Manufacturing Fuel Cell Manhattan Project

Presented by the Benchmarking and Best Practices Center of Excellence

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I. Foreword

Through the Navy Centers of Excellence, the ONR ManTech mission has placed a critical focus on the technologies, processes, and enabling manufacturing capabilities that provide direct benefit to the warfighter. This endeavor has been orchestrated in a cooperative environment with industry, academia, and the Navy warfare centers and laboratories. The Office of Naval Research (ONR) Benchmarking and Best Practices Center of Excellence (B2PCOE), through the stewardship of ACI Technologies, Inc. and in conjunction with Montana Tech of The University of Montana (MTT), is an example of the collaboration that is possible in providing valued information on affordable and implementable fuel cell technology.

As part of the mission of the ONR ManTech platform, the B2PCOE was created to facilitate such projects through the sharing of best-in-class practices, processes, methodologies, systems, and manufacturing technologies. The B2PCOE is an important conduit in advancing manufacturing technology through public and private sector partnership, technological innovation, technology transfer, and competitiveness, with the end objective of providing affordability and performance for defense platforms and weapon systems. Pursuant to the ONR ManTech platform mission, the data and information collected from the Manufacturing Fuel Cell Manhattan Project will advance the status of the current and recommended best practices for fuel cells. Subsequently, a foundation can be established for pursuing innovative and cost effective methods of resolving the issue around affordability and implementation into Naval and other DOD platforms.

During the first phase of the project (fall 2010), fuel cell manufacturing cost drivers and the related manufacturing processes were identified for both polymer and ceramic fuel cell systems. A follow-up session occurred in the spring of 2011 and developed a technology roadmap. The focus of this undertaking is to articulate the current manufacturing gaps and prioritize specific projects to address those gaps that decrease manufacturing costs and improve the reliability for the commercial industry in areas applicable for the Navy and other DOD applications.

As in other in-kind Manhattan Projects of this type, the selection of the Subject Matter Experts (SMEs) was of paramount importance in lending credibility to the recommendations derived from their findings. The result of gathering the top fuel cell manufacturing experts provided a broad and detailed account of the issues associated with developing cost effective fuel cell systems for the more stringent and performance driven warfighter platforms. Despite the diverse range of fuel cell applications required by the Navy and other military platforms, there are some manufacturing similarities where the opportunities for cost reduction and improved performance could be utilized for the common benefit. This is not always the case since many of the costs from the various manufacturing process are specific to the application and its requirements. Even where application specific differences were delineated, the process of outlining and defining the associated manufacturing steps proved to be valuable in identifying and prioritizing the focus in reducing cost and increasing DOD applicability for fuel cells.

Realistically, the future of fuel cells as a feasible power source within the DOD relies very heavily on leveraging the advantages of broad based use within the commercial markets. The current low volume and relatively high cost of producing fuel cells for commercial enterprises makes the Navy objective of affordable fuel cells a difficult endeavor. Raw material costs, special processing, and undefined quality control metrics all add to the challenges of creating a fertile environment for expansive use of fuel cell technology. The research into advanced manufacturing techniques and alternate materials, such as the ones being investigated by

Montana Tech University, will contribute to the understanding of the potential for efficient and cost effective fuel cell systems. This document, which was produced by the collective efforts of the SMEs, will communicate current industry best practices, but more importantly, recommends manufacturing projects to advance fuel cell manufacturing.

II. Preface

EXECUTIVE SUMMARY

Justification

Fuel cells offer certain tactical advantages for military applications in support of the warfighter in areas of transport, communications, and reconnaissance. The potential for reduced fuel and battery consumption, fewer supply convoys, reduced weight and volume for the soldier, and quiet power make fuel cells a tactically attractive alternate to standard generators.

A major disadvantage of fuel cells is the economics of implementing customized systems in their present form due to the high cost of manufacturing, as well as questions on the reliability of fuel cell systems in rugged military environments. To help understand how manufacturing affects the cost of fuel cells, the ONR undertook a study to determine the current manufacturing practices, identify gaps and issues preventing cost reduction, and to recommend manufacturing solutions to reduce the cost of fuel cells. This objective was achieved by commissioning a team of subject matter experts (SME) in the field of fuel cells.

The study focused in on the affordability and manufacturability of ceramic and polymer fuel cell systems under 10 kilowatts, along with their complementary balance of plant (BoP) and fuel processing (FP) subsystems. The specific power systems were selected as an area of study because they offered the greatest manufacturing maturity, and are of interest to several military services, including the Navy.

Methodology

The SMEs were asked to document those manufacturing processes that would affect cost and not those factors where increase in volume would produce economies of scale. The major cost drivers are covered in more detail in subsequent sections and form the foundation for the selection of projects to reduce cost. These projects were down-selected as providing the greatest benefit within a 3-year period.

The articulation of manufacturing processes incorporated:

- Current manufacturing processes
- Gaps and issues in the current processes
- Recommendations to resolve the gaps

The specifics on the manufacturing processes are detailed in the subsequent chapters.

Sequential to the process documentation, the team of experts produced a series of project proposals to address the cost issues. Certain assumptions were made to form a common cost baseline.

- Cost savings based on 5000 units per year
- Standardized at 10 kW for each unit
- Cost savings realized in three years or less
- Manufacturing technology not “bleeding edge” – no major changes in infrastructure
- Cost savings standardized in $/kW or in percentage of savings respective to the specific manufacturing process

Technology Areas

The projects recommended by the SMEs fall under the four technology areas:

- Polymer – can also be referred to as PEM (polymer electrolyte membrane)
- Ceramic – also referred to as SOFC (solid oxide fuel cell)
- Balance of Plant (BoP)
- Fuel Processing (FP)

Each of the four technology areas were subdivided into areas that were used as the baseline to assess the current best manufacturing practices. A detailed breakdown of the respective nesting processes or taxonomy can be seen in the manufacturing chapters.

Manufacturing Areas

There are five manufacturing categories nested within the four major fuel cell technologies, requiring manufacturing resolution to meet the cost reduction objective. A synopsis of the issues provided the following observations.

Production – *including automation and material processing*

Many of the projects focused on improving methods of catalyst deposition, dispersion, and efficiency primarily to reduce cost in the polymer manufacturing area, with one project specific to improving automation in ceramic manufacturing.

Quality Control- *in process and final product*

Both the *polymer* and *ceramic* SMEs detail projects that correlate raw material properties to component performance. Just as significant, is identifying what attributes of component quality ultimately affects performance of the final fuel cell system. One project on ceramic powder characterization is already underway at Montana Tech.

Hardware - *availability and performance*

Balance of plant as well as *fuel processing* cost is greatly affected by both hardware availability and finding COTS (commercial off the shelf) parts that will meet the stringent performance requirements needed for fuel cells. The projects that affect BoP could potentially be the quickest path to reducing overall fuel cell costs.

Materials- *new and improved*

Materials have a large impact on cost, especially in the production of the MEA. The polymer SMEs have advocated projects to address the efficiency of catalyst usage and methods of deposition to help lower the costs of the most expensive material in MEA processing. Other material projects that promoted cost reductions, called for improvements to insulation for high temperature fuel cells, protective coatings on ceramic substrates, and alternate bipolar plate materials.

Design

Manufacturing *design* projects are intended to address, at a high level, what design features in the manufacturing of a fuel cell should be considered to meet the performance requirements of the application. The current default position is to design for all performance contingencies, which tends to escalate the price of fuel cells. Additional quality addendums, known as “feature creep” that are commonly post scripted into existing requirements, also add to costs if the feature is unnecessary.

Investment

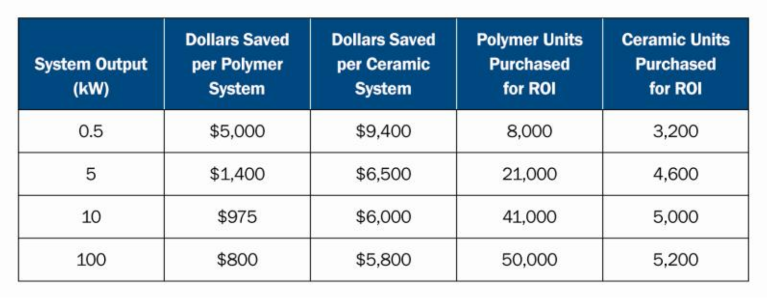
The investment to implement all the recommended projects is about $76 M. **Table II-1** breaks down the investment within each manufacturing area:

Manufacturing Area	Cost	Fuel Cell Technology
Production	$10.2M	Ceramic
	$17.9M	Polymer
Quality Control	$0.4M	BoP
	$1.5M	Ceramic
	$2.4M	Polymer
Hardware	$6.0M	BoP
	$2.4M	Ceramic
	$9.3M	FP
Materials	$6.4M	Ceramic
	$5.3M	Polymer
Design	$5.4M	BoP
	$2.2M	Ceramic
	$ 6.4M	Polymer

Table II-1: Cost breakdown by manufacturing area

A detailed breakdown of the project investments can be found in the project synopsis (section 9.2) or in section III Appendix A.

The return on investment can be illustrated in terms of the amount of units purchased at a given power output (**Table II-2**). This table assumes an investment of $40 M in polymer projects, and $30 M in ceramic projects.



System Output (kW)	Dollars Saved per Polymer System	Dollars Saved per Ceramic System	Polymer Units Purchased for ROI	Ceramic Units Purchased for ROI
0.5	$5,000	$9,400	8,000	3,200
5	$1,400	$6,500	21,000	4,600
10	$975	$6,000	41,000	5,000
100	$800	$5,800	50,000	5,200

Table II-2: Return on investment at each power level

Recommendations

The subject matter experts have provided a structured roadmap of how fuel cell cost can be reduced substantially with the implementation of the projects detailed in this report. On average, a 50 % savings can be realized with current sustainable volumes of 5000 units a year leveraging the present technological infrastructure. Essentially, these savings are independent of full scale commercial production.

The recommendations are classified into two categories. The first category will focus on the specific project implementations that address the core issues preventing cost effective fuel cells. The second category will center on the organizational mechanisms that will be required to manage, organize, and prioritize the enactment of these projects from the concept to transition.

The government leadership and SMEs underwent a rigorous process to evaluate the appropriate course of action as part of the roadmap to a successful global transition to fuel cells. In keeping with the objectives of the MFCMP, the most important recommendations that can be offered is to expand the existing DOD and industry alliance on fuel cells and to give careful consideration to implement the projects proposed in this report.

Project Recommendations

- Improve catalyst efficiency
- Improve available BoP supply chain
- Improve coatings and composites
- Better definition for material and final product quality control
- Base specifications on performance requirements
- Transition to automated processes to improve reliability, quality, and reduce manual costs
- Improve fuel processing

Recommended Organizational Mechanisms

To achieve cheaper fuel cells, it is critical that fuel cell manufacturing technologies have continued leadership at DOD, JDMTP, OSD, DOE, DARPA, and other interagency levels. The project mechanisms listed are just some of the potential opportunities to meet those objectives, and are by no means exclusively restricted to the following recommendations.

- Establish government-industry consortia to address over-arching issues
- Support continued ONR efforts through the B2PCOE and MTT
- Establish a new ONR Alternative Energy Center of Excellence

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1. Introduction

The warfighter of today has become increasingly dependent on electronics to achieve battle superiority. Their reliance on the production of electricity can range from small batteries to large diesel generators. However, reliance on these forms of power generation is becoming increasingly problematic. Use of batteries creates large and expensive logistical footprints while diesel generators are noisy, maintenance intensive, and consume large amounts of fossil fuels. Recent advances in fuel cells have made this form of energy a potential source for the generation of electricity. No matter what the weapons system, from the smallest hand held device to large naval platforms, the potential advantages of a fuel cell for providing energy include: low acoustic and thermal signatures, reduced maintenance, reduced weight, reduced volume, and environmentally beneficial.

The advantages offered by fuel cells depend on their actual applications. For example, when used as an auxiliary power unit (APU)/battery charger, they can provide electric power in areas where it is not feasible or practical to rely on a generator. This facilitates the use of rechargeable batteries and reduces the logistical footprint and life cycle costs. When used to provide power to unmanned systems, mission times can be increased. If used as a replacement for generators, they offer quiet, clean, low maintenance power. Even in large ships, they are seen as a distributed power source, simplifying the overall design and reducing the threat to a ship that sustains damage during combat.

However, before fuel cells can be widely utilized in military weapon systems and support activities, there are challenges that must be overcome.

- Ability to use logistics fuels
- Reduced unit costs
- Increased reliability of current designs

The use of logistics fuels to support the “one fuel forward” philosophy is still a goal being pursued. Considerable research and development resources are being applied to reform JP8 in fuel cell systems. Based on current efforts, achievement of this goal remains for future development and may not be practical or affordable, particularly in small man-portable systems. There are non-JP8 fuel cell systems with a high technical readiness level (TRL) that use packaged fuels (methanol and propane) that can potentially be used in the near term, but these systems have high unit costs and low reliability due to a relatively immature production base.

Although fuel cell technology has been around for many years, there has been no large-scale commercial or military demand due to cost and reliability problems. Companies that do produce fuel cells for the commercial market do so in a “custom, hand-made” type of operation. Some of the high costs are offset by government sponsored research and development (R&D) and tax incentives. For companies developing fuel cells for the military market, only R&D prototypes have been delivered. Recent investments by DOD, along with stated needs by several DOD program managers, have resulted in advancements for smaller fuel cells, making them a viable power source in military environments.

Although the basic technology has reached a relatively high TRL, the manufacturing readiness level (MRL) still lags behind due to the general lack of accepted manufacturing best practices. The lack of significant volume for fuel cell products has hampered the industry’s ability to make capital investments in implementing improvements and automation required to reduce unit prices and improve reliability. If the military is to widely adopt fuel cells as an energy source, these investments are required to further develop the manufacturing technology, process tools, and equipment to allow for more efficient production of these systems.

The overarching goal of this effort is to establish a common baseline of fuel cell manufacturing practices. This baseline is then compared to what is required to improve reliability and cost. Finally, R&D efforts are proposed where gaps exist. The identification of these fuel cell manufacturing best practices and the creation of a fuel cell technology roadmap were accomplished through the project Phase I and II efforts. The subsequent dissemination of data through the efforts of the Benchmarking and Best Practices Center of Excellence and others will allow R&D sponsors an insight into the requirements for the inclusion of fuel cells into Navy and other DOD and federal systems.

2. Objectives

It is important to note that this report elaborates on the manufacturing aspects of fuel cell production, as opposed to espousing any specific technology platform or industry. The assumption is that what is presently being manufactured by industry will eventually be produced in suitable quantities to meet warfighter cost and performance. “Bleeding edge technology” or “not ready for prime time” applications residing at the conceptual stage were not benchmarked or addressed. There is also a realization that in some cases the demarcation between technology and manufacturing is not well defined. Provisionally, a more lenient approach was taken toward defining this division.

The objectives for this project are delineated as follows.

Identify the Major Manufacturing Cost Drivers

Precipitated by a lack of long-term capacity driven commitments, the current fuel cell industry suffers from the same capital resource deficiency as any other enterprise manufacturing a low volume and high mix of products. Understanding this prerequisite allowed the industry SMEs to focus on areas of manufacturing, where a combination of process efficiency, resourceful material usage, and the elimination of unnecessary quality measures could be implemented to reduce cost. The specific cost drivers are explained in greater detail in the body of the report

Identify Current Best Practices in Fuel Cell Manufacturing Technology

For polymer and ceramic systems, a key step is to identify the best practices of today. The nature of business is such that certain technological and manufacturing proprietorship exists to maintain a competitive edge in the commercial and military markets. Recognizing the difficulty of obtaining explicit manufacturing information, the extraction of the best practices was intended to concentrate more on the “what” aspect of manufacturing, rather than on the largely proprietary “how” facet of production. For example, attributes such as temperature, time, pressure, and concentration were avoided and considered to be in the domain of the proprietor. The industry was more willing to share the manufacturing steps from process to process, which in most cases was specific enough to identify the underlying gaps and issues associated with cost reduction.

Identify Manufacturing Technology Gaps and Projects where the DOD can Target Investments to Meet the Objectives

Having ascertained the current and recommended best practices, the SMEs were tasked to document the impediments preventing the implementation of the recommended best practices. This is the precursor to the construction of a roadmap that articulates specific proposals on how to address the gaps, the time needed for transition, and the resources required for execution. There are certain actions that are within the purview of industry that can affect cost and implementation. The technological expertise to precipitate change lies within the fuel cell industry, while the DOD and other government agencies can provide motivation for change by investment and endorsement of effective and cost cutting technologies.

Identify Potential Best Practices in Fuel Cell Manufacturing

In some cases what was currently perceived as a manufacturing best practice was also deemed as the foreseeable recommended best practice. In most cases, the current manufacturing practice was lacking in cost or process efficiency and industry recommendations were made to improve both elements. Care was given to differentiate between what was the probable execution of a viable manufacturing process given the appropriate resource, versus an undefined or embryonic process still requiring large non-existent infrastructural changes to facilitate them. In some cases, what was currently perceived as a best manufacturing practice was also deemed as the foreseeable recommended best practice.

3. Military Perspective on Fuel Cells

The military is currently non-committal regarding the technology and fuel source for fuel cells providing the approach meets the required performance and safety parameters. However, for those systems that are considered to be deployable, the desired fuel source is JP-8 in accordance with the mandate of one fuel forward. For the smaller systems below 500 watts, the emphasis is on a packaged fuel. Currently, propane and methanol are the leading candidates. For those systems that are to be installed in fixed locations (i.e., material handling equipment (MHE) or backup systems), such as military installations in the United States, fuel sources such as direct hydrogen or natural gas would be acceptable.

Another reason that the military is interested in fuel cells is that it is the only power generation technology scalable to meet requirements. A fuel cell can be designed to be easily carried by a warfighter or large enough to power a tent city (not that scale up is trivial, but the basic technologies are the same). This allows for some economy of scale in the overall production.

Fuel cells can offer significant advantages over traditional combustion engines (diesel generators and gas turbines).

- Increased power efficiencies
- Better modularity and power integration
- Lower hydrocarbon emissions
- Lower audible noise
- Lower thermal signatures
- Reduced fuel consumption

No matter the application, fuel cells offer a highly efficient technology with the potential to reduce the overall logistical footprint and dependence on fossil fuels.

3.1. NAVY PERSPECTIVE ON FUEL CELLS

The challenge related to fuel cells for Navy applications, especially in low acoustic and thermal signature applications, is not only their ability to provide power, but to be cost effective and endure the marine and littoral environments in which the Navy operates. Cost, durability, size, weight, thermal, and water management are major barriers and challenges to the commercialization of fuel cell technology in both commercial and military applications.

To expand fuel cell usage in the Navy, fuel cells must use logistical fuels already in the DOD supply chain (e.g., JP-8, JP-5, and F-76). The power ranges that are of current interest to the Navy and Marine Corps for tactical applications are mobile power (1 kW to 100 kW) and stationary power (>100 kW). These ranges and fuel choices narrow the fuel cell technologies of interest to solid oxide fuel cells (SOFC) and to polymer electrolyte membrane (PEM) fuel cells. Exceptions to the use of battlefield fuels can be made when justified by exceptional performance, when nothing else can do the job (notably in the areas of small battery chargers), and unmanned vehicles. For permanent installations and facilities in secure or domestic locations, the fuel choices can expand to include natural gas and even hydrogen. The feasible applications can also expand to include buildings for combined heat and power (CHP), road and off-road vehicles, mobile auxiliary power, materials handling, and backup power (power reliability). Indeed, any of the various civilian applications for fuel cells, many of which are currently undergoing demonstration programs, are candidates for adoption by the military. Justification for these applications includes economic, environmental, logistic, energy security, and political reasons.

There are technical issues that must be solved in order to bring fuel cells to broad Navy application, with fuel reforming the most prominent. Fuel reforming, cleanup, and purification are key technologies for processing raw fuel into basic reactants that can be consumed by the fuel cell. Sulfur and other reformate contaminant removal is a critical technology to enable use of logistics fuels in fuel cells. Significant manufacturing and acquisition costs can be lowered by reducing or eliminating the use of precious metal catalysts (such as Pt) to reform fuels. Other manufacturing issues include development of automated production lines to reduce manufacturing costs associated with manual assembly lines. Increasing automation decreases product variation and reduces worker error in the assembly process.

Matching the appropriate fuel cell technology with an application is a critical aspect of power sources management. Fuel cells are part of the overall power system and are often hybridized with power electronics and batteries for power conditioning in the electric grid. Power management techniques for fuel cell power systems and hybrid power systems must be modeled to develop fuel cell standards for applications with different power ranges.

The Navy has shown a keen interest in the adoption of fuel cell technology as a supplemental power source on electric ships. Increased energy efficiency is a key driver to the utilization of fuel cells. A projected two-fold increase over conventional hydrocarbon fuels can be realized without additional greenhouse pollutants (such as nitrogen oxide) that are by-products of gas turbine and diesel engines. Endurance, size, and power flexibility are also key attributes required for successful implementation into naval power systems. In addition, modularized fuel cell power systems are well suited for the distributed power systems sought for implementation of next generation integrated power systems (NGIPS).

For a given power level, fuel cells require less airflow and have a lower exhaust temperature. The smaller intake and exhaust ducting frees space for other ship systems. Fuel cells can be dispersed throughout the ship instead of being co-located with the ship's shaft. Distributed power will reduce the need for a central ship power station and improve the ship's survivability, design flexibility, and energy efficiency.

The advantages of fuel cells over combustion engines (diesel generators and gas turbines) are mostly the same in shipboard systems as in ground based platforms; increased fuel efficiencies, modularity, lower hydrocarbon emissions, reduced audible noise, and reduced thermal signatures.

While fuel cells have the potential for use in all-electric ships and unmanned vehicles, there are a number of challenges remaining. These include high acquisition costs, high maintenance costs (e.g., stack replacement), and the high cost of energy production. Fuel cells cannot directly use logistics fuels. These fuels must be reformed to produce a hydrogen rich fuel stream. The current state of reforming technology creates a time lag of seconds for power load changes (the requirement is less than a tenth of a second) and reduces the power density to less than that of combustion engines. Fuel cells also take several minutes to start up and would not be considered feasible for replacing emergency generators without the inclusion of a startup battery. The use of power electronics conversion modules can assist the fuel cells to better interface with the power distribution system.

Leading fuel cell experts indicate that these challenges are all solvable with technology improvements to reformers, fuel cells, power electronics, balance of plant (BoP), and manufacturing processes.

3.2. ARMY PERSPECTIVE ON FUEL CELLS

The ability of the United States military to decisively defeat its enemies is greatly due to the ability of its warfighters to see first, react first, and strike first. This high degree of lethality is heavily dependent on the electronics equipment and weapon systems at their disposal. Electronics systems utilized by military personnel range from global positioning systems, tactical radios, small robots, and small unmanned aerial vehicles (UAVs) to larger systems, such as tracked vehicles, large UAVs, and satellite communications. The dependence on electronics has increased immensely over the last 60 years. **Figure 3-1** shows the WWII standard “walkie-talkie” which was powered by 4 “D” cell batteries. This radio was the only portable electronic device used by a soldier, and not every soldier had one. The picture on the right shows the typical soldier of today using batteries in his gun sight, his squad radio, his global positioning system unit, his NightVision goggles, and even his watch.

Figure 3-1: WW II “walkie talkie” (left); Soldier of today (right)

The logistical support provided to the warfighter has also dramatically changed. There was a commonly accepted notion that an “iron mountain” of supplies can be built up to support warfighters in combat operations. This includes a decidedly higher level of stocks supplied to the rear echelon than in previous operations. All of these facilities and equipment have one thing in common, the need for electrical energy. This need for energy is climbing faster than can be efficiently provided to the user. Currently, the vast majority of this energy comes from two sources, batteries and fossil fuel generators. Although both of these sources of energy are well integrated into the warfighter’s operating procedures, they also represent a significant logistics burden during combat with an associated high life-cycle cost.

Two conclusions can be drawn: the demands for power are increasing, and the logistical footprint for providing this power is increasing. This is becoming an increasing concern in recent conflicts where the movement of supplies throughout a combat area has introduced vulnerabilities that require an increase in resources needed for protection. Consequently, the military is looking at methods to reduce the logistical footprint of energy while meeting the increased force capabilities. Fuel cells are emerging as a technology with the potential to meet some of these increasing military energy requirements.

Fuel cell power generation can be divided into five broad categories: soldier portable, man-portable, mobile, weapon platforms, and stationary systems. The advantages for each system are described below.

Soldier Portable Fuel Cell Systems

Soldier portable systems are carried by the individual warfighter. They typically weigh less than approximately 12 pounds, and normally generate less than 100 watts of power. They:

- Allow the warfighter to charge a battery while in motion
- Decrease the weight and volume of batteries required to complete a mission
- Decrease in weight as energy is produced (for both soldier and man-portable systems)

Man-Portable Fuel Cell Systems

Man-portable systems are not dedicated to a specific soldier. They normally weigh less than 36 pounds and generate between 100 and 500 watts of power.

- Are significantly quieter than a generator – a critical asset, especially for silent watch operations
- Support the greater use of rechargeable batteries by pushing the battery charging capability forward
- Reduce the overall logistics footprint (which increases capacity for other equipment)
- Allow for the use of packaged fuel
- Provide an energy source greater than solar or wind powered alternatives

Mobile Fuel Cell Systems

Mobile systems can produce up to 20 kilowatts of power and are usually transported via a trailer or mounted on a vehicle. They are typically used for rear echelon support.

- Operate quieter
- Size more easily to meet actual demand (e.g., load following)
- Reduce maintenance
- Reduce logistics footprint due to greater efficiencies

Weapon System Platforms (e.g., UAV, UGV)

Weapon Systems platforms offer hybrid power generation.

- Extend the run/mission time for a system without needing extra batteries. (Especially in small robots and unmanned vehicles using a fuel cell/rechargeable battery hybrid)
- Reduce weight which allows increased weapons or sensor packages
- Reduce maintenance
- Allow distributive power
- Simplify the design of “all electric” systems

Stationary Fuel Cell Systems

Stationary systems are not moveable under normal circumstances.

- Can be renewable (e.g., waste to energy)
- Provide distributed power generation
- Are applicable off-grid
- Use waste heat for higher efficiencies
- Provide a cost effective solution where “spark spread” is favorable

The higher efficiency of fuel cells decrease the fuel needs which in turn reduces the amount of combat resources needed to protect the supply lines during combat operations. Fuel cells also have the potential for greater energy independence for the warfighter, especially in remote locations.

3.3. AIR FORCE PERSPECTIVE ON FUEL CELLS

The Air Force need for fuel cells is focused primarily on providing logistic support for warfighter efforts. Providing anything from portable energy for battlefield airman to the incorporation of hybrid electric propulsion systems, portable power generation and management is a key ingredient to obtain the balance between energy and power densities. Micro air vehicles weighing less than 1 lb. can be deployed using wearable power ranging from 10 watts to 100 watts. Unmanned aircraft systems (UAS) can be hand launched and weigh less than 20 lbs. while logistically fueled UAS systems can provide long-range ground or air launched capability with a platform weight of less than 150 lbs. and increased payload capabilities.

Research into hybrid electrical propulsion systems have produced successful small unmanned aerial system (SUAS) hand launched vehicles such as the Puma and Raven that provide longer flight endurance and increased mission functionality. The key lessons learned were that SUAS design and power systems should be integrated to maximize endurance, reliability, and ruggedization. Reconnaissance, surveillance, and targeting are important mission roles to support forward operating base security and stabilization operations into remote airfields and villages. The Small Unmanned Renewable enerGy long Endurance Vehicles (SURGE–V) program is developing a UAV smaller than 20 pounds for missions longer than four hours. Technical challenges for fuel cell systems in these hand-launched UAVs are greater mission endurance, larger payloads, rapid start-up, and the compliance to MIL-STD-810 requirements for ruggedization. The operational challenge is to use logistic fuels as a feedstock while providing a muted system signature (thermal, acoustic, visual) to avoid detection. Environmental conditions (such as high winds, wet and dusty surroundings) must be overcome as operations may impose g-forces from drop or air-launched maneuvers. Tube launched systems necessitate an even greater endurance to high-g forces.

Reliability remains a concern since most mishaps occur during takeoff or landing. Propulsion systems require increased endurance and run times for continuous operation to minimize the number of takeoff and landing operations per tactical mission. Currently, the limiting factor for propulsion systems is the short intervals between maintenance (100 hours). If system maintenance intervals could be increased to 1000 hours, the added capital cost of an advanced propulsion system would be offset. With less moving parts than combustion generators, fuel cells present an opportunity to reduce these maintenance intervals.

Portable Electronic Power Supply for Aero-medical Evacuations (PEPSAE) is another area where fuel cells can make a significant impact. The current systems are too heavy (980 lbs.), cause cabin congestion due to excessive cables, and have a high potential for electric sparking. A lightweight, high-powered, portable fuel cell system such as the PEPSAE would provide long duration continuous power for medical equipment, giving critical patients superior care. The Air Force has engaged in other portable power generation efforts. The battery renewable integrated tactical energy system (BRITES) program was initiated to develop and integrate portable power generation, storage, and distribution technology to support the dismounted airman. The objective was to produce a warfighter utility comprising a 50 W fuel system with the capability of reducing current battery weight from 35.5 lbs. to 17.9 lbs. for a standard 72-hour mission profile. The tactical advantage of reducing the weight burden and increasing power flexibility is a distinctive improvement for reducing physical stress and increasing maneuverability.

3.4. IMPACT OF MILITARY REQUIREMENTS ON FUEL CELL COST AND DESIGN

There are certain characteristics that the military desires in a fuel cell. Primarily, does it provide a capability that does not exist today? Can it allow unmanned vehicles to loiter for longer periods? Will it extend the range of an IED (improvised explosive device) robot? Does it shorten supply lines as it applies to batteries? Is it a replacement for an existing power source because it is lighter, smaller, and quieter? Does it make the mission simpler? Will it provide improved life cycle costs?

As with many other items, the military desires to leverage advances in the commercial marketplace to keep procurement cost minimized. For an emerging technology such as fuel cells, this is also true, but due to military requirements that have no parallel in the commercial world, dual use technology is not always possible. The ability to leverage fuel cell technologies is dependent on the intricacies of the system. For large systems, especially stationary systems, a fuel cell designed for operating in a manufacturing facility or hospital will also work in a depot. Even trailer-mounted systems can have a large amount of synergy between commercial and tactical environments. The biggest difference is the extra design work required to ruggedize the commercial system for tactical purposes.

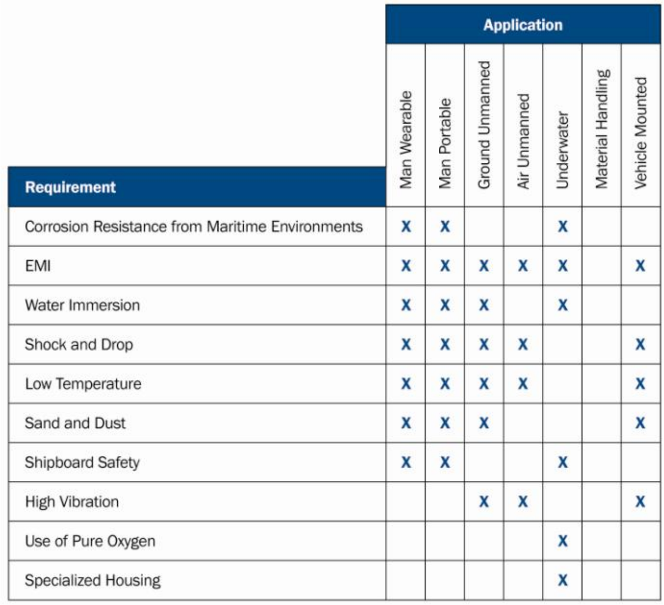
As fuel cell systems become smaller (along the lines of the soldier wearable and man-portable systems), the ability to use commercial systems and components begins to diverge. This is largely due to the requirement that these systems must not only survive abuse, but must also perform in a wide variety of environments, from high to low temperatures and from jungles to mountaintops. In addition, it must meet these requirements in a small, lightweight package.

Military systems must withstand extreme environmental exposures that that are not required commercially. The requirement to make portable fuel cells smaller and lighter is already a challenge, but is further complicated by this need for ruggedization. Even if a small fuel cell system were commercially available, it would not meet the ruggedization requirements imposed by the military. If it did, it would be an overdesign for the commercial market and an unnecessary expense. With these systems, there is very little “trade space” between system performance, ruggedization, and the need to perform acceptably under all sets of conditions.

- Operating and storage: temperatures, altitude, and humidity levels
- Shock and vibration exposures during shipment and use
- Low noise levels and thermal signature
- Electromagnetic interference (EMI) with other soldier equipment
- Rain, dust, wind, and sand protection
- Thermal shock
- Water immersion, salt - fog

How does this impact costs? For the larger systems, the cost may be minimized through partial ruggedization of the system enclosure (shock mounts, better filtration systems). For the smaller systems, these costs can be significant. A major cost driver is the military's requirement for short start up times. The costs related to meeting military requirements are also found in the balance of plant, where components in the commercial market are either not available, extremely expensive, or when available, must be modified to meet design criteria. Another major cost driver is reforming JP8.

The end item application for a fuel cell dictates the precise design requirements. For generator systems, weight and size is critical since they must be mobile and survive and operate in tactical environments. The design constraints on the soldier or man-portable systems are stringent. Size, weight, and the ability to withstand rough handling are very critical. Such systems must be light enough to be carried by a single individual, be simple to use and maintain, and survive under a wide range of conditions such as being dropped, high and low temperatures, dust, humidity, and rain. Some of the unique requirements that need to be considered are depicted in **Table 3-1**.



	Application						
Requirement	Man Wearable	Man Portable	Ground Unmanned	Air Unmanned	Underwater	Material Handling	Vehicle Mounted
Corrosion Resistance from Maritime Environments	X	X			X		
EMI	X	X	X	X	X		X
Water Immersion	X	X	X		X		
Shock and Drop	X	X	X	X			X
Low Temperature	X	X	X	X			X
Sand and Dust	X	X	X				X
Shipboard Safety	X	X			X		
High Vibration			X	X			X
Use of Pure Oxygen					X		
Specialized Housing					X		

Table 3-1: Fuel cell requirements per application

3.5. MILITARY FUEL CELLS ADAPTATIONS AND COMMERCIAL APPLICATIONS

Phase II of the Manufacturing Fuel Cell Manhattan Project (MFCMP) included multiple presentations by representatives of the user/developer community in an effort to understand the impact of unique government requirements on the manufacturing process, and hence cost and reliability goals. The MFCMP strategy is to extract and detail the fuel cell manufacturing practices, identify the major costs, and recommend solutions to resolve the high cost currently associated with manufacturing. The intent is to be as application neutral as possible, while focusing efforts in improving manufacturing efficiencies and addressing gaps within the fuel cell system infrastructure. Having said that, nobody buys just a fuel cell stack. They buy a fuel cell system to meet a particular application. In military platforms, most FC applications are very specific to the mission requirements as delineated in the product specifications. Industry providers will often customize their manufacturing processes to meet the product requirements, though many of the components and production methods remain generic enough for a multiple range of applications. The applications described in this section were generally agreed to benefit from any improvements derived from this manufacturing study. A more detailed review of the applications can be located in Appendix A.

There are nine fuel cell application areas of high interest to the DOD:

- Unmanned Aerial Vehicles (UAVs)
- Unmanned Undersea Vehicles
- Tactical Vehicle auxiliary power units (APUs)
- Aircraft APUs
- Shipboard APUs
- Material Handling Equipment
- Distributed stationary Power
- Emergency backup power
- Portable soldier power

3.5.1. Unmanned Aerial Vehicles (UAVs)

Unmanned aerial vehicles were originally used by the military as remote-controlled airplanes for anti-aircraft training of artillery men. More recently, special purpose UAVs have become a valuable tool for intelligence, surveillance, and reconnaissance missions including communication relays, air-to-land combat missions, and border patrol monitors. Future uses include commercial and military applications for fire surveillance, weather stations, traffic, construction, communications relays, food/water rescue drops, and even mail/shipping.

Military UAVs typically fall into one of five functional categories:

- **Target and decoy** – providing ground and aerial gunnery a target that simulates an enemy aircraft or missile
- **Reconnaissance** – providing battlefield intelligence
- **Combat** – providing attack capability for high-risk missions (see Unmanned combat air vehicle)
- **Logistics** – UAVs specifically designed for cargo and supply chain management
- **Research and development** – to further develop technologies for field deployed UAV aircraft

3.5.2. Unmanned Undersea Vehicles (UUVs)

The Unmanned Undersea Vehicles (UUV) program was created with the goal of extending knowledge and control of the undersea battlespace through clandestine off-board sensors. UUVs allow a ship or submarine to safely access denied areas using revolutionary sensors and weapons. These areas may be denied based on unacceptable risks such as extremely shallow water, very poor acoustic conditions, or mined waters. UUVs provide unique capabilities and extend the "reach" of naval platforms while reducing the risk to a nuclear powered submarine (SSN) and its crew.

The first UUVs fielded on SSNs will support mine warfare. The Long-term Mine Reconnaissance System (LMRS) will greatly improve submarine mine hunting capabilities in the near future. Ultimately, a mission reconfigurable UUV will provide more capabilities and lower risk to future SSNs, helping to maintain future undersea dominance against any threat.

Contributing to SSN mission areas such as Mine Warfare (MIW) Intelligence, Surveillance, Reconnaissance (ISR), and undersea environmental sensing and mapping, future Navy UUV activities are envisioned to include:

- Intelligence, Surveillance, Reconnaissance
- Mine Countermeasures
- Anti-Submarine Warfare
- Inspection / Identification
- Oceanography
- Communication / Navigation Network Node
- Payload Delivery
- Information Operations
- Time Critical Strike

3.5.3. Tactical Vehicle Auxiliary Power Units (APUs)

The need exists for improved non-primary electric power that will support military ground vehicle engine-off operations. The means of generating this electricity must offer better fuel efficiency and have lower thermal and acoustic signatures than idling of the main engine. Current battery, alternator, and APU technology cannot meet silent watch requirements. There is no technology in the Army inventory, besides batteries, that can meet the acoustic signature requirements of silent watch. The Army has mandated use of JP8 fuel that has resulted in the elimination of simpler APU prepackaged fuel options.

The Army’s approach to resolving this issue is to integrate the complex components of reformation, energy storage, and fuel cell technologies. Through technology programs that the ONR, ARL, TARDEC and others have initiated, fuel cells have been designed and developed for military environments targeted to operate for 1000 hours. As a result, a never before designed JP8 reformer system and fuel cell combined into a defined space, has produced a non-primary power for engine-off operations.

There is a need for long term testing of fuel cells and reformer systems operating in a complete integrated system. The balance of plant components, along with the inefficiency of test data sharing amongst military organizations, renders tests and system builds as a major expense. In terms of reliability, manufacturing robust fuel cell stacks and BoP support hardware to withstand the operational environment requires acceptable performance in shock and vibration.

3.5.4. Aircraft Auxiliary Power Units (APUs)

The aircraft industry has historically powered all their auxiliary equipment using the jet engines. Over time, with fuel costs rising, pressure from various countries to reduce aircraft emissions, and the trend toward electrification of aircraft and airport ground support equipment, an opportunity for high-efficiency clean fuel cells is emerging. One major aircraft manufacturer is exploring a phased approach to fuel cells onboard jet aircraft, beginning with hydrogen and PEM fuel cells for galley power, incrementally expanding this to include other hotel loads, and eventually reforming jet fuel onboard the aircraft to produce as much as 1 MW of hotel power.

Applications under consideration are rotorcraft, fixed wing aircraft, high altitude long endurance aircraft, and airport infrastructure. Onboard applications could include auxiliary power units, flight motive power, powered landing gear, galley power, water production, back-up power, nose wheel power, and distributed power. Airport ground applications under consideration include mobile refueling vehicles, tugs, general maintenance equipment, back-up power, radios, portable generators, portable lighting, de-icing, and sustained electrical power quality for airport operations.

Opinions differ on the fuels to be used for these fuel cells. Hydrogen is preferred by some, while reforming jet fuel is demanded by others. Some advocate for methanol, metal hydrides, butane, or chemical hydrides. Areas of agreement center on the need for affordability, high technology readiness levels, both PEM and SOFC technologies, reliability, small size, and low weight – even more than in automotive applications. There are also commonalities with other fuel cell applications. Ground support equipment (GSE) shares aspects of material handling equipment (MHE) applications such as forklifts. Power generation technologies for aircraft are similar to those with stationary and back-up fuel cells. Finally, portable applications (e.g., lighting, radios, and portable generators) share commonalities with fuel cell portable power.

Manufacturing issues associated with onboard aircraft and airport fuel cells include membranes, catalyst layers, and reforming hydrocarbon fuels. Other balance of plant issues include pumps, valves, blowers, sensors, fans, and power conditioning. Success in fuel cell niche markets, such as forklifts and emergency back-up power, will pave the way for future gains in the more demanding aircraft and airport markets.

3.5.5. Shipboard APUs

The benefits of generating shipboard power from fuel cell based generators include reduction in acquisition and life cycle costs (due to greater fuel efficiency) and reduced maintenance costs. By basing the shipboard fuel cell generator on commercially designed distributed power products, the development time can be reduced, and considerable savings realized. There are operational benefits to replacing engine-based generators with fuel cells. Ship survivability is enhanced due to reduced acoustic and infrared emissions, and by distribution of numerous smaller generators in multiple locations around the ship. Finally, fuel cells are modular by design. This enables flexibility in ship machinery layout and allows use on multiple platforms with the same design.

Fuel cells provide low emissions and support all goals of the U.S. Navy green fleet initiatives. Fuel cells have higher efficiencies and lower CO_2 emissions. Since they do not use a combustion process, they have greatly reduced NO_x, CO, hydrocarbon, and particulate emissions. The Secretary of the Navy recently announced plans for a future green fleet running on nuclear power and biofuels. Biofuels do not include sulfur, making them an enabler for fuel cells.

According to studies by the U.S. Navy and the U.S. Coast Guard, there is a significant potential commercial market for shipboard fuel cells in the 500 kW to 1500 kW range (approximately 3,000 units per year over the next 5 years). Fuel cells provide emissions, noise, and efficiency benefits over existing commercial marine power generation systems.

From preliminary design studies, polymer exchange membrane (PEM) fuel cells (including high temperature PEM), and molten carbonate fuel cell (MCFC) types are currently mature enough and have the potential for the high power levels required. These types can provide from 35 % to 50 % energy efficiency. Slightly less mature solid oxide fuel cells (SOFC) have the potential to provide up to 60 % fuel efficiency.

Fuel cell based power plants possess the potential of superior performance with optimized fuel efficiency and environmental impact. The Office of Naval Research (ONR) and the Naval Sea Systems Command (NAVSEA) are conducting advanced technology development programs to develop and demonstrate fuel cell components and electric power generators for surface ship applications. A principal goal of the Navy’s Ship Service Fuel Cell (SSFC) Program is to demonstrate that commercially developed fuel cell technology can utilize naval logistic fuels and operate in a marine environment.

3.5.6. Material Handling Equipment (MHE)

Perhaps the most successful early market for fuel cells is MHE, particularly forklifts. Battery powered forklifts, while critical for indoor warehousing applications, have a number of drawbacks. These include:

- The need to have three batteries for every lift truck; one in the forklift, one being charged, and one cooling after charging
- The need to have a battery charging room which contains hazardous materials and takes up significant square footage in a warehouse
- Noticeable degradation of power toward the end of a shift as the battery charge depletes

Hydrogen PEM fuel cells have demonstrated that they can compete with batteries for MHE applications on a life cycle cost and performance basis. The key elements for an ideal business case are:

- Multi-shift operations within the warehouse
- A minimum of 25 or more lift trucks in use at the site
- Utilization of existing hydrogen and fuel cell tax credits
- ‘Greenfield’ sites where dual infrastructure (battery and hydrogen) can be avoided

From a performance standpoint, productivity gains of as much as 20 % have been observed in high tempo operations due to the steady power a fuel cell provides throughout the shift, as well as faster refueling times (2-3 minutes compared to 15-30 minutes to swap out a battery).

In summary, PEM fuel cells have found a near term niche market in material handling equipment. Continued success in these fuel cell early markets will, in turn, lead to more manufacturing improvements that can translate to fielding major PEM applications, such as light duty vehicles.

3.5.7. Distributed Stationary Power

Fuel cell power plants produce electricity and useful thermal energy at high efficiency, in some cases approaching 80 %, with minimal emissions of SO_x and NO_x. The thermal energy can be used for heating purposes, or when combined with an adsorption chiller, can be used to cool a facility. In addition, they can also be designed to operate either connected or independent of the local electric grid. Therefore, they can simultaneously replace the electric grid, heating and cooling systems, and emergency generators in many building applications.

The U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) continues to successfully test stationary fuel cell power plants in a variety of applications at military bases around the U.S. Applications include base housing, emergency shelters, hospital training schools, and housing.

Several commercial deployments are beginning to emerge which capitalize on fuel cell's unique benefits (i.e., the ability to operate independently of the electric grid and the ability to provide thermal energy for either heating or cooling), and have direct military applications.

One example is the fuel cells installed at the First National Bank of Omaha, Nebraska. Serving almost 7 million customers nationwide, First National recognized that the electric grid would be unable to provide the power reliability that the data center requires. During one particular grid outage, the backup generators failed to start and the timely processing of several million dollars of credit card transactions for a major U.S. retailer became problematic. The bank estimates that one hour of downtime is valued at $2-5 million. In order to prevent this in the future, the bank installed four 200 kW fuel cells plus rotary UPS systems to provide assured power. The fuel cells were installed in semi hardened underground rooms with cooling towers and limited access for further protection. More details can be found in the DOE/EE report "Case Study: Fuel Cells Increase Reliability at First National Bank of Omaha Technology Center." [1]

3.5.8. Emergency Backup Power

A recent Battelle study identified backup fuel cells were cost competitive with diesel generators on a life cycle cost basis. Fuel cells can provide up to 72 hours of emergency backup power continuous runtime. Anything less than 8 hours can usually be provided by a battery-based uninterruptable power supply (UPS). Run times over 72 hours require too many bottles of hydrogen (for a hydrogen PEM fuel cell system) and are best provided by a diesel generator. Fortunately, this 8-hour to 72-hour range is frequently the requirement, particularly in the wireless telecom industry. Fuel cell backup power has proven to be highly reliable with lower life cycle costs and has been employed in both government and commercial applications.

DOE ARRA awards to both Sprint and AT&T have led to hundreds of deployments across cell tower sites throughout the US.

Within the DOD, the CERL in partnership with DOE has overseen backup power installations in several locations, including the New Mexico National Guard, Fort Jackson (SC), Aberdeen Proving Ground (MD), Fort Hood (TX), Picatinny Arsenal (NJ), West Point (NY), NASA Ames (CA), 29 Palms USMC (CA), Ohio National Guard, Fort Bragg (NC), and Cheyenne AFB (CO).

Other successful DOD deployments include the Los Alamitos Joint Forces Training Base (CA) and the Marine Corps Logistics Base (Barstow, CA). In each of these cases, a cost share was provided to help offset the added capital costs associated with fuel cells (compared to diesel generators). Additionally, the high emissions associated with diesel generators have caused some jurisdictions (e.g., South Coast Air Quality Management District, CA) to limit their use by mandating higher permitting fees for their continued operation. Fuel cells are also more efficient in that they are load following, as opposed to diesel generators that run at rated capacity even if the load is much less.

Army CERL has collected reliability information on the backup fuel cell deployments they have overseen and has also provided lessons learned from the fuel cell backup power deployments they have witnessed. CERL has highlighted the need to:

- Improve lifespan/reliability
- Increase users knowledge
- Standardize installation requirements
- Incorporate power purchase agreements and lease options
- Utilize the federal investment tax credit through 3rd party ownership of the fuel cell
- Reduce overall costs

3.5.9. Portable soldier power

(See 3.2. Army perspective on fuel cells)

4. Fuel Cell Manufacturing Overview

4.1. TECHNOLOGY

Fuel cells produce electricity through electrochemical reactions similar to a battery. They have an anode, a cathode, and an electrolyte, but unlike a battery, they will run for as long as fuel is supplied and maintain a consistent output voltage over time. Fuel cells are not like generators, which produce electricity by rotating metals in a magnetic field, they do not burn fuels like internal combustion engines, and they have a much lower noise signature than typical generators. Instead, fuel cells use electrochemical methods to harness the electrical energy released in a controlled chemical reaction and are much more efficient than internal combustion engines producing heat and water as by-products. There are several types of fuel cells and they are typically classified by their electrolyte material.

PEM (polymer electrolyte membrane or proton exchange membrane) and ceramic based SOFC (solid oxide fuel cells) are believed to have the greatest promise for a breadth of DOD missions while also finding dual use that will facilitate the scale necessary to achieve reduced manufacturing costs. Consequently, this document focuses on various PEM and SOFC architectures. In both types of fuel cells, fuel (usually in the form of hydrogen) is typically introduced at the anode. The anode facilitates a chemical reaction by using a catalyst on the surface or by running at high temperatures. Electrons are stripped from the hydrogen at the anode and moved from the anode into the conductive internal wiring system of the fuel cell, producing electricity. This process creates a direct current (DC) similar to a battery. A converter must be used to provide alternating current (AC). The hydrogen without its electron (called a proton) moves through the electrolyte to the cathode where it combines with oxygen (usually from air supplied to the cathode) and the externally supplied electron to form water. Every fuel cell uses fuel and contains a cathode, anode, and electrolyte. The various types of fuel cells are differentiated by the type of electrolyte, the fuel, the chemical reactions, the operating temperatures, and the catalysts used.

The efficiency of a fuel cell is determined from the amount of power drawn from it, meaning the more current drawn from the cell results in a lower efficiency. The percent efficiency represent the amount of energy that will be produced from hydrogen, the remaining percentage is the amount of heat that will be produced. A simple calculation can be done to determine the efficiency of a cell. It is: the voltage output of the cell divided by 1.48 volts. This calculation is based on the enthalpy or heating value of the reaction. A typical range of efficiency for a correctly functioning PEM cell is 40-50%, while SOFCs can achieve efficiencies of 65% or greater. Fuel cells can operate at a much higher efficiency compared to Carnot cycle engines due to the difference between the reaction types, as in, a fuel cell functions based on direct electrochemical reactions producing Direct Current (DC) as opposed to combustion reactions. Other factors that can influence efficiency are electrolyte and fuel cell geometry. The electrolyte material must be specifically designed to allow only the passage of protons and not electrons. The geometry of the cell must allow for sufficient surface area of the anode and cathode to facilitate the necessary reactions.

4.2. ORGANIZATION OF THE MANUFACTURING SECTION

The scope of fuel cell manufacturing includes an expansive mosaic of various technologies and applications. Manufacturing processes overlap in many cases, while in some areas additional core competencies are required to meet production specifications. In the case of this study, the manufacturing taxonomy is organized into polymer and ceramic based fuel cells, which comprise most of the manufacturing ready technologies currently in use. The ranges of technologies within those two categories were still too extensive for this endeavor, and were narrowed down to focus on power ranges of less than 10 kW (**Figure 4-1**). Below is a representation of where certain applications would be positioned within the power ranges of interest.

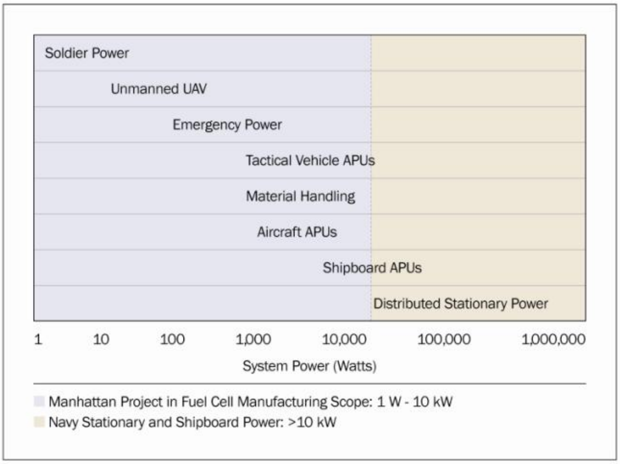


Figure 4-1: Power versus application

Since this is a study of current and best manufacturing practices, the amount of data accessible at the lower power ranges presented a greater availability of comparative practices. Large stationary and non-tactical systems were given secondary consideration to fuel cells that had a current or more immediate potential for military applications. In the light of this selection process, many manufacturing technologies that can be referenced in other DOE and DOD studies were excluded from the body of this report, but as with many fuel manufacturing processes, there is synergy to a wide range of power and applications.

The manufacturing sections for the polymer fuel cells were partitioned into generalized areas covering: membrane electrode assembly (MEA), balance of stack (stack minus MEA), and balance of plant. The ceramic fuel cell manufacturing sections were divided into planar, tubular, and balance of plant. Within each of these general areas, manufacturing processes were detailed accordingly to provide an outline of the specific steps associated with the manufacturing of the individual components that comprise the working fuel cell.

After further diagnosis of the cost drivers and manufacturing processes associated with both polymer and ceramic fuel cells, the taxonomy was modified to combine the BoP manufacturing process as a first tier study. Additionally, since fuels are a prerequisite and a substantial cost differentiator to the manufacturer of any fuel cell, fuel processing was added as a separate additional area of investigation. **Figure 4-2** shows the modified organizational structure.

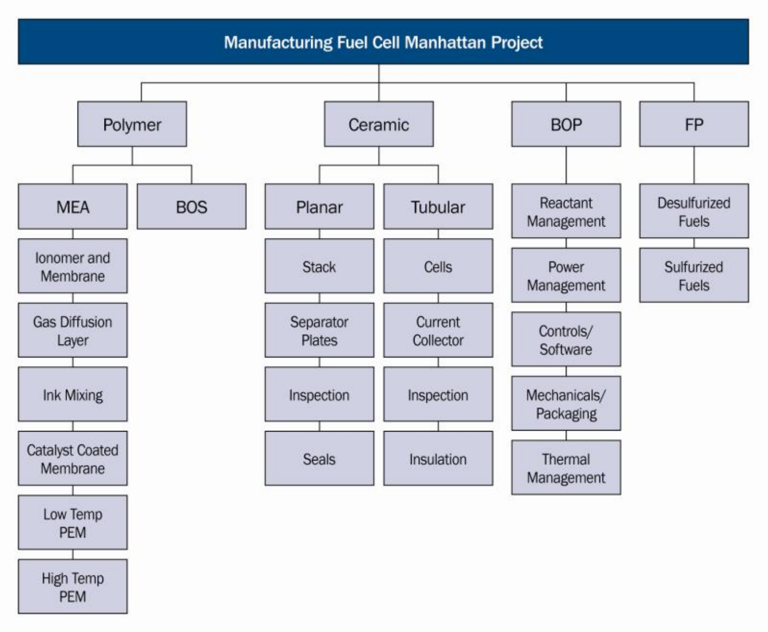


Figure 4-2: Modified manufacturing sections

Each respective subsection of the taxonomy chart is in essence a manufacturing process area that is delineated in detail in the subsequent chapters. In simplified terms, the manufacturing chapters set the direction for the ensuing project proposals that address the deficiencies found in current fuel cell manufacturing. The organization of the manufacturing processes is arranged in the following manner.

- **Current Best Practices** – defined as the most contemporary manufacturing process used for the particular process area
- **Gaps and Issues** - Articulates the most pressing problems in advancing fuel cell manufacturing efficiency and cost reduction
- **Recommended Best Practices** – Addresses the gaps derived from the current manufacturing practices and proposed solutions to meet the cost reduction and efficiency objectives. This section essentially outlines the projects that are defined in more detail in the second section of this report.

The Fuel Cell Projects

The projects are organized to extract the basic information to address the gaps and issues found in fuel cell manufacturing. A comprehensive list of gaps and project details can be located in Appendix A. The write-up of each project includes the following information:

- Project Description
- Problem Solved
- Benefits Derived
- Resources Needed
- Time to Project Completion

4.3. FUEL CELL SYSTEMS COST OVERVIEW

4.3.1. Polymer Fuel Cell Cost Drivers

Membrane Electrode Assembly (MEA) Cost Drivers

The primary cost drivers identified for the manufacturing process producing polymer fuel cells are focused in two areas, the MEA and the Balance of Stack.

The MEA, which comprise the power generating components of the fuel cell, are divided into the following areas:

- **Catalyst** – which comprises about 30 % of the manufacturing process costs. Though the cost of the Pt catalyst itself is not controlled by the manufacturer, the uniformity and the efficiency of the deposit has been identified as a major contributing factor.
- **Gas Diffusion Layer** – has been acknowledged as the second major cost driver in the MEA assembly at about 15 % of the process costs. The GDL acts as gas diffusion medium to provide uniform gas access to catalyst sites and is usually comprised of either a woven or non-woven polymer or paper that removes excessive water keeping the PEM conductive. It also serves to protect the catalyst layer.
- **Membrane** – accounts for 8% of the manufacturing costs. The uniformity of the membrane can drive the efficiency of catalytic process.
- **MEA Frame** – comprises seals and gaskets that account for 8 % of the cost.
- **Catalyst Application** – can occur by coating onto the GDL, or decaled to the membrane using release films and lamination methods. Release films can account for up to 3% of processing costs.

Balance of Stack Cost Drivers

BOS constitutes the Bipolar Plate (BP), which surrounds the MEA stack, and for polymer systems is processed accordingly as either a low temperature or high temperature component. The BP comprise about 25% of the total cost of the stack for LTPEM fuel cells with values as high as 35% for HTPEM fuel cells. The individual manufacturing process for Balance of Stack includes:

- Bipolar plate – 25 %
- Endplates, hardware, stack sealing, and packaging together comprising 12 % of the total stack cost

The composite cost excluding labor and BoP for each area of the polymer fuel cell stack is shown in **Figure 4-3**.

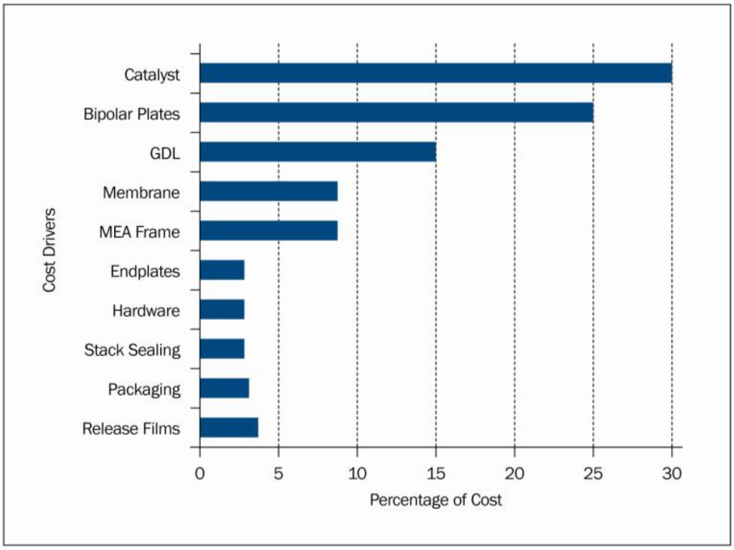


Figure 4-3: Cost drivers for polymer fuel cell stacks

4.3.2. Ceramic Cost Drivers

Planar Fuel Cells

Ceramic fuel cells are divided into planar and tubular types with the cost drivers varying somewhat as a function of the power output, especially with tubular systems. The Cold Zone components are typically considered BoP functions and are covered in subsequent discussions. The Hot Zone components are ostensibly the core of the ceramic fuel cells and the focus of the subsequent cost topics. The major costs associated with **planar** systems are

- **Planar Cells** – compose 40 % of the cost of the fuel cell and can be considered the equivalent function of an MEA in polymer systems.
- **Separator Plates** – account for 23 % of the Planar fuel cell costs and generally composed of an inert plate or a conductive ferrous material that separates the planar cells.
- **Seals** – comprises 15 % of the planar fuel cell costs and functions to separate the air and fuel mixtures as well as a bonding agent for the components.
- **Manifolds** – account for 7% of the fuel cell costs; they serve to feed fuel and oxidant gases and remove unreacted and product gases to and from the fuel cell stack.
- **Compression means** – account for 7% of the fuel cell costs; they consist of clamps, bars, rods and fasteners to hold the stack together. They are made from high temperature refractory metal alloys
- **Contact layers** – consists of 5 % of the fuel cell costs; There are two contact layers that electrically connect cells to the separator plate, including gas flow channels or fields.

- **Terminal Conductor (End) Plates** – consist of 3% of the remaining costs of the planar cells. These connect the planar fuel cell stack to the power conditioning electronics of the fuel cell system.

The composite cost excluding BoP for each area of planar ceramic fuel cells is shown in **Figure 4-4.**

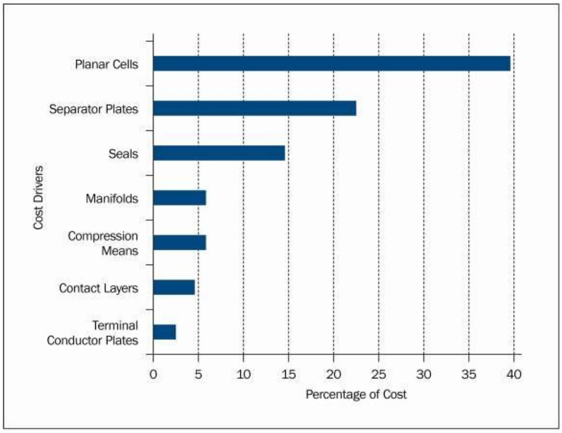


Figure 4-4: Cost drivers for planar ceramic fuel cells

Tubular Fuel Cells

Tubular fuel cells are advantageous in small systems for tactical purposes because of the small territorial footprint in relation to the power output. The percentage of cost each manufacturing area contributes to the tubular fuel cell cost changes according to the power output (**Figure 4-5**). For the purpose of this document, the cost drivers are separated into systems of less and greater than 500 watts, though the individual components remain virtually the same. Again, focusing on the hot zone the major cost drivers are:

- **Tubular Cell** – since it is the active electrochemical mechanism, the larger cells will appropriate a greater share of the cost at about 27%.
- **Recuperator** – recovers the heat from the exchangers and accounts for 26 % of the cost.
- **Current Collectors** - employs metallic current collectors to distribute electrical current along the length of the fuel cell tube. It is presently being hand wound. It averages about 20 % of the cost.
- **Insulation** - Typical ceramic fuel cells operate between 800 and 1000 °C and require specialized insulation. The cost can vary depending on the power output. The cost averages at about 15 %.
- **Burner, mechanical enclosure, seals, reforming, and manifold** – make up the remainder of the ceramic cost drivers at about 10%.

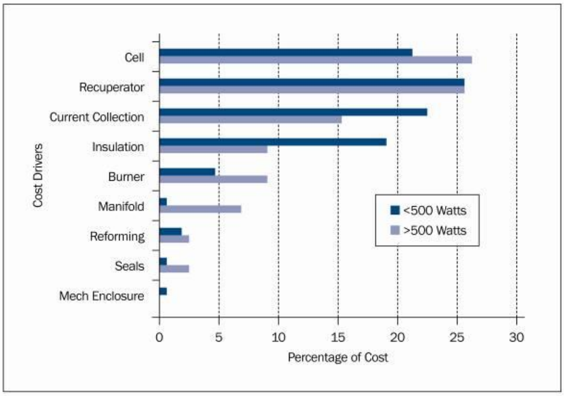


Figure 4-5: Cost drivers for tubular ceramic fuel cells

4.3.3. BoP Cost Drivers

Representative generic fuel cell systems were evaluated to determine cost drivers. Although a multiplicity of fuel cells sizes are currently being designed and manufactured, it was determined that a higher (2 kW to 10 k) and lower (<2 kW) power system could be generically extrapolated from this arbitrary division in power ranges. Additionally, these power ranges were further broken down into hydrogen based systems, reformed fuel systems, high temperature polymer, and direct fueled (DMFC) systems. The cost of drivers of the polymer fuel cell stack and the BoP components are shown in **Table 4-1**.

Division of Costs in Polymer Fuel Cell Systems

Cost Component	Range		Average
	Low	High	
Stack	17%	43%	30%
Reactant Management	19%	41%	30%
Power Management	11%	20%	15%
Mechanicals/Packaging	6%	15%	11%
Controls/Software	7%	20%	9%
Thermal Management	5%	6%	6%

Table 4-1: Polymer fuel cell stack and the BoP cost drivers

BoP components include pumps, blowers, filters, sensors, seals, fluid handling, electronics, and thermal management. These components account for as little as 50% of the total system cost, to as much as 80% depending on application and power range. Lower power systems tend to have a higher (relative to the fuel cell) cost component associated in the BoP than larger power systems.

The BoP components are broken down into the five major areas. Proper design, selection, and integration of BoP components are a key factor in the performance, lifetime, and cost of the power generation system.

The *Power Management* subsystem consists of internal power conditioning, external power conditioning, electronics thermal management, capacitance, hybridization, and EMI protection measures. The *Reactant Management* subsystem contains fuel processing (if needed), fuel and oxidant delivery, and water management. In the *Thermal Management* subsystem are cooling and heating equipment, and well as heat dissipation devices. The *Controls* subsystem contains active and passive control and monitoring equipment. Finally, the *Mechanical and Packaging* of the system is treated as another BoP component, providing structure, mounting, and protection.

For the sake of analysis, representative power ranges for fuel cell systems were evaluated for cost drivers, broken first into less than 500 W, then 500 W to 10 kW, and finally, systems ranging from 10 kW to 250 kW. Although other power ranges of fuel cell systems are currently being designed and manufactured, it was determined that these power ranges are representative of DOD needs and could be generically extrapolated from this arbitrary division in power ranges.

From the division of costs in these systems BoP components, the Reactant Management subsystem is a substantial cost driver, followed by power management, controls, packaging, and finally thermal management.

Reactant Management subsystem, further delineations were made to focus on specific cost drivers, including fuel delivery, oxidant delivery, and anode re-circulation equipment.

The second highest cost component was the Power Management subsystem which was broken down into hybridization, internal power conditioning, external power conditioning, electronics thermal management, capacitance, and finally EMI protection.

The Controls component of the BoP was not identified as a significant area for focus in the manufacturability cost reduction effort, with the exception of integrations of controls and software for elimination of mechanical equipment in the system.

Mechanical and Packaging accounted for the next highest portion of BoP costs. Although this area is mature from a design perspective, some focus is spent on hardening aspects for passing military acceptance testing, such as MIL-STD-810.

The last identified component of the BoP is the Thermal Management subsystem. Although not a significant cost driver, it was determined that modest investments to advance the design and integration of heat exchangers could result in significant system advantages. **Figure 4-6** details the major BoP cost drivers.

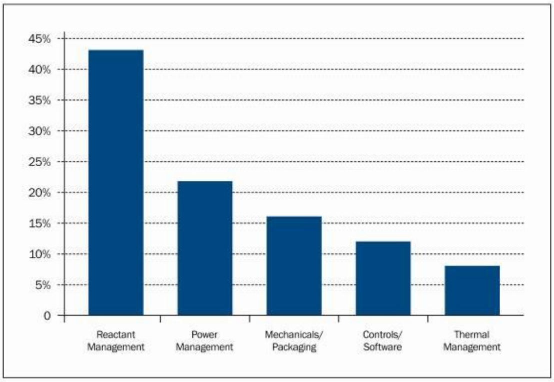


Figure 4-6: BoP cost drivers

4.4. FRAMEWORK FOR THE SELECTION OF PROJECTS

The following sections will layout the methodology used to meet the cost reduction objectives. As was stated in the methodology section of the executive summary, certain assumptions were agreed upon to formulate the project selection process. They are delineated as follows.

- Cost savings based on 5000 units per year
- Each unit was standardized at 10 kW
- Cost savings realized in three years or less
- Manufacturing technology not “bleeding edge” – no major changes in infrastructure
- Cost savings were standardized in \$/kW or in percentage of savings respective to the specific manufacturing process

4.4.1. PEM Membrane Electrode Assembly (MEA)

The approach taken for the PEM study to quantify the stack cost reduction opportunity was to determine (a) where are we today in terms of stack cost (in \$/kW), and (b) where do we think we can get to by 2015. The difference represents the cost gap to be addressed by the group. The group agreed to model a 10 kW stationary stack and to set the 2015 stack cost target at ~\$500/kW. The 10 kW stack model is representative of current commercial stack deliveries. Volumes were considered to be equivalent to low rate production runs (e.g. 10,000 stacks/year). A realistic total platinum loading of 0.5 mg/cm^2 was assumed.

A current state-of-the-art stack costs about \$800/kW. **Table 4-2** shows that the MEA cost of \$510/kW is the primary cost driver and can be further reduced to ~\$240/kW. To simplify the cost analysis, the MEA was assigned baseline and target costs for each component.

	Baseline MEA Cost ($/kW)			Target MEA Cost ($/kW)			
Component	Material Cost	Yield	Total Cost	Material Cost	Yield	Total Cost	Cost Gap
Membrane	$28	61%	$46	$14	82%	$17	$29
GDL	$55	60%	$92	$28	80%	$35	$57
Catalyst Layer	$126	60%	$210	$126	80%	$157	$53
MEA Frame	$45	100%	$45	$25	100%	$25	$20
Decal Transfer Film	$12	75%	$16	$0		$0	$16
Ink Mixing Labor			$1.5			$1.0	$0.5
Coating Labor			$9			$6	$3
Decal Transfer Labor			$20			$0	$20
MEA Assembly Labor			$70			$1	$69
Total			$510			$243	$267

Table 4-2: Cost analysis of the MEA

Methodology for the Down-Selection of Project Proposals

In the first workshop, the MEA group identified cost reduction opportunities and methods to address known gaps. The team took the many ideas generated and grouped them into common categories. From this grouping, three main categories were identified.

- Improving catalyst utilization
- GDL cost reduction
- Quality tools and transfer function development

The next step was to generate actionable projects for each category. For the GDL, the actionable cost reduction projects identified were (a) the development of continuous ink mixing systems, and (b) development of paper GDLs for high temperature PEM application. Finally, a Pugh matrix was used to prioritize the projects and assign owners (See Supplemental Information Appendix B).

Detailed Cost Reduction Analysis

Membrane

The membrane cost reduction of ~$29/kW is achieved with a material price reduction from $28/kW to $14/kW along with a manufacturing yield improvement from 60% to 80%.

GDL

The GDL cost reduction of ~$57/kW is achieved with a material price reduction from $55/kW to $28/kW (representing a target cost of $14/kW each for the anode and cathode), in addition to a MEA manufacturing yield improvement from 60% to 80%.

The target cost of the GDL is on track to be achieved in fiscal year 2011 as a result of projects funded by the Department of Energy.

The MEA team agreed in this workshop that a significant cost reduction of up to 40% could be achieved for high temperature PEM by developing a paper GDL to replace the incumbent fabric GDL.

Catalyst Layer

The catalyst layer cost reduction of $52/kW is achieved by a MEA manufacturing yield improvement from 60% to 80%.

Two other projects are proposed to address catalyst layer cost reduction through development of designs that lower platinum loading. These projects reduce costs beyond the identified $267/kW gap, and they are targeted at MEA design and not necessarily MEA manufacturing, but they are included here as follows:

- Development of gas diffusion electrode designs with total platinum loadings at or below 0.15 mg/cm^2
- Development of GDEs having platinum gradients in the X-Y plane that take advantage of hydrogen-rich inlets and hydrogen-depleted outlets

By understanding the direction and needs of advanced designs and design ideas, manufacturing engineers can down-select corresponding enabling technologies for next-generation manufacturing lines.

Elimination of Decal Transfer Processes

Eliminating the need to decal transfer catalyst layers from release films by directly coating catalyst layers to the membrane or GDLs would represent a total cost reduction of $36/kW. This is further broken down into cost reductions of $20/kW in labor and $16/kW in release film material.

Automation of MEA and Stack Assembly Processes

Automating MEA assembly processes will reduce cost by up to $69/kW. It is understood that justification for capital expenditures on automated assembly equipment would be driven by volume and demand.

In preparation for high volume manufacturing, there is a need to understand and eliminate the technological barriers for continuous roll-good manufacturing and automated assembly. A project is proposed to evaluate technologies and concepts needed to develop roll-to-roll processes and to scale up and automate MEA and stack assembly processes. This includes development of robust leak testing methods for plates, MEA seals, and finished stack assemblies.

Manufacturing Trade-Off Analysis

A proposal to reduce costs by performing a manufacturing trade-off analysis between incoming supplied materials versus the resulting manufactured product would be accomplished by:

- Determining critical product parameters and assigning validated measurable tolerances
- Developing the necessary measurement tools

- Using physics and design of experiments, develop transfer functions that relate to critical product, raw material, and process parameters to process and product performance
- Developing non-contact, non-destructive, in-process inspection and characterization techniques
- Facilitating company-to-company information and knowledge exchange to reduce development times

The benefits of this project would be improved manufacturing yields and lower material costs for MEAs.

4.4.2. Ceramic

The gaps for SOFC manufacturing were consolidated to 12 major gap or project titles and subsequently ranked for significance in a Pugh Matrix. The group decided on eight criteria and weighting factors to rank the significance of the project:

1. Cost savings: What effect does the project have on reducing the SOFC manufacturing cost?
2. Reliability improvement: Does the project improve reliability or lifetime of the SOFC?
3. Capital Expenditures (CAPEX): What capital expenditures does the project call for?
4. Production scalability: Does the project lend itself to high-volume manufacturing by being able to scale up the process?
5. Improved throughput: Will the project improve the speed of manufacturing?
6. Low risk (performance and timing): Is the project low risk with respect to affecting SOFC performance?
7. Applicability to both tubular and planar: Does the project apply to both design geometries?
8. Applicability to all power ranges: Does the project apply to all ranges of SOFC system power output?

Each project was graded on how it meets a given criterion: 1 = positive rating; 0 = no effect; or -1 = negative rating. The criteria weights ranged from 1 to 10; ten being the most significant.

A Pugh Matrix ranking of the projects was prepared comparing the projects for each criterion (Appendix B). Some explanation is needed for the results. The lesser ranked projects still show great significance in closing SOFC manufacturing gaps. For example, the coil winding project was ranked below the median because it applies only to tubular cells; otherwise, it would have scored in the top three because of the major impact the interconnect has on tubular cells. In addition, Powder Acceptance project was ranked low because as part of production and purchase planning it does not need to influence the production line. It is also difficult to propose a project that would benefit a significant number of SOFC fabricators, because each company requires different composition and particle characteristics for cathode materials based on their design and manufacturing methods.

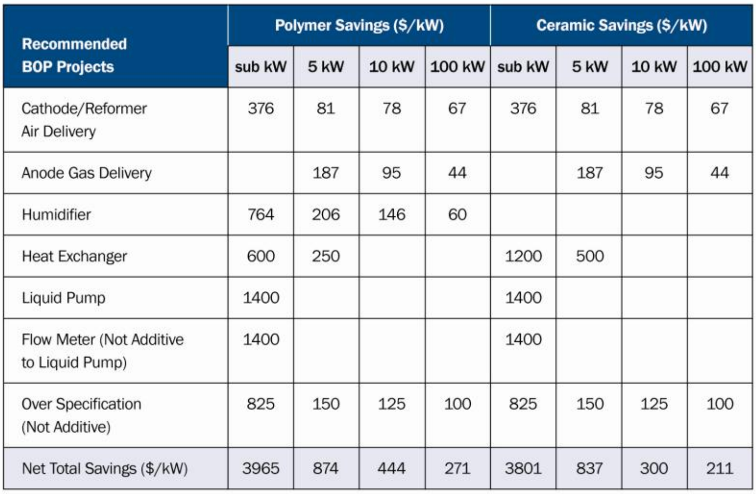
The main benefit of the aqueous solvent project is that water is environmentally friendly. However, this project is rated low because it is difficult to use water-based binder systems in forming slurries and inks for tape casting, spraying, and printing processes. Moreover, precise humidity control is needed in drying, storing, and handling parts made using water-based binder systems, which increases capital and energy costs.

Finally, although the Inspection project ranked above the median, it seems clear that it would be difficult to define a project based solely on this expansive subject. Consequently, the group decided to include inspection and QC as a component of all the projects and eliminate inspection as a stand-alone project.

The Appendix B table on the Ceramic group summarizes the Project ID number, Project Name, Technical Area, Gap description, and Gap number.

4.4.3. Balance of Plant

The detailed rationale and explanation of the cost reduction process for each of the selected projects is contained in Appendix A III.3 which contains a description of the component, the manufacturing gaps addressed, and the expected outcomes and payoff. **Table 4-3** contains a summary of the projected net total savings ($/kW), assuming all the BoP cost reduction initiatives are successful, rolled up to the system level for two different stack types and four different power levels. Savings range from about $200/kW for the highest power systems to $4000/kW for the lowest power systems.



Recommended BOP Projects	Polymer Savings ($/kW)				Ceramic Savings ($/kW)			
	sub kW	5 kW	10 kW	100 kW	sub kW	5 kW	10 kW	100 kW
Cathode/Reformer Air Delivery	376	81	78	67	376	81	78	67
Anode Gas Delivery		187	95	44		187	95	44
Humidifier	764	206	146	60				
Heat Exchanger	600	250			1200	500		
Liquid Pump	1400				1400			
Flow Meter (Not Additive to Liquid Pump)	1400				1400			
Over Specification (Not Additive)	825	150	125	100	825	150	125	100
Net Total Savings ($/kW)	3965	874	444	271	3801	837	300	211

Table 4-3: Summary of recommended BoP projects and cost reductions (by stack type and power level)

Not all of the blocks within the table are noted with a cost savings. This is a result of not having sufficient information for that power level, or in some cases, an improvement in cost savings would not be realized.

