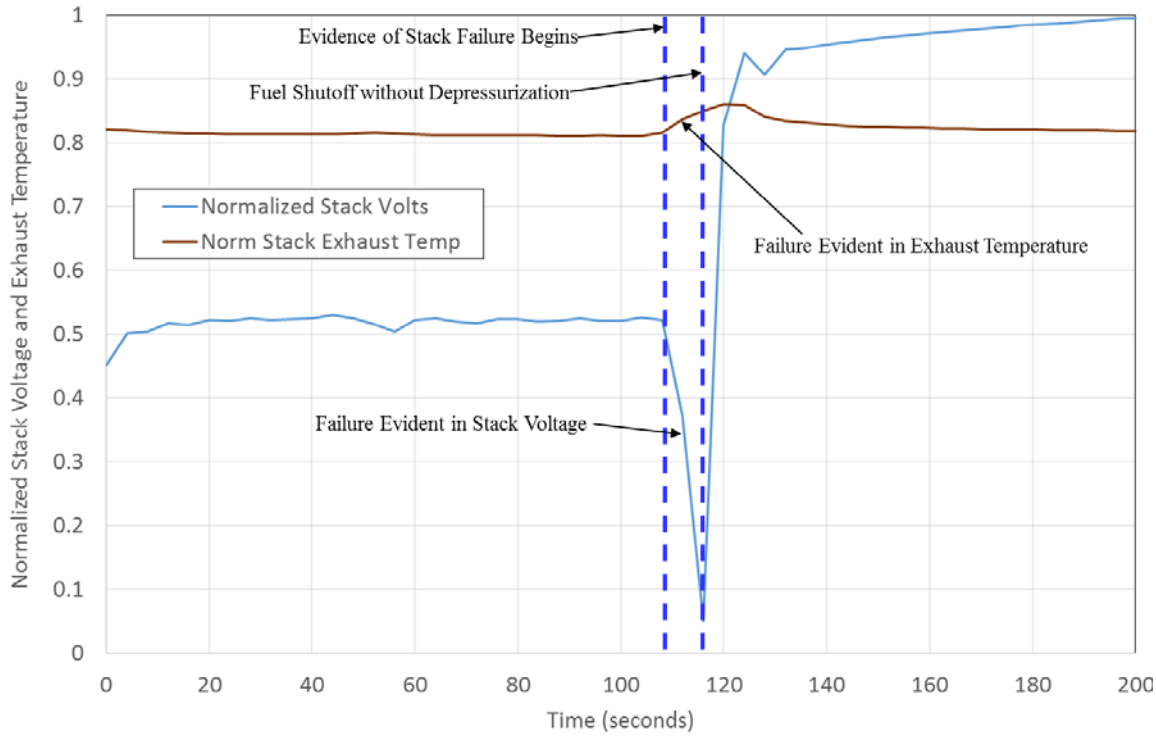

Figure 20. Second SOFC stack controlled failure test

After cool down of the second SOFC stack testing unit, the system was disassembled, and the stack was removed from the pressure vessel and inspected. The second SOFC stack tested also showed no significant thermal damage outside of the cell stack active area. In both the wiring failure and sudden stack failures seen during the controlled testing, the shutoff of the fuel flow to the stack quickly stopped the overheating events and prevented any propagation of the failure to other components.

7. CONCLUSIONS

The FAA project "Evaluation of a Lightweight Fuel Cell Containment System for Aircraft Safety" evaluated the potential impacts for an example future solid oxide fuel cell- (SOFC) based power system to be integrated into a small aircraft, as described in Title 14 Code of Federal Regulations (CFR) part 23. A target SOFC system using a liquid desulfurized fuel, onboard reformation, and a hybrid battery was assessed for impacts to existing aircraft safety regulations, new failure modes, similarity to existing systems, and potential approaches for safe integration of the aircraft. Analyses of worst-case failure modes for SOFC technology were performed to bound the expectations of the failure effects and also the timing for failure identification. A mobile SOFC stack testing unit was built and controlled failure testing was performed on two development stacks made by different suppliers.

Assessment of the liquid fueled SOFC power system in comparison to traditional light aircraft internal combustion engine propulsion systems shows that many of the components used in an SOFC-based system are similar to those flown on other aircraft. The components unique to the SOFC power system are related to potential reformation and the electrochemical stack functions,

but the protections for potential failures of these solid, non-moving components are comparable to other high temperature components already certified for flight. The majority of existing 14 CFR 23 regulations could be directly applicable to the integration of an SOFC system with minor language modification to make existing requirements more inclusive to SOFC technology.