5. Polymer Electrolyte Membrane

5.1. INTRODUCTION

Polymer electrolyte membrane fuel cells (also known as proton exchange membrane fuel cells) have a lower operating temperature range than other fuel cells and use a special membrane that allows the passage of protons but not electrons or gases. PEM fuel cells dissociate hydrogen molecules into protons and electrons at the anode side of the membrane. The electrons travel through the external circuit and the protons travel through the membrane to the cathode where they react with oxygen and the returning electrons to form water. They can be broadly classified as either low-temperature (LT) or high-temperature (HT) based on the type of proton exchange membrane used.

Low temperature cells are typically fabricated using a membrane based on perfluorosulfonic acid (PFSA). This ionomer is expensive when purchased in small volumes. Systems must be operated with a precise humidity control that can be challenging in some military operational environments. It is typical to operate LT cells at approximately 80 °C, a temperature that can pose heat rejection challenges when high ambient conditions are encountered such as in desert climates. Direct methanol fuel cells (DMFC) are typically constructed using a PFSA membrane; however, humidification issues are replaced by other considerations, such as the need for a relatively high catalyst loading. Material alternatives to PFSA are being sought that have the near-term potential to replace the dominance of PFSA.

Several high-temperature materials are also under exploration. The most well developed material is based on a polybenzimidizole (PBI) sol-gel containing a high concentration of phosphoric acid. These cells are typically operated at 120 °C to 180 °C. They do not require humidification and reject heat more efficiently (e.g., smaller radiators can be used). At these operating temperatures, catalysts are less susceptible to carbon monoxide poisoning which can be important if fuel cell systems are to be run on reformed logistics fuels that may contain impurities.

There are many architectural and manufacturing similarities between LT and HT PEM components. In the interest of brevity, the sections that follow will first address typical LT PEM elements and then unique considerations related to HT PEM manufacturing will be called out where appropriate.

5.2. MEMBRANE ELECTRODE ASSEMBLY (MEA)

Overview

The Membrane Electrode Assembly (MEA) comprises the polymer electrolyte membrane sandwiched between gas diffusion layers (GDL) with catalyst at the interface of the GDL and membrane. This is typically the first building block created to form a fuel cell stack. In LT PEM systems, it is common to add seals to this single unit known as a Unitized Electrode Assembly (UEA). This section describes the fabrication of the UEA, which is used to build the fuel cell stack. Elements of a typical UEA are shown in **Figure 5-1**.

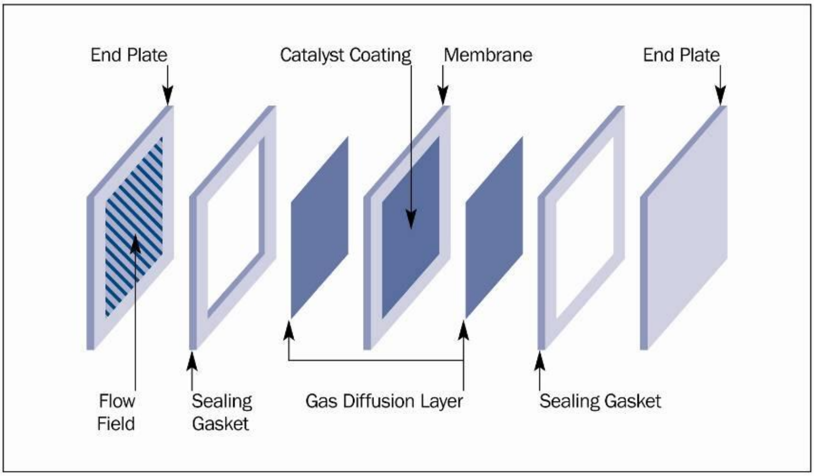


Figure 5-1: Elements of a typical Unitized Electrode Assembly (UEA)

The fabrication of the LT MEA begins with the production of ionomer that is converted to a dispersion for electrode ink and fabricated into a membrane. The electrode ink is composed of ionomer, precious metal catalyst, solvent, and other ingredients. The electrode ink is used to form the catalyzed coating that is applied to the membrane in catalyst coated membranes (CCM) or applied to the gas diffusion layer (GDL) in gas diffusion electrodes (GDE). The MEA can then be constructed by either applying GDL to either side of the CCM or GDE to either side of a bare membrane. A UEA is produced when seals are integrated with a MEA.

The general categories of MEAs found in fuel cells include low temperature PEMs and high temperature PEMs (PBI-based). Low temperature PEMs include hydrogen, reformate, and direct methanol fuel cell MEAs. Either CCM or GDE may be used to construct these MEAs. In the case of high temperature PEMs, only GDE is typically used.

The MEAs are commonly converted to bordered or edge sealed UEAs for low temperature PEM applications. In the case of high temperature PEMs today, seals are generally provided external to the MEA. In this instance, UEAs (or MEA plus seal), gasketing, and plates are interleaved to build a stack.

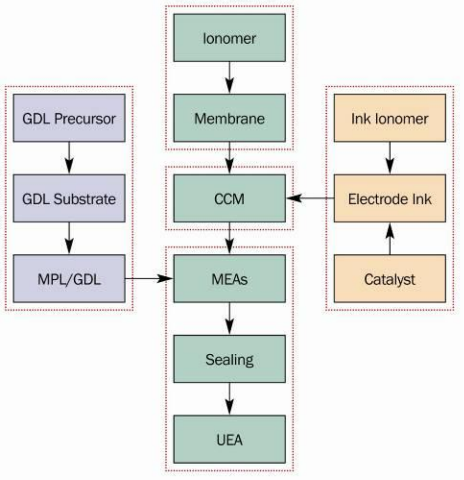


Figure 5-2: Low temperature polymer CCM

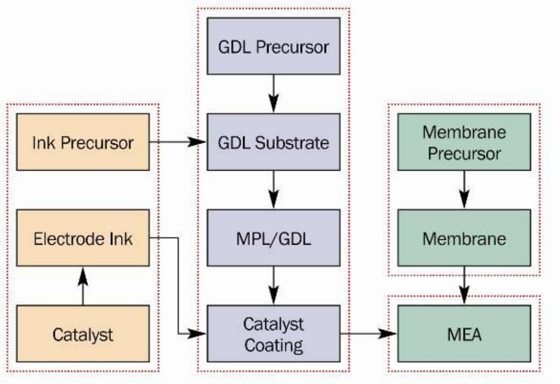


Figure 5-3: High temperature PBI-based MEA

The low temperature polymer CCM flow diagram (**Figure 5-2**) illustrates the general steps necessary to construct a low temperature catalyst coated MEA. Note that the general process steps required for HT MEA manufacturing (**Figure 5-3**) have many similarities.

Each major step in the manufacturing process is illustrated by red-dashed boxes. The following section will describe the current best practice, the gaps and issues, and recommended best practice for each major step in constructing the MEA.

Because precious metal catalyst in the electrode is the major cost driver (**Figure 5-4**), manufacturing best practices will focus on methods to maximize the utilization of the catalyst, maximize process yields, and minimize the residence time (or lead time) of catalyst in the plant. Likewise, membrane and GDL are currently expensive materials, particularly in the low volume production that represents the current state of the fuel cell industry.

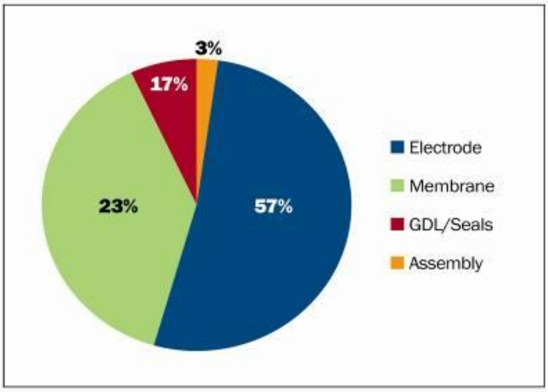


Figure 5-4: Current Cost Breakdown for LT MEA

While membrane and GDL unit costs are likely to drop dramatically with volume, precious metal catalyst will unlikely drop in unit cost. Thus the major cost driver for membrane and GDL are volume driven while the main cost driver for the electrode is a fundamental materials cost.

It is not the intent of the MFCMP effort to individually reduce the cost of each component (including the overall MEA) at the expense of quality. The purpose is to identify methods to reduce these unnecessary costs. The fuel cell stack is a major cost driver in fuel cell systems. MEAs are not, in themselves, a cost driver because fuel cell stacks are most often constructed with more MEAs than absolutely necessary. If the quality and performance of MEAs can be improved (with a combination of both design and manufacturing), then the number of MEAs employed in building a stack could be reduced. Likewise, today many of the materials used to construct the MEAs are over designed, adding unnecessary costs to the MEA. Recommended best practices that follow should not be implemented without a comprehensive analysis of the effect on the cost of the overall system throughout its life cycle. Some recommendations will require a relatively simple modification to an existing process, while other recommendations may require redesign of a key component.

High Temperature PEM (HTPEM) MEA Overview

There is considerable interest in the use of high temperature PEM MEAs (such as Celtec™ produced by BASF Fuel Cell Inc.) as an alternative to conventional low temperature PEM MEAs. The MEAs shown in **Figure 5-5** employ a sol-gel membrane containing polybenzimidazole (PBI) and phosphoric acid.

Figure 5-5: High temperature PEM MEAs
[1]

At the heart of the HTPEMFC MEA is the sol-gel PBI membrane (**Figure 5-6**). Unlike the Nafion™ type of low temperature membrane, the HTPEM membrane does not need to remain hydrated to maintain proton conductivity since the electrolyte is phosphoric acid. The operating temperature of the HTPEMFC MEA is in the range of 160 ºC to 180 ºC.

Figure 5-6: PBI sol-gel membrane
[2]

HTPEMFC systems have several potential benefits compared to low temperature systems [2].

- Simplification or elimination of humidification and water management systems
- Increased tolerance to fuel impurities (e.g., CO), allowing a broader range of fuels, simplified fuel reforming, and lower reforming costs
- Improved electrode kinetics
- Higher proton conductivity
- Ability to operate at higher ambient temperatures requires smaller heat exchangers or radiators
- High quality waste heat

As a result, high temperature systems are significantly smaller, simpler, and less costly than a corresponding low temperature system.

HTPEMFCs can be used for a variety of applications.

- Portable fuel cells (e.g., reformed methanol fuel cells (RMFCs) for soldier power)
- Combined heat and power (CHP) systems for residences, businesses, and industrial settings
- Stationary power systems
- APUs

The PBI systems are particularly well suited for any application where a reformed hydrocarbon fuel may be used.

Low Temperature PEM (LTPEM) DOE Overview

Because of their relatively low operating temperature (~80 °C), Nafion PEM fuel cells have a fast start capability which makes them ideal for transportation and backup power applications. The specific energy density of LTPEM satisfies the requirements of many applications including material handling equipment, auxiliary power, light duty vehicles, and backup power.

Early on, the U.S. Department of Energy (DOE) recognized the immaturity of LTPEM technology and established a strong LTPEM research, development, and demonstration program. A majority of the DOE investment is in the area of PEM fuel cell component development. DOE supported national laboratory researchers are involved in basic and applied materials science and electrochemistry and have made progress toward achieving the performance, durability, and cost goals established by the U.S. Department of Energy [3]. for light duty vehicles. Additionally, DOE's goal to develop and demonstrate fuel cell power system technologies for transportation have greatly benefited near term applications such as backup power and material handling equipment. Stationary and portable applications for LTPEM have also benefited from the DOE-supported activities. Importantly, the DOE research and development success are readily carried over to Department of Defense (DOD) applications.

The DOE has invested considerable research and development funds to reduce the platinum catalyst content in LTPEM fuel cells. In recent years, the escalating cost of precious metals has added to the LTPEM fuel cell cost. One of the great successes of the DOE research is the reduction of the platinum content by an order of magnitude for LTPEM fuel cells which has counterbalanced the rising cost of platinum.

In 2005, the DOE increased the scope of their research and development activity to include manufacturing of LTPEM fuel cell systems. The DOE sponsored roadmapping activities sought to identify manufacturing research and development approaches for the production of LTPEM fuel cell systems. This would assist industry by building the manufacturing infrastructure necessary to penetrate the light duty vehicle market by 2020. Manufacturing research and development needs, along with supply chain networks, were identified for market introduction and economic growth [4].

The DOE LTPEM manufacturing roadmap was followed by a "Gap Analysis" that identified the manufacturing limitations for LTPEM fuel cell systems [5]. The following highlights the manufacturing gaps for LTPEM fuel cell systems as of 2007.

- High-volume MEA processes
- High-speed bipolar plate processes
- High-speed sealing techniques
- Stack assembly techniques
- BoP components and fuel cell systems
- Quality control processes

To resolve these gaps, the DOE funded manufacturing research and development activities in 2007.

The manufacturing readiness of the LTPEM manufacturers supplying the material handling equipment market and the backup power market was assessed in 2009 by the DOE [6]. This assessment identified that production rates at LTPEM manufacturers were below the Low Rate Initial Production level of 1,000 units per year at each of the manufacturers. The overall manufacturing readiness level for the companies interviewed was at MRL-6.

> **MRL-6 - Critical Manufacturing Process Prototyped:** Critical manufacturing processes prototyped, targets for improved yield established. Process and tooling mature. Frequent design changes still occur. Investment in machining and tooling identified. Quality and reliability levels identified. Design to cost goals identified. Pilot line operation demonstrated.

The fuel cell companies had only progressed to the pilot stage of production in many cases. A consensus from the companies was the need for the federal government to increase the demand for fuel cell systems through direct purchases or through tax incentives. The U.S. government has responded to the industry-wide recommendation with a tax incentive of $3,000/kW for fuel cell systems.

A follow-up assessment of the market readiness of the LTPEM manufacturers identified that companies still have not achieved Low Rate Initial Production of 1,000 units per year (with the exception of one company that operated at this rate for a 16 month period). Many of the companies reported design changes for the LTPEM fuel cell systems because of customer feedback. These companies appear to have overestimated the maturity of the LTPEM technology. Many of these design changes are affecting manufacturing processes.

The lessons learned from the industry manufacturing experience are:

- The learning process from deployment of fuel cell systems is critical to advancing the technical maturity
- The cost of LTPEM fuel cell systems is primarily materials driven (the platinum catalyst is the most expensive)
- The complexities of manufacturing a fuel cell system are high
- Continued manufacturing research and development is required to drive down cost and increase manufacturing rates

Automation of PEM – Lessons Learned

Beginning over ten years ago, BASF Fuel Cell and its predecessor enterprises, in conjunction with researchers at the Center for Automation Technologies and Systems at Rensselaer Polytechnic Institute (RPI), began developing the manufacturing processes necessary to fully automate MEA fabrication. To date, BASF Fuel Cell remains the dominant commercial HT PEM supplier.

The first fully automated manufacturing line was designed and built in New York State and commissioned in Frankfurt, Germany. The pilot line was initiated from a clean sheet of paper, through laboratory manufacturing process R&D, to specification development, source selection, and detailed design, build, and installation. While it is highly unusual to find such a forward-thinking start-up willing to commit early to automation, the lessons learned were invaluable, as were the opportunities to further refine the process before the onset of high volume production.

Early experience with automation revealed many things.

- When there are uncertainties related to materials, designs, architectures and manufacturing processes, it is best to employ modular, flexible manufacturing processes and systems.
- Distributed control architectures allow for easy process and systems debug and great flexibility in both process and system design.
- Dimensional and registration tolerances that are easy to achieve with conventional precision machined components are very difficult to achieve with materials that are flexible, easily deformed and damaged, and affected by temperature and humidity.
- Commercially available production equipment (e.g., thermal presses, robots) may not be adequate for processing materials found in fuel cell components. For example, commercial robot systems seldom have to contend with acid bearing materials.
- When designing pilot scale manufacturing lines, plan for the unexpected.
- Proper materials selection for production equipment is critical in order to avoid possible contamination of the product.
- The time spent in thoughtful preparation of the system requirements document pays back ten-fold during the project execution.
- System cost is not the most important evaluation criteria when selecting an automation system provider.

An enhanced pilot line that offers higher capacity relies heavily on information driven manufacturing processes to replace hard tooling wherever possible. This facilitates the sort of high product mix and rapid product evolution common with a still emerging industry while greatly reducing cost and lead time when products change or new products must be brought on line. Relevant manufacturing process parameters for all steps leading up to the finished MEA are logged in a database, and there is a wide use of advanced manufacturing technologies such as robotics, vision systems, lasers, and ultrasonics.

5.2.1. Ionomer & Membrane

Overview

There have been a large number of perfluorinated, partially fluorinated, and non-fluorinated hydrocarbon based membranes studied and employed to different degrees of success in fuel cell systems over the past fifty years. Perfluorosulfonic acid (PFSA) ionomer is used today for low temperature polymer electrolyte membrane fuel cells.

Originally extruded membrane processes were employed to produce PFSA membranes that were used for early fuel cell stacks. This traditional extrusion-cast membrane manufacturing process was developed for “thick” films, typically greater than 125 micron, but further developed for thinner membranes. The extruded sulfonyl fluoride polymer film was then converted from the SO_2F to the SO_3K form using an aqueous solution of potassium hydroxide and dimethyl sulfoxide, followed by an acid exchange with nitric acid to the final SO_3H form [7].

Thinner membrane enables higher performance hydrogen fuel cells, so 25 micron or thinner membrane was demanded by fuel cell stack developers and manufacturers. This increased demand for thinner membranes pushed production rates to levels that meet the lower cost goals required for fuel cell applications. Furthermore, there is a growing demand for larger production lot sizes, increased roll lengths, and improved physical appearance. To meet this need, fuel cell membrane manufacturers developed solution-casting processes and automated membrane electrode assembly processes [8, 9] to supply high-volume, low-cost membrane to an emerging fuel cell industry.

Current Best Practices [10]

The thin membrane solution casting manufacturing process is shown in **Figure 5-7**. The backing film (1) is unwound and measured for thickness (2). Ionomer dispersion is applied (3) to the substrate and both materials enter a dryer section (4). The composite membrane/backing film is measured for total thickness (5) and the membrane thickness calculated. Then the membrane is inspected for defects (6), protected with a coversheet (7), and wound on a master roll (8); all within a clean room environment (9). Master rolls are then slit into product rolls and individually sealed and packaged for shipment.

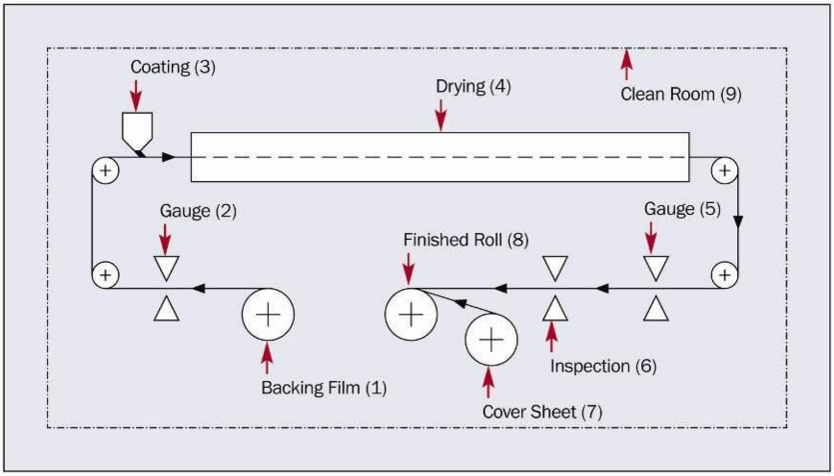


Figure 5-7: Thinner membrane manufacturing processes

This process has several key advantages.

- **Large dispersion batches can be inspected for quality** (e.g., free of contamination) and performance (e.g., acid capacity)
- **Overall production rates increased for solution-casting** polymer electrolyte membrane (as compared to polymer extrusion followed by chemical treatment)
- **Thickness control and uniformity improved**, including the production capability of very thin membranes (e.g., 12.7 microns)

Two patented high-pressure processes, solvent-based [11] and water-based [12], are used to convert DuPont™ Nafion® ionomer (sulfonic acid form) into polymer dispersions with 5% to 20% solids content by weight. These dispersions are formulated into carbon inks and catalyst coatings, and used either "as supplied" or with modifiers [13] and reinforcement materials to fabricate electrode coatings and membranes [14,15,16].

Gaps and Issues

- **The need to minimize the cost of precious metal catalyst**. The key for MEA manufacturers to minimize the cost of precious metal catalyst is to minimize residence time in the plant and cut yield losses resulting from the current fabrication process. The current process uses a decal transfer to minimize swelling of the ionomer membrane due to the water content in electrode coating inks (which compromises the dimensional stability of the resulting catalyst coated membrane). Decal processes add another step to the fabrication of MEAs and potentially introduce yield loss and extend residence time in the plant.
- **The need to optimize the electrode ink ionomer for coating.** Currently, the precious metal catalyst utilization in the final electrode structure is maximized but the ionomer is not optimized for coating. Ionomer/membrane suppliers and their MEA customers do not share information that would lead to advances in ionomer dispersions for electrode ink, as well as improvements in membrane morphology to enable a direct coated CCM (and thus eliminate the need for decal transfer processes).

Recommended Best Practice

- **Improve precious metal catalyst utilization in the coated electrode by developing better ionomer dispersions.** Nominally, one mil cast and one mil reinforced membranes are the accepted industry standard for the manufacture of catalyst coated membranes fabricated using a decal transfer process. Likewise, these same materials are employed for GDE approaches and DMFC MEAs. DuPont™ Nafion® ionomer and similar dispersions are the current best practice for electrode inks today.
- **Develop a membrane morphology that enables direct coating of membrane with the electrode layers.** It is unknown whether these ionomer dispersions may also enable the direct coating of membrane without a separate change in the membrane morphology that would reduce the effect of swell. Presumably, less membrane ionomer (thinner membrane) may also reduce the effect of membrane swell during direct coating. Alternative membrane ionomer, thinner membrane, or reinforced

membrane may all be different routes to enable direct coating. Today, membrane is the second highest cost driver in the MEA behind the electrode. Higher volume manufacture, as well as ionomer reduction, may enable improvement in the overall cost of manufacture. Additionally, a higher performance, durable MEA resulting from ionomer and membrane improvements in the utilization of precious metal catalyst, should reduce the overall MEA count in the stack, reducing the amount of precious metal catalyst tied up in the fuel cell system. Increased demand in fuel cell systems, and the resulting increase in overall MEA volume, would not be expected to reduce the cost impact of precious metal catalyst without significant improvement in precious metal catalyst utilization in the both the MEA design, as well as in the MEA manufacturing process.

- **Improve the cast and extruded membrane processes to deliver high performance durable MEAs that meet current and future design needs.** Development of improved transfer function relationships between ionomer dispersion preparation parameters and membrane fabrication parameters would be a high payoff effort. The ability to relax release specifications of ionomer dispersions and membrane properties should improve first pass yield and lower manufacturing cost. Although traceability of ionomer dispersion and membrane properties to the resulting MEA properties is generally good, any improvements in relating product characteristics and process parameters of the dispersion and membrane to the resulting MEA release specifications should enable better first pass yield.

5.2.2. Gas Diffusion Layer (GDL)

Overview

To discuss the gas diffusion layer (GDL), it is important to have a basic understanding of the steps involved in making the GDL and its primary functions in the fuel cell. The making of the GDL involves multiple process steps performed on a number of various machines before reaching its final form. Though some GDL is still made in discrete sheets, several manufacturers have developed continuous roll to roll processes. In general, the continuous process involves four steps.

1) The GDL is made by starting with a carbon fabric or carbon paper precursor
2) The precursor is then put through a series of heat treatment steps making it into GDL substrate
3) PTFE is added for hydrophobicity
4) MPL coatings are applied to tailor the flow of reactants and manage water to make the final GDL product that goes into the MEA assembly

The GDL functions are required to perform a number of tasks during fuel cell operation.

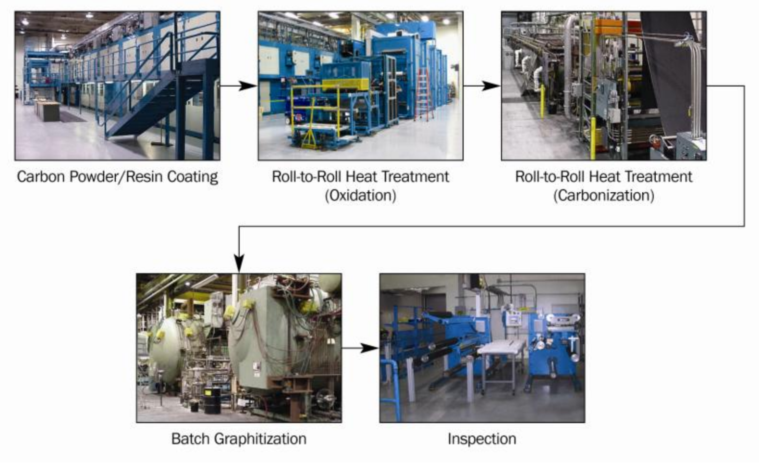
- Create a minimally resistant path for the flow of electrons from the electrode interface to the current collectors
- Manage the flow of reactant gases to and from the electrode interface
- Transport water to the membrane and out of the catalyst layer
- Provides thermal properties required to manage the heat generated in the MEA

As such, the GDL plays a key role in the proper functioning of the MEA and needs to meet many different requirements depending on the fuel cell design and application.

The GDL precursor can be a carbon fabric, woven following processes similar to a woven textile. This adds to the cost of the precursor. The first step in the process is the conversion of polyacrylonitrile (PAN, or other materials such as pitch or rayon) to a highly thermoset ladder polymer called oxidized PAN. The oxidized PAN is then converted into long worsted staple fiber yarns that are woven into the construction designed for the application.

A less expensive process uses a carbon fiber paper backbone made on specialty forming machines following a wet-laid process using short-chopped, carbonized PAN fibers, and a binder. The low-density carbon fiber paper is then impregnated in continuous roll format with a carbon powder/resin solution. Many companies use a solvent-based phenolic resin solution for impregnation. The equipment required to coat these types of solutions must be explosion proof to accommodate the solvent, and the process has added environmental issues such as hazardous disposal and abatement. Some GDL substrate manufacturers use water based carbon powder solutions for impregnation. These solutions tend to be more environmentally friendly and require less specialized equipment to process them, making this method less costly. It should be noted however that GDLs made in this fashion may not be suitable for some types of fuel cells.

The precursor then undergoes an oxidation step which converts the material into a lower molecular weight form of the original organic polymer. Oxidation is followed by a continuous carbonization step to volatilize the remaining hydrogen, nitrogen, and oxygen atoms bound to the carbon surfaces [17]. At this stage, the materials are 88% to 95% carbon by weight [18]. Finally, the precursor goes through a graphitization step that heats the material in an inert environment to approximately 1700 °C to 2000 °C. This results in a 99+% carbon substrate with graphitic properties. Once through this series of heat treatment steps, the material is a GDL substrate (**Figure 5-8**).


Carbon Powder/Resin Coating

Roll-to-Roll Heat Treatment (Oxidation)

Roll-to-Roll Heat Treatment (Carbonization)

Batch Graphitization

Inspection

Figure 5-8: GDL manufacture involves multiple processing steps
(Courtesy of Ballard Material Products)

PTFE is then added for hydrophobicity and finally microporous layer (MPL) coatings are added as desired. Once the GDL material has been coated, it is then put through one last heat treatment step, sintering, and then is slit to the desired format. It is then inspected and ready in its final GDL form (**Figure 5-9**).

PTFE Impregnation
and
Microporous Layer Coatings

Continuous Sintering

Final Visual Inspection

Figure 5-9: PTFE added for hydrophobicity and microporous layer coatings added
(Courtesy of Ballard Material Products)

There are many publications [19] studying different characteristics of the GDL – hydrophobicity and hydrophilicity, porosity, permeability, transport properties, electrical resistivity, compressibility, and structure. Several methods have been developed to measure and quantify these various properties. However, it is extremely difficult to measure many of these properties in a timely manner.

Current Best Practices

- **Have as many process steps as possible for GDL production in one location.** This allows for better control of the process, helps to provide a better understanding of the interrelationships of each process step and helps to reduce the GDL cost. It is critical for fuel cell manufacturers to develop close collaborations with the vendors that perform other steps externally.
- **Minimize capital expenditures by running lower volume processes on shared equipment.** For example, the precursor is made on standard equipment designed to process other types of paper and the heat treatment equipment needed for making the GDL substrate is usually also used to produce other carbon products. In addition, the coating steps are usually performed on the same coating equipment, which has been designed with the flexibility to be changed-over for different coating processes.
- **Roll material is processed in continuous runs to maximize yields on each machine.** This minimizes cleanup, changeover, and setup time for each process step.
- **Standard size is 80 cm width and roll sizes up to 800 meters in length.**
- **Common specifications for GDL include basis weight, thickness, thickness under compression, resistivity, air permeability, tensile strength, bending stiffness, and visual defects.** These specifications characterize some aspects of the GDL, but not all. Product release specifications do not completely characterize critical GDL parameters as they relate to final overall product performance. Problems arise when product fails due to unquantifiable issues. Work is being done to develop methods and tools

for measuring critical GDL parameters. There are many projects currently underway at many universities for developing some of these methods. The DOE has funded projects to help in this matter.

- **Ensure product uniformity through continuous in-line measurement and control of certain variables.** Beginning and end of roll samples are still taken, but with lengths upwards of 800 meters between start and end, the in-line tools help to assure uniformity throughout the whole roll. Tools include in-line viscometers, mass flow meters, beta or gamma gauge basis weight, thickness measurements, dryer web temperature profiling, dew point measurements, and in-line vision defect inspection.
- **Inks are mixed for the carbon powder impregnation solution and microporous layer (MPL).** Currently, batch processing is the norm. Refer to the ink mixing section for current best practices.

Gaps and Issues

- **It will be necessary to have dedicated coating lines and heat treatment equipment to run GDL product as volumes significantly increase.** New equipment should be designed to handle double width rolls to the current 80cm width. The lines should be able to switch from roll to roll continuously. A continuous graphitization furnace will become necessary at very high volumes. Many special considerations will be required in constructing this type of furnace because it needs to run under vacuum and at extreme temperatures. This will drive the cost up and may make this type of equipment cost prohibitive even with increased volumes.
- **In the case of GDEs made for the high-temperature PEM, the GDL has historically been a carbon fabric.** If a paper design could be used instead of the fabric there could be a cost savings. A significant effort would be required to develop a paper design that would meet the requirements of this type of system.
- **There is currently a lack of tools that are capable of measuring key GDL parameters in real time.** Some of the existing measurement tools are difficult to use and others do not even measure the actual parameter of interest. Some modern tools may exist, but they are considered trade secrets and manufacturers are reluctant to share them. This makes it difficult to have a common acceptable standard for product comparison and QC.
- **There is a reluctance of suppliers and customers to share information with each other.** There are typically different manufacturers for each part of the MEA (and in some cases different parts of the GDL), When a customer is having a problem, they may notify the supplier, but usually will not provide details about the problem nor let the supplier know which lots are causing the problem.
- **Many paper properties cannot be measured until it has been converted to a substrate material.** There are several upstream steps and process variables that may be important, but are not well understood because of the multiple process steps between the process variable and measurement of the paper property. This means that many potential upstream variables are lost in the noise.
- **Many visual defects are rejectable because of a lack of understanding on design.** Vendors are starting to incorporate in-line vision systems to help

measure and quantify "blemishes." Work is required to determine what "blemishes" affect final performance and are therefore defects that should be rejected. This information must be fed back to the suppliers so they can take adequate measures to reduce and eliminate sources of these defects. Work is currently being done at NREL and supported by the DOE to address this specific issue. Using GDL material donated by commercial vendors, NREL is able to use a segmented cell to compare the power output of material with and without "blemishes" for true comparison. The power loss due to a specific type of "blemish" can then be quantified and the information used to determine what actually is a "defect" in the GDL.

Recommended Best Practices

- **Dedicated coating lines should be designed and fabricated to handle wider widths, longer rolls, and continuous roll to roll coating.** Accumulators and turrets can be used to keep the line running while performing roll changes, especially as volumes increase and capital expenditure is warranted, Even without capital upgrades, coating in campaigns (coating several rolls of the same coating one after the other) will help to reduce cleaning, changeover and setup costs. In addition, any work that can be done to increase the speed of existing processes would help to reduce costs and increase capacity.
- **Further develop in-line functional measurement techniques in order to ensure roll uniformity from beginning to end.**
- **Develop traceability of product characteristics, raw materials, and processes parameters.** Identify and minimize variability of each process step to produce a consistent and uniform product. Develop collaborations between vendors and customers to better understand and address problems that may arise.
- **Develop transfer functions relating parameters to performance.** Develop tools to universally measure and quantify critical properties and compare products fairly. Data from these tools must be related to final product performance for the customer. GDL specifications should be established based on the customer's findings to ensure proper functionality. In order to accomplish this, it is imperative to have joint collaborations between the various suppliers and manufacturers.
- **Develop continuous mixing technologies.** In-line mixing of the inks will reduce costs. (See ink mixing best practices and recommendations.)
- **Develop technology to apply multiple layers in one coating pass**. The microporous layer coatings can involve several coating and drying passes. Each pass adds to the cost of the material. If several coatings could be applied at one time and then dried, or if a tandem coating line could be setup, frequent starts and stops could be eliminated. A tandem coating line is a large capital expenditure and is not feasible at current volumes. A multilayer coating station could help reduce process steps and product costs as long as the dryer has capacity for the added wet load. Multilayer coating may be difficult due to solution compatibility and interactions between the layers. This must be addressed to effectively coat multiple layers at once.

- **Minimize the noise in the entire process by identifying variability in each process step.** Pinpoint the source and implement ways to minimize or eliminate the variability.
- **The substrate manufacturer should coat the substrate with PTFE (for hydrophobicity) and apply different MPL coatings (or catalyst coatings in the case of the GDE) depending on the desired GDL properties.** This simplifies the GDL manufacturing process and keeps the cost low.
- **Improve material utilization employing master batch and master roll techniques, combined with processing in continuous runs.**

5.2.3. Ink Mixing & Delivery

Current Best Practices

The best current practice for ink mixing and delivery consists of the following process steps (**Figure 5-10**):

- Combine raw materials, consisting of one or more of the following:
    - **Catalyst powder** - The catalyst powder may be one of several types and still fit into this general manufacturing process. Examples include Pt metal dispersed on a variety of carbon types, Pt alloy metal dispersed on a variety of carbon types, or Pt black. One example of a catalyst technology that would not fit into this general manufacturing process is the 3M nano-structured thin film electrode.
    - **Ionomer dispersion** - Any ionomer dispersed in a solvent mix would fit into this general process.
    - **Solvents** - Various solvents, including water and various alcohols, may be added to the ink.
    - **Other** - Additives serving various functions may be included in the catalyst ink. The function may be either product-related or manufacturing-related, such as rheology modifiers.
- Blend/mix raw materials to create a catalyst ink. The mixing step is most commonly performed in a batch process. For example, all materials would be combined and mixed in a single bottle using a variety of mixing methods including blade mixing, rotary ball mill mixing, and ultrasonic mixing.
- Dispense ink into a hopper or coating die. Depending on the system, the finished ink is directly transferred to a coating apparatus, or it may be transferred to a hopper or holding pond, awaiting a later transfer step to the coating apparatus. The transfer is most commonly accomplished using either a gravity-fed system or by a mechanical pump.

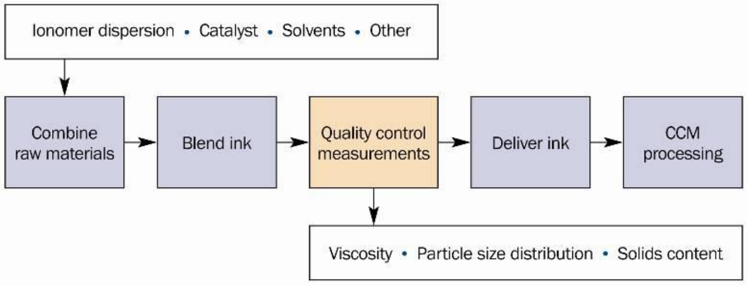


Figure 5-10: Current process for ink mixing and delivery

The catalyst ink is the point in the MEA fabrication process where the precious metal catalyst is introduced. Since this is the most expensive material in the MEA, it is critical that the yield be maximized and the scrap be minimized. Scrap in the ink mixing and delivery processes are most often due to waste incurred during start-up and shut-down of the process. When the equipment is torn apart for cleaning or maintenance, there is unused ink in the feed lines, the mixing vessel, and the transfer hopper. All of the unused ink in these various pieces of equipment is collectively referred to as “skins.”

To help minimize the ink scrap, the batch size should be maximized. For a batch process, this is achieved by increasing the individual batch size and also by combining multiple batches into a master blend. In addition to minimizing scrap, increasing the batch size also decreases the number of start-up and shutdown events. These events are generally costly in terms of equipment down-time as well as the labor required to set up for a run. It is also noted that some manufacturers use a continuous mixing process to decrease the relative amount of skin loss. Since this technology is not widely adopted in industry, it will be a recommended best practice.

A second way to minimize scrap is to minimize the surface area in the system available for skinning. This technique includes reducing the tubing length between the mixing vessel and the holding vessel or the coating apparatus. Maximizing the mix vessel size is also effective in reducing the surface area / volume ratio.

A third way to minimize scrap is to reduce the frequency of cleaning, since it is only during the cleaning session that the ink skin is truly scrapped. Whether using longer tubes or smaller mixing vessels, cleaning only once in every ten campaigns instead of once every two campaigns reduces the amount of scrap by a factor of five.

To help maximize yields, quality control tools are employed. Three QC tools employed in current best practices include rheology, particle size distribution, and solids weight percent. All three measurements are currently off-line techniques that require a sample to be withdrawn from the ink and measured. While the rheological properties of the ink are important for the ink application step, it is unclear what effect, if any, these three metrics have on the end performance of the MEA and across all manufacturing steps.

The result of this lack of understanding of the “transfer functions” is twofold. First, the tolerance on the known metrics are most likely too tight. This is a natural reaction to achieve desired performance. Second, there are almost certainly metrics that have not yet been defined that are important to the performance.

Gaps and Issues

- **All raw materials in the ink are measured using an accurate balance and then manually added to the mixing vessel due to low volume demands.** This requires increased labor and results in higher levels of scrap due to a number of transfer steps.
- **The batch scale mixing processes used by some manufacturers for ink production and delivery provides too large a surface area for skin formation in the mixing vessels, transfer vessels, and connection tubing.**
- **The current process for collecting samples and taking QC measurements is labor intensive and on a batch-scale.** Only one or perhaps several data points are taken during a run.
- **There is a lack of understanding of what the critical metrics are that affect the product performance.** While not specifically related to ink mixing and delivery, it is more generally present in the fuel cell environment, One reason for this lack of understanding is the significant degree of interaction present within the fuel cell system. For a fuel cell to function properly, all the different components must work together flawlessly, and a change in one component can lead to a change in performance that is sometimes significant. These significant interactions greatly increases the negative effect of “bracketing”, or the practice of focusing on a specific area without having understanding of what is going on in other areas.

Recommended Best Practices

The recommended process steps remain the same as used in current best practices. Combining raw materials, blending, and then delivering the ink are still the basic blocks. There are, however, nine improvements recommended for future ink mixing and delivery systems.

- **Automatically measure and dispense the raw materials when volumes increase**. Industrial equipment can be used to automate this process to reduce the required labor and reduce the scrap since the number of transfer steps would be reduced.
- **Minimize the dwell time of the ink between mixing and delivering to the coating operation.** Use lean manufacturing best practices to address uncertainty regarding shelf life / stability of the mixed ink.
- **Minimize the surface area available throughout the system for skin formation.**
- **Maximize the throughput of ink between cleaning / maintenance cycles of the equipment.**
  Move to continuous, automated processing throughout the ink processing block, including automated dispensing of raw materials, continuous feed of raw material mixture into a continuous, flow-through mixer/blender, continued flow of the blended ink directly into the coating operation.
  If continuous processing is not implemented, maximize the number of batches of ink per campaign. Reduce the number of these vessels used in the batch process to reduce the available surface area for skin formation.
- **Improve the understanding of the requirements on the ink product.** Determine what tolerance is truly needed for existing QC measurements. Determine if all existing QC measurements necessary or if any additional measurements are required.

- **Implement on-line QC techniques.** The benefits of moving to on-line, real-time measurements include the reduction in labor (no sample collection, no manual measurement procedures), as well as more data. While a batch-sample process involves one or several data points per batch, continuous QC allows for several data points across a run. This provides more resolution of the data during the run. Finally, if the data collection is real-time, then a process control loop can be set up to actively monitor the data and adjust appropriate process parameters (if the measurement and the parameters are known), or to alert an operator.
- **Side-stream sample for a continuous production process**. This would apply where on-line, real-time QC techniques cannot be implemented (perhaps because the QC technique is destructive, or because the technique is inherently a batch technique). This sampling technique can be automated, and the collected samples are then post-processed, if necessary, and measured off-line.
- **Maintain real-time traceability of raw material lots**. This includes process parameter set points and feedback, and product QC measurements.
- **Encourage designers and process engineers to continuously work together.** This collaborative work could include developing meaningful, data-driven tolerances on existing metrics, and to develop new metrics (transfer functions) that relate the ink product properties to downstream product requirements.

5.2.4. Catalyst Coated Membrane

CCMs are designed for the electrodes to be directly transferred to the membrane thereby potentially increasing the efficiency of the catalyst usage. There are certain technical challenges that will have to be overcome as described in the following section.

Current Best Practices

To discuss the catalyst coated membrane (CCM), it is important to have a basic understanding of the role of the CCM in the fuel cell membrane electrode assembly (MEA).

The MEA consists of five components: anode GDL, anode catalyst layer, proton exchange membrane, cathode catalyst layer, and cathode GDL. MEAs can be gas-diffusion-electrode (GDE)-based (as shown in **Figure 5-11A**) or CCM-based (as shown in **Figure 5-11B**).

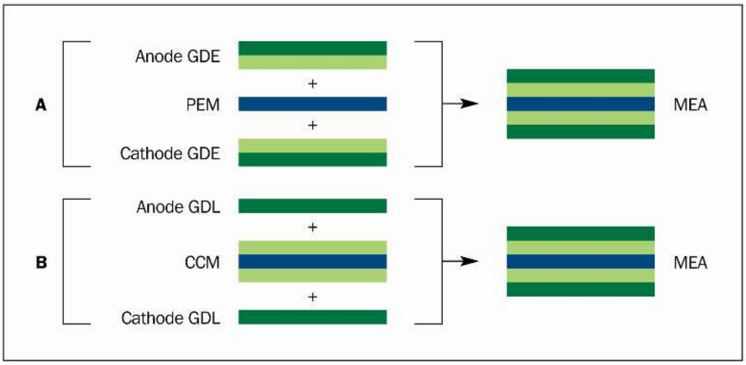


Figure 5-11: Membrane electrode assembly (MEA): A– GDE-based; B- CCM-based

In a GDE based MEA (**Figure 5-11A**), the catalyst layer is applied onto GDLs to produce a GDE. The anode and cathode GDE are then bonded, or hot-pressed, to either side of the proton exchange membrane (PEM) to produce an MEA. The proton exchange membrane softens, or reflows, at the hot press temperature which produces the adhesion necessary to create the bond between components.

In a CCM-based MEA (**Figure 5-11B**), the catalyst layer is coated onto the proton exchange membrane to produce a CCM. The anode and the cathode GDL are then bonded, or hot pressed, to either side of the CCM to produce an MEA. Because catalyst coats the membrane, no bond can be made between the layers during hot pressing. An adhesive layer is added to the GDLs to facilitate this bond. The adhesion of GDLs to the CCM is not trivial and adhesion methods are kept proprietary. One of the primary reasons to adhere the CCM to the GDL is the need to keep the membrane dimensionally stable in-situ as it undergoes thermal, mechanical, and hygroscopic stresses.

For low temperature PEM, the need to continuously coat ultra-low-loaded catalyst layers has led many manufacturing engineers to choose to coat catalyst onto membranes (B) rather than onto GDLs (A).

Coating on membrane offers the following advantages:

- Smooth film surfaces enable consistent deposition of coated layers below a thickness of 1 micron (dried thickness)
- Consistent and predictable surface energies lead to predictable and consistent coating runs
- Membranes can be handled around tight roller radii leading to greater degrees of freedom for coating line design
- Carbon fiber contamination is a non-issue in the coating line

Because precious metal catalyst and membrane are the major cost drivers in MEA design, manufacturing best practices will focus on methods to maximize the utilization of precious metal catalyst and membrane, maximize process yields, and minimize the residence time of precious metal catalyst in the plant.

Table 5-1 outlines the primary inputs to the CCM manufacturing technology development process. Some inputs are basic (i.e., ease of scale up to high volume), while others are derived from advanced R&D concepts (i.e., ability to coat built-in precious metal loading gradients in a single pass). Technology evaluation and down-selection can be carried out by understanding how many of the critical design and process inputs can be satisfied. Because fuel cell technology is currently focused on lower volume demand, primary consideration should be given to “ease of scale-up to high volume.”

CCM Technology Development Inputs			
Type of Input	**Baseline Needs**	**Cost Reduction**	**Flexibility**
Design	Ability to coat below 1 g Pt/m^2	✔	✔
Design	Ability to coat to 1 - 7 g Pt/m^2 in a single pass	✔	✔
Process	Ability to hold coat weights that are 6 sigma capable (cross-direction and machine direction)	✔	
Design	Ability to coat various catalyst ink types		✔
Design	Ability to deliver design-intent catalyst structures		✔
Process	Demonstration of yields >99%	✔	
Process	Demonstration of ink utilisation >98%	✔	
Process	Ease of scale-up to high volume		✔
Process	Degree of customisation		✔
Process	Ability to deliver inks to coating head with minimal/no ink shearing and drying	✔	
Process	Ability to meet labour targets	✔	
Design	Ability to coat onto various types of webs		✔
Process	Ability to coat over large viscosity ranges (higher design degree of freedom)		✔
Design	Ability to print segments	✔	
Process	Ability to deliver a fully direct-coated CCM	✔	
Design	Ability to coat built-in loading gradients in a single pass	✔	✔
Process	Ability to coat multiple layers at once	✔	✔

Table 5-1: Catalyst coated membrane (CCM) technology development inputs

Current catalyst coated membrane (CCM) coating processes are roll-to-roll continuous and can deliver dry catalyst coated layers of less than 1 micron (which represents precious metal loadings of 0.05 mg/cm^2 or less). For these low loadings, a small ink particle size distribution is critical. For single pass coatings, precious metal loadings as high as 0.7 mg/cm^2 can be achieved (which represents a dry layer thickness of 8 microns and above).

Current CCM coating processes can deliver coated yields (defined as defect-free coatings and in-specification precious metal loadings) upwards of 99.9% (demonstrated over miles of coating runs). To maximize precious metal catalyst utilization, long coating campaigns are favored. For a given reservoir volume and given line losses, the longer the campaign, the higher the precious metal utilization. This said, coating reservoirs should be designed for minimum volume and ink hoppers should be located as close as possible to the coating head to minimize line losses. For a 1 kilometer coating run, precious metal utilization rates above 98% have been demonstrated.

In-line systems such as X-ray fluorescence (XRF) or beta backscatter gauges are used to monitor and control precious metal loading in real time. Feedback (automated or manual) from the gauges is used to control precious metal loading in the cross-web and machine direction. In current best practices, Six Sigma capability on precious metal loading is being achieved.

Water-based and solvent-based inks are currently used for coating catalyst layers. Water-based inks simplify equipment design, as explosion-proofing and exhaust scrubbing are not critical.

Incoming and outgoing product is 100% traceable. Pre-determined process routes ensure error-proof movement of product through the manufacturing line. As a requirement to begin a process cycle, fixed barcode readers scan the incoming product. The product's proper location in the process sequence is verified before equipment will cycle. All upstream quality control gates are verified to have "passed" or else equipment will not cycle. Critical process parameters are continuously monitored and logged. Times are logged whenever a product's barcode is scanned and the product processed, enabling direct correlations to be made to continuously monitored process parameter levels.

All manufacturing documentation is formally controlled, with changes requiring both a technical review and a final updated documentation review. Comprehensive manufacturing documentation includes the following hierarchy: Process Flow Diagrams (PFDs), Process Failure Modes and Effects Analysis (PFMEA) of each step in the PFD, review of PFMEA critical parameters and cascading into Control Plans and Process Specifications, Shop Floor Work Instructions and Set-Up Checklists with cascaded critical parameters. For products at the prototype stage and beyond, adherence to documentation is the rule. Any deviation must be formally reviewed and signed-off by program and technical managers. Deviations are formally logged and controlled.

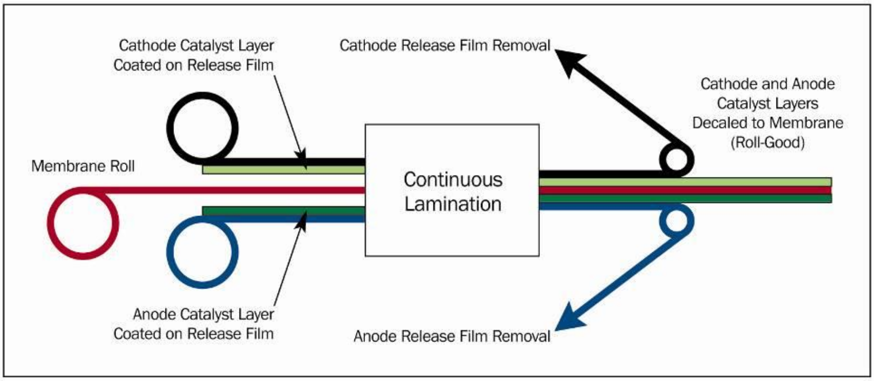


Figure 5-12: Schematic of continuous lamination

Because of the inherent nature of Nafion-based membranes to expand when coated directly with ink, current CCM manufacturing methods utilize decal transfer processes to laminate catalyst layers to the membrane. Decal transfer processes involve coating catalyst layers onto release films and bonding them to the membrane using continuous lamination techniques (**Figure 5-12**).

Gaps and Issues

- **A need to evolve away from decal transfer methods and move toward fully direct-coated processes.** Membrane swelling is currently a technological hurdle to a fully direct-coated CCM.
- **A need to develop robust methods of printing catalyst ink segments or patterns on a moving web.** This increases precious metal utilization in framed MEA designs as catalyst can be removed from underneath the frame.
- **A lack of transfer functions relating critical product and process parameters to performance.** Cost is added when non-conforming product travels through value-adding processes before being detected and removed at final performance QC testing. As well, cost is added to the manufacturing process development effort, as designed experiments must necessarily use in-situ performance as the response variable. Finally, without an understanding of transfer functions, products tend to be over-designed with tight tolerances, which lowers process capability and adds pressure to the ability to achieve and maintain high manufacturing yields.
- **A need to develop in-line, at speed, non-destructive measurements of critical product properties.** Currently, in-line methods are used for precious metal loading only. Once valid transfer functions can be developed relating critical product properties to performance, in-line measurement of those properties is needed (i.e., catalyst layer structure, porosity, diffusivity, thickness, and visual defects).
- **A reluctance of suppliers and customers to share information with each other.** This slows down development efforts.

Recommended Best Practices

Develop a fully direct-coated CCM. A proof of concept has been demonstrated, concept process drawings completed, and capital quotes obtained. **Figure 5-13** is a schematic of a direct-coated process.

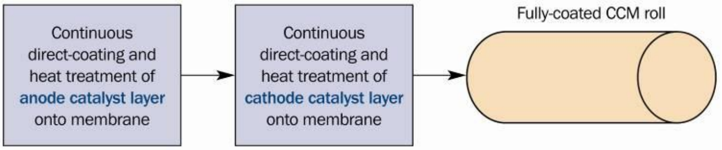


Figure 5-13: Schematic of a direct-coated process

Direct coating is an enabling manufacturing technique delivering the following benefits and cost reductions due to the elimination of the decal transfer process step.

- Reduced labor
- Reduced yield loss potential
- Reduced capital cost during scale-up
- Reduced residence time of precious metal catalyst in the plant
- Increased precious metal catalyst and membrane utilization as decal transfer processes necessitate coating wider catalyst layers to address alignment tolerance stack up and membrane shrinkage issues

- Elimination of release film costs
- For ultra-low precious metal loadings, all the precious metal is coated onto the membrane as opposed to decal transferring, which can leave residues on the release film. At ultra-low loadings, this can become significant
- Elimination of web handling issues. These problems are inherent in handling webs that are close to their reflow temperatures

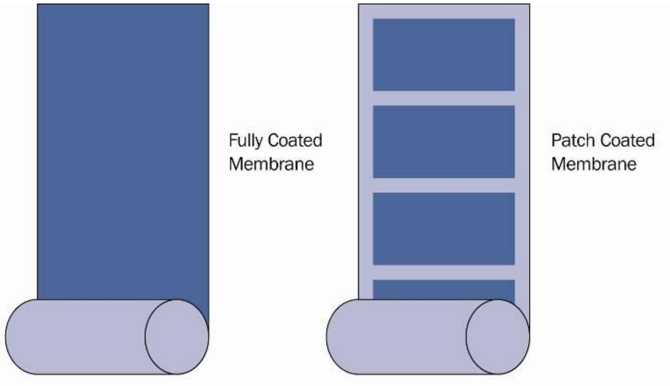


Figure 5-14: Comparison of fully coated and patch coated membrane

Develop robust methods of continuously coating segments or patterns on a moving web as a means of increasing precious metal utilization for designs using framed MEAs (**Figure 5-14**).

- **Develop transfer functions relating critical product and process parameters to performance**. This removes non-conformances at the source instead of continuing through value-adding processes before being detected and removed at final performance QC testing. As well, lack of transfer functions adds cost to the manufacturing process development effort as designed experiments must necessarily use in-situ performance as the response variable. Finally, without an understanding of transfer functions, products tend to be over-designed with tight tolerances, which lowers process capability and adds pressure to the ability to achieve and maintain high manufacturing yields.
- **Develop in-line, at speed, non-destructive measurements of critical product properties** such as catalyst layer structure, porosity, diffusivity, thickness, and visual defects
- **Improve exchange of information between suppliers and customers**

5.2.5. MEA Low Temperature PEM

Joining the gas diffusion layer (GDL) and the catalyst coated membrane (CCM) is the last step in forming an MEA, or in the case where integral seals are included this is sometimes referred to as a Unitized Electrode Assembly (UEA).

Current Best Practices

There are two primary approaches to creating low-temperature UEAs: bordered (or framed) MEAs, which are most common, and edge-sealed (or flush-cut) MEAs. In both cases, it is necessary to maintain tight dimensional, registration, and thickness tolerances to prevent leaking or unfavorable tolerance stack-up during the stack assembly process. It is paramount that manufacturing processes consistently deliver MEA components that do not leak when integrated into a stack as rework is impractical in high-volume manufacturing. Robot-based pick and place, often guided by machine vision, is used to achieve high precision placement of components on automated manufacturing lines. Fixturing and features embedded in subcomponents are used to assure repeatable part location on manual assembly lines. MEA alignment features are also used to facilitate correct location in downstream operations such as stack construction. Hand assembly of MEAs using human visual alignment would not lead to high yield and low cost MEAs.

While automation provides the best repeatability and traceability of parts, it generally takes thousands of stacks per year to cost justify fully automated manufacturing lines. Inserting islands of automation in critical process steps is sensible, but it is not clear if this practice is widespread. Semi-automated and manual operations are common throughout the fuel cell industry to support the low volume high mix nature of frequently changing designs. In some manual assembly operations, process flow interlocks gated by barcode scanners are used to ensure that product is processed in correct sequence and that manufacturing steps are not skipped. This time stamps manufacturing process steps that can be related back to historical process operating parameter logs.

It should be noted that an alternative stack sealing approach in practice by one manufacturer may have implications for the MEA manufacturing process (i.e., relaxed tolerances). This manufacturer assembles all stack elements and seals in one bulk operation after the entire stack is constructed (i.e., essentially potting the stack in elastomeric sealant).

Bordered/Framed MEA

Bordered (or framed) MEAs facilitate easier precision registration or alignment during subsequent stack building operation because the frame material is typically of sufficient rigidity to support precision location on process tooling. This construction is illustrated in cross-section in **Figure 5-15**.

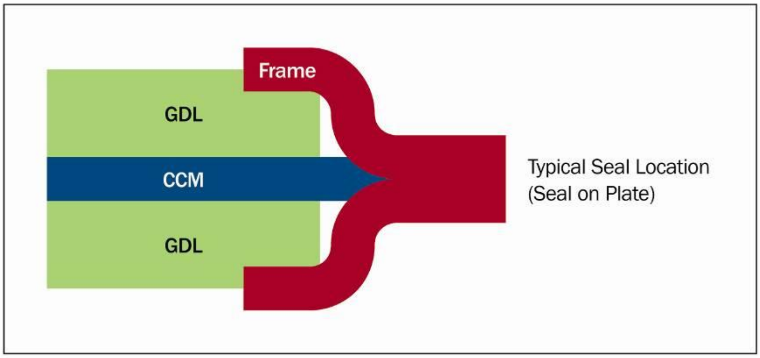


Figure 5-15: Bordered or framed MEA

Note that it is typical to fully coat the CCM with catalyst, so considerable catalyst area is obscured by the frame in this construction. This drives cost and reduces performance for a given amount of catalyst. However, this MEA construction has been found to be more durable than the edge-sealed (i.e., flush-cut) architecture described below using currently available materials. It is generally accepted that where stack life must exceed 20,000 hours in stationary applications, this architecture would be used. This 20,000 hour figure is in a non-military application and does not account for life-time de-rating for operation in harsh environments.

Edge-sealed or Flush-cut MEA

Edge-sealed (or flush-cut) MEA construction enables higher precious metal catalyst utilization because nearly the entire CCM/GDL sandwich is available for reaction. PEM membrane is coated with catalyst and then GDL is bonded to both sides of this membrane. The sandwich is flush cut and an elastomeric sealant, typically fuel cell grade silicone, is injected around the edge of the CCM/GDL sandwich. The sealant impregnates the electrodes to prevent cross-over leakage, and it is designed such that when compressed between the bipolar plates to achieve desired GDL compression, that it seals against the plate to prevent over-board leakage. This construction is illustrated in **Figure 5-16**.

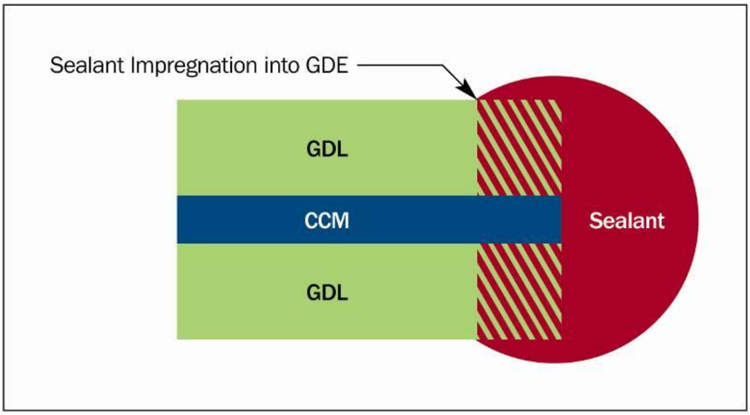


Figure 5-16: Edge-sealed (or flush-cut) MEA construction

It is typical to extend molded seal material on each end of the MEA to accommodate sealing of manifold passages in the bipolar plates. It should be noted that these illustrations are not to scale and that actual catalyst waste was reduced in one example by approximately 85% by moving from the frame-based construction to the edge-sealed construction. This approach is favored for very small, as well as high-aspect ratio (rectangular) MEAs in order to minimize the amount of border area covering up electrode. As membrane hydration varies, and because the membrane is constrained from expanding linearly into the sealant, this construction may lead to additional stress that could cause the GDL to puncture the membrane or drive the GDL into flow-field channels in the bipolar plate. This MEA construction is typically considered for use in applications requiring less than 20,000 hours and where aggressive load (or membrane hydration) cycling will not be experienced.

Non-sealed MEA

One fuel cell manufacturer does not integrate seals in individual MEAs, but instead performs the sealing operation after assembling the MEAs and bipolar plates into a stack. This may impact MEA manufacturing by relaxing some critical parameters (e.g., thickness or registration tolerances) related to sealing of hundreds or thousands of surfaces found in a traditional stack.

Gaps and Issues

- **Membrane electrode assemblies and many other components in fuel cell systems, are routinely over-designed.** There are tighter critical parameters than necessary such as dimensional or registration tolerances) due to a lack of understanding about which critical process parameters ultimately affect performance (i.e., durability, reliability, efficiency). This can have a dramatic impact on the cost of tooling and process equipment necessary to manufacture MEAs to such exacting specifications. It also leads to considerable yield losses – many of which may cull functional MEAs from service due to artificially restrictive specifications. Particularly troublesome is that subjective visual inspection (by humans) is often used at various points during the MEA manufacturing process in place of objective data driven quality control (QC) decisions. Thus, perfectly functional MEAs are sometimes eliminated for cosmetic reasons due to a lack of understanding of critical parameters and a lack of measurement capability. This is particularly relevant when considering on-line in-process measures that could be used to correct process deviation or abort an errant process.
- **There is widespread consensus that it is likely that some critical parameters remain unknown, perhaps more critical than those used in current MEA specifications.** In other instances, they may be known but difficult or impossible to measure on-line, at full process speed, in a non-destructive manner. This inhibits the understanding of how material and process parameters ultimately relate to in-system MEA performance. This ultimately is a cost driver in reduced yield and reduced system durability, which in turn, increases total life-cycle costs for fuel cell systems.

Recommended Best Practices

- **MEA and other component critical parameters should be carefully evaluated**. Cross-functional development teams that bring together fuel cell system designers with experienced manufacturing process developers should be encouraged so that cost implications of design decisions and tight tolerance specifications can be fully appreciated. “Throwing it over the wall from design to manufacturing” does not work well in any field, and it is especially unlikely to bear fruit in a field as interdisciplinary as fuel cells.
- **Material and process tolerances should be relaxed wherever possible**. It is critical that thinking “that’s my suppliers problem” be amended to a broader team approach for appreciating cost implications up and down the supply chain. The Japanese vertical modern keiretsu model (e.g., Toyota) for deeper partnerships in the fuel cell industry should be explored. The gathering of subject matter experts for this report was a good first

step toward such a cross-enterprise collaboration that also incorporated defense and university perspectives.

- **It is necessary to quickly test subsystem components at high production volumes,** Leak testing and functional burn-in tests should be eliminated. Measures at the MEA assembly stage that support this elimination are of critical importance. Preliminary reports from W. L. Gore and Associates should be investigated.
- **Reliably adhere GDLs to CCM (for low temperature CCM MEAs),** It would be beneficial to identify an improved manufacturing process for making this bond, and it would be equally useful to develop a non-destructive test metric that could be applied to confirm good bonds are being produced.

5.2.6. MEA High Temperature PEM

High Temperature PEM MEA fabrication shares many similarities with low temperature MEA fabrication, although catalyst is introduced during GDE fabrication rather than being directly applied to the membrane.

Please refer to the LTPEM for Current Best Practices, Gaps and Issues, and Recommended Best Practices.

5.3. BIPOLAR PLATES

Within a low temperature Proton Exchange Membrane (LTPEM) fuel cell stack, the second largest cost element is the molded graphite resin bipolar plate, ranging between 25% and 35% of the total stack cost (as illustrated in **Table 5-2**).

Component	Company A	Company B	Company C
Bipolar Plate	25%	22%	35%
End plates	10%	10%	3%
Hardware	6%	<10%	1%
Stack sealing	<10%	>10%	1%
Packaging	3%	<10%	<10%
Labor	15%	15%	10%

Table 5-2: Comparison of component costs

It is believed that the cost of the plate for HTPEM stacks will be a greater percentage since these plates require two elevated temperature processing/treatment steps due to the more corrosive environment in these stacks. In addition, if HTPEM stacks adopt the cooling methods (i.e., circulating liquids such as water/steam or high temperature coolants) used in a conventional phosphoric acid fuel cell (PAFC), it would add further cost elements to the stack. There are several possible approaches to reduce the cost of these parts:

LTPEM

- **The rejection rate of molded graphite resin bipolar plates can add to the plate cost**. This rejection rate is caused partially by the plates not passing critical design parameters (CDP) testing. Consideration should be given to modifying those CDPs, which could also allow the use of alternate graphite resin mixtures that would facilitate easier molding. The impact of changing CDPs on the overall cost of the stack and to the overall power plant life cycle cost should be evaluated.

- **The substitution of a metallic plate for a molded graphite resin plate** would use conventional manufacturing processes to lower cost. However, this would require identification of a low cost metallic system, either plated or not plated, which has long-term stability in LTPEM cells. Such an identification would be considered a leading edge technology.

HTPEM

- **The two heat treatment steps required to fabricate a HTPEM bipolar plate add additional cost** because of the cost of these individual steps and the increased rejection rates associated with each step. As is the case for LTPEM bipolar plates, modifying the CDPs might result in a reduction in plate rejection rate, however, the impact of modifying these parameters on stack cost and overall life cycle cost must be evaluated.
- **The substitution of a resin bonded graphite plate, which does not require multiple heat treatments steps, could also reduce the plate cost**. This, however, would require identification of a polymer which has long term stability in HTPEM cells and can also be fabricated in a cost effective manner.
- **The substitution of an alternative form of carbon, known as "glassy carbon," for the dual heat treated plate could also result in cost reduction.**
- **If the cooling techniques used in high temperature PAFC were utilized in HTPEM, it would add additional parts such as a metallic cooler, graphite Teflon cooler holder, and protective graphite plates.** If air could be used as a coolant, as is done in LTPEM cells, those elements could be eliminated. The use of air cooling in conventional PAFC is problematic due to evaporation of the acid into the air coolant stream leading to shortened cell life. Since HTPEM cells employ PBI polymer (polybenzimidizole) embedded with PAFC, the vapor pressure of the latter might be reduced. There are some data from industry which indicates that is the case. The use or air cooling in high temperature PEM cells in the air reactant channels could eliminate several stack parts associated with water/steam, and liquid cooling. This requires verification of the vapor pressure of phosphoric acid embedded in PBI as well as that in the electrode catalyst layers utilized with PBI.

PEM Bipolar Plate

The use of graphite/resin combinations, either as molded or with added heat treatment steps, are commonly used to achieve CDPs that maximize conductivity and power density, while minimizing porosity, cracking, and issues with flatness/parallelism.

Low Temperature PEM Bipolar Plate

The bipolar plate in LTPEM fuel cells is typically resin bonded and is fabricated in either of two methods known as "Compression Molding" and "Embossing". In both cases, the bipolar plate consists of a mixture of graphite and resin fabricated into the required form to provide reactant flow fields and points of contact between the bipolar plate and the electrode surfaces. These processes are depicted in **Figure 5-17** and **Figure 5-18**.

Current Best Practices

The compression molding process consists of the following steps:

- Selection of the optimum graphite to resin mixture
- Mixing to insure a uniform composition throughout the final product
- Inserting the mixture into a die contained in a press
- Closing the die and increasing its pressure and temperature to insure flow of that mixture into all sections of the die
- Holding the die at temperature and pressure until the resin in fully cured
- Reducing the pressure and temperature
- Ejecting the finished part
- Surface finishing the part to remove any excess “flashing”
- Quality testing of the part to assess its ability to meet the required CDPs typical properties such as thermal and electrical conductivity and gas permeability
- Rejection (scrap rate) or acceptance of parts based on the quality testing

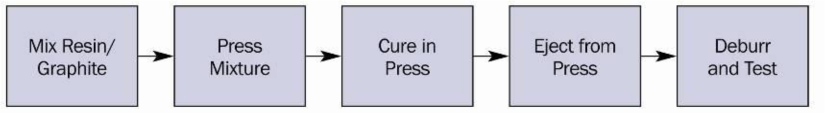


Figure 5-17: Low temperature bipolar plate compression molding process

The embossing process consists of the following steps as outlined in **Figure 5-18**.

- Embossing a sheet of a flexible commercial graphitic material, such as Grafoil®, with the required flow fields for the bipolar plate
- Impregnating that plate with a resin to insure low levels of porosity
- Curing the resin in the impregnated plate
- Die cutting the cured part into several bipolar plates
- Quality testing of the bipolar plate to assess its ability to meet the required CDPs, such as thermal and electrical conductivity and gas permeability
- Rejection or acceptance of parts based on the quality testing

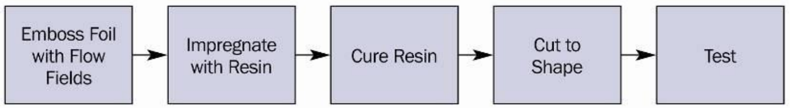


Figure 5-18: Low temperature bipolar plate compression embossing process

Both of these processes result in a bipolar plate whose cost is a significant part of the fuel cell stack cost. This high cost is caused partially by several factors:

- Failure of the fabricated bipolar plates to meet the required CDPs results in rejection rates (scrap rates) higher than desired.
- The cost of the compression molding process which uses a less than ideal graphite resin molding mixture required to meet the required CDPs. For example, low resin content results in optimum thermal, electrical, and permeability properties, but high resin contents are preferred for optimum compression molding.

An alternative approach to the use of resin-bonded graphite for bipolar plates is the use of a metal such as stainless steel containing flow fields for reactant gas distribution within each cell. Typically, materials such as stainless steel or nickel are used for fabricating these plates. However due to the relatively corrosive environment within LTPEM cells, these materials are typically unacceptable for long term use. The corrosion of these materials can lead to holes on the bipolar plate, which result in mixing of the reactant gases, increasing cell temperatures, and ultimately cell failure. In addition, corrosion byproduct ions can react with the membrane material leading to its failure.

In order to protect the metal bipolar plate from corrosion, approaches such as coating with corrosion resistant materials (such as gold), has typically been employed. An alternative approach is to utilize a composite consisting of two metals that have good corrosion resistance to either the cathode or anode environment. Earlier research by the General Electric Company, under NASA sponsorship, identified tantalum and columbium as materials with good corrosion resistance to the anode and cathode environments.

HTPEM Bipolar Plate

The bipolar plate, in high temperature acid and high temperature PEM fuel cells, is fabricated using compression molding of a graphite resin mixture, followed by two heat treatment steps, namely carbonization and graphitization (**Figure 5-19**). These two steps are necessary to increase the corrosion resistance of the bipolar plate to address the more severe environment in HTPEM. Flow fields during the initial molding are added by machining the final graphitic plate.

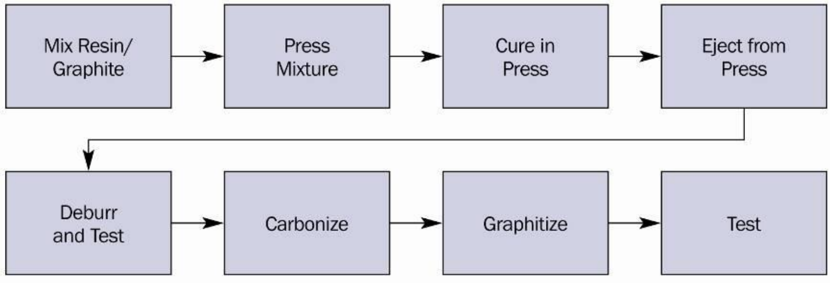


Figure 5-19: HTPEM bipolar plate compression process

Compression Molding: The compression molding process consists of the following steps.

- Selection of the optimum graphite to resin mixture
- Mixing to insure a uniform composition in the final product
- Inserting that mixture into a die contained in a press
- Closing the die and increasing its pressure and temperature to insure flow of that mixture into all sections of the die
- Holding the die at temperature and pressure until the resin is fully cured
- Reducing the pressure and temperature
- Ejecting the finished part
- Surface finishing the part to remove excess “flashing”
- Quality testing of the part to assess its ability to meet the required CDPs, such as thermal and electrical conductivity and gas permeability
- Rejection and acceptance of parts

Carbonization: The carbonization process consists of the following steps:

- Heat treatment of the bipolar plate to covert the resin into non-crystalline carbon. This process must be done slowly with “holds” at one or more temperatures to permit release of gaseous byproducts. Rapid release of these byproducts would cause “blistering” of the plate.
- Quality testing of the bipolar plate to assess its ability to meet the required CDPs, such as flatness.
- Rejection and acceptance of parts.

Graphitization: The graphitization process consists of the following steps:

- Heat treatment of the carbonized bipolar plate in a high temperature furnace to convert the carbonized material into a crystalline graphitic material. This process must also be done slowly to permit removal of any remaining volatiles with a final hold at an elevated temperature to assure conversion of all the carbon into graphite.
- Removal of any burrs.
- Quality testing of the bipolar plate to assess its ability to meet the required design parameters, such as flatness, gas permeability, conductivity and in some cases subscale corrosion testing.
- Rejection and acceptance of parts.

All these processes result in a bipolar plate whose cost is a significant part of the fuel cell stack costs.

LTPEM Bipolar Plate Cooling

Low temperature cooling is achieved by bonding two bipolar plates, forming integrated cooling channels between the plates. This process eliminates the need for additional materials and provides an intimate cooling surface for controlling temperature in PEM stack assemblies. This bonding process separates cooling water from the gas streams. Failure of the bonding process can result in internal and external leaks. Internal leaks interrupt gas flow distribution and shorten stack life. External leaks may cause electrical shorts or corrosion of balance of plant components. Leak checking individual plates for bond line leaks can be time consuming and add cost prior to stack assembly but can identify failed components before building an entire stack.

HTPEM Cooling

Conventional high temperature phosphoric acid fuel cells are cooled by circulating a water/steam mixture through a cooling plate assembly inserted every eight cells. Because of the high pressure of the mixture at these temperatures, it must be contained in high strength metal tubing. In order to protect these metals from acid corrosion, the metals must be protected by a graphite/Teflon assembly. The molded mixture of graphite/Teflon and stainless steel ensures thermal transfer of heat while preventing acid corrosion of the cooling tubes and plate.

Gaps and Issues

LTPEM Bipolar Plate

Reducing the required CDPs results in potential issues and gaps for example:

- **The impact of the reduction in CDPs on the cost and performance of other components in the cell stack.**
- **The impact of the reduction in CDPs on the cost of the total fuel cell power plant and its resulting life cycle cost.**
- **The identification of candidate metals and coating process which would result in a cost effective metal separator plate.** The identification of a metallic plate is considered a leading edge technology (**Figure 5-20**).

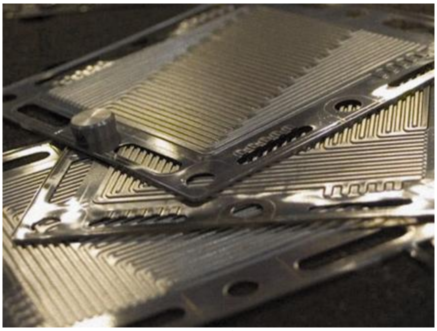


Figure 5-20: Example of Metal Bipolar Plates
[Courtesy of Dana Corp.]

HTPEM Bipolar Plate

Reducing the required CDPs and identification of alternative materials result in potential issues and gaps for example:

- The impact of the reduction in CDPs on the cost and performance of other components in the cell stack.
- The impact of the reduction in design parameters on the cost of the total fuel cell system and its resulting lifecycle cost.
- The identification of candidate resins compatible with high temperature acid that would permit the use of bipolar graphite resin plates in HTPEM cells. Identification of resins suitable for use in HTPEM cells is considered a leading edge technology.
- The use of bipolar plates consisting of an alternative form of carbon could result in cost reduction however, this form of carbon is extremely brittle and the impact of its mechanical properties on stack design should be evaluated.

Low Temperature PEM Bipolar Plate Cooling

- The identification of candidate metals and coating processes that would result in a cost effective metal cooling plate. The identification of a durable, low cost metallic plate is considered critical to achieving affordable bipolar plates, especially in the automotive sector.

HTPEM Cooling

- Conventional phosphoric acid fuel cells cannot be easily air cooled because of evaporation of phosphoric acid into the cooling stream. Will phosphoric acid evaporate less in a HTPEM due to the physical and chemical properties of the acid in the membrane permitting the use of air cooling?

Recommended Best Practices

LTPEM Bipolar Plate

- **Consider reducing the required CDPs to allow a higher acceptance rate of the bipolar plates after quality testing.**
- **Use higher resin content in the graphite resin mixture** to permit more optimum molding properties which could reduce the press cycle time. This change in resin content would probably require a change in the CDPs.
- **Identify potential metals and coating materials which could be used to fabricate metallic bipolar plates**, such as tantalum and columbium, for use as a substitute for the graphite resin plates which are the current best practice. The US Department of Energy, Energy Efficiency is funding such a program [20].

HTPEM Bipolar Plate

- **Identify cost effective potential resins compatible with high temperature acid to permit elimination of the carbonization and graphitization steps, and use of a resin/graphite bipolar plate directly in the HTPEM cell.**

HTPEM Cooling

- **Air cooling is preferred.**
- **Eliminate or reduce the water/steam cooler assembly** to reduce the cost of a HTPEM stack.

Adjust Quality and Performance Requirements to Reduce Fuel Cell Capital Cost

Fuel cells have typically been designed to meet a given set of application performance requirements such as power density and efficiency. This has resulted in fuel cells which meet the application requirements but whose cost is high. A recurring theme is to consider reducing the performance requirements in order to reduce initial cost.

Reducing these requirements could result in a reduction in the cost of the individual components contained in fuel cells, and therefore the overall cost of the fuel cell.

Examples include:

- **Bipolar plates:** Typical bipolar plates design requirements include such properties as electrical and thermal conductivity, gas diffusion, mechanical strength, and life. While the specific required values for these parameters have been calculated based on meeting the application requirements, the impact of reducing these requirements on the cost of the plate has not been determined. For example, a reduction in the design requirements of gas diffusion could reduce manufacturing cost by decreasing scrap rate. Another example is to decrease the design requirements of electrical and thermal conductivity. This could permit the use of more resin in the plate which could reduce the manufacturing cost by reducing the time required in a compression molding process which is typically used to fabricate the plates.
- **MEA:** Typical MEA design requirements include power density, efficiency, mechanical strength, porosity ("holes"), and gas diffusion. While the impact of changing these parameters on fuel cell performance and life has been quantified by a number of investigators, the impact of reducing these requirements on cost has not yet been fully quantified. For example, increasing the allowable gas diffusion rate would reduce efficiency but could also reduce

manufacturing cost by lowering scrap rate or by simplifying the manufacturing process.

- **Fuel Processor:** In order to meet application requirements, the fuel processor efficiency and life are maximized. An example is the need to remove the carbon monoxide in a fuel-processing stream to very low levels, typically 5 ppm or less. This can result in complicated control strategies to insure these concentrations during electrical transients. Increasing the allowable carbon monoxide concentrations could result in system simplification and reduced cost.

5.4. PROPOSED PROJECTS FOR POLYMER

Note – Enhanced descriptions of project proposals can be located in the Appendix A

5.4.1. Manufacturing Trade-Off Analysis on Raw Material

Develop a robust manufacturing process that relies more on design quality than removing defects through incoming inspection. By relaxing tolerances on in-coming raw materials, competition, lower cost, and higher first pass yields are achieved. Incoming raw material inspection, inspection tooling, and costs can be reduced or eliminated by relying on supplier certification of analysis. Efforts to manufacture hygroscopically robust membranes could also be linked to projects that are not currently within the Manufacturing Fuel Cell Manhattan Project.

Problem Solved (Gap)

- Need to move from decal transfer methods
- Need for direct printing of catalyst onto membrane
- Develop robust methods of printing ink on moving web
- Need to maximize catalyst utilization

Benefits Derived

- Reduce raw material cost because reduced tolerances on in-coming raw materials enable competition and lower cost as well as supply chain assurance.
- Customer ultimately achieves higher first pass yield and may be able to minimize inspection tooling and cost.
- Customers operate a more robust manufacturing process.

Resources Needed

- Project investment of $4.8 M

Timeline to Completion

- Two years

5.4.2. Develop a Process for 0.15 mg/cm^2 Total Pt Loading

Platinum cost is the current principal cost driver for MEA that cannot be reduced with volume because platinum spot pricing is not only uncontrollable, but generally high and increasing. Successful project completion will minimize platinum usage (and thereby cost) and potentially improve first pass catalyst coated membrane (CCM) yield.

This project will develop a robust manufacturing process that produces anode and electrodes with a Pt total loading <0.15 mg/cm^2. The electrodes will be created with commercially available materials using a robust process and high volume commercially available manufacturing equipment. Quality assurance measuring equipment will also be developed.

Problem Solved (Gap)

- Lack of transfer functions relating critical product, raw material and process parameters to performance and durability
- Lack of understanding of effects on MEA performance of perceived defects in PBI membrane for HTPEM and GDL/GDE
- The need for in-line nondestructive real-time QC measurements of critical properties
- Supplier and customer information is hard to obtain
- Cut yield loss from fabrication process by relaxing release specs of ionomer dispersions and membrane properties

Benefits Derived

- Save $3.0 M in catalyst cost
- Potentially improve first pass CCM yield

Resources Needed

- Project investment of $4.8 M

Timeline to Completion

- Two years

5.4.3. Development of Patch Coating Methods for Catalyst Inks

The objective of this project is to lower the cost of framed MEA designs by developing patch coating methods to deposit catalyst only in design active areas. In present designs, both the GDL and the catalyst coated membrane are sandwiched between framing materials. A seal is cast either onto the frame or onto the plate assembly. Upon subsequent assembly, there can be a considerable amount of in-active and wasted catalyst under the frame. Catalyst that is patch coated only in the design active area. Will result in a significant cost savings. This project will develop viable patch coating methods.

Problem Solved (Gap)

- Current manufacturing techniques result in deposition of catalyst outside the active area

Benefits Derived

- A significant cost savings can be realized by using less catalyst
- 15% reduction in the manufacturing cost of the MEA

Resources Needed

- Project investment of $2 M

Timeline to Completion

- Two years

5.4.4. Elimination of the Decal Transfer Process

(A) Development of Coating Slot Die Process

This project will reduce the cost of the catalyst coated membrane by developing direct coating slot die processes that are scalable to high volume manufacturing.

Problem Solved (Gap)

- One of the largest cost drivers in a LTPEM stack is the catalyst. Because of this, current state-of-the-art designs utilize low-loaded catalyst layers ranging in thickness from 2 μm (on the anode) to 10 μm (on the cathode). A majority of manufacturers have found that coating catalyst inks against a film, as opposed to coating on a GDL, offers advantages for thin layers. Films present very consistent surface roughness, surface energies, and handling characteristics compared to GDLs.
- A technological hurdle exists, however, when coating inks against a Nafion membrane: the Nafion membrane absorbs water and swells and wrinkles. It does not return to its original flat and stable state after the ink is dried during a subsequent heat treatment step. To mitigate this, catalyst ink layers are first coated on release films, dried, and subsequently decal transferred to the membrane using lamination methods.
- Decal transfer release films and labor add $36.40/kW (or 12%) to the cost of a 10 kW fuel cell stack. Developing methods to enable the direct coating of catalyst layers against the membrane will enable this 12% cost reduction.

Benefits Derived

- Elimination of decal transfer labor
- Elimination of release/backer films
- Increase catalyst utilization by 5%
- 12% reduction in the cost of a 10 kW fuel cell stack

Resources Needed

- Project investment of $1.6 M

Timeline to Completion

- One year

(B) Direct Coated Layers on GDL

There is a cost associated with the release film, and as with any process step, an associated yield that is nearly always less than 100%. The reduced yield is carried through the entire process and contributes to increasing the overall cost. Additionally, labor associated with handling, laminating the electrodes on release film is considerable, and there is specific scrap associated with electrode material that does not transfer from the release film to the membrane. All of these reasons serve to increase the cost of the MEA. One way to eliminate the release film is to coat the catalyst-containing ink directly on the GDL, thus forming gas diffusion electrodes (GDE). Subsequently, the anode and cathode GDE is directly laminated with the membrane, forming the final MEA.

Problem Solved (Gap)

- Catalyst release film required for coating catalyst on GDL adds labor and material cost

Benefits Derived

- The baseline cost savings includes material and labor associated with elimination of the release film, and a 5% yield improvement on the catalyst

Resources Needed

- Project investment of $2.7 M

Timeline to Completion

- Two years

5.4.5. Develop Paper GDL for High Temperature PEM (HTPEM)

This project will reduce the cost of the HTPEM MEA (membrane electrode assembly) by substituting a properly engineered paper GDL for the fabric GDL. This substitution is anticipated to have at least a 50% savings in the cost of the GDL; 30% by switching from a fabric to a paper and 20% by reducing the associated process coating steps necessary to form the GDE.

Problem Solved (Gap)

- To reduce the cost of the HTPEM MEA by substituting a properly engineered paper GDL for the higher cost fabric GDL currently used
- Eliminate the issues associated with semi-flexible or woven GDLs such as stretching, wrinkling, flexing, and cutting that affect yield

Benefits Derived

- The reduction in GDL cost by switching to a paper substrate will be at least 30%
- A reduction in process coating steps may realize savings of an additional 20%

Resources Needed

- Project investment of $3.2 M

Timeline to Completion

- Two years

5.4.6. Develop Continuous Mixing Process

The objective of this project is to improve catalyst utilization by reducing the amount of platinum lost in the manufacturing process, specifically in the ink mixing process. The reduction is achieved by minimizing scrap losses through the replacement of batch processing of catalyst inks with in-line mixing and the associated reduction in labor. Moving to in-line mixing will also improve the consistency of the catalyst ink. Substituting an in-line mixer instead of a batch processor will allow the total ink volume made for a given run to more accurately match the amount needed to complete the run, thus eliminating the “unused” solution that is typical of ink made in batch processes. Catalyst inks have a short shelf-life and therefore the “unused” ink typically cannot be saved for later use. In addition, there is a 30% reduction in labor costs in moving from batch processing to inline mixing due to shorter mixing times. Another advantage of in-line mixing is improved batch uniformity whose properties can be continuously monitored for consistency.

Problem Solved (Gap)

- Minimize scrap losses through the replacement of batch processing of catalyst inks with in-line mixing and the associated reduction in labor
- Eliminate batch to batch inconsistencies

Benefits Derived

- A 5% increase in catalyst ink utilization
- Reduction in touch labor of 30%
- Cost savings of $16.6/kW based on a 10kW system

Resources Needed

- Project investment of $2 M

Timeline to Completion

- 2.3 years

5.4.7. Improve Ink Mixing Process

The current best practice for producing a polymer membrane electrode assembly (MEA) includes coating a catalyst-containing ink onto a substrate. The ink is a complex system, containing a dispersed catalyst on carbon, a proton conductive polymer, at least one solvent that may include water and various alcohols, and potentially a variety of additives. The ink is commonly characterized using various metrics, including viscosity, solids content, and particle size distribution. It is not uncommon to find that a batch of catalyst ink results in a coating with defects. Two of the more common defects include bumps and voids in the coating. Although coating defects are necessarily an interaction between the coating substrate and the ink, it is believed that if the ink were more robust, then these defects could be avoided. Since the defects can sometimes occur even when the measured properties of the ink are within process specification limits, it is apparent that one or more critical properties of the ink are not being measured or controlled. This project will determine and then develop control methods for the critical ink properties that can lead to two of the most common coating defects: bumps and voids.

Problem Solved (Gap)

- Bumps and void coating defects cause additional scrap

Benefits Derived

- 10% yield improvement on the catalyst

Resources Needed

- Project investment of $1.0 M

Timeline to Completion

- One year

5.4.8. Process Development for Mitigation from Discrete to Continuous MEA Fabrication

This project facilitates migration from discrete component handling (currently performed manually or with automated discrete part handling), to automated systems that handle continuous materials for more rapid MEA fabrication. Efficiency gains are anticipated if material continuity can be maintained and carried forward into the stack assembly process as well. In many cases, this alleviates the need to reacquire component orientation or registration and allows materials to feed into the process quicker than when handling discrete parts. It is important to identify current commercial best practices for manufacturing one (or more) fuel cell MEA architectures. Critical manufacturing process parameters and registration tolerances must be identified and capabilities of known web handling and alternative fuel cell MEA fabrication approaches must be characterized.

Problem Solved (Gap)

- Develop underlying manufacturing methods to move from discrete part handling to continuous material handling in PEM MEA manufacturing, thereby facilitating higher throughput and more efficient stack assembly material handling.
- Develop methods to perform automated stack leak testing both in-situ during stack assembly and post-assembly as a quality control measure.

Benefits Derived

- Reduce labor
- Improve consistency
- Cost savings is \$67/kW on a 10 kW MEA

Resources Needed

- Project investment of \$2.2 M

Timeline to Completion

- Three years

5.4.9. Develop Precious Metal Gradients Across Membranes

Non-uniform catalyst loading may improve overall MEA performance by reducing the current density variation across the membrane. This project will develop a manufacturing process that can deposit spatially varying quantities of catalyst across a PEM GDE or CCM. This will lead to MEAs with less platinum-group metals (PGMs) loading but comparable performance to homogenously catalyzed MEAs. As reactants flow from inlet to outlet through a bipolar plate (BP), they are consumed, creating a reactant concentration gradient on the surface of the fuel cell membrane with the highest concentration at the inlet and lowest concentration at the outlet. Traditional gas diffusion electrodes (GDE) and catalyst coated membranes (CCM) have a homogenous catalyst loading across the membrane surface. This does not account for changes in reaction rate caused by reduced reactant partial pressures. Consequently, a spatially varying reaction rate across the membrane is expected to adversely impact fuel cell durability and reliability.

Problem Solved (Gap)

- Reduced catalyst utilization

- More effective catalyst utilization (put it where it's most needed)

Benefits Derived
- Reduces catalyst use

Resources Needed
- Project investment of $1.6 M

Timeline to Completion
- Two years

5.4.10. Reduce Critical Design Requirements and Defect Rejection Criteria

This project will quantify the impact of changing critical design parameters (CDP) and defects on the cost of the fuel cell stack and power plant components and their performance. Through discussions with their suppliers, fuel cell stack/power plant manufacturers (SPPM) will quantify the relationship between typical component CDP and defects on manufactured cost of that component. With that information, the fuel cell SPPM will determine the impact of changing that critical design parameter or accepting certain defects on fuel cell stack/power plant cost and performance. Through additional discussions with fuel cell stack/power plant purchasers, the fuel cell SPPM will determine if changing the fuel cell stack/power plant performance and cost will impact the buying decision of the purchaser.

Problem Solved (Gap)
- The relationship between typical component CDP and defects on manufactured cost of that component are not known
- The impact of changing that critical design parameter or accepting certain defects on fuel cell stack/power plant cost and performance is not known

Benefits Derived
- Accepting certain "defects" the fuel cell stack/power plant manufacturers (SPPM) may be able to reduce the cost of the fuel cell stack/power plant
- Clearly define acceptable from unacceptable product
- Minimize unnecessary testing of noncritical parameters

Resources Needed
- Project investment of $4 M

Timeline to Completion
- Two years

5.4.11. Development of a Low Cost Resin Suitable for HTPEM Bipolar Plates

This project will develop a low cost bipolar plate to replace the heat treated (carbonized and graphitized) plates presently used.

Problem Solved (Gap)
- Cost of high temperature PEM bipolar plates

Project Description
- Develop a low cost bipolar plate to replace the heat treated (i.e., carbonized and graphitized) plates presently used

Benefits Derived

- A resin compatible with the environment in HTPEM cells would eliminate two heat treatment steps (carbonization to convert the phenolic resin into carbon and a further higher temperature step to convert the carbon into more corrosion resistant graphite)
- Reduce the bipolar plate processing costs by $130/kW for a 10kW system

Resources Needed

- Project investment of $600,000

Timeline to Completion

- One year

5.4.12. Measurement of Vapor Pressure of Phosphoric Acid over HTPEM

This project will determine if the vapor pressure of phosphoric acid over the HTPEM is low enough to enhance the air cooling of HTPEM cells or to reduce the number of cooler arrays if steam cooling is utilized. In addition, a lower vapor pressure may permit higher operating temperatures.

Problem Solved (Gap)

- Expensive and complex cooling of HTPEM cells

Benefits Derived

- Reduced vapor pressure may permit higher operating temperatures
- Reduce high cost cooling methodologies used in conventional phosphoric acid fuel cell (PAFC)
- Potential cost reduction due to simplified cooling
- Potential increase in the output of the fuel cell

Resources Needed

- Project investment of $ 1 M

Timeline to Completion

- One year

5.4.13. Development of Metallic Bipolar Plates for LTPEM

This project will identify candidate metals and protective coating processes that can use low cost metallic plates as a replacement for the molded graphite resin plates.

Problem Solved (Gap)

- Reduce the cost of LTPEM bipolar plates by substitution with metallic plates

Benefits Derived

- Reduced cost weight and volume
- A low cost separator plate would decrease the cost of the stack
- Molded graphite plates are too high in cost to meet the low cost goals of transportation applications
- The physical dimensions of molded graphite plates do not meet the volume requirements of a transportation fuel cell

Resources Needed

- Project investment of $ 500,000

Timeline to Completion

- One year

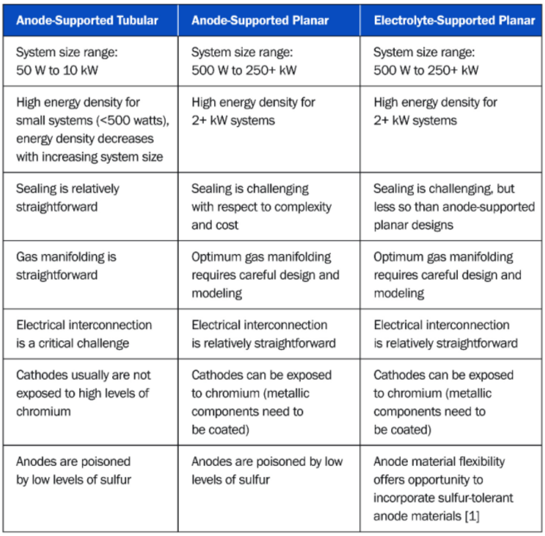
6. Ceramic

Manufacturing of Solid Oxide Fuel Cells

6.1. INTRODUCTION

A solid oxide fuel cell (SOFC) is an electrochemical conversion device that produces electricity by directly oxidizing a fuel. Features that distinguish SOFC fuel cells from other fuel cells include a higher operating temperature range (500 °C to 1000 °C) and the use of a solid oxide or ceramic electrolyte material. Instead of conducting protons through a polymer electrolyte like a PEM fuel cell, SOFCs use the solid electrolyte to conduct negative oxygen ions from the cathode to the anode, where they react with the fuel

The MFCMP considered solid oxide fuel cell stack designs for three power ranges: 50 W to 500 W, 500 W to 10 kW, and 10 kW to 250 kW. Additionally, three primary types of solid oxide fuel cell stacks were selected for consideration in this study. These include anode-supported tubular, anode-supported planar, and electrolyte supported planar. The primary advantage of tubular stack designs is that sealing is very straightforward, although electrical interconnection is challenging. The advantages of planar designs are related to the relative simplicity of electrical interconnection, although sealing is the primary technical challenge. A summary of the attributes of these three designs is provided in **Table 6-1**, and schematics of planar and tubular stack designs are provided in **Figure 6-1** and **Figure 6-2**. Electrolyte supported stacks will be discussed in the subsequent planar sections.



Anode-Supported Tubular	Anode-Supported Planar	Electrolyte-Supported Planar
System size range: 50 W to 10 kW	System size range: 500 W to 250+ kW	System size range: 500 W to 250+ kW
High energy density for small systems (<500 watts), energy density decreases with increasing system size	High energy density for 2+ kW systems	High energy density for 2+ kW systems
Sealing is relatively straightforward	Sealing is challenging with respect to complexity and cost	Sealing is challenging, but less so than anode-supported planar designs
Gas manifolding is straightforward	Optimum gas manifolding requires careful design and modeling	Optimum gas manifolding requires careful design and modeling
Electrical interconnection is a critical challenge	Electrical interconnection is relatively straightforward	Electrical interconnection is relatively straightforward
Cathodes usually are not exposed to high levels of chromium	Cathodes can be exposed to chromium (metallic components need to be coated)	Cathodes can be exposed to chromium (metallic components need to be coated)
Anodes are poisoned by low levels of sulfur	Anodes are poisoned by low levels of sulfur	Anode material flexibility offers opportunity to incorporate sulfur-tolerant anode materials [1]

Table 6-1: Attributes of competing SOFC stack designs
[1]

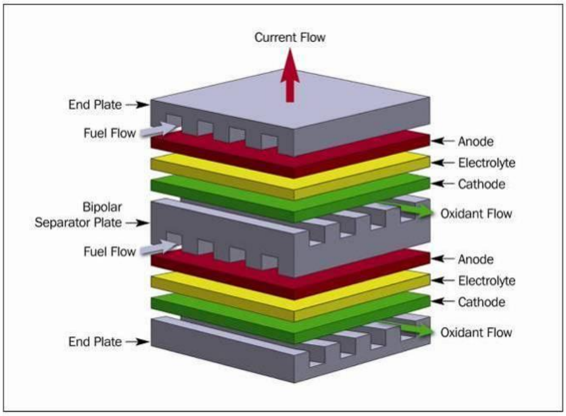


Figure 6-1: Schematic of repeat unit in a planar SOFC stack

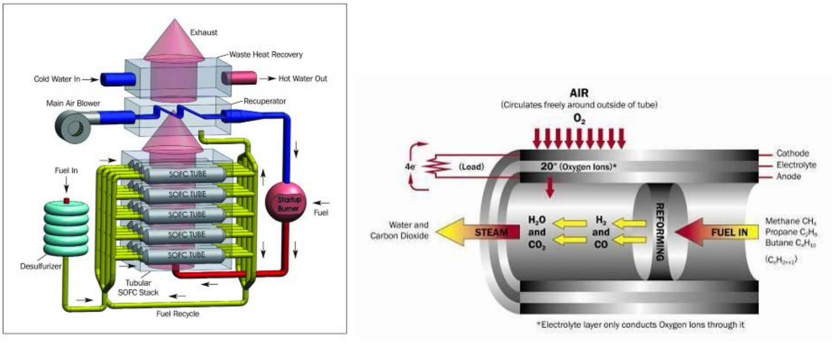


Figure 6-2: Schematics of tubular solid oxide fuel cell stacks
[Courtesy of Acumentrics]

Solid Oxide Fuel Cell Application Areas

Solid oxide fuel cell systems which operate in the 50 W to 500 W power range are generally based on tubular stack designs rather than planar because non-repeat units (manifolds and compression systems) are relatively heavy in planar stacks. This means that planar stacks are not competitive when weight is used as a primary metric. Systems of this size have many potential military applications, including battery chargers, auxiliary power units, and power sources for unmanned vehicles (UAVs and UGVs). Commercial applications include power supplies for recreational vehicles and sailing vessels.

Solid oxide fuel cell systems which operate in the 0.5 kW to 10 kW range generally have either a tubular or planar geometry. Typical potential applications include distributed power household or industrial power, military applications such as backup generators utilizing logistical fuel, auxiliary power units (APU) for military and commercial vehicles, and in the longer term, micro-combined heat and power (micro-CHP) units for homes.

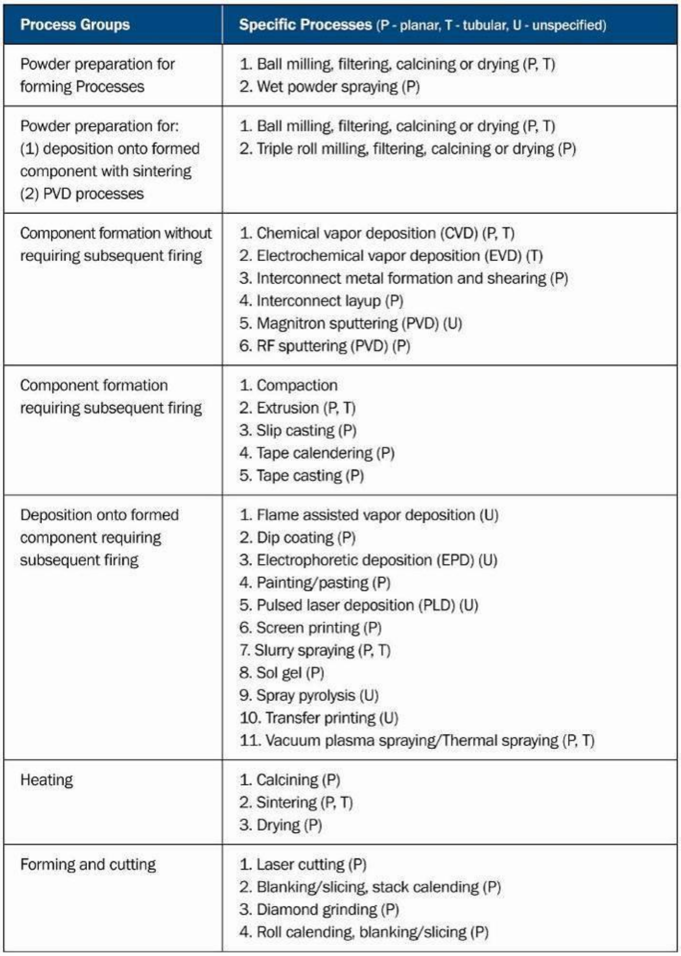
Solid oxide fuel cell systems which operate in the 10 kW to 250 kW range generally can be based on tubular or planar stacks. Within the military, potential markets include large auxiliary power units, power for tent cities, and distributed power generation on ships. Numerous commercial applications exist including distributed generation, combined heat and power systems for industrial facilities and hotels. Planar stack producers in particular are moving into this space. For example, two SOFC OEMs are working together to scale their planar SOFC technology to 250 kW scale systems.

Solid Oxide Fuel Cell Material Sets

Regardless of cell design, essentially the same materials sets are used in the manufacture of solid oxide fuel cells. A comprehensive list of various SOFC materials is provided in Appendix A. The more common SOFC materials sets are described below.

- **Electrolyte Materials -** The most commonly used ceramic electrolyte material is yttria-stabilized zirconia (YSZ), which has the formula: $(ZrO_2)_{1-X}(Y_2O_3)_X$. The most common YSZ electrolyte material has 8 mole percent Y_2O_3 and is referred to as YSZ-8. YSZ electrolyte compositions with lower yttria content (e.g., YSZ-3) also are used. In general, there is a trade-off between higher ionic conductivity for higher Y_2O_3 doping levels and higher mechanical strength for lower Y_2O_3 doping levels. Scandia stabilized zirconia (ScSZ) also has been used with Sc_2O_3 doping levels between 6 and 10 mole percent. ScSZ offers significantly higher ionic conductivity, but is significantly more expensive than YSZ. Gadolinium and samarium doped ceria (GDC and SDC) materials cannot be used as the electrolyte membrane because they have finite electronic conductivity at SOFC operating temperatures. However, SDC and GDC often are used as interlayers between the electrolyte and electrode layers, and also as additives for both anode and cathode materials.
- **Anode Materials -** The most commonly used anode materials are made from composites of nickel oxide and an electrolyte material (YSZ, ScSZ, SDC, and GDC). The anode material needs to be formed such that it has sufficient porosity to allow fuel reactants (H_2 and CO) to the electrolyte interface and oxidized products (H_2O and CO_2) away from the electrolyte interface. The anodes are formed with nickel oxide in its fully oxidized state, with the nickel oxide being reduced to its metallic state during the stack-conditioning step.
- **Cathode Materials -** A number of different materials are used as the cathode material in solid oxide fuel cells, most of which are perovskite structure compounds with the general formula $(La_{1-X}Sr_X)BO_3$ (where B is one or more transition elements such as manganese, iron, and cobalt. The most common cathode materials are $(La,Sr)MnO_3$ (LSM), $(La,Sr)FeO_3$ (LSF), and $La,Sr(Co,Fe)O_3$ (LSCF). The cathodes are also applied as porous coatings to allow diffusion of air to the electrolyte interface and diluted air (nitrogen) away from the electrolyte interface.

The above materials are typically purchased from suppliers, although some SOFC stack manufacturers produce their own materials. There are well established sources of YSZ electrolyte and nickel oxide (NiO) powders. The other SOFC materials (ScSZ, GDC, SDC, LSM, LSF, and LSCF) are typically made in low volume production runs by specialty ceramic powder houses.



Process Groups	Specific Processes (P - planar, T - tubular, U - unspecified)
Powder preparation for forming Processes	1. Ball milling, filtering, calcining or drying (P, T) 2. Wet powder spraying (P)
Powder preparation for: (1) deposition onto formed component with sintering (2) PVD processes	1. Ball milling, filtering, calcining or drying (P, T) 2. Triple roll milling, filtering, calcining or drying (P)
Component formation without requiring subsequent firing	1. Chemical vapor deposition (CVD) (P, T) 2. Electrochemical vapor deposition (EVD) (T) 3. Interconnect metal formation and shearing (P) 4. Interconnect layup (P) 5. Magnitron sputtering (PVD) (U) 6. RF sputtering (PVD) (P)
Component formation requiring subsequent firing	1. Compaction 2. Extrusion (P, T) 3. Slip casting (P) 4. Tape calendering (P) 5. Tape casting (P)
Deposition onto formed component requiring subsequent firing	1. Flame assisted vapor deposition (U) 2. Dip coating (P) 3. Electrophoretic deposition (EPD) (U) 4. Painting/pasting (P) 5. Pulsed laser deposition (PLD) (U) 6. Screen printing (P) 7. Slurry spraying (P, T) 8. Sol gel (P) 9. Spray pyrolysis (U) 10. Transfer printing (U) 11. Vacuum plasma spraying/Thermal spraying (P, T)
Heating	1. Calcining (P) 2. Sintering (P, T) 3. Drying (P)
Forming and cutting	1. Laser cutting (P) 2. Blanking/slicing, stack calending (P) 3. Diamond grinding (P) 4. Roll calending, blanking/slicing (P)

Table 6-2: SOFC cell manufacturing processes
[2]

A number of ceramic manufacturing processes have been used in the manufacture of solid oxide fuel cells of planar and tubular configurations. A comprehensive list of these processes is provided in **Table 6-2**. The manufacture of planar and tubular SOFC cells is discussed separately below.

6.2. PLANAR SOFCS

Manufacturing Overview

Planar solid oxide fuel cell stacks are made with two types of cells differentiated primarily by the material (anode or electrolyte) which provides the primary mechanical support for the cell. Anode supported cells comprise a relatively thick porous anode layer (300 μ to 1000 μ thick), a thin and dense electrolyte membrane layer (10 μ to 20 μ thick), and a thin porous cathode layer (20 μ to 40 μ thick). Conventional electrolyte supported cells are made with a relatively thick and dense electrolyte membrane layer (150 μ to 300 μ thick) with thin and porous anode and cathode layers (20 μ to 40 μ thick). These cells typically are made using traditional ceramic fabrication methods, including tape casting, screen printing, spraying, and sintering methods; the specific processes used for each layer vary with the specific design and manufacturer. Tape casting (**Figure 6-3**) and screen printing are especially important unit operations in the manufacture of planar SOFC cells.

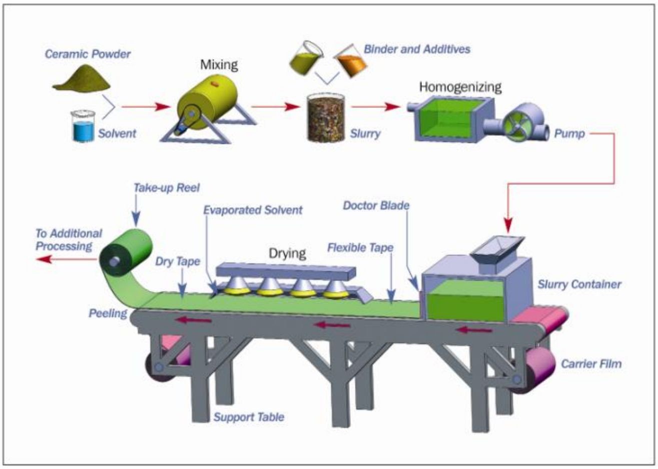


Figure 6-3: Schematic of tape casting process for making green tape layers

Examples of planar cell manufacturing processes are shown in **Figure 6-4**, **Figure 6-5**, and **Figure 6-6**. At the current technical maturity and manufacturing scale, the cost of planar cells constitutes a significant fraction of the solid oxide fuel cell stack. Much of this cost is due to the current high cost of the ceramic materials (anode, cathode, and electrolyte materials), and labor for executing the various manufacturing and quality control steps. In addition, many of the unit operations are amenable to recycling of unused material, but this isn't always done. Current cell manufacturing yields (>90 percent) are acceptable for the scale and labor intensity of cell production. Higher production volumes and aggressive cost targets would necessitate implementation of recycling processes.

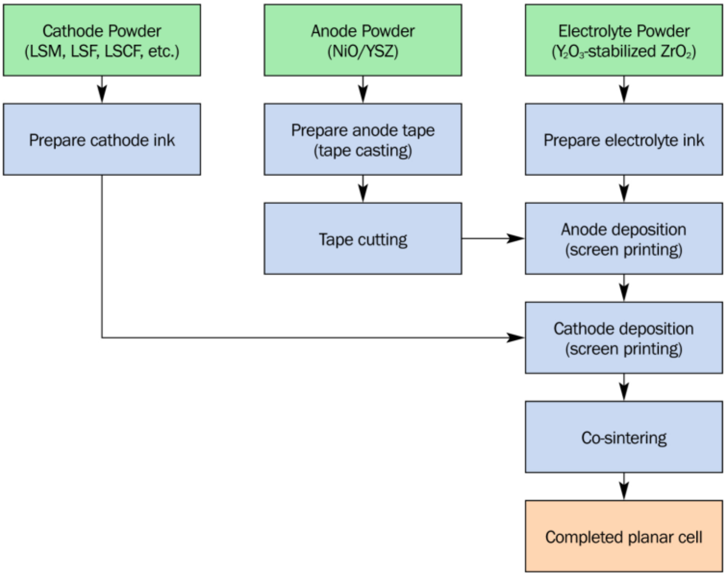


Figure 6-4: Fabrication of anode-supported planar cells by co-sintering of anode, electrolyte, and cathode layers

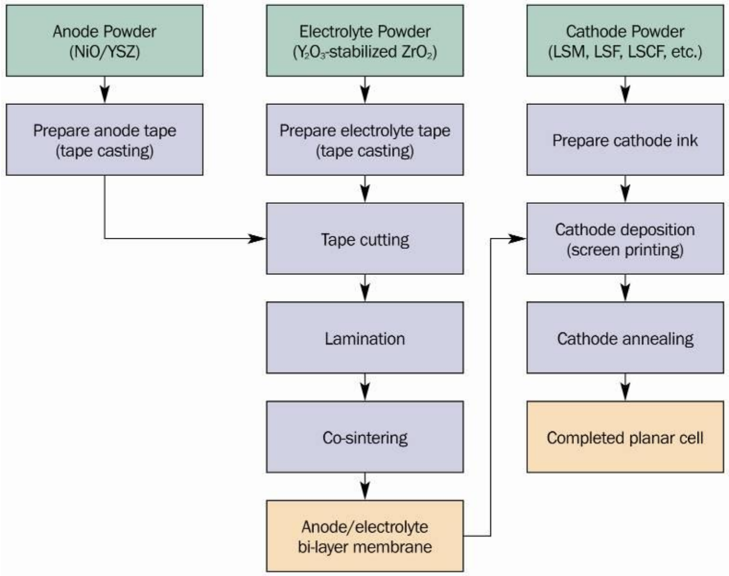


Figure 6-5: Fabrication of anode-supported planar cells by co-sintering of anode and electrolyte layers, followed by deposition of cathode layers

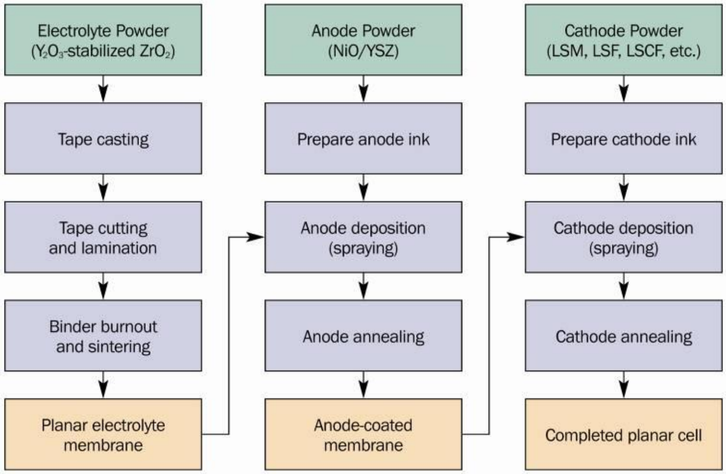


Figure 6-6: Fabrication of electrolyte supported planar cells by fabrication of electrolyte membranes, followed by separate deposition steps for anode and cathode layers

The execution of continuous processes to reduce labor in cell manufacturing is precluded due to the current low manufacturing scale. As an example, It takes considerable time to collect statistical process data required for reducing inspection cost at low production scales. Safety and environmental compliance is required for anode and electrolyte processes requiring non aqueous solvents like toluene and xylene. As production scale increases, it may be difficult to obtain regulatory approval for installation of manufacturing processes where large volumes of solvents are used. This mandates a switch to aqueous based tape casting processes that involves extremely challenging process development. For the most part, the currently used manufacturing processes for planar cells can be scaled to large-scale manufacture with a substantial reduction in cost associated with high volume production.

Some level of cost reduction can be achieved by combining unit operations (e.g., co-sintering of anode and cathode layers for electrolyte supported cells). However, such approaches must be implemented without compromising performance. In the case of planar cells manufactured by tape casting, there is a significant amount of *cut tape* that can be recycled. Currently, planar cells are subjected to 100 percent inspection at multiple steps in the manufacturing process. The automation or elimination of manual inspection will help limit the amount of testing needed and provide a robust statistical basis for determining the frequency of sampling.

6.2.1. Stack Assembly Commissioning and Testing

When viewed from a manufacturing perspective, the largest, single manufacturing cost driver for SOFC stacks is in the final commissioning and testing stage, either at a stack level or a final system level. Stack suppliers will no doubt be required by their customers to verify a specified level of electrochemical performance prior to stack or system shipment. The capital required to commission and perform acceptance testing of stacks is a considerable fraction of the total stack cost. There is a real need to get the cost of the commissioning and testing steps down, with reliable, affordable, production robust stands.

Current Best Practices

Currently, suppliers of planar stacks and SOFC systems are generally at prototype or low volume levels of fabrication. As such, program spending still needs to be apportioned to create a proper balance between engineering and development needs and those of manufacturing and manufacturing development. Stack assembly is largely done by hand, with an absence of high volume, automated assembly equipment. This necessarily makes the stack assembly operations labor intensive. The final stacks (**Figure 6-7**) are comprised of a large number of repeat and non-repeat components that are simply stacked together as building blocks.

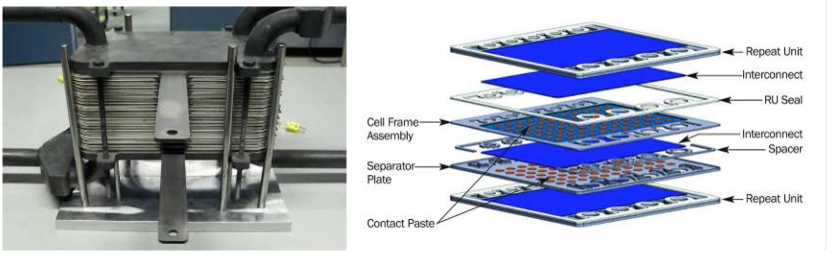


Figure 6-7: Final stacks are a large number of components stacked together
[Courtesy of NexTech Materials (left); Courtesy of Delphi (right)]

After the planar SOFC stack is assembled, it is placed into a furnace and brought up to a high temperature. The required temperature is based upon the various manufacturers' needs for debindering, achieving proper contact with any applied interconnect pastes, anode reduction, and seal requirements. Typically, a stack is ramped up to the required temperature, reduced, performance tested (when the stack is reduced and electrochemically active), and ramped back down in temperature in a single, high temperature stand. The process of commissioning the stack (making it electrochemically active) and completing the requisite acceptance testing typically can take a day or longer. Stack acceptance testing conducted on the as-built stack can take a variety of forms, and may include polarization testing, fuel utilization, load profile and cycling, thermal cycling, or other functional tests to assure acceptable stack performance. Sample performance curves, generated on as-built planar SOFC stacks are shown in **Figure 6-8**.

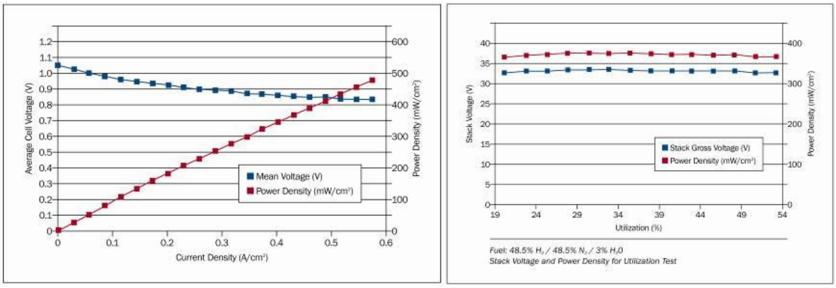


Figure 6-8: Sample performance curves, generated on as-built planar SOFC stacks
[3]

The stands used for stack builds, commissioning, and acceptance testing are typically useable for other development testing needs. They tend to be expensive capital items, due in part to the stack build requirements and to the testing requirements. Stand requirements generally include, but are not limited to, the following.

- A wide breadth of functions (process, characterize, and perform the product development/validation testing)
- High temperature materials
- Safety requirements (product and personnel)
- A flexible platform to allow for new tests to be performed or developed (software costs)

Depending on the size of the stack being commissioned and the requirements noted above, the stands typically cost $100,000 minimum.

Gaps and Issues

- **Robotic stack assembly equipment is expensive and currently unaffordable at today's low volumes.** Each company has needed to assess its spending needs and the mix of funding directed to engineering/development and to manufacturing/development. For much of the industry, it is believed that stack assembly is largely done by hand, with an absence of high volume, automated assembly equipment. Until volumes ramp up toward production, funding has been better spent on product development and manufacturing development as opposed to capital equipment for volume production.
- **The capital investment required for the stack commissioning and acceptance testing is a substantial fraction of the total capital required** to build stacks in high volume stack production, Stands may be expected to cost up to $100K and more. One industry estimate places the investment in commissioning and test stands to be approaching a third of the total stack capital investment required for high volume production. Additionally, the high temperature commissioning and acceptance testing of a stack may take a day or more to complete. The long cycle time results in a low throughput of qualified stacks from expensive capital equipment.
- **"Assembly of the stack module and its quality control represent about ten to fifteen percent of the total direct manufactured cost of the module.** This is mostly due to the QC cost, which must be carried out on each stack module and which takes about twelve hours to complete (includes heat up, reduction of the stack and a full battery of functionality tests)." [3]
- **"Higher utilization of production equipment capacity in the ceramics production line reduces the capital cost distribution.** Limited scalability of the equipment can reduce the capacity factors from about 80% for or more for all process units at 250 MW/yr. down to as low as 10-20% for some of the process equipment when the production is 5 MW/yr. Consequently, the capital cost has to be amortized over a smaller production, raising unit cost. Partially, this is because the number of shifts may be reduced from three to two in order to contain labor costs. However, even in that event the sintering ovens and QC testing will continue 24 hours per day." [3]

- **Experience to date with suppliers of large (1 kW to 25 kW) commissioning and test stands has been varied.** Experience has ranged from successful implementation, to a need for substantial co-engineering between stand customer and supplier, to a need to significantly re-engineer and re-build stands caused by failure of the stands to meet performance specifications. Some commercial stack suppliers have decided (or been forced) to build their own stands, as opposed to sourcing them to outside stand suppliers. From a stack supplier perspective, confidence in the supplier base for commissioning and test stands for 1 kW to 25 kW planar SOFC stacks is limited.
- **There is a small number of qualified stand suppliers**, and as an industry, we may still be going through the learning curve for design and manufacture of these stands. Customers typically provide stand requirements and little industry standardization is currently in place. Stand software ownership, in particular, has been one area of disagreement with some stand suppliers.

Recommended Best Practices

- **Stack assembly will require increased automation** as volume levels increase to assure stack quality, repeatability, and yield in high volume production. Suppliers will need to be tooled for quality, repeatable components, and stack suppliers will need to install automated assembly equipment to take advantage of more repeatable incoming components.
- **Automated pick and place stacking equipment will add consistency to stack component position, registration, and variation**. This type of stack assembly automation has been demonstrated previously for high temperature stacks, and there is some basis of knowledge in the automation industry for the design and implementation of stack assembly automation for fuel cell manufacturing. Cell assembly, i.e., assembly of cell active components, seals and gaskets, current collection plates, and associated frames, with robotic machinery has also been demonstrated for polymer electrolyte membrane (PEM) cells, and may be a source of best practices implementable for SOFC cells.
- **There is a need to determine and specify the minimum level of stack acceptance testing to ensure proper function when the stack is delivered to a customer.** Commissioning (high temperature sintering and reduction) and testing of stacks currently requires stands that are very expensive, and may have more content than needed for high volume production needs. Stands typically have more function than required for a production environment commissioning and minimal amount of acceptance testing. The acceptance testing needs to be quick, cheap, and an accurate measure of stack quality. The commissioning and test stands then need to be decontented to satisfy the minimum testing required, at minimum cost.
- **Decouple the sintering/commissioning function from the test function of the stand(s)** to allow for more efficient utilization of capital. For example, if the majority of the cycle time of the stand is taken for the sintering/commissioning function, and the majority of the stand cost is related to the testing function, separating the functions into different pieces of capital equipment may be appropriate. In such a scenario, multiple stacks could potentially be sintered/commissioned in a stand,

and the resultant stacks transferred to a test stand for acceptance testing. Another possibility to increase throughput during acceptance testing would be to develop a test at significantly lower temperature that, while perhaps not directly measuring stack electrochemical performance, would correlate to that performance at operating temperature.

6.2.2. Planar Stack Separator Plate

Background/Summary

Over the past ten years, this technology has developed from a scientific concept to cell technologies that can achieve 1.8 W/cm^2 under laboratory conditions, and stacks that can achieve initial power densities of 300 mW/cm^2 to 500 mW/cm^2. The power density of this technology has allowed the engineering of integrated systems for small-scale stationary power and APU applications [4]. Now, with the conclusion of 25 kW stack tower demonstrations and the integration engineering to modularly combine towers into 50 kW, 125 kW, and 250 kW stack modules/systems, the SOFC industry is entering its next phase- proof of concept system demonstrations for commercial roll-out, for a wide range of high-volume applications.

For solid oxide fuel cells (SOFCs) to become economically viable, systems must demonstrate high efficiency operation that is stable for as long as 40,000 hours. Planar SOFC stack developers have demonstrated stacks with the requisite performance and projected manufacturing costs to meet the anticipated application demands, but have not yet validated low-cost paths to extended lifetimes.

While the focus of this section is intermediate temperature (650 °C to 800 °C), planar SOFCs, the general mechanisms of stack degradation and failure include the growth and spallation (layer-by-layer flaking) of corrosion scale on metallic interconnects (ICs) and degradation of cathodes by chromium poisoning. It is acknowledged that for SOFCs to reach the cost targets of widespread application, interconnect and cathode current collector components, which comprise about half the part count in planar SOFC stacks, will need to be made of inexpensive ferritic stainless steel alloys. Ferritic alloys grow high resistance oxide scales during use that increase the stack resistance. When the oxide scale becomes thick, it can spall from the metal during operation or during thermal cycling, and as a result, degrade the electrical contact within the stack, and its performance. Further, ferritic alloys are susceptible to volatilization of chromium-based vapor species that poison cathode function. To overcome these issues, low-cost protective coatings are required for the metallic interconnects.

Current Best Practices

As shown in **Figure 6-9**, the fundamental nature of the fuel cell, especially the high temperature solid oxide fuel cell, includes the electrochemical combination of fuel, hydrogen containing gas, and an oxidant, typically air. This results in a physical environment where from a design for manufacture, cost, and life standpoint, the materials of construction must sustain, individually, or simultaneously:

- At the fuel inlet: highly reducing gases/moderately humid gases
- At the fuel outlet: moderately reducing gases/high humidity gases
- At the oxidant inlet: typically, air

- At the oxidant outlet: typically, vitiated air (higher in nitrogen, less than 21% oxygen)

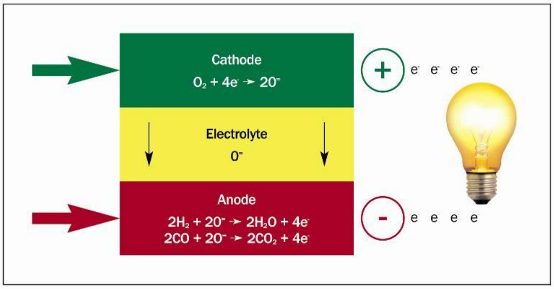


Figure 6-9: Electrochemistry of the SOFC; defines the gas environments and temperatures required for the materials of construction

The operating parameters of the SOFC drive material selections at the cell, stack, and system level include:

- For flow fields within the cell: materials of construction and coatings that are compatible with either the fuel or the oxidant gas
- For the separator plate and end plate in some designs (**Figure 6-10**): selection of materials of construction and coatings that are dual-atmosphere, both fuel and oxidant gas-compatible
- For the pipes and heat exchangers upstream and downstream of the stack: materials of construction and coatings that are compatible with- the fuel inlet, fuel outlet, oxidant inlet, oxidant outlet, and depending on the system design, the combustion gas that results from the burning of the fuel outlet and oxidant outlet

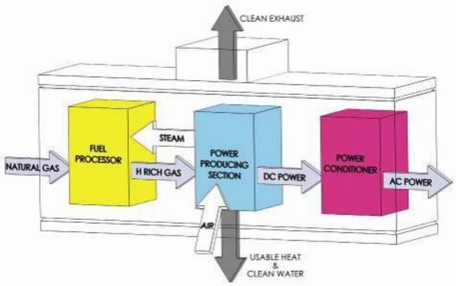


Figure 6-10: Block diagram of a fuel cell power system

In general, the choices for interconnects and flow field materials of construction fall into the following broad categories, roughly grouped by temperature:

- For high-temperature operation (900 °C to 1000 °C): ceramic (lanthanum or yttrium chromite). These materials, while chemically stable and compatible with the MEA from a chemical and thermal expansion perspective, are mechanically weak and costly.
- For intermediate-high temperature operation (800 °C to 900 °C): Cr-based or Ni-based superalloys. These materials are chemically stable at 900 °C, but they require additional coatings to prevent Cr poisoning of the electrodes. In addition, they are expensive and difficult to form.

- For intermediate temperature operation (650 °C to 800 °C): ferritic steel (coated or uncoated). While uncoated steels are chemically unstable, especially during thermal cycling, coated steels provide corrosion resistance as well as acceptable conductivity when new. Given that the focus of this section is intermediate temperature, planar SOFCs, certain development aspects of real system validation such as thermal cycling, performance, and robustness in real stacks-in-systems, and manufacturability for cost and life remain to be completed.

From the cell/stack level perspective, the features that require consideration for manufacturing solutions to cost and life include:

- end plates
- bipolar plate: anode and/or cathode side
- flow field: anode or cathode side

Present technology

A large body of work is on-going at a number of private and national labs, primarily through the US Department of Energy Solid State Energy Conversion Alliance (SECA) Program, to determine the optimum material set for performance and life, for the interconnects and flow fields. For this section, work conducted at the Pacific Northwest National Laboratory (PNNL) will be used as a representative example of the technology status in this area.

The PNNL work is conducted from the repeat part/cell block perspective, as depicted in **Figure 6-11**, with the following objectives.

- Long term improved understanding of performance of Ce-modified $(Mn_{0.5}CO_{0.5})_3O_4$ spinel coatings on AISI 441 steel: via parameters such as area specific resistance (ASR); oxidation behavior; and scale adhesion at 800 and 850 ºC
- Evaluation of alloy surface treatments: via collaborations with Allegheny Ludlum and NETL-Albany
- Optimization of Ce-modified $(Mn_{0.5}CO_{0.5})_3O_4$ spinel coatings: via parameters such as ultrasonic spray process; and effect of coating thickness
- Evaluation of cost reduction approaches

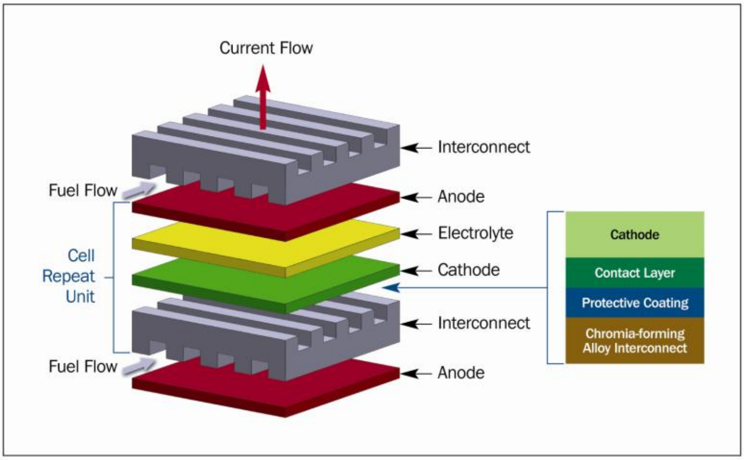


Figure 6-11: Technical focus for interconnect materials and coatings gap resolution [5]

While an alloy-route to a long term solution can be pursued for the upstream/downstream piping and heat exchangers, the interconnects and flow fields will typically require a combination of alloy compositional-plus-coating solution due to the electrochemistry and part configurations obtained within each cell. In general, effective coatings appear to come from the spinel and perovskite structured families, including transition metal and rare earth oxide compounds.

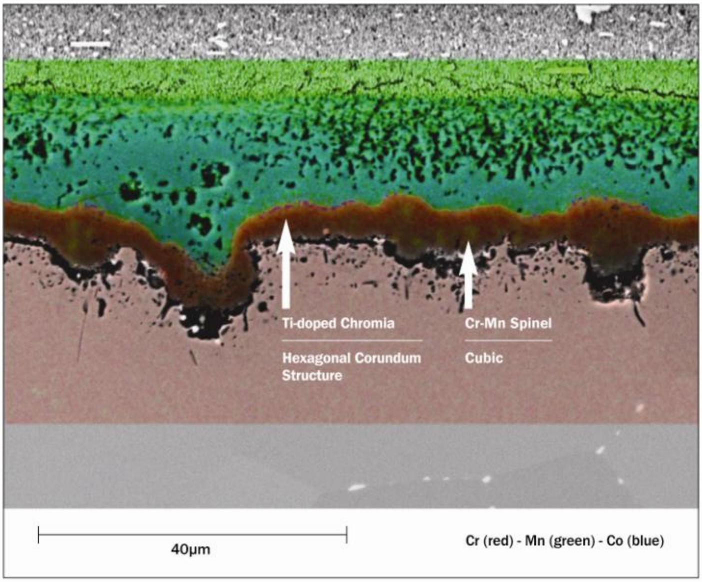


Figure 6-12: Ce-modified (Mn0.5Co0.5) 3O4 spinel coatings on AISI 441 steel [6]

Figure 6-12 provides a snapshot of a state-of-the-art coating system, a spinel-structured compound containing manganese (Mn) and cobalt (Co), applied to AISI type 441 stainless steel. This Mn-Co spinel coating was subjected to a durability screening test which characterized the material's performance and life-affecting resistance as a function of time; and, as shown in **Figure 6-13**, this system yielded an eight times reduction in the resistance in more than a year of testing.

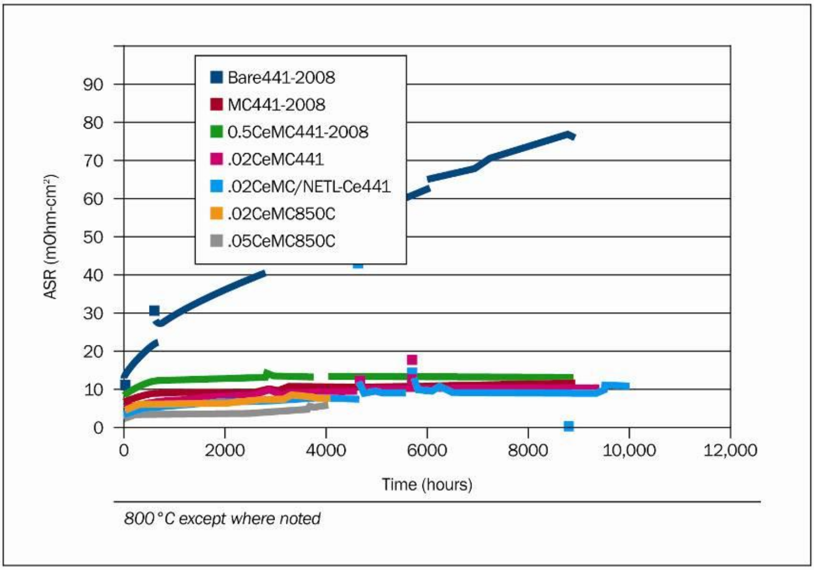
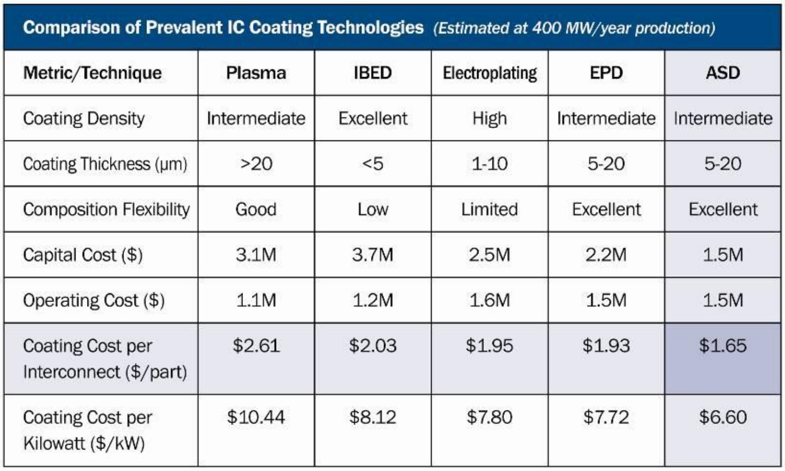


Figure 6-13: Long-term area specific resistance (ASR) measurements: 800 °C and 850 °C [6]



Comparison of Prevalent IC Coating Technologies *(Estimated at 400 MW/year production)*					
Metric/Technique	**Plasma**	**IBED**	**Electroplating**	**EPD**	**ASD**
Coating Density	Intermediate	Excellent	High	Intermediate	Intermediate
Coating Thickness (μm)	>20	<5	1-10	5-20	5-20
Composition Flexibility	Good	Low	Limited	Excellent	Excellent
Capital Cost ($)	3.1M	3.7M	2.5M	2.2M	1.5M
Operating Cost ($)	1.1M	1.2M	1.6M	1.5M	1.5M
Coating Cost per Interconnect ($/part)	$2.61	$2.03	$1.95	$1.93	$1.65
Coating Cost per Kilowatt ($/kW)	$10.44	$8.12	$7.80	$7.72	$6.60

Table 6-3: Preliminary coating manufacturing screening study results
Plasma= plasma sprayed; IBED= Ion Beam Electro deposition;
EPD = electrophoretic deposition; ASD = aerosol spray deposition) [7]

One SOFC company recently completed a preliminary coating manufacturing screening study, where the Mn-Co spinel coating was baselined against several alternative processes. As shown in **Table 6-3**, an aerosol based spray/heat treatment scheme resulted in the lowest cost, which for the range of relevant interconnect and flow field thicknesses corresponds roughly to $5 to $13 per kg.

Gaps and Issues

While the research to date is promising, the gap lies in the need for resolution of the final materials/coating systems that are both functional (from a performance and life perspective) and amenable to high speed/high volume manufacturing processes.

Endplates for planar SOFC stacks currently are made using time-consuming and wasteful machining methods. This component cost can be reduced by using net-shape manufacturing processes. Economical net-shape manufacturing processes for endplates need to be identified and validated. Corrosion protection coatings also are needed for the end plates.

Recommended Best Practices

- With regard to final materials/coating systems functionality, the materials/coating systems that have been characterized as acceptable in the lab now need to be scaled up and proven in full area cells, in full area/full height stacks, and in stacks in systems. The gross functional requirements which must be simultaneously built into these now-manufactured materials/coatings systems (in full size stacks) include:
    - Oxide scale and coating adherence
    - Chromium barrier
    - Oxidation resistance
    - Conductance
    - Compatibility with adjacent stack materials
    - Compatibility with seals
- With regard to amenability to high speed/high volume manufacturing processes, the researchers and manufacturers are required to coordinate heavily, as there will inevitably be limitations on the final solution implemented due to the constraints of the manufacturing processes employed, especially as the manufacturers will be charged with achieving function at cost.
- At the same time, the materials/coatings systems will be constrained for cost. The coating application methods can range widely, including dip, paint, spray, and plating, where oftentimes base alloy material development is iteratively tailored to, or optimized for, the coating process. This iterative process is time consuming and costly in itself, which dictates the immediate need for the resolution and selection of the preferred scheme for coating deposition/processing.
- Related to these gaps is the broader need for validation of five year functionality within a constrained, compressed timeline typical of highly competitive commercialization efforts. This speaks to the need for an accelerated testing protocol to predict lifetime of materials/coated components (not just stack, backup power also); for example, an

accelerated regimen that enables the prediction of a five year stack-in-system lifetime in less than five years. This accelerated strategy would take into account the following parameters: thermal cycling; load cycling; fuel compositions; temperature; oxygen exposure; dual atmosphere exposure; humidity level on cathode side; contaminant levels; including acceptable current/voltage.

The recommended practices include:

- Final integrated development and manufacturing gap resolution
- Selection of materials/coatings compositions
- Further process development
- Process rollout to yield coatings and alloys amenable to pipes, heat exchangers, formed embossments, and flat sheets
- Integral cost targets, expressed as “less than, a ~$XX per kg price premium
- Net shape manufacturing of end plates

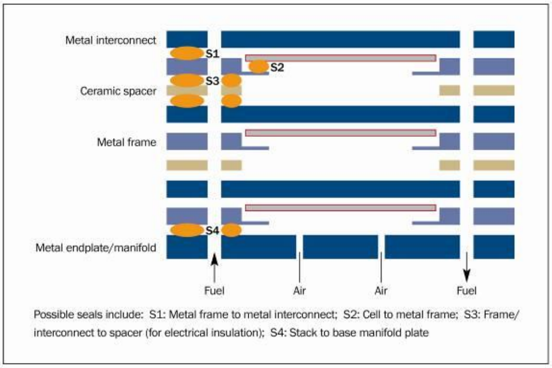
6.2.3. Planar Inspection

See Tubular inspection 6.3.3.

6.2.4. Seals for Planar Stacks

Sealing of planar SOFC stacks is a significant technical challenge, and the sealing approach used in a given stack design has significant impact on overall stack manufacturing cost (as well as performance and durability). Seals in planar SOFC stacks are required to prevent mixing of fuel and oxidant and to prevent outboard leakage of fuel to the ambient. In some planar stack designs, the seals also provide mechanical bonding of components and electrical insulation between stack components. The seal materials must be chemically and physically stable at high temperatures in both oxidizing and reducing atmospheres, and must be low in cost and amenable to low-cost stack manufacturing methods. Thermal expansion match with the SOFC materials is also required for thermal cycling capability.

All of these requirements are tough to meet simultaneously. Planar stack designs require a minimum of two seals per cell, and a single seal failure ultimately, can lead to stack failure. The significance of the sealing challenge cannot be overstated. Several possible seal types are shown in **Figure 6-14** for a planar stack with metallic interconnects. There are a number of sealing material options and configurations that have been evaluated in planar SOFC stacks, but the specific materials and approaches used for sealing are proprietary to stack developers. There are two fundamentally different sealing strategies that are being developed: glass-based seals that bond to mating surfaces and provide a hermetic seal; and inorganic seal gaskets that are compressed to minimize leakage without physical bonding that provide a non-hermetic seal with an acceptably low leak rate.



Possible seals include: S1: Metal frame to metal interconnect; S2: Cell to metal frame; S3: Frame/interconnect to spacer (for electrical insulation); S4: Stack to base manifold plate

Figure 6-14: Possible seal types in a planar SOFC stack
[4]

With glass and glass-based seals, a hermetic seal is achieved through melting of the glass phase and adhesion of the glass to the mating surfaces. Alkaline earth-alumina-silica glasses are commonly used for glass-based seals. Some glass seal materials are designed to be rigid during SOFC operation (via crystallization of the glass or design of the glass composition such that the glass softening point is higher than the SOFC operating temperature). For these rigid seals, thermal expansion of the seal materials must be closely matched to the other stack components. Other types of glass-based seals are designed to have some amount of compliance; this is achieved by designing a glass composition with a glass softening point lower than the SOFC operating temperature. With compliant glass seals, the thermal expansion match requirement is somewhat relaxed. Technical challenges with glass-based seals, regardless of type, include brittle failure of seals and adjacent cells, volatilization of glass constituents (e.g., silica, alkali, borate) and subsequent poisoning of the electrodes of SOFC cells; and adverse interactions between the glass and adjacent interconnect components.

Compressive seal gaskets have been made from several materials, including ceramic felts (e.g., alumina, zirconia), inorganic sheet-like minerals gaskets (e.g., mica, vermiculite), or ceramic and composite sheets made by tape casting. In general, gasketed seals require the application of a significant compression force in order to keep leakage to an acceptable minimum. However, these materials can be less reactive with adjacent stack components, and less prone to volatilization of potential electrode poisons. Depending on the compliance of the seal gaskets, compressive sealing also may allow for increased tolerances with respect to surface quality of mating surfaces. Potential challenges with respect to compressive gasket sealing are related to thermal stability of the specific seal material being used.

Current Best Practices

For planar stacks, repeating unit to repeating unit seals are typically tape cast into sheets and the seal patterns are cut from these sheets (see **Figure 6-15**). An advantage of tape casting is that the resulting tape is extremely compliant, which allows the seals to conform well to the mating surfaces during initial compression. Although the tape has the benefit of compliancy, the thin patterned seals cut from the tapes can be difficult to handle. While stack assembly is typically by hand today, automated stack assembly could benefit from less delicate seal forms. The patterned seals are then placed between repeat units during stack assembly. In their as-produced form, the tape cast seals contain a significant fraction of organic material (e.g., binders, solvents). These organics are volatilized during initial heating of the stack (during commissioning).

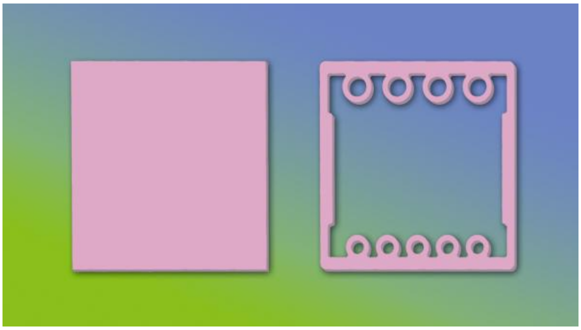


Figure 6-15: Cast seal tape and seal gasket cut from tape sheet
[Courtesy of Delphi]

Gaps and Issues

- Cutting patterned seals from sheets of cast tape leads to inefficient material usage with a significant amount of waste.
- Tape casting is a relatively slow and high cost process for fabricating the repeat unit to repeat unit seals.
- Planar stacks require seals between each repeat unit, so a high volume production process needs to be developed to replace tape casting.
- A high volume process of seal application is needed, whereby the seal is formed/located only where required, such as by dispensing, molding, or other net shape process of forming in order to reduce seal material seal costs.

Recommended Best Practices

- **The off-cuts from seal tape manufacture need to be re-cycled.**_From a materials usage perspective, a relatively small percentage of seal tape is used for each gasket. This leads to a significant amount of waste. Recycling of this off-cut tape will be a significant development effort, but it will be essential for large scale manufacture.
- **A better sealing approach may be to selectively deposit seal material at specific locations where the seal is required**. This approach would likely be used in conjunction with an automated stack assembly system. The tape casting process currently used to make seals involves organic solvents (toluene, xylene) that must be handled properly to maintain safety.
- **Modify the tape casting process to accommodate an aqueous based solvent system**. As the scale of stack manufacturing increases, it may become advisable or necessary depending on local regulations.
- **Extrude or spray the seal onto the specific areas using a high speed X-Y printer as an alternative approach**. Since tape cast seal tapes are flimsy and easy to tear, it becomes more difficult to handle as the cell area grows. This would require a significant capital equipment expenditure.

6.3. TUBULAR FUEL CELLS

Manufacturing Overview

Tubular solid oxide fuel cell stacks are typically fabricated with a porous anode support material providing the structural support. The tubular cells forming the stacks are differentiated primarily by their geometry, with smaller diameter tubes (1 mm to 5 mm) being preferred for smaller power systems (50 W to 500 W), and larger diameter tubes (5 mm to 40 mm) preferred for larger power systems (0.5 kW to 10 kW). Wall thicknesses of the anode support tubes also vary with diameter, with smaller diameter tubes having relatively thin walls (200 μ to 500 μ) and larger diameter tubes having thicker walls (500 μ to 1000 μ).

Tube lengths vary with stack design but they generally range from 5 cm to 100 cm for most applications. The base tube for anode supported tubular cells are commonly fabricated using extrusion or cold isostatic pressing. Selection of the forming technique is ultimately dependent upon the required tube size being fabricated. For smaller cells and therefore lower power units, extrusion is the current preferred technique. In contrast, pressing of the support tube is currently favored for larger tube and higher power units.

The functional layers utilized in anode supported cells are applied using a variety of techniques including spray coating, dip coating, and screen printing. A number of sintering steps are then undertaken which are in general batch based. The specific processes used for application of each layer vary with the design or final application and the manufacturer. Example of anode-supported tubular cells are shown in **Figure 6-16**.

Examples of manufacturing processes used for anode-supported tubular cells are shown in **Figure 6-17.**

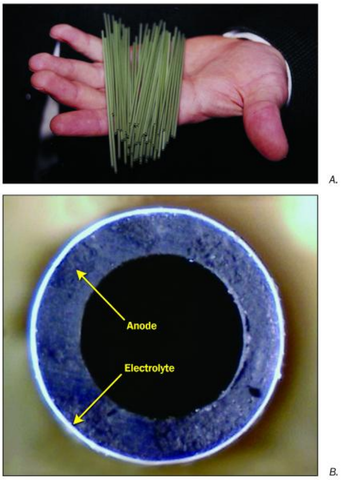


Figure 6-16: Anode-supported micro-tubular elements (prior to cathode deposition)
[Courtesy of Adaptive Materials, Inc.]

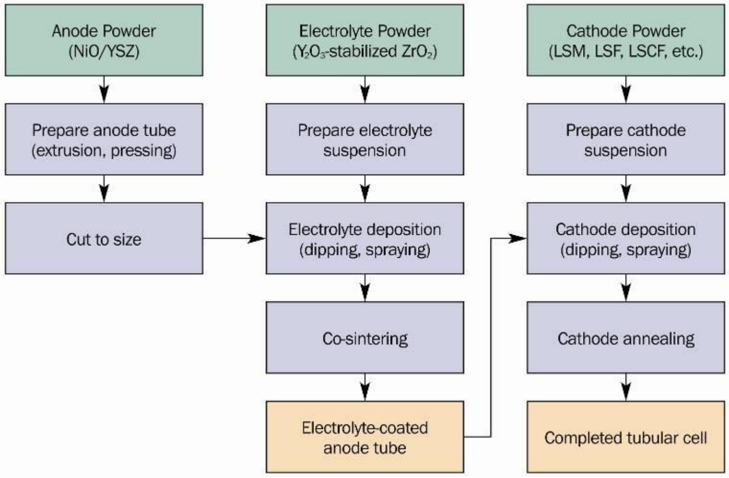


Figure 6-17: Isostatic pressing of anode supported tubular cells

At the current level of technical maturity and manufacturing scale, the cost of tubular cells constitutes a significant fraction of the overall fuel cell stack. In particular forming of the anode substrate tube is key to cost reduction from both a labor and materials viewpoint. Cell and stack current collection is also a significant cost driver with a large contribution from both the labor and materials involved. The details relating to this and the recommended manufacturing process are found in section 6.3.2 of this report.

For tubular cells and stacks, quality control is apparent throughout the entire process and in many places 100% inspection persists due to lack of statistical data. To reduce cell costs, these steps must be eliminated or fully automated. Tube quality control is discussed in section 6.3.3 of this report. Finally, many of the unit operations are amenable to recycling of unused material, but this isn't always undertaken.

Current tubular cell manufacturing through process yields are greater than 80 percent and as such, improvements in this area are being actively pursued. Current cell manufacturing best practice is dominated by batch processing steps with little to no automation of part transfer between the steps. This is an area where automation could be used to drive down the labor costs associated with cell fabrication.

6.3.1. Cells

The currently established manufacturing practices used today for producing tubular fuel cells are amenable to high volume manufacture and consequently these processes form the basis of the recommended manufacturing process.

Current Best Practices

Outline of BP

- QC - Incoming Materials
    - Powder size distribution (PSD), tap density, chemical analysis (particle-induced X-ray emission – PIXE analysis), pressing bar conductivity, make slurry test viscosity, spraying/dipping ink prep, build test SOFC cells for functional testing

- Anode substrate
    - powder press support tube, bare anode, sintering
    - coextruded anode, anode functional layer (AFL), and electrolyte
- Electrolyte application
    - Dip or spray electrolyte
    - Coextruded anode, AFL, and electrolyte
    - Sintering
- QC - Inspection Process
    - Visual inspection –gross defects, discolorations, etc.
    - Straightness inspection
- Anode Interconnection
    - Apply patterned oxide interconnect to exterior of tube
- Apply Cathode Layers
    - Apply barrier layer, sintering
    - Apply cathode, oxide ceramic, sintering
- Anode Reduction
    - Reduce anode,
- QC Testing
    - Leak Check - electrolyte gas tight
    - Cathode and anode electrical conductivity
- Tube to manifold sealing
    - Apply sealing material and bond SOFC tube to manifold

BP overview

- **Form the tube by extrusion and in some cases co-extrude the anode and electrolyte**. For smaller power systems (50 W to 500 W), this fabrication technique, with some modifications, is the recommended fabrication technique for high volume small diameter tube fabrication. As mentioned previously for tubular cells, formation of the anode tube substrate (**Figure 6-18**) is one of the largest cell cost drivers. The forming methodology employed is dependent upon the diameter, aspect ratio, and length of the tube required.

Figure 6-18: Extrusion equipment for small diameter, anode substrate tubes
[Courtesy of LOOMIS PRODUCTS]

- **Due to the demanding tube geometry, diameter, aspect ratio, and length, for larger power systems 0.5 kW to 10 kW, the current best practice is to form the tube by isostatic pressing**. Compared with traditional molding technologies, the pressed parts formed from isostatic pressing possess exceptional uniformity along the length. For larger cells, isostatic pressing is the norm, but just like extrusion, some process and fixture development is required to implement a semi continuous process.
- **For functional layers that are applied to tubular solid oxide fuel cells, the current application techniques are already scalable high volume manufacturing techniques**. It is considered that the currently adopted layer application processes are eminently suitable and therefore the recommend manufacturing practice.
- **Most tubular processing methodologies are batch in nature with limited automated part movement between the different processing steps.** To enable high volume cell manufacturing and therefore cost minimization, significant part movement automation is required to connect the different fabrication methodologies.
- **For smaller power systems (50 W to 500 W) the recommended anode substrate tube forming technology is extrusion**. Development of this technique is required to enable the semi continuous operation demanded to realize significant cell cost reduction. To enable semi continuous operation, development and implementation of semi-continuous plastic processing methodologies to prepare the extrusion feedstock is needed. Technology may be leveraged from the rubber industry that currently uses such methodologies for mixing large quantities of material with increased homogeneity at a lower cost. If the mixer capacity is scaled to the correct size, a continuous feedstock may be provided for continuous extrusion of the anode or co-extrusion of the anode and electrolyte. Alternatively, an in line mixer and extruder may be developed for this application. Such equipment is already being utilized in other industries.
- **For larger power systems (0.5 kW to 10 kW), the recommended anode substrate tube forming technology is isostatic pressing.** As with extrusion of smaller tubes, this forming technique needs further development to allow semi-continuous pressing of the larger tube geometry. The gap between the current tube pressing methodology and a semi-continuous solution is small, and solutions already exist for the automated isostatic pressing of ceramic parts in other related industries. The issue is technology transfer and development of an appropriate pressing regime for anode substrate tube manufacture.
- **For both anode substrate tube-forming technologies, dimensional tube tolerance will need to be re-established after introduction of any modified forming technique**.
- **Another related issue is the requirement to produce a thin electrolyte layer (generally between 10 μ to 20 μ), that is gas tight after sintering.** Any development of the anode support tube fabrication technique will require a re-evaluation of electrolyte quality.

Gaps and Issues

- Anode forming – dimensional tolerance of tube, difficultly in forming high aspect ratio tube with thin walls.

- Electrolyte application – difficulty of applying a repeatable ultra-thin (10 to 30 micron) ceramic powder coating to a curved substrate without defects or flaws introduced either by the coating process, handling, or firing process.
- Significant development time will be required to make the transition from batch firings to the recommended manufacturing technique of continuous firings. In general, sintering of the applied layers is currently batch firing orientated as the volume demand for the product that would warrant continuous firing technology has not yet materialized. The move to high volume continuous firing is a necessary development to realize low cost fuel cell manufacture. Cell cost reductions will also be realized by combination of processing steps, particularly firing steps with the ultimate goal of a single continuous firing step for all assembled cell components. There are however significant processing and material interaction issues to overcome to reach this stage.
- An issue for tubular SOFC cell fabrication is the batch nature of some of the processing techniques and the need to develop and move to continuous processing methodologies. In particular, with anode substrate tube forming constituting a significant proportion of tube cost, it is considered that tube-forming methodologies require special attention.
- Gaps
  - <500W
    - Design and implementation of a feeder mechanism to support semi-continuous co-extrusion of anode and electrolyte feed rods.
    - Transitioning statistical process controls and QC methods from the small-scale, thermoplastic mixing process, to large scale mixing equipment.
    - Ensuring repeatable die flow behavior downstream during the coextrusion process.
  - 500 W to 10 kW
    - Prove out feasibility of automated powder introduction and semi-continuous pressing, followed by design and implementation of a full system.

Recommended Best Practices

- Anode and Electrolyte forming process
  - Tube size and geometry dependent – diameter, aspect ratio, length
  - <500 W – small diameter tubes, between 1 mm and 10 mm
    - Recommended practice is co-extrusion of multiple layers or extrusion and coating
    - Recommended manufacturing process improvements for co-extrusion
      - Semi-continuous feed rod co-extrusion of anode and electrolyte layers to reduce cycle time between feed rods
      - Adopt semi-continuous industrial thermoplastic mixing methods from the tire rubber compounding industries for larger batch size for increased homogeneity and lower cost

  - 500W to 10 kW – larger diameter and longer length tubes, nominally 10mm to 40mm in diameter
    - Recommended practice is semi-continuous automated iso-pressing of the anode support tube

6.3.2. Current Collector

Overview [8, 9, 10]

Tubular solid oxide fuel cell (SOFC) systems with power output in the range of 50 watts to 10 kilowatts employ metallic current collectors to distribute electrical current along the length of the fuel cell tube. Tubular membrane electrode assembly (MEA) designs between 1 mm and 40 mm in diameter have been selected for power generation applications in the 50 W to 10 kW application range due to the benefits of simplified fuel and air sealing and potential for lower stress states during rapid thermal cycling. The challenge with a tubular MEA architecture is current collection and distribution along the tube axis. The conductive path length in a tubular MEA architecture per active area is considerably longer than a planar stack, therefore, ohmic losses (resistive losses) in a tubular SOFC are the typical dominant loss mechanism. **Figure 6-19** is a conceptual design proposed by Robert Kee of the Colorado School of Mines [8] of the internal and external current collectors along the exterior and interior of the SOFC MEA.