Failure analysis focused on failures occurring in the planar SOFC stack, a component that would be new to aircraft flight testing and use. The worst-case failure for an SOFC stack was determined to be fuel and air mixing through leakage in an SOFC stack causing a sudden stack failure. Analyses of both high temperature leakage and low temperature leakage effects were performed. The high temperature leakage failure is considered more probable, as SOFC nominally operates above the auto-ignition temperature of fuels. Combustion calculations of the failure scenarios highlighted that the release of energy from an SOFC stack leakage would be less when operating on a reformed liquid fuel than a pure hydrogen fuel. Combustion analysis also identified that the majority of the energy that would be released in a high temperature leakage would be transferred into the surrounding gas stream.

Mitigation of any failures for a future SOFC-based power system must be approached using two methods: 1) integration of redundancy and safety of flight concerns must be part of the initial system configuration and design, and 2) existing active and passive safety components, such as firewalls, instrumentation, and fuel shut-off valves, can be used to identify and limit the propagation of any failure that does occur. Analysis of failure detection showed that the most sensitive method of detecting a failure would be via monitoring the SOFC stack voltage. Because of the need for fuel to continuously be provided to an SOFC stack, a failure in the SOFC stack can be contained by stopping the fuel supply to the stack.

Controlled failure testing was performed on two different planar SOFC stacks as a part of this project. Failure was induced by applying a pressure differential between the fuel and oxidant sides of the SOFC stacks. The tests were able to validate the sensitivity of stack voltage versus temperature monitoring when a sudden failure was induced. In both tests, the fuel flow was shut-off once the stack voltages became severely diminished, and this action stopped the thermal propagation of the induced failure. Teardown of both test articles verified that no damage propagated to outside of the stack in either test, and that no damage from the failure was seen in the surrounding components. This demonstrated that shutting off the fuel flow to the SOFC stack based on stack voltage monitoring was effective in limiting any thermal damage to within the SOFC stack component itself. Testing also showed that the integration of any sensors or wiring into the SOFC system needs to protect against the introduction of potential hazardous gas leakage sites.

The analysis and testing of two different stack SOFC corroborates that for a sudden SOFC stack failure in an SOFC power system, shutting off of the fuel flow to the stack using existing sensor technology would prevent a sudden stack failure from propagating into a critical system failure.

This project provided both analysis and test data to show that safely integrating a liquid fuel SOFC-based power system into a light aircraft is feasible. Although additional failure modes are introduced with new SOFC technology, containment and mitigation of the new failure modes are similar to existing aircraft safety approaches. SOFC-based power system technology still requires significant development, system design for reliability, and comprehensive testing of systems

designed for flight to be considered for integration in a 14 CFR 23 aircraft. Assuming that SOFC power system technology advances to a more mature stage, this project concludes that the safe integration of that SOFC technology into a light aircraft, or other future aircraft, would be achievable using safety components and methods comparable to those presently used.

8. REFERENCES

1. Stoia, T., Balan, C., Atreya, S., O'Neil, P. (2018). *Solid Oxide Fuel Cell – Steam Reformation Power System Configuration Options for an All-Electric Commuter Airplane Flight Demonstrator* (AIAA 2018-3358). Presented at the 2018 Aviation Technology, Integration, and Operations Conference, Atlanta, GA. Retrieved from https://doi.org/10.2514/6.2018-3358

2. Borer, N.K., Geuther, S.C., Litherland, B.L., Kohlman, L.W. (2018). *Design and Performance of a Hybrid-Electric Fuel Cell Flight Demonstration Concept*. (AIAA 2018-3357). Presented at the 2018 Aviation Technology, Integration, and Operations Conference, Atlanta, GA. Retrieved from https://doi.org/10.2514/6.2018-3357

3. Papathakis, K.V., Schnarr, O.C., Lavelle, T.M., Borer, N.K., Stoia, T., Atreya, S. (2018). *Integration Concept for a Hybrid-Electric Solid-Oxide Fuel Cell Power System into the X-57 'Maxwell'*, (AIAA 2018-3359). Presented at the 2018 Aviation Technology, Integration, and Operations Conference, Atlanta, GA. Retrieved from https://doi.org/10.2514/6.2018-3359

4. Airworthiness Standards: Normal Category Airplanes, 14 CFR 23 (2016)

5. Rechberger, J., Kaupert, A., Hagerskans, J., Blum, L. (2016). Demonstration of the First European SOFC APU on a Heavy Duty Truck. *Transport Research Procedia, 14*, 3676–3685.

6. Meadowcroft, A.D., Howroyd, S., Kendall, K., Kendall, M. (2013). Testing Micro-Tubular SOFCs in Unmanned Air Vehicles (UAVs). *ECS Transactions, 57*(1), 451–457.

7. Precision Combustion, Inc. (n.d.), Microlith® Fuel Reformer. Retrieved from https://www.precision-combustion.com/products/fuel-processors/fuel-reformers. Accessed December 2018.

8. OxEon Energy, LLC. (n.d.). Digital image of "Ruggedized hermetic stack that enables energy storage solutions and high purity gas production" and solid oxide fuel cell overview, Retrieved from https://oxeonenergy.com/. Accessed December 2018.