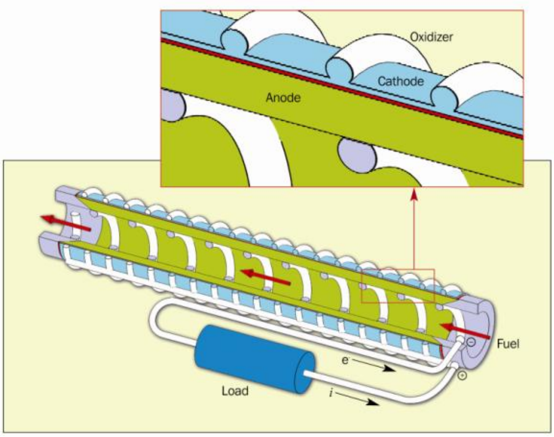


Figure 6-19: Current collectors along the exterior and interior of the SOFC MEA [8]

Every fuel cell organization producing tubular SOFC cells, stacks, and systems share a common set of building blocks; a tubular MEA and current collector wire. The conductive metallic wire arrangement upon the cell is different for different SOFC producers. Some manufacturers apply all the current collection to the outer diameter of the cell making separate contact with the anode and cathode; this can simplify the mechanism of current collection application. Other manufacturers make external contact with the cathode and then have an internal current collection contact mechanism for the anode. Both current collection methods are effective in the transport of current along the tube axis. A variety of tubular size scales and current collector winding patterns, geometries, and material selections have been developed by domestic organizations such as Adaptive Materials Inc. and

Acumentrics. The manufacturing labor and cycle time cost and scrap rates of existing wire wrapping and winding process methods are a significant cost in every tubular SOFC design. In addition, the material cost of the current collection wire is a significant cost driver and as such, methodologies to reduce the current collection requirement or use of alternative materials are ongoing.

The same type of wire is also required to form the series connection between adjacent cells although the form of the wire may be different. Making this series connection when stacking the cells to produce a system is labor intensive and automation or stack design modifications need to be pursued to reduce cell costs.

Manufacturing Opportunity

The adaption and implementation of high rate automated wire winding and tie off equipment from the electric motor and electronic inductor industries would help the entire tubular solid oxide fuel cell industrial base to reduce labor, cycle time, and scrap rates while increasing repeatability and reliability. In addition, attachment of the series connection between cells when assembling cells into a stack would benefit significantly from automation.

Current Best Practices

The current manufacturing process employed by tubular SOFC organizations is a combination of handwork and single axis wire winding equipment for attachment of current collection to the anode and cathode. The electrical interconnection between cells is accomplished via wire-to-wire connections. Sometimes these series connections may use the same wire that has been processed into different forms.

- Anode Current Collector.
    - <500 W – metallic anode current collector inserted into the inside of the tube
    - 500 W to 10 kW – apply a conductive oxide layer to an exposed anode surface and collect current via a metallic wire wrap around the tube exterior
- Interconnect
    - Make a series connection between the anode and neighboring cathode using metallic wires or wires that have been processed into another form (cathode and anode current collectors)

Gaps and Issues

- **The transition to SOFC tubular MEAs will require the development, integration, and implementation of complex secondary wire winding and tie off operations** to create not just a current conductor winding, but also the electrical interconnection with neighboring fuel cell tubes.
- **Manufacturing processes do not currently exist to coat low cost stainless steel wires with the same protective coatings adopted by planar SOFC technologies** [6, 7, 10, 11]. The existing coating processes are not capable of creating an impervious conductive barrier coating on a small diameter wire form that can withstand the stresses during handling, spooling, winding, or other wire forming operations. This limitation reduces the possibility of raw material cost reduction below the current raw material cost point.

Recommended Best Practices

> **Adaptation and implementation of high rate automated wire winding and tie off equipment** from the electric motor and electronic inductor industries is the recommended manufacturing process. Industrial best practice is exemplified by stator coil winding machines for small electric motors. Electric motor winding equipment is capable of extremely rapid wire winding in a continuous computer controlled pattern. [12]

6.3.3. Inspection

Introduction

Quality control, and methodologies to track and improve quality, is an essential component of any manufacturing enterprise. Quality control is also expensive. As products become mature, quality control requirements should decrease as processes are better understood and controlled. However, for nascent manufacturing efforts, quality control is necessarily of great importance and creating quality control methodologies and inspection techniques is critical. For fuel cells, these early market requirements are compounded by two additional factors. First, the serial nature of the stack creates a situation where any cell failure results in a reduction in performance of the entire stack. And second, the extremely harsh operating environment encountered by the cell, in which multiple degradation mechanisms operate on most of the components of the cell, makes even low levels of variability or small discrete defects potential failure initiation points.

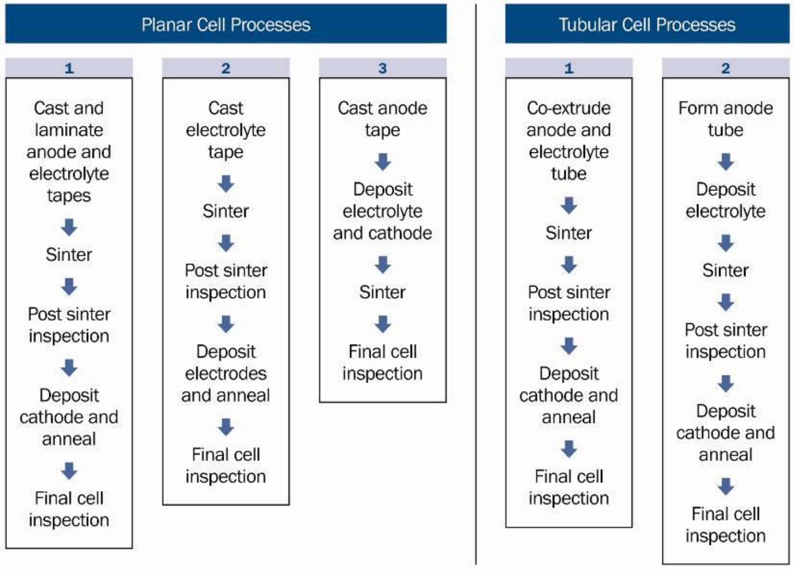


Figure 6-20: Process flow for planar and tubular ceramic cell manufacturing

In-line/in-process non-destructive testing techniques are widely used in industry. Sources of variability and defects are numerous, including material property variations, process variability, tooling and process equipment wear or failure, uncontrolled environmental conditions, and many sources of contamination, both by contact and airborne. Inspection of parts has been highly developed for automotive, aerospace, microelectronics, and other similar industries. Most of these measurements are to inspect dimensions, using a variety of laser systems for example, or to inspect for visible defects, using different camera technologies loosely described under the term ‘vision systems’. These techniques are highly capable and should be applicable to some of the quality control needs for SOFC cells. However, as described in **Figure 6-20**, because of the fuel cell operating environment, the cell materials typically have many critical parameters, all of which are important to proper operation. For example, cell active layers must have structural properties to ensure physical integrity under compression and extreme thermal loading, porosity to enable reactant gas transfer, electrical properties to enable current conduction, and appropriate chemical composition to enable the desired chemical and electrochemical reactions. In addition, the multi-layer nature of the cell defines interfaces that must have the appropriate bonding or contact. Many of these functional (rather than dimensional or positional) characteristics may be of interest to measure in process, and thus techniques and methods must be evaluated or developed. Methods developed for the paper, films, and foils, microelectronics, and solar PV industries in some cases may be applicable to the needs for SOFC cells, but must be validated for the specific materials and process conditions of interest. In addition, other than so-called vision systems, most in-line inspection techniques are point measurements, which take data at a single point on the part or sheet, or are rastered back and forth across the surface of interest. This provides spatially averaged data which can be used to assess statistical variability, but not (in most cases) to identify spatial variability or discrete defects. Again, as noted above, even small defects in some cases can act as initiation points for the multitude of degradation and failure mechanisms present in the fuel cell. Thus, imaging inspection techniques that can be used to provide a ‘quality map’ of the part may be of high value if they can be integrated into the process environment.

Current Best Practices

Planar and tubular SOFC geometries share several inspection practices. These mainly involve the characterization of raw materials imported from suppliers or made in-house. Raw materials include ceramic powders, screen printing inks, tape cast, or dip coat slurries, and spray coat suspensions used to form the cathode, electrolyte, anode, contact layers and seals; and metal sheets or wire used for the cell separator or interconnect.

The possibility of variations between batches requires the inspection of all powder batches using standard analytical techniques. These include:

- **Particle size** – Analysis is performed with a suspension of powder in an acceptable solvent and using light scattering, laser diffraction, or settling time to determine the particle size distribution of the powder. In the best case, small samples from the vendors are prequalified before shipping. Variations from the acceptable size and distribution result in further testing to determine if the batch should be accepted or refused.
- **Tap density** – This technique is used to determine the density of a powder packed in a container that has been “tapped” a fixed number of times from a fixed height. This density gives an idea of the flowability of the powder, and hence the particle shape and surface roughness.

Unacceptable variations of density in this test would trigger further investigation with microscopy.

- **Chemical composition** – The chemical composition of powders are analyzed using X-ray fluorescence, emission spectroscopy methods, or chemical titration to verify the elements present in the material. X-ray diffraction is also a method used to verify the crystal structure of the material. Much of these analyses are expensive in terms of capital equipment.
- **Electrical conductivity** – Tests are performed at temperature by pressing powder into bars, sintering the bars, and measuring conductivity to verify the electrical properties of the material. This time consuming inspection is desired for every batch of powder. After the ceramic powders have been qualified for use, they are further processed by adding organic binders and release agents for dry forming, or if slurries or inks are made, dispersants, solvents, binders, and plasticizers are blended with the powders. Tests are performed to characterize these mixtures.
- **Viscosity of slurry/ink** – Quick rheology checks are made on new batches of slurries and inks to monitor and maintain flow characteristics for casting, printing or spraying. A cone and plate viscometer provides the most useful data at low capital cost.
- **Witness samples** – To pretest the tube forming, tape casting, screen printing, spraying or dip-coating processes for new batches of material, standard formulations of powders and slurries are formed into small test samples to examine visually, mechanically and if possible electrically.

As the materials are introduced into the production line, more inspections are needed. Large production rooms and facilities are difficult to maintain cleanliness. It is well known in materials processing that silica from dust and dirt is the universal dopant in various processes. Keeping the environmental impurities low requires following activity protocols and monitoring airborne particles in the production spaces. This is critical in specialized clean room facilities where thin (<10 μm) electrolytes are produced and handled. Small dust particles or hair can be larger than the thickness of the electrolyte causing pinholes or cracks during sintering.

Figure 6-21 shows the effect of different activities performed within a class 10,000 clean room. The left axis scales the particle count of 0.5 μ particles, correlating to the green data points that has an acceptable limit of 352,000 particles per cubic meter. The right axis scales the particle count of 5.0 μ particles, correlating to the blue data points, which has an acceptable limit of 2,930 particles per cubic meter. The activity taking place in level 1 produced an unacceptable level of 0.5 μ particles without affecting the 5.0 μ particles. Whereas, the activities in level 2 lead to the introduction of 5.0 μ particles in the room above the acceptable limit without affecting the 0.5 μ particle level. By vacating the room, both particle counts drop to the baseline. By modifying the activity in level 3, both 5.0 μ and 0.5 μ particle counts become acceptable. This example of monitoring and inspection of production activities illustrates the need to monitor and establish acceptable activity protocols within the production process in the clean room. It is also important to understand the degree of concern for the presence of various particle sizes. The 5.0 μ particle contamination may be of concern, whereas the 0.5 μ contamination may not have a real effect on the process.

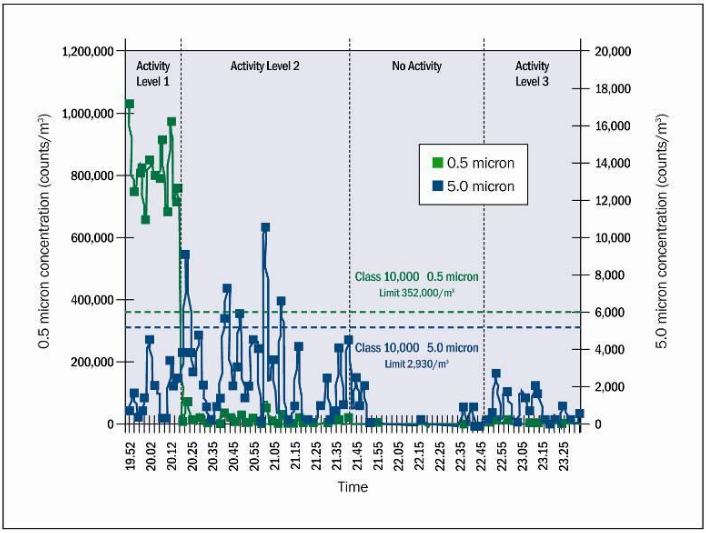


Figure 6-21: Particle level change in a clean room with different activities

In the current manufacturing practice, a significant inspection takes place after the first sintering process of the cells. In this first sintering process, manufacturers will try to co-sinter at least two or more layers together. Usually the two components consist of the supporting anode substrate and the electrolyte whether it is a tubular or planar cell. Some manufacturers will co-sinter the cathode, electrolyte, and anode components in a single step. For electrolyte-supported cells, the electrolyte is usually sintered alone and the electrodes are deposited in subsequent sintering steps.

Electrolytes supported by the cermet anode are usually made from yttria-stabilized zirconia and can be less than ten microns thick, which is true for both planar and tubular geometries. At this thickness, small cracks, pinholes, or flaws may allow gas to flow between the fuel and air electrodes. This burns and can potentially serve as an origin of cell cracking and ultimately, stack failure.

Thick self-supporting electrolytes (~200 µ thick) require the use of materials with greater ionic conductivity, such as scandium oxide doped zirconia, to reduce electrical resistance losses. Significant flaws in this thick plate usually results in catastrophic failure of the cell. Smaller flaws lead to weaknesses that may become evident as cell failure during the stacking process, transport of the stack, fuel cell operation, or thermal cycling of stacked cells. Leakage in thick electrolyte cells occurs through cell fracture or sealing flaws. Hybrid designs exist where thick frames of electrolyte material will support thin areas of electrolyte.

Inspection of the electrolyte is easily performed if it is left exposed as an open surface after sintering. Current manufacturing practice involves visual inspection of the electrolyte for flaws. Tubular cells can also be pressure tested at room temperature for leaks in a specialized test rig. The largest fallout on yield comes in the first post sintering inspection. This necessitates 100% inspection of parts after sintering.

Other physical inspections rely mainly on dimension tolerance checks. Tubular cells are inspected for straightness and gross defects (pinholes, discoloration) in the electrolyte by rotating the tube and using visual, manual, or optical (laser) measurement techniques. Planar cells are inspected for thickness variations, surface topology, and edge defects using laser or optical profilometers.

Figure 6-22 illustrates some of the defects that can occur after the first sintering process. The black areas are circles from a marker pen identifying the small flaws on the surface of an electrolyte/anode bilayer. Some of the flaws are created during processing but were not identified in the pre-sintering inspection. Other flaws can occur from materials falling from the furnace during sintering.

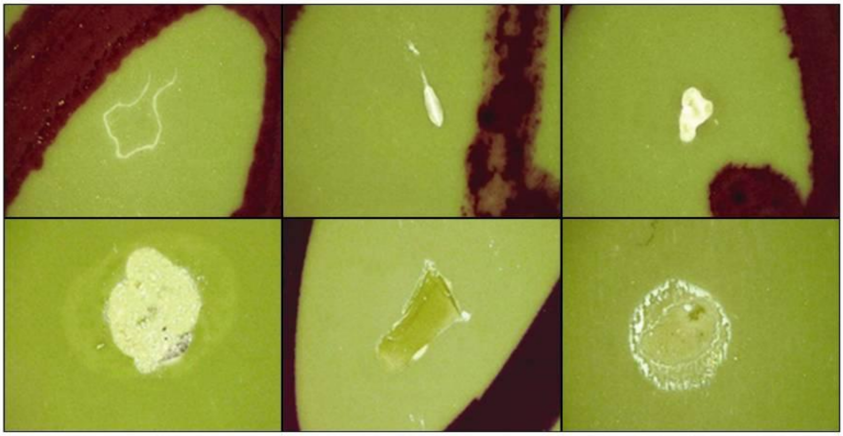


Figure 6-22: Flaws found in the post-sintering inspection of fuel cell components

Subsequent layers are inspected for surface defects after each sintering step, although these steps normally have higher part yield than the initial sintering process.

As cells are assembled into stacks, seals and contact layers are applied to planar cells as they are assembled with separator plates. Stack inspection is done on the fly as the layers are assembled. It is difficult to inspect the viability of a stack until the ultimate stack conditioning process. Here the anodes are reduced from nickel oxide to the metal, the seals are melted and sintered, and initial electrical tests are run to get an idea of the electrochemical performance of the stack. As stack conditioning is a critical step, this will be treated in more detail in a subsequent section.

Gaps and Issues

- **New inspection practices need to be developed which involve less human intervention and occur with less frequency at points of critical importance.** Inspection procedures in SOFC manufacturing take place in nearly every step along the manufacturing process. These are mostly performed by direct human observation, which cannot be scaled to high volume manufacturing if 100% of the parts are being inspected. The farther upstream in the manufacturing process the inspection can be made (i.e., defects or unacceptable variability can be identified), the better, because less value has been added to the part.

- **Given the operational environment of the fuel cell, discrete defects are just as critical to identify as unacceptable statistical variability.** Most currently validated automated inspection techniques use point measurements (that typically cannot identify discrete defects). Consequently, imaging measurements would be of high value to create 'quality maps' for each part with image analysis software to identify unacceptable defects. Furthermore, a method is needed to map in the center layers of thick opaque laminates. X-ray transmission methods similar to medical radiology imaging would allow inspection of the bulk of plate components. Similar techniques need to be developed to map defects in tubular SOFCs. Defects need to be identified in the pre-sintered state that will result in a critical defect in the post-sintered part.
- **Current powder acceptance testing methods do not identify all variability in incoming material lots, which results in electrochemical performance variability.** Tests need to be developed that will validate the electrical and electrochemical performance characteristics of the material, without having to fabricate and test a fuel cell. At this point, there is still work to be done in identifying which powder properties are critical to specify and control for minimizing functional variation. Lot to lot variation in powder supply, even when the powder lots pass current quality control acceptance tests, are seen as significant contributors to cell performance variation.
- **Materials suppliers often do not consider the solid oxide fuel cell industry to be a large enough revenue stream and do not optimize powders for SOFCs.** Larger powder batch orders would support greater QC testing for each batch by the powder supplier.
- **Manufacturing research directed toward cataloging and classifying the criticality of pre-sintering defects is needed.** This will increase the part yield and allow the lowering of inspection frequency. The catalog would identify what are allowable anomalies versus real defects.

Recommended Best Practices

The series of manufacturing processes involved in fabricating a planar or tubular cell, can be seen as a succession of steps, each of which adds value to the initial starting piece or material.

- **It is advantageous to perform inspection as far forward in the manufacturing process as possible**. This minimizes the value of a part (or batch or roll) that may be deemed unacceptable and scrapped. For these cells, two key opportunities for improving quality control methodologies and reducing scrap by inspecting earlier in the process are the tests for electrolyte layer quality and cell leakage. As noted, the electrolyte layer, whether planar or tubular, is typically visually inspected after it is fired with the anode to identify pinholes, thin spots, and other defects that may lead to leakage and/or shorting. By this process, the value of the firing step has already been 'added to' the cell; thus, scrapping the cell at this point because of poor electrolyte layer quality wastes the value of the firing.
- **Assess the viability of performing the electrolyte inspection for 'defect precursors' prior to firing**. This would save the value of the firing step. It must be determined; however, if a quality check on the electrolyte layer in

the ‘green’ state (prior to firing) is valid. This same practice could be replicated for all layers subsequently added to the cell (e.g., the cathode).

- **Perform the cell leakage test after the initial firing on the anode rather than at the end of the cell fabrication process.** This assumes the structure or architecture of the fired assembly allows for leak testing at that point in the process. This practice would save the value of numerous subsequent coatings and firings. The validity of this suggested new practice must be verified.
- **Evaluate and qualify automated non-destructive inspection methods for fired and green assemblies.** This enables reduction of labor, improvement in inspection capability, and transition to higher volume manufacturing techniques. Layer thickness, topography, and uniformity, especially that of the electrolyte layer, is of critical importance. Many techniques could be applicable, and must be assessed relative to cost, accuracy/resolution, and capability, including but not limited to vision systems, laser and optical systems, x-ray/gamma/beta source-based techniques, and UV and IR systems. Reflective and absorptive methods may be useful for surface measurements, whereas penetrating sources must be applied for full volume measurements. Designing and configuring measurement techniques for in-process application is not trivial, especially for continuous manufacturing processes. In addition, whereas application of many techniques to planar cells will be straight-forward, application of the same techniques to the tubular platform may be more complex, especially for those based on transmitting/penetrating beams. Additional development may be required in these cases, for example, development of specialized sensors that can fit and operate inside the tube.
- **Perform a comprehensive study of the effect of powder material properties on cell performance, using statistical experimental methods such as factorial designs.** There is not currently a good understanding of how cell performance variability resulting from lot-to-lot changes in powders, especially the cathode material, correlates to specific material properties of the powder. If the cause of the performance variability can be identified, quality and analytical methods can be established and incorporated into the powder acceptance/qualification process so that these lot-to-lot changes can be identified and dealt with before use of the powder in production.
- **Asses layer interface quality.** For example, electrolyte layers which are coated onto an anode support may not have the required bonding or contact with the anode at all locations as a result of material non-uniformities or errors in the coating/extruding or sintering processes. This lack of contact, for example, may lead to reduced local conductivity or mechanical failure initiation points, for example. A recommendation is to evaluate and develop methods to non-destructively inspect for poor contact or bonding at layer interfaces.

6.3.4. Insulation

Overview

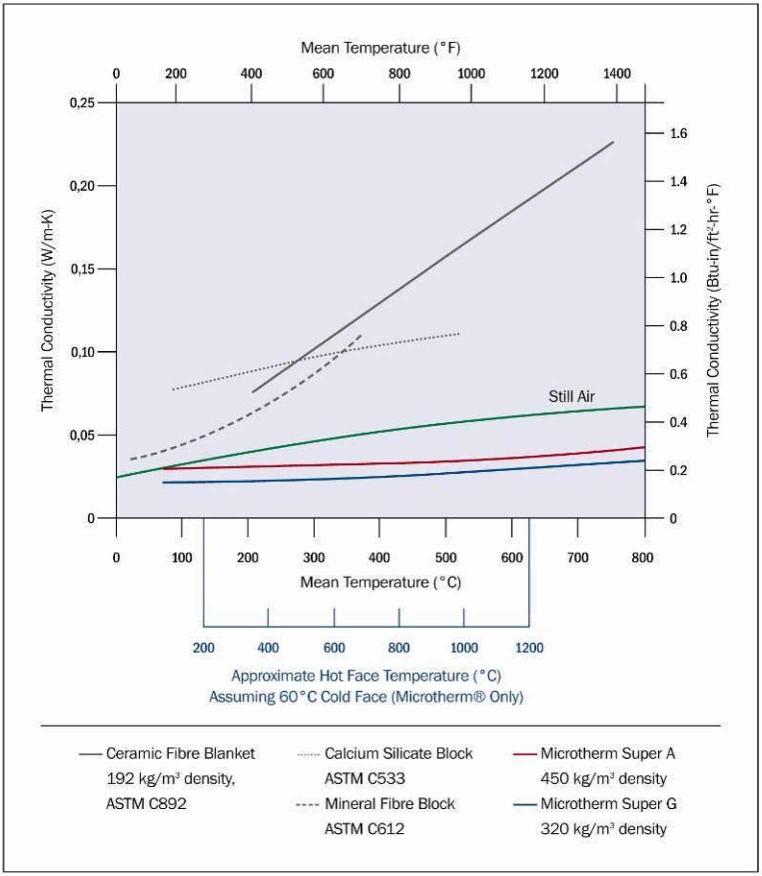
Solid oxide fuel cells operate at elevated temperatures between 600 ºC and 1,000 ºC. The best practices for insulation materials and methods are a balance between cost and performance. Extremely high performance insulation materials, typically termed microporous insulation, exist in the industry. The use of these materials is driven by the universal need to reduce packaging weight and volume across the entire SOFC industry; including both planar and tubular systems at every power level. The importance of minimizing insulation weight and volume is obvious for portable and mobile solid oxide fuel cell systems. In these demanding markets, customer purchasing decisions are strongly influenced by overall unit system size and weight. There exists a critical need for light weight high performance insulation for high power stationary solid oxide fuel cell applications. The need to minimize mass and volume of insulation within a stationary generation unit is a function of cost and package integration. Minimizing the footprint of a stationary generation unit will help open new markets such as roof top generation applications, reduce shipping expenses, and remove the need for onsite assembly and integration during installation.

Today fuel cell manufacturers source insulation boards, machine to dimension, then laboriously hand assemble the insulation into an insulated chamber, typically termed the ‘hot box’. While geometries differ between tubular and planar systems at the differing power levels, SOFC manufacturers follow the same general process originally developed for the low volume and high cost high temperature furnace industry.

At the lower power levels, especially below 500 watts, the cost of the insulation package is a significant cost driver of the overall fuel cell unit. At below 500 watts, the insulation package cost is 19% of the overall SOFC stack cost. Between 500 watts and 10 kilowatts, the relative cost of insulation is as high at 15% of the stack cost. In summary, there exists a need across the entire SOFC industry for a low cost net shape or near net shape forming process for high performance insulation materials. [13]

Current Best Practices

Microporous insulation materials are the highest performing insulation material on the market today. Microporous insulation has the necessary combination of dimensional stability at high temperatures and chemical stability in solid oxide atmospheres. Its insulation performance is world class; even higher performing than silica aerogel at elevated temperature. The reported thermal conductivity at 800 ºC is 0.02 watt/meter-ºK (**Figure 6-23**), as low as still air. [14]



Thermal conductivity values for insulating materials other than Microtherm® Super G and Super A are taken from relevant ASTM specifications. Microtherm® Super G and Super A values are as measured by the National Physical Laboratory, UK, according to ISO 8302 and ASTM C 177.

Figure 6-23: Insulation Properties of MICROTHERM® microporous insulation [14]

The challenge with microporous insulation is that it is currently only available in sheet form. The raw materials used in microporous insulation are a by-product of the cement industry, consisting of low cost silica powders, ceramic fibers, and opacifiers [14]. Fuel cell manufacturers must machine the dry pressed microporous sheet insulation materials into the required geometries. An example of machined microporous insulation is shown in **Figure 6-24**.

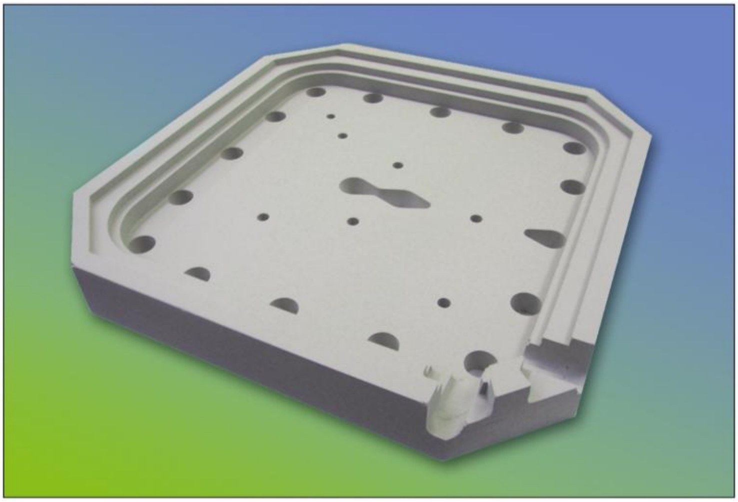


Figure 6-24: Machined microporous insulation
[15]

The manufacturing process for high performance Microtherm® insulation is described in the process flow sheet in **Figure 6-25**. Incoming dry pressed sheets of microporous insulation are pre-cut (if necessary) and then CNC machined to shape. The parts are carefully removed from the machine tool and a surface coating is applied to reduce surface discharge of dust. The individual machined microporous parts are assembled into the required final form according to the specific designs of the fuel cell manufacturer. The result is a lightweight, compact, and extremely high performance and high temperature insulation package.

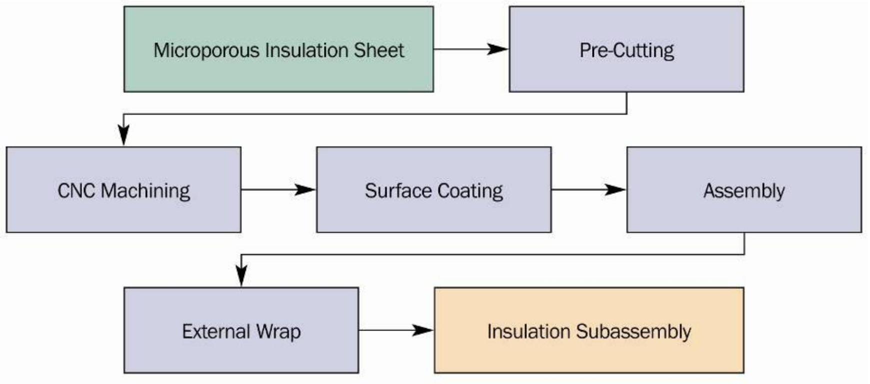


Figure 6-25: Insulation process flow

The only manufacturing method available to the industry is machining. Machining microporous insulation is extremely challenging. The mechanical properties of Microtherm® are akin to a dried sand castle. While the material will hold its shape with careful handling, it is extremely low strength and friable. Current machining processes require specialty CNC machine tools with sealed spindles, enclosed machining volumes, and HEPA dust collection. The machining process must be isolated from other manufacturing areas to avoid cross contamination. This subtractive forming process, like machining, reduces a majority of the expensive insulation board into waste.

The final machined part must then be encapsulated with a surface coating to capture surface dust from the machining process or dust release during subsequent handling or operation. Once the individual machined pieces are hand assembled an external wrap of fiberglass, sheet metal, foil, or other material is applied to create a sealed or partially sealed final unit. The external wrap is especially important for insulation which will be subjected to excessive vibration in applications such as transportation (e.g., long haul trucks).

Gaps and Issues

Dry press tool design and processing methods are not currently available for microporous insulation in forms with sufficient fidelity or component size for the solid oxide fuel cell industry. Casting methods and casting capable materials for microporous materials have not been developed.

Recommended Best Practices

- **The proposed processes are pressing or casting operations.** The technology does not exist today to dry press microtherm materials into components more complex than a sheet or clam shell. The recommended manufacturing practice is a process capable of creating a net shape or near net shape microporous insulation part. Using tooling to create the component geometry instead of subtractive machining processes, it will be possible to achieve the lowest possible raw materials cost per insulation component. The pressing or casting operation should include die or mold features to create pass through holes for electrical and fluid connections.

6.4. PROPOSED PROJECTS FOR CERAMIC

6.4.1. Protective Coatings for Metallic Stack Component

Metal stack components in the hot zone need to be coated to reduce thermal cycling degradation and to prevent the spread of chromium to the active regions of the cathode. While some components can be coated with a non-conductive layer, the tubular wire interconnect, and the planar interconnect face and mesh current collectors need to have an electrically conductive coating. This project will establish an inexpensive, high throughput coating method and QC inspection techniques to replace the use of expensive metals such as silver or gold.

Problem Solved (Gap)

- Need to eliminate expensive alloys used to prevent corrosion

Benefits Derived

- Reduce cost by enabling the use of inexpensive alloys for the interconnect components
- Reduce cost by replacing currently used silver with less expensive metal alloys
- Improve stack durability by limiting corrosion and the concomitant release of volatile chromium species that lead to poisoning of SOFC cathodes

- Improve stack durability by stabilizing corrosion products against spallation that is a common source of thermal cycling degradation.

Resources Needed

- Projected investment of $5.3 M

Timeline to Completion

- Two years

6.4.2. Defect Free Electrolyte Layer

This project will establish high-throughput manufacturing processes to apply uniform and repeatable thin (~10 µm) electrolyte coatings and develop inline inspection and QC procedures. From several potential deposition methods identified to deposit thin films, a single process will be selected that best achieves film specifications.

Problem Solved (Gap)

- Reduce the high cost of SOFC cell components through the use of automated production and in-line testing

Project Description

- Establish high-throughput manufacturing processes to deposit flaw-free, thin (~10µm) electrolyte films on tubular and planar SOFC anode substrates

Benefits Derived

- The cost of cell components can be reduced by efficient use of capital equipment
- Critical flaws can be identified and separated from the production line before the value-added sintering process
- $460/kW savings for a tubular SOFC system capable generating 500 W to 10 kW

Resources Needed

- Project investment of $1.3 M

Timeline to Completion

- One year

6.4.3. Manufacturing of Low-Cost, High-Efficiency Insulation Package

There exists a need across the entire SOFC industry for a low cost net shape or near net shape forming process for high performance insulation materials. This project will capture the best practices from outside the fuel cell industry and develop a scalable and repeatable method for low cost manufacturing of SOFC insulation that reduces cost by more than 50%.

Problem Solved (Gap)

- The raw material waste stream from the currently used machining operations can be as high as 80%

Benefits Derived

- Reduce the cost of SOFC insulation subassemblies by developing and validating a scalable, single step, net shape forming process to transform low cost raw materials into final components

Resources Needed

- Project investment of $2.4 M

Timeline to Completion

- Two years

6.4.4. Solid Oxide Fuel Cell Automated Assembly

For cells and stacks, proper alignment and registration of the individual parts are critical to maximize performance and minimize stresses. Automated pick and place stacking equipment will add consistency to stack component position, registration, and variation. Automated assembly solutions should be implementable for both tubular and planar SOFC cell systems.

Problem Solved (Gap)

- The need for stack quality, repeatability, and yield in high volume production, stack assembly will require increased automation as volume levels increase

Benefits Derived

- Increased reliability, repeatability, and quality
- Savings of $450/kW for planar solid oxide fuel cells

Resources Needed

- Project investment of $2.9 M

Timeline to Completion

- One year

6.4.5. Solid Oxide Fuel Cell Stack Manufacturing, Commissioning, and Testing

Stack acceptance testing conducted on the as-built stack can typically can take up to 48 hours. A high-rate and high-utilization processes is needed to increase the throughput and utilization of stack manufacturing capital equipment.(i.e., seal conditioning, anode reduction, and electrochemical acceptance testing.

Problem Solved (Gap)

- The process of commissioning the stack (making it electrochemically active) and completing the requisite acceptance testing typically can take up to 48 hours
- The stands tend to be expensive capital items, due in part to the stack build requirements and to the testing requirements

Project Description

- Establish high-rate, high-utilization processes for (1) seal conditioning; (2) anode reduction; and (3) electrochemical acceptance testing

Benefits Derived

- Increased throughput
- Savings of $900/kW for planar SOFCs

- Savings of $300/kW for tubular SOFCs

Resources Needed

- Project investment of $4.3 M

Timeline to Completion

- One year

6.4.6. Net Shape Manufacturing of Stack Manifolds

Stack manifolds, referred to as “endplates” for planar stacks and “plenums for tubular” stacks, are currently made using time-consuming and wasteful machining methods. This project aims to identify and validate economical net-shape manufacturing processes for SOFCs.

Problem Solved (Gap)

- Stack manifolds currently are manufactured using expensive machining methods

Benefits Derived

- A substantial reduction of stack cost when manufacturing volumes increase

Resources Needed

- Project investment of $2.7 M

Timeline to Completion

- 1.5 years

6.4.7. Powder Acceptance

Ceramic cathode powder characterization techniques are needed that could determine the electrochemical activity of powder, without making and testing a sample fuel cell to validate each powder lot. This project focuses on developing quality control methods that can be used at the powder manufacturer or at fuel cell fabricators to ensure that acceptable ceramic cathode powder lots are produced.

Problem Solved (Gap)

- Many types of ceramic powders, with varying degrees of consistency, are used in the manufacture of solid oxide fuel cell electrolytes, anodes, and cathodes. The bulk of the reproducibility issues occur with the oxygen electrode or cathode powders. The requirement for consistent cathode powders is a significant need.

Project Description

- Develop powder characterization technique to determine the electrochemical activity of the powder, without requiring the time-consuming process of making and testing a fuel cell to validate the powder.

Benefits Derived

- A set of quick and inexpensive evaluation tests (3-4 hours) for ceramic electrode powders replace what is currently a full weeks effort

Resources Needed

- Project investment of $1.5 M

Timeline to Completion

- One year

6.4.8. SOFC Current Collection

The overall objective of this project is to fully automate the application of the current collection system upon tubular SOFC. The present methodology involves hand wrapping wire along the tube length which leads to issues with quality and cost.

Problem Solved (Gap)

- Present best practice for application of tubular current collection solutions involves the hand wrapping of wire along the tube length with time consuming wire anchoring operations at the start and finish of the wire wrap. This application process is labor intensive, creates significant scrap or rework and in addition does not generally provide a uniform and repeatable current collection solution.
- With tubular systems, the conductive path length is considerably longer than in a planar stack, therefore ohmic losses (resistive losses) in a tubular SOFC are typically the dominant loss mechanism.

Benefits Derived

- Eliminate 95% labor from the current collection application process through automation.
- Improve the quality of the applied current collection layer through ensuring uniform repeatable coverage of the cathode and effective termination of the wire at the start and finish of winding.
- Improve cell robustness to thermal cycling through application of the current collection at uniform tension.
- Eliminate the re-work and scrap associated with the incumbent wire winding process.

Resources Needed

- Project investment of $2.2 M

Timeline to Completion

- Two years

7. Balance of Plant

General Introduction

Balance of Plant (BoP) consists of the remaining systems, components, and structures that comprise the complete fuel cell system. It would require a separate book if every balance of plant component of every fuel cell system of interest to DOD was detailed from a current and best manufacturing process standpoint. It would also be unproductive, as these components are often COTS items with a high TRL and MRL for their intended application. In other words, they already represent the best manufacturing practice and no further discussion is needed. With increased volume of fuel cell sales, fuel cell companies will have the leverage to tailor many of these BoP components for various fuel cell systems. Until then, fuel cells companies will continue to leverage components developed for other markets.

Rather than cover as many as 400 individual balance of plant components across dozens of fuel cell systems; it was determined that the most effective approach is to discuss it within the framework of the five functional areas that comprise the balance of plant. In the polymer section, balance of plant is composed of five major subsystems.

- Mechanicals and Packaging
- Power Management
- Controls
- Thermal Management
- Reactant Management

This taxonomy for balance of plant is shown in **Figure 7-1**. Two of these five major subsystems, Mechanicals and Packaging and Controls, do not lend themselves to further investment from the fuel cell community. Conversely, Thermal Management, Power Management, and Reactant Management have been identified as significant focus areas for manufacturing improvements. Within these three subareas, a particular emphasis on thermal and reactant management will be discussed in detail. Thermal management areas include lightweight heat exchangers for UAV applications and the need to reduce the overall cost of heat exchangers for fuel cells. Reactant management includes fuel processing, fuel and oxidant delivery, and water management. Each of these subareas are in need of further improvements, particularly fuel and oxidant delivery.

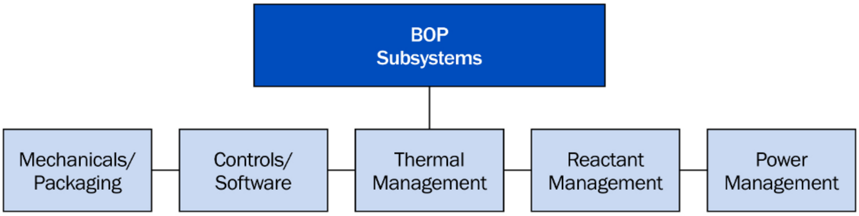


Figure 7-1: Balance of Plant

In fuel cell Balance of Plant (BoP), the predominant baseline practices involve a combination of adaptive COTS and designed components. The general rule of thumb is to first try to identify a COTS application that works. Failing that, try to adapt a COTS component to the fuel cell requirement; and if neither is possible, custom design the component.

Mechanicals and Packaging baseline practices are considered sufficient to meet DOD and civilian fuel cell needs. This is also true for Controls. Both of these BoP areas have well established manufacturing practices and there is very little additional adaptation required to meet fuel cell requirements.

Power Management represents between 11-20 % of the BoP cost drivers. COTS products from similar applications continue to be selected. Increased volumes of fuel cell orders are necessary to drive COTS electronics suppliers toward developing products specifically for fuel cells. One area of Power Management that requires further advancement is integration with alternative power sources from wind, solar, waste, or thermal energy systems.

Thermal Management, representing only 5-6 % of BoP costs, will be only selectively discussed for manufacturing improvements. Thermal management of fuel cells in lightweight applications require heat exchangers with reduced weight. Unmanned Aerial Vehicles (UAVs), for instance, will need these lightweight heat exchangers for increased range and loiter time. Heat exchangers are also a significant cost driver in fuel cell systems. They need to become more affordable in the future, as they represent a significant portion of BoP costs.

Reactant Management manufacturing practices are by far the key areas for improvement, as they represent the largest cost driver share (19-41 %) for BoP. These areas can be further subdivided.

- Fuel processing technology and manufacturing, with a detailed discussion on desulfurization of military logistics fuels (e.g., JP-8)
- Reducing the cost, size, and purification of reformates, including developing a process to replace existing pressure swing absorption (PSA) processes with membrane separation technology
- Transitioning from existing expensive tubular humidifiers to flat sheet planar humidifiers
- Minimizing fuel recirculation requirements wherever possible
- Using Design For Manufacture and Assembly (DFMA) techniques to match system needs with the right blowers, compressors, and pumps
- Developing more advanced and affordable water management systems

Because BoP is spread across so many fuel cell systems, it is critical to identify cost drivers across a smaller number of systems that are still representative of the fuel cell BoP at large. To that end, BoP cost drivers are addressed using three general fuel cell system applications: (1) 2-10 kW PEM autothermal reforming (ATR) natural gas (e.g., Tactical APUs); (2) 2-10 kW PEM direct hydrogen fueling BoP components (e.g.; material handling equipment); and (3) 500 W reformed methanol fuel cell (e.g., portable soldier power).

Military Perspective on Balance of Plant

The Balance of Plant can be defined as the peripheral and supporting infrastructure around the working fuel cell. The manufacturing issues around this topic will be given further consideration in the body of this report, but it is of considerable importance that BoP has a major impact on military performance requirements for power sources, because they are developed on the basis of application and user needs. While the major emphasis is on providing the warfighter with a power source that has the smallest size, lowest weight, and highest energy, the complete set of requirements are developed based on the operational and usage scenarios that the system is likely to be exposed during its transportation, storage, use, and disposal. These include the following considerations.

- The operating/storage temperature, altitude and humidity levels
- Exposure to shock, drop, and vibration during shipment and use
- Force protection – noise levels and thermal signature
- EMI/EMC interference with other soldier equipment
- Rain, dust, wind, and sand protection
- Thermal shock
- Water immersion

The above considerations are translated into a specific set of requirements that are typically communicated to systems developers and integrators. The ultimate objective is to ensure that systems survive these extreme conditions when deployed. The MIL-STD-810 test procedures covering all the categories listed above are requirements for fuel cell systems.

Conformance to MIL-STD specifications, also known as "system ruggedization requirements," imposes a number of constraints on the system design, packaging, materials, component selection, and the specific manufacturing process and tolerances allowed. For example, systems and platforms used in military applications have to operate at ambient temperatures that can range from −40 °C to +85 °C. This may require high performance insulation materials or the installation of an energy source (battery) to facilitate the operation at low temperatures. Products must also withstand extreme shock, vibration, humidity, and other challenging environmental factors. Special shock mounts may need to be incorporated in the design to absorb extreme shocks to the system. More often than not, the system developer or manufacturer will find that trying to accommodate the ruggedization requirements leads to a product that is heavier and larger than what is required by the military. In addition, ruggedization requirements almost always lead to higher cost for the BoP components as a percentage of the resulting final product.

7.1. COST DRIVERS FOR BALANCE OF PLANT

Introduction

The balance of plant encompasses all the components in the device other than the fuel cell stack. This includes pumps, blowers, filters, sensors, seals, fluid handling, electronics, and thermal management. These components account for as little as 40% and as much as 80% of the total system cost depending on the application. Lower power systems tend to have a higher cost component (relative to the fuel cell) associated in the balance of plant than higher power systems. One possible exception is in DMFC systems where stack costs continue to dominate.

Proper design, selection, and integration of balance of plant components is a key factor in the performance, lifetime, and cost of the power generation system. The Power Management subsystem consists of internal power conditioning, external power conditioning, electronics thermal management, capacitance, hybridization, and EMI protection measures. The Reactant Management subsystem contains fuel processing, fuel and oxidant delivery, and water management. The Thermal Management subsystem contains the cooling and heating equipment as well as heat dissipation devices. The Controls subsystem contains active and passive control and monitoring equipment. Finally, the Mechanical and Packaging of the system provides structure, mounting, and protection and is treated as another balance of plant component.

BoP Component Breakdown

The breakdown for BoP is as follows: Power Management, Mechanicals and Packaging, Controls, and finally Thermal Management. In the Reactant Management subsystem, delineations were made to focus on specific cost drivers. The generic Reactant Management system was further broken down into fuel processing, fuel and oxidant delivery, and water management components. Each of these components was determined to have a significant cost driver to the overall system. In the fuel processing subsystem, the major focus areas for cost reduction and advancement were identified as desulfurization and hydrogen separation. In the fuel and oxidant delivery system, it was determined that humidification (also included in the water management category), fuel recirculation, and oxidant delivery methods were significant cost drivers.

The second highest cost component was the Power Management system which was broken down into hybridization, internal power conditioning, external power conditioning, electronics thermal management, capacitance, and finally EMI protection. A focus area for the Power Management system was identified as integration with emerging and other alternative power sources.

Mechanicals and Packaging accounted for the next highest portion of BoP costs. Although this area is mature from a design perspective, some focus is spent on hardening aspects for passing military acceptance testing, such as MIL-STD-810.

The Controls component of the Balance of Plant was not identified as a significant area for focus on manufacturability cost reduction effort.

The last identified component of the BoP is the Thermal Management system. Although not a significant cost driver, it was determined that modest investments in advancements in design and integration of heat exchangers could result significant system advantages.

The breakdown, as shown in **Figure 7-2**, highlights each sub-area within the major components that requires additional development to meet cost reduction.

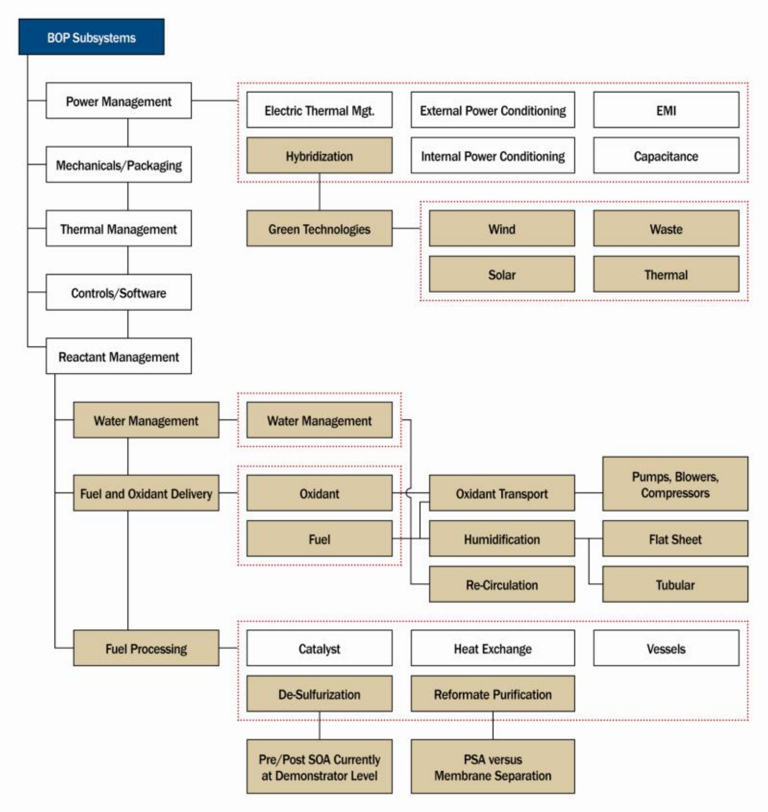


Figure 7-2: Focus area breakdown for balance of plant
(Brown highlighted sub-areas require additional development to meet cost reduction)

The best current practices for integration of balance of plant systems and components in polymer fuel cell systems focuses on elimination, and when possible, utilization of un-modified commercial components or systems. If elimination is not feasible, modified COTS components are used when necessary. Custom designed solutions are incorporated when COTS components are not compatible, fail to meet requirements, or cost or manufacturability drivers preclude their use in the system.

System designs that represent best current practices utilize well-known design principles for DFMA, lean manufacturing practices, and integration of quality checks in the design and manufacturing process.

Quality Assurance for BoP Components

The best candidates for manufacturing process improvement were determined by rating specific components by total cost and assessing that the potential for improvement was high. In some cases, specific components were selected if their costs were high even if the potential for improvement was only medium.

- **Design for Manufacture and Assembly** (DFMA) is a well-known analysis tool that calculates the cost to manufacture and assemble a component part by accumulating the time for the selected individual manufacturing steps on a complete design (catalogued with associated operating time) and applying company labor rates and burden. In this way, various approaches can be tried until the minimum cost is attained. As an example, the cost to machine a finished shaft from a rough casting would be determined by imputing the diameters of the original and desired part, material type and condition, surface finish, lathe or other material removal tool, material placement and removal techniques, and machine/labor/burden rates. The output would be the cost versus the manufacturing technique used.

- **Lean Manufacturing** is used by most mature fuel cell OEMs as their primary manufacturing philosophy in order to reduce capital investment, retain flexibility in configuration, and reduce or minimize manufacturing costs even at modest production levels. This approach is composed of many elements including: cellular/one piece flow, assembly teams, and various proven foreign assembly techniques such as taktzeit, poka-yoke, and Kanban. The essential principle is that a worker or a team of workers move the component through several assembly stations in the cell as it is completed. Generally, the final station has automated functional testing and quality control. All the parts and tools are available at each station for the step to be completed at that station along with “foolproof” instructions. In this way, low cost labor can be used. Production volume is increased simply by increasing the number of workers.
- **Six Sigma** is a well proven manufacturing quality control approach popularized by GE. At a 6σ level there are 3.4 failures per one million parts.

The fundamental gaps for the specific subsystems will be discussed in detail in later sections. The high-level gaps in this discussion relate to the level of use of simplification, DFMA, lean and Six Sigma practices in the industry. Short project timelines and low volume delivery of product reduces the implementation of these practices. Large investment in NRE, tooling and design optimization efforts are not compatible with short delivery schedules and small volume deliveries. Opportunities exist for advancement in these areas by commitment to acquisition of these power generation systems or increased market penetration. Current Best Practices, when utilized, offer appropriate levels of cost reduction and reliability for these systems. At the highest level, volume acquisitions of these systems offers the best path to further cost reduction.

7.2. REACTANT MANAGEMENT

Introduction

The Reactant Management System (RMS) is a closed system that catalytically converts hydrocarbon fuel and an oxidant (typically air, but in special applications pure oxygen, or LOX), to reformate, a hydrogen rich stream that may be pure hydrogen or a mixture with other components. After hydrogen leaves the RMS, it is delivered to the fuel cell stack where it is used to produce electrical power, heat, and water. Typically, fluids in the exhaust of the stack are returned to the RMS for use in the conversion process. The overall process removes non-hydrogen contaminants from the fuel as it proceeds in a step by step process until adequately pure hydrogen is produced. The Reactant Management System increases in complexity as the hydrocarbon fuel has a higher carbon fraction. Logistical fuels require the greatest number and complexity of components. There are a number of different arrangements for the individual process steps, including catalyst based reactors, mechanical separation, and heat exchangers, but all must lead to a low ppm level of carbon monoxide (CO). The most common process components are described below (not necessarily in sequential order).

- **Desulfurizer** - can be a physical or chemical separation device to remove the sulfur compounds present in hydrocarbon fuels, such as mercaptans, thiophenes, and sulfides. Sulfur acts as a poison to the fuel cell catalyst as well as several fuel processor catalysts. The desulfurizer can precede the reformer or follow depending on the design of the reformer. For steam methane reformers, the desulfurizer precedes the reformer because of the high reactivity of the nickel catalyst with sulfur. For autothermal reformers and catalytic partial oxidation reformers, the desulfurizer can either precede or follow the reformer.
- **Autothermal reformer** - is a catalytic reactor that converts the hydrocarbons into a syngas (H_2, CO, CO_2, N_2, H_2O, and trace amounts of CH_4 and other hydrocarbons). In order to accomplish the partial oxidation and steam reforming reactions, the reformer operates at very high temperatures, greater than 800 °C. The purpose of the remainder of the components is to remove the CO, trace amounts of HC, and reduce the nitrogen to the greatest degree possible. Sulfur compounds in the feed stream are converted to H_2S.
- **Shift reactor** -_is also a catalyst based reactor and enables the water gas shift (WGS) reaction ($CO + H_2O \rightarrow CO_2 + H_2$). The forward reaction is favored at lower temperatures so the shift reactors operate between 200 °C and 450 °C. The fuel processor will often have two different shift reactors: a high temperature shift (350 °C) and a low temperature shift (200 °C). The use of the WGS enriches the hydrogen content of the syngas.
- **Preferential Oxidizer** - operates at 100 °C to 200 °C and can further reduce the CO to the ppm level, but consumes hydrogen in the oxidation process.
- **Stack Anode Air Injector** - adds air to the reformed gas at stack temperature to reduce the CO level to the lowest possible value while minimizing the amount of hydrogen consumed.
- **Anode Tailgas Oxidizer** - the major heat source for the RMS generated by catalytically oxidizing the H_2 not consumed by the fuel cell and exiting in the tailgas.
- **Membrane Separator** - is a membrane in a plate frame construction that is permeable to only CO_2 and H_{2S} and therefore could separate out contaminants leaving an enriched hydrogen stream. When used in conjunction with a WGS reactor, it can eliminate the need for a preferential oxidizer by reducing the CO concentration.
- **Pressure Swing Absorber** - is a separator consisting of two or more vessels containing contaminant sorbents that alternately take up the CO_2, N_2, H_2S, and CO leaving pure hydrogen for the fuel cell stack. It eliminates the need for a preferential oxidizer.

In addition to utilizing the components described above, other conditions must be met by the RMS. Two overarching requirements must be satisfied in the RMS design.

- The components must be highly thermally integrated to have maximum use of heat energy.
- They must be able to respond rapidly to transients without degrading reformate quality.

These requirements flow down to all the components described above. Of these components, the desulfurization and reformate purification have been selected for detailed analysis of current and future manufacturing practices.

The three representative BoP systems, the material handling equipment (MHE), soldier power battery charger, and tactical auxiliary power unit (APU) have different system configurations to meet the performance specification for the application because they use different fuels (hydrogen, methanol, and JP8, respectively). **Figure 7-3** indicates the sequence of flow through the RMS - typical for gaseous hydrocarbon fuels for the purpose of understanding the function of the components and system before evaluating their current and best manufacturing practices for low temperature PEM fuel cell systems.

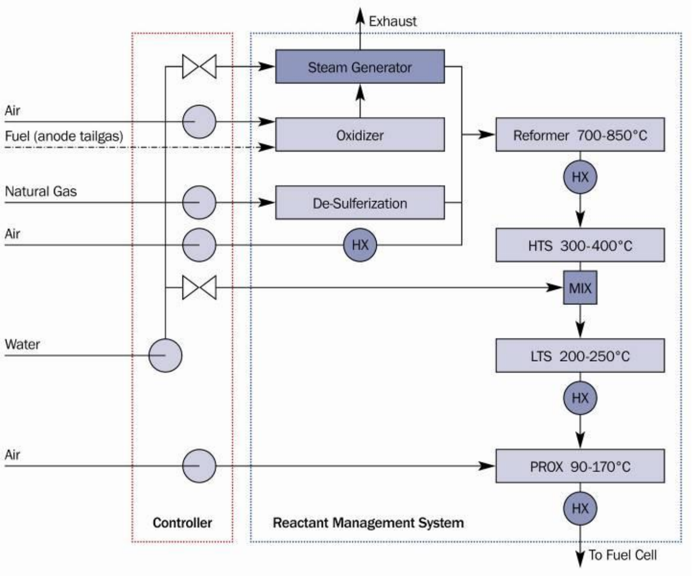


Figure 7-3: Gaseous flow through the RMS

Water Management / Humidification

Low temperature PEM fuel cell performance and life are improved if the humidity of the inlet fuel and oxidant stream to the stack is maintained at a high level. The flow of fuel and oxidant in these systems can result in net moisture being carried away from the stack via humidification of the fuel and oxidant streams exiting the stack, resulting in membrane “dry out” and loss of conductivity. Maintaining the humidity of the inlet reactants at a high level minimizes the loss of moisture from the Nafion membrane during operation, thus maintaining the proton conductivity of the membrane. Humidification of the inlet reactant streams can be easily achieved if an external source of water is available. However, for self-contained complete power system solutions where the use of an external water source is not an option, humidification is typically achieved by transferring water from the stack exit streams to the corresponding inlet streams. The balance of plant components that are used to accomplish this are referred as the water management subsystem.

Direct Methanol Fuel Cells also require a water recovery step in addition to the humidification of the inlet reactant streams. Water is recovered from the exiting cathode air stream and used to dilute the concentration of the methanol fuel. Maintaining the concentration of methanol fuel that is fed to the anode side of the stack below a threshold level is important to minimize “fuel crossover” across the membrane and maximize the system efficiency. The process steps that make up the water recovery system include condensation of the water in the exiting cathode stream and subsequent transfer of water to the anode feed side.

Current Best Practices

- In low temperature PEM systems the fuel and oxidant feed streams are pre-humidified before being fed to the stack by exchanging water vapor with their respective exit streams from the stack. The fuel and oxidant exit streams from the stack are typically at a higher temperature and saturated with water vapor when compared with the respective feed streams to the stack. Thus, a natural partial pressure gradient is available for water transport from the exit streams to the respective feed streams.
- Nafion membrane base separator modules facilitate the transport of water vapor from the exit stream to the feed stream without allowing mixing of other constituents in the streams.
- Tubular membrane based modules are readily available as COTS components (e.g., Perma Pure) in a variety of sizes and are commonly used in the industry for humidification.
- Planar membrane based modules in plate and frame configurations can be significantly cheaper due to the cost advantage of flat Nafion membranes over tubular Nafion membranes. However, flat membrane modules may be significantly larger due to the low active surface area per unit volume that can be achieved in this configuration. Flat membrane modules may also be more expensive than tubular membrane modules since they are not available as COTS components having to be custom designed and built.
- Water recovery is accomplished by using finned air-cooled heat exchangers where the oxidant stream exiting the stack is cooled. This results in the condensation of excess water vapor that is then fed to the anode fuel-mixing tank via a pump. The heat exchanger is typically located downstream of the membrane based module to capture the remaining water vapor in the oxidant stream.

Gaps and Issues

- Military fuel cells are required to perform over a wide environmental temperature performance range (typically -20 °C to +55 °C). At the high end of the ambient temperature range, the temperature differential between the exiting reactant streams from the stack and the feed streams is narrowed. In the case that the ambient humidity conditions are also high, the membrane surface required for water transfer in the water management module would also increase resulting in higher weight and cost.
- Similarly, the heat exchanger surface area needed for water recovery also increases resulting in increased costs. Lowering of the upper temperature limit for performance may reduce the surface area requirement for water transport resulting in lower costs for the water management module.

Recommended Best Practices

- Develop DFMA designs for the water management modules and use lean manufacturing Six Sigma principles in order to lower the cost of this sub-system. These guidelines are prescribed for both the flat membrane as well as tubular designs.
- Novel membranes are now available from European manufacturers that have properties that are similar to Nafion but significantly cheaper. DFMA designs need to be developed for these new membranes and the modules assembled and qualified for use in fuel cells.
- For water recovery, emerging best practices include development of microchannel or louver type finned heat exchangers that are designed for manufacturability. Fin designs and heat exchanger thickness can be optimized for cost and weight.
- Address the leakage that plagues the current designs. These can minimize the failure rates of these modules and expand their operating life. New robust designs and manufacturing processes are needed to minimize failure due to leakage. Process steps that can facilitate the identification of defective membranes in the manufacture of these modules can help in maximizing yields and promote long life operation.
- Current designs need to be examined for utilization of membrane surface area. The gas flow distributions in current designs may not be optimized for residence time resulting in significant over design. There is a significant opportunity to reduce the membrane surface area by designing and assembling the modules for maximum utilization of the available membrane area. Manufacturers of fuel cell systems have not invested the time and effort necessary to conduct statistically significant studies and generate empirical performance data that can be used to develop optimal designs for these modules.
- Development of high performance stacks that can operate at a lower stoichiometry will prevent water loss from the stack through evaporation, thus reducing the demands on water recovery and management.

Fuel and Oxidant Delivery Subsystems

The Fuel and Oxidant Delivery Subsystems consist of the pumps, regulators, valves and plumbing that supply the three required reactants to the fuel cell stack: liquid or gaseous fuel, air (i.e., gaseous oxidizer, but in special applications could be oxygen or LOX), and water, as shown in the top level of **Figure 7-4**. While the specific requirements and implementation of these components will vary according to the size, fuel and performance requirements of an application, three typical systems representative of military and commercial applications were considered for determination of potential for improved manufacturing practices: hydrogen powered material handling equipment (MHE) systems, methanol powered battery chargers, and liquid hydrocarbon (i.e., JP8) powered APUs. Although a multiplicity of other designs and implementation exist, these systems are representative of the components required for operation of polymer fuel cell systems. The major components and their function are described below and shown in **Error! Reference source not found.**.

- **Air pump(s)** supply and control the amount of oxidant flowing to the fuel processor and the fuel cell stack. Specific implementation may utilize one cathode pump, two pumps, or one pump and a regulator valve. These specific implementations vary by application and vendor since flow and control requirements differ among these systems and applications.

- **Hydrogen regulator** controls the pressure and flow of hydrogen from a pressurized tank to provide the desired amount of power. This is specific to direct hydrogen powered systems, as alternative pressure and flow methods may be used in reformed systems.
- **Anode tailgas (hydrogen) recirculation pump** returns the anode tailgas to the inlet of the stack for further use, increasing system efficiency and hydrogen utilization.
- **Fuel pump** supplies and controls fuel to the fuel processor to provide the desired amount of power. This is not required in direct hydrogen powered systems.
- **Water pump** can supply and control water to a humidifier, if needed.
- **Membrane Humidifier** - Water is supplied through membrane humidifiers to the anode and cathode sides of the PEM membrane to prevent dry out and hot spots, which could lead to stack degradation. Some systems are capable of eliminating one or both humidifiers in specific system configurations and operating conditions. Water may be provided as a liquid or as a vapor, and is typically recovered product water from system reactions.

The air pump and the anode tailgas recirculation pump were selected as the components of the Fuel and Oxidant Delivery Subsystem that could benefit most from best practices evaluation due to their cost and commonality in most FC systems, both military and commercial.

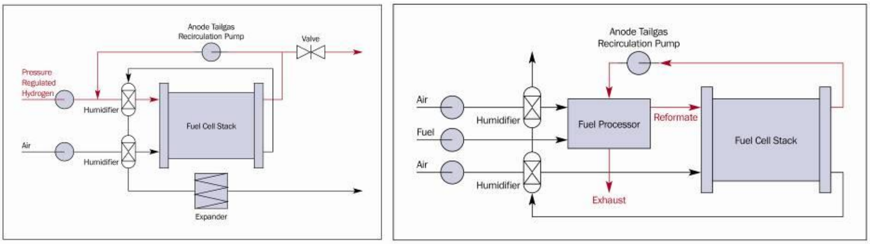


Figure 7-4: Simplified MHE and reformate fuel and oxygen delivery subsystem

7.2.1. Fuel Supply

Current Best Practices

- The baseline practice for this component is essentially the same as for the oxidant supply pump, but at a higher level of difficulty for hydrogen fuel. There are fewer vendors because the hydrogen pump market is smaller than the air pump market and there is a greater concern about the safe use of hydrogen. Further, compatible material choices are more limited due to sparking and hydrogen embrittlement and being more expensive. Safe sealing and product certification is a major concern and adds to the cost. Hydrogen pumps are specific to the MHE application.

Gaps and Issues

- The gaps and Issues for hydrogen pumps are similar to those for the oxidant pump except for those facilitated by the unique characteristics of hydrogen. The greatest potential for pump cost reduction of any considered opportunity is the use of a hydrogen ejector.

- It is expected that capital cost to establish a manufacturing facility would be lower than that for any other pump type. The liquid ring pump, because of its reduced tolerances, should be the second lowest manufacturing and capital cost.
- Both of these pump approaches are high risk, high payoff, and need further study and DFMA to assess true cost.
- There are fewer vendors because the hydrogen pump market is smaller than the air pump market and there is a greater concern about the safe use of hydrogen.
- Further, compatible material choices are more limited due to sparking and hydrogen embrittlement and being more expensive. Safe sealing and product certification is a major concern and adds to the cost. Hydrogen pumps are specific to the MHE application.

Recommended Best Practices

The best practices would be essentially the same as the current practices for the oxidant supply pump, but at a higher level of difficulty for hydrogen fuel. There are two additional practices specific to hydrogen and the water friendly nature of the membranes:

- The evaluation of a liquid (water) ring pump and the use of a custom designed ejector. If the technical benefits of this approach can be verified, a complete system analysis and DFMA to establish cost/benefit should be performed.
- Liquid ring pumps are essentially vane pumps in which the cylindrical rubbing surface for the vane would contact a ring of water that remains within the pump and rotates with the vane. Water vapor that condenses or micro-droplets that escape could be knocked out simply prior to the stack inlet.
- Ejectors are simple static devices that use the higher pressure of one liquid component to pump another component. A common example would be a steam ejector for pumping water. Of all the hydrogen pumping devices, this should be the least costly since there are no moving parts. Commercially available devices do not generally satisfy the specifications for fuel cell BoP critical parameters. Further design and analysis is warranted.

7.2.2. Air Supply

Current Best Practices

- Materials are often not compatible with fuel cell systems, so custom more expensive incarnations are required.
- In addition, the specified design range for the fuel cell application only partially overlaps the commonly available operating range for the applications for which the pumps were originally developed. Generally, a larger or higher powered version is used resulting in inefficient, bulky, or expensive components. Pump parasitic power is typically 10% or more of the system output and has a serious effect on system efficiency.
- System integrators utilize air delivery pumps that are primarily modified versions of available COTS components. These modifications are generally minor, such as changing the direction or location of an inlet or outlet connection since it is very difficult to modify the operating range of a pump without a complete aerodynamic redesign.

- An unintended consequence of the difficulty and lateness in establishing the pump specification and finding a best fit pump.

Gaps and Issues

- The market volume for fuel cells has not yet reached levels where pump suppliers are willing to invest in developing commercial products for the industry because their ROI is below acceptable levels.
- Component OEM suppliers and system integrators are reluctant to establish a class of blower optimized for the FC application due to associated costs and limited ROI.
- Stack and fuel processor air supply pumps are generally not built by the fuel cell system integrator. They are provided by suppliers according to a specification developed by engineering to meet the product requirements. The performance specifications for these devices are complex, since the pump must operate over a range of pressures and temperatures under both static and dynamic conditions, while meeting stringent parasitic loss budgets.
- The load curve is built on the resistances of many smaller subcomponents that will change over the lifetime of the product. This effect adds another degree of uncertainty that normally is addressed by making the specification more conservative. Eventually, critical parameters and tolerances will be developed.
- Two of the most critical parameters are pressure ratio and flow rate. Unfortunately, in most cases the pressure ratios approach 1.4, a higher flow rate than the operating point of common economical centrifugal pumps for non-facility applications. The result is that a more expensive positive displacement pump must be used. These pumps typically have rubbing or clearance seals that either require higher power or have limited wear capability.

Recommended Best Practices

- **Subcomponent Reduction/Simplification and Collaboration** - A significant cost reduction can be made through joint, open participation of component OEM suppliers and system integrators. This requires communication in a more integrated manner, earlier in the development process before individual subcomponent designs are finalized. Individual subcomponents should be methodically reviewed, their functions analyzed, and combined, if possible, resulting in fewer parts to handle. DFMA should be performed on the resulting subcomponent configuration.
- **System Integration** -_The reduced number of subcomponents, including pump, piping, instrumentation, and cooling valves that interact with the pump should be combined into a highly integrated modular package surrounding the pump with the fewest external connections and both mechanical and fluid integration.
- **Performance Map Flexibility** - Develop a mechanical design approach for the pump that would allow the pump to be modified to vary the performance map. This could be accomplished by designing the pump with an outer shell for strength and an inner liner and rotor/lobe/gear/etc. that can be easily replaced to tune the pump. Alternatively, a set of inserts or breakaway tabs could be provided that would change swept volume.

- **Family of Pumps** - Develop the critical parameters for a family of pumps (instead of just one) and establish the associated set of specifications so that designs can be specifically engineered of different capacities to cover the common operating range for the FC products. The NRE cost of having a custom positive displacement pump designed for each product would be dramatically reduced because the design costs would be spread over many FC products. This would be equivalent to the family of centrifugal pumps designs that range from radial to mixed flow to axial covering a broad range of specific speeds. Combining this approach with the performance map flexibility could yield even lower costs over a larger operating range for the industry.
- **Alternative Pump Types** - Evaluate alternative positive displacement machine designs (i.e., vane, lobe, liquid ring, scroll, and diaphragm) to become the technology foundation for a family of pumps.
- **Lower Materials Cost** - Examine potential alternative low cost materials (i.e., compatible plastics) for their ability to satisfy the pump cost, life, and durability requirements. Utilize data from industries that have similar operating environments and fluids.
- Improve interest in the FC market by convincing the pump suppliers to design and develop a family of devices that have a broader application rather than just one customer.

7.3. POWER MANAGEMENT

Introduction

Power management in fuel cell systems encompasses the practices around converting, storing, and providing electrical power to the system as well as to the system loads. Power management is a critical component in fuel cell system design and operation, without which fuel cell systems would be extremely limited in scope and application. For evaluation purposes, the Power Management component is divided into six major sections including: (1) electronics thermal management (converter losses = heat), (2) internal power conditioning (DC/DC conversion), (3) external power conditioning (DC/AC inverter), (4) capacitance (transient response), (5) EMI protection, and (6) hybridization (integration of battery, generators, and other renewable sources).

Electronics thermal management in the Power Management system provides removal of waste heat from power electronics. Electrical thermal management may be independent from other heat management in the system, or may integrate with other thermal management systems.

Internal power conditioning provides parasitic or house power to the balance of plant. Typically, this includes power conversion and intelligent flow of power from the fuel cell and hybrid energy sources in the system to the components.

External power conditioning converts the energy produced into the form needed for the application (regulated DC, AC, battery charging). This is similar to internal power conditioning, with the exception of a typically higher complexity and control for external power conditioning and delivery.

EMI covers electronic susceptibility and emission. Protection against transmission of electromagnetic interference and susceptibility to noise may be required in commercial, industrial, and military applications with various levels of stringency, with military needs being typically the most severe.

Capacitance and hybridization cover required peaking and system integration requirements and capabilities. These power sources typically provide start up power for the system, load leveling, and inrush current from loads.

These divisions are shown in **Figure 7-5**.

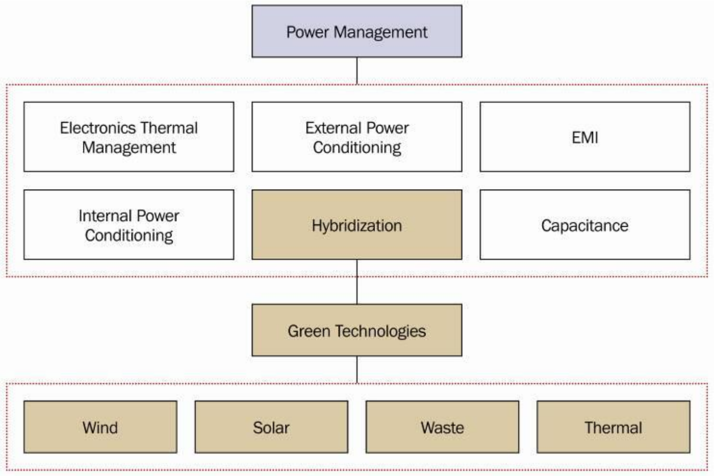


Figure 7-5: Power management system

Of special interest in the Power Management area, is hybridization with other power sources from both conventional and alternative areas. Technology in this area has been advanced in a variety of industries, including high volume manufacturing processes in the electronics industry. There remains a need for system design specifically tied to hybridization with alternative and emerging energy sources such as solar, wind, thermal, and waste electrical generation.

7.3.1. Power Management in PEM Fuel Cell Systems

Current Best Practices

- Use designs that incorporate unmodified commercial alternative energy systems to integrate alternative energy hybridization in polymer fuel cell systems.

Gaps and Issues

- Little to no technological advancement is required for these implementations, but investment in integrated system design and demonstration would show a path to cost effective hybrid power generation systems.

Recommended Best Practices

- Integrate other green and alternative technologies with fuel cell systems as part of an overall system implementation. Design concepts that fully integrate hybridization of additional renewable technologies offers a path to cost reduction on a per watt basis for both the fuel cell system and the alternative power generation method. Integration of these systems offers a part count reduction, removal of redundant components, and expanded system capabilities.

7.3.2. Power Management in Ceramic Fuel Cell Systems

It is typical to develop purpose-built SOFC fuel cell system power management hardware. COTS hardware available in the renewable energy industry generally is not leveraged because it lacks some critical features required for fuel cell system operation while at the same time having other features that are of no utility. Fuel cell systems have a variety of parasitic loads such as pumps, compressors, blowers, and controls that must be managed. Capacitance must be provided to accommodate in-rush currents from some loads, such as pumps and compressors, and it is typical to employ a hybrid system that can integrate battery, generator, and other renewable power sources into a single control system. This is particularly important given the delay in SOFC start-up and the need for controlled cool-down. Note that the power management sub-system discussed here is also often known as a Power Conditioning System (PCS), as shown in **Figure 7-6** from a DOE SECA program presentation.

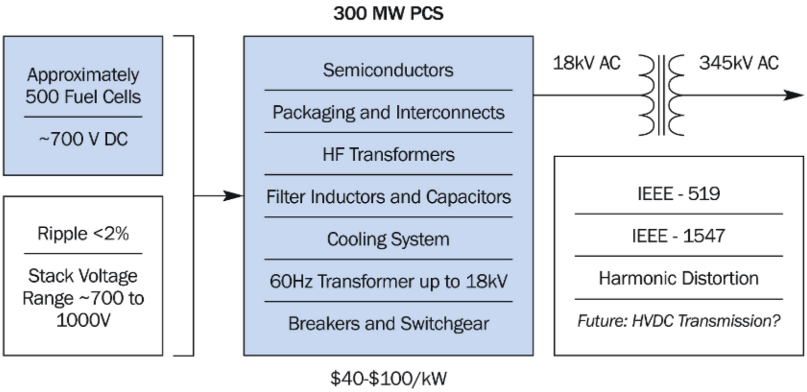


Figure 7-6: FC power plant requirements for high-megawatt PCS

Current Best Practices

- It is typical for companies to outsource some or all of the power management electronics. Many report performing in-house circuit design engineering, but then outsource board layout, component population, and in some cases testing. Others have outsourced the entire power management (or balance of plant electrical) subsystem but this can take years and several iterations to perfect such a partnership.
- Given the relatively high temperatures at which stacks operate and, in the case of transportation applications, the very hot environments these systems could be operated in, it is necessary to engineer components to

survive at under the hood temperatures of 105 °C with transient excursions as high as 125 °C.
- Maximizing power management circuit efficiency and minimizing losses are most critical for low power systems, as there is very little budget for parasitic losses or thermal rejection due to circuit losses. This also motivates custom engineered electronics in most applications.
- It is preferable to buy COTS components for the BoP wherever possible; however, current development methodology is to begin with the stack design and only later determine what components may serve in the balance of plant (BoP).

Gaps and Issues

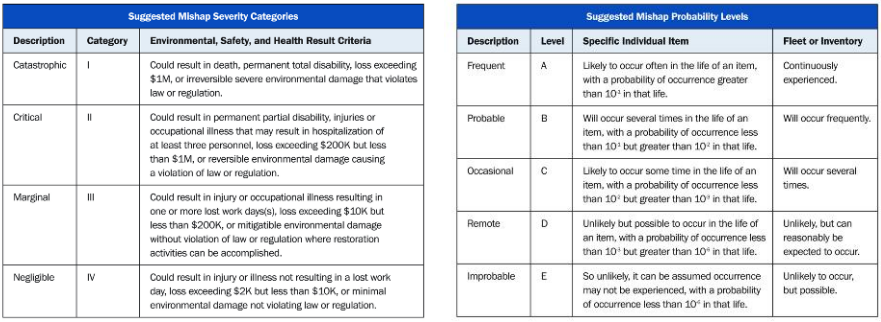
- New power conversion devices may drive the need for new manufacturing technologies, but it is too early to determine any cost implications from a manufacturing perspective. New technology will be needed to meet the aggressive cost goals (reports from the DOE Solid State Energy Conversion Alliance (SECA) program).
- Manufactured costs are high because of the reduced the number of inexpensive board-level COTS components (i.e., integrated circuits and discrete components) that are qualified for use in the electronics sub-system.
- In many cases, this results in the need for BoP components that do not exist or are not well matched to the requirements of the stack. This may increase costs or space claims of the power management sub-system.

Recommended Best Practices

- Pursuing a system level design approach to incorporate BoP components is a more cost effective method than modifying the fuel cell systems after they are built. In fact, while volumes remain relatively low, it may even be preferable to tailor a stack to the BoP components that are readily available in the commercial marketplace.
- Identifying power management circuits or sub-systems that may have alternate uses, for example in an uninterruptable power supply (UPS), may offer an opportunity to spread non-recurring engineering (NRE) costs over a wider product base and consequently reduce costs.

7.4. CONTROLS AND SOFTWARE

Controls and software are integral parts of fuel cell systems. The combination of control hardware, software, and safety devices is a driver in systems safety, reliability, and cost. Although not always a large portion of the cost of a system, hardware based safety can affect the bottom line in system expense, depending on design, implementation, and reliability. The same can be said for controls and feedback systems, where making measurement based decisions can increase the cost of the overall system. One example is measuring mass flow of the oxidant stream, and adjusting delivery based on this measurement. Calibration of flow curves offers an alternative method of flow control and eliminates what is a potentially high cost item (mass flow sensor/control) from the system. Elimination (or inclusion, when necessary) of safety systems should be based on known requirements (codes and standards) and well known safety analysis method like Failure Mode Effect Analysis (FMEA) and Hazard and Operability Studies (HAZOP). These studies are typically performed against the devices process and instrumentation diagram (P&ID). They typically call for redundant safety measures, where no single fault error can offer the significant likelihood of a significant hazard. The military uses a document that outlines the process for evaluating hazards in systems, MIL-STD-882 (Standard Practice for System Safety). Evaluation criteria for the standard are shown in **Table 7-1**.



Suggested Mishap Severity Categories

Description	Category	Environmental, Safety, and Health Result Criteria
Catastrophic	I	Could result in death, permanent total disability, loss exceeding $1M, or irreversible severe environmental damage that violates law or regulation.
Critical	II	Could result in permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, loss exceeding $200K but less than $1M, or reversible environmental damage causing a violation of law or regulation.
Marginal	III	Could result in injury or occupational illness resulting in one or more lost work days(s), loss exceeding $10K but less than $200K, or mitigatible environmental damage without violation of law or regulation where restoration activities can be accomplished.
Negligible	IV	Could result in injury or illness not resulting in a lost work day, loss exceeding $2K but less than $10K, or minimal environmental damage not violating law or regulation.

Suggested Mishap Probability Levels

Description	Level	Specific Individual Item	Fleet or Inventory
Frequent	A	Likely to occur often in the life of an item, with a probability of occurrence greater than 10^{1} in that life.	Continuously experienced.
Probable	B	Will occur several times in the life of an item, with a probability of occurrence less than 10^{1} but greater than 10^{2} in that life.	Will occur frequently.
Occasional	C	Likely to occur some time in the life of an item, with a probability of occurrence less than 10^{2} but greater than 10^{3} in that life.	Will occur several times.
Remote	D	Unlikely but possible to occur in the life of an item, with a probability of occurrence less than 10^{3} but greater than 10^{6} in that life.	Unlikely, but can reasonably be expected to occur.
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced, with a probability of occurrence less than 10^{6} in that life.	Unlikely to occur, but possible.

Table 7-1: Suggested mishap severity categories and probability levels
[Tables A-I and A-II from MIL-STD-882]

Generally, a hazard is defined as a characteristic of a system that offers a potential for accident. This may be a single event or combination of events that can happen during system quiescence, start up, operation, and/or shut down. The aim of FMEA and HAZOP analysis is to identify hazards and processes or designs that could reduce the likelihood or severity of the hazard. Typical safety systems in solid oxide fuel cell (SOFC) devices include:

- Combustible gas detection
- Overpressure relief
- Redundant valves
- Check valves
- Flow reduction systems
- Relays
- Pressure switches
- Redundant fuel and oxidant delivery

When feasible, safety and control systems should be minimized without loss of system fidelity or increase in hazard. Some loss in system fidelity may be acceptable, based on cost savings from simplification. Software based safety systems offer potential per unit cost savings, by eliminating expensive hardware based safety devices. However, software based safety systems may lead to requirements for integrated watchdog processing, and separation of safety software from control software.

Although a conservative approach to safety is prudent, existing codes and standards for safety and certification of fuel cell systems from bodies like UL, CSA, and CE often have more stringent requirements for fuel cell equipment than for traditional counterparts in industry. Many of the systems in fuel cell power generation devices closely mimic tried and true methods in industry, and the addition of extra safety measures often increases the cost of the system. In some cases, the additional requirements may reduce reliability; based on the addition of components (more failure points) as well as false positives in safety systems.

Current Best Practices

- Current best practices for integration of controls and software emphasize hardware elimination or replacement with logic controllers and software, to meet safety and standards needs.
- When software controls or electronics replacement for hardware solutions are not suitable, available COTS hardware should be used.
- When no equipment is available, utilize existing manufacturers for design of the required hardware.
- Custom, internal designs should be the last resort for integration into the system.

Gaps and Issues

- Current best manufacturing practices are not used across industry, often resulting in mechanical solutions when software is a viable safety solution.
- Education, along with codes and standards harmonization with existing industrial equipment codes, is a potential cost reduction solution by eliminating overly stringent requirements placed on the fuel cell industry.

Recommended Best Practices

- Current best practices are acceptable

7.5. MECHANICAL & PACKAGING

7.5.1. Ruggedization in PEM Fuel Cell Systems

Introduction

Fuel cell system design has typically focused on performance and cost. There has been less attention paid to ruggedization to meet the challenging requirements for military applications. As a result, fuel cell systems often fail to pass the environmental testing requirements of MIL-STD-810 and the electrical requirements of MIL-STD-462.

These standards were developed by the government to provide guidance and requirements for demonstration of the ability of equipment to survive the harsh battlefield environment that military gear is regularly subjected. The tests described are broken into methods and procedures which can be tailored to a specific application of equipment. This requires identification of the planned uses for all the equipment. For example, a stationary fuel cell system would not need to survive the drop and shock tests, but would need to be moved to the field via truck, plane, or helicopter. Based on this information, specific methods would be selected for evaluation of the system with chosen procedures that match the environmental condition experienced.

Current Best Practices

- **Identify the operational and test requirements** of the system and utilize good engineering and design practice to design and build systems to meet the test requirements. The systems are then tested and weaknesses identified and addressed. Retesting then demonstrates the efficacy of changes.

Gaps and Issues

- **Most fuel cell companies lack experience in the design, test, and redesign of systems to meet military requirements**. Often fuel cell systems focus on mass and volume reduction, which typically does not align with improvements in the ruggedness of systems. Opportunities exist to help align industry with appropriate government prime contractors and test labs to integrate military environmental and electrical requirements into initial system designs.

Recommended Best Practices

- Current best practices are acceptable for non-military BoP. Ruggedized BoP still requires improvements.

7.5.2. Fuel and Oxidant Delivery in Ceramic Fuel Cell Systems

The fuel and oxidant delivery subsystems consist of the pumps, compressors, regulators, valves and plumbing that supply required reactants to the system: liquid or gaseous fuel, air and water (when needed). While the specific requirements and implementation of these components varies due to size, fuel, and performance requirements of an application, three typical systems representative of military and commercial applications were considered: low power systems (<500 W), intermediate power systems (500 W to 10 kW), and high power systems (10 kW to 250 kW). Although a multiplicity of other designs and implementations exist, these systems are representative of the components required for operation of ceramic fuel cell systems (**Figure 7-7**).

- **Air filtering injection and metering (pumps, blowers, turbines, compressors)** clean, supply and control the amount of oxidant flowing to the system. Specific implementation may utilize one pump, multiple pumps, recirculation, or other methods of delivery.
- **Flow regulators** control the pressure and flow of fuel and oxidant to provide the desired amount of power.
- **Anode recirculation** returns the anode tailgas to the inlet of the stack for further use, increasing system efficiency and fuel utilization.
- **Fuel pumping** supplies and controls fuel to system. This is not required in gaseous fueled systems.
- **Water pumps** can supply and control temperature of liquids to heat exchangers and for recapture, if needed.
- **Heat exchangers & recuperators** provide heat transfer in the system.

The air injection and metering, liquid fuel pumping, and the anode recirculation were identified as the components of the fuel and oxidant delivery subsystem that could benefit most from best practices evaluation due to their cost and commonality in most FC systems, both military and commercial.

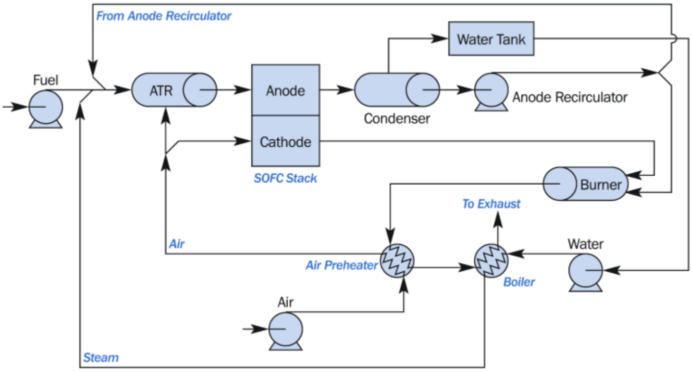


Figure 7-7: Mechanicals and packaging for a SOFC system

Current Best Practices

- Current best practices for elimination or integration of liquid (fuel) pumps, anode recirculation devices, and air movement equipment (turbines), utilize COTS equipment for integration into ceramic fuel cell systems whenever possible.
- COTS equipment that is not suitable for use is modified for integration.
- Use existing manufacturers equipment when specialized equipment is not available.
- Use custom, proprietary and internal designs.

Gaps and Issues

- **Existing solutions for ceramic fuel cell balance of plant components often suffer from the lack of matched equipment.** Typically, pumps, blowers, and compressors used in these systems were designed for a different application and modified to fit the fuel cell implementation, or were custom made for a specific system. Both of these paths will result in higher cost components than for those made as a commodity to fit an application.
- **Need to identify multi-use paths for designed components in these systems that allow design leverage and a path to cost reduction.** This would result in an advancement of manufacturing base for equipment needed for these systems. This has been undertaken to some degree with anode recirculation equipment for these systems, where it was determined that no pumps exist in reasonable packages due to inlet temperatures for the application (~800 C hot anode), but these pumps could also be useful in semiconductor manufacture and in industrial processing.

Recommended Best Practices

- Current best practices are acceptable, but could be improved with components designed for fuel cell applications.

7.6. THERMAL MANAGEMENT

Thermal management in fuel cell systems encompasses the heating and cooling of all system components, including stacks, electronics, and other generators and consumers of heat energy.

7.6.1. Thermal Management in PEM Fuel Cell Systems

Introduction

One area that can benefit from investment and advancement is lightweight heat exchangers that are designed to integrate with fuel cell systems. Technology in this area has advanced in a variety of industries, including high volume manufacturing processes in areas such as the automotive industry. There remains a need for heat exchangers designed specifically for fuel cell systems.

Heat exchangers for cooling PEM fuel cells in UAVs must be customized for each vehicle, as compatible off the shelf heat exchangers do not exist. Typically, heat rejection for PEM fuel cells in UAVs requires a liquid cooling loop and an ambient air stream heat exchanger. This increases the aerodynamic drag of the vehicle and must also be lightweight to maintain performance. The typical solution is to use heat exchangers made entirely of aluminum. Aluminum provides the best trade-off of thermal conductivity and material density for this application. The limiting factor for performance is the total surface area on the air side of the heat exchanger since the heat transfer coefficient is much lower on the air side than the coolant side. A folded fin structure that is brazed to the coolant loop is typically used to maximize available air side heat transfer area, much like a radiator for an automobile. The heat exchanger is also customized for the size and shape of the UAV and to minimize weight.

Another area for heat exchanger development is to minimize corrosion. The heat exchanger can corrode on both the inside or outside. This can be mitigated by coating the inside with an impervious coating like Parylene coating and by anodizing the outside.

Current Best Practices

- The current best practices for heat exchangers in polymer fuel cell systems eliminates their use when possible, utilizes un-modified commercial heat exchanger systems if elimination isn’t feasible, modifies COTS components when necessary, and designs custom solutions when the other options are not viable.

Gaps and Issues

- The primary existing gaps include material compatibility of COTS devices, effectiveness, mass, and volume considerations. Often, COTS heat exchangers fall short in one or more of these areas. There exists an opportunity for investment to stimulate fuel cell system developers and heat exchanger OEMs to collaborate on improvements. This is of elevated importance in UAV systems, where mass and volume are critical drivers to flight times and payloads. Designed integration into UAV and other systems offers an opportunity for cost and complexity reduction, while improving reliability and performance for the described systems.

Recommended Best Practices

- The best practice for fuel cell system designers is to use COTS heat exchangers, leveraging DFMA, design experience, and volume manufacturing in industrial heat exchanger manufacture.

7.6.2. Thermal Management in Ceramic Fuel Cell Systems

Introduction

Heat exchangers are required components of the solid oxide fuel cell (SOFC) power generation system. They are used to pre-heat the fuel and oxidant streams, to maintain the temperature of the stack, and to enhance overall thermal efficiency. With liquid fuels, heat exchangers vaporize the liquid prior to reforming to achieve good mixing and avoid coking.

Operation of the SOFC stack requires balancing of heat generation from electrochemical reactions with heat removal through three mechanisms – heat loss to the surroundings, convective losses to the flowing streams (anode and cathode), and cooling due to endothermic reforming.

Convective cooling is the main mechanism for heat removal from the stack (mainly cathode side excess air). The temperature rise due to convective cooling is limited, generally to about 150 °C, due to the operating characteristics of the stack. Heat recovery requires efficient high temperature recuperators with associated cost, weight, and volume impacts to achieve small approach temperatures.

Heat for incoming air and anode recuperation can be recovered from the convective cooling streams from the stack itself, from the partial oxidation (POX) reformer, and from the anode tailgas oxidizer. **Figure 7-8** shows a typical SOFC system flow diagram that includes anode recycle.

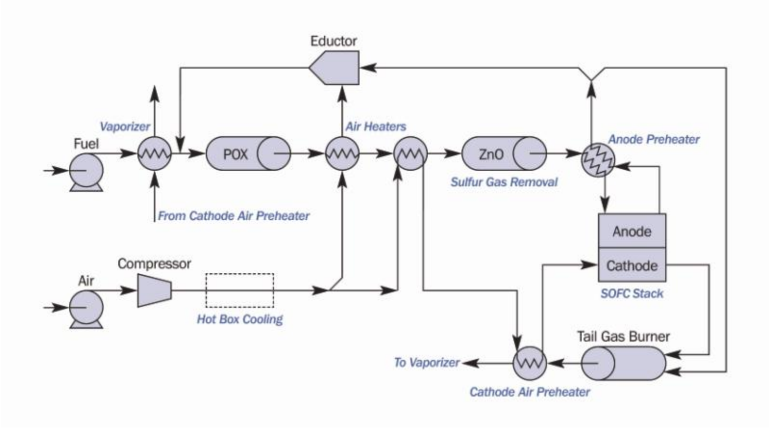


Figure 7-8: SOFC system flow diagram

Current Best Practices

Manufacture of plate-fin heat exchangers is an established practice, with numerous firms qualified to perform the required services. The manufacturing steps for a plate-fin 'compact'-type heat exchanger are as follows:

- HX design and materials selection
- Plate, fins, and frame fabrication
- Jig design and construction
- HX stacking with braze alloy (alternate, stack for laser welding or diffusion bonding)
- Braze in furnace (or weld), under inert or reducing atmosphere
- Cool, remove from jig, and leak test

Until manufacturing quantities ramp up, current practice is recommended for construction of heat exchangers for SOFC power systems.

- The preferred heat exchange design is a plate-fin type, providing high performance in a small package to maximize system performance. Depending on the high temperatures involved, the construction is brazed, welded, or diffusion bonded with no 'soft' seals that can deteriorate and leak at high temperatures.
- The heat exchanger can be a COTS component, but it is more typically a custom designed and manufactured component. Alternate designs include brazed plate-frame and finned-tube heat exchangers. Soft sealed plate-frame can be used when temperatures allow.

Gaps and Issues

- Issues for SOFC heat exchanger construction include material selection and method of fabrication. Materials are typically low-alloy corrosion-resistant materials. Due to SOFC sensitivity, chromium evaporation must be avoided, so alloys that form passivating layers with no chromium content are preferred.

Recommended Best Practices

As production rates increase, automation will become cost effective for the component fabrication, stacking, and welding processes, and should result in reduced manufacturing cost. Plate-fin compact heat exchangers are a good choice for the smaller and medium power portable and mobile applications where system volume and high performance are required. Less expensive plate-frame and shell-tube heat exchangers are good choices for stationary applications where volume is not critical and cost is more important.

Research efforts to improve heat exchanger performance and reduce costs are described below.

- An alternative to the plate-fin design is the microchannel heat exchanger design. These can offer 1 to 2 orders of magnitude size reduction from typical (shell-tube HX) volumes, and can be half the volume of compact (plate-fin) heat exchangers [1,2]. These are currently under development under a DOE SECA project.
- Projects need to be developed for cost effective and durable high temperature recuperators that are suitable for SOFC/GT hybrid systems. Manufacturing processes include laser cutting, electrochemical machining, and laser welding.

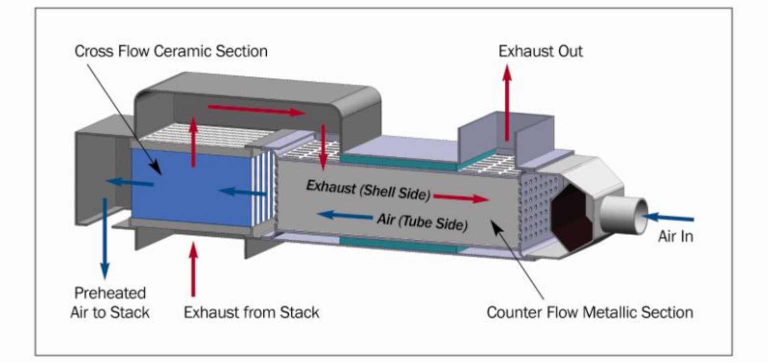


Figure 7-9: Ceramic/metallic heat exchanger system
[3]

- Due to the high temperatures involved in the operation of SOFC systems, a novel ceramic/metallic hybrid heat exchanger is under development (**Figure 7-9**) DOE SECA reported benefits include low cost materials, modular manufacture, reduced temperature gradients, reduced fouling oxidation, and lower cost. [3]
- In fuel cell systems, aluminizing, which forms an electrically insulating surface oxide, should be applied to piping to prevent a coking reaction and chromium migration. The aluminizing coating should be developed and applied to the extended surfaces internal to a heat exchanger.
- Mg-Al-spinel coatings are effective in preventing Cr migration from metallic separation plates in SOFC cells.

7.7. BALANCE OF PLANT SUMMARY

The military has encouraged the use of COTS components to minimize costs in systems. The industry has responded by making available many COTS BoP components that conform to military standards, like pumps and blowers. However, the key challenge for the system integrators is to ensure that packaging these components leads to a complete system that will conform to requirements. Special mounting and packaging requirements are needed to ensure that the final system will pass the MIL-STD tests that have been specified. Testing for conformance at the component level can prove to be prohibitively expensive for the system integrator. Instead, conformance to MIL-STD requirements is typically verified when the system is developed to a TRL 5-6 level. The system is subjected to the test protocol for each of the MIL-STD tests and the results are recorded. Testing can be done by the contractor at a certified test facility or conducted by the government. The results are communicated back to the system developer who can incorporate the findings in future design iterations and further advance the maturity of the system.

Once the systems have been qualified to conform to the performance parameters and ruggedization requirements in the laboratory environment, they are tested in the field by the military users. This allows the user the opportunity to operate the power system in actual use conditions and provide feedback on such things as size, weight, and ease of use. The system integrator can then further refine the design.

Each stage of development and testing as described above is important and helps progress the system towards procurement. Due to the stringent performance requirements of most military applications, somewhat higher costs can often be tolerated. The ultimate cost will depend on the nature of the application, the competing incumbent technology, and the military advantage a new leading edge technology can provide to the warfighter.

7.8. PROPOSED PROJECTS FOR BALANCE OF PLANT

7.8.1. Manufacturing of Low-Cost, High-Efficiency Heat Exchangers

At present, there is no defense industrial base for heat exchangers suitable for fuel cells. Fuel cell manufacturers modify COTS heat exchangers or design and build heat exchangers customized for FC systems. Component durability in the high temperature oxidizing environment is of particular concern. In low volume production, expensive tooling costs limit advanced forming options, and assembly is entirely by hand and often includes time consuming braze material application or highly skilled hand welding. This project will use system integration, application of volume production methods, DFMA, and lean manufacturing to produce low cost heat exchangers that use optimized materials and designs for fuel cells.

Problem Solved (Gap)

- Present heat exchanger systems are expensive and bulky and not optimized for fuel cell design.

Benefits Derived

- Cost optimized heat exchanger design and manufacturing process that will significantly reduce cost while simultaneously increasing reliability and process yield.
- Ceramic heat exchanger cost reduction of 80%.
- Polymer cost reduction of 40%. Savings are less due to the more mature nature of the available polymer heat exchangers.

Resources Needed

- Project investment of $2.0 M

Timeline to Completion

- Two years

7.8.2. Manufacturing Improvements for Liquid Flow

(A) Improvements for Liquid Metering Pumps for Sub-Kilowatt Reformer Based FC Generators

Liquid metering pumps specifically designed for fuel cell applications are generally not available. Few adequate pumps exist, and those that do are borrowed from other specialized applications and industries often at high cost. The project will reduce the cost of precision metering pumps by reducing the cost of manufacturing associated with close tolerance gear pump designs. Specific attention will be paid to fuel cell specific applications. The output of this project will be a pump design, assembly procedure, and process for manufacturing high precision pumps.

Problem Solved (Gap)

- Few commercial off-the-shelf (COTS) metering pumps exist to meter liquid accurately with the low pulsation critical to feeding liquid fuel to reformer based fuel cell systems and those that do are very expensive.

Benefits Derived

- Reduce hand fitting and selection of parts by optical screening and automated pairing of closely mated parts. Use self-aligning designs where feasible.
- Cost savings of 70%.

Resources Needed

- Project investment of $800,000

Timeline to Completion

- One year

(B) Improved Liquid Flow Meters for Sub-Kilowatt Reformer Based FC Generators

Fuel cell systems operating on liquid fuels require liquid handling components to control flows to the reformer subsystem. This project will reduce metering subsystem costs to make a significant savings in the BoP budget. The output of this project will be a pump/flow meter design, assembly procedure, and process for manufacturing.

Problem Solved (Gap)

- Design for manufacture and assembly (DFMA) analysis needs to assess true cost of fuel and oxidant delivery systems. Present systems are costly.
- Commercially available devices do not satisfy specifications for critical parameters.

Benefits Derived

- Savings of 70%

Resources Needed

- Project investment of $0.9 M

Timeline to Completion

- One year

7.8.3. Improved Anode Gas Delivery Devices

Choosing an inexpensive COTS pump for anode gas delivery may satisfy cost targets, but the pump may fail prematurely or incur higher than anticipated maintenance costs. Expensive pumps may provide the performance and life expectancy, but quickly become the target for cost reduction.

This project will determine the best manufacturing practice to provide solutions to the issues currently faced by fuel cell/balance of plant integrators for anode gas delivery pumps. The resulting pump will meet selection criteria and lifetime cost will be minimized.

Problem Solved (Gap)

- Design for manufacture and assembly (DFMA) analysis is needed to assess the true cost of fuel and oxidant delivery systems. Present systems are costly.
- Not enough broad applications for pumps to justify a commercial off-the-shelf (COTS) version for fuel cell applications.

Benefits Derived

- Reduction of failures of balance of plant components
- Lower cost, simpler design, weight reduction, reduced failure of parts, higher reliability, higher quality, and a strengthened supply chain
- Cost savings \$44/kW to \$195/kW

Resources Needed

- Project investment of \$ 800,000

Timeline to Completion

- One year

7.8.4. Manufacturing Improvements for Fuel Cell Humidification Systems

In many fuel cell power generators, the humidification subsystem represents a meaningful cost factor. Advancement of humidification manufacturing maturity and techniques offers a path to cost reduction in both capital and operating costs for fuel cell systems.

Problem Solved (Gap)

- Large water transport needed for performance at upper temperatures, thus increasing size and weight
- Water leakage plagues current designs
- DFMA analysis needed to asses true cost of fuel and oxidant delivery systems, as present systems are costly

Benefits Derived

- Reduce rates of infant mortality, improved reliability, improved performance, extend lifetimes, and reduce costs associated with these humidification systems
- Cost savings of \$380/kW

Resources Needed

- Project investment of \$ 800,000

Timeline to Completion

- One year

7.8.5. Specification Analysis for Fuel Cell Power Systems

This project will develop a set of standards for fielding and installing fuel cell systems in commercial and military installations and missions. The project will provide guidelines for matching specifications to applications, and will reduce the over design and over specification issues that add cost to fuel cell systems. Further costs reductions will be based on environmental requirements (MIL-STD-810), electrical, and other alignments of requirements.

Problem Solved (Gap)

- Need integration of environmental and electrical requirements into system designs

Project Description

- Align specifications for military equipment to existing technology requirements, such as JP 8 generator sets
- Further decrease costs based on environmental requirements (MIL-STD-810), electrical, and other alignments of requirements

Benefits Derived

- Lower cost, better fit solutions for fuel cells power systems
- Provide guidelines for matching specifications to applications, and reduce the over design and over specification issues that currently plague fuel cell systems

Resources Needed

- Project investment of $0.7 M for sub kW
- Project investment of $1.1 M for 5 kW
- Project investment of $1.8 M for 10 kW
- Project investment of $1.8 M for 100 kW

Timeline to Completion

- One year

7.8.6. Manufacturing Improvements for Cathode Air Delivery System Pump Blower

This project will perform a comprehensive DFMA so features that add value and simplify the system build can be achieved without the high cost of modifying a COTS scroll air blower for fuel cell applications. By designing features into the blower, the extensive labor for hand fit-up and rework modifications to COTS is not required.

Problem Solved (Gap)

- Limited commercial availability for fuel cell suitable version – unique requirements depending upon size (noise, weight, volume, efficiency, heat, size, lifetime, leakage, reliability, pulsation)
- Cost (efficiency, reliability and quality trade off required)
- Close tolerances, gap clearance (cost to get clearance in smaller units – the cost of near net forming)
- Lack of integration of pumping and metering
- Pulseless flow requirement limits selection
- High speed balancing required

Benefits Derived

- A 50% reduction in the current unit manufacturing cost
- An increase in compressor electrical efficiency of 2 % to 4 %
- Simplification of the BoP by elimination of an additional system component (the flow meter) and its attendant positive impact on durability
- An increase in system efficiency
- A reduction in system weight /volume
- An overall increase in BoP quality control

Resources Needed

- Project investment of $1.1 M

Timeline to Completion

- One year

8. Fuel Processing

8.1. REFORMER

Reformers are part of the balance of plant but discussed separately due to the emphasis placed on reforming military logistics fuels. Reformers are catalytic reactors designed to react hydrocarbon fuels with steam and/or air. The process produces a reformate stream containing the desired hydrogen, along with methane, carbon dioxide, carbon monoxide and hydrogen sulfide (if sulfur is present). In addition, nitrogen (from air) and excess steam is present. To maximize hydrogen production and make the reformate suitable for the fuel cell, the reformate gas requires further processing to increase hydrogen yield, completely remove sulfur, and reduce the level of CO to less than 0.1 ppm. In some cases, gas separation technology is used to purify the hydrogen or remove the CO_2.

Current Best Practices

There are a variety of reforming technologies available for methane and light hydrocarbon fuels. It is more difficult to reform the heavier hydrocarbons preferred by the military. Autothermal reforming (ATR) using steam, air, and fuel, is the most compact method of hydrogen creation from hydrocarbon fuels. It is useful for systems requiring high power density and it provides good efficiency if not operated at high pressure (~2 atmospheres), since air compression reduces net power delivered. Autothermal reformers are at TRL-7 and MRL-6. The catalyst is typically supported on finely divided structured ceramic or structured metal supports.

Catalytic partial oxidation reformers (CPOX) are TRL-7 and MRL-7. They operate as fuel rich thermal reactors and are susceptible to coking. They form high levels of CO_x which must be shifted to increase hydrogen yield, requiring steam and temperature controlled shift reactors, effectively turning the CPOX process into an ATR process.

Steam Reformers (SR) are TRL 10 for methane and TRL 5 for JP-8, and are suitable for methane production or for larger fuel cells (>500 kW) due to their low outlet temperatures and bulky construction.

Plasma Reformers have been demonstrated to TRL-4 (MRL-1). They either have limited effectiveness (low temp plasma) or require high power electronics (high temperature plasma).

Reformers require welded metal housings for catalyst retention and support, and fluid penetrations for the various process streams.

Gaps and Issues

- Operating at high temperatures, the ATR requires expensive support and housing materials. Structured ceramics degrade in the presence of moisture (steam) and the metal supports are easily degraded by temperature excursions. High pressure operation is required for hydrogen separation, reducing net system efficiency.
- CPOX reactors are susceptible to coking, and operate inefficiently due to the required downstream processing. Like an ATR, CPOX forms high CO requiring shift to produce hydrogen. Due to high temperatures, they require internally

insulated housings, and a filter (susceptible to clogging) is required to prevent carbon migration.

- Steam reformers are suitable for methane production or for larger fuel cells (>500 kW). Since the heat must be transferred, they are peak temperature limited, resulting in high methane levels, decreasing hydrogen production. There is limited experience using steam reformers for heavier hydrocarbons.
- Low temperature plasma reformers are at a low R&D TRL, and high temperature plasma reformers are inefficient.
- Low volume reformer housings can be expensive due to extensive machining and hand welding operations.

Recommended Best Practices

Autothermal reforming appears to be the best choice for the high performance required for tactical applications. For operation of PEM fuel cells on methane, SR is a good choice if high temperature heat transfer materials can be utilized, or weight is not a factor. CPOX is a good choice for tactical applications if efficiency is not critical, since it eliminates the requirement for steam.

8.2. DESULFURIZATION OF MILITARY FUELS FOR USE IN FUEL CELL POWER SYSTEMS

Fuel cell-based power plants have the potential of providing electric power generation at significantly higher efficiency and lower exhaust emissions than generation alternatives. Unfortunately, both the fuel cells and the fuel processing system that converts logistic fuel to a hydrogen rich gas for the fuel cells are susceptible to degradation from the sulfur in logistic fuels. The additional equipment and energy required for sulfur treatment can significantly affect system performance in terms of increased weight and volume, and reduced efficiency. If not 100% effective, residual sulfur can cause complete failure of both the fuel reforming process and the electrochemical conversion process.

Current Best Practices

The preferred fuels for military operations are NATO F-76 Diesel fuel, and the turbine fuels JP-8 (Army) and JP-5 (Navy). These fuels can contain up to 3,000 to 5,000 ppm sulfur. Autothermal reformer fuel processors can tolerate several hundred ppm of sulfur, however the fuel cells can tolerate less than 1 ppm sulfur. Sulfur treatment falls into two general classes; pre-reforming treatment and post-reforming treatment. Pre-reforming treatment can be performed at the refinery (typically hydrodesulfurization) to ultra-low-sulfur diesel (ULSD) levels, or in the field with separate or integrated fuel processing units. Hydrodesulfurization is an energy intensive process and requires a source of hydrogen gas and bulky high-pressure catalyst and sorbent beds reactors for NATO F-76 or medium pressure reactors for JP-5. During the medium pressure/medium temperature testing of JP-5 containing 1100 ppm sulfur, system pressure could be reduced to 90 psig and still produce a fuel stream with <100 ppm sulfur. ZnO desulfurization alone without hydrodesulfurization was also successful for bulk sulfur removal and resulted in a fuel stream of ~200 ppm sulfur. [1]

Another option for pre-treatment includes fractionation, where the fuel is separated into light and heavy fractions, with most of the sulfur (typically 60-80%) remaining in the heavy fraction. The light fraction can then be further treated before entering the reformer. The heavy fraction can be used in a non-sulfur sensitive part of the process. This is only partially effective. After fractionation, the light end can be further treated by pi-complexation sorbents which absorb the entire sulfur containing fuel molecule. However, these sorbents are low capacity and require frequent regeneration.

Post-treatment (after reforming) involves removal of the hydrogen sulfide from the reformate stream. This is normally accomplished in a batch reaction over a metal oxide sorbent. The metal oxide must then be replaced when depleted, or regenerated in place for continuous operation. Zinc oxide is the preferred sorbent for the high steam-level reformate streams due to favorable equilibrium. Capacity can be up to 35% of sulfur by weight, however breakthrough occurs well before the ultimate capacity is reached due to mass transfer limitations. Commercial sorbent is reliable up to 5-10% sulfur by weight before breakthrough. Commercially available nano-ZnO increases the sulfur capture capability by 2½ times over standard ZnO. It is also able to withstand twenty-five regeneration cycles without performance degradation. [1] Lead-lag bed design, or layered (commercial-over-nano) ZnO beds can also enhance performance.

Gaps and Issues

Based on the results of the above described efforts, and additional efforts not discussed here, it is clear that the presence of sulfur is a major barrier to adoption of fuel cells for military tactical operations. Chemical treatment of fuel and reformate streams is possible and has been demonstrated in commercial processes or to Acquisition Decision Memorandum TRL levels. However, the negative effects on the power system characteristics cannot be overcome with current technology, making current sulfur tolerant (military) fuel cell designs difficult.

The selective membrane technology is at TRL-4 and needs to be improved to TRL-6 or greater. There are those who believe the military will eventually operate using a ULSD-type fuel, however, this is not the case today, nor will it be in the near future. It is recommended, if the military is to reap the benefits of fuel cell deployment, that a source of sulfur-free low flash point fuel be made available through the logistic supply chain.

Recommended Best Practices

From a fuel cell power system design standpoint, the best scenario is to have little or no sulfur in the fuel at the start of the process. This relieves the system of the burden of sulfur separation and elimination. Specialty fuels such as methanol, ethanol, and light petroleum gasses have very little sulfur, and can be treated with little effect on the power system hardware. However, these fuels are not preferred by the military for tactical power generation, and may only be suitable for special tactical applications such as battery replacement or battery charging. In non-tactical (domestic) situations, natural gas and ultra low sulfur diesel (typically < 15 ppm) can be used for a variety of fuel cell applications.

The selective membrane removes the H_2S from the syngas without removal of the hydrogen. Laboratory efforts have demonstrated removal from 100 ppm to less than 10 ppm.

8.3. REFORMATE PURIFICATION

8.3.1. Gas Clean up of CO and Hydrogen Generation for PEM Fuel Cells

Reduction of CO in reformed fuel is necessary for PEM fuel cell systems. For low temperature PEM fuel cells, poisoning of the fuel cell occurs at <4 ppm CO with a target of 0.2 ppm CO. Carbon monoxide is easily combined with steam by way of the water gas shift (WGS) reaction to produce hydrogen and carbon dioxide. The CO concentration in the gas stream is readily reduced from 10% to less than 1% by the WGS. However, the WGS processors do not reduce the CO concentration to an acceptable level (<4 ppm) for the low temperature PEM fuel cell. The WGS reactors do however, reduce the CO to acceptable levels for the high temperature PEM fuel cell. Three design concepts for the WGS reactor are Fixed Bed WGS reactor, Plate & Frame WGS reactor, and Microchannel Reactor.

Current Best Practices

The use of Fixed Bed WGS Reactor

- The manufacture of Fixed Bed WGS reactors is a mature technology. The design of the fixed bed reactor is a catalyst packed bed with heat exchanger tubes running through the packed bed. The manufacturing process is metal working; a metal reactor cylinder with small cylindrical tubes inside of the reactor cylinder. The inner tubes are heat exchangers to maintain the thermal balance which is critical for efficient conversion of carbon monoxide-water to hydrogen–carbon dioxide.

Gaps and Issues

The three WGS reactors have manufacturing issues consistent with their designs as discussed in the following.

Fixed Bed WGS Reactor

- **Proper location and distribution of the heat exchange tubes to maintain (or approach) isothermal operation is an important manufacturing issue.** The tubes are welded into a frame support and welded onto end caps to optimize alignment and distribution of the heat exchangers. The welding process is labor intensive and the fixture of the heat exchanger tubes is also labor intensive.
- **A drawback of the fixed bed WGS is the low turnover rate of the exothermic reaction.** As the temperature increases, the equilibrium shifts toward CO formation and the rate of reaction decreases. The low turnover rate requires excess catalyst that increases the size of the reactor.
- **Control of the temperature is an important factor and the design and manufacturing tolerances strongly influence the efficiency of the WGS reaction.**

Plate & Frame WGS Reactors

- **Present technology uses nickel brazing which has an operation temperature limit**. Welding of plate & frame WGS reactors is an alternative approach that needs additional development.
- **Automated assembly with automated welding stages is a necessary manufacturing transition** to low cost high performance plate & frame WGS reactors.

Microchannel WGS Reactors

- **Manufacturing of the microchannel reactors is a new challenge for the industry**. Early fabrication included photoetching of foils with lamination of the foils to form a microchannel plate. The foils are assembled into a microchannel plate by stacking alternating heating channel foils and catalyst channel foils. The microchannel plates are then stacked to form the microchannel reactor. The manufacturing method involves considerable handwork and is an area requiring manufacturing improvements.

- **Applying the catalyst coating to the assembled microreactor is very difficult** because an even distribution of the catalyst is difficult without localized buildup of the catalyst that would change the flow and thermal characteristics of the microchannel reactor. Over $100 million was (and continues to be) invested in research and development on microchannel reactors by the U.S. Department of Energy, Battelle Memorial Institute, and private investment.

Recommended Best Practices

Plate & Frame WGS Reactor

- Compact designs for WGS reactor designs for small PEM fuel cell systems turned to plate and frame heat exchanger concepts for the WGS reactors to optimize heat transfer. The WGS manufacturing process was greatly simplified with the change in design to a plate and frame heat exchanger. Development of automated, high rate welding and assembly process are critical manufacturing improvements for the plate & frame WGS reactor.
- For very large JP-8 fuel processing systems equivalent to several megawatts of fuel cell power, the production volume may be very low and the costs of installing a production line with automated catalyzed plate and frame heat exchanger assembly and welding could be cost prohibitive. The high volume production of the heat exchanger WGS reactor for smaller processors (less than 1 megawatt) will push down the manufacturing cost.

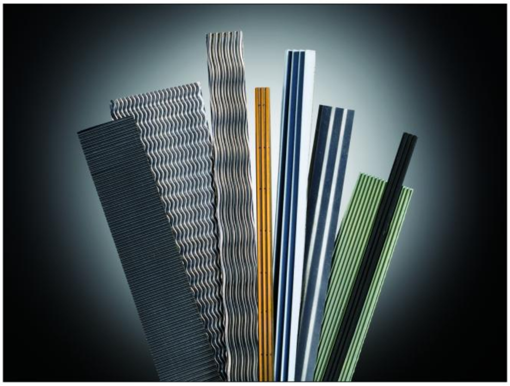


Figure 8-1: Ceramic/metallic heat exchanger system
[Courtesy Catacel Corporation]

Even with the better control of the heat distribution with the plate and frame heat WGS reactors, the low turnover rate for the reaction is not resolved. The catalyst content of the reactor is still large and the size of the plate and frame heat exchanger is dictated by the amount of catalyst. (**Figure 8-1** shows catalyzed heat exchanger plates and **Figure 8-2** shows a plate and frame heat exchanger reactor).

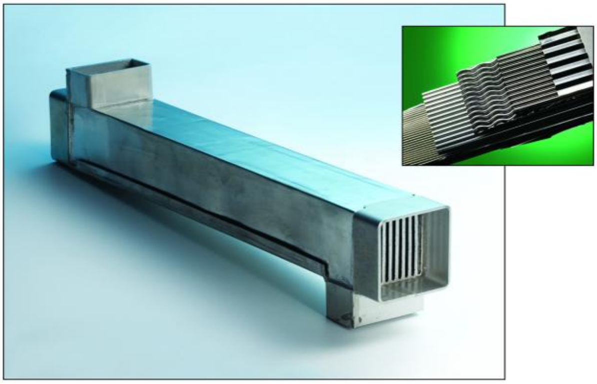


Figure 8-2: Plate and frame heat exchanger reactor

Microchannel WGS Reactor

- Continuing with the concept of optimizing the heat transfer properties of WGS reactors, Pacific Northwest National Laboratories pushed the heat transfer driven design to what may be a limit, the microchannel reactor. Microchannel WGS processes are accelerated 10 to 1,000 fold by reducing heat and mass transfer distances. The microchannel WGS reactor resolves the low turnover issue associated with the fixed bed WGS reactor and the plate & frame WGS reactor. Another benefit of the microchannel WGS is a reduction in the catalyst layer.
- Improvement of the manufacturing process for the fabrication of a microchannel reactor can be achieved through automation and the application of high rate processing technology developed for the electronics and semiconductor industry.

8.3.2. Ultra-Low CO Clean-up for PEM Fuel Cells

Additional processing is required to reach the ultra-low CO concentration for low temperature PEM fuel cells and three approaches are considered (**Figure 8-3**): (1) preferential oxidation, (2) membrane separation- water gas shift (MS-WGS), and (3) methanation. These clean-up methods have been developed to reduce the carbon monoxide content to less than 4 ppm and approaching the 0.2 ppm target proposed to the DOE.

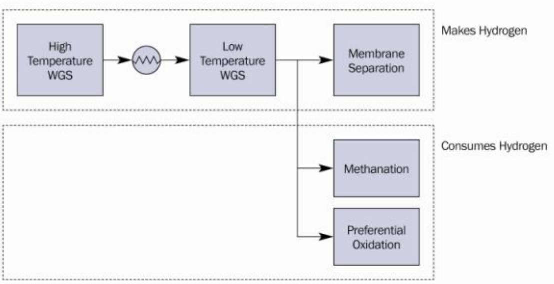


Figure 8-3: Schematic of carbon monoxide cleanup process

Preferential Oxidation

For low temperature PEM fuel cells, preferential oxidation attempts to preferentially react the carbon monoxide in the hydrogen stream with injected oxygen to form carbon dioxide. Unfortunately, hydrogen is also consumed at the rate of 4 hydrogen molecules for every carbon monoxide consumed.

The advantage of preferential oxidation is the simplicity of the reactor, with manufacturing process gaps consistent with the plate & frame WGS reactor. Control of the thermal distribution in the reactor is critical to prevent runaway of the hydrogen oxidation reaction.

Automated assembly with automated welding stages is a necessary manufacturing transition to low cost high performance plate & frame preferential oxidizer. A possible improvement could be the transition to the microchannel reactor design.

Membrane Separation-Water Gas Shift Reactor

Methods for shifting the equilibrium of the WGS reaction toward the formation of hydrogen can optimize the reaction of carbon monoxide with water and increase the hydrogen content in the reformer stream. By integrating the WGS shift reactor with a membrane that selectively removes the CO_2, the concentration of carbon monoxide can be reduced to < 4 ppm and approach 0.2 ppm. The membrane has additional capability to remove the H_2S.

CO reduction using the MS-WGS is at TRL-4; component/subsystem validation in laboratory environment. Manufacture of the membrane is laboratory based. A critical issue is that prototype membrane manufacture and prototype membrane separation module construction and testing are needed to advance to TRL-6.

Methanation

Methanation is a method to reduce the CO concentration to <4ppm in reformate feed for low temperature PEM fuel cells. Methanation catalysts are well established and designs similar to the plate & frame WGS reactor design are feasible.

Manufacturing gaps & issues are consistent with the plate & frame WGS reactor. Automated assembly with automated welding stages is a necessary manufacturing transition to achieve low cost high performance plate & frame selective oxidizers.

Selective oxidation is the current best practice for the final cleanup of the CO because it is well established and at a TRL-8, even though it reduces the efficiency of the fuel cell system because it consumes hydrogen. The recommended best practice is membrane separation integrated with low temperature WGS based on laboratory data and the ability to increase the hydrogen availability to greater than 97%. Methanation is not recommended because of the additional reaction of carbon dioxide with hydrogen to form methane. In addition, primary carbon monoxide methanation reduces the efficiency of the fuel cell.

8.3.3. Other Technology for CO Clean-up

Gas Clean-up of Carbon Dioxide and Nitrogen for PEM Fuel Cells

Carbon dioxide and nitrogen are diluents to the hydrogen stream produced by the reforming of JP-8. Removal of carbon dioxide and nitrogen increases the hydrogen concentration entering the fuel cell. The fuel cell performance increases with greater hydrogen concentration (following the Nernst equation). Well established commercial processes exist for the removal of these two gases: 1) pressure swing adsorption and 2) palladium membranes. New technology, high pressure membrane separation, is on the horizon for removal of carbon dioxide and nitrogen from the reformed JP-8 stream. For pressurized hydrogen storage, purification to 99.97% hydrogen is a target.

Pressure Swing Adsorption (PSA) [2]

A representative composition of reformed JP-8 that has undergone water gas shift (WGS) cleanup to form syngas is 21.5% carbon dioxide, 1.5% carbon monoxide, 45% hydrogen, and 32% nitrogen on a dry basis. Gas impurities are adsorbed at higher pressure and released when the pressure is reduced. Pressure swing adsorption (PSA) gas cleanup starts when the syngas is pressurized to approximately 100 psig. The pressurized syngas is directed to one of two adsorption tanks using valves in a control manifold. Each tank contains multiple adsorbents. The adsorbents have different adsorption capacities for each of the impurities, the impurities are removed in different areas of the tank. This is shown schematically in **Figure 8-4**. The heavier and more polar impurities are removed at the entry level, with the lightest impurities removed at the exit level.

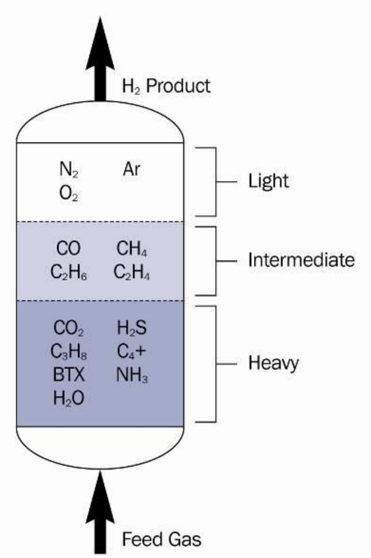


Figure 8-4: Schematic representation of PSA tank

Near continuous gas cleanup is possible using two adsorber tanks in a PSA unit. This cycle of adsorption and de-adsorption results in a continuous production of a purified hydrogen stream with the ability to achieve 99.999% purity.

PSA is a mature technology with over thirty years of optimization. The manufacturing limitations of pressure swing adsorption are:

- Welding and assembly of the PSA reactor
- Reduction or optimization of the number of valves and controls for the PSA
- Development of automation and continuous assembly of PSA

Palladium Membrane Clean-up of Hydrogen

Palladium membrane purification utilizes the ability of palladium to adsorb hydrogen atoms into the atomic lattice of the palladium metal and transfer the hydrogen atoms through the lattice to be released at the other side of the palladium membrane. Molecules and atoms other than hydrogen are rejected and are not adsorbed into the atomic lattice of palladium. The transport of hydrogen through palladium is accelerated by elevated temperature; as high as 300 °C. Maintaining a hydrogen pressure differential across the membrane is essential to transport of the hydrogen through the membrane; the partial pressure of the hydrogen in the syngas must be greater than the partial pressure of the hydrogen at the purification side. This partial pressure differential requirement is an efficiency loss since not all of the syngas hydrogen can be transported through the membrane and the partial pressure of hydrogen must remain greater on the syngas side of the membrane.

Manufacturing limitations for palladium membrane purification are:

- Develop ultra-thin palladium membrane to offset the high cost of the palladium membrane.
- The hydrogen differential pressure across the membrane requires the membrane have sufficient strength with either a thick palladium membrane or an ultrathin palladium membrane supported on a ceramic porous substrate. There is a need to develop a stable ceramic porous substrate.
- Optimize palladium alloys to prevent phase changes.

Selective Membrane Separation for CO_2

Chemically selective membranes efficiently remove carbon dioxide from the syngas stream and concentrate the hydrogen. The chemically selective membranes operate at atmospheric pressure and low temperatures (130 to 200 °C). The chemically selective membrane enriches the hydrogen concentration but does not remove the nitrogen from the syngas; the nitrogen concentration can be as high as 30%.

CO_2 separation using the chemically selective membranes is at TRL-4; component/subsystem validation in laboratory environment. Manufacture of the membrane is laboratory based. Prototype membrane manufacture and prototype membrane separation module construction and testing are needed to advance to TRL-6 and this is a critical issue.

8.4. PROPOSED PROJECTS FOR FUEL PROCESSING

8.4.1. Low Cost Fuel Efficient Tactical Fuel Processor for Desulfurized Fuels

Successful execution of this proposal results in a low cost, reliable, fuel efficient, tactical fuel processor operating on desulfurized logistics fuel (i.e., JP-8, JP-5 or F76). The goal is to achieve a fuel processor with lower manufactured cost through improved design and manufacturability while insuring reliable operation. This project will stand alone in achieving its goals of low cost but will require a successful fuel desulfurization and non-volatile residue removal project for the specified fuels.

Problem Solved (Gap)

- Fuel processing of logistics fuel is presently a barrier in providing quiet, fuel efficient, affordable, and reliable generators

Benefits Derived

- Provide a logistics fuel processor at a manufactured cost of $220/kW

Resources Needed

- Project investment of $4.7 M

Timeline to Completion

- Three years

8.4.2. High Efficiency Fuel Processor for Logistics and Renewable Fuels (Sulfur Containing)

A successful execution of this proposal results in a low cost, tactical fuel processor operating on sulfurized logistics fuel. The goal is to achieve a fuel processor with lower manufactured cost through improved design and manufacturability while insuring reliable operation with sulfur containing logistic fuels and other renewable fuels.

Problem Solved (Gap)

- Sulfur remains a major barrier to adaptation of fuel cells for military tactical applications
- ATR metal supports are easily degraded by temperature excursions
- CPOX reactors susceptible to coking and operate inefficiently
- Steam reformers are temperature limited producing high methane levels and decreased H_2 production

Benefits Derived

- Achievement of $250/kW manufactured cost
- Field demonstration that provides database for 40,000 hour life trend forecast
- May be used with polymer and ceramic fuel cells
- May be used with logistic fuels JP-8, JP-5, and F-76 containing sulfur impurities, renewable biogas fuels from anaerobic digester and landfill gas, and biodiesel

____**Resources Needed**

- Project investment of $4.6 M

Timeline to Completion

- Three years

9. Summary

9.1. GAPS AND ISSUES

During the course of this project several key areas in fuel cell manufacturing were identified which require further development to make fuel cells a viable and cost effective option for military applications. The specific background details of each recommended technical approach can be found in the manufacturing section of this document. The successful implementation of these developmental efforts would require support from both industry and government. The following section delineates the manufacturing areas which require recommended actions.

There are eight fuel cell manufacturing areas of interest as articulated by the subject matter experts as key enablers for fuel cell volume production and cost reduction. These summaries outline the gaps and deficiencies related to the respective areas of polymer, ceramic, BoP, and fuel processing detailed in the previous sections.

Seventy gaps were noted and subsequently consigned into generic categories. The projects positioned to address the gaps are detailed in each section. In many cases, multiple gaps can be resolved from the implementation of one project. The matrix chart below (**Table 9-1**) shows the number of gaps in each fuel cell manufacturing area and production category. Each of the major categories is discussed below in greater detail. The last row shows the number of projects required by each fuel cell area to resolve the respective gaps. As an example, only seven BoP projects are needed to address the 21 BoP identified gaps.

Fuel Cell Manufacturing Gaps

Production Category	Polymer	Ceramic	BOP	FP	Totals
Automation/Machinery	●●	●●●	●		6
Material Processing	●●●● ●●	●●●● ●●●			13
QC Manufacturing Processing	●●●●	●●●	●		8
QC Final Product	●●●	●●	●●		7
Hardware Availability			●●●●	●●	6
Hardware Performance			●●●● ●●●	●	8
New/Improved Materials	●●●● ●●●●	●●			10
Design Performance Specifications and Control	●●●● ●	●	●●●● ●●		12
Total Gaps Per Area	28	18	21	3	70
Projects Required to Resolve Gaps	12	10	7	3	32

Table 9-1: Gap matrix chart

Automation/Machinery

The lack of automated equipment has made the production of fuel cells a labor intensive effort that affects both polymer and ceramic fuel cell systems. The areas specifically influenced include the production of the polymer fuel cell gas diffusion layer where batch process are currently expensive and make inefficient use of the very expensive catalyst. The direct coating of membranes has been conceptualized, but the handling of the membrane requires equipment and engineering to obtain a robust process. In the making of ceramic fuel cells, the lack of feeder mechanisms to support the co extrusion of anode and electrolyte feed rods reduces yields and increases the cost of manufacturing. Some automated equipment common to commercial industries exists already, and with a little adaptation would have an immediate benefit to the coil winding process for the ceramic current collectors.

Material Processing

The efficient use of materials is essential in mitigating the cost of manufacturing. Ionomer and membrane processes require optimization, by clearly defining the characteristic attributes of the membrane and ionomer dispersions that will ultimately affect the MEA performance. Given the expense of the catalyst, minimizing the yield losses and optimizing the most efficient use of catalyst deposition is seen as a necessary procedure for the development of a cheaper fuel cell. For GDL and GDE production, reducing the batch size eliminates waste. One way to achieve this is by dispensing measured amounts of the material components, which requires automated precision dispensing.

In ceramic fuel cell manufacturing, an aqueous based dispersion for green tape should be investigated to avoid the cost incurred by solvent based systems. Process development is needed in the formation of ultra-thin electrolytes and the uniform extrusion of high aspect ratio ceramic tube walls. Many of the material processes associated with fuel cells need development to transition from lab scale to manufacturing scales. Efficiency in the use of gaskets and seals for stacking requires moving away from die cutting sheets to a suitable dispensing material. Additionally, the formation of complex microporous shapes would help reduce the cost of insulation.

QC Manufacturing Processes

The need for better understanding of how and what QC measure should be implemented, cuts across the broad spectrum of fuel cell manufacturing. Some of the more mature process can benefit from the application of Six Sigma principles, while other areas are in need of quantitative validation, so that the metrics currently used can be correlated to quality and performance. The ionomer/membrane process can benefit from an understanding of how membrane defects affect MEA performance, and its subsequent behavior on HTPEM failure modes. There is a need for non-contact inspection and characterization techniques from real time on-line QC measurements, which are compatible with high throughput in line speeds. Associating raw material property variability (for example ceramic powder) with a performance metric is critical in reducing down line rejects where they can incur greater cost. Certain types of designs are plagued by water leakage, necessitating the development of faulty membrane identification techniques. Generally speaking, inspection and QC is currently labor intensive and steps to automate and correlate through Design of Experimentation and nested ANOVAs are highly recommended.

QC Final Products

It is often difficult to associate the performance of the comprehensive fuel cell with the individual process that composes the system. There are some critical parameters which need to be developed to objectively assess the quality of subsystem components. One such example is the bond between GDLs and CGM, where a non-destructive test is needed to assure that the bonding process will not diminish fuel cell performance. Another such example, is the ability to predict tape quality at the green stage prior to firing.

Final QC testing comprises an expensive part of the fuel cell. A better understanding of the relationship between component materials and processes is certainly warranted. Beyond that, a development of acceleration factors used to predict product life and performance are needed. This includes defining the burn-in and other environmental test requirements to correlate test performance with product performance and eliminate any extraneous, lengthy testing.

Hardware Availability

There are systems for reformate purification and desulfurization that currently exist for stationary and large-scale operations. For tactical applications where the size and volume of the fuel cell is of concern, there remains a gap to provide sulfur free logistic fuels. Development of sulfur separation and elimination on a smaller scale is needed for tactical applications. The same applies for pressure swing adsorption which is expensive and inefficient. The currently used palladium membrane is costly and readily poisoned by sulfur species, and a development effort aimed at producing a copper/ silver alloy will improve the durability of the membrane. Fuel and oxidant delivery systems are expensive and a DFMA analysis is required to provide the true cost of fuel. Also, the alternate use of hydrogen injectors and liquid water pump systems can potentially reduce cost. Integration of subcomponents, and whenever possible, the synergistic use of COTS equipment, will help alleviate some of the cost. This requires good collaboration between OEM suppliers and system integrators.

Hardware Performance

Balance of Plant incorporates subsystems such as reactant management and reformate purification, whose designs and performance are widely varied. Along with water management, fuel and oxidant delivery, thermal management systems and heat exchangers, these systems comprise the greater part of BoP. ATR metal supports are degraded by the numerous thermal excursions. An investigation into alternate material supports is warranted. CPOX reactors, which are susceptible to coking and require a number of peripheral subsystems to alleviate the problem, need an efficient system to reduce cost and weight. Many of the subsystems, such as the ones for the removal of CO and CO2, as well as water management systems, are currently utilized for large stationary systems and require engineering and design modifications for tactical applicability. COTS equipment for fuel delivery and thermal management systems do not have the ruggedization requirements for military fuel cells. A collaborative effort between OEMs and fuel cell developers is needed to redesign systems and leverage COTS availability to reduce cost.

New and Improved Materials

Material development for the purpose of achieving cost reduction and improved performance is a common thread among fuel cell producers, and covers a wide array of manufacturing processes. These can be categorized as areas requiring: membrane development, ionomer compositions, bipolar plate composites and coatings, separator plate materials, and thin conductive coatings. In the MEA area, the need to address specific improvements in membrane morphology, and to develop an alternate scaffolding structure for the precursor, such as a non-woven paper in lieu of the presently used carbon fabric, can help reduce cost. Replacement coatings and metals for the presently used graphite resin composites in bipolar plates also need to be explored. This includes assessing and understanding the environmental ruggedness of the alternate metals and coatings, especially in HTPEM applications where thermal conditions can exacerbate the degradation process. Materials for stack plates that have been developed in lab scales need engineering and process development for manufacturing volumes. There is also the challenge to address the current collectors in ceramic tubes by developing a thin and inexpensive conductive coating that can withstand the rigors of wire forming operations.

Design Performance, Specifications, and Controls

Producing specifications which can subsequently correlate the physical attributes and behavior of a product derived from a given manufacturing process, continues to be a challenge for fuel cell producers. Manufacturers typically overcompensate for the absence of reliable performance data by designing for virtually every failure contingency. This adds expense, delay, and is not conducive to large manufacturing volumes. The overall stringent requirements for fuel cell, either self-imposed or as required by application, have driven up costs.

Raw material suppliers need to work with the MEA manufacturers to identify the process parameters critical to the MEA by correlating material characteristics to product performance. There is a need to understand the effects on MEA from perceived defects in PBI membranes and in the GDL/GDE processes, and develop meaningful, validated tolerances for the critical process parameters. In the area of water management and humidification, optimization of the residence time for gas flow distributions are needed to maximize membrane utilization. There is also a need for design concepts to fully integrate the hybridization of green power generation systems.

9.2. PROJECT SYNOPSIS

9.2.1. BoP Projects

Projects can be broken down into several key areas that in some cases may require multiple projects to meet the reduced costs. Balance of Plant issues center primarily around equipment availability and performance. Generally speaking, as the system power requirement and territorial footprint decreases, the cost associated with the manufacturing and design of the BoP components increases in a nonlinear fashion. Conversely, for the fuel cell stacks, the increase in power output and volume necessitates a higher amount of material costs due primarily to the increased volume of the electrochemically active components. **Figure 9-1** shows the cost power curves for BoP and MEA.

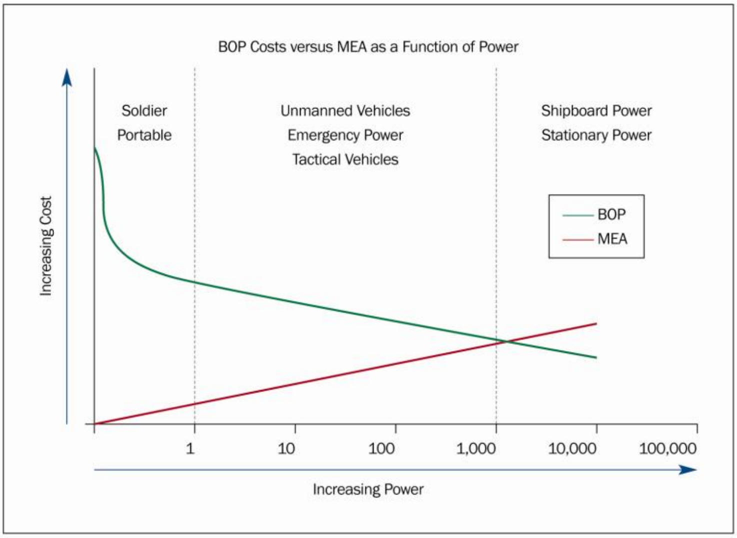


Figure 9-1: BoP and MEA cost curves

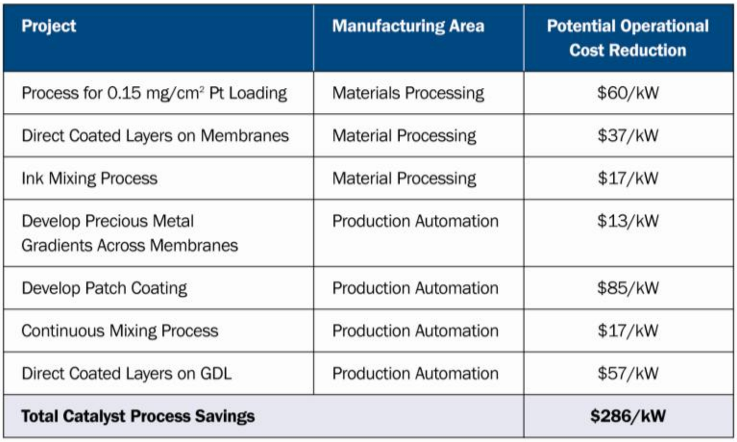
BoP projects are critical to reducing overall fuel cell costs especially in tactical applications where specialized components are needed to meet the ruggedized environments. **Table 9-2** shows a breakdown in the cost savings of both polymer and ceramic BoP components as a function of system power. The biggest savings are on the smaller systems. Depending on the specific component and power requirement, a range of 30-80 % savings can be realized on BoP components with the implementation of the suggested projects.

Project	Manufacturing Area	Potential Operational Cost Reduction
Cathode/Reformer Air Delivery	Hardware Availability and Performance	$150/kW
Anode Gas Delivery	Hardware Availability and Performance	$110/kW
Humidifier	Hardware Availability and Performance	$295/kW
Heat Exchanger	Hardware Availability and Performance	$640/kW
Liquid Pump	Hardware Availability and Performance	$1,400/kW
Flow Meter	Hardware Availability and Performance	$1,400/kW
Over Specification	Design, Performance, and Specification	$300/kW
Total BoP Savings		**$4,295/kW**

Table 9-2: Savings for BoP Projects

9.2.2. MEA Catalyst Reduction and Efficiency Projects

For polymer fuel cells, the projects (**Table 9-3**) target three general problematic areas that presently are impediments to cost reduction. The first addresses MEA manufacturing operations that center on catalyst reduction and efficiency improvements as keys to reducing stack costs. A range of 30 % to 40 % cost reduction can be realized with the implementation of these projects.

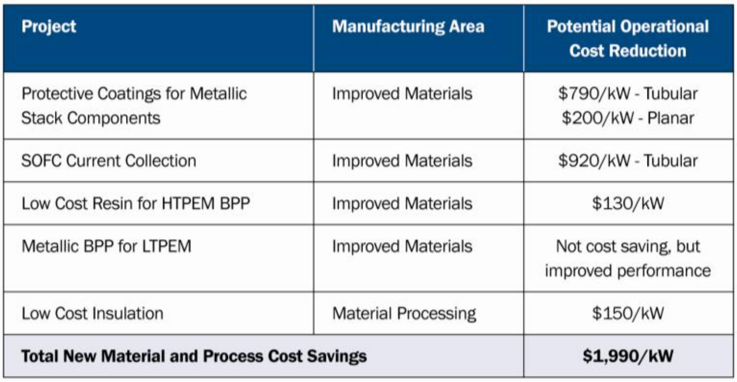


Project	Manufacturing Area	Potential Operational Cost Reduction
Process for 0.15 mg/cm^2 Pt Loading	Materials Processing	\$60/kW
Direct Coated Layers on Membranes	Material Processing	\$37/kW
Ink Mixing Process	Material Processing	\$17/kW
Develop Precious Metal Gradients Across Membranes	Production Automation	\$13/kW
Develop Patch Coating	Production Automation	\$85/kW
Continuous Mixing Process	Production Automation	\$17/kW
Direct Coated Layers on GDL	Production Automation	\$57/kW
Total Catalyst Process Savings		**\$286/kW**

Table 9-3: Savings for catalyst projects

9.2.3. Alternate Materials and Coatings Projects

Certain operations that affect both polymer and ceramic fuel cells can benefit from the development of materials that act as either insulators or protective coatings. Their functionality extends from precision thin wire wound conductive layers, to thermally form-fitted insulating layers, to low cost resin composites capable of withstanding high temperatures. The key physical attribute these materials must possess is high temperature endurance, especially relevant for ceramic and high temperature PEM fuel cells. The projects of value in meeting the technical and potential cost advantages are detailed in **Table 9-4**.



Project	Manufacturing Area	Potential Operational Cost Reduction
Protective Coatings for Metallic Stack Components	Improved Materials	\$790/kW - Tubular \$200/kW - Planar
SOFC Current Collection	Improved Materials	\$920/kW - Tubular
Low Cost Resin for HTPEM BPP	Improved Materials	\$130/kW
Metallic BPP for LTPEM	Improved Materials	Not cost saving, but improved performance
Low Cost Insulation	Material Processing	\$150/kW
Total New Material and Process Cost Savings		**\$1,990/kW**

Table 9-4: Savings for alternate materials and coatings projects

9.2.4. Quality Control and Defining Specifications Projects

The QC projects resolve two critical cost inefficiencies in the manufacturing of fuel cells. The first is to address an improvement in correlating raw material attributes to component performance. This lack of correlation manifests as an increase in waste and a decrease in product yield. Ideally, raw material characterization and QC should be resolved before any subsequent and expensive component processing has commenced. Some of the projects address better methods of assessing the attributes and physical properties required for component performance.

Another set of QC projects determine the correlation between final product performance and stack quality. Quite frequently, evaluating the effectiveness of the final product is protracted and involves other peripheral components that constitute a working fuel cell system. There is a need for a correlative mechanism that ensures that the stack itself meets the requirements of the application prior to integration with other systems.

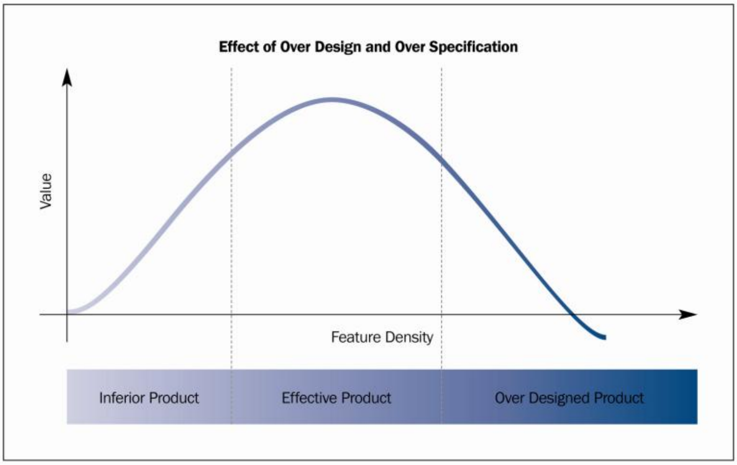


Figure 9-2: Over design versus over specification

Some projects address what is commonly known as “feature creep” by assessing the critical design parameters and removing nondescript terminology such as “must be defect free.” This is schematically shown in **Figure 9-2** where the cost incurred for extra criteria adds substantially to the cost of the fuel cell and at some point reaches a stage of diminishing returns.

QC and specification projects are delineated in **Table 9-5**.

Project	Manufacturing Area	Potential Operational Cost Reduction
Defect Free Electrolyte Layer	Material Processing	$460/kW
Powder Characterization	QC Manufacturing Processes	Not defined but has far reaching cost advantages
Manufacturing Cost Trade Off Analysis	QC Final Product	$49/kW
Vapor Pressure Measurement H_3PO_4	Improved Materials	Not defined
Specification Analysis for FC Power Systems	Design, Performance, and Specification	Not defined but has far reaching cost advantages
Manufacturing Cost Trade Off Analysis	Design, Performance, and Specification	$49/kW
Improve Definition of Design and Rejection Criteria	Design, Performance, and Specification	Not defined but has far reaching cost advantages
QC and Specification Cost Savings Total		**$561/kW**

Table 9-5: Savings for quality control and specification projects

9.2.5. Fuel Processing Projects

Two major impediments exist around the DOD desire to use logistics fuel in tactical military applications. The first hindrance to a more expansive use of fuel cells is the desulfurization process of existing logistic fuels, which is expensive and not yet viable for tactical applications. The second is the development of a more tolerant fuel cell processor for sulfur and other impurities that exist in both logistic and renewable fuel sources. **Table 9-6** shows the projects that address both of those concerns.

Project	Manufacturing Area	Potential Operational Cost Reduction
Low Cost Fuel Efficient Tactical Fuel Processor for Desulfurized Fuel	Hardware Performance and Availability	$580/kW
High Efficiency Fuel Processor for Logistic and Renewable Fuels	Hardware Performance and Availability	$600/kW
Fuel Processing Cost Savings Total		**$1,180/kW**

Table 9-6: Savings for fuel processing projects

9.2.6. Global Projects

In the recommendation section of the report there are references to global and consortium projects. During the project appraisal process, it became apparent that certain issues and gaps required a more expansive industry participation to adequately resolve them. Some of the projects articulated in this report are considered global in nature and may be better served using a consortium model where participation between government agencies, labs, universities, and industry can expedite solutions to the most universal pressing issues. Chapter 10 details a listing of global projects that, as an example, academic institutions like MTT are able to assume.

10. Global Projects

Subject matter experts at the Manufacturing Fuel Cell Manhattan Project sessions identified numerous issues associated with fuel cell manufacturing and documented specific solutions for addressing them. Some of the projects are application specific and provide a more immediate benefit to a specific fuel cell manufacturer. Other projects noted by the SMEs are more universal in scope and may be beyond the ability of one enterprise or company to implement because of its expansive scope and cost prohibitive elements. The following projects were identified as "global" projects that can be supported by a collaborative effort of academia, industry, and government organizations. These global, collaborative projects are listed below.

Potential Global Projects

- Ceramic powder characterization
- Hydrogen purification substrate development
- Protective coatings for metallic stack components
- Low cost, fuel efficient, tactical fuel processor
- Development of metallic plate for LTPEM
- Catalyst deposition optimization
- Electrolyte process development
- Reformate desulfurization
- Auto thermal reformer (ATR) metal support investigation
- Thermal management systems
- Aqueous process development
- Reformer catalyst optimization

As an example, the Center for Advanced Mineral and Metallurgical Processing (CAMP), through Montana Tech has identified areas where their core competency may be utilized to resolve some key fuel cell manufacturing issues. MTT, with assistance from the ONR, Industry and other national labs such as NIST, is currently undertaking a project to address ceramic powder characterization. This example of a "global" project is described below.

Ceramic Powder Characterization

Raw material variability was a significant problem identified by fuel cell manufacturers during the ceramic portion of the recent MFCMP. Their experience indicates that there is too much lot-to-lot variation in the raw materials, particularly the ceramic powders used to fabricate planar and tubular membranes in solid oxide fuel cells (SOFC). For an unknown reason, membranes made from certain lots of powder do not meet specifications. All powders pass current incoming specifications but some result in defective membranes. Using current acceptance specifications, powder from a "good" lot is indistinguishable from a "bad" lot.

The following scope of work is proposed.

- Talk to individual SOFC manufacturers about their powder problems and membrane manufacturer.
- Investigate the ceramic powder manufacturing process.
- Obtain blind samples of "good" and "bad" powder from each SOFC company.
- Use imaging and analytical equipment to characterize powder.
- Identify differences between "good" and "bad" powders.

- Work with SOFC manufacturers and powder producers to develop specification to make acceptable powder.

Other global projects that can be done in a collaboration (industry, government, academia), are described below,

Hydrogen Purification using Palladium Alloys on Novel Substrates

CAMP is currently working on an ONR project to purify hydrogen using palladium and palladium alloys. The current method is to form a thin film of palladium on a porous stainless steel substrate using electroless plating. The porous support substrate is produced using a 3-D metal printer which may show better results than current technology using off the shelf stainless steel filter disks.

Proposed Work Scope: Continue present work by testing membranes.

- Investigate different sintering methods to obtain optimum substrate
- Minimize palladium usage
- Investigate palladium alloys
- Use reformate (or surrogate) to investigate poisoning by sulfur and CO
- Work with National Energy Technology Laboratory (NETL) to confirm results

Protective Coatings for Metallic Stack Components

This project aims to establish scalable manufacturable processes for applying protective coatings on air-facing metallic components in both planar and tubular SOFC stacks. These coatings are needed for four purposes.

- To reduce cost by enabling the use of inexpensive alloys for the interconnect components
- To reduce cost by replacing currently used silver with less expensive metal alloys;
- To improve stack durability by limiting corrosion and the concomitant release of volatile chromium species that lead to poisoning of SOFC cathodes
- To improve stack durability by stabilizing corrosion products against spallation (a common source of thermal cycling degradation)

Low Cost, Fuel Efficient Tactical Fuel Processor

The goal is to achieve a fuel processor manufactured cost of $250/kW through improved design and manufacturability while insuring reliable, 40,000 hours operation with JP-8, JP-5, and F-76. Demonstration of operation with natural gas, LPG, Ethanol and Methanol as a means to increase volume production for commercial markets is desirable.

Development of Metallic Plate for LTPEM

Identify candidate metals and protective coating processes that would permit the use of low cost metallic plates as a replacement for the molded graphite resin plates.

11. Recommendations

Collaboration between government and industry is key to ensuring a successful transition of fuel cells for military applications. DOD and other federal agencies should seriously consider allocating resources to fund all or a portion of these projects. The recommendations suggested in this report reflect a thoughtful and deliberate process by the SMEs to generate a series of actions that will ultimately lead to a more economical fuel cell for both military and commercial applications. The funding of these efforts will also advance the MRL of fuel cells.

The recommendations are classified into two categories. The first category will focus on the specific project implementations that address the core issues preventing cost effective fuel cells. The second category will center on the organizational mechanisms that will be required to manage, organize, and prioritize the enactment of these projects from the concept to transition.

The government leadership and SMEs underwent a rigorous process to evaluate the appropriate course of action as part of the roadmap to a successful and global transition to fuel cells. In keeping with the objectives of the MFCMP, the most important recommendation that can be offered is that the existing DOD and industry alliance on fuel cells be expanded, and that projects proposed in this report be given careful consideration for implementation.

The recommended projects in **Table 11-1** have been offered.

Project	Section #	Technical Area	Manuf Areas	Invest.	Project Area
Process for 0.15 mg/cm^2 Total Pt Loading	5.4.2	Polymer	Production	$4.8 M	Catalyst Efficiency
Patch Coating for Catalyst Inks	5.4.3	Polymer	Production	$2 M	Catalyst Efficiency
Coating Slot Die Process	5.4.4.(A)	Polymer	Production	$1.6 M	Catalyst Efficiency
Direct Coated Layers on GDL	5.4.4.(B)	Polymer	Production	$2.7 M	Catalyst Efficiency
Develop Paper GDL for HTPEM	5.4.5	Polymer	Materials	$3.2 M	Catalyst Efficiency
Develop Continuous Mixing Process	5.4.6	Polymer	Production	$2 M	Catalyst Efficiency
Improve Ink Mixing Process	5.4.7	Polymer	Production	$1 M	Catalyst Efficiency
Discrete to Continuous MEA Fabrication	5.4.8	Polymer	Production	$2.2 M	Catalyst Efficiency
Precious Metal Gradients Across Membranes	5.4.9	Polymer	Production	$1.6 M	Catalyst Efficiency
Efficient Tactical Fuel Processor for Desulfurized Fuels	8.4.1	FP	Hardware	$4.7 M	Fuel Processing
Process Logistics & Renewable Fuels (Sulfur Containing)	8.4.2	FP	Hardware	$4.6 M	Fuel Processing
Protective Coatings for Metallic Stack Component	6.4.1	Ceramic	Materials	$5.3 M	Coatings and Composites
Low-Cost, High-Efficiency Insulation Package	6.4.3	Ceramic	Hardware	$2.4 M	Coatings and Composites
Net Shape Manuf. of Stack Manifolds	6.4.6	Ceramic	Production	$2.7 M	Coatings and Composites
SOFC Current Collection	6.4.8	Ceramic	Materials, Production	$2.2 M	Coatings and Composites
Low Cost Resin for HTPEM Bipolar Plates	5.4.11	Polymer	Materials	$0.6 M	Coatings and Composites
Vapor Pressure of Phosphoric Acid over HTPEM	5.4.12	Polymer	Materials	$1 M	Coatings and Composites
Metallic Bipolar Plates for LTPEM	5.4.13	Polymer	Materials	$0.5 M	Coatings and Composites
Defect Free Electrolyte Layer	6.4.2	Ceramic	Production	$1.3 M	Material and Product QC

Project (Continued)	Section #	Technical Area	Manuf Areas	Invest.	Project Area
SOFC Stack Manufacturing, Commissioning, and Testing	6.4.5	Ceramic	Design, Production	$4.3 M	Material and Product QC
Powder Acceptance	6.4.7	Ceramic	Quality Control	$1.5 M	Material and Product QC
Specification Analysis for Fuel Cell Power Systems	7.8.5	BoP	Design	$5.4 M	Performance Specification
Reduce Design Requirements and Defect Rejection Criteria	5.4.10	Polymer	Design	$4 M	Performance Specification
Solid Oxide Fuel Cell Automated Assembly	6.4.4	Ceramic	Production	$2.9 M	Reduced Manual Operations
Manufacturing Trade-Off Analysis on Raw Material	5.4.1	Polymer	Design, QC	$4.8 M	Reduced Manual Operations
Low-Cost, High-Efficiency Heat Exchangers	7.8.1	BoP	Hardware	$2 M	Supply Chain
Liquid Metering Pumps for Sub-kW Reformer Based FC Generators	7.8.2.(A)	BoP	Hardware	$0.8 M	Supply Chain
Liquid Flow Meters for Sub-kW Reformer Based FC Generators	7.8.2.(B)	BoP	Hardware	$0.9 M	Supply Chain
Improved Anode Gas Delivery Devices	7.8.3	BoP	Hardware	$0.8 M	Supply Chain
Improvements for Fuel Cell Humidification Systems	7.8.4	BoP	Hardware, QC	$0.8 M	Supply Chain
Cathode Air Delivery System Pump Blower	7.8.6	BoP	Hardware	$1.1 M	Supply Chain

Table 11-1: Project recommendations

11.1. PROJECT RECOMMENDATIONS

Catalyst Efficiency

Fund the efficient use of the catalysts in fuel projects, which include both reformulation of the electrochemical components to reduce catalyst concentrations and the various catalyst-to-substrate deposition methods. The first project should center on reducing yield loss in current catalyst systems, leveraging improved methods to increase catalytic uniformity.

BoP Supply Chain

As an increasing percentage of the cost drivers, an investment in BoP will especially benefit military platforms. Program managers should consider this a priority when utilizing fuel cell systems. A study should be established with BoP vendors and fuel cell manufacturers to determine the best way to supply efficient and economical components for fuel cells. The priority areas include:

- Investigation of what existing hardware is available for immediate use for fuel cells which has not been explored
- Designing of parts not currently available
- Research of the modifications needed to make them “field ready”
- Funding the environmental testing and validation of the components within a given fuel cell system

Improved Coatings and Composites

Support efforts to extend the lifetime of fuel cell stacks in harsh environments. Projects that address corrosion in high temperature fuel cells should be subsidized to qualitatively improve the composition and deposition of temperature resistant coatings.

Project support for uniformly coating wire wrapped current collectors in tubular cells is warranted to increase yields.

Material and Product Quality Control

Continue the follow-up activities of the powders characterization project started by ONR (see MTT global projects) through additional funding from other sources such as DOE, NAVSEA, NAVICP, and other agencies with a stake in SOFC fuel cells.

Performance Specifications

- Support projects that correlate material or component performance with final product performance
- Reduce over specification in military applications

Reduced Manual Operations

Support the projects that eliminate technological barriers to future automation of fuel cell fabrication and stack assembly.

- Achieve product consistency and higher throughput capabilities
- Prevent production from migrating to low-wage off-shore locations that may turn hostile to American interests at times of greatest need

Fuel Processing

Subsidize projects to desulfurize logistic fuels and support efforts to develop fuel processors that can accommodate a range of logistic and alternate fuels

11.2. RECOMMENDED ORGANIZATIONAL MECHANISMS

To achieve cheaper fuel cells, it is critical that fuel cell manufacturing technologies have continued leadership at DOD, JDMTP, OSD, DOE, DARPA, and other interagency levels. The project mechanisms list are just some of the potential opportunities to meet those objectives, and are by no means exclusively restricted to the following recommendations.

Establish government-industry consortia to address over-arching issues

The nature of some of these projects lend themselves to be more cost effective if there is a shared funding approach among industry and government entities. This will also help support the competitiveness of the North American fuel cell manufacturing base.

- Provide the resources required to continue the engagement of the government SMEs in the MFCMP. Essentially, maintain the collaborative ‘esprit de corps’ developed during the project.
- Establish a group consisting of members from the National Defense Industrial Association (NDIA) which includes the SMEs from the MFCMP.
    - Provide a forum for labs and academia to report on new developments related to manufacturing.
    - Capture manufacturing needs and issues for DOD and DOE consumption and action.

    - Gather the government inputs necessary for funding and planning fuel cell projects.
    - Establish a three way dialog between the government, industry, and the supply chain on the tradeoff between requirements and unit price.
    - Submit a white paper on MFCMP findings.
- Establish support for the MFCMP by leveraging the efforts of the Fuel Cell Technology Working Group (TWIG) to supply military requirements for fuel cells.

Support continued ONR efforts through the B2PCOE and MTT

- Fund a new effort by the MFCMP to address fuel cell power management and integration using the appropriate team of SMEs.
- Support efforts to distribute the findings and data of the MFCMP to various government agencies so that replication of effort among government agencies is avoided. Fuel cell manufacturing is important to realize these leading edge technologies and should have continued leadership at DOD, JDMTP, OSD, DOE, DARPA and other interagency levels.

Establish a new ONR Alternative Energy Center of Excellence

Establishing a COE on alternative energy fits in well with the Secretary of the Navy's vision of a green fleet.

- Assess new fuel cell manufacturing technologies that would benefit naval platforms.
- Work with industry partners to develop cost effective and green fuel cell projects that can be transitioned into naval platforms.
- Interact with the Electronics Manufacturing Productivity Facility (EMPF) to integrate power and control requirements for alternative energy.
- Collaborate with the Army Power Division at Aberdeen Proving Ground (APG) to exchange information and application requirements for fuel cells and other alternative energy.

III. Appendix A

III.1. POLYMER FUEL CELL PROJECT DESCRIPTIONS

III.1.1. Manufacturing Cost Trade-Off Analysis on Raw Material

Project Description

Gaps

- Need to move from decal transfer methods
- Need for direct printing of catalyst onto membrane
- Need robust methods of printing ink on moving web
- Need to maximize catalyst utilization

Background and Objective

- Perform a manufacturing cost trade-off analysis on raw materials
- Establish strong communications link between a supplier and a customer
- Identify critical parameters to measure in supplier release product and customer release product
- Identify tools and techniques for measuring critical parameters

Statement of Work

Develop robust manufacturing process that produces anode and electrodes with a total Pt loading <0.15 mg/cm^2

Major Tasks

- Identify commercially available materials for the electrodes
- Identify commercially available equipment for creating electrodes in high volume
- Develop robust electrode manufacturing process
- Develop measuring technology for quality assurance

There are critical milestones or go/no-go decision points within the first year.

- Identify commercially available materials and equipment that would enable achieving the goal of <0.15 mg/cm^2 total platinum loading by the end of second quarter
- Identify the critical parameters to measure by the end of second quarter
- Identify critical tools and techniques for analysis by end of third quarter
- Develop measurement methodology by end of first year

Project Costs

Project investment of $4.8 M over two years

Expected Outcomes and Payoffs

A successful cost trade-off analysis would contribute cost savings of $41/kW in materials and $97/kW in yield improvements for membrane, gas diffusion layer, and catalyst. Approximately half of that savings could be attributed to the transfer function development, then $49/kW in savings could be claimed by the transfer function work.

For 50,000 kW of production a year, the resulting cost savings would be \$2.4 M per year. The resulting return on investment would be 1.9 years.

There are a number of improvements that result from this project.

- Quality designed-in prior to starting manufacturing process
- Incoming raw material inspection eliminated or minimized; depend on supplier certification of analysis
- Reduced raw material cost because reduced tolerances on incoming raw materials enable competition and lower cost as well as supply chain assurance
- Higher first pass yields for suppliers because of tolerance relaxation on their product release parameters
- Released tolerances on supplier incoming raw materials while maintaining manufacturing process within a more robust range with broader control limits
- Higher first pass customer yield and minimized inspection tooling and cost
- More robust manufacturing process for customers

Platinum cost is the current principal cost driver that cannot be reduced with volume because platinum spot pricing is uncontrollable and generally high and increasing. This project addresses achieving dramatic reductions in platinum loading in MEAs that is consistent with reducing the MEA cost at all volumes.

This project can be linked to the other defined projects to reduce cost of the MEA such as improved ink mixing, continuous mixing, and direct coating onto gas diffusion layer and membrane. Efforts to manufacture hygroscopically robust membranes could also be linked to projects that are not currently within the Manufacturing Fuel Cell Manhattan Project.

III.1.2. Develop a Process for 0.15 mg/cm^2 Total Pt Loading

Project Description

Gaps

- Lack of transfer functions relating critical product, raw material, and process parameters to performance and durability
- Lack of understanding how MEA performance is affected by perceived defects in PBI membrane for HTPEM
- Lack of understanding how MEA performance is affected by perceived defects in PBI membrane and GDL/GDE
- Need for non-contact, in-process inspection, and characterization techniques compatible with high throughput line speeds
- Lack of tools that can measure key GDL parameters in real time
- Need for on-line real-time QC measurements
- Need nondestructive in-line measurements of critical properties
- Need valid supplier and customer information; there is a reluctance of suppliers and customers to share information with each other because there are typically different manufacturers for each part of the MEA (and in some cases different parts of the GDL)
- Relax release specs of ionomer dispersions and membrane properties to reduce yield loss from fabrication process

- Subjective visual inspections

Background and Objective

Platinum cost is the current principal cost driver for MEA that cannot be reduced with volume because platinum spot pricing is uncontrollable and generally high and increasing.

- Develop a robust manufacturing process that produces anode and electrodes with a Pt total loading <0.15 mg/cm^2
- Identify commercially available materials for the electrodes
- Identify commercially available equipment to create electrodes in high volume
- Develop robust electrode manufacturing process
- Develop measuring technology for quality assurance

There is a critical milestone or go/no-go point at six months into the project to identify commercially available materials and equipment that would enable achieving the goal of <0.15 mg/cm^2 total platinum loading.

Project Costs

Project investment of $4.8 M over two years

Expected Outcomes and Payoffs

- Minimized platinum catalyst cost
- Improved first pass catalyst coated membrane (CCM) yield

For 50,000 kW of production a year, the resulting cost savings would be $4.3 M per year for a 0.5 mg/cm^2 total loading. Successfully switching to 0.15 mg/cm^2 total loading for 50,000 kW of production would further save $3.0 M in catalyst cost. The resulting return on investment would be 1.7 years.

III.1.3. Development of Patch Coating Methods for Catalyst Inks

This project will lower the cost of framed membrane electrode assembly (MEA) designs by developing patch coating methods that deposit catalyst only in design active areas.

Project Description

Statement of Work

The schematic shown in **Figure III-1** outlines a basic assembly technique for a framed MEA. In this design, both the GDL and the catalyst coated membrane (CCM) are sandwiched between framing materials. A seal is cast either onto the frame or onto the plate assembly.

The top-most technique shows a fully coated membrane sheet with catalyst coated beyond the design active area (i.e., the area accessed by hydrogen that contributes to cell performance). Upon subsequent assembly, there can be a considerable amount of in-active catalyst (i.e., catalyst not accessed by hydrogen and not contributing to cell performance) under the frame.

In the bottom-most technique, catalyst is patch coated only in the design active area. Because of using less catalyst, a significant cost savings can be realized in this scenario. Note that due to alignment stack up tolerances (between the frame and catalyst layer and between the anode and cathode catalyst patch coatings), and possible design needs, some catalyst still may be required underneath the frame, but the overall amount can be significantly reduced.

This project will develop viable patch coating methods.

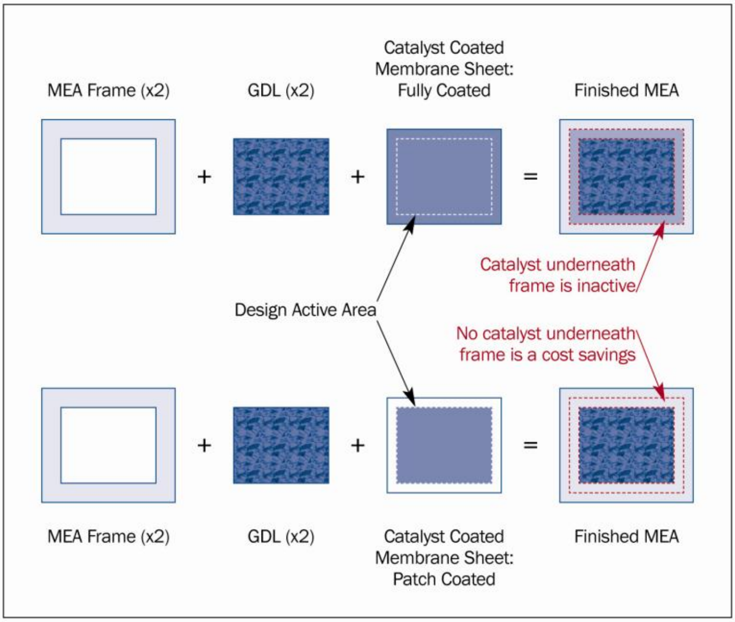


Figure III-1: Schematic of patch coating methods

Major Tasks

This project will achieve the following:

- Determination of optimal design active area. Determine how much, if any, catalyst is needed under the frame by design (16 weeks)
- Determination of tolerance stack up needed between the frame and catalyst layer and between the Anode and Cathode catalyst patch coatings (3 weeks)
- Development of patch coating techniques
  - Technology evaluation and down-selection (12 weeks)
  - Ink development (12 weeks)
  - Proof of concept field trials (12 weeks)
  - Capital purchases (16 weeks)
  - Equipment installation, commissioning, qualification (4 weeks)
  - Coating process development (16 weeks)
  - Process capability and control (16 weeks)

Patch coating can be integrated into the direct membrane coating project proposal.

Project Costs

Project investment of $2.0 M over two years

Expected Outcomes and Payoffs

- Cost savings of $25/kW
- Decreased amount of catalyst coating in a framed MEA by 15%

For 50,000 kW of production a year (5,000 – 10kW stacks), the resulting cost savings would be $1.2. The resulting return on investment would be 1.7 years.

III.1.4. Elimination of the Decal Transfer Process

(A) Development of Coating Slot Die Process

Project Description

Reduce the cost of catalyst coated membrane by developing direct coating slot die processes that are scalable to high volume manufacturing.

Gaps Addressed

- Need to move from decal transfer methods
- Need for direct printing of catalyst onto membrane
- Develop robust methods of printing ink on moving web

Statement of Work

One of the largest cost drivers in a LTPEM stack is the catalyst. Because of this, current state-of-the-art designs utilize low-loaded catalyst layers ranging in thickness from 2μm (on the anode) to 10 μm (on the cathode). A majority of manufacturers have found that coating catalyst inks against a film, as opposed to coating on a GDL, offers advantages for thin layers. Films present very consistent surface roughness, surface energies, and handling characteristics compared to GDLs.

A technological hurdle exists, however, when coating inks against a polymer electrolyte membrane. The membrane absorbs water, then swells and wrinkles. It does not return to its original flat and stable state after the ink dries during a subsequent heat treatment step. To mitigate the wrinkling, catalyst ink layers are first coated on release films, dried, and subsequently decal transferred to the membrane using lamination methods.

Decal transfer release films and labor add $36/kW (or 12%) to the cost of a 10 kW fuel cell stack. Developing methods to enable the direct coating of catalyst layers against the membrane will enable this 12% cost reduction.

Major Tasks

Milestone 1: Translate R&D lab scale findings to pilot coater. Partner with coating experts EDI in Chippewa Falls, Wisconsin (- 15 weeks)
Milestone 2: Develop vacuum roller slot die coating with experts WebEx in Neenah, Wisconsin (- 6 weeks)
Milestone 3: Capital purchases and pilot coater upgrades (- 14 weeks)
Milestone 4: Commissioning and qualification(- 6 weeks)
Milestone 5: Process optimization and control (- 13 weeks)

Project Costs

- Project investment of $1.6M
  Milestone 1: Develop slot die coating on pilot scale = $289,000
  Milestone 2: Show proof of concept of slot die coating on vacuum roller = $139,000
  Milestone 3: $680,000 (capital costs)
  Milestone 4: Commission and qualify new equipment = $161,000
  Milestone 5: Optimize and control process = $300,000

Expected Outcomes and Payoffs

- Cost Savings of $46/kW
- Elimination of decal transfer labor - $20/kW cost savings
- Elimination of release/backer films - $16/kW cost savings
- Increase catalyst utilization by 5%- $9/kW cost savings
- Total cost savings $45/kW

For 50,000 kW of production a year (5,000 – 10kW stacks), the resulting cost savings would be $2.3 M. The resulting return on investment would be 9 months.

(B) Direct Coated Layers on GDL

Project Description

Background and Objective

The current best practice for producing a polymer membrane electrode assembly (MEA) includes coating a catalyst-containing ink on a plastic release film to make an electrode. This is done for both the anode and the cathode electrodes. After drying the electrodes, one anode and one cathode are laminated with a membrane using heat and pressure to make a catalyst-coated membrane (CCM). The release films are then peeled from the CCM and discarded. The final MEA is prepared by adhering two gas diffusion layers (GDL) on either side of the CCM.

It is desirable to eliminate the release film material and the associated process steps and labor associated with the release film. First, there is a cost associated with the release film. Second, with any process step, there is an associated yield which is nearly always less than 100%. This yield is rolled through the entire process and contributes to lowering the overall yield, which raises cost. Third, there is labor associated with handling and laminating the electrodes on release film. Finally, there is specific scrap associated with electrode material that does not transfer from the release film to the membrane. All of these reasons serve to increase the cost of the MEA.

One way to eliminate the release film is to coat the catalyst-containing ink directly on the GDL, thus forming gas diffusion electrodes (GDE). The anode and cathode GDE are then directly laminated with the membrane, forming the final MEA.

Gaps

- Need to move from decal transfer methods.

- Need robust methods of printing ink on moving web
- Need to maximize catalyst utilization

Statement of Work

This proposal will include at least the following four broad areas of work.

- Definition of success in the project
    - Definition of metrics, nominal values for the metrics, and, where appropriate, specification limits on the metrics
    - Comparison of metrics with a baseline reference of the current best practice
- Development of the catalyst ink and/or the gas diffusion media to result in measurable properties that enable successful fabrication of gas diffusion electrodes
- Development of processes to enable successful fabrication of complete MEAs using the gas diffusion electrodes produced above
- Evaluation of the metrics using the complete MEA or a partially prepared MEA, as appropriate

Major Tasks

At least some of these major task groups listed below would appear in a reasonable project under this proposal. The cost analysis was performed assuming that all the work is accomplished in a single project lasting two years. Year 1 focuses on developing the ink or GDL to enable GDE, and the analytical characterization of the electrodes, while year 2 introduces electrochemical characterization of the GDE, as well as complete MEA fabrication and fuel cell performance and durability evaluation. Please note that illustrative examples are given throughout the possible task list below.

- Establish the metrics and the desirable values for the metrics based on experience and current best practice performance. Examples of relevant metrics may include catalyst loading, catalyst activity, MEA fuel cell performance (beginning of life and durability), and yield improvement.
- Tune the catalyst ink properties to enable effective coating onto the GDL. Since the GDL is a relatively porous, hydrophobic material, good engineering will be required to produce a successful catalyst-coated GDL. Key properties to tune may include ink rheology and ink surface tension. This may be accomplished by adjusting ink control parameters such as solvent composition (alcohols and water), weight fraction of solids, and the addition of rheology and surface tension modifiers. If the anode and cathode catalyst inks are different, then this exercise must be done on both inks.
- Tune the GDL properties to enable effective reception of catalyst ink. Key properties to tune may include porosity, surface flatness, and surface energy. This may be accomplished by adjusting GDL control parameters such as paper density, microporous layer ink properties (such as viscosity), and calendaring conditions.
- Quantify the variability of the catalyst distribution in the GDE. Most likely, this will require indirect or direct measurements of the aerial weight of the electrode. Techniques include sample weight

measurement of the GDE, or direct catalyst quantification via calibrated X-ray fluorescence. If possible, quantify the catalyst distribution through the thickness of the GDE, since catalyst ink penetration into the depth of the GDE is quite possible and undesirable.

- Evaluate the electrochemical activity of the GDE (both anode and cathode). This test will help determine if the catalyst that is on the GDE is available for fuel cell reactions. For Pt catalysts, techniques include hydrogen adsorption/desorption and carbon monoxide stripping.
- Fabricate full MEA (comprising an anode GDE and a cathode GDE, a membrane, and possibly a supporting frame/edge protection). Different techniques and process set points may be needed to achieve good MEAs. For example, since the substrate in the GDE is typically compressible, the allowable lamination force may be substantially less than what is allowed when the substrate is a largely incompressible plastic release film.
- Evaluation of fuel cell performance and durability of the MEA containing the GDEs. These results will most likely be compared with baseline MEAs prepared using the current best practice.
- Evaluation of the cost benefit of coating the catalyst layers directly on GDL. This will include the material cost savings by eliminating the release film, plus any cost savings realized by labor reduction and yield improvements.

Project Costs

Project investment of \$2.7 M over 2 years. There is a convenient break point in the tasks to allow for the project to be divided into 1 year blocks. The first year would cover tasks 1-4, and would cost ~\$0.8M, while the second year would cover tasks 5-8, and would cost ~\$1.9M. The table below illustrates the breakdown.

Expected Outcomes and Payoffs

The feasibility of removing the material and process steps involved with coating on a release liner can be demonstrated. The potential cost gap closure from the baseline model is ~18% or ~\$50/kW if successful in removing the release liner. For a 10 kW system at 5,000 per year, this represents a potential cost savings of \$2.5M per year. The baseline cost savings includes material and labor associated with elimination of the release film and a 5% yield improvement on the catalyst.

Note that this project overlaps with the direct coating on membrane project since both achieve the same objective of eliminating the release liner film from the current best practice.

III.1.5. Develop paper GDL for HTPEM

Project Description

Background and Objective

In the mid-1990s, carbon fabric was one of the first commercially available gas diffusion materials. During the 2000s, paper-based gas diffusion layer (GDL) substrate material was developed to provide a cost effective alternative to the fabric-based materials. This has been widely adopted by many low-temperature PEM (proton exchange membrane) fuel cell manufacturers. However, high temperature PEM manufacturers and system builders have continued to rely on carbon fabric gas diffusion layer materials.

In an effort to reduce the cost of the HTPEM MEA, substituting a properly engineered paper GDL for the fabric GDL is anticipated to have at least a 50% savings in the cost of the GDL. This would be accomplished by switching from a fabric to a paper which is the primary savings estimated to be about 30%. An additional cost savings of roughly 20% would be achieved by reducing manufacturing process operations necessary to form the GDE. One example of this would be the reduction of the number of MPL (microporous layer) coating passes made possible by the different characteristics of a paper as compared to a fabric and by optimizing MPL ink formulations.

Potential secondary savings may be realized by

- Increasing coating yield/throughput - since a relatively rigid paper may be easier to handle than a fabric that is susceptible to stretch, shear, and wrinkling
- Reducing yield loss associated with woven fabric GDL defects (e.g., knots)
- Delivering a GDE that is easier to cut for simplified MEA assembly and leads to fewer stack assembly yield losses due to thread separation in the woven electrode

Statement of Work

A domestic GDL paper substrate manufacturer will be solicited to develop a structure that will be compatible with high-temperature PEM applications. This supplier will work closely with one or more HTPEM manufacturers to ensure that GDL designs are compatible with the new ultrasonic sealing process used to seal the MEA assembly (see 5.2.4 Catalyst Coated Membrane for a description of how a HTPEM MEA is assembled). The team will also include at least one HTPEM stack developer so impacts on assembly and system operation can be assessed.

It is possible to manufacture GDL designs with similar overall thickness and basis weight but with extremely different structures, diffusivity, porosity, and mechanical properties. This can be accomplished in a number of ways which may include the following:

1) The microstructure and mechanical properties of the non-woven substrate can be altered by modifications to the carbon fiber mat construction, the saturation ink formulations, and the heat treatment processes
2) The hydrophobicity of the final GDL designs can be altered by modifications to the treatment chemistry and also to the processing condition

3) The MPL designs can be easily modified by using a variety of carbon/graphite powders and other additives in the MPL formulation

Additionally, multiple MPLs can be added to a GDL which allows for a graded pore structure.

Major Tasks

Phase I

- Identify critical requirements for a paper GDL
- Develop wet laid paper construction to meet thickness and mechanical requirements
- Develop MPL formulations for HT PEM applications
- Perform catalyst coating and any post-treatments (cooperation between GDL supplier and MEA manufacturer) – this involves the coating of the GDL with catalyst which is a high materials cost step
- Optimize traditional and high-throughput sealing processes for MEA manufacturing with paper GDLs
- Conduct single cell testing to verify performance and optimize final GDL design for performance and cost –This is a high materials cost step due to the cost of the CCM
- Iterate as necessary

Phase II

- Stack design/build/test.

Project Costs

The projected cost for this project is estimated to be $3.2 million over a two year period. Labor costs are split up about 10% management, 30% engineering, and 60% technicians and account for about 70% of the total cost project. The remaining 30% are material and other costs.

Expected Outcomes and Payoffs

Project investment of $ 3.2 M. The reduction in GDL cost by switching to a paper substrate will be at least 30%. If a reduction in process coating steps can be realized the savings could be an additional 20%. There may also be other secondary savings as mentioned above. Based on a 2011 projected sales volume for fabric GDL substrate, and assuming only 50% of the sales of fabric GDL substrate switch to the newly developed paper GDL, an annual savings of at least $1,000,000 would be realized. Based on these conservative savings numbers, the ROI on this project would be about 3.25 years.

III.1.6. Develop Continuous Mixing Process

Project Description

Background and Objectives

The objective of this project is to improve catalyst utilization by reducing the amount of platinum lost in the manufacturing process, specifically in the ink mixing process. The reduction is achieved by minimizing scrap losses through the replacement of batch processing of catalyst inks with in-line mixing and the associated reduction in labor. Moving to in-line mixing will also improve the consistency of the catalyst ink. Catalyst inks have been historically made using a batch process. Raw material ingredients are loaded into a vessel and mixed for several hours. Once the mix is complete, it is transferred to a dispensing vessel. Remaining in the tank after each batch is a certain level of “skins” or waste liquid resulting in a yield loss. The mix vessel is then cleaned to prepare for the next mix. Another cause of yield loss is that batch processing limits the user to a set volume. Smaller batch sizes cannot be made.

Substituting an in-line mixer instead of a batch processor will allow the total ink volume made for a given run to more accurately match the amount needed to complete the run, thus eliminating the “unused” solution that is typical of ink made in batch processes. Catalyst inks have a short shelf-life and therefore the “unused” ink typically cannot be saved for later use. In addition, there is a 30% reduction in labor costs in moving from batch processing to inline mixing due to shorter mixing times. Another advantage of in-line mixing is improved batch uniformity whose properties can be continuously monitored for consistency. An in-line mixer would also have less surface area and thus less “skin” waste. Also, in-line mixers can typically be cleaned in place (CIP) which reduces cleanup time and waste volumes.

Major Tasks

- Research in-line mixers. There are some different types out there with the ideal one being dependent on fluid properties and mixing requirements
- Research dry and wet dispensing systems to support the move to a continuous process
- Characterize the fluids, understand the mixing requirements to produce the catalyst inks with the desired properties and determine if they are feasible for in-line mixing
- Narrow selection of mixers and dispensing ancillary equipment based on raw material , fluid and mixing needs
- Run pilot trials at vendors
- Down select final mixer and other ancillary equipment. There is typically an 8-12 week lead time on large items
- Install and debug equipment
- Perform Design of Experiment (DOE) testing to understand how new process variables relate to key parameters
- Test optimized inks made on in-line mixer in coating operation
- Verify catalyst mixture via single cell testing
- Perform cell stack testing to verify final performance of in-line mixed inks

Project Costs

Project investment of $2 M over a two year period. Labor costs are about 10% management, 60% engineering, and 30% technicians and account for about 65% of the total cost project. The remaining 35% is for equipment costs.

Expected Outcomes and Payoffs

A 5% increase in catalyst ink yields is expected due to switching from batch processing to in-line mixing of the catalyst inks. The labor savings in moving to in-line catalyst ink mixing is 30%. Per the baseline cost calculation discussed earlier in this section, this is a $17/kW reduction. For 5000 10 kW units/year, that is a savings of $832,000/year for a 2.3 year payoff timeline.

III.1.7. Improve Ink Mixing Process

Project Description

Background and Objective

The current best practice for producing a polymer membrane electrode assembly (MEA) includes coating a catalyst-containing ink onto a substrate. The ink is a complex system, containing a dispersed catalyst on carbon, a proton conductive polymer, at least one solvent that may include water and various alcohols, and potentially a variety of additives. The ink is commonly characterized using various metrics, including viscosity, solids content, and particle size distribution.

It is not uncommon to find that a batch of catalyst ink results in a coating with defects. Two of the more common defects include bumps in the coating and voids in the coating. Although coating defects are necessarily an interaction between the coating substrate and the ink, it is believed that if the ink were more robust, then these defects could be avoided. Since the defects can sometimes occur even when the measured properties of the ink are within process specification limits, it is apparent that one or more critical properties of the ink are not being measured or controlled. This project will determine and then develop control methods for the critical ink properties that can lead to two of the most common coating defects: bumps and voids.

Statement of Work

Favored projects submitted under this proposal will include at least the following four broad areas of work.

- Literature survey. Other industries, more mature than the fuel cell industry, use rheologically complex slurries. A literature and patent survey will be undertaken to determine whether there are techniques that are currently in use to characterize this class of ink, and whether there are known metrics that lead to an increased likelihood of bumps and void coating defects.
- Propose at least one new ink parameter that may be critical to the elimination of bumps and voids. The same parameter does not need to affect both defect types. In fact, since the two defect types are so different, it is unlikely that the same parameter would be critical to both.
- Modify the chosen parameters to show that the defects can be turned on and off.
- Propose a method to control the parameters in a continuous manufacturing environment.

Major Tasks

At least some of these major task groups listed below would appear in a reasonable project under this proposal. Please note that examples are given throughout the possible task list below. However, these examples are only illustrative and may not be included by respondents to a solicitation generated from this proposal.

- Perform a literature and patent survey to leverage the experience of other applications and industries that use rheologically complex inks. Industry examples may include the photographic industry and the ink jet printing industry. The purpose of the literature survey is to catalog what the more mature industries have determined to be key metrics for the ink to allow for robust, high quality coatings. Any specific links between ink metrics and the two coating defect types that are the focus of this proposal (bumps and voids) would be the ideal output of this task.
- Using the literature and patent search, choose one or more ink metrics that are most likely to give the strongest signal for each of the two defects. Note that it is quite likely that the metrics will be different for the two defect types. Some examples of key metrics may include rheology, particle size distribution, pH, ink surface tension, ink conductivity, and stability (change in a metric over time).
- Acquire lab-scale instrumentation to perform the chosen measurements, if necessary.
- Determine methodologies to enable independently controlled variation of the chosen metrics, while minimizing the variation of all other ink metrics. The methodologies will be highly dependent on the particular metric and may require significant development effort. For example, to control pH, one might choose to add an acid or base to the ink; however, the effect of such an addition on the rheology or other metrics should be minimal.
- Using the above control methods, prepare inks with wide variations in the chosen metrics, and determine if there is a sensitivity of the chosen metric on the degree of the coating defect. This will require coating on a substrate. The substrate should be representative of the current best practice, and should remain constant throughout this study. It is understood that the presence of coating defects is highly dependent on the coating substrate. Therefore, changing the substrate may affect the presence of the defects. However, the objective of this proposal is to make the ink as robust as possible, which should enable an easier transfer from one substrate to another without leading to more coating defects.
- If one or more of the ink metrics is found to be a significant predictor of one of the defect types, propose a methodology to control the ink metric.

Project Costs

Project investment of $1.0 M over one year

Expected Outcomes and Payoffs

Ink metrics that affect the occurrence of bump and void coating defects will be identified. Also, preliminary control strategies will be proposed for the critical ink metrics. The potential cost gap closure from the baseline model that can be realized if successful in removing the release liner is ~10%, or ~$26/kW. For a 10kW system at 5,000 per year, this represents a potential cost savings of $1.3 M per year. The baseline cost savings includes a 10% yield improvement on the catalyst. This project overlaps with the direct coating on membrane project, since both achieve the same objective of eliminating the release liner film from the current best practice.

III.1.8. Process Development for Mitigation from Discrete to Continuous MEA Fabrication

Project Description

Objective

Develop underlying manufacturing methods to move from discrete part handling to continuous material handling in PEM MEA manufacturing, thereby facilitating higher throughput and more efficient stack assembly material handling.

Develop methods to perform automated stack leak testing both in-situ during stack assembly and post-assembly as a quality control measure.

Gaps

The team generated cost model shows that MEA assembly labor represents the single largest potential savings available within MEA fabrication. Moreover, continuing with manual-built MEA components practically guarantees the value added manufacturing moves offshore as quantities increase, and this places a technology that will become increasingly critical to DOD at risk of supply interruption during future conflicts.

If continuous material handling can be maintained into the stack assembly process, additional productivity and associated cost benefits should be realized in stack assembly as well.

Statement of Work

Eliminating technological barriers to future automation of MEA fabrication and ultimately stack assembly is critical to achieve product consistency and higher throughput capabilities while preventing production from migrating to low-wage offshore locations that may turn hostile to American interests at times of greatest need. The fuel cell industry has been slow to adopt automated production methods largely because of historically low volumes – thus setting up the classic “chicken and egg” problem. However, this delay in preparing for automated production also means the industry has largely delayed discovery of related manufacturing challenges and their solutions. An early investment in pilot scale production automation for HTPEM resulted in discovery of material incompatibilities, identification of sensors that perform well and those that do not, and led to unit manufacturing processes substitutions that brought much greater capacity and flexibility to the line. Moreover, producing product on an automated line results in greater product consistency which facilitates earlier process parameter optimization.

This project facilitates migration from discrete component handling, either currently performed manually or achieved with automated discrete part handling, to automated systems that handle continuous materials for more rapid MEA fabrication. Efficiency gains in stack assembly are anticipated if material continuity can be maintained and carried forward into the stack assembly process as well. In many cases this alleviates the need to reacquire component orientation or registration, and makes material in-feed to a process quicker than when handling discrete parts. It is important to identify current commercial best practices for manufacturing one (or more) fuel cell MEA architectures. Critical manufacturing process parameters and registration tolerances must be identified, and capabilities of known web handling and alternative fuel cell MEA fabrication approaches must be characterized. Research and laboratory experimentation may be required to determine whether known unit operations can be applied effectively with web material handling. Critical sensors and controls needed to maintain MEA precision, web registration, tension control, and other critical parameters must be identified and where necessary tested. A laboratory scale proof-of-principle-model may be needed to prove out critical elements of material handling and unit operations. Results will be used to inform selection of best methods for material in-feed to automated stack assembly, and prototype automated stack assembly capability will be demonstrated and its performance assessed. Leak detection methods suitable for high volume manufacturing processes must be explored for use during assembly as well as in post-assembly quality control, and the most promising method should be demonstrated with the prototype stack assembly system.

Proposals that address both continuous MEA material handling as well as high rate stack assembly will be particularly impactful in advancing the DOD objective of attaining reduced cost fuel cell systems for our nations war fighters. However, note that it is not the intent of this project to fund installation of production capital equipment, but rather to ensure that the underlying process technology is available and ready for integration. This activity will reduce risk to fuel cell manufacturers as high-risk elements of the automated production system are prototyped, and it will reduce risk and consequently should reduce procurement costs with automation integrators who generally inflate first costs to account for ill-defined specifications or a sense of risk on a firm fixed-price contract. Experience has shown that clearly defined system specifications presented to an automation design/build firm will lead to fielded automation system cost reduction and reduced time to equipment commissioning.

Major Tasks

- Identify current commercial best practice for manufacturing one (or more) fuel cell membrane electrode assembly
- Identify critical manufacturing parameters and registration tolerances that must be maintained
- Compare process capabilities of known web handling and alternative fuel cell MEA fabrication approaches
- Research and conduct laboratory experiments to determine applicability of current MEA manufacturing process unit operations to continuous material handling
- Identify sensors and controls needed to maintain MEA precision, web registration, and tension control
- Demonstrate continuous material handling using laboratory scale proof-of-principle-model
- Develop methods to use resulting material format(s) for in-feed to automated stack assembly processes
- Demonstrate prototype stack assembly capabilities using new methods and assess their performance
- Research candidate technologies suitable for high throughput automated leak testing both during stack assemble and as a post-assembly quality control measure
- Select most promising leak detection technology and incorporate with demonstration prototype stack assembly system

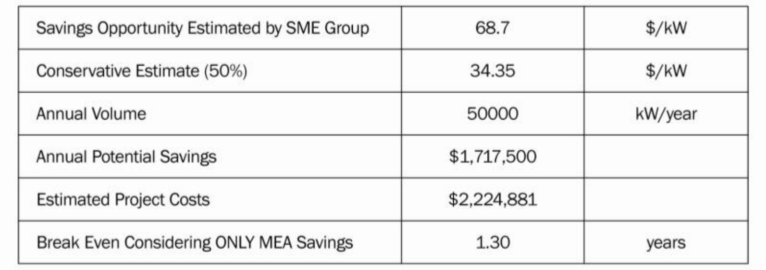
Project Costs

Project investment of $2.2 M over three years

Milestones: Best practice/critical parameters report; demo of continuous material handling capability on lab-scale proof of principle model; demo of prototype stack assembly capabilities; demo of stack leak detection technology.

Expected Outcomes and Payoffs

Project will impact not only the labor costs associated with automation (the largest savings opportunity identified by the group), but by addressing stack assembly automation and in-situ or subsequent leak testing, the impact potential grows even more significant. Savings opportunity forecast by SME group was $68.70/kW. Conservatively assuming that half this benefit is realized by MEA automation, and neglecting the savings offered by improving stack assembly (for which the SME group did not have solid labor estimates), a break-even return on investment is 1.3 years as shown in **Table III-1**.



Savings Opportunity Estimated by SME Group	68.7	$/kW
Conservative Estimate (50%)	34.35	$/kW
Annual Volume	50000	kW/year
Annual Potential Savings	$1,717,500	
Estimated Project Costs	$2,224,881	
Break Even Considering ONLY MEA Savings	1.30	years

Table III-1: Mitigation from discrete to continuous return on investment

The SME group believes there will be considerable additional savings from automating the stack assembly process.

The labor costs that can be eliminated with automation represent the largest savings opportunity identified by the group. Automation will lead to a more consistent performance of MEAs and stacks, both of which should reduce total costs of ownership by improving durability and reliability. Additionally, this consistency should lead to less scrap and lower unit costs provided the volumes necessary to justify the automation can be reached.

III.1.9. Develop Precious Metal Gradients Across Membranes

Project Description

Objective

- Reduced catalyst use
- More effective catalyst utilization (placed where it is most needed)

Gaps

- High cost of precious metal catalyst in PEM fuel cells

Statement of Work

As reactants flow from inlet to outlet through a bipolar plate (BP) they are consumed, thus creating a reactant concentration gradient on the surface of the fuel cell membrane with the highest concentration at the inlet and lowest concentration at the outlet. Traditional gas diffusion electrodes (GDE) and catalyst coated membranes (CCM) have a homogenous catalyst loading across the membrane surface and this does not account for changes in reaction rate caused by reduced reactant partial pressures. Consequently, this leads to a spatially varying reaction rate across the membrane that is expected to adversely impact fuel cell durability and reliability. Both simulation and experimental results confirm this spatial variation in reaction rates and resulting current densities as shown in **Figure III-2** and **Figure III-3**.

Objectives

Reduce cost of Catalyst Coated Membrane by developing direct coating slot die processes that are scalable to high volume manufacturing.

Gaps Addressed

- Need to move from decal transfer methods
- Need for direct printing of catalyst onto membrane
- Develop robust methods of printing ink on moving web

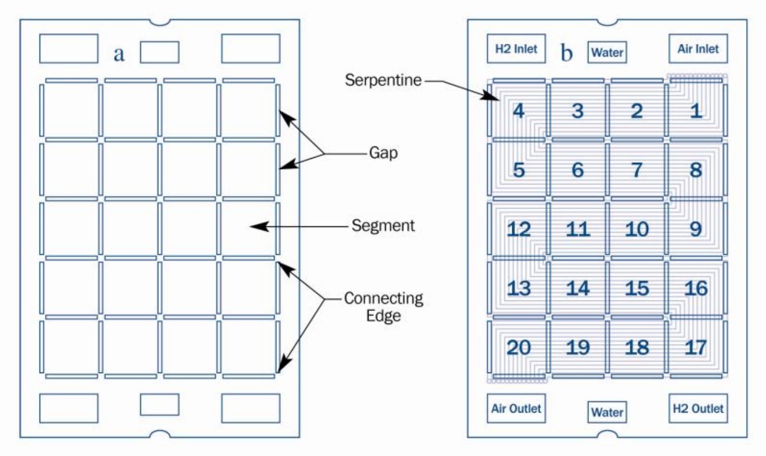


Figure III-2: Numbering the flow field measurement points on the cathode side

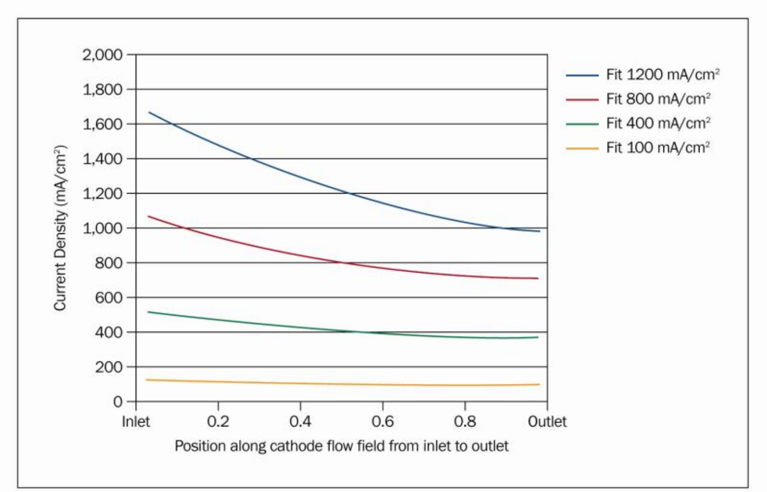


Figure III-3: Local current density along the flow field at different overall current densities

Simulation results suggest that a non-uniform catalyst loading may improve overall MEA performance by reducing the current density variation across the membrane. [1] Consequently, it is desirable to determine a manufacturing process that is capable of depositing spatially varying quantities of catalyst across a PEM GDE or CCM. It should be possible to reduce catalyst loading while maintaining or even improving overall cell performance, durability, and reliability.

Proposers should identify one or more strategies for tailoring catalyst loading on PEM GDEs or CCMs to effect a more efficient utilization of catalyst and correspondingly reduced costs. Manufacturing processes should be implemented either in the laboratory or in partnership with others who manufacture electrodes or catalyst coated membranes to implement a graded catalyst structure. Resulting reduced catalyst graded MEAs should be tested for performance, and optimization should be performed to achieve a comparable performance to a baseline (non-gradient catalyst coated) MEA. This will likely require considerable iteration and should be scheduled accordingly. Note that the same catalyst ink formulation used in the baseline MEAs should be used in the graded catalyst MEAs to ensure a meaningful comparison and assessment of the benefits of manufacturing graded catalyst structures. Ideally, the same catalyst deposition methods would also be used to fabricate the gradient catalyst MEA and the baseline (non-gradient) comparison to enable a meaningful head to head comparison. It is not the intent of this project to facilitate new catalyst development efforts, but rather to focus on the development of scalable manufacturing techniques suitable for realizing spatially gradient catalyst structures for PEM fuel cells.

Major Tasks

- Identify baseline commercial MEA(s) with established performance and catalyst loading
- Identify alternatives for manufacturing GDL and/or CCM with a spatially varying catalyst loading

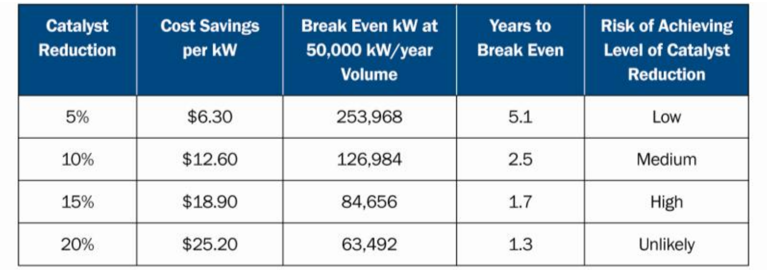
- Assess likely production costs and scalability of varied alternatives to manufacturing spatially varied catalyst coatings
- Coat spatially graded catalyst on GDL or CCM
- Fabricate resulting GDL or CCM into completed MEAs (not less than 5 per individual spatially graded catalyst configuration)
- Conduct single-cell testing to assess performance of graded catalyst MEAs
- Optimize (iterate) graded catalyst deposition geometry and loading to achieve a graded catalyst MEA performance comparable to the baseline homogenous MEA
- Conduct durability testing of resulting optimized graded catalyst MEA and compare results with baseline MEA

Project Costs

Project investment of $1.6 M over 2 years.

Expected Outcomes and Payoffs

Information on potential catalyst savings was not available as catalyst has traditionally been homogenously applied on a given MEA. However, if one assumes a potential reduction in catalyst of 5%, this implies a savings of approximately 3% after considering other perhaps more obvious methods for reducing catalyst loading. Assuming a savings of $6.30/kW suggests a breakeven when 250MW of PEM fuel cells utilize the results. Given a 50,000 kW/year consumption rate, this implies a return on investment of 5.1 years. However, were a higher assumption of catalyst reduction made, much more favorable payback scenarios emerge as shown in the **Table III-2**.



Catalyst Reduction	Cost Savings per kW	Break Even kW at 50,000 kW/year Volume	Years to Break Even	Risk of Achieving Level of Catalyst Reduction
5%	$6.30	253,968	5.1	Low
10%	$12.60	126,984	2.5	Medium
15%	$18.90	84,656	1.7	High
20%	$25.20	63,492	1.3	Unlikely

Table III-2: Precious metal gradients across membranes return on investment

This project will lead to MEAs with less PGM loading but comparable performance to homogenously catalyzed MEAs. Since PGM costs constitute a significant portion of the MEA costs and PGM costs will likely continue to increase as the fuel cell market develops further, any reduction in PGM loadings will yield a positive impact on future fuel cell affordability. This project should have positive impact on all PEM manufacturers reliant on PGM metal catalysts.

III.1.10. Reduce Critical Design Requirements and Defect Rejection Criteria

Project Description

The proposal is trying to quantify the impact of changing CDP and defects on the cost of fuel cell stack/power plant components and fuel cell stack/power plant stack/power plant performance.

Statement of Work

Through discussions with their suppliers, fuel cell stack/power plant manufacturers (SPPM) will quantify the relationship between typical component CDP and defects on manufactured cost of that component. With that information, the fuel cell SPPM will determine the impact of changing that critical design parameter or accepting certain defects on fuel cell stack/power plant cost and performance. Through additional discussions with fuel cell stack/power plant purchasers the fuel cell SPPM will determine if changing the fuel cell stack/power plant performance and cost will impact the buying decision of the purchaser.

Major Tasks

- Discussions with fuel cell stack/power plant component suppliers quantify impact of changing CDP or defect acceptance on component cost
- Quantify impact of changed critical design parameter and defect acceptance on fuel cell stack/power plant cost and performance
- Establish impact of possible reduced fuel cell stack/power plant performance and cost on customer's purchase decision

Fuel cell stack/power plant stack/power plants are designed to meet specified performance requirements such as efficiency, weight, life, and cost. In order to meet those requirements, the fuel cell SPPM specified certain critical design parameters (CDP) to the suppliers of fuel cell stack/power plant components. In addition, the fuel cell SPPMs frequently specify that a component should be "…free of defects." Manufacturing components to meet CDP or to be "… free of defects" can increase costs through increased testing by the supplier, increased scrap rate, and utilization of less economic manufacturing methods.

By changing these CDP or by accepting certain "defects," the fuel cell SPPM may be able to reduce the cost of the fuel cell stack/power plant, but the performance of the fuel cell stack/power plant may be reduced. The relationship between critical design parameters, defects, and the performance and cost of a fuel cell stack/power plant is not known in most cases. In addition, the effect of reduced fuel cell stack/power plant performance at lower cost on customers' buying decision is also not known.

An approach to this issue requires a cooperative program between the suppliers of fuel cell stack/power plant components, fuel cell SPPMs, and their customers. The proposed project would consist of the following steps.

Critical Design Parameters

1. Certain costly components in the fuel cell stack will be identified by the fuel cell SPPM
2. The identity of those components will be supplied to the suppliers of those components, along with the specified CDP for those components
3. The costs of selected components will be estimated by the supplier for several changes in value for the CDP and that information will be supplied to the fuel cell SPPM
4. The fuel cell SPPM will quantify the impact of the changed CDPs on fuel cell stack/power plant performance (i.e., efficiency, life, cost).
5. The impact of changed fuel cell stack/power plant performance and cost of potential market will be assessed

6. Recommendations for further work

Defects

1. The fuel cell SPPM will identify costly components within the stack that manufacturer specified are to be "free of defects"
2. The fuel cell SPPM will supply the identified components to the supplier of those components
3. The supplier of those components will estimate the cost of those components if the "free of defects " requirement were removed
4. The supplier will provide to the fuel cell SPPM the costs of those components with the "free of defects" requirement removed and identify which defects will be present with the that requirement removed
5. The fuel cell SPPM will evaluate qualitatively which defects might be acceptable
6. The fuel cell SPPM testing will quantitatively determine the impact of the defects identified in 5 on stack/power plant cost, efficiency, and life.

Project Costs

Project investment of $4 M over 2 years

Expected Outcomes and Payoffs

This project could reduce the cost of fuel cell stack/power plants.

- Select fuel cell component to be evaluated
- Select critical parameters to be changed
- Determine the impact of changed parameter on fuel cell power plant performance
- Through discussions with suppliers estimate the impact of changed design parameters on component cost
- Accepting certain "defects" the fuel cell stack/power plant manufacturers (SPPM) may be able to reduce the cost of the fuel cell stack/power plant
- Clearly defined standards of acceptable from unacceptable product
- Minimize unnecessary testing of noncritical parameters

III.1.11. Development of a Low Cost Resin Suitable for use in HTPEM Bipolar Plates

Project Description

Gaps

Cost of high temperature PEM bipolar plates.

Objective

To develop a low cost bipolar plate to replace the heat treated (i.e., carbonized and graphitized) plates presently used.

Statement of Work

Due to the corrosive environment in HTPEM fuel cells, bipolar plates must be constructed of very corrosion resistant materials. Typical suitable materials are graphite and fluoropolymers (such as PTFE and FEP). HTPEM bipolar plates are typically fabricated by molding a mixture of graphite and fluoropolymer or a mixture of graphite and phenolic resin followed by heat treatment steps. These heat treatment steps include carbonization to convert the phenolic resin into carbon and a higher temperature step to further convert the carbon into the more corrosion resistant graphite.

These steps are costly because they require special high temperature furnaces, are batch operations, and typically require long conversion times in the furnaces. In the case of graphite fluoropolymer plates, the cost of the resin and the molding is high due to high molding temperatures and long mold residence times.

A resin compatible with the environment in HTPEM cells would eliminate these heat treatment steps and reduce the plate processing costs by $130/kW for a 10kW system.

A program to identify a suitable resin would consist of the following steps:

- Literature search of possible resins
- Identify candidate resins
- Fabricate molded graphite/resin bipolar plates
- Estimate cost of graphite resin bipolar plates and compare to heat treated and fluoropolymer plates
- Laboratory testing to determine corrosion resistance and mechanical properties of candidate bipolar plates
- Subscale cell testing of suitable bipolar plates
- Stack testing of bipolar plates
- Recommendations for further work

Major Tasks

- Literature search
- Identify candidate materials
- Fabricate molded plates
- Laboratory testing
- Subscale testing
- Stack testing

Project Costs

Project investment of $0.6 M over 1 year

Expected Outcome and Payoffs

- A resin compatible with the environment in HTPEM cells would eliminate two heat treatment steps (carbonization to convert the phenolic resin into carbon and a further higher temperature step to convert the carbon into more corrosion resistant graphite)
- Reduce the bipolar plate processing costs by $130/kW for a 10kW system

III.1.12. Measurement of Vapor Pressure of Phosphoric Acid over HTPEM

Project Description

Gap

Cooling of HTPEM cells can be expensive and complex

Objective

The objective is to measure the vapor pressure of phosphoric acid (PA) over HTPEM to determine if it sufficiently low to enhance air cooling of HTPEM cells or to permit fewer cooler arrays if steam cooling is utilized. In addition, if the vapor pressure is reduced versus conventional phosphoric acid, it may permit higher operating temperatures.

Statement of Work

The vapor pressure of PA over HTPEM will be measured as a function of temperature and the typical HTPEM operating conditions. The resulting values will be compared to conventional phosphoric acid and, if lower, determine the range of acceptable operating temperatures, gas flows, and stack designs that meet application goals.

Major Tasks

- Measurement of vapor pressure over a range of operating conditions
- Compare vapor pressure to that of conventional phosphoric acid
- Initial analytic modeling of HTPEM stack designs and operating conditions utilizing the vapor pressure measurements

Expanded Project Description

One life limitation of certain fuel cell types is the slow evaporation of the electrolyte into the fuel cell gas reactant streams. One example is conventional phosphoric acid cells in which electrolyte evaporation, due to its vapor pressure, into the reactant streams is the variable which limits life. Since HTPEM also utilizes phosphoric acid as part of its electrolyte system, its vapor pressure and resulting evaporation rate is a variable which could affect the life of that technology as well. Quantification of these values is necessary in order to design HTPEM fuel cells. Since the vapor pressure of phosphoric acid is typically a strong function of the cell operating temperature and acid concentration, these data must be measured at both the average cell temperature, “hot spot” temperatures, and reactant gas exit temperatures.

High temperature PEM cells are typically cooled by circulating air through a separate passage within the cell. An alternative approach is to employ the method used in conventional phosphoric acid fuel cells, which is to circulate water/steam through separate metallic coolers every six or so power producing cells.

Since the amount of acid that evaporates into the reactant gas streams is a function of the temperature of that stream temperature, control is critical. In order to minimize the acid loss, the cell exit temperature is lower than is desired for optimum cell performance. In addition, for air cooled cells, lower cell exit temperatures results in the need for higher air flows, increasing system pressure drops and parasitic power losses. For water/steam cooled systems reducing the cell exit temperature results in the need for more costly metallic coolers within the fuel cell stack to insure that the individual cell furthest away from the cooler will have an exit temperature that minimizes acid evaporation and loss.

Companies such as United Technologies Corporation and Monsanto have measured the vapor pressure of acid over phosphoric acid to help design the cooling of their fuel cell power plants. With their present design, they have estimated cell stack life at approximately 80,000 hours. In order to achieve that life, careful attention was paid both to the design and number of coolers.

In order to design and build fuel cells based on HTPEM, the vapor pressure of acid over phosphoric acid as a function of temperature and acid concentration must be quantified.

A program to quantify these properties would consist of the following steps:

- Review literature and interface with fuel cell suppliers to assess range of cell operating conditions
- Measurement of vapor pressure over HTPEM and PA
- Comparison of results to conventional phosphoric acid
- Analytic modeling of cell stack operating conditions using vapor pressure measurements

Project Costs

Project investment of $1 M over 1 year

Milestones

- Based on SOA operating conditions for conventional PA, determine range of temperatures and operating conditions to conduct vapor pressure measurements
- Measurement of vapor pressure
- Comparison of results to conventional phosphoric acid
- Analytic modeling of cell stack operating conditions using vapor pressure measurements

Expected Outcome and Payoffs

- Could eliminate high cost cooling methodologies used in conventional PAFC
- Ability to design HTPEM fuel cells
- These data are necessary to properly design HTPEM fuel cells
- Potential increase in the output of the fuel cell
- Potential cost reduction due to simplified cooling

III.1.13. Development of Metallic Bipolar Plates for LTPEM

Project Description

Reduce the cost of LTPEM bipolar plates by substitution of metallic plates.

Gap

- Molded graphite plates are too high in cost to meet the low cost goals of transportation applications
- The physical dimensions of molded graphite plates do not meet the volume requirements of a transportation fuel cell

Objective

This project will identify candidate metals and protective coating processes which would permit the use of low cost metallic plates as a replacement for the molded graphite resin plates.

Statement of Work

Low cost candidate metals, coatings, and clad metals will be identified and tested at the laboratory level for compatibility in the LTPEM environment. The candidate materials which meet the initial criteria will be fabricated into separator plates and tested in LTPEM cells. Examples include metals and metal alloys containing tantalum, titanium, and columbium

Expanded Project Description

Low temperature PEM fuel cells utilize bipolar plates consisting of a molded graphite resin mixture. The cost of these plates is ~$120/kW, approximately 20% of the cost of a PEM stack. Over 10% of the goal cost for a stationary fuel cell power plant and many times the cost goal of the entire fuel cell power plant for transportation applications. Examination of the cost elements of this bipolar plate indicates that there are no major elements whose improvement would significantly change the cost of the plate. In addition, the physical dimensions of the graphite resin bipolar plate are too large for inclusion in the space available for a transportation fuel cell.

An alternative approach is to substitute a metallic bipolar plate for the molded plate. This would eliminate the many steps - mixing, compounding, and compression molding - required to fabricate a molded plate, therefore reducing its cost while also reducing the physical dimensions of the plate, making it more suitable for transportation applications.

However, the corrosive environment present in the PEM cell make many metals (such as conventional 316 stainless steel, and metals such as nickel, copper, and aluminum) unsuitable for use in the cell. However, there are other metals such as titanium, columbium, tantalum and zirconium which are compatible to the environment on either the air or hydrogen electrode side of the cell, but incompatible on the other side. In addition, there may be ways to treat stainless steels (such as SS316) to passivate the surface with a corrosion resistant oxide layer. However, in many cases these layers are not electronically conductive necessitating techniques to overcome this impediment.

One approach is to utilize a bimetallic plate fabricated from a metal which is compatible with the air electrode environment and another metal which is compatible with the hydrogen electrode environment. This bimetallic plate can be fabricated by a variety of candidate manufacturing techniques such as plating, cladding, or by coating a layer of one metal powder plus a binder to the other metal which is in sheet form. This binder would preferentially be a hydrophobic material (such as a fluoropolymer) to prevent corrosive species from penetrating the protective composite metal layer and corroding the base metal plate which is not compatible with that electrode side.

A program to identify candidate materials for a bimetallic bipolar plate for use in low temperature PM cells would consist of the following steps:

1) Literature review of corrosion information
2) Identify candidate materials
3) Compare the material cost of the metals in a metallic plate to the cost of a molded plate

4) Compare physical properties of candidate metals to determine if there any inherent obstacles to the concept
5) Select materials whose cost is comparable to a molded plate
6) Laboratory corrosion testing of the base metals in the appropriate PEM environment
7) Fabricate bimetallic samples of compatible metals
8) Laboratory testing in simulated mixed environment
9) Recommendations for further work

Project Costs

Project investment of $500,000 over 1 year

Expected Outcome and Payoffs

- Reduced weight and volume
- Decreased stack cost with a low cost separator plate

III.2. CERAMIC FUEL CELL PROJECT DESCRIPTIONS

III.2.1. Protective Coatings for Metallic Stack Component

Project Description

Objective

This project establishes scalable, manufacturable processes for protective coatings on air-facing metallic components in both planar and tubular SOFC stacks. These coatings are needed for four purposes:

1) To reduce cost by enabling the use of inexpensive alloys for the interconnect components
2) To reduce cost by replacing currently used silver with less expensive metal alloys
3) To improve stack durability by limiting corrosion and the concomitant release of volatile chromium species that lead to poisoning of SOFC cathodes
4) To improve stack durability by stabilizing corrosion products against spallation that is a common source of thermal cycling degradation

Statement of Work

Several protective coating materials and deposition processes have been identified and proven at the laboratory scale, which will serve as a starting point for work on this project. This project aims to establish pilot-scale processes for applying these protective coatings and to validate performance of coated metal alloys at the component and stack levels (both planar and tubular).

Major Tasks

The cathode faces of the interconnects (or separator plates) and endplates (or manifolds), and all of the surfaces of the cathode current collector meshes, need protective coatings. These are the primary metallic components used in planar SOFC stacks. In tubular stacks, the two primary metallic components that require protective coatings are the manifolds (or plenums) and the cathode current collector wires. A number of different alloys used in SOFC stacks are relatively expensive and are specifically designed for SOFC applications or the automotive industry. These include stainless steel, high-chrome ferritic alloys such as Crofer 22 APU and AL 441HP, or more common alloys such as SS-409 and SS-430.

Several protective coating materials (most notably spinel structured manganese cobalt oxide) and significant improvements in long-term corrosion resistance have been demonstrated. Several deposition processes have also been identified, including plasma spray, ion beam deposition, electroplating, electrophoretic deposition, and aerosol spray deposition. The optimum deposition method depends on the geometry of the specific component being coated.

This project will focus on the deposition of protective coatings on metallic SOFC components, with the aim of reducing cost and improving durability of SOFC stacks. The level of cost savings depends on the specific alloy used and the targeted life of the SOFC system. Specific subtasks are described below.

Task 1. Interconnect Coatings for Planar SOFC Stacks

In this task, existing laboratory-scale materials and processes will be adapted for pilot-scale deposition of protective coatings on planar metallic interconnects. A literature review and vendor survey will be conducted to select the coating material(s) and pilot scale candidate coating processes. The alloys used for coating trials will be selected based on availability and application requirements. Coating deposition trials will be performed in conjunction with a manufacturer of pilot-scale deposition equipment. Coating work will initially be performed on alloy coupons. A matrix of experiments will be designed to assess the effects of alloy material and coating process, coating thickness, and annealing conditions. The coated coupons then will be subjected to comprehensive characterization and testing (e.g., long-term electrical conductivity measurements, thermal cycling experiments, and scanning electron microscopy).

Coating formulations and processes will be down-selected for stack-level validation testing. Cathode faces of interconnects will be coated by the down-selected process and tested in short stacks of 3 to 5 cells. The stacks will be configured with multiple voltage taps, to allow degradation rates associated with interconnect corrosion to be separated from other causes. The duration of these tests will be 1000 hours or longer depending on the target application. After testing, the stacks will be disassembled and interconnect components will be subjected to post-mortem characterizations.

Task 2.Cathode Current Collector Coatings for Planar SOFC Stacks

In this task, existing laboratory scale materials and processes will be adapted for pilot-scale deposition of protective coatings onto alloy meshes used for cathode current collectors in planar SOFC stacks. A literature review and vendor survey will be conducted to select the coating material(s) and candidate (pilot scale) coating processes. The alloy meshes for coating trials will be selected based on availability and application requirements and can be manufactured by existing vendors from alloy sheet stock if meshes are not available. Coating deposition trials will be performed in conjunction with a manufacturer of pilot-scale deposition equipment. A matrix of experiments will be designed to assess the effects of alloy material and coating process and annealing conditions. Samples of coated meshes will be sectioned and analyzed by SEM to assess coating density, thickness, and uniformity. Coating formulations and processes will be down-selected for single-cell and stack-level validation testing. Single-cell tests will provide the first level of validation for minimum durations of 1000 hours. Short-stack validation tests will be performed in the same manner as was described for interconnect coating validation tests in Task 1, with multiple voltage taps allowing degradation rates associated with cathode current collection to be separated from other causes. The duration of these tests will be 1000 hours or longer depending on the target application, with thermal cycling of the stack at regular intervals during the long-term test. After testing, the stacks will be disassembled, and the current collector components will be subjected to post-mortem characterizations.

Task 3. Cathode Current Collector Coatings for Tubular SOFC Stacks

In this task, existing laboratory scale materials and processes will be adapted for pilot-scale deposition of protective coatings onto metal wires used for cathode and anode current collectors in tubular SOFC stacks. A literature review and vendor survey will be conducted to select the coating material(s) and candidate (pilot scale) coating processes. The metal wires for coating trials will be selected based on availability and application requirements. Coating deposition trials will be performed in conjunction with a manufacturer of pilot-scale deposition equipment. A matrix of experiments will be designed to allow the effects of alloy material and coating process (if more than one selected), and annealing conditions to be assessed. Key parameters to be assessed include density, thickness, and thickness uniformity of deposited coatings, since these parameters will greatly impact the success of the coated wire in the application.

Coating formulations and processes will be down-selected for more comprehensive testing. Single-cell tests will provide the first level of validation and will be performed for minimum durations of 1000 hours. Following successful single-cell tests, coated wires will be used as current collectors in short stacks of 10 to 20 tubes. To the extent possible, these tests will be conducted so that degradation rates associated with cathode current collection can be separated from other causes. The duration of these stack tests will be 1000 hours or longer depending on the target application, with thermal cycling of the stack at regular intervals during the long-term test. After testing, the stacks will be disassembled, and the coated current collector wires will be subjected to post-mortem characterizations.

Task 4. Test and Quality Measurements for Protective Coatings

While ASTM and similar measurement standards exist for the key measurements on the planar, mesh, and the wire substrates discussed in Tasks 1 through 3, development and validation of non-destructive testing techniques is important to support both the lab scale experimentation, and more critically, the subsequent scale up of the developed coating processes. These techniques will be useful for both initial development and ongoing quality control. The thickness, uniformity, and density of these protective conducting and non-conducting oxide layers are critical-to-quality parameters that must be measured. A variety of optical and electronic methods for measuring thickness of thin oxide coatings are available, including spectral reflectance, eddy current, magnetic, and ultrasonic techniques. The applicability of these methods depends on the composition of the substrate and coating. The sensitivity and accuracy of these or other methods, as well as the suitability of each method to continuous or high rate manufacturing methods, will be evaluated for the substrate and coating materials, and processing conditions of interest. Measurement of the density of these coatings, especially in an in-process environment, is less well known, though some work has been done using x-ray methods. More detailed development work will be performed to demonstrate a feasible technique for the materials and processes of interest.

Project Costs

Project investment of $5.3 M

Expected Outcomes and Payoffs

Although the primary benefit of the project will be reduced cost, the project will also have a significant impact on long-term durability and thermal cycling capability. The benefits of this project are immediate and do not require a minimum stack production volume for benefits to accrue. This project supports both planar tubular SOFC systems over a wide range of power outputs. The ROI was calculated for three scenarios:

- For planar SOFC stacks (1 kW to 100 kW scale), the project saves $190 per kW and the full project cost can be recovered with 27 MW of SOFC stack production
- For tubular SOFC stacks of 500 W to 10 kW scale, the project saves $790 per kW and the full project cost can be recovered with 6.6 MW of SOFC stack production
- For a tubular SOFC system capable of generating 500 W or less, a break even ROI is achieved at 8,000 units of production

III.2.2. Defect Free Electrolyte Layer

This project is crosscutting to both planar and tubular SOFC stacks over the full spectrum of power ranges. Critical flaws can be identified and separated from the production line before the value-added sintering process.

Project Description

This project will establish high-throughput manufacturing processes to deposit flaw-free, thin (~10 μm) electrolyte films on tubular and planar SOFC anode substrates. Several common deposition methods have been utilized to deposit thin films: tape lamination, wet spraying, and dip-coating are the most common methods. From these or other processes identified in a review, a single process will be selected that best achieves film specifications. The application process should also ease the requirements for clean-room environments.

In support of the development of the electrode coating, evaluation and qualification of automated in-line and in-process non-destructive inspection methods for fired and green assemblies is required. Layer thickness, topography, and uniformity are of critical importance. Defects such as cracks, pinholes, thin spots, or delamination from the anode support affect performance and lifetime. Many techniques could be applicable and must be assessed relative to cost, accuracy, resolution, and capability. These include vision systems, laser and optical systems, X-ray/gamma/beta source-based techniques, electron source techniques, ultrasonic, and UV and IR imaging systems. Beyond assessment of the inspection technique, suitability to the different anode geometries must be proven. While application of these techniques to planar cells may be straight forward, additional development may be required to enable operation relative to tubular cells.

Major Tasks

PLANAR:

- Establish a high-throughput continuous process to deposit a high quality thin film (~10 μm) of electrolyte onto a planar anode substrate. The process should produce a film of uniform thickness and density, which is pinhole and inclusion-free. Environmentally friendly and recyclable solvent systems are favored
- Establish an unattended QC procedure to evaluate the uniformity of thickness and particle density in the film, and which will identify and note the positions of individual pinholes, inclusions, and thickness variations. The procedure should have the capability to differentiate between critical flaws and defects that do impair function
- Establish a feedback procedure to determine the root causes of defects in the film and eliminate or mitigate the cause in the coating process

TUBULAR:

- Establish a high-throughput continuous process to coat a high quality thin film (~10µm) of electrolyte onto a tubular anode substrate using automated manufacturing equipment that handles individual tubes or continuously extruded tubes that will be sectioned in a later step.
- Establish an unattended QC procedure to evaluate the uniformity of thickness particle density in films and identify the positions of individual pinholes, inclusions, and thinned or raised regions. The procedure should have the capability to differentiate between critical flaws and defects that do not impair function.
- Establish a feedback procedure to determine the root causes of defects in the film and eliminate or mitigate the cause in the coating process.

Project Costs

Project investment of $1.3 M

Milestones

- Install preferred high-volume, quality coating process
- Install QC equipment to identify defects, determine root cause
- Demonstrate feedback procedure to eliminate critical flaws in the deposited film
- Demonstrate thin electrolyte (~10µm) film coating method

Expected Outcome and Payoff

This project is similar to applying the supported catalyst layer to the electrolyte membrane or the GDL. Although the final state of the SOFC is a rigid ceramic multilayer composite, the initial stages of processing for the planar SOFC geometry can be related to processes utilized in PEM fabrication. Inspection requirements and QC equipment may also be similar. The contrast between the two technologies is that the PEM coating would be black and opaque on a transparent substrate, while the ceramic layer would be white and opaque deposited on a green substrate.

Successful completion of this project will reduce unit costs by increasing the throughput of cells and increasing the acceptance rate of cells by identifying and eliminating critical flaws in thin electrolyte films and ignoring defects that do not impair function.

A tubular SOFC system capable of generating 500 W or less would achieve a break even ROI at 3,300 units of production, equivalent to 1,000 kW of power generation capacity.

A tubular SOFC system capable generating 500 W to 10 kW would achieve a break even return on investment at 2800 units of production, equivalent to 3500 kW of power generation capacity. This is equal to a saving of $460/kW.

III.2.3. Manufacturing of Low-Cost, High-Efficiency Insulation Packages

Project Description

Objective

Fuel cell manufacturers at every power level are in need of high performance insulation materials to reduce the size, weight, and cost of their systems. The insulation industry currently produces a microporous material compatible with the performance requirements of solid oxide fuel cells; however, it is only available in sheet form. The current best practice for manufacturing high performance, shaped insulation pieces, is to dry machine pressed sheets of microporous insulation into a final shape. In the case of tubular solid oxide fuel cell stacks (from 500 W to 10 kW), the machining waste stream can be as high as 80% since the insulation material is highly friable. Manufacturing scale up and cost reduction is limited by the speed and capacity of the machine tool spindle speed, table dimensions, and dust collection rate.

The objective of this project is to capture best practices from outside the fuel cell industry and develop a scalable and repeatable method for low cost manufacturing of SOFC insulation that reduce costs by more than 50%.

Overview

Solid oxide fuel cells (SOFC) operate at temperatures between 600 ^{0}C and 800 ^{0}C and require highly efficient insulation materials. The best practices for insulation materials and methods are a balance between cost and performance. Extremely high performance insulation materials, typically termed microporous insulation, exist in the industry with reported thermal conductivity at 800 °C of 0.02 watt/meter-°K. The use of these materials is driven by the universal need to reduce packaging weight and volume across the entire SOFC industry, including both planar and tubular systems at every power level. The importance of minimizing insulation weight and volume is obvious for portable and mobile solid oxide fuel cell systems. In these demanding markets, customer purchasing decisions are strongly influenced by overall unit system size and weight. There also exists a critical need for lightweight, high performance insulation for high power stationary solid oxide fuel cell applications. The need to minimize mass and volume of insulation within a stationary generation unit is a function of cost and package integration. Minimizing the footprint of a stationary generation unit will help open new markets such as roof top generation, reduce shipping expenses, and remove the need for onsite assembly and integration during installation.

A low cost net shape or near net shape forming process for high performance insulation materials is needed across the entire SOFC industry. Fundamentally, the raw material is extremely low cost; a complete insulation assembly for a SOFC system (less than 500 W) is less than $10. The cost gap between raw material (silica, refractory fiber, opacifiers, and binders) and the pressed boards used as the starting material for the machining operation offers a significant cost reduction opportunity for a single step, net shape forming process.

Currently, microporous insulation is made from low cost silica powders, ceramic fibers, and opacifiers formed into sheets. Fuel cell manufacturers then machine these sheets into the geometries required to insulate components.

- Incoming dry pressed sheets of microporous insulation are pre-cut
- The material is then CNC machined to shape
- The parts are carefully removed from the machine tool and a surface coating is applied to reduce surface discharge of dust
- The individual machined microporous parts are assembled into the required final form according to the specific designs of the fuel cell manufacturer
- The result is a lightweight, compact, and extremely high performance and high temperature insulation package

Specialty CNC machine tools with sealed spindles, enclosed machining volumes, and HEPA dust collection is required to machine this friable, low strength material. This process must be isolated from other manufacturing areas to avoid cross contamination. Subtractive forming processes, like machining, reduce a majority of the expensive insulation board into waste. The final machined part must then be encapsulated with a surface coating to capture surface dust from the machining process or dust release during subsequent handling or operation. Once the individual machined pieces are hand assembled, an external wrap of fiberglass, sheet metal, foil, or other material is applied to create a sealed or partially sealed final unit. The external wrap is especially important for insulation that will be subjected to excessive vibration in applications such as transportation. This process flow is represented in **Figure III-4**.

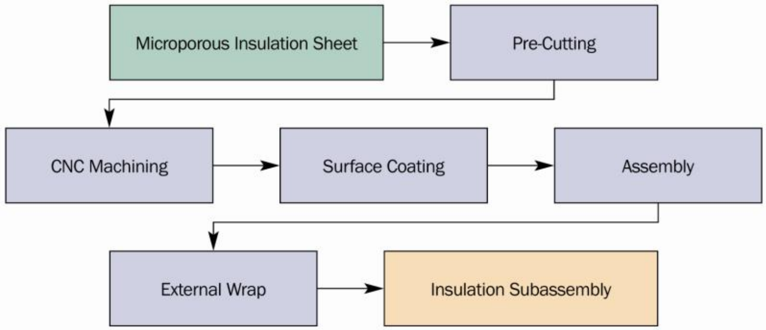


Figure III-4: Process to insulate components using Microtherm® microporous sheets

The technology does not exist today to dry press or cast high performance insulation materials into components more complex than a sheet or clam shell. The recommended manufacturing practice is to create a net shape or near net shape microporous insulation part using pressing or casting processes with tooling to create the component geometry. Including die or mold features to create pass through holes for electrical and fluid connections will help achieve the lowest possible cost per insulation component.

Quality Control Element

Along with the proposed net shape ceramic insulation forming process, this project also requires identification of potential defects that will negatively impact the insulating properties, strength, and shock resistance of the final product. Once these performance affecting, forming process related defects are identified, the project solution must also identify and validate non-contact, high-speed measurement technologies for process control. These measurement technologies must provide for rapid detection of the defects and for verification that the resulting parts meet dimensional and geometrical tolerances typically required by SOFC manufacturers.

Defect Detection

A common approach for defect detection is ultrasonic flaw detection, which uses several variable parameters (frequency range, type of waves, radiation conditions, and means of making contact).

Dimensional and Geometrical Verification

A high-speed inspection method for process control must be identified that demonstrates the required accuracy suitable for determining if the product parts (manifolds) meet the cell designer's dimensional and geometrical tolerance requirements. The critical measurement parameters should be identified and the process control strategy delineated.

- A suitable high-speed inspection technique will be identified by surveying the accuracy requirements of SOFC manufacturers. Consideration should be given to non-contact, structured-light measurement technologies for the fastest inspection, or more conventional contact measurement approaches if better accuracy is needed.
- An evaluation of non-contact structured-light measurements should include a quantitative evaluation of common errors inherent to the technique.

Major Tasks

1) Initial materials and operational consideration baseline
    - Using existing documentation and a mature SOFC insulation package design, compile the desired and functional objectives, design validation plan and reporting, bill of materials, and design failure modes effects analysis
2) Initial materials selection and manufacturing assessment of insulation systems
    - Materials selection – survey existing material sets from across the fuel cell OEMs and industrial insulation material manufacturers.
    - Manufacturing method – survey the industrial best practices for insulation forming methods (dry pressing, wet casting, precursors)
3) Engineering trade off analysis for materials and manufacturing process
    - Conduct an engineering trade study to determine not more than two material sets for follow on prototyping, down selection, and validation
    - Conduct the manufacturing assessment to select not more than two forming methodologies that can made be compatible with the functional objectives, insulation system design, and stack assembly process
4) Prototype manufacturing process assessment of stack insulation system
    - Design for manufacturing and assembly (DFMA) Conduct manufacturing and engineering development of the insulation system design, materials sets, processing methods, and final assembly on a prototype process design

    - Engineering design of process parameters, tooling, and assembly fixtures
    - Fabricate multiple units with down selected materials sets and prototype manufacturing methods
    - Evaluate fabricated components against manufacturing and performance targets
    - Perform a preliminary cost analysis and determine gap from program goal
5) Quality control and inspection process development
    - Design and integrate suitable inspection processes into the incoming raw material, forming, and assembly processing steps
    - Prototype revision of manufacturing process and materials
    - Engineering revision of the insulation manufacturing process, materials, tooling, fixtures, and assembly methods
    - Engineering revision of the quality control and inspection process
    - Manufacture and validate a statistically valid number of insulation systems in fully functional SOFC stack units
6) Low rate initial production (LRIP)
    - Demonstrate manufacturing process at designed production rate for a period of two weeks
7) Process Cost Analysis
    - Compile LRIP production data
    - Assemble a complete production cost analysis and calculate ROI
    - Conduct a supply chain analysis
8) Final Reporting

Project Costs

Project investment of $2.4 M

Expected Outcomes and Payoffs

The proposed program will reduce the cost of SOFC insulation subassemblies by developing and validating a scalable, single step, net shape forming process to transform low cost raw materials into final components. The output of the program will be the raw material selection, forming process procedures, tooling designs and prototypes, DFMA insulation design, assembly procedures, quality control and inspection methods, and cost analysis.

The final insulation manufacturing process will be demonstrated with a low rate initial production including quality control and inspection methods. The timing study, yield, and rate information will help compile a production cost analysis (at 5,000 units per year).

The cost metrics for the program are different based on SOFC geometry and power output. As an example, the cost metric for a tubular SOFC at less than 500 W is a threshold cost of $300 and an objective cost of $150.

The primary objective and timeline of the insulation project is independent of other Manufacturing Fuel Cell Manhattan Projects and can be run independently or in parallel with other projects. At the end of the insulation project, the fuel cell industry will benefit from a validated, low cost, and scalable manufacturing process for use in both tubular and planar solid oxide fuel cells.

Return on Investment

A tubular SOFC system capable of generating 500 W or less would achieve a break even ROI at 5,700 units of production, equivalent to 1,700 kW of power generation capacity.

A tubular SOFC system capable of generating more than 1 kW would achieve a break even ROI at 5,200 units of production, equivalent to 4,300 kW of power generation capacity.

III.2.4. Solid Oxide Fuel Cell Automated Assembly

Project Description

The need for stack quality, repeatability, and high yield in high volume production requires increased automation of stack assembly. Suppliers need tooling for high quality and repeatable components, while stack suppliers need to install assembly equipment to take advantage of more repeatable incoming components. Automated pick and place stacking equipment will add consistency to stack component position, registration, and variation. The assembly of cell active components, conductive pastes, seals and gaskets, current collection conductors, and associated frames, with robotic machinery can be implemented for SOFC cells, both tubular and planar. For automated assembly of both cells and stacks, proper alignment and registration of the individual parts are critical to maximize performance and minimize stresses. Exact dimensional measurements are not required, but rather the relative misalignment must be controlled between cell functional layers (in cell assembly) or cells and separator plates (in stack assembly). Vision systems mounted on the robotic or automated equipment help ensure the proper positioning of the sequentially assembled parts. Spatial sensitivity, lighting, and data processing for the vision system must be evaluated and optimized for the materials, throughput, and other desired process conditions.

Major Tasks

Automation of cell manufacturing:

- Identify scalable automated assembly methods for tubular and planar cells
- Design and build pilot-scale equipment and tooling
- Demonstrate cell assembly equipment at a daily rate equivalent to 150,000 units/year

Automation of stack assembly:

- Identify scalable automated assembly methods for tubular and planar stacks
- Design and build pilot-scale equipment and tooling
- Demonstrate stack assembly equipment at a daily rate equivalent to 5,000 units/year

Development and validation of automated inspection:

- Identify appropriate vision systems or other tools capable of registration and alignment inspection in conjunction with the automated assembly methods developed in the first two tasks

- Determine optimal operational conditions and parameters for implementation of these inspection techniques at the defined throughput rates

Project Costs

Project investment of $2.9 M

Expected Outcomes and Payoffs

For planar SOFCs, this project would result in an estimated savings of $450/kW from 3 kW to 300 kW. This results in a break even ROI after 6500 kW (1600 units) are produced.

For tubular SOFC, this project would result in an estimated savings of $480/kW from 300 W to 10 kW. This results in a break even ROI after 6100 kW (7600 units) are produced. A system capable of generating 500 W or less results in a break even ROI at 5400 kW (or 17,800 units) of power generation capacity.

III.2.5. SOFC Stack Manufacturing, Commissioning, and Testing

Project Description

This project establishes high-rate and high-utilization processes for (1) seal conditioning; (2) anode reduction; and (3) electrochemical acceptance testing by increasing the throughput and utilization of stack manufacturing capital equipment.

After a SOFC stack is assembled, it needs to be placed into a furnace and brought up to a high temperature. The required temperature is based upon the various manufacturers' needs for debindering, achieving proper contact with any applied interconnect pastes, anode reduction, and seal requirements. Typically, a single stack is ramped up to the required temperature, the anode reduced and made electrochemically active, performance tested, and ramped back down in temperature in a single, high temperature stand. The process of commissioning the stack (making it electrochemically active) and completing the requisite acceptance testing typically can take up to 48 hours. Stack acceptance testing conducted on the as-built stack can take a variety of forms, and may include polarization testing, fuel utilization, load profile and cycling, thermal cycling, or other functional tests to assure acceptable stack performance. The stands tend to be expensive capital items due in part to the stack build requirements and to the testing requirements. Stand requirements generally include, but are not limited to the following.

- Capabilities to process, characterize, and perform product development and validation testing)
- Handle high temperature materials
- Safely handle hydrogen and other combustible gasses
- Provide a flexible platform to allow for new tests to be performed or developed (software costs)

Depending on the size of the stack being commissioned and the requirements noted above, the stands typically cost between $100,000 and $500,000 depending on the furnace size and gas flow capability. This accounts for a significant portion of the overall cost of manufacturing a stack.

Sample images of stack build, commissioning, and test stands currently in use for planar SOFC stack fabrication are shown in **Figure III-5**.

Figure III-5: Test stands for planar SOFC stack fabrication

Major Tasks

Seal Conditioning & Leak Check: Design, build, and demonstrate pilot-scale equipment capable of conditioning at a rate of 9 to 12 stacks/day. Equipment must be capable of processing both planar and tubular stacks with minor tooling changes.

Anode Reduction & Electrochemical Acceptance Testing: Design, build, and demonstrate pilot-scale equipment capable of anode reduction and electrochemical testing at a rate of 9 to 12 stacks/day. Equipment must be capable of processing both planar and tubular stacks with minor tooling changes.

- Combine anode reduction & electrochemical testing into one piece of test equipment
- Separate anode reduction & electrochemical testing into separate pieces of test equipment if it can improve manufacturing throughput or reduce capital costs

Project Costs

Project investment of $ 4.3 M

Expected Outcomes and Payoffs

For planar SOFCs, this project would result in an estimated savings of $920/kW from 3kW to 300 kW and a break even ROI after 4700 kW (or 1200 units) are produced.

For tubular SOFCs, this project would result in an estimated savings of $290/kW from 500 W to 10 kW and a break even ROI after 11,900 kW (or 14,900 units) are produced. A system capable of generating 500 W or less would achieve a break even ROI after 4,500 kW (or 15,000 units).

III.2.6. Net Shape Manufacturing of Stack Manifolds

Project Description

Stack manifolds (referred to as "endplates" for planar stacks and "plenums" for tubular stacks) are currently manufactured using expensive machining methods. This project will identify, validate, and reduce the cost of net-shape manufacturing processes for manifolds of planar and tubular stacks.

Major Tasks

In a planar SOFC stack, the manifolds provide the critical function of evenly distributing and directing the flow of air and fuel to the cathode and anode plenums, as well as providing sufficient mass for stack compression. Precise tolerances on intricate gas flow channels, surface finish, and flatness of endplate surfaces are critical to stack functionality. Similarly, the manifolds for tubular SOFC stacks provide a means of properly distributing fuel and air. These components are typically made from a metal plate with holes that are sized to the individual tubular cells. Traditionally, endplates for planar stacks and plenums for tubular stacks are fabricated via custom machining of high temperature alloys; however, use of a lower cost, faster, and scalable manufacturing method is essential to commercialization of SOFC stack technology. This project will focus on net shape manufacturing of planar stack endplates and tubular stack plenums. Specific subtasks are described below.

Task 1. Net-Shape Manufacturing of Endplates for Planar SOFC Stacks

A planar stack design will be selected in this task. Investment casting or similar methods will be considered for net-shape manufacturing of endplates of the selected design. The stack developer will engage metal fabricators to review the endplate design to identify potential processing issues. Features such as wall thickness of gas channel ribs, aspect ratios of thin-walled features, and dimensions of flat surfaces for subsequent welding operations will be considered. The stack developer and metal fabricator will make any necessary design modifications to optimize endplate design for net-shape manufacture without compromising stack performance.

The metal fabricator then will attempt to manufacture the endplates by the selected process. The endplate material will be a high-chrome alloy, selected on the basis of desired properties and availability. The stack developer then will build and test stacks with the net-shape manufactured manifolds to evaluate their performance. Multiple endplate design/manufacturing/test cycles will be executed before the final low-cost endplate design is achieved.

Task 2. Net-Shape Manufacturing of Plenums for Tubular SOFC Stacks

A tubular stack design will be selected in this task. Investment casting, stamping or similar methods will be considered for net-shape manufacturing of plenums for the selected design. The stack developer will engage metal fabricators to review the plenum design to identify potential processing issues. Features such as orifice tolerance, aspect ratios of thin-walled features, and dimensions of flat surfaces for subsequent welding operations will be considered. The stack developer and metal fabricator will make any necessary design modifications to optimize plenum design for net-shape manufacture without compromising stack performance.

The metal fabricator then will attempt to manufacture plenums by the selected process. The plenum material will be a high-chrome alloy, selected on the basis of desired properties and availability. The stack developer then will build and test stacks with the net-shape manufactured manifolds to evaluate their performance. Multiple plenum design/manufacturing/test cycles will be executed before the final low-cost design is achieved.

Task 3. Initial Product Component Specification Validation and Process Control Solution for Critical Parameters

To identify a casting process for SOFC tubular and planar stack manifolds, two quality related elements must be addressed.

- It must be demonstrated that the manifolds produced by the casting process meet typical manufacturer dimensional and geometrical specifications and that the impact of common casting defects (i.e., gas porosity, shrinkage defects, mold material defects, pouring metal defects, and metallurgical defects), if present, do not impact the manufacturer's application specific performance
- A high-speed inspection method for process control must be identified that demonstrates the required accuracy suitable for determining if the product parts (manifolds) meet the cell designer's dimensional and geometrical tolerance requirements. The critical measurement parameters monitored should be identified and the process control strategy delineated.

Project Costs

Project investment of $2.7 M.

Expected Outcomes and Payoffs

This project is related to the "Protective Coatings" project. Further reduction of endplate costs can be achieved with successful implementation of protective coatings. The primary benefit the project will be a substantial reduction of stack manufacturing cost when volumes reach 1 MW to 10 MW per year.

III.2.7. Powder Acceptance

Project Description

Many types of ceramic powders with varying degrees of consistency are used in the manufacture of solid oxide fuel cell electrolytes, anodes, and cathodes. The bulk of the reproducibility issues occur with the oxygen electrode or cathode powders. The subject matter experts agree that the requirement for consistent cathode powders is a significant need, Every SOFC developer literally has their own composition for oxygen reduction activity, conductivity, and particle characteristics for their processing needs. There is an art to synthesizing and depositing the cathode. However, they could not agree on what type of project could be made applicable to all parties. The group consensus was that a general development in powder characterization technique was needed that could determine the electrochemical activity of the powder, without requiring the time-consuming process of making and testing a fuel cell to validate the powder.

This project focuses on developing quality control methods that can be used at the powder manufacturer or fuel cell fabricators to ensure that acceptable powder is produced. A consortium of powder manufacturers and fuel cell fabricators could be formed to supply both “good” and poor” batches of powder to support the development of the methods. Because of the proprietary nature of testing a wide variety of ceramic powders from various powder manufacturers and fuel cell fabricators, secure data handling is necessary. At the same time, the service must demonstrate value to the industry partners as a whole.

As a starting point, “good” ceramic powders are defined as those that form acceptable cathodes while “bad” powders are those that form unacceptable cathodes. Therefore, the determination of acceptability ultimately is determined when the powder has been formed into a cathode, is tested and demonstrates acceptable electrical conductivity and electrocatalytic performance resulting in a low area specific resistance or cathodic overpotential.

A test plan will need to be developed that identifies tests that may shed light on powder inconsistencies. Statistical experimental design methods will be used to develop a testing matrix. The test plan may be modified as additional information is discovered during the testing phase. As a minimum, the test plan will specify the following:

- Analytical methods along with quality assurance/quality control aspects
- Quantity of sample required
- Test organization
- Number of samples/replicates/controls
- Sampling techniques
- Downstream processing steps for cathode formation, with QA/QC included

Preliminary test results will be reported to the participants of the study. Recommendations will be made regarding testing necessary for detecting acceptability of ceramic powders. The intent of these recommendations is to develop relatively simple and inexpensive standardized tests that the entire industry can use to determine the acceptability of ceramic powders and allow manufacturer to produce more consistent lots. In addition, a preliminary cost analysis will be completed that shows the true cost of the recommended testing.

Project Costs

Project investment of $1.5 M

Expected Outcomes and Payoffs

The benefit of developing a set of quick and inexpensive evaluation tests for ceramic electrode powders amounts to 3-4 hours of evaluation time to determine if the powder will perform as it is designed instead of a week of technician effort each time a batch of powder is delivered.

III.2.8. SOFC Current Collection

Project Description

Objective

The overall objective of this project is to fully automate the application of the current collection system upon tubular SOFC. The present methodology involves hand application of the wire, which leads to issues with quality and cost.

- Eliminate 95% labor from the current collection application process through automation
- Improve the quality of the applied current collection layer through ensuring uniform repeatable coverage of the cathode and effective termination of the wire at the start and finish of winding
- Improve cell robustness to thermal cycling through application of the current collection at uniform tension
- Eliminate the re-work and scrap associated with the incumbent wire winding process

Statement of Work

Tubular solid oxide fuel cell (SOFC) systems with power output in the range of 50 W to 10 kW employ metallic current collectors to distribute electrical current along the length of the fuel cell tube. Presently, the best practice for application of tubular current collection solutions involves the hand wrapping of wire along the tube length, with time consuming wire anchoring operations at the start and finish of the wire wrap. This application process is labor intensive, creates significant scrap or rework, and does not generally provide a uniform and repeatable current collection solution.

Another related challenge, is the effective distribution of current along the tube axis. With tubular systems, the conductive path length is considerably longer than in a planar stack, therefore ohmic losses (resistive losses) in a tubular SOFC are typically the dominant loss mechanism.

Every fuel cell organization producing tubular SOFC cells, stacks, and systems, share a common set of building blocks; a tubular membrane electrode assembly (MEA) and current collector wire. The conductive metallic wire arrangement upon the cell is different for different SOFC producers. Some manufacturers apply all the current collection to the outer diameter of the cell, making separate contact with the anode and cathode. This can simplify the mechanism of current collection application. Other manufacturers make external contact with the cathode and then have an internal current collection contact mechanism for the anode. Both current collection methods are effective in the transport of current along the tube axis.

For developers of tubular solid oxide fuel cells, the manufacturing labor, cycle time, cost, and scrap rates for the existing wire wrapping and winding process methods account for a nominal 20% of the total cell cost.

The adaption and implementation of high rate automated wire winding and tie off equipment from the electric motor and electronic inductor industries would help the entire tubular solid oxide fuel cell industrial base to reduce labor, cycle time, and scrap rates while increasing repeatability and reliability of the fuel cell stack. In addition, attachment of the series connection between cells when assembling cells into a stack would significantly benefit through automation since this step is also a manual process.

Major Tasks

The major tasks required to implement a fully automated current collection system are detailed below.

Best practice identification - Identify the wire winding technologies utilized by other industries such as the electric motor and electronic inductor industries that may be applicable for technology transfer. Assess technologies and determine the preferred solution based upon ability to achieve cost and technical criteria. Task Duration 500 hours.

Proof of concept trials – Run proof of concept trials at vendor to fully evaluate available technologies. Task Duration 300 hours.

Milestone: Down select to one or two possible solutions.

Fabricate semi-automatic proof of concept fixture – Build semi-automatic proof of concept fixture capable of validating the selected current collection application methodology. The selected technique must be capable of applying the wire in a uniform secure fashion and allow tie on and tie off capability. Task Duration 900 hours.

Development of automated quality assurance methodology and equipment – In parallel with the fabrication and demonstration of a semi-automatic proof of concept fixture, automated quality assurance equipment will be developed and integrated with the winding fixture. The alignment and registration of the interconnect wires wound onto the cell tube are critical to minimize electrical resistance losses in the tube stack. Exact dimensional measurements are not required. Rather, the placement of the wires relative to the anode and cathode segments of the tube must be verified. Vision systems can be mounted on the robotic or automatic winding equipment to ensure the proper interconnect winding location. Sensitivity, lighting, and data processing for the vision system will be evaluated and optimized for the tube and interconnect materials, winding speed, and other process conditions. Task duration 480 hours.

Current collection evaluation - A number of evaluation schedules and tests will be performed upon cells with the current collection applied using the developed fixture.

- Electrochemical testing - Single cell electrochemical testing will be undertaken to evaluate cell performance at standard operating conditions. Accelerated lifetime trials will then be completed to evaluate performance at different current densities and temperatures. A thermal cycle evaluation will also be undertaken to determine the robustness of the cells are when undergoing this operation. Single cell electrochemical data will form the basis for iterative feedback to allow improvements in the winding technique to take place in an ongoing basis. Task Duration 600 hours.
- SEM Analysis - In this subtask the interface between the metallic current collection system and the electrode will be probed and evaluated. Task Duration 80 hours.
- Cost Analysis - An initial cost screening will be undertaken to evaluate the potential cost of the fully automated current collection application system. Task Duration 80 hours.

Milestone: Summarize current collection evaluation developments and identify areas of fixture optimization.

Fully automated fixture development – Based upon feedback from the initial testing results, modifications to the fixture will be implemented to optimize and fully automate the current collection application methodology. Task duration 700 hours.

Deposition methodology optimization – Optimize cycle time and quality of application. Task duration 500 hours.

Series connection testing – Evaluate the robustness of the series connection between cells prepared with the updated current collection system. In its simplest form, this will involve the connection in series of two cells, followed by electrochemical evaluation. This evaluation will include an assessment of how robust the cells current collection and series connection is to repeated thermal cycling and elevated current density conditions. Following electrochemical evaluation, the cells will be inspected to determine any failure mechanisms through a visual inspection and SEM analysis. Task duration 700 hours.

Stack Test and Evaluation – A number of stacks will be assembled from cells having their current collection system applied through the developed wire winding technology. These stacks will then be evaluated for overall performance. Task duration 700 hours.

Final report – A final report will be prepared to detail the cost savings realized and document the success of the project. Task duration 80 hours.

Project management – Project management will be undertaken throughout the entire project to ensure that milestones are achieved on time.

Milestone:

- Down select to one or two possible automation solutions at the end of Q2, year 1
- Fully fabricated proof of concept fixture at end of Q3, year 1
- Summarize current collection evaluation developments and identify areas of fixture optimization at the end of Q4, year 1
- Fully automated fixture by end of Q2, year 2
- A final report will be prepared to detail the cost savings realized and document the success of the project at the end of Q4, year 2

Project Costs

Project investment of $2.2 M

Expected Outcomes and Payoffs

The project described in this proposal has a relationship with another identified project, “Protective Coatings for Metallic Stack Components.” The fully automated current collection application system must be able to accommodate the incumbent wire and also the coated wire developed in the protective coatings for metallic stack components project.

The benefits of this project are itemized below.

- Eliminates 95% of the labor associated with current collection application
- Eliminates the scrap and rework associated with the current hand application system
- Significantly improves current collection uniformity and therefore repeatability between cells
- Performance improves at both the cell and stack level due to current collection uniformity – cell to cell performance spread narrowing
- Cells and stacks will be more robust to thermal cycling due to application of the current collection system at uniform, pre-determined tension

A tubular SOFC system capable of generating 500 W or less would achieve a break even ROI at 950 kW (or 3,200 units) of power generation capacity. A system capable of generating more than 1 kW but less than 10 kW would achieve a break even ROI 3,000 kW (or 2,400 units) of power generation capacity. This equates to a saving of $920/kW.

III.3. BOP FUEL CELL PROJECT DESCRIPTIONS

Summary

The Balance of Plant (BoP) consists of all the subsystems of a fuel cell power system that support stack operation (either a polymer or ceramic stack). It has a manufacturing cost 40% to 80% of total system cost depending on the specific system configuration or application. The five major BoP subsystems: (1) Reactant Management; (2) Thermal Management; (3) Controls; (4) Power Management; and (5) Mechanical /Packaging include pumps, blowers, filters, reactors, separators, humidifiers, dehumidifiers, heat exchangers, inverters, sensors, and electronics. The subsystem with the largest cost impact and the one singled out for major cost reduction is Reactant Management, although some of its components (i.e., heat exchangers) are used in other subsystems as well. Reduction in the manufacturing cost of the BoP is challenging because the BoP has many different complex configurations that are fuel cell specific and the choice/design of the subcomponents is system/application dependent.

The Reactant Management subsystem is subdivided into fuel processing, fuel and oxidant delivery and water management. Several projects have been developed for cost reduction. The specific BoP components and their typical application within the Reactant Management Subsystem or other subsystem are noted below:

- **Anode gas delivery** - (Fuel and Oxidant Delivery) – Examples include: centrifugal blowers, compressors, positive displacement machines such as scroll, diaphragm or roots type, that are compatible with hydrogen rich gas
- **Humidifier** - (Water Management) – Examples include: membrane tube and sheet type
- **Heat exchanger** - (Fuel and Oxidant Delivery, Fuel Processor and Thermal Management) – Examples include: preheaters, recuperators, radiators
- **Liquid pump** - (Fuel and Oxidant Delivery, Fuel Processor) – Examples include: piston, peristaltic, positive displacement machines such as scroll, diaphragm or roots type
- **Flow meter** - (Fuel and Oxidant Delivery) – Examples include: film, anemometer, positive displacement
- **Over specification** (All components)
- **Cathode /reformer air delivery** - (Fuel and Oxidant Delivery, Fuel Processor) – Examples include: centrifugal blowers, compressors, positive displacement machines such as scroll, diaphragm or roots type

Four factors were used to select these specific components: potential for significant cost reduction at the system level, application to different stack types and power levels, as well as, diversity of military applications.

Table III-3 contains a summary of the projected net total savings ($/kW) rolled up to the system level for the two different stack types and four different power levels developed from the project results assuming all the BoP cost reduction initiatives are successful. Savings range from about $170/kW for the highest power systems to $3100/kW for the lowest power systems.

Recommended BOP Projects	Polymer Savings ($/kW)				Ceramic Savings ($/kW)			
	sub kW	5 kW	10 kW	100 kW	sub kW	5 kW	10 kW	100 kW
Cathode/Reformer Air Delivery	376	81	78	67	376	81	78	67
Anode Gas Delivery		187	95	44		187	95	44
Humidifier	764	206	146	60				
Heat Exchanger	600	250			1200	500		
Liquid Pump	1400				1400			
Flow Meter (Not Additive to Liquid Pump)	1400				1400			
Over Specification (Not Additive)	825	150	125	100	825	150	125	100
Net Total Savings ($/kW)	3965	874	444	271	3801	837	300	211

Table III-3: Summary of recommended BoP projects and cost reductions

III.3.1. Manufacturing of Low-Cost, High-Efficiency Heat Exchangers

Project description

Present systems expensive and bulky.

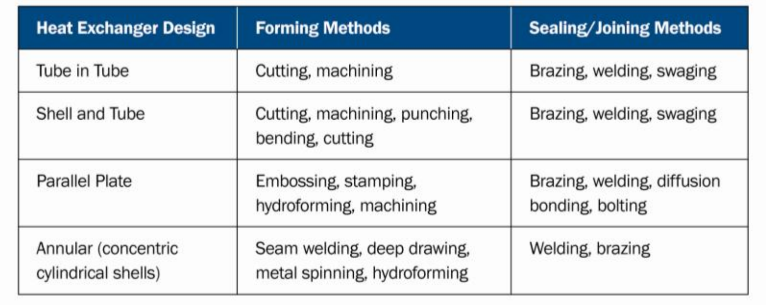
Objectives

Solid oxide fuel cells operate at temperatures well above about 650 ºC. The heat balance to maintain this temperature can be challenging while feeding large amounts of ambient air for cathode reactant supply. Thermally self-sustaining solid oxide fuel cell (SOFC) systems typically employ exhaust recuperators to recover exhaust heat and preheat the cathode air prior to entering the stack. The recuperator design can be selected from among many heat exchanger types. Regardless of the chosen design, certain performance criteria must be met for the particular application including:

- Low pressure drop
- High thermal effectiveness
- High thermal stability and thermal cycle durability
- Light weight and low volume
- Ease of integration with the system
- Low cost

At present, there is no defense industrial base for heat exchangers suitable for fuel cells. Fuel cell manufacturers design and build their own heat exchangers customized for their own design needs. While these custom models meet most of the above performance requirements, the cost is far from targets necessary for commercialization. To date the choice of materials has been towards risk minimization and expediency of execution. Usually, this is driven by the timeline of developing whole fuel cell systems in a relatively short period, typically less than 12 months. Inconel and other high nickel super-alloys are the materials of choice because of experience in workmanship and certainty in materials compatibility with the working environment of the SOFC stack. Flexible but expensive and wasteful machining methods are used because of their expediency. Consequently, there are many opportunities for optimizing the design manufacturing process for reducing cost.

Heat exchanger technology and design theory in general is very mature and well understood. The main types of heat exchanger designs available are listed in **Table III-4** along with typical manufacturing techniques.



Heat Exchanger Design	Forming Methods	Sealing/Joining Methods
Tube in Tube	Cutting, machining	Brazing, welding, swaging
Shell and Tube	Cutting, machining, punching, bending, cutting	Brazing, welding, swaging
Parallel Plate	Embossing, stamping, hydroforming, machining	Brazing, welding, diffusion bonding, bolting
Annular (concentric cylindrical shells)	Seam welding, deep drawing, metal spinning, hydroforming	Welding, brazing

Table III-4: Types of heat exchangers

In addition to these heat exchanger types, multi-functional elements that in part serve the recuperation function are also of interest. For example, the insulation package could also serve as one wall of the exhaust side gas channel in the recuperator. Nevertheless, a specialized recuperator of this type would likely fall under one of the four main heat exchanger types in the table above.

Cost is ultimately a function of the raw materials and the manufacturing process. High temperature alloys (e.g., Inconel 600 series) are often used as the bulk of material in construction in order to achieve the durability goals in the high temperature, oxidizing environment. Even with exotic alloys, however, the material cost typically does not exceed a few tens of dollars. The high costs are mostly driven by the low maturity of the manufacturing processes employed in the industry today. For each of the heat exchanger types, the component parts are formed, assembled, and sealed/joined. In low volumes, expensive tooling costs typically limit advanced forming options and assembly is entirely by hand and often includes time consuming braze material application or highly skilled hand welding. Thus, the challenge in reducing fuel cell system recuperator cost is primarily a design for manufacture and assembly (DFMA) and investment in manufacturing equipment.

Statement of Work

The ultimate objective of this project is to exploit the opportunities described above and reduce the cost of the extant SOFC recuperator component. This project will focus on materials and design selection, elimination of unnecessary design features, optimization of heat exchanger and system integration, application of volume production methods, DFMA, and lean manufacturing. Given the nature of many of the metal forming and joining methods employed, this project will have a significant tool design and optimization component.

Success will be judged by demonstrated costs of limited production runs and design verification testing of performance and lifetime testing under representative SOFC operating conditions. Risk will be minimized by planning for multiple design/build/test iterations for optimization of cost and performance.

Major Tasks

Recuperator DFMA

This task will optimize the materials and manufacturing approach for cost minimization of the recuperator component. Beginning with current and demonstrated recuperator designs, a thorough review and comparison of integration strategies, materials selection, and manufacturing methods will be completed. This task will be executed in parallel with the task "evaluate manufacturing methods" below in order to incorporate demonstrated and optimized manufacturing data into the design.

Evaluate manufacturing methods

Tradeoffs among forming and joining methods will be evaluated in this task. This task will also provide baseline data for manufacturing processes employed in later tasks. For example, if a stamping forming method is chosen, representative tooling will be built and tested and used to not only demonstrate confidence in the technique but also calibrate design rules for final tool production. If edge welding is chosen for joining, test parts and welds will provide valuable data for establishing optimized welding parameters. Other forming and joining methods would provide similar guidance and confidence before proceeding to limited production runs in the next task.

Component durability in the high temperature, oxidizing environment, sometimes directly exposed to combustion processes, is of particular concern in this program. Materials and joints from representative test articles will be tested for durability (e.g., oxidation resistance) in simplified tests like weight gain measurements in long term furnace exposure and thermal cycle testing.

Limited production run

Full size tooling will be built in this task for forming and joining methods chosen in the previous tasks and used to produce small (~25) production lots of recuperator components to be used in the SOFC system. Examples of tooling produced in this task include forming dies, cutting and end-prep jigs braze applicators or printers, and assembly and alignment jigs. Welding tracks braze furnaces, presses, and other equipment will be sourced or otherwise built as necessary.

While joining-method test articles from the previous task will significantly reduce risk in initial production, it is expected that some tuning will be necessary in this task. Alignment, straightness of parts, and leakage will be tested. Multiple production runs will be executed for optimization of the production process steps with the purpose of maximizing quality and yield.

Design verification testing

Production runs with acceptable quality will be evaluated for performance, durability, and function in the fuel cell system. This task will start with relatively simple performance verification to measure pressure drop and heat exchanger effectiveness against design model expected performance.

The bulk of this task will demonstrate durability in representative operating conditions. Testing will include not only long-term durability at steady state conditions, but resilience at high temperature excursions, thermal cyclic tolerance (stability of oxide scales, spalling resistance, and mechanical stresses), redox resistance, and other chemical resistance factors.

Expected degradation effects include parts deforming resulting in increased pressure drop and leak formation from joint corrosion or stress cracks. If necessary, this task will allow iteration on the heat exchanger design and manufacturing process to address any problems that might arise or to exploit further opportunities to reduce cost.

Project Costs

The total proposed project cost is $2 M for two years broken into materials ($580,000), labor ($1.1 M), and other direct costs ($150,000). Materials include specialized tooling and raw materials for prototype test articles and manufacturing runs of new heat exchanger designs including the DFMA changes. Multiple productions runs allow investigation of alternate manufacturing approaches and iterations on the manufacturing process. Advanced manufacturing equipment and test equipment for design verification are also included in the materials budget.

Expected Outcomes and Payoffs

The expected cost reductions from this program and ROI are shown in **Table III-5** for two different SOFC generator power ranges.

These costs include materials and labor. The raw materials cost for one of these components can be easily calculated. Assuming an expensive high temperature alloy (e.g., Inconel 625) at less than $15/lb, and a recuperator weight of 10 lb in a 5 kW application, the raw materials cost falls well below the $500 target cost. Lightened designs will show even more savings. With manufacturing optimized for cost, there appears to be no obstacle to achieving the target cost. The targets in the table represent not only what appears to be achievable with optimized manufacturing but also component prices necessary to achieve overall acceptable system cost targets.

Power Range	Current Average Cost	Target Cost	Savings per kW	# Systems for ROI	ROI per kW
<500 W	$750	$150	$1,000	3,300	1,700
1 to 10 kW	$2,500	$500	$200	10,000	5,000

Table III-5: Cost savings and ROI per power range

The returns on investment for sub-kilowatt systems, with tactical applications including battery chargers, and specialized generators [e.g., unmanned aerial vehicles (UAVs), unmanned underwater vehicles (UUVs)] acquisitions exceeding 5000 units in two years is easily achievable resulting in a positive return on investment (ROI) in well under 2 years. Similar unit demands for mobile power and auxiliary power unit (APU) applications in the 1 to 10 kW range are also projected and lead to an ROI in two years.

The output of this project will be a cost optimized heat exchanger design and manufacturing process that will significantly reduce cost while simultaneously increasing reliability and process yield. Given the high cost of custom manufacturing of current heat exchangers, this program is expected to enable commercialization of SOFC generators. Indeed, without these proposed reductions, the current heat exchanger solutions are cost prohibitive for most markets.

III.3.2. Manufacturing Improvements for Liquid Flow

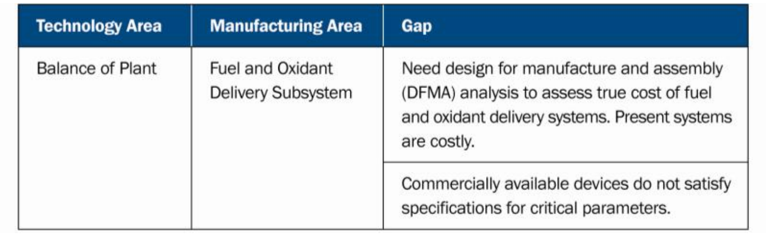
(A) Improvements for Liquid Metering Pumps for Sub-Kilowatt Reformer Based FC Generators

Project Description

Description of Component

The ability to meter liquid accurately and with low pulsation is critical to feeding liquid fuel to reformer based fuel cell systems particularly for small portable systems. The liquid metering pump fulfills this purpose, but few commercial off-the-shelf (COTS) articles exist and those that do are very expensive.

Gaps are noted in **Table III-6**.



Technology Area	Manufacturing Area	Gap
Balance of Plant	Fuel and Oxidant Delivery Subsystem	Need design for manufacture and assembly (DFMA) analysis to assess true cost of fuel and oxidant delivery systems. Present systems are costly.
		Commercially available devices do not satisfy specifications for critical parameters.

Table III-6: Gaps for Liquid Metering Pumps

Objectives

Fuel cell systems operating on liquid fuels require liquid handling components to control flows to the reformer subsystem. All reformer approaches (except premixed methanol/water fuels) require controlling the fuel/air or fuel/steam ratios of the feed mixture to the reformer accurately. In some cases, particularly partial oxidation approaches, the accuracy and precision requirements on this feed ratio are very high necessitating high quality metering components. In addition to accurate control, other desired features include low weight, small volume, reliable long lifetime, and low pulsation.

As with most balance of plant (BoP) components, liquid metering pumps specifically designed for fuel cell applications are generally not available. Few adequate pumps exist, and those that do are borrowed from other specialized applications and industries often at high cost. For example, a dosing pump designed for pharmaceutical manufacturing might offer the accuracy and low pulsation needs, but also might include unnecessary features such as low toxicity materials.

Machinery that achieves accurate and pulseless flow typically employs a gear or gerotor pump head. To minimize the effects from changes in downstream pressure on the metered flow rate, these parts are fitted with very close tolerances to minimize internal leakage, and smaller scale applications require even more stringent tolerance dimensions. Manufacturing processes employed to achieve these tolerances typically include expensive machining, surface preparation, and hand fitting steps. Furthermore, controlling flow (open loop) also requires controlling motor speed, which is typically achieved using a combination of a motor with an encoder or feedback Hall effect sensors, and a motor controller circuit, both of which add significant cost to the system.

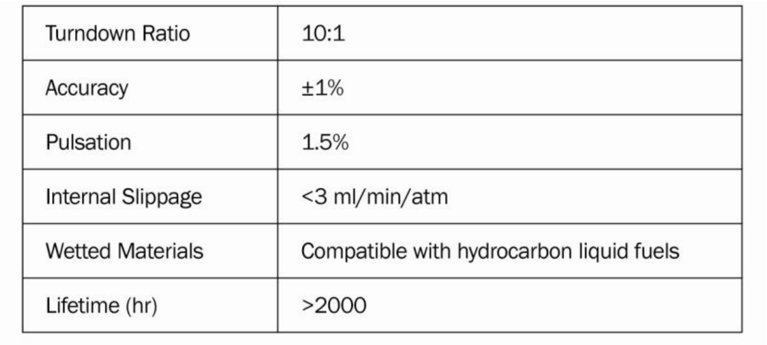
Improvements to manufacturing of these devices should be directed to lower cost and achieve fuel cell system specific performance requirements. COTS pumps available today that meet typical fuel cell system performance requirements can easily exceed $1000. Specific cost reductions of a factor of 2 to 10 are desired to meet BoP cost budget goals with smaller applications requiring the larger reduction.

Statement of Work

Fuel cell manufacturers are typically not pump manufacturers. Reducing the cost of the liquid handling component will most likely require the fuel cell manufacturer or the fuel cell community to approach pump manufacturers with the specific performance needs of the fuel cell applications.

The proposed program will reduce the cost of precision metering pumps by reducing the cost of manufacturing associated with close tolerance gear pump designs that offer continuous and accurate flow. Specific attention will be paid to fuel cell specific applications. The output of this program will be a pump design, assembly procedure, and process for manufacturing high precision pumps.

While the pump flow requirements will vary with regard to the application in which it is used, applications of less than about 1 kW are of particular interest. Thus, pumps should provide a maximum flow rate of less than about 10 ml/min or a maximum of only about 1 ml/min for generators of about 100 W output. For a given maximum flow rate, the new pump will also exhibit the characteristics shown in **Table III-7**.



Turndown Ratio	10:1
Accuracy	±1%
Pulsation	1.5%
Internal Slippage	<3 ml/min/atm
Wetted Materials	Compatible with hydrocarbon liquid fuels
Lifetime (hr)	>2000

Table III-7: Pump flow requirements

Turndown is required for load following and shut down operations, and the reported accuracy should be delivered over the full flow range. Delivery pressure requirements for most applications are small (< 7000 Pa) unless a downstream membrane separator is used. In either case, the pump should be able to deliver the required flow characteristics.

Major Tasks

Device design and assembly process evaluation

Manufacturing improvements to improve cost will start with relaxing existing product requirements to provide only the features necessary for fuel metering applications in fuel cells. Existing pump designs will be evaluated for these potential changes. Opportunities for streamlining and cost reduction might be found in both the device design and the assembly process.

Optimize design and manufacturing for cost reduction

In addition to eliminating unnecessary design and process steps for the pump, its design and assembly process will be modified specifically for cost reduction (i.e., DFMA). The following discussion suggests possible improvements, some of which might already be implemented in the manufacture of existing pumps. Individual parts will be examined for applicability for near net forming methods to reduce the need for secondary machining and surface preparation. Fitting close tolerance moving parts often requires an iterative hand fitting process. This task will reduce hand fitting and selection of parts by optical screening and automated pairing of close-mated parts and using self-aligning designs where feasible. Pre-assembly wear-in jigs might also speed production.

Apply optimized manufacturing processes for high precision pump parts

In this task, trial production runs will examine the practicality and effectiveness of the DFMA strategies developed in the previous task. Limited production runs of 20 to 50 units will incorporate these changes and output prototypes to be used in the next task that will verify the design performance. These production runs will also enable direct labor measurements to predict volume costs.

Characterize and test pumps

Pumps produced in this program will be tested under conditions relevant for the targeted fuel cell application. Performance testing over at least a 1000-hour lifetime will characterize degradation if any in accuracy, pressure/flow characteristics, pulsation output, and internal slippage.

Project Costs

Project investment of $815,000 is broken into materials ($310,000), labor ($475,000), and other direct costs ($30,000). Materials include manufactured parts for prototype runs of new pump designs including the DFMA changes. Multiple productions runs allow investigation of alternate manufacturing approaches and iterations on the manufacturing process. Advanced manufacturing equipment and test equipment for design verification are also included in the materials budget.

Examples of currently available pumps easily exceed $1000 when purchased by the fuel cell integrator. It is likely that some of this cost will be reduced in volume purchases. This project will specifically and significantly reduce manufacturing costs as described above. The estimated cost savings is about $700 per unit and $1200 per kW basis.

The expected ROI is $740/kW (or 1500 systems). For sub-kilowatt systems, with tactical applications including battery chargers, and specialized generators (e.g., unmanned aerial vehicles and unmanned underwater vehicles), acquisitions exceeding 2000 units in two years is easily achievable.

Liquid Pump Manufacturing ROI

The proposed program will reduce metering pump costs to make a significant savings in the BoP budget. Given the current cost of precision metering pumps for small (sub-kilowatt) fuel cell systems, the promised reduction in cost could represent the single largest contribution to the system cost reduction and ultimately determine its commercial viability.

An alternative approach to this project is to reduce the reliance of pump metering accuracy by implementing closed loop control that utilizes a separate liquid flow measurement device. Existing flow meters, especially at low flow ranges, suffer from similar availability issues as precision metering pumps.

(B) Improved Liquid Flow Meters for Sub-Kilowatt Reformer Based FC Generators

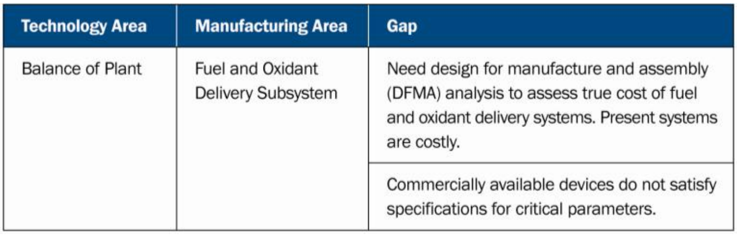
Project Description

Description of Component

The ability to meter liquid accurately is critical to feeding liquid fuel to reformer based fuel cell systems, particularly for small portable systems. An accurate liquid flow meter, used in closed loop control with a low-cost low-pulsation pump, has the potential to replace prohibitively expensive commercial off-the-shelf (COTS) metering pumps and reduce the overall cost of the fuel metering subsystem.

Problem Description

Gaps are noted in **Table III-8**.



Technology Area	Manufacturing Area	Gap
Balance of Plant	Fuel and Oxidant Delivery Subsystem	Need design for manufacture and assembly (DFMA) analysis to assess true cost of fuel and oxidant delivery systems. Present systems are costly.
		Commercially available devices do not satisfy specifications for critical parameters.

Table III-8: Gaps for liquid flow meter

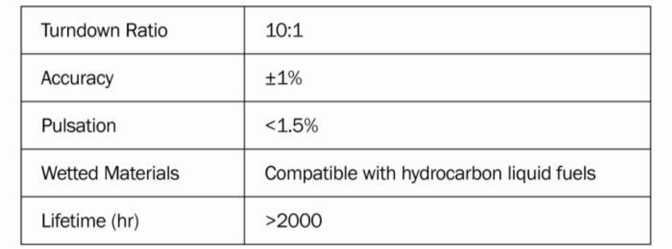
Objective

Fuel cell systems operating on liquid fuels require liquid handling components to control flows to the reformer subsystem. All reformer approaches (except premixed methanol/water fuels) require controlling the fuel/air or fuel/steam ratios of the feed mixture to the reformer accurately. In some cases, particularly partial oxidation approaches, the accuracy and precision requirements on this feed ratio are very high necessitating high quality metering components. In addition to accurate control, other desired features include low weight, small volume, reliable long lifetime, and low pulsation.

Metering pumps that can be used in an open loop configuration eliminates the need for a flow meter, but these pumps require very high precision, close fitting parts that significantly increase cost. When metering a liquid in a closed loop control configuration, both a pump and flow meter are required, but the performance requirements of the pump are significantly lessened. As with most balance of plant (BoP) components, these liquid metering components specifically designed for fuel cell applications are not available. Few adequate pumps and flow meters exist, and those that do are borrowed from other specialized applications and industries often at high cost.

Statement of Work

The proposed program will reduce the cost of closed loop liquid metering by reducing the cost of manufacturing associated with low pulsation pumps and especially liquid flow meters. Specific attention will be paid to fuel cell specific applications. The output of this program will be a pump/flow meter design, assembly procedure, and process for manufacturing.



Turndown Ratio	10:1
Accuracy	±1%
Pulsation	<1.5%
Wetted Materials	Compatible with hydrocarbon liquid fuels
Lifetime (hr)	>2000

Table III-9: Liquid metering system characteristics

While flow requirements will vary with regard to the target application, applications of less than about 1 kW are of particular interest. A metering system should provide a maximum flow rate of less than about 10 ml/min or a maximum of only about 1 ml/min for generators of about 100 W output. For a given maximum flow rate, the liquid metering system will also exhibit the characteristics shown in **Table III-9**.

Turndown is required for load following and shut down operations, and the reported accuracy should be delivered over the full flow range. Delivery pressure requirements for most applications are small (< 7000 Pa) unless a downstream membrane separator is used. In either case, the metering system should be able to deliver the required flow characteristics.

The combined pump and flow meter system has a proposed combined threshold cost of $500 with a low target less than $200.

Major Tasks

Flow meter design and DMFA

This task will develop candidate flow meter technology designs for sub-kilowatt fuel cell applications including thermal mass flow methods and pressure drop measurements. These technologies, well established for larger flow applications, require miniaturization and materials selection for fuels particularly with regard to manufacturing processes. The flow meter must meet accuracy requirements as well as low sensor drift over time.

Specific manufacturing improvements to meet cost targets at low volumes depend on the sensing technology chosen. Thermal mass flow methods, which are the least susceptible to signal drift, typically require wire wrapping of a flow element and sealing the element to fittings or means for convenient connection to the system. Miniaturization of these assembly steps is challenging and prone to defects in low-volume hand-assembled components. This task will apply wire wrapping automation and optimization of the seal design and assembly to improve yield and lower component cost.

Pump specification and DFMA

The ability of a flow meter to enable closed loop control greatly reduces the performance requirements of the liquid pump and increases the selection of COTS pumps that can meet the requirements of the application. In particular, internal leakage can be tolerated, which directly reduces the pump head tolerance requirements and therefore the pump cost. Lifetime durability exceeding 2000 hours requires wear resistance and durable shaft seals or flooded motors. A COTS pump solution might be available for this application, but integration with the flow meter will be required and this integration process with regard to manufacturing the whole flow metering system will be developed in this task.

Trial production

In this task, trial production runs will examine the practicality and effectiveness of the DFMA strategies developed in the previous tasks. Limited production runs of about 25 units (pump and flow meter) will incorporate these changes and output prototypes to be used in the next task that will verify the design performance. These production runs will also enable direct labor measurements to predict volume costs.

Test prototypes

Liquid metering subsystems produced in this program will be tested under conditions relevant for the targeted fuel cell application. Performance testing over at least a 1000-hour lifetime will characterize degradation if any in accuracy (sensor drift), flow characteristics, and pulsation output.

Project Costs

The overall project cost estimate is $0.92 M broken down into labor ($410,000); materials ($15,000), and project portions ($500,000). Materials include manufactured parts for prototype runs of pump and flow meter sub-systems designs including the DFMA changes. Multiple productions runs allow investigation of alternate manufacturing approaches and iterations on the manufacturing process. Advanced manufacturing equipment and test equipment for design verification are also included in the materials budget.

Expected Outcomes and Payoffs

Examples of currently available pumps in combination with flow meters easily exceed $1000 when purchased by the fuel cell integrator. It is likely that some of this cost will be reduced in volume purchases. The expected ROI is about $800/kW (or 1600 units). For sub-kilowatt systems, with tactical applications including battery chargers, and specialized generators (e.g., unmanned aerial vehicles and unmanned underwater vehicles) acquisitions exceeding 2000 units in two years is easily achievable.

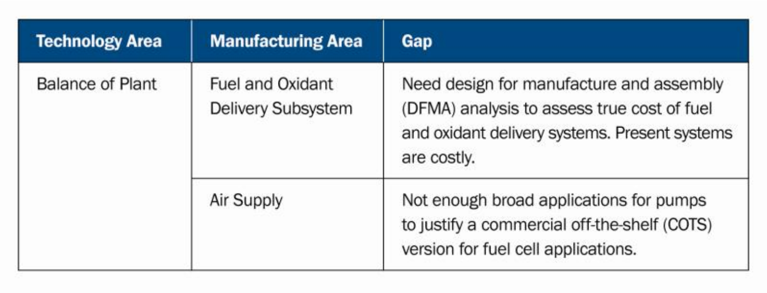
The proposed program will reduce metering subsystem costs to make a significant savings in the BoP budget. Given the current cost of liquid flow meters for small fuel cell systems, the promised reduction in cost could represent the single largest contribution to the system cost reduction and ultimately determine its commercial viability.

An alternative approach to this project is to eliminate the need for a flow meter by using a precision metering pump (see project III.3.2). Existing metering pumps especially at low flow ranges suffer from similar availability issues as low-flow liquid flow meters.

III.3.3. Improved Anode Gas Delivery Devices

Project Description

Gaps are noted in **Table III-10**.



Technology Area	Manufacturing Area	Gap
Balance of Plant	Fuel and Oxidant Delivery Subsystem	Need design for manufacture and assembly (DFMA) analysis to assess true cost of fuel and oxidant delivery systems. Present systems are costly.
	Air Supply	Not enough broad applications for pumps to justify a commercial off-the-shelf (COTS) version for fuel cell applications.

Table III-10: Gaps for anode gas delivery devices

Background

Stack life and cost has historically been the development focus of fuel cell/balance of plant (BoP) integrators. As stack life is now exceeding many thousands of hours, BoP component life and cost has become a higher priority problem. It is common practice to develop a fuel cell, then after reviewing the criteria, select the best COTS anode gas delivery device (pump or blower) for the application. The COTS pump will be a mature product and its cost already benefits from years of design improvements and volume production. Rarely does this compromise meet all the criteria required for the fuel cell system, and typically, it is the source of pre-mature failure or is so expensive that it becomes a major cost driver.

Navy, Army, and Air Force program managers indicated BoP components as a major source of failures, and quite often, blowers and pumps were singled out. This most often results from the scarcity of qualified fuel cell BoP suppliers and unproven or inadequately modified COTS components.

Additionally, ruggedization for military applications will impose further demands on BoP components.

Anode gas delivery devices can be referred to as a blower or a pump depending on the application. Both share the following problems.

Problem Description

- Limited commercial availability – unique requirements depending upon size, noise, weight, volume, efficiency, heat, lifetime, leakage, reliability, pulsation
- Reliability and quality cost trade off
- Close tolerances, tip clearance (cost to get to clearance in smaller units – the cost of near net forming)
- Unacceptable leak rates
- Performance
- Costly electronic controllers
- Lack of integration of pumping and metering
- Pulseless requirement limits selection
- High speed balancing
- Military ruggedization (additional gaps of vibration, shock, acceleration, thermal and acoustic signature, dust/sand, and salt-water immersion)

Objective

The objective of this project is to determine the best manufacturing practice to provide solutions to the issues currently faced by fuel cell/ balance of plant integrators for pumps. The resulting pump will meet selection criteria and lifetime cost will be minimized.

This gap will be overcome by applying SLEDS (Selection /Lean /Elimination /DFMA /Six Sigma) and Automation.

Statement of Work

Pump selection for the balance of plant tries to satisfy all the requirements of the application. Choosing an inexpensive COTS pump may satisfy cost targets, but fail prematurely or incur higher than anticipated maintenance costs. Expensive pumps may provide the performance and life expectancy, but quickly become the target for cost reduction. Improvements to manufacturing of these devices should be directed to lower cost and achieve fuel cell system specific performance requirements.

Corrective Solutions

- **Selection**: selection of cots pump – If a COTS pump meets all the criteria of the application, then move on to supplier evaluation for DFMA/lean/and quality to stay on a cost savings target
- **Improvement of COTS pump:** If a COTS pump may satisfy some of the criteria, design for manufacturing the remainder to satisfy the criteria

- **Design pump to meet specific requirements**, perform value added value engineering (VAVE) analysis of the reactant supply system eliminating and/or combining functions wherever possible. Injection molded parts (to reduce cost, increase productivity, possibly reduce weight) identify/select appropriate ruggedization requirements, and then move on to supplier evaluation for DFMA/lean/and quality to stay on a cost savings target
- **Elimination:** during DFMA, look for opportunities to reduce the impact of a pump on a system (i.e., can tube joints and fittings be minimized, can electrical connectors be reduced or simplified)
- **DFMA:** design for manufacturing, can the assembly be automated to reduce assembly time and provide repeatability
- **Lean Manufacturing:** during manufacturing remove all waste; motion, delay, conveyance, correction, over processing, inventory, over production and time. Provide build instructions as standard work
- **Six Sigma:** insure quality is built-in to the manufacturing process with inspection and data collection for statistical analysis to promote continuous improvement and eliminate defects.

Outcome includes incremental cost savings from each of the steps applied to the anode gas delivery device.

Project Costs

The project investment of $ 800,000 is broken into these areas: $220,000 for design and DFMA; $220,000 for prototypes; $160,000 for lean manufacturing; $120,000 for selection of correctly sized pump; and $80,000 for six-sigma quality control.

Expected Outcomes and Payoffs

While cost savings are necessary, the hidden benefit of this process is the reduction of failures of balance of plant components. A review of military fuel cell applications showed BoP failures were more common than stack failures. More robust BoP components mean longer life for the fuel cell system. Benefits include lowest cost, simpler design, weight reduction, reduced failure of parts, higher reliability, higher quality, and strengthened supply chain.

Options to consider are listed below.

- Eliminate or minimize this device in the BoP
- Simulate a large demand for this product
- Apply DFMA to the device to reduce the impact of time and labor on its cost
- Apply lean production techniques to minimize manufacturing cost
- Apply six sigma analysis of quality issues and continuous improvement to eliminate waste

The ROI for the anode gas delivery system versus system power is shown in **Figure III-6**.

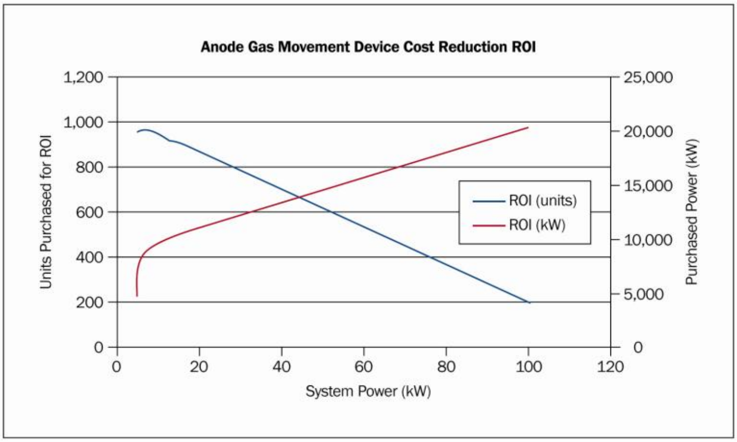


Figure III-6: Anode gas delivery device ROI versus system power

III.3.4. Manufacturing Improvements for Fuel Cell Humidification Systems

Project Description

Description of Component

Humidification systems are used to maintain the water content of polymer electrolyte membranes that enables ionic conductivity and proton transport. Typically, these systems are installed in the air or fuel delivery systems upstream of the stack. Water for these units is collected from the cathode tailgas and recycled to the humidifier.

Problem Description

There are several types of humidifiers each with their own set of specific problems as well as common problems as indicated below:

- Plate & Frame Humidifiers
    - Materials selection
    - Sizing Optimization (scrap/yield improvements)
    - Support structures
- Tubular Humidifiers
    - Porous Tubes (crossover/effectiveness)
    - Potting Occlusions
- Ceramic Humidifiers
    - Motor / Shaft Wear
    - Sealing / Pressure induced failures
- Endemic humidifier issues
    - Lack of automation
    - Effectiveness (assembly related quality control issue)

  - Performance & mechanical degradation
  - Fouling
  - Alignment
  - Inspection, quality assurance
  - Crossover
  - Limited effective lifetime
  - High “touch time”

Objectives

This proposal is aimed at improving the manufacturing processes for humidification systems used in proton exchange membrane (PEM) fuel cells. The proposed improvements will reduce rates of infant mortality, improve reliability, improve performance, extend lifetimes, and reduce costs associated with these humidification systems. Existing gaps are overcome by addressing the identified issues, and institution of process, inspection, and quality changes that will alleviate the identified gaps.

Statement of Work

Developments in fuel cell membrane electrode assemblies (MEAs), stacks, and systems have greatly reduced the humidification requirements for proton exchange membrane (PEM) based fuel cell systems. In fact, these developments have allowed the elimination of humidification devices in some systems. However, there are specific application spaces (temperature and altitude extremes) and potential lifetime benefits that can be enhanced by retaining cathode humidification in PEM fuel cell systems. In many fuel cell power generators, the humidification subsystem represents a meaningful cost factor in the overall capital and operating cost for the system, and implementation of some specific manufacturing techniques and methods offers an opportunity to reduce the cost of the humidification system, and potentially to enhance their performance.

Advancement of humidification manufacturing maturity and techniques offers a path to cost reduction in both capital and operating costs for fuel cell systems. Although advancements in humidification systems have been realized, additional efforts offer further opportunities for cost reduction.

The proposed effort will focus on enhancement of manufacturing techniques for tubular, plate & frame, and ceramic humidification systems. Although each of these systems has unique issues, there are several overarching issues that can be applied to the three differing technologies. These will focus on material selection, assembly and inspection techniques, incoming inspection and prescreening, integration of additional high volume manufacturing practices, and pre-construction activities, such as potting, for tube based systems.

Projected cost reduction benefits are shown in **Figure III-7**.

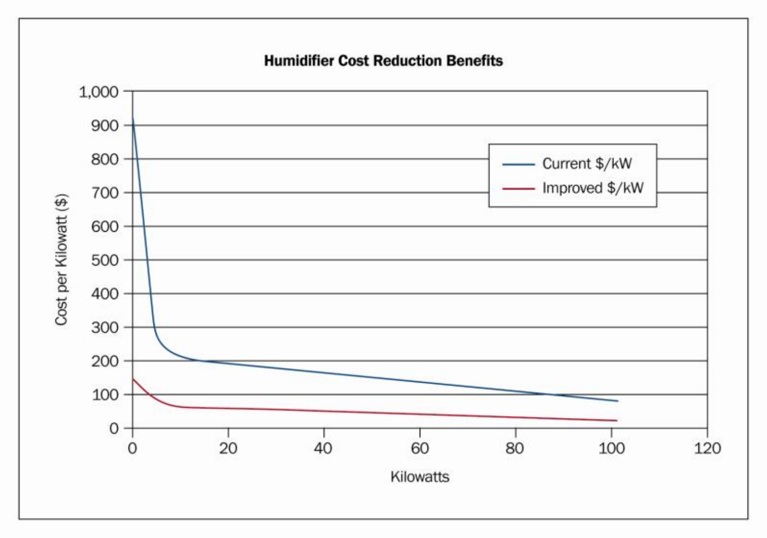


Figure III-7: Humidifier cost reduction benefits

Major Tasks

PEM Fuel Cell Humidifier Issues

Clearly, when the application space and system implementation allow; and their removal does not overly complicate or increase system costs, humidification subsystems should be eliminated from PEM systems. However, in cases where humidification is desired, there are several issues that can be addressed to reduce capital costs, service costs, expand operating envelopes, and extend lifetimes for PEM systems. The specific proposed solution implementations are outlined below, in no particular order:

- Real Time Inspection (Assembly Improvements)

One issue for assembly of these systems is continuous monitoring and real time inspection for the systems. Implementation of these techniques will allow for earlier identification of potential faults, failures and scrap in humidifiers.

- Material Selection

Material selection for housing, sealing, plates, and frames is not always optimized for cost or application. Proper material selection offers a path for cost reduction and improvements in reliability and performance.

- Tube Potting

Tube potting is an issue for tube-based humidifiers. Often the ends of the tubes are occluded in the potting process, reducing the effectiveness (and thereby increasing the price) of the humidifier. Investigation into improved manufacturing techniques offers a potential for cost reduction.

- Custom Assembly / Automation Equipment

Current manufacturing techniques for humidification systems often involve a high component of touch labor for assembly. Investment in automation assembly techniques offers a path for improvements in reliability, repeatability while also allowing for cost reduction.

- Spiral Wound Rapid Manufacturing

Integration of designs that utilize a spiral wound design may offer another path for cost reduction. The other techniques described in this effort can also be applied to a spiral wound humidifier implementation.

- Yield Rate Increase

This proposed effort would involve the analysis of scrap rates, and identification of the scrap locations in the manufacturing process. This information would then be used to focus on high scrap activities in the process. The high scrap activities will then be pursued to reduce scrap and re-work rates.

Project Costs

The project investment of $ 800,000 is broken down into these tasks: $200,000 custom assembly and automation equipment; $124,000 tube potting; $113,000 yield rate improvement; $111,000 inspection; and $252,000 materials

The project is divided between labor ($334,000), materials ($252,000), and other direct costs (ODCs, $214,000).

Expected Outcomes and Payoffs

Average cost savings is $380/kW.

Figure III-8 shows the return on investment for manufacturing cost improvements for PEM humidifier systems in terms of ROI per kilowatts of power purchased, as well as per quantities of units purchased for each power range.

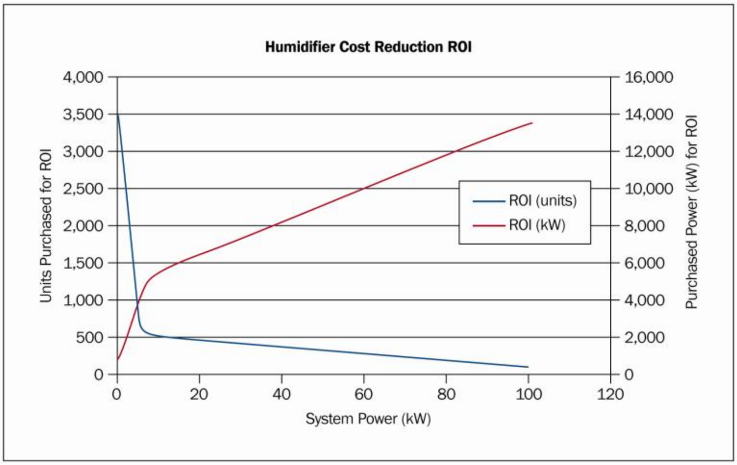


Figure III-8: Humidifier Cost ROI

If this program were applied to humidification systems for 5 kW material handling gear, the payback on the program would be met in 786 units. Material handling equipment in this size range shipped more than 1500 units in 2010, offering a six month payback period.

Implementation of these efforts offer a potential to lower the cost of PEM fuel cell systems, improve the reliability and lifetime metrics, and keep wide environmental operating ranges for these systems.

III.3.5. Specification Analysis for Fuel Cell Power Systems

Project Description

Specifications for fuel cell systems from internal, commercial, and military sources have shown a tendency to set levels beyond industry standards for similar power generation, back up, and motive sources. This bias toward over-specification often results in expensive components and systems that are often able to exceed the requirements for performance and lifetime, but result in expensive acquisition costs. This project proposal will offer paths towards tightening specifications for systems to meet application and cost targets.

Objectives

This proposal will address the specification space for military fuel cell systems, which often over-specify requirements of fuel cell applications, which can significantly increase the cost these devices.

This proposal will overcome the gap by funding efforts to align specifications for military equipment to existing technology requirements, such as JP 8 generator sets. Additionally, this effort is expected to further decrease costs based on environmental requirements (MIL-STD-810), electrical, and other alignments of requirements.

Statement of Work

Over-specification and over-design are well-known phenomena in industry, primarily in new product design, development, and introduction. Over-specification is the definition of a service or product beyond what is truly needed to meet the customer and implementation needs. Over-design is the act of designing a product or service beyond the products or services specifications and requirements to successfully accomplish the product or services intent. The act of over-specification and over-design results in a multiplication of the cost factors associated with each.

Over-specification often results from the desire to leave all options open for a particular product or service. For example, a power generation unit may be specified to be IP 54 rain and dust resistant in order to leave the option open for utilization in watercraft applications. If the device is intended for use on land-borne applications, this over-specification of water resistance can result in longer development times, more expensive equipment, and can remove focus from specifications that are more important for the intended use of the device. This behavior is also known as "feature creep."

Over-design (**Figure III-9**) is the result of developers designing a device or service to meet every conceivable application or specification, and to design the product or service to over-deliver on identified specifications.

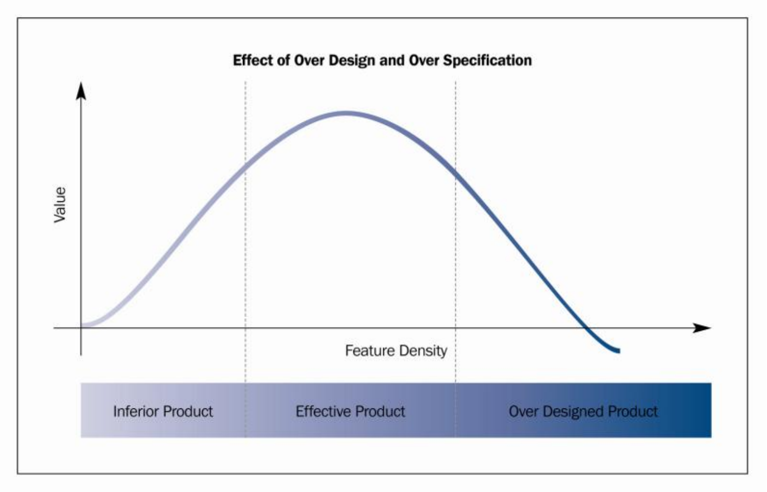


Figure III-9: Effect of over design and specification

These two forces, one external and one internal to the development of a product or service, result in overly expensive and complex products that are capable of meeting the actual intent of the device. The fuel cell industry also experiences over-design and over-specification in the setting of tolerances, measurement, and performance. These specifications are set for several reasons: ignorance of the effects on not meeting the specification, intent to over-perform, and designs that can meet performance goals outside those already set by specifications.

Often these issues contribute to expense in both time and materials, "more than 25% of development efforts are invested in issues and activities that do not add value …and may be considered *garbage time*." [3]

In order to avoid feature creep, each item must all be critically judged to meet the application. Only mandatory items should be inserted in the specification process. "Should Have" and "Nice to Have" items should not be put into specifications, and should be price and product differentiators for industry to address. Adding these items to specifications encourages or even requires over design for applications.

Major Tasks

The major focus of this program will be to develop a set of standards for fielding and installation of fuel cell systems in commercial and military installations and missions. This effort will begin with a study of existing specifications for installations of existing equipment in applications that fuel cells can offer potential for superior implementation. This information will then be used to allow for application of a consistent set of standards for fuel cell systems designed to replace or enhance the current solution. In applications where fuel cell offer a unique solution or capability, a set of standards that fulfills the mission or application requirement will be developed. This will allow for consistent application of standards, requirements, and specifications for fuel cell applications, placing them on an even footing for design, lifetime, and performance goals.

Project Costs

This project effort will need to focus on both size ranges and application space for the fuel cell system specification activities under discussion. Milestones for each project size range will include:

- Application identification
- Existing specification identification
- Specification modification
- Review proposed specifications
- Publish specifications
- Identify design guidelines to meet specification
- Publish design guidelines

The project investment is $720,000 for sub-kilowatt; $1.1 M for 5 kilowatt; $1.8 M for 10 kilowatt; and $1.8 M for 100 kilowatt programs.

Expected Outcomes and Payoffs

Figure III-10 shows the estimated cost savings based on system power rating.

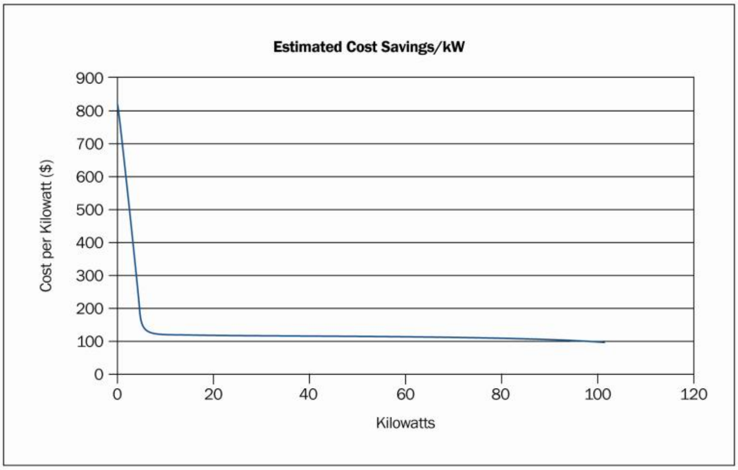


Figure III-10: Specification cost savings

The return on investment for each power level are 900 units for sub-kilowatt; 700 units for 5 kilowatt; 700 units for 10 kilowatt; and 90 units for 100 kilowatt programs.

This project will result in lower cost, better fit solutions, and will give good guidelines for matching specifications to applications that reduce the over design and over specification issues that currently plague fuel cell systems.

III.3.6. Manufacturing Improvements for Cathode Air Delivery System Pump Blower

Project Description

The function of the cathode air delivery system blower/compressor is to supply the oxidant (air) at elevated pressure in a controlled manner or flow rate to downstream components (i.e., the stack or reformer). It ranks as one of the top five most expensive components of a typical fuel cell power system and is a leading candidate for substantial cost reduction with DFMA analysis and implementation. In higher power systems, the reformer air blower is also a major cost contributor but is generally less costly than the cathode air blower due to its smaller relative size. These cost improvements would be applicable to both polymer and ceramic stack systems over a wide power range and multiple applications. A specific blower has been selected to provide a detailed illustration of the cost reduction process, but the same technique could be applied to any component that provides the same function. A scroll type blower configuration was selected for improvement because it is widely used for its high efficiency, few moving parts, low pulsation discharge, low noise, compactness, higher pressure ratio capability at design flows, and a positive displacement compression mechanism. This mechanism, in conjunction with measurement of air discharge pressure and temperature by low cost sensors, provides the ability to meter flow as a function of rpm, eliminating the need and extra cost for separate metering.

Description of Component

The scroll configuration is an ideal solution to the non-standard operating point requirements (low flow, high-pressure ratio) for many fuel cells. However, it is expensive due to the requirements for smaller gaps and tolerances for clearance sealing necessary for high efficiency and an oil-free air supply. That the COTS version of the scroll compressor does not require such close tolerances should not be a surprise when one considers its development heritage and current use as a refrigeration compressor and a supercharger. As a refrigerant compressor, it did not require the same close tolerances as air compressors due to the presence of lubricants that filled the gap. As an automotive supercharger it also did not require close tolerances because the additional parasitic loss (about a half kilowatt) was nearly inconsequential while operating with an engine that was developing several hundred kilowatts. In a five kilowatt fuel cell power system, an additional half kilowatt would reduce efficiency by 10 %.

Problem Description

The COTS scroll air blower selling price is nearly tripled when it is modified for fuel cell applications due to necessary manufacturing changes. The modifications are generally performed with extensive labor for hand fit-up and rework. The current practice of incorporating changes to COTS blowers does not allow inclusion of features that could add further value and simplify the system build that can be achieved if a comprehensive DFMA had been performed. Other gaps to be addressed are detailed below for their manufacturing component (design specific gaps have been separated out and covered in the solution discussion).

- limited commercial availability for fuel cell suitable version – unique requirements depending upon size (noise, weight, volume, efficiency, heat, size, lifetime, leakage, reliability, pulsation)
- cost (efficiency, reliability and quality trade off required)
- close tolerances, gap clearance (cost to get clearance in smaller units – the cost of near net forming)
- lack of integration of pumping and metering
- pulseless flow requirement limits selection
- high speed balancing required

Universally, the various Navy, Army, and Air Force PMs who presented to the MFCMP team, indicated BoP components as the major source of failures, and quite often, blowers and pumps were singled out as the most problematic. This shortfall most often results from the scarcity of suppliers of suitable FC BoP components and unproven or inadequately modified COTS components.

Corrective Actions

The gaps identified above would be overcome through DFMA by a combination of the following actions depending on the specific component features desired for a comprehensive correction.

- Evaluate the reactant delivery system for component elimination, simplification, or combination
- Identify/select appropriate ruggedization requirements
- Standardize requirements, possibly using supplier/consortium process
- Modify an off the shelf scroll compressor with a dedicated design
- Optimize and automate the manufacturing process
- Evaluate alternative materials; enabling injection molding, if possible
- Manufacture using six sigma, lean manufacturing, and statistical analysis techniques
- Use “design of experiments” to economize component testing

Statement of Work

Perform DFMA analysis of the cathode/reformer air delivery system blower including compression and metering functions to reduce the manufacturing cost by 50% at a volume of 2000 mid-size units (7 kW) per annum and 60% at full production while incorporating additional features that would further reduce the overall cost of the reactant supply system. It is expected that the project would be performed jointly by the system integrator and the component supplier with the first two major tasks led by the system integrator and the remaining tasks led by the component manufacturer with technical support by the system integrator, as needed.

Major Tasks

DFMA

- Establish blower operating point requirements - flow rate and state (temperature, pressure, or pressure ratio [PR]), either by working with a specific customer (system integrator) or establishing a consortium of customers who would have common or overlapping requirements for an operating point. Standardize requirements establishing families of non-overlapping capabilities. Select one specific family (flow and PR) for scroll compressor development. For that operating point, determine the full specification including tolerances, mating system, if possible, and the desired features to be included in the machine.
- Perform Value Analysis / Value Engineering (VA/VE) analysis of the reactant delivery system eliminating and/or combining functions in the compressor wherever possible.
- Perform DFMA utilizing the extant COTS design as a starting point to establish a modified design and manufacturing process.

Design

- Gap - Shrink the gap between scrolls consistent with Services Oriented Architecture (SOA) manufacturing technology to maximize isentropic efficiency with oil free operation. Consider other means for closing the gap, such as abradable seals, and water injection.
- Flow measurement - Incorporate instrumentation (P, T) function in the design necessary to enable direct flow measurement.
- Motor – Evaluate and incorporate ironless high efficiency brushless DC (BLDC) motor in design, if possible.

Materials

- Evaluate the use of SOA moldable carbon fiber reinforced composite materials capable of withstanding operating stress and suitable for high speed molding of scroll, housing, Oldham mechanism, or other complex shapes.
- Incorporate selected material in low cost manufacturing process, if possible. Prepare and test samples.

Net Shape Manufacturing

- Net Shape - Review complex components for applicability of near net shape casting or forming techniques to eliminate post casting/forming steps. Prepare and test samples. If successful, incorporate in manufacturing process.
- Inspection - Institute high speed non-contact manufacturing inspection techniques for complex shapes.

Manufacturing Evaluation

- Prioritize and select top candidates for cost reduction and quality improvements. Establish budget and plan for their implementation.
- Implement plan, purchase, install and verify manufacturing equipment.
- Manufacture first article using six sigma, lean manufacturing techniques, verify manufacturing process and correct shortfalls.
- Manufacture statistically significant sample and determine manufacturing parameters (to print defects, process robustness, scrap, quality, and cost). Use DOE techniques to analyze test data.

Performance Demonstration and Documentation

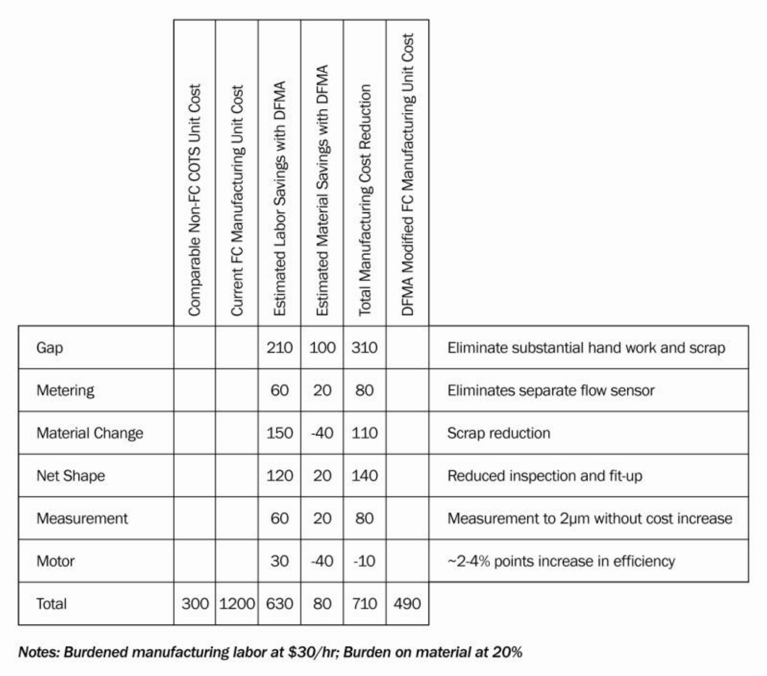
- Demonstrate that compressor meets established performance criteria.
- Rework manufacturing process as necessary within budget to meet performance and cost targets.
- Write report documenting results.

Project Costs

The project investment of $1.1 M has been rolled up from the tasks described above that achieve the associated DFMA based manufacturing cost reduction.

Expected Outcomes and Payoffs

The expected outcome for each of the six initiatives is estimated in **Table III-11**. These values are estimated from the system integrator's perspective rather than from the component manufacturer's perspective due to the proprietary nature of manufacturing data. The non-FC COTS machine used for a cost baseline is a standard commercial scroll based refrigeration compressor vessel including motor and valves that would be comparable in power to that needed for a scroll based air compressor for a 7 kW FC system. This size was chosen as representative of typical CABs, since at current FC system sales levels, at least 1000 to 2000 FC power plants are produced per annum that utilize the scroll compressor technology in their design. The costs for this and other sizes are estimated from available pricing. Assuming that only 80% of the possible $710 cost reduction is achieved, the result would be a 50% reduction in the current unit manufacturing cost. The expected increase in compressor electrical efficiency of ~2 % to 4 % would be a welcome bonus that is not included in the calculations of benefits resulting from the DFMA based analysis.



	Comparable Non-FC COTS Unit Cost	Current FC Manufacturing Unit Cost	Estimated Labor Savings with DFMA	Estimated Material Savings with DFMA	Total Manufacturing Cost Reduction	DFMA Modified FC Manufacturing Unit Cost	
Gap			210	100	310		Eliminate substantial hand work and scrap
Metering			60	20	80		Eliminates separate flow sensor
Material Change			150	-40	110		Scrap reduction
Net Shape			120	20	140		Reduced inspection and fit-up
Measurement			60	20	80		Measurement to 2µm without cost increase
Motor			30	-40	-10		~2-4% points increase in efficiency
Total	300	1200	630	80	710	490	

Notes: Burdened manufacturing labor at $30/hr; Burden on material at 20%

Table III-11: Estimated cost savings with DFMA improvements for 7 kW systems

The manufacturing cost reduction would be recouped after sales of approximately 2000 units of 7 kW size or total sales of 14,000 kW at the average saving of $150/kW for units of different power levels.

In addition to the blower cost reduction and subsequent investment payback, the specific benefits of performing the DFMA analysis project would be simplification of the BoP by elimination of an additional system component (the flow meter) and its attendant positive impact on durability, an increase in system efficiency, a reduction in system weight /volume, and an overall increase in BoP quality control.

Since nearly all FC systems will have a combustion/reformer air blower as part of their BoP, its selection will be interdependent with the selection of other non-blower BoP components and may lead to the elimination or specific identification of required components. Generally, its performance specification will be determined by the system integrator after the stack and fuel processor components are identified.

III.4. FUEL PROCESSING PROJECT DESCRIPTIONS

III.4.1. Low Cost Fuel Efficient Tactical Fuel Processor for Desulfurized Fuel

Project Description

A successful execution of this proposal results in a low cost, reliable, fuel efficient, tactical fuel processor operating on desulfurized JP-8, JP-5 or F76. The expectation is to move the fuel processor TRL/MRL from 3-4 to 6-7.

Fuel processing of logistics fuel is presently a barrier in providing quiet, fuel efficient, affordable and reliable generators that are able to operate on JP-8, JP-5 and F76. Global state of the art for fuel processors operating on natural gas at the 1 kW to 5 kW power level is presently at $900/kw, 40,000 operating hours life, 5000 units per year production, and TRL/MRL levels of 8 to 9. Fuel processors for military logistics fuels are presently at TRL/MRL levels of 3-4. The goal of this project is to provide a logistics fuel processor at a manufactured cost of $220/kW and TRL/MRL levels of 6-7.

The recommended approach in achieving this goal will include a combination of reducing parts, simplifying geometry, reduced welding, component integration, and automated assembly and welding. Structured catalyst capable of achieving much higher space velocities and more uniform temperature gradients than existing pellet bed technology offer potential to decrease bed size and simplify overall fuel processor design. The ideal design will allow practical scaling across power ranges and would allow multi fuel operation with some adjustment or minor changes in design. Operation on natural gas, LPG, ethanol and methanol would be desirable as a means to increase application scope and manufactured quantities leading to further reduction in cost.

Simulation tools should be developed and validated at component and full system level to guide the design and enable scaling. The design must be appropriate for a specific fuel cell technology and result in a full system having > 30% efficiency. Specifications of the fuels and final product gas should be developed and confirmed as early in the project as possible. Integration of required purification with the fuel processor should be considered as a means to reduce cost. Examples of purification technology that could be integrated include high or low temperature shift beds, palladium alloy membrane, or catalytic preferential oxidation.

The project must include extensive testing to validate the potential for 40,000 hour operating life. This project is dependent, but does not include, liquid phase sulfur and nonvolatile residues removal from the logistics fuel. The proposal should have two phases separated by a go/no go decision and allow for at least two design and test iterations followed by a demonstration of an automated manufacturing cell.

Objective

The goal is to achieve a fuel processor manufactured cost of $220/kW (**Table III-12**) through improved design and manufacturability while insuring reliable operation to 40,000 hours with JP-8, JP-5, and F-76. Demonstration of operation with natural gas, LPG, ethanol and methanol as a means to increase volume production for commercial markets is desirable.

Statement of Work

Develop low cost, simplified, highly manufacturable, and scalable fuel processor design. Develop operating procedures to prevent coking and premature catalyst failure. Perform 2000 hour test and demonstrate trend supporting 40,000 hour lifetime. Demonstrate an automated manufacturing cell for metal forming, assembly, and welding.

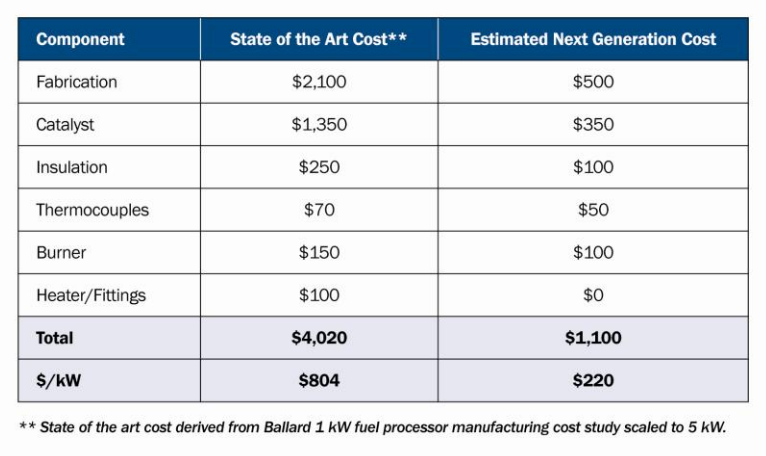
Major Tasks

- Set fuel specification to include full range of seasonal and geographic variation and set specification of purified gas stream for appropriate fuel cell technology
- Develop initial simulation of proposed design and experimentally validate
- Create initial design
- Review component cost and cost of manufacturing
- Fabricate initial units
- Design and build representative test station
- Test 2000 hours and validate trend supporting 40,000 hour life
- If required, perform second iteration design, build, and test
- Demonstrate automated manufacturing cell for forming, assembly, and welding

Project Costs

Project investment of $4.7 M

Expected Outcomes and Payoffs



Component	State of the Art Cost**	Estimated Next Generation Cost
Fabrication	$2,100	$500
Catalyst	$1,350	$350
Insulation	$250	$100
Thermocouples	$70	$50
Burner	$150	$100
Heater/Fittings	$100	$0
Total	**$4,020**	**$1,100**
$/kW	**$804**	**$220**

*** State of the art cost derived from Ballard 1 kW fuel processor manufacturing cost study scaled to 5 kW.*

Table III-12: Costs for low cost fuel-efficient tactical fuel processor for desulfurized fuel

Expected Return on Investment

Reducing manufactured cost from $804/kW to $220/kW would repay the project cost of $4.7M (maximum) within 5164 kW of manufacture. This would equate to 1,608 - 5 kW generators or approximately one year of procurement. Inclusion of fuel cost savings would be a significant and additional return.

- Achievement of $220/kW manufactured cost
- Reliable 2000 hour operation with 40,000 hour life trend demonstrated
- Supports fuel cell/fuel processor system with significantly higher efficiency than today's generators (goal >30%)

Relationship to Other Projects

This project will stand alone in achieving its goals of low cost but will require a successful fuel desulfurization and non-volatile residue removal project for the specified fuels.

III.4.2. High Efficiency Fuel Processor for Logistic and Renewable Fuels (Sulfur Containing)

Project Description

The goal is to achieve a fuel processor manufactured cost of $250/kW through improved design and manufacturability while insuring reliable operation to 40,000 hours with sulfur containing logistic fuels JP-8, JP-5, F-76 and renewable fuels such as biogas from anaerobic digester.

Approach

Fuel processing of logistics fuel is presently a barrier in providing quiet, fuel efficient, affordable and reliable generators that are able to operate on JP-8, JP-5 and F76. Global state of the art for fuel processors operating on natural gas at the 1 kW to 5 kW power level are presently at $900/kW, 40,000 operating hours life, 5000 units per year production, and TRL/MRL levels of 8 to 9. Fuel processors for military logistic, sulfur containing fuels are presently at TRL/MRL levels of 4 to 6. The goal of this project is to provide a logistics fuel processor at a manufactured cost of $250/kW and TRL/MRL levels of 6-7 and capable of 8-9.

The recommended approach in achieving this goal will include a combination of reducing parts, simplifying geometry, reduced welding, component integration, and automated assembly and welding. Autothermal reformer designs and structured catalyst capable sulfur tolerance for an ATR and high temperature water-gas shift reactors are recent developments that can achieve much higher space velocities and more uniform temperature gradients than existing technology. Integration of membrane purification technology with water-gas-shift reactors offers the potential to decrease bed size, simplify manufacturing processes, and optimize the overall fuel processor design. The ideal design will allow practical scaling up and down in power and would allow diverse ceramic or polymer fuel cell applications including multi fuel operation with a readily simple modification of fuel processor design.

Simulation tools should be developed and validated at component and full system level to guide the design and enable scaling. The design must be appropriate for a specific fuel cell technology and specifications of the fuel or fuels and final product gas should be developed and confirmed as early in the project as possible. Integration of required purification with the fuel processor is a pathway to reduce cost. Catalytic preferential oxidation can be considered an add-on for the polymer fuel cell design; however, air bleed in the anode chamber should remove any residual carbon monoxide. The approach with include on-site demonstration of the fuel processor for logistic and renewable fuels must include extensive testing to validate the potential for 40,000 hour operating life.

Problem Description (Gaps)

Apply DFMA to achieve reduced parts count and develop automated forming, welding and assembly to reduce manufactured cost.

Apply DFMA to integrate AutoThermal Reformer (ATR) tolerant to sulfur impurities in fuel with multiple subassemblies into a single unit with reduced net weigh, reduced system complexity, and improved thermal management.

For ceramic fuel cells, integrate membrane purification unit with pre-reformer for removal of sulfur species between pre-reformer (ATR would be one approach) and fuel cell system and optimize design for thermal balance using DFMA.

For polymer fuel cells, use DFMA to integrate water-gas-shift reactors with sulfur membrane clean-up system to remove sulfur impurities from ATR reformed fuel stream and optimize hydrogen content of fuel.

For biogas fuels use DFMA to optimize integration of sulfur membrane cleanup system and carbon dioxide removal system with anaerobic digester or landfill for generation of pipeline quality methane and fuel cell quality methane.

For biodiesel fuels used with polymer fuel cells use DFMA to optimize integration ATR with water-gas-shift / carbon dioxide clean up membrane reactors for fuel processor with high efficiency.

Optimize design and manufacturing for increased fuel flexibility catalyst beds to optimize catalyst functionality and operating temperature uniformity leading to improved performance and reduced cost.

Statement of Work

Develop low cost, simplified highly manufacturable and scalable fuel processor design compatible and adaptable for both ceramic and polymer fuel cell systems. Develop operating procedures for sulfur removal and to prevent coking and premature catalyst failure.

Perform 2000 hour test and demonstrate trend supporting 40,000 hour lifetime.

Demonstrate an automated manufacturing cell for metal forming, assembly, and welding.

Milestones

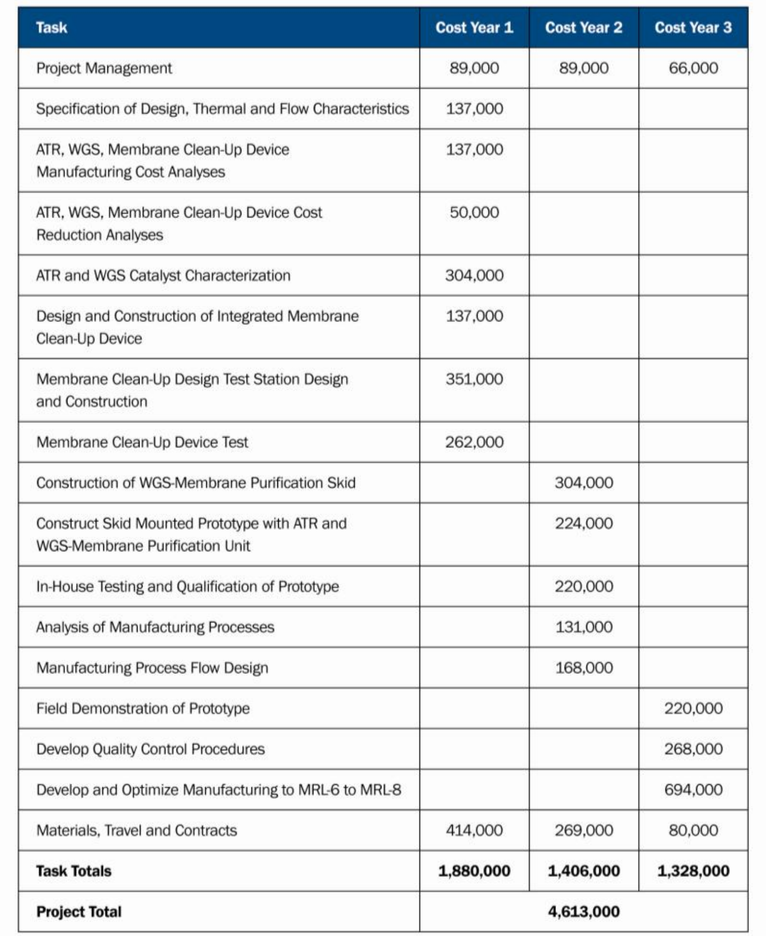
- Design review before build in Task 6.5
- Membrane Clean-up device demonstrated - Task 6.7
- Prototype skid mounted ATR - Membrane Purification qualified- Task 6.10
- Acceptance of Manufacturing Process Flow Design - Task 6.12
- Completion of Prototype Field Demonstration - Task 6.13
- Optimization of Manufacturing to MRL-6 to MRL-8

Relationship to other Projects

This project will stand alone in achieving its goals of high efficiency fuel processor for logistic and renewable fuels compatible with sulfur containing JP-8, JP-5, F-76 and renewable fuels such as biogas from anaerobic digester or landfill gas.

Project Costs

The project investment of $4.6 M is shown for each task in **Table III-13**.



Task	Cost Year 1	Cost Year 2	Cost Year 3
Project Management	89,000	89,000	66,000
Specification of Design, Thermal and Flow Characteristics	137,000		
ATR, WGS, Membrane Clean-Up Device Manufacturing Cost Analyses	137,000		
ATR, WGS, Membrane Clean-Up Device Cost Reduction Analyses	50,000		
ATR and WGS Catalyst Characterization	304,000		
Design and Construction of Integrated Membrane Clean-Up Device	137,000		
Membrane Clean-Up Design Test Station Design and Construction	351,000		
Membrane Clean-Up Device Test	262,000		
Construction of WGS-Membrane Purification Skid		304,000	
Construct Skid Mounted Prototype with ATR and WGS-Membrane Purification Unit		224,000	
In-House Testing and Qualification of Prototype		220,000	
Analysis of Manufacturing Processes		131,000	
Manufacturing Process Flow Design		168,000	
Field Demonstration of Prototype			220,000
Develop Quality Control Procedures			268,000
Develop and Optimize Manufacturing to MRL-6 to MRL-8			694,000
Materials, Travel and Contracts	414,000	269,000	80,000
Task Totals	**1,880,000**	**1,406,000**	**1,328,000**
Project Total		**4,613,000**	

Table III-13: High efficiency fuel processor for logistic and renewable fuels (sulfur containing)

Expected Outcomes and Payoffs

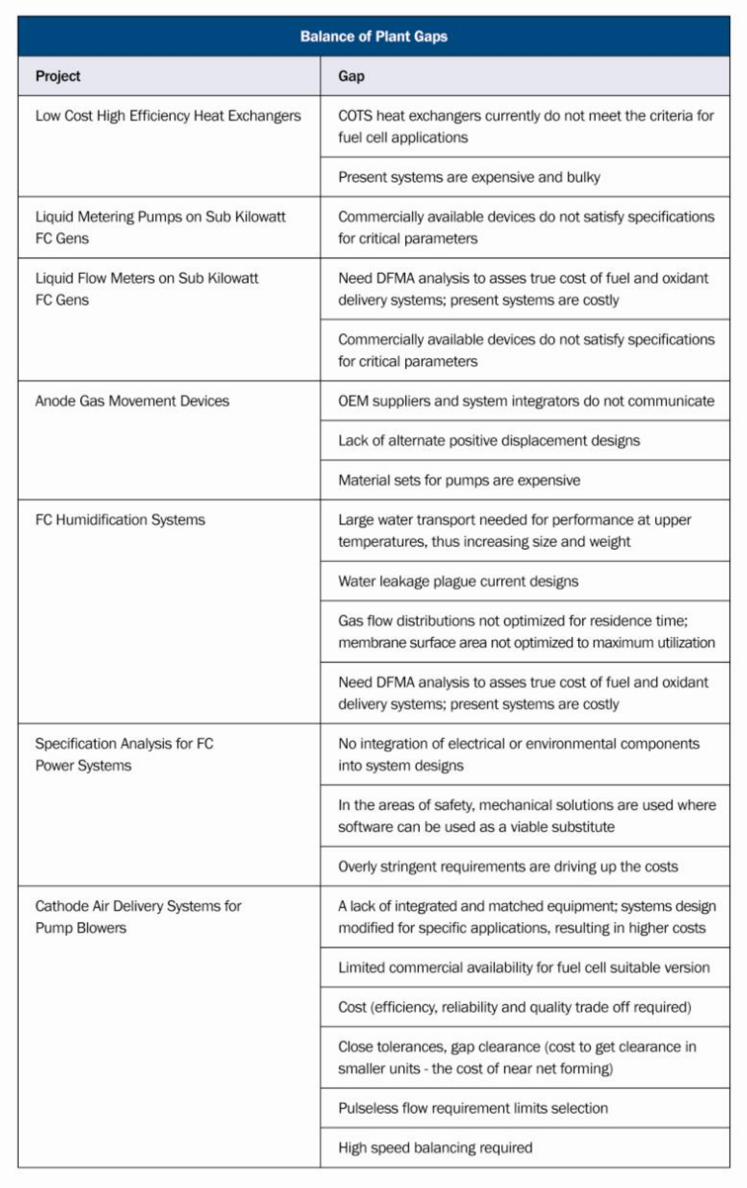
- Achievement of $250/kW manufactured cost
- Field demonstration that provides database for 40,000 hour life trend forecast

IV. Appendix B

SUPPLEMENTAL INFORMATION

Chapter 4

4.4 Framework for the Selection of Projects

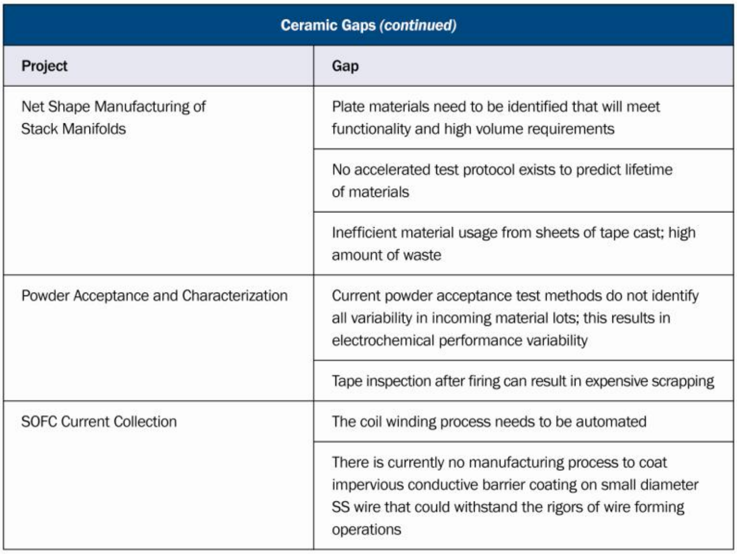


Balance of Plant Gaps	
Project	**Gap**
Low Cost High Efficiency Heat Exchangers	COTS heat exchangers currently do not meet the criteria for fuel cell applications
	Present systems are expensive and bulky
Liquid Metering Pumps on Sub Kilowatt FC Gens	Commercially available devices do not satisfy specifications for critical parameters
Liquid Flow Meters on Sub Kilowatt FC Gens	Need DFMA analysis to asses true cost of fuel and oxidant delivery systems; present systems are costly
	Commercially available devices do not satisfy specifications for critical parameters
Anode Gas Movement Devices	OEM suppliers and system integrators do not communicate
	Lack of alternate positive displacement designs
	Material sets for pumps are expensive
FC Humidification Systems	Large water transport needed for performance at upper temperatures, thus increasing size and weight
	Water leakage plague current designs
	Gas flow distributions not optimized for residence time; membrane surface area not optimized to maximum utilization
	Need DFMA analysis to asses true cost of fuel and oxidant delivery systems; present systems are costly
Specification Analysis for FC Power Systems	No integration of electrical or environmental components into system designs
	In the areas of safety, mechanical solutions are used where software can be used as a viable substitute
	Overly stringent requirements are driving up the costs
Cathode Air Delivery Systems for Pump Blowers	A lack of integrated and matched equipment; systems design modified for specific applications, resulting in higher costs
	Limited commercial availability for fuel cell suitable version
	Cost (efficiency, reliability and quality trade off required)
	Close tolerances, gap clearance (cost to get clearance in smaller units - the cost of near net forming)
	Pulseless flow requirement limits selection
	High speed balancing required

Table IV-1: Gaps for Balance of Plant Projects

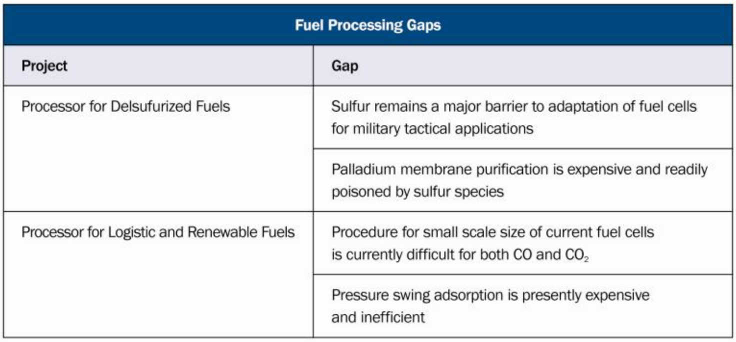
Ceramic Gaps

Project	Gap
Protective Coatings for Metallic Stack Components	Applying a uniform and repeatable ultra-thin electrolyte coating to a curved substrate without flaws is difficult
	Current validated automated inspection techniques cannot identify discrete defects
Defect Free Electrolyte Layer	Inspection presently very labor intensive and produce high rates of scrap
	Current validated automated inspection techniques cannot identify discrete defects
	Current powder acceptance test methods do not identify all variability in incoming material lots; this results in electrochemical performance variability
	Difficulty in forming thin high aspect ratio tube walls
	Tape inspection after firing can result in expensive scrapping
Low Cost Insulation Package	Dry press tool design and processing methods not available with sufficient fidelity in microporous foams to suit SOFC industry
SOFC Automated Assembly	Lack of a feeder mechanism to support semi-continuous co-extrusion of anode and electrolyte feed rods
	No present method of transitioning small lab scale mixtures to high volume manufacturing
	Need for stack quality, repeatability, and yield in high volume production; stack assembly will require increased automation as volume levels increase
SOFC Stack Manufacturing, Commission, Testing	Components are not designed for high-speed stack assembly; stacks are primarily hand assembled
	Stack failure rates are too high
	Lengthy burn-in and testing of stacks is incompatible with even modest production rates
	Stacks are primarily hand assembled
	Long cycle time
	Non aqueous solvent based systems will incur additional cost at high volume manufacturing
	QC time on each stack is currently high



Ceramic Gaps *(continued)*	
Project	**Gap**
Net Shape Manufacturing of Stack Manifolds	Plate materials need to be identified that will meet functionality and high volume requirements
	No accelerated test protocol exists to predict lifetime of materials
	Inefficient material usage from sheets of tape cast; high amount of waste
Powder Acceptance and Characterization	Current powder acceptance test methods do not identify all variability in incoming material lots; this results in electrochemical performance variability
	Tape inspection after firing can result in expensive scrapping
SOFC Current Collection	The coil winding process needs to be automated
	There is currently no manufacturing process to coat impervious conductive barrier coating on small diameter SS wire that could withstand the rigors of wire forming operations

Table IV-2: Gaps for Ceramic Fuel Cell Projects

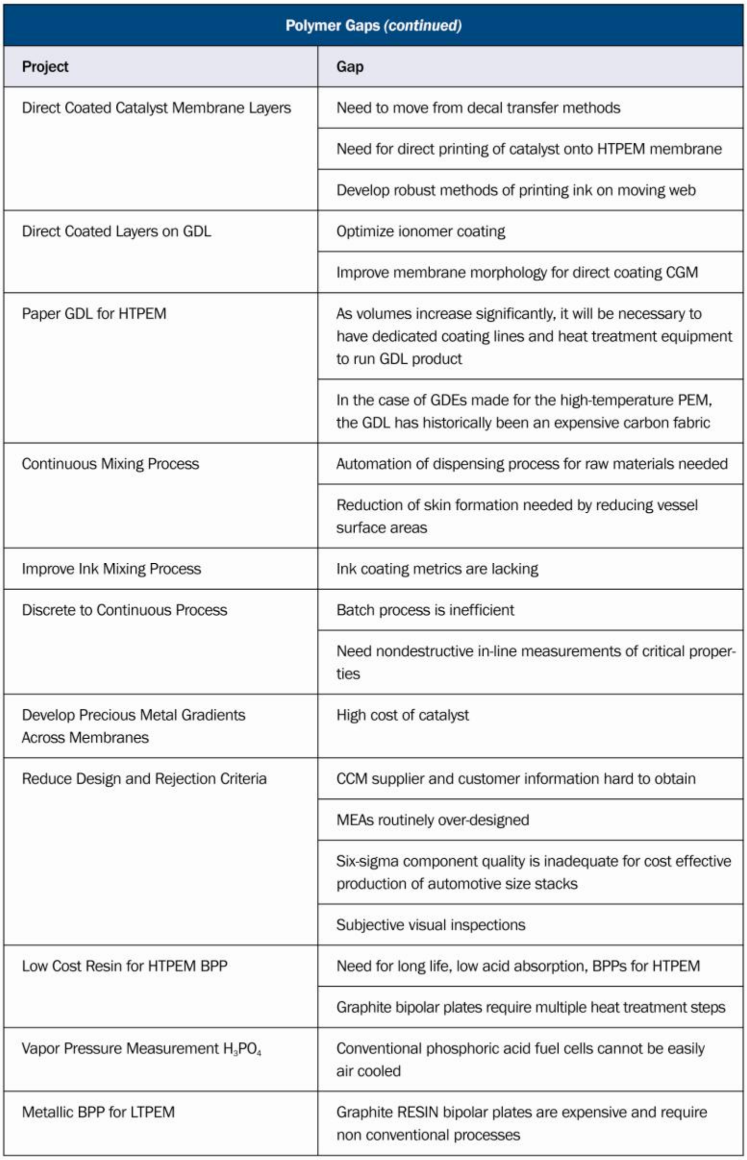


Fuel Processing Gaps	
Project	**Gap**
Processor for Delsufurized Fuels	Sulfur remains a major barrier to adaptation of fuel cells for military tactical applications
	Palladium membrane purification is expensive and readily poisoned by sulfur species
Processor for Logistic and Renewable Fuels	Procedure for small scale size of current fuel cells is currently difficult for both CO and CO_2
	Pressure swing adsorption is presently expensive and inefficient

Table IV-3: Gaps for Fuel Processing Projects

Polymer Gaps

Project	Gap
Manufacturing Cost Trade Off Analysis	Need to move from decal transfer methods
	Need for direct printing of catalyst onto membrane
	Develop robust methods of printing ink on moving web
	Need to maximize catalyst utilization
	Some critical parameters not understood or difficult to measure
	Stack and cell designs lead to unnecessarily tight tolerances on MEA manufacturers
	Six-sigma component quality is inadequate for cost effective production of automotive size stacks
Process for 0.15 mg/cm^2 Pt Loading	Lack of transfer functions relating critical product, raw material, and process parameters to performance and durability
	Lack of understanding of effects on MEA performance of perceived defects in PBI membrane for HTPEM
	Lack of understanding of effects on MEA performance of perceived defects in PBI membrane and GDL/GDE
	Need for non-contact in-process inspection and characterization techniques compatible with high throughput line speeds
	There is currently a lack of tools that are capable of measuring key GDL parameters in real time
	The need for on-line real-time QC measurements
	Need nondestructive in-line measurements of critical properties
	Because there are typically different manufacturers for each part of the MEA (and in some cases different parts of the GDL), suppliers and customers are typically reluctant to share information with each other; supplier and customer information hard to obtain
	Cut yield loss from fabrication process by relaxing release specs of ionomer dispersions and membrane properties
	Subjective visual inspections
Develop Patch Coating for Catalyst Inks	Develop robust methods of printing ink on moving web



Polymer Gaps *(continued)*

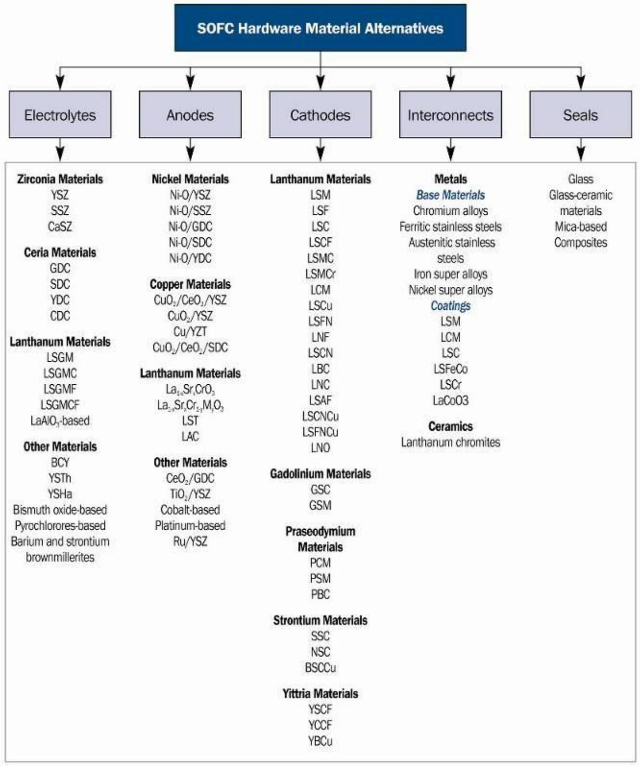
Project	Gap
Direct Coated Catalyst Membrane Layers	Need to move from decal transfer methods
	Need for direct printing of catalyst onto HTPEM membrane
	Develop robust methods of printing ink on moving web
Direct Coated Layers on GDL	Optimize ionomer coating
	Improve membrane morphology for direct coating CGM
Paper GDL for HTPEM	As volumes increase significantly, it will be necessary to have dedicated coating lines and heat treatment equipment to run GDL product
	In the case of GDEs made for the high-temperature PEM, the GDL has historically been an expensive carbon fabric
Continuous Mixing Process	Automation of dispensing process for raw materials needed
	Reduction of skin formation needed by reducing vessel surface areas
Improve Ink Mixing Process	Ink coating metrics are lacking
Discrete to Continuous Process	Batch process is inefficient
	Need nondestructive in-line measurements of critical properties
Develop Precious Metal Gradients Across Membranes	High cost of catalyst
Reduce Design and Rejection Criteria	CCM supplier and customer information hard to obtain
	MEAs routinely over-designed
	Six-sigma component quality is inadequate for cost effective production of automotive size stacks
	Subjective visual inspections
Low Cost Resin for HTPEM BPP	Need for long life, low acid absorption, BPPs for HTPEM
	Graphite bipolar plates require multiple heat treatment steps
Vapor Pressure Measurement H_3PO_4	Conventional phosphoric acid fuel cells cannot be easily air cooled
Metallic BPP for LTPEM	Graphite RESIN bipolar plates are expensive and require non conventional processes

Table IV-4: Gaps for Polymer Projects

Chapter 6

6.1 Introduction

Solid Oxide Fuel Cell Material Sets



SOFC Hardware Material Alternatives

Electrolytes

Zirconia Materials
YSZ
SSZ
CaSZ

Ceria Materials
GDC
SDC
YDC
CDC

Lanthanum Materials
LSGM
LSGMC
LSGMF
LSGMCF
$LaAlO_3$-based

Other Materials
BCY
YSTh
YSHa
Bismuth oxide-based
Pyrochlorores-based
Barium and strontium brownmillerites

Anodes

Nickel Materials
Ni-O/YSZ
Ni-O/SSZ
Ni-O/GDC
Ni-O/SDC
Ni-O/YDC

Copper Materials
$CuO_2/CeO_2/YSZ$
CuO_2/YSZ
Cu/YZT
$CuO_2/CeO_2/SDC$

Lanthanum Materials
$La_{1-x}Sr_xCrO_3$
$La_{1-x}Sr_xCr_{1-y}M_yO_3$
LST
LAC

Other Materials
CeO_2/GDC
TiO_2/YSZ
Cobalt-based
Platinum-based
Ru/YSZ

Cathodes

Lanthanum Materials
LSM
LSF
LSC
LSCF
LSMC
LSMCr
LCM
LSCu
LSFN
LNF
LSCN
LBC
LNC
LSAF
LSCNCu
LSFNCu
LNO

Gadolinium Materials
GSC
GSM

Praseodymium Materials
PCM
PSM
PBC

Strontium Materials
SSC
NSC
BSCCu

Yittria Materials
YSCF
YCCF
YBCu

Interconnects

Metals
Base Materials
Chromium alloys
Ferritic stainless steels
Austenitic stainless steels
Iron super alloys
Nickel super alloys
Coatings
LSM
LCM
LSC
LSFeCo
LSCr
LaCoO3

Ceramics
Lanthanum chromites

Seals

Glass
Glass-ceramic materials
Mica-based
Composites

Table IV-5: SOFC material options
[2]

V. Appendix C – Biographies

Joseph V. Bonadies

Joseph began his career with Delphi in 1987, and has had assignments in process, product, and applications engineering. Much of his career was spent working in automotive catalysts and emission control systems for diesel vehicles. He earned a B.S. in Metallurgical Engineering from Purdue University in 1986, and a M.S. in Engineering Management from the University of Dayton in 2004. Joseph's current position is Engineering Manager of Cell Development in Delphi's Solid Oxide Fuel Cell Group located in Fenton, Michigan. He is a certified Design for Six Sigma Black Belt and Shainin REDX Apprentice. He currently holds 15 U.S. patents.

Paul W. Bratt

Paul Bratt is a Senior Materials Manufacturing Engineer at ACI Technologies, Inc. with over twenty years of experience in Materials Science and Engineering and high reliability electronics. He is currently a Project Manager and Project Lead Engineer for several Navy ManTech projects and the Editor of *Empfasis* – a Navy sponsored publication of ACIT and the EMPF. Prior to working at ACIT, Paul was a Lead Materials Design Engineer for several space satellite programs, a Process Engineer for fiber optic devices, a Quality Manager for automation systems, and an R&D Chemist for silicate products. He earned a BS degree in Materials Science and Engineering from Cornell University and studied for a PhD in Materials Science and Engineering ABD at Northwestern University.

John David Carter

David Carter began his career in Materials Science as a Laboratory Technician at Ceramatec of Salt Lake City, Utah. He earned a BS in Materials Science and Engineering from the University of Utah (1988) and a MS (1989), and PhD (1992) in Ceramics Engineering from the University of Missouri-Rolla.

After graduation, David became a Visiting Scientist at Risoe National Laboratory in Denmark, working for two years in the Danish SOFC program. He joined Argonne as a Post-Doctoral Appointee and was later promoted to staff, working in the Fuel Cells group. Currently, he is the leader of the Electrochemical Ceramics Group, which is continuing in the RD&D of fuel cells and related materials.

David is the author of 27 publications, 34 presentations, and 11 patents.

Mark Cervi

Mr. Cervi began his Navy career at the Naval Ship R&D Center in Annapolis, MD as an engineering co-op student in 1969. He graduated from Drexel University with a BS in Chemical Engineering in 1974. During 37 years of Navy service he specialized in the area of chemical-systems engineering and electro-chemical energy conversion, and participated in programs involving undersea fuel cell applications for DSRV, Deep Quest, SEAL Delivery Vehicles, Unmanned Undersea Vehicles, and Ship Service Fuel Cells. He also worked in the submarine life support area including oxygen generators, CO_2 scrubbers, and gas management systems, and has participated in programs for undersea Air Independent Propulsion, including PEM fuel cells, closed-cycle Brayton, Stirling, and Diesel engines, and emergency submarine fuel cell generators. After retiring from his civilian US Navy engineering position in 2007, Mr. Cervi has continued to support US Navy fuel cell and power generation programs as a Senior Engineer with General Dynamics Information Technologies under contract to the Naval Sea Systems Command, Ship Systems Engineering Station in Philadelphia, PA. He currently provides program support for power system development, test design, test installation, and test operating support at the Naval Fuel Cell Development Center for a variety of power system programs under ONR and NAVSEA sponsorship, and evaluates and advises Navy program managers on emerging technologies.

Paul Chalmers

Paul Chalmers joined Hydrogenics through the acquisition of Stuart Energy in January, 2005, As Production Manager, he is responsible for the delivery of hydrogen power products, including fuel cells for worldwide distribution. His focus has been the lean and agile manufacturing transition from R&D and custom project quantities of fuel cell systems to production level quantities. Paul was Manufacturing Specialist and Planner at Stuart Energy Systems from 2001 and set-up that facility to meet the flexible manufacturing requirements for hydrogen infrastructure equipment. Stuart Energy (now Hydrogenics On-Site Generation business unit) is the world leader in supplying clean hydrogen via water electrolysis for industrial, fuel cell vehicle refueling and environmentally friendly energy storage applications. Prior to Stuart, Paul had 10 years of management experience in A.S.M.E Pressure Vessel, heat exchanger, and high vacuum design and construction. Paul studied Agricultural Mechanization at the University of Guelph before joining Caloritech, an industrial heating manufacturer in 1984.

John Christensen

John Christensen serves as a consultant to NREL on Fuel Cell Early Markets as well as the OSD Manufacturing Science and Technology Program. He retired from Defense Logistics Agency (DLA) in 2007 after 28 years of federal service, the last 8 as the R&D Chief. During his time at DLA, he planned and began the execution of four fuel cell lift truck pilots at four locations across the DOD, totaling 100 forklifts. Since then, he has been working with DOD and other federal agencies to facilitate other fuel cell and hydrogen-related market transformation projects. John also served six years in the Navy on active duty and 22 years in the Reserves, retiring in 2007 at the rank of Commander.

John holds a Professional Engineering license and received his BS from the University of Florida (Environmental Engineering) and two MS degrees; one from Virginia Tech (Systems Engineering) and the other from the Industrial College of the Armed Forces (National Resource Strategy). He recently received a Special Recognition Award (2010) from the Department of Energy's Hydrogen and Fuel Cells Program for his efforts in spurring the use of fuel cells across federal agencies.

Aaron Crumm

Aaron Crumm, co-founder of Adaptive Materials, is a widely-recognized expert in the solid oxide fuel cell industry. Adaptive Materials' propane-powered fuel cell systems deliver 50 to 300 watts of portable electricity. The company was recently acquired by defense industry giant Ultra Electronics. Adaptive Materials manufactures from raw ceramic powder to completed fuel cells at its Ann Arbor facility, delivering units to the US military for use in unmanned ground and aerial vehicles as well as for portable soldier power. Currently, the company is expanding its manufacturing to include commercial fuel cells for the RV and boating recreation markets.

Crumm earned his BS in nuclear engineering from Purdue University and a PhD in material science from the University of Michigan.

William Ernst

Dr. William D. Ernst has over 40 years of experience that includes a long and distinguished tenure developing fuel cell technologies. He initiated, championed, obtained sponsorship, developed, managed and directed all fuel cell activity at Mechanical Technology Incorporated (MTI) that became the basis for Plug Power, Inc., one of the leading fuel cell system developers in the United States. He retired from Plug Power in late 2008 where he held the office of Vice President and Chief Scientist. There, he was responsible for proton exchange membrane (PEM) fuel cell technology assessment and advanced development, as well as technical initiatives within the government sector. Most recently, he investigated the applicability of solid oxide fuel cell (SOFC) stack and system technology to various continuous power applications. Prior to joining Plug Power, Dr. Ernst was business area manager of the technology division at (MTI), where he was responsible for management and development of the fuel cell, hybrid electric vehicle and flywheel business. Dr. Ernst is the author of over 100 technical reports and papers on subjects including fuel cell technology development and application and non-Newtonian fluid dynamics. Dr. Ernst is the recipient of the 1998 Partnership for the Next Generation of (Fuel Cell) Vehicles Award and in 2002, a Special Recognition award from the Department of Energy (DOE) Transportation Fuel Cell Program for his outstanding technical contributions. Further, he has served as a peer reviewer for the DOE over the last five years evaluating fuel cell technology. He has consulted for a number of private companies in the past and most recently with National Renewable Energy Laboratory. In addition, he is currently serving on a National Academy of Science committee broadly reviewing the strategy and structure of a large joint government/industry program, offering suggestions and guidance for improving the program and its outcome.

Matthew Fay

Mr. Matthew Fay is a Senior Process Engineer within the Manufacturing Engineering division of General Motors Company. Since 2007, he has focused on the development of manufacturing processes for the Unitized Electrode Assembly (UEA) component, a multilayer construction of the core fuel cell components where the power is produced. Prior to joining Manufacturing Engineering in 2007, Mr. Fay spent four years in the R&D group at GM where he focused on fuel cell UEA durability and supplier development. Before joining GM, Mr. Fay spent five years at T/J Technologies in Ann Arbor, Michigan (now a division of A123 Systems), developing novel cathode and anode materials for lithium ion batteries. Mr. Fay has six patents or published patent applications. He has a MS degree in chemical engineering from the University of Minnesota, and a BS degree in chemical engineering from State University of New York at Buffalo.

Marc Gietter

Mr. Gietter is currently working in the Army Research Development and Engineering Center's Army Power Division as an electronics engineer and project leader. Mr. Gietter's current responsibilities include overseeing the Army's American Recovery and Reinvestment Acts 300 watt manportable fuel cell program, chairperson of the Fuel Cell Systems Technical Working Group and Power Sources Technical Working Group along with the NATO technical group on fuel cells. Mr. Gietter is also the chairperson of the Defense Standardization Program Office's Joint Standardization Board for Power Source Systems. Prior to working with fuel cells, Mr. Gietter was a project leader for the creation of the DOD Power Sources Roadmap along with various projects related to the development and production of advanced nonrechargeable batteries. Mr. Gietter also has extensive experience related to industrial base and defense mobilization production efforts. Mr. Gietter has a Bachelor of Science in Chemical Engineering and a Master of Science in Engineering Management.

Leo J. Grassilli

Leo Grassilli completed his active duty US Navy career in September 2003 after serving twenty-two years of service, the final two and a half as a Special Assistant for the Secretary of the Navy. In that assignment, Commander Grassilli worked Navy and Marine Corps policy issues for alternative fuels including opportunities for hydrogen and fuel cells where he started the Navy-Marine Corps fuel cell vehicle program. Prior to that assignment, he served onboard USS NEW JERSEY (BB-62) and USS DAVID R RAY (DD-971), and with FIGHTER SQUADRON TWO (VF-2) onboard USS RANGER (CV-61). He also served at the Naval Inventory Control Point-Philadelphia, Hughes Aircraft Company, and Naval Air Station Adak, Alaska. He was the Commander of the Defense Fuels Office-Mediterranean in Pisa, Italy from 1994 through 1997 providing fuel support to US and NATO forces in Southern Europe and the Mediterranean and especially in support of operations in Rwanda and Bosnia.

In his second career, Leo Grassilli continues to pursue applications for alternative fuels and the development of hydrogen and fuel cell technology. Mr. Grassilli has also worked to bring a number of fuel cell and hydrogen reformation technologies closer to operational use by Fleet units both to reduce operating costs and improve capabilities.

Leo Grassilli earned a Bachelor of Science degree in Business Management from San Diego State University, a Master of Science in Petroleum Management from the University of Kansas, and a Master of Arts in National Security and Strategic Studies from the Navy War College.

Randy Hiebert

Randy Hiebert is a Senior Process Engineer at the Center for Advanced Mineral and Metallurgical Processing (CAMP) located on the campus of Montana Tech. Mr. Hiebert has Bachelor of Science and Masters of Science Degrees in Chemical Engineering from Montana State University. He has over 28 years of experience in petrochemical processing, biotechnology, and environmental remediation. Mr. Hiebert has managed and supported numerous projects in diverse industries such as petroleum, mining remediation, explosives manufacturing, and Federal and State Government. His expertise lies in the areas of biotechnology and process engineering, specifically the preparation of process flow diagrams, mass/energy balances, process simulation, and process optimization. Mr. Hiebert is a registered Professional Engineer in the states of Montana and Pennsylvania and has a current record with the National Council of Examiners for Engineering and Surveying (NCEES).

Robert Hyatt

Robert Hyatt is a Program Manager and Research Engineer for the Center for Advanced Mineral and Metallurgical Processing (CAMP) located on the campus of Montana Tech. Mr. Hyatt has a Bachelor of Science degree in Mechanical Engineering from Stanford University and a Master of Science degree in Manufacturing Systems Engineering from Lehigh University. Mr. Hyatt has more than 22 years of experience in advanced generation process development, robotic automation, product design, engineering design, research and development, program management and senior corporate management. He has designed, built and run manufacturing lines for Ford, Automation Tooling Systems, and Electroglas. Mr. Hyatt has led development functions at Intel and Electroglas focused on next generation products and processes. He has been a principal investigator for an AFRL advanced ballistic and blast mitigation materials development program. Mr. Hyatt is currently the principal or the co-investigator for the ARL Titanium Free-Form Project, Department of Transportation Hydrogen Project, ONR Fuel Cell Design and Manufacturing Development Program, and the Space and Missile Defense Command Adaptive Lightweight Materials Project. Mr. Hyatt also works with several private sector companies focusing on next generation thermal management materials and photovoltaic materials and systems.

Rick Kerr

Rick is currently the Staff Manager for Solid Oxide Fuel Cell Stacks and Cells, responsible for design, development, and manufacturing. His 31+ years of experience in GM/Delphi have been primarily in the Materials Engineering field, across numerous product lines. He has provided support for valve train components, gasoline and diesel injection systems, throttle bodies, and fuel handling systems. In addition, he supervised the Materials Engineering, Analysis, and Development groups, supporting spark plugs, fuel handling, air induction, exhaust species chemical sensors, and exhaust product lines. His fields of technical expertise include ferrous metallurgy, fuels, heat treating processes, and metalworking technologies. Areas of analytical expertise include electron and optical microscopy, mechanical testing, x-ray diffraction, x-ray spectroscopy, x-ray radiography, and fuels test methods.

Rick received his ME in Metallurgical Engineering - Materials Science from Carnegie-Mellon University in 1984 and his BS in Metallurgical Engineering from Michigan Technological University in 1979. He is an Apprentice Statistical Engineer, holds eight US patents, is a member of American Society of Materials (ASM) International - Saginaw Valley Chapter and received the Federal Laboratory Consortium 2009 Award for Excellence in Technology Transfer.

Dennis Kountz

Dennis is responsible for identifying and managing government-based business opportunities for DuPont's Chemical and Fluoroproducts business. This includes a wide range of chemical products and familiar brands including Teflon®, Freon®, Suva®, and Nafion®.

Dennis earned a PhD in Physical Chemistry from The Ohio State University, a BA from Wittenberg University in Physics and Chemistry and a MBA from Pfeiffer University. He has authored or co-authored numerous publications and US Patents. He joined DuPont in 1984 at a North Carolina fiber manufacturing site and has filled a number of roles including marketing, manufacturing, product management, research and development, and government program management. In 2006, Dennis secured a Defense Acquisition Challenge Project for DuPont to work with the US Army PEO Soldier office to adapt commercial DuPont™ Nafion® Membrane Electrode Assembly and SFC Smart Fuel Cell portable fuel cell system technology for Army Land Warrior use. Dennis led the team that won the 2008 DDR&E

Wearable Power Prize at the Marine Corps Air Ground Combat Center in Twentynine Palms, CA. Dennis has also led a team that has recently completed a Defense Production Act of 1950 Title III Project to implement the manufacturing of Membrane Electrode Assemblies for Direct Methanol Fuel Cells that Provide Soldier Power. DuPont continues to work under contract with the US Army PEO Soldier Office to evolve next generation light-weight fuel cell technology for recharging military lithium batteries.

Jay McCloskey

Jay McCloskey is the Acting Director for the Center for Advanced Mineral and Metallurgical Processing (CAMP) located on the campus of Montana Tech. Mr. McCloskey has Bachelor of Science and Masters of Science Degrees in Metallurgical/Mineral Process Engineering from Montana Tech. Mr. McCloskey has managed and supported projects for numerous Private and Federal projects. Mr. McCloskey has over 27 years of experience in manufacturing, mainly in the mining, smelting, refining industry, and environmental remediation. For the past 17 years, Mr. McCloskey has supported manufacturing sustainability efforts at numerous Army Munitions Facilities within the Department of Defense (DOD) Complex, specifically in Waterveliet, NY, Scranton, PA, and Radford, VA. Currently, Mr. McCloskey is the principal or the co-investigator for the Army Research Laboratory Titanium Free Form Project; Department of Transportation - (DOT) Hydrogen Project; US Navy Fuel Cell Design and Manufacturing Development Project; and Army Space and Missile Defense Command /Radiance Technology - Alternative Light-Weight Materials (ALM) Project.

Carmine Meola

Formerly the manager of the Manufacturing Factory and Training Center at ACI Technologies, Inc., Carmine Meola is presently a R&D Project Manager with ACI. Mr. Meola has an extensive background in electronic materials, substrate processing, plating, and packaging in the PCB and semi-conductor industry. He has also leveraged his experience as a certified ISO-9001 internal auditor, and applied it in both the electronic and pharmaceutical industry. His activities led to patents for anisotropic conductive adhesives, WLBI conductive interposer, and EMI conductive foams. Mr. Meola was involved in two start up plants, and was responsible for facilitating design, procuring equipment, and process implementation for both manufacturing and laboratory.

Rebecca Morris

Rebecca Morris is a Product and Applications Engineer at ACI Technologies, Inc. and is a co-chair on the Military Power Sources Committee of the National Defense Industrial Association (NDIA) manufacturing division. As co-chair, she is dedicated to facilitating communications between the government and the battery/fuel cell industries. At ACI, Ms. Morris works on various battery, fuel cell, and power electronics projects. As the ACI technical advisor on power sources projects, she worked to qualify a new USA based thermal battery manufacturer. As an ACI staff member of the Navy Electronics Manufacturing Center of Excellence, she is cognizant of power electronics miniaturization nuances in state of the art electronics manufacturing as well as electronics material engineering challenges. Prior to working at ACI, Ms. Morris worked for over 13 years with Alliant Techsystems, Inc. at their Power Sources Center in Horsham, Pennsylvania. Her responsibilities included development of manufacturing technologies for lithium ion batteries. In addition, she was responsible for the formal training of new engineers and technicians in the production and test departments. Rebecca Morris holds a Bachelor degree in Physics from Mount Holyoke College.

Randy J. Petri

Mr. Petri has over 32 years of experience in the start-up and operation of fuel cell technology, stack power module design/engineering, systems product development and field demonstrations. He is currently the Principal and Director of Product Development & Federal Programs at Versa Power Systems, Inc. where he has over a decade of tenure. Prior to that, he served as Chief Engineer and Director, Product Development and Delivery at M-C Power Corp. Mr. Petri has over 40 publications and 12 patents. He received his MBA in Finance and Marketing from The University of Chicago - Booth School of Business and his BS in Chemical Engineering from the Illinois Institute of Technology.

Joseph C. Poshusta

Dr. Poshusta has led portable solid oxide fuel cell (SOFC) technology and product development programs for nine years at Protonex Technology. Under his technical direction, Protonex delivered its first propane and liquid hydrocarbon fueled generators to government clients. He is an expert in fuel processing and thermal integration of SOFC systems as well as an experienced system integrator. He holds chemical engineering undergraduate and Masters degrees from Washington State University and a PhD also in chemical engineering from the University of Colorado.

Jolyon Rawson

Dr. Rawson joined Acumentrics Corporation in October 2000 and is currently employed as Director of Engineering for the Cell Manufacturing and Development group. In this capacity Dr. Rawson is responsible for all aspects of cell manufacturing development from raw material specification and procurement to completed cells. To facilitate low cost high volume fuel cell production, he is also responsible for identification, evaluation and implementation of enabling fabrication technologies and their subsequent automation and scale-up. A further area of responsibility lies with material selection and testing with the end goal of enhanced cell performance and cost reduction.

His previous experience was with Ceram Research, a research and technology organization, where he held a number of roles including Technology Strategy Analyst, Project Manager and Materials Scientist. He has more than 16 years ceramic processing experience, complemented by an MBA from Manchester Business School, which he completed part time while employed at Ceram Research. He also holds a PhD in materials science from Hallam University and a BS degree from Sheffield City Polytechnic.

Kathryn Rutter

Kathy has worked for the past three years for Ballard Material Products in Lowell, Massachusetts as a senior process engineer on their carbon paper and GDL manufacturing product line. She is the manufacturing engineer for the DOE program (DE-FG36-08GO18051) entitled “Reduction of Fabrication Costs of Gas Diffusion Layers.” This program focuses on the reduction of manufacturing costs of GDLs through both process simplification and utilization of new process technologies for continuous in-line measurements. Kathy came to the company with 20 years manufacturing experience in the film coating and web handling industry. She spent twelve of those years at Polaroid improving quality and efficiencies of processes and leading the development/implementation of new processes. Kathy has successfully applied her coating, drying and web handling knowledge to improve quality and yields while reducing the costs of GDLs. Kathy has a BS in Chemical Engineering from Rensselaer Polytechnic Institute and a MS in Chemical Engineering from Northeastern University.

Shailesh Shah

Shailesh Shah is currently working as the Leader, Fuel Cell Development Team, US Army RDECOM CERDEC. Prior to joining the Army, Mr. Shah’s professional career spanned over 15 years, mostly involved in technology and product development in the battery and fuel cell industries. Mr. Shah has made key contributions in the areas of battery systems design, development of proprietary electrode formulations and fabrication processes. His work on primary chemical hydrides led to the design and development of novel, high energy density portable hydrogen generator systems. Mr. Shah is also experienced in business development and commercialization of portable power technologies. Mr. Shah has an MS in Chemical Engineering from Bombay University.

Mark Shinners

Mark Shinners is a Senior R&D Engineer at ACI Technologies, Inc. with over 14 years of experience in research and development. He was formerly employed with Stonhard, a division of the Stoncor Group, a manufacturer of industrial flooring, specializing in chemically-resistant coatings and floors. His career at Stonhard began as a Laboratory Technician and rose through the ranks to Group Leader. Mark has worked more than 13 years in a R&D laboratory setting geared toward new product development and has over six years of project management, overseeing technical personnel and carrying out daily administrative duties. His successes include product development involving different coating chemistries, universal pigment dispersion used across several chemistries, and developing/implementing new testing procedures and equipment. His expertise extends to formulating industrial maintenance coatings as well as ultra-low VOC “green” products. Mark holds a MS in Materials Engineering from Drexel University in Philadelphia, PA and a BS in Physics from Kutztown University in Kutztown, PA.

Duarte Sousa

Duarte Sousa has spent 23 years in the manufacturing field, with 11 of those years working for Ballard where he was responsible for the installation of discrete and continuous manufacturing lines. He is Lean Manufacturing Certified by the Society of Manufacturing Engineers, and has a black belt certification from the American Society for Quality. His most memorable professional experience was a two-year foreign assignment in the Loire Valley, France, where his toughest decision on weekends was which castle to visit. He mentors engineering students at the University of British Columbia, coaches little league baseball, and is a scout leader. He has been married 20 years with three children and three Labradors.

Eric Stanfield

Eric has worked at NIST in the Dimensional Metrology Group for 18 years as a Mechanical Engineer/Dimensional Metrologist. His duties include providing measurement services to customers in support of the dissemination of the SI unit of length and he is responsible for conducting measurement research to ensure NIST continues to provide world-class uncertainties. Eric studies and understands the uncertainty of dimensional measurement at a level equivalent to only a small number of experts in the world. He has an A.A.S. in Metrology (1991) from Butler County Community College in Butler, PA and a B.S. in Mechanical Engineering (2004) from George Washington University. In 2004, he received the Judson C. French Award for “Outstanding Leadership in the Development of Improved Dimensional Calibration Services with Higher Efficiency, Accuracy, and Customer Satisfaction.” Eric has been the NIST Mechanical Metrology Division’s (formerly the Precision Engineering Division) project leader for the DOE Hydrogen and Fuel Cells Program sponsored efforts under the project titled “Metrology for Fuel Cell Manufacturing” since 2007.

Matt Steinbroner

Mr. Steinbroner has led research, development, and commercialization of fuel cells and fuel cell systems for 15 years at several companies, including The Electrosynthesis Company, Giner Electrochemical Systems, Idatech, and Protonex Technology Corporation. Mr. Steinbroner has leveraged diverse system experience to advance the robustness of components and systems, provide cost reduction strategies for a variety of electrochemical programs and products for the military and commercial markets. Mr. Steinbroner holds an ACS BS in Chemistry from the State University of New York at Fredonia.

Scott Swartz

Scott L. Swartz, PhD is the Chief Technology Officer and a co-founder of NexTech Materials. His current focus is on management of NexTech’s intellectual property portfolio, business development, and providing technical leadership and vision to the company. Dr. Swartz holds a BS in Ceramic Engineering from Alfred University, and a PhD in Solid State Science from The Pennsylvania State University. His previous affiliations include Battelle Memorial Institute and Mission Research Corporation. During his seven years tenure at Battelle, Dr. Swartz advanced to the level of Senior Research Scientist, and managed numerous R&D projects related to electronic ceramics, ferroelectric thin films, and optical materials. After co-founding NexTech Materials in 1994, Dr. Swartz shifted his technical focus to ceramic electrochemical systems, helping to establish NexTech’s presence as an international player in this field. Dr. Swartz has been principal investigator on several NSF, DOE, DOD, ATP and state funded programs related to sensors, catalysts, and solid oxide fuel cells. He has authored more than 60 papers in the technical literature. Dr. Swartz has received has received 12 patents, with multiple others pending.

John Trocciola

Mr. Trocciola has served as a full time employee, a private consultant, both professionally and on a pro-bono basis, for a variety of fuel cell developers and users, while developing and evaluating emerging and existing fuel cell technologies. He is widely valued for his expertise in fuel cell and electrochemical technologies and applications.

Present clients include UTC Power, The US Department of Energy (through Sentech Corp.), Agnion Energy and Elcomax. Previous clients included Advent-Energy, the US Department of Defense, US and overseas utilities (including NY Power Authority, Long Island Power Authority, RWE, and National Grid), Scripps Investments and Loans, Power Management Concepts, Connecticut Clean Energy Fund, Connecticut Department of Homeland Security, Massachusetts Technology Collaborative and several Town Governments in the State of Connecticut.

Prior to working as a private consultant, Mr. Trocciola served a variety of roles at the United Technologies Corporation, International Fuel Cells Division and UTC Power, from 1963 - 2004. His position as Manager of Advanced Materials and Development for International Fuel Cells allowed him to investigate the basic limits of materials for all fuel cell technologies including AFC, PEM, PAFC and MCFC. Testing at temperatures ranging between 120 and 1400°F in a variety of corrosive environments, Mr. Trocciola was able to identify the fundamental thermodynamic properties of carbons, graphites, metals, and polymers to determine their suitability for use in fuel cells. As a result of this work, most of the materials presently in use in PAFC and PEM fuel cells, i.e., various graphite and carbon types, catalyst supports, ceramics and polymers, were developed under his direction. He has been issued over 40 US Patents in all areas of fuel cells, manufacturing, and catalysis and is a past recipient of the Fuel Cell Seminar Award.

Mike Ulsh

As Senior Engineer, Manufacturing R&D Lead, Mr. Ulsh leads NREL's Fuel Cell Manufacturing R&D project and focuses on developing diagnostic systems for in-line quality control of both low and high temperature fuel cells, electrolyzer cells and components. He also studies the performance and durability effects of manufacturing defects in these materials.

Mr. Ulsh is the point of contact for NREL's manufacturing assessment and market transformation activities in support of the DOE Fuel Cell Technologies Program. Prior to joining NREL, Mr. Ulsh worked at 3M Company for 11 years, where he developed processes and products based on multi-layer polymer film constructions, transferring these technologies to a continuous manufacturing environment.

Mr. Ulsh has a Master's degree in Mechanical Engineering from the University of Colorado, and a Bachelor's degree in Aerospace Engineering from Virginia Tech. He has 8 issued patents as well as 11 journal articles related to polymer film processing.

Douglas Wheeler

Douglas Wheeler formed DJW Technology, LLC to provide fuel cell consulting services and hydrogen energies technology to industry, the Department of Defense, National Laboratories and universities. He has an international reputation as leader in the fuel cell area. Mr. Wheeler has successfully directed multi-million dollar research and development programs that led to fuel cell power plant for transportation vehicles that are currently the state-of-the-art ambient pressure fuel cells.

Presently, DJW Technology has a Phase I STTR contract from ONR to determine the feasibility of an Advanced Hydrogen Reformate Stream Purifier for Fuel Cell Applications and has recently been awarded the Phase II contract for this activity as well. As a consultant, Mr. Wheeler supports the University of Hawaii in their operation the Office of Naval Research program on the testing and development of fuel cell power plants. The ONR program has established world class, full size fuel cell testing capability at the Hawaii Fuel Cell Test Facility that is part of the Hawaii Natural Energy Institute of the University of Hawaii.

Mr. Wheeler received his MS in 1976 from Case Western Reserve University. He has over 30 publications and presentations as well as 35 patents which include 18 U.S. Patents.

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VII. FUEL PRIMER

At present, US Navy logistics fuels are defined by three specifications. The preferred source is NATO F-76. JP-5 and Marine Gas Oil (MGO) can be used if F76 is unavailable. While NATO F-76 has been successfully used by existing gas turbines and diesels, high sulfur (1% maximum) and aromatic content makes it a difficult to reform for use in fuel cells. There has been initial discussion within the Navy for conversion to a single fuel using JP5, which lowers overall sulfur content to 0.3% max, or lowering the sulfur specification for F76. However, worldwide availability and total usage of the fleet may prevent this in the near term. Therefore, any change may be delayed until the Navy can buy fuel that has significantly lower sulfur levels.

There is no indication that worldwide sulfur levels are dropping. As a result, the Navy is investing in the development of advanced liquid phase desulfurization technology focused on removing sulfur before the reforming process. This approach significantly reduces the overall system complexity by eliminating high pressures and temperatures associated with the regenerative hydrodesulfurization process. It also enables the future use of more integrated reformers, which reduces the total number of system auxiliaries and valves. Liquid phase desulfurization systems in development by Altex Technologies/Penn State University, Mesoscopic Devices, and Cal Novatech/University of Southern California have all shown initial success in removing all sulfur species associated with the Navy logistics fuel.

In addition to liquid phase desulfurization, research is proceeding through FuelCell Energy to develop gas phase high capacity nano ZnO sorbent. The nano ZnO can provide significant improvements for the fuel cell power plant system characteristics. Based on initial indications of potential doubling of the capacity for sulfur adsorption, the size of the ZnO sulfur sorbent reactors could be decreased proportionately. This would contribute significantly to the reduction on the size and weight of the logistic fuel processing equipment.

Conversely, keeping the volume for the new nano zinc oxide same as what is currently specified for the commercial ZnO, operating time between sorbent bed regeneration cycles could potentially double. In this case, the beneficial result would be increase in the operating time between maintenance required for sorbent replacement, resulting in a significant reduction of the overall maintenance requirements for the power plant.

Liquid Phase Absorption

Bulk liquid-phase absorption studies of Ti-Ce-O, Ti-Ce-Al-O, and Ti-Ce-Al-Ag-O compounds mixed with alumina were performed using real fuel JP-5 (~1000 ppmw sulfur) under Navy sponsorship to optimize the formula for maximizing sulfur absorbent capacity. Absorption studies were carried out at room temperature, 50 C, 100 C, and 200 C. Additional studies were conducted in fixed beds with flowing fuel and gas flow including air and oxygen (safety concerns exist for these processes).

No benefit was observed from operating at elevated temperatures, either in speed of absorption or ultimate capacity. Sulfur removing without gas flow was the most effective for long contact time adsorption. For the short fuel-sorbent contact time, O_2 flow could improve sulfur removal at 100 C. The result indicated that Ti-Ce-Al-Ag-O adsorbent (A) has the highest ultimate sulfur adsorptive capacity (7.49 mg-S/g-A) when the loading of Ag is 20.2 wt% in the compound, after 12 hours. Breakthrough capacity is approximately 2.5 mg-S/g-A or about 2 gr-fuel/gr-A.

The low absorbent capacity achieved in these studies clearly indicate these types of sorbents may be suitable for polishing, but are completely unsuitable for bulk sulfur removal.

Fractionation

As part of the liquid phase absorption programs, fractionation of the raw fuel was employed as a first stage process to reduce the sulfur burden on the downstream liquid phase sorbents. This was basically a low order packed bed distillation column designed to produce, in a single stage, a 30% light fraction and 70% heavy fraction stream (approximate ratios). The heavier sulfur compounds stay in the heavy fraction, and the light fraction results in a less challenging feed stream to the downstream process. The fractionation demonstration was successful, and the process can be accomplished efficiently if properly designed. However, the rejected heavy end stream no longer meets the specifications of the original fuel. It was proposed to send the heavy end stream back to the original fuel tank to be diluted and mixed back in with the remaining fuel. However, this is problematic since it may alter the original fuel properties and depending on relative quantities, might make it all unsuitable for other engines.

Oxidative Desulfurization

The objective of this work is to develop a selective oxidation process for the sulfur compounds present in the real fuel especially the recalcitrant ones. Aim is to develop a system which can be carried out in a single phase (organic phase) rather than a double phase system (the aqueous and organic system). Potential oxidants that work in a single organic phase system include oxygen, ozone and certain organic hydro peroxide which don’t require an aqueous system.

Selective oxidation ensures that the polarity of the compound is increased, which in turn increases the adsorption capacity and selectivity of the adsorbent for sulfur compounds. Molybdenum based catalysts have exhibited good activity for oxidation of DBT’s and substituted DBT’s present in the model fuel. After oxidation and analysis there is a disappearance of the sulfur peaks with appearance of new peaks which correspond to the sulfones that were generated by oxidation of sulfur compounds by cumene hydroperoxide. The corresponding sulfones were adsorbed using activated carbon derived from coke. Almost all sulfones produced during oxidation were removed by activated carbon.

The oxidative desulfurization is a proven process, however it requires a source of oxidizing compound, and activated carbon sorption beds. These requirements may not be compatible with mobile or volume limited (e.g., shipboard) applications.

Nano Zinc Oxide sorbents

The Navy has sponsored development work on production and characterization of nano-particle zinc oxide compounds for absorption of hydrogen sulfide gas from reformate streams. The finely divided nano zinc oxide enhances mass transport and increases sorbent bed capacity before breakthrough occurs. Bed capacity can be increased from 25-30 % of ultimate capacity to 60-70% of ultimate capacity, depending on process flow conditions and bed geometry. The nano zinc oxide can be regenerated with a hot dilute air stream, so a continuous process can be created with alternating beds of sorbent.

Pressure drop is an issue with the finely divided sorbent material, so layered beds with conventional sorbent pellets followed by the finely divided nano zinc oxide material may be required. Capacity should not suffer greatly using this arrangement. In addition to the nano zinc oxide material, finely divided conventional zinc oxide material, suspended in a metal fiber matrix, can also be used to enhance mass transfer.

This design requires sulfur tolerant reformers. ATR reformers have been demonstrated to be tolerant to up to 500 ppm sulfur, although higher temperatures are required and reforming efficiency suffers. Fractionation of the fuel has been shown to be effective in reducing the sulfur content in the light ends. A combination of fractionation and sulfur tolerant reformer may be required for fuels with higher sulfur content.

Palladium Membrane Separation of Hydrogen

Palladium membranes allow diffusion of hydrogen gas exclusively, producing a pure hydrogen fuel stream while rejecting all other contaminants. There are several issues with purification of reformate made from logistic fuels using palladium. Pure palladium is the preferred alloy for high diffusivity, however it is not tolerant of the hydrogen sulfide. Alloys of palladium with silver are more tolerant; however diffusion coefficients are lower resulting in larger units and increased cost. When designing the diffusion element, the thinnest possible palladium layer is desired to reduce the cost. However, this layer must be supported to tolerate the high differential pressure across the membrane that drives the diffusion process and maximizes hydrogen recovery. Thin layers are susceptible to damage and defects. Steam reformers are amenable to high-pressure operation, however the nickel based catalysts are not sulfur tolerant, and the platinum based catalysts are not hot enough in the SR to be effective. Autothermal reformers can run hotter, but they require high pressure air to maximize hydrogen recovery through the palladium. This requires a lot of energy and reduces system efficiency.

For best results, sulfur should be removed prior to entering the palladium separation unit. It is best to maximize the hydrogen content in the reformate stream by shifting the carbon monoxide prior to entering the palladium membrane unit. However, the shift reactors operate at lower temperatures than the separation unit, resulting in thermal integration issues.

Palladium membranes have been successfully used in the past for small steam reformer based fuel cell systems fuelled by methanol, natural gas, or kerosene. However, the addition of sulfur to the fuel causes system design issues, and the high cost of palladium precludes its application in larger (over 10 kW) applications.

Acid Gas Membranes

Low temperature polymer-based membranes which selectively diffuse acid gasses (carbon dioxide and hydrogen sulfide) are possible solutions for reducing the acid gas content of the reformate stream. These membranes have been studied in the past for reformate cleanup, however progress has been slow, and, while selective, the process does not result in complete removal of the hydrogen sulfide.

Thermal integration is also an issue since the polymer-based membranes operate at lower temperatures than shift reactors, zinc oxide sorbent beds, or palladium-based (dense membrane) separation units.

Sulfur Sensors

Continuous, online methods for sulfur analysis, for both liquid phase and gas phase streams, are required in order to control the sulfur removal processes and maximize the available sorbent capacity. At the same time, the sensitive fuel cells must be protected from contamination due to unintended breakthrough of sulfur compounds. Existing sulfur analysis sampling methods will be difficult to adapt to this requirement. If the sulfur content of the incoming fuel is known, this information can be used to adapt the controls to the known capacity of the sorbent materials, however variations in sorbent capacity can still put the fuel cells at risk of damage if breakthrough occurs.

Process Design

There has been some success in the development of sulfur tolerant components and processes for logistic fuel reforming and cleanup. The fuel cells themselves remain sulfur intolerant, so at that point in the process, all sulfur has to be removed. System studies have indicated that the sooner sulfur can be removed from the process, the better the overall outcome, and desirability of the resulting system from both a process standpoint and a user standpoint. A solution using several sulfur mitigation approaches might make the overall process acceptable; for example a combination of liquid phase fractionation, sulfur tolerant reformer, and zinc oxide final cleanup. Under the green fleet initiative, the Navy desires to introduce biofuels, which typically have lower sulfur content, and which could provide benefits to military fuel cell acceptability.

A regenerable liquid-phase sorbent could make the process easier to operate from a user standpoint. Changing out expended beds of solid sorbents makes these designs unacceptable for military applications due to undesirable maintenance requirements, and risk of irreversible damage to the expensive fuel cell stacks should this maintenance be deferred. To this writer's knowledge, acid gas ethanolamine-based scrubbers have not been studied in detail for reformate cleanup for military fuel cell applications, and might provide an acceptable solution to the issue of high sulfur content of logistic fuels. This process, already in use on submarines for life support, removes both hydrogen sulfide and carbon dioxide, enhancing reformate quality to the fuel cell anode. However, the absorption process operates at low temperature, complicating thermal integration.

Le Chatelier's Principle and the Water Gas Shift Reactor

Improvements to the WGS process through optimization of the heat transfer has had limited success. Raising the temperature has a negative effect on the process and can push the equilibrium in the opposite direction. Methods for shifting the equilibrium of the WGS reaction toward the formation of hydrogen can accelerate the reaction and simultaneously improve the manufacturing process. The overall reaction is shown in the equation below.

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \ (\Delta H = 41.16 \text{ kJ/mol})$$

Le Chatelier's Principle predicts that if you decrease the concentration of one of the product gases, the equilibrium will shift towards the products and reduce the carbon monoxide content. A fuel cell quality level hydrogen can be achieved. Two approaches are currently under development using Le Chatelier's Principle: 1) removal of hydrogen using a hydrogen selective membrane and 2) removal of carbon dioxide using a carbon dioxide selective membrane. By integrating either one of these processes with the WGS reactor, the carbon monoxide concentration in the hydrogen stream is reduced to levels acceptable for PEM fuel cell operation.

High Pressure Membrane Removal of Hydrogen

General Electric (GE) has developed a WGS Membrane Reactor Module concept integrating the WGS with hydrogen removal. The system requires the development of a hydrogen selective membrane. As part of the GE program, Idaho National Laboratory (INL) will identify membrane materials and provide them to GE who will develop membrane supports and system design. The pore size of the INL membrane is designed to selectively allow only the small hydrogen molecules to pass through the membrane.

There exists hydrogen selective, silica based membranes that were patented in 1997. The pores of these membranes are designed to be small enough to selectively allow the passage of hydrogen molecules. A high-pressure differential is the driving force for the GE and silica systems to separate the hydrogen from the syngas using the small, selective pores. The pressure differential maintains a hydrogen gradient across the porous membrane.

The silica membranes are reported to be unstable in the presence of steam (which is a major component of the syngas). The high-pressure requirement for the hydrogen containing reformate is a limitation of this process. Manufacturing processes are immature and the technology is in the demonstration stage.

Polymer Separation Membranes

Chemically selective membranes that react with the carbon dioxide and selectively transport the carbon dioxide out of the LT-WGS reactor, produce the Le Chatelier's Principle and shift the reaction to the right in chemical equation 8.1. These membranes have been demonstrated in the laboratory and have not been manufactured at a commercial level. Scale up of this technology is supported by ONR.

Optimize the WGS process using two potential pathways.

- **Design microchannel WGS reactors to optimize heat transfer** and maximize the rate of reaction for the conversion of water and carbon dioxide to hydrogen and carbon monoxide. This is a technical approach consistent with the evolution of WGS reactors.

- **Develop reactors that incorporate Le Chatelier's Principle** to revolutionize the WGS reactor process. This approach will decrease reactor size and eliminate the requirements for selective oxidation or methanation.

- **Reduce cost through the automation of the welding and assembly processes for the manufacture of WGS reactors.** This is essential for microchannel WGS and WGS reactors operating using Le Chatelier's' Principle. These two emerging WGS technologies have designs that are consistent with the automation of the manufacturing facility and design for manufacturing techniques can readily be applied. Manufacturing and quality control research and development are needed to develop cost competitive WGS reactors.

A variety of commercial processes are available for reducing the carbon monoxide content of the reformate, increasing the hydrogen partial pressure, and preventing deactivation of the PEM membrane catalyst. Selection of a specific process depends on the performance requirements of the power system. Several experimental processes may become available, as they are developed and mature, and provide improved system performance in the future. In many cases, the separations described above are derived from mature commercial processes operating on a large scale. Adapting the procedure to the small size scale of current fuel cells becomes a design and packaging challenge.

Palladium Membrane Purification

Palladium membrane purification utilizes the ability of palladium to adsorb hydrogen atoms into the atomic lattice of the palladium metal and transfer the hydrogen atoms through the lattice to be released at the other side of the palladium membrane. Molecules and atoms (other than hydrogen) are rejected and are not adsorbed into the atomic lattice of palladium. The process requires dissociation of molecular hydrogen into atomic hydrogen at the "inlet" side of the membrane and the association of atomic hydrogen into molecular hydrogen at the "outlet" side of the membrane. The conduction of atomic hydrogen through palladium is accelerated by temperatures as high as 300 °C. Maintaining a hydrogen pressure differential across the membrane is essential to transport of the hydrogen through the membrane. The partial pressure of the hydrogen in the syngas must be greater than the partial pressure of the hydrogen at the purification side. The pressure differential maintains a hydrogen gradient for driving the hydrogen from the syngas side of the membrane to the purified hydrogen side of the membrane. This partial pressure differential requirement is an efficiency loss since not all of the syngas hydrogen can be transported through the membrane and the partial pressure of hydrogen must remain greater on the syngas side of the membrane.

The failure mode of palladium membranes is a phase transition of the palladium that occurs with the adsorption and release of hydrogen and produces fracture of the membrane. The phase transition is also associated with the heating and cooling of the palladium membrane. Alloying the membrane with silver or copper is reported to eliminate or greatly reduce the phase transition with a durability improvement for the membrane.

Manufacturing limitations for palladium membrane purification are:

- The high cost of the palladium membrane.
- The hydrogen differential pressure across the membrane requires the membrane have sufficient strength with either a thick palladium membrane or an ultrathin palladium membrane supported on a substrate.
- The requirement for ultrathin, pore free membranes to increase the hydrogen selectivity and transport is a technical challenge.
- Reduced efficiency is the result of the requirement that the partial pressure of the hydrogen be greater on the syngas side of the membrane and ignition of the unused hydrogen in the impurity purge.
- The palladium membrane is readily poisoned by sulfur species and desulfurization will be required prior to hydrogen purification using a palladium membrane.

Alternative Synthesis Gas Cleanup

Chemically selective membranes can efficiently remove hydrogen sulfide and carbon dioxide from the syngas stream and concentrate the hydrogen. The chemically selective membranes operate at atmospheric pressure and reduced temperatures (130-200 C) compared to palladium membranes. Integration of a chemically selective membrane with a WGS reactor will reduce the carbon monoxide concentration and deliver PEM fuel cell quality hydrogen. The chemically selective membrane enriches the hydrogen concentration but does not remove the nitrogen from the syngas, which can be as high as 30%. The chemically selective membranes are in the research and development stage.

The high-pressure membrane removal of hydrogen was developed by General Electric (GE) as the WGS Membrane Reactor Module concept, integrating the WGS with hydrogen removal. The process (described earlier) is limited by the high pressure requirement. The manufacturing processes are immature and the technology is in the demonstration stage.

Conclusion

A variety of commercial processes are available for reducing the carbon dioxide content of the reformate and increasing the hydrogen partial pressure. Selection of a specific process depends on the performance requirements of the power system. Several experimental processes may become available, as they are developed and mature, and provide improved system performance in the future. In many cases, the separations described above are derived from mature commercial processes operating on a large scale. Adapting the procedure to the small size scale of current fuel cells becomes a design and packaging challenge.

